# The Climate Lab Business Plan

By Glenn Weinreb

***MISSION:*** *Save the planet from climate change at the lowest cost to society.*

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# 1. Executive Summary

This is a business plan for *The Climate Lab* (TCL), a proposed laboratory that is tasked with solving the entire climate problem at the lowest cost to society.

Our current climate strategy is to encourage individuals, companies, cities and nations to "do something" about climate. Unfortunately, the cost and effectiveness of their efforts is rarely quantified, and this leads to wasteful spending. One might not care if someone else wastes their own money; however, there is a problem with waste. It is not scalable, and we need large volumes to tackle climate. More specifically, lawmakers are hesitant to expand programs perceived as low-value for money. In other words, due to political constraints and high volume requirements, the climate problem needs to be tackled at the lowest cost. This is a subtle point that is often ignored, and it suggests our society's current approach to climate is destined to fail.

Also, this presents an opportunity for a new organization to mathematically solve the entire problem at the lowest cost. One might refer to this as an "engineered approach to climate."

The proposed new laboratory is a collection of approximately 60 R&D funds that are maintained by established foundations. Each fund is overseen by a manager who has the authority to issue purchase orders, and each manager is overseen by a participating foundation.

For a 27-minute video that summarizes the TCL concept, click here.

## Decarbonization Cost

There are many initiatives that reduce carbon dioxide emissions. Each has a cost to society and an amount of carbon dioxide that is reduced. One can divide these two numbers to calculate the cost to reduce emissions by one metric ton of carbon dioxide ($/t$CO_2$). One can think of these parameters as "cost" and "impact." If decarbonization was pursued strictly in lowest cost order, for example, initiatives costing $10 per ton would be addressed first, followed by initiatives costing $12 per ton, and so forth. Many lawmakers ask "Why spend $200 to reduce carbon dioxide emissions by one ton, when we can do it for $20?" This suggests they favor decarbonizing in lowest cost order, if at all.

## A Beautiful Decarbonization

We define a "Beautiful Decarbonization" (BD) as one where costs to society are negligible over the entire decarbonization period. In other words, decarbonization occurs in lowest cost order, and R&D is successful at keeping green energy costs below fossil fuel costs as one goes through time. TCL aims to perform a beautiful decarbonization.

## Decarbonization Strategy

Approximately one-third of carbon dioxide emissions are from electrical power generation, another third from material and chemical production, and a final third from transportation. Also, a small percentage is from natural gas based building heat. If these were tackled in lowest-cost order, the additional cost to consumers during the early years would be close to zero. However, after several years of digesting "low hanging fruit," decarbonization would become more difficult. To make later years more tolerable, green energy costs could potentially be reduced with more R&D. Yet what might be developed? That is the point of this business plan—to identify areas currently not being addressed that could potentially have a significant impact.

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## Decarbonization Plan

In theory, software could identify how to decarbonize strictly in lowest cost order, and present a decarbonization plan. Yet why have we not seen such plans? In part, many people would lose their jobs due to being associated with high decarbonization costs (i.e., high $/t$CO_2$). Unfortunately, those responsible for solving the climate problem are often incentivized to do otherwise. What to do? Developing a website that creates a decarbonization plan based on user requirements would be helpful.

- R&D Fund: **Website Development - Score Climate Remedies**
  Support the creation of websites that evaluate existing decarbonization initiatives. For each initiative, the following parameters are estimated: cost to society, amount of $CO_2$ reduced, and cost per metric ton of $CO_2$ reduced (ref).

- R&D Fund: **Website Development - Generate Decarbonization Plan**
  Support the creation of websites that generate a decarbonization plan based on user-defined criteria. For example, a website user might request a plan that reduces U.S. carbon dioxide emissions by 1/30$^{th}$ each year over 30 years, in lowest-cost order, driven by gov't requirements, without taxes or subsidies, and with additional costs passed onto consumers.

## Sunlight Reflectivity Plan

If the U.S. fully decarbonizes, and other nations do not, little will be accomplished. Also, many climate models say runaway climate change is more likely than not, even with decarbonization. More specifically, observations show climate change is accelerating, and this is likely to worsen over the coming decades as tipping points activate.

In theory, sunlight could be reflected back into outer space to cool the planet and avoid tipping points. However, developing a planet cooling capability might cost tens of billions of dollars and take several decades. Yet by then it might be too late. What to do? Developing a website that explains both the global climate problem and potential solutions would be beneficial.

- R&D Fund: **Website Development - Assess Climate Situation**
  Support the creation of websites that summarize the climate problem with several graphs, after the user specifies a climate model (via a well-known scientist) and number of years they expect our society to emit carbon dioxide.

- R&D Fund: **Website Development - Generate Reflectivity Plan**
  Support the creation of websites that calculate how much sunlight needs to be reflected back into outer space to achieve a user-defined objective (e.g., prevent the collapse of the West Antarctic Ice Sheet), and generate a corresponding R&D plan.

## Automate Nuclear Power Construction

In theory, specialized machines could be developed that automate the construction of extra-safe nuclear power plants (ref). The cost to develop these machines would be small compared to the global cost of fossil fuel, which totals approximately $4,000 billion per year. This includes $2,500 billion per year for oil, $1,000 billion per year for coal, and $500 billion per year for natural gas.

Typically, around 66% of the energy produced by a nuclear fission reactor is lost to the environment as unused heat. However, this could potentially be utilized by co-located industrial processes (ref).

- R&D Fund: **Nuclear Power Automated Construction R&D**
  Support the development of custom machines that automate the construction of nuclear fission power plants.
- R&D Fund: **Processing Platform Standards Development**
  Support the development of plug-and-play standards that define how heat sources (e.g., fission reactors) connect to adjacent platforms of chemical processing equipment.
- R&D Fund: **Platform Transportation R&D**
  Support the creation of a transportation system that moves platforms of chemical processing equipment from factories to power generation sites.

## Achieve Commercial Fusion ASAP

Currently, scientists are exploring how to generate energy within a chamber that contains a hot plasma. This is referred to as "fusion," and it is not expected to become commercially available for another 20 years. However, a multi-billion dollar R&D initiative could potentially accelerate development.

The U.S. government currently spends approximately $800 million each year on basic fusion research. However, they do not "pick winners and losers," which means they do not focus on any one approach.

Several fusion companies are hoping to develop a machine in the 2030s that produces electricity. However, these would be paid for by investors, not electricity customers. Therefore, the cost of their electricity would be high, and not competitive in an electricity market. In the best-case scenario, these companies are not expecting to deliver competitively priced electricity until the 2040s, which is too late to address climate change.

Fortunately, a paper-only design of a fusion reactor that produces low-cost electricity does exist (ref). However, it relies on technologies still under development, such as liquid metal walls and 3D-printed magnets. TCL intends to focus on these with a surge in funding.

## Governments, Companies, and Foundations

There are two primary sources of R&D funding: Climate Money and Investment Money. Climate Money hopes to save the planet from climate change, whereas Investment Money hopes to make more money. Each has constraints. For example, Investment Money will not participate if too complicated, too risky, or consumer demand is lacking. Climate Money, on the other hand, often requires engineers and researchers to freely share their developments. This open sharing: (a) maximizes global utilization of developed technology, (b) promotes candid peer review, (c) encourages development of interconnection standards, (d) minimizes misleading or exaggerated claims, and (e) reduces reliance on individual researchers or institutions.

Governments, foundations, and individual donors are sources of Climate Money, whereas companies and investment funds are sources of Investment Money.

Companies often prioritize their own financial interests, over climate interests. For example, they typically avoid sharing information unless required to do so since transparency can interfere with: (a) securing patents, (b) developing proprietary products, and (c) attracting further investment.

## National Energy Strategy

Nations are concerned about energy security, energy economics, and climate change. Energy security involves reducing dependence on other nations who might withhold energy to gain influence; energy economics involves reducing energy costs to gain economic advantage; and climate change involves reducing carbon dioxide emissions.

Climate typically receives low priority. However, it would cost little to: (a) decarbonize ~20% of $CO_2$ emissions via solar and wind power, (b) increase R&D in key areas, and (c) shutdown ineffective programs. In other words, do more for less.

## Decarbonization Law

The lowest cost way to decarbonize is to enact laws that require it, without subsides, without taxes, and with additional costs passed onto consumers. An example of this is the U.S. Clean Air Act in 1972. This required power companies and refineries to emit less air pollution. To comply, they filtered more, and passed additional costs onto consumers. Requirements such as these can be instituted without engagement from *each* citizen, company, city and state. In other words, one can focus on a few control points within an economy, and burn as little political capital as possible. However, we rarely see requirement laws at large scales when decarbonization costs are high. Therefore, more R&D is needed to reduce these costs.

## Small Money First

Initial R&D does not need to be expensive. One often spends small money before medium money, and medium money before big money—and only advances if technically and economically feasible. Small typically involves rough designs, cost models, and proposal writing. This is sometimes referred to as "Phase I." Medium typically entails detailed designs and prototypes. And big typically involves setting up factories that produce large volumes.

## Unique Organizational Structure

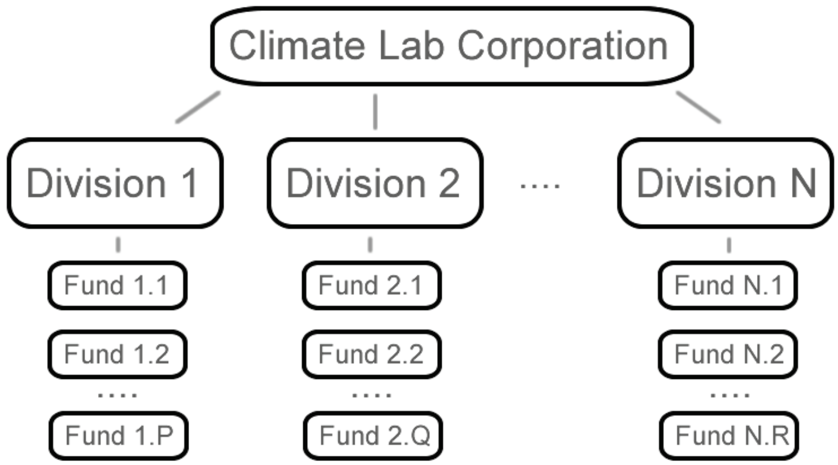
R&D for large initiatives is typically avoided by companies due to excessive risk; avoided by research universities due to a reliance on professor-sized projects; and avoided by governments due to a lack of technical leadership.

TCL aims to overcome these obstacles through a unique organizational structure. It intends to operate as a small 501c3 nonprofit organization, led by a group of top scientists and engineers who oversee the TCL System.

Open-source is needed to coordinate many people at many different organizations. More specifically, scientists and engineers who receive funding are required to make produced materials freely available via an open-source license. This reduces dependency on the original creators, maximizes the utilization of developed materials, accelerates decarbonization efforts, and elicits trust among Sponsors.

## The TCL System

The TCL System is a virtual laboratory that is overseen by The TCL Corporation, a 501c3 non-profit.




The TCL System consists of multiple R&D Divisions, each of which consists of multiple R&D Funds.

Each R&D Fund is maintained by a Managing Foundation, which is an existing organization that has experience handling donations, and spending that money wisely.

An R&D Fund is an account with money, and an R&D Fund Manager is a human with the authority to issue purchase orders on that account. Most chapters within this document describe one R&D Division and its funds.

An R&D Fund Manager presides over an R&D Fund. An R&D Division Manager presides over an R&D Division. And the TCL Corporation presides over multiple R&D Divisions.

More specifically, R&D Fund Managers can issue purchase orders, R&D Division Managers can add/subtract R&D Funds and hire/fire R&D Fund Managers, and the TCL Corporation can add/subtract R&D Divisions and hire/fire R&D Division Managers.

R&D Fund Managers are technical experts in the work being handled by the R&D Fund. For example, a fund that supports the development of experimental spray airplanes for SAI, might be managed by an engineer with experience developing crop duster or firefighting aircraft.

## Managing Foundations

Managing Foundations are large established organizations that are known for responsibly managing large amounts of money.

Within the TCL System, Managing Foundations are responsible for: (a) receiving tax free donations from Sponsors, (b) maintaining these funds in a physical bank account, (c) maintaining an online accounting system with purchase orders and invoices, and (d) recruiting/managing R&D Fund Managers.

Managing Foundations are required to support overhead costs incurred at their own organizations with their own money, not Sponsor money. This includes paying R&D Fund Managers and administrative staff. In other words, 100% of a Sponsor's money passes through a Managing Foundation, to support scientists/engineers via PO's. This elicits trust among Sponsors, and reduces a foundation's incentive to add unnecessary internal overhead costs.

## TCL Corporation

The TCL Corporation is responsible for: (a) maintaining a website that provides open access to developed materials, (b) communicating the TCL concept via video/film (c) setting up Managing Foundations, (d) recruiting Sponsors, and (e) recruiting R&D Division Managers.

The TCL Corporation also maintains agreements between TCL and Managing Foundations, between Managing Foundations and Sponsors, between TCL and R&D Division Managers, between Managing Foundations and R&D Fund Managers, and between Managing Foundations and recipients of purchase orders.

A large amount of additional R&D is needed to avoid climate change tipping points, and the TCL Corporation initiates this expansion.

## Sponsors

Sponsors financially support the TCL System. More specifically, they direct money to: (a) a specific proposal, (b) an R&D Fund, (c) an R&D Division, (c) a Managing Foundation, or (d) the TCL System.

If money is directed to the TCL System, the TCL Executive Panel decides how it is used.

Through an on-line system, Sponsors can view Purchase Requisitions, view Purchase Orders, and view Proposals. Also, they can personally interact with R&D Fund Managers, and R&D Division Managers.

## R&D Funds

Each R&D Fund begins with $0.3M to $3M of "Phase I" activity. This supports rough design, cost modeling, experiment design, proposal writing, review, etc. Phase I activity is used to determine economic and technical feasibility. If feasibility is lacking, further support is unlikely.

Each R&D Fund is set up with the following procedure: (1) Sponsor commits to Phase I support in an R&D Fund of their choosing, (2) Managing Foundation recruits R&D Fund Manager, (3) Fund Manager enters Purchase Requisition into accounting system, (4) request is approved, and (5) Purchase Order is issued to scientist or engineer.

## We Need Help!

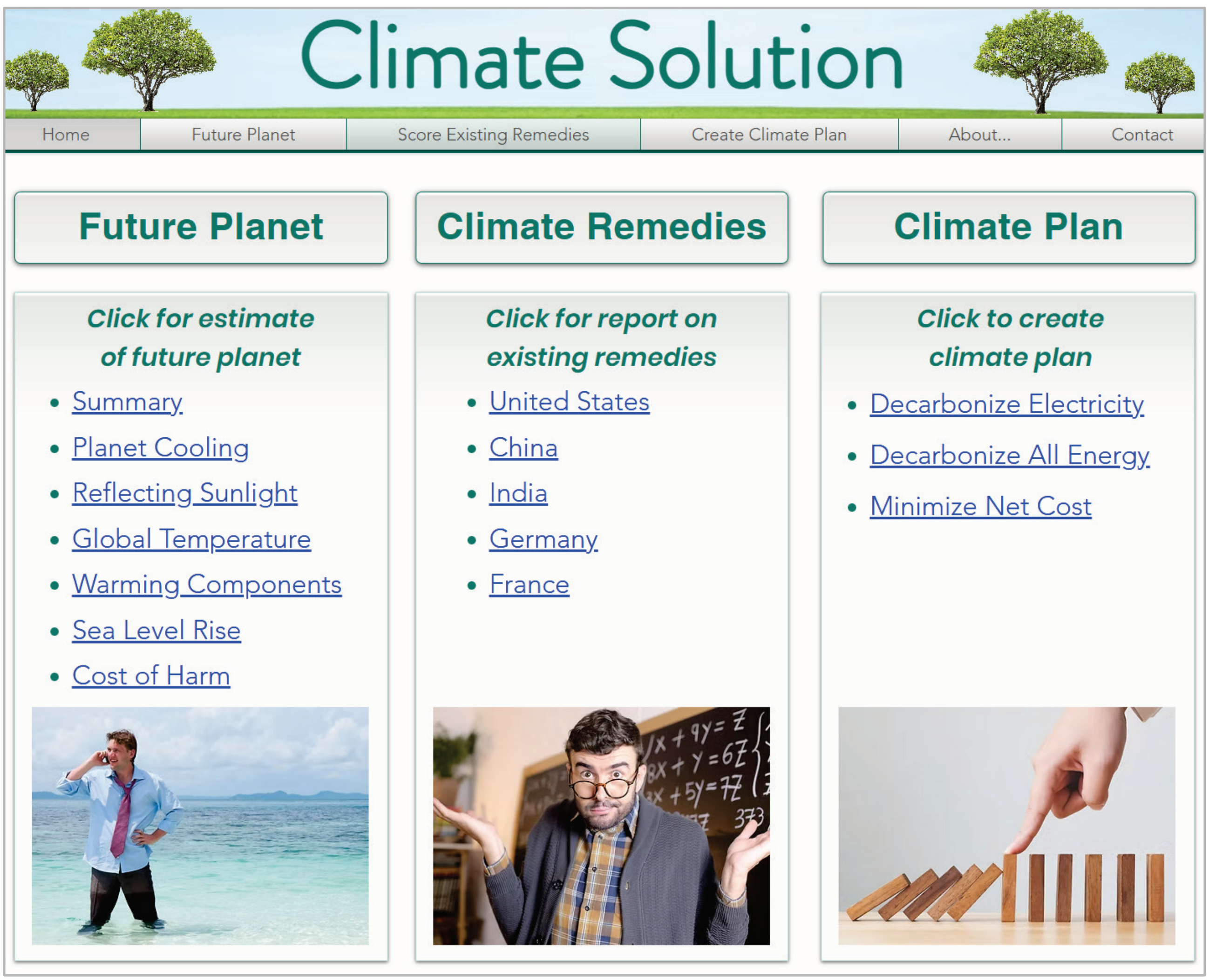
The TCL Corporation seeks collaboration with governments, foundations and individuals who wish to participate in The TCL system.

# 2. Climate Solutions Website

To survive climate change, the public needs to understand the problem *and* the solution. This is difficult to describe in a document. Therefore, we propose a website be built that breaks the problem down into four parts:

| | | |
|---|---|---|
| Part 1 | Score Climate Remedies: | *Quantify impact of decarbonization remedies* |
| Part 2 | Generate Decarbonization Plan: | *Create plan that reduces $CO_2$ emissions* |
| Part 3 | Assess Climate Situation: | *Summarize climate problem with several graphs* |
| Part 4 | Generate Reflectivity Plan: | *Generate plan that increases atmosphere's reflectivity* |

We call this website "Climate Solution," and we built a non-functional prototype that demonstrates the concept, pictured below. The document you are reading is open-source, which means anyone can copy (i.e., bifurcate), modify, and rename for free via the CC BY 4.0 license. For original files, click here.



## Website Part 1 - Score Climate Remedies

From an economics perspective, decarbonization involves initiatives that reduce $CO_2$ emissions. Each initiative has a cost to society, and an amount of $CO_2$ that is reduced. One can divide these two numbers to calculate the cost to reduce emission by one metric ton of $CO_2$.

For example, when homeowners install solar panels, it typically cost over $100 to reduce $CO_2$ emissions by one ton of $CO_2$. Conversely, when building solar farms or wind farms, it typically cost less than $20 per ton.

The first part of the website evaluates decarbonization initiatives, and presents the results in a Summary Remedy Table (SRT). Within this table, initiatives are listed in rows, while columns show cost to society ($), $CO_2$ reduced (mt$CO_2$), and cost per metric ton of $CO_2$ reduced ($/mt$CO_2$).

The table is sorted by cost per ton, placing the most cost-effective programs at the top. In theory, policymakers could expand effective programs, while reducing others.

The website supports multiple nations, since everyone needs to decarbonize—not just one nation.

## Website Part 2 - Generate Decarbonization Plan

It is unlikely lawmakers would support significant changes to their economy without a detailed decarbonization plan. While such plans currently do not exist, they could be generated using software and existing economic energy models (such as NEMS).

The proposed website creates a climate plan after the user specifies a strategy. For example, a user might request a plan to "Decarbonize nation Z, over X years, in lowest-cost order, without taxes or subsidies, driven by gov't requirements, and with additional costs passed directly onto consumers."

A decarbonization plan consists of a set of tables, one table per year, where individual initiatives are shown in rows, and key parameters (e.g., cost, tons of $CO_2$ reduced, and cost per ton) are shown in columns. Also, summary parameters are displayed at the bottom of each table (e.g., total societal cost per year, total $CO_2$ reduced per year, and average cost per ton).

### *How Much Does It Cost to Fix This?*

A climate plan answers the critical question, "How much would it cost to solve the entire climate problem?" This question is of profound importance, yet rarely discussed. An example answer is shown below.

| | | Year 1 | Year 2 | Year 3 | … | Year 10 | … | Year 20 | … | Year 30 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Decarbonization** | R&D | $8 | $8 | $8 | … | $8 | … | $8 | … | $8 |
| | Operations | $10 | $20 | $32 | … | $142 | … | $445 | … | $727 |
| **Reflecting Sunlight** | R&D | $5 | $5 | $5 | … | $5 | … | $5 | … | $5 |
| | Operations | | | | … | $27 | … | $27 | … | $27 |
| TOTAL | | $22 | $33 | $45 | … | $182 | … | $485 | … | $767 |

In this table, costs values are in units of dollars per American per year, although Europeans would see similar numbers. These costs would manifest as an increase in the price of goods and services, in addition to government and foundation expenditures for climate change.

The first two rows refer to a Decarbonization Plan, while the last two rows refer to a Sunlight Reflectivity Plan. The user clicks on rows to “drill-down” and see a breakdown with more information.

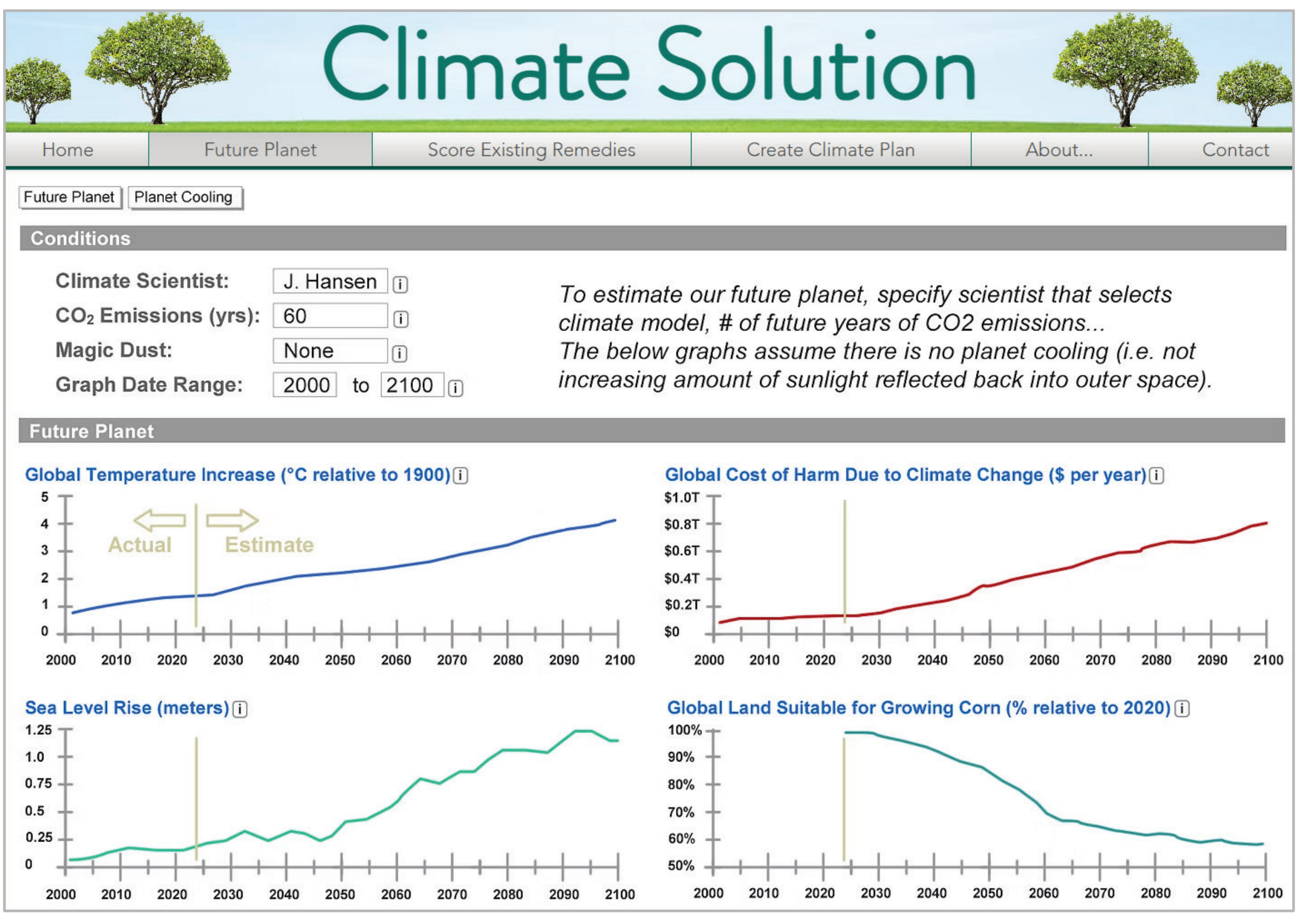
This example table assumes a steady decarbonization rate over a 30-year period, with initial “green premium” costs starting at $20 per ton of $CO_2$ reduced, and gradually rising over 30 years to $80 per ton. In theory, these costs can be reduced with more R&D.

The left portion of the table represents Years 1, 2, and 3 (the “early years”), whereas the right portion covers Years 10, 20, and 30 (the “later years”). The early years are relatively easy, since green premium costs are proportional to the amount of $CO_2$ reduced, and initially this would be small.

For a video that further explains this table, click here.

## Website Part 3 - Assess Climate Situation

The “Future Planet” section of the website summarizes the climate problem with several graphs. These estimate changes over the next century, including global temperature increase, sea-level rise, reduction in food production, amount of planet cooling needed to prevent cascading tipping points, costs associated with planet cooling, and economic losses due to climate change. A concept illustration of these graphs is shown below.



This data would be generated by climate models. However, selecting a model and its driving parameters is complicated. Therefore, climate models would be selected and set up by leading scientists, and the website user would choose a scientist, instead of a model. For example, one user might trust the leader of the IPCC, while another prefers the leader of NOAA.

The website user would also specify how many more years they expect our society to emit $CO_2$ (e.g., 30, 40, 60, or 120 years). Many economists expect emissions to continue for over 100 years, whereas climate activists prefer less than 40.

After the user selects a scientist and decarbonization timeframe, graphs would summarize the climate problem, and indicate what it takes to avoid tipping points. In other words, for a given level of decarbonization and planet cooling, the user can see expected outcome.

## Website Part 4 - Generate Reflectivity Plan

In theory, reflecting more sunlight back into outer space could cool the planet and prevent climate tipping points. However, it might take several decades and tens of billions of dollars to build up this capability. This presents us with a risk—by the time this capability is established, it might be too late. To help manage this risk, the website generates a sunlight reflectivity R&D plan based on objectives specified by the user (e.g., avoid a specific tipping point).

## Solving the Entire Climate Problem

If a foundation, university or government wants to solve the entire climate problem, it should consider writing software that creates a **Comprehensive Climate Plan** based on user requirements. This would include reflecting sunlight plans for the entire planet, and decarbonization plans for individual nations. To be truly useful, it would need to support requirements sought by lawmakers. These include things like “solve the entire climate problem at the lowest cost” and “drive down the cost of green energy to below that of carbon-based energy using R&D.”

## Spending Billions of Dollars to Save Trillions

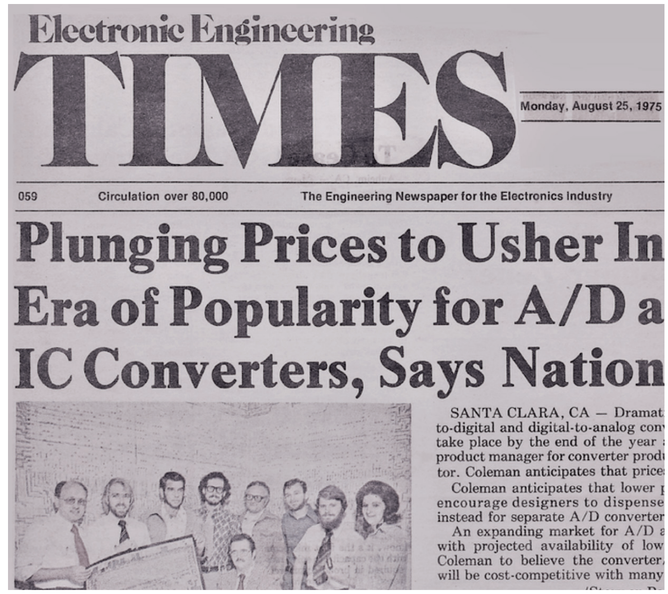
Currently, the world spends $4T each year on fossil fuel. This includes $2.5T for oil, $1T for coal, and $0.5T for natural gas. If the world decarbonized, then $4T *instead* would be spent annually to produce green energy. This includes things like paying down the mortgage on solar farms and wind farms.

Ok, let's focus on this $4T number for a moment. In a green new world, this is roughly how much money would be spent to produce green energy each year. Also, this cost can be reduced with targeted R&D. For example, if $20B was spent annually over 5 years on additional R&D ($100B total), and this caused 30 years of green energy costs to decrease by 20%, then each R&D dollar would save 240 green energy production dollars ($4T x 20% x 30yrs / $100B). In other words, we should think about how to spend billions of dollars on R&D, to save trillions of dollars.

## What R&D?

Ok, but what R&D? Or more specifically, what can we develop that is currently not being developed, that has the potential for significant impact?

## AspenCore Climate Solutions Research Center


Electronic Engineering
TIMES
Monday, August 25, 1975
059 Circulation over 80,000 The Engineering Newspaper for the Electronics Industry

Plunging Prices to Usher In
Era of Popularity for A/D a
IC Converters, Says Nation

SANTA CLARA, CA — Dramat
to-digital and digital-to-analog con
take place by the end of the year
product manager for converter produ
tor. Coleman anticipates that price
Coleman anticipates that lower
encourage designers to dispense
instead for separate A/D converter
An expanding market for A/D
with projected availability of low
Coleman to believe the converter
will be cost-competitive with many

Answering this question is the job of the AspenCore Climate Solutions Research Center.

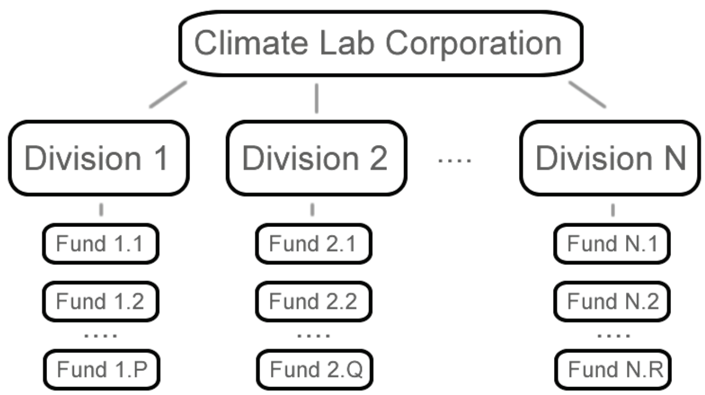
AspenCore is the largest publishing company in the electronics industry. They publish Electronics Design News, Power Electronics, and EE Times.

EE Times has been active for over 50 years. For example, in 1972 they snail mailed a weekly physical newspaper to 60,000 electrical engineers.

Fast forward to modern times and we have AspenCore CEO Cyrus Krohn noticing many readers are interested in electrical power, energy, and climate change. He responded by setting up a Climate Solutions Research Center to identify how to solve the entire problem at the lowest cost to society via engineering. Over 50 climate solution articles and over 13 climate solution videos have been published, and highlights have been copied into a Climate Lab Business Plan.

AspenCore does not pay people to do R&D, and does receive money to do R&D. Instead, they publish free suggestions for others. Climate solution research is not easy. For example, 25 researchers were interviewed for the fission and fusion chapters of the lab business plan.

## R&D Packages




Additional R&D for climate change can be broken down into separate R&D areas, or "Packages," where each is supported by multiple R&D Funds. An R&D Fund is an account with money, and an R&D Fund Manager is a human with the authority to issue purchase orders.

The Climate Lab Business Plan devotes one chapter to each of eight suggested R&D Packages. These include: (a) develop a climate solution website, (b) achieve economic fusion within a few years, (c) automate the construction of nuclear power sites, (d) develop underground nuclear power plants, (e) develop an automated system that places solar material directly onto soil, (f) develop a swappable car battery standard, (g) develop next generation building automation & control standards, and (h) determine how to reflect approximately 1% of sunlight back into outer space at a reasonable cost without harm. These R&D areas are currently not being worked on in a significant way, and have the potential for significant impact.

The Climate Lab Business Plan has two purposes: (a) it helps to set up a virtual R&D laboratory that is tasked with solving the entire climate problem, and (b) it helps to describe R&D Packages within a Comprehensive Climate Plan for society.

## Small Money First

Initial R&D does not need to be expensive. One often spends small money before medium money, and medium money before big money—and only advances if technically and economically feasible. Small typically involves rough designs, cost models, and proposal writing. Medium typically entails detailed designs and prototypes. And big typically involves more software, more refinements, and small scale operations.

One might refer to small, medium, and large as Phase I, II and III activity. A national climate plan would specify the following for each phase within each fund: (a) estimated cost, (b) estimated duration, and (c) brief description. This information would help populate the budget table for each R&D Package.

## Giving Technology Away For Free

Companies typically focus on increasing the value of their stock, while foundations and governments typically focus on solving the climate problem. In theory, foundations and governments could support R&D that drives down the cost of green energy to below that of fossil fuel. And to facilitate global decarbonization, they could then give this technology away for free.

There is two types of R&D. One is Product R&D and the other is Production R&D. The former involves product development, while the later involves developing a factory that mass produces a product. In some cases, the factory is 100-times more complicated than the product. If a company devotes 15% of its revenue to Product R&D, and 15% to Production R&D, for example, then costs decrease 30% if someone else pays for their R&D.

## Open-Source Requirement

The climate problem is large, and it follows that the solution would be large too. For example, if $20B was spent each year on additional climate R&D, and $500K/year was devoted to each technical person, then 40,000 technical people would be needed ($20B ÷ $500K). This goes beyond what one university could handle. Therefore, money would need to flow too many organizations.

An open-source requirement is probably needed to coordinate many people at many organizations. In other words, people who receive money through a climate lab system would probably be required to place developed materials on the internet, and marked open-source. Subsequently, they could be used by others for free. The alternative would likely introduce inefficiencies that discourage funding sources from participating. In other words, to get money to flow, open-source probably needs to be required.

Also, open-source is needed to distribute developed technology to companies, to reduce green energy costs worldwide, to reduce global $CO_2$ emissions.

## Working with Costs

Comprehensive Climate Plans involve several types of costs. These include decarbonization operations costs (“green premium”), decarbonization R&D costs, reflecting sunlight operations costs, reflecting sunlight R&D costs, and climate harm costs. These costs are often interdependent. For example, if decarbonization operations costs *decrease*, then climate harm costs will probably *increase*. Or if decarbonization R&D costs *increase*, then decarbonization operations costs will probably *decrease*.

The website estimates these costs, and helps the user find a path that meets their satisfaction. Also, the website calculates the cost of the various options, and identifies the lowest cost approach.

Developing this website requires climate scientists that work with climate models, energy economists that work with economic models, and computer programmers that write software.

## What is the Role of For-Profit Companies?

If $120T was spent to produce green energy over 30 years at $4T per year, for example, it would need to flow to for-profit companies who provide products and services. In some cases, these companies would utilize open-source technology developed by others.

## Who Pays For What?

It is not necessary for a Comprehensive Climate Plan to specify: (a) where R&D money comes from, (b) where R&D money goes, (c) organizations that maintain R&D Funds, (d) R&D Fund Managers who have the authority to issue purchase orders, and (e) researchers who receive money for work. This information is important; however, funding sources would first need to specified requirements. For example, a national government might support several R&D Funds at a specific level, and require money be spent locally.

## R&D Funds: Climate Solution Website Development (CSW)

Below is a list of suggested R&D Funds that support the development of software that creates a Comprehensive Climate Plan. Doing this to the satisfaction of multiple national governments would probably exceed the capabilities of one research group; therefore, we advocate R&D Funds be established that support this kind of work.

- R&D Fund: **Website Development - Score Climate Remedies**
  Support the creation of websites that evaluate existing decarbonization initiatives. For each initiative, the following parameters are estimated: cost to society, amount of $CO_2$ reduced, and cost per metric ton of $CO_2$ reduced (ref).

- R&D Fund: **Website Development - Generate Decarbonization Plan**
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emissions by 1/30th each year over 30 years, in lowest-cost order, driven by gov't requirements, without taxes or subsidies, and with additional costs passed onto consumers.

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  Support the creation of websites that summarize the climate problem with several graphs, after the user specifies a climate model (via a well-known scientist) and number of years they expect our society to emit carbon dioxide.

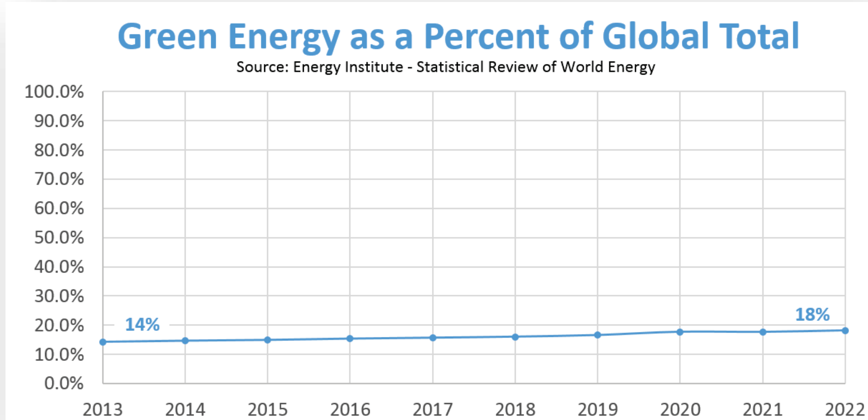
- R&D Fund: **Website Development - Generate Reflectivity Plan**
  Support the creation of websites that calculate how much sunlight needs to be reflected back into outer space to achieve a user-defined objective (e.g., prevent the collapse of the West Antarctic Ice Sheet), and generate a corresponding R&D plan.

# 3. Laboratory Strategy

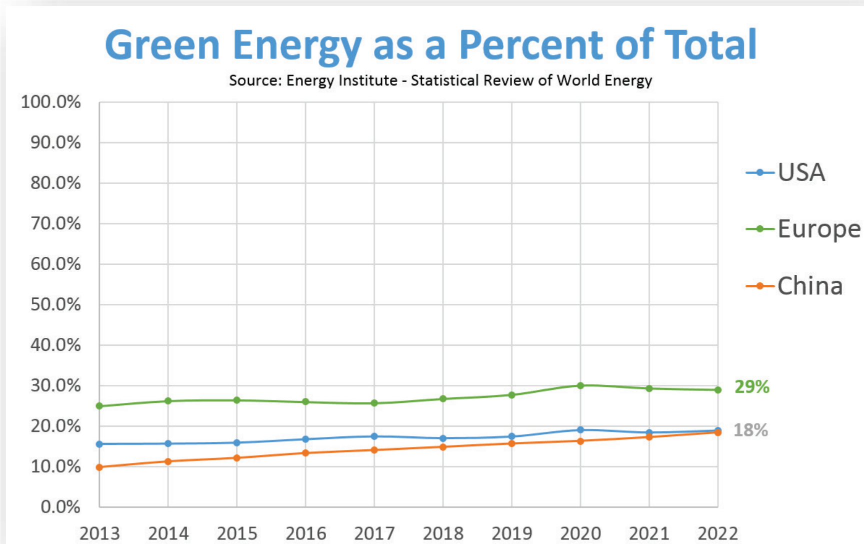
The public is inundated with gloomy news reports that emphasize the need to decarbonize.

But is anyone paying attention?

Let's explore.




This graph shows the percentage of global energy that does not emit carbon dioxide. It represents all energy forms—not just electricity—and applies to the entire world rather than any single nation. As one can see, the global share of carbon-free energy has increased only modestly, from 14% to 18%, over the past decade. At this pace, achieving full decarbonization would take approximately 200 years—far too long to effectively address the climate problem.




We can also examine progress in specific regions: the U.S. is currently on track to fully decarbonize over ~250 years, Europe over ~175 years, and China over ~100 years.

Why not decarbonize?

## The Prisoner's Dilemma Problem

To better understand our lack of progress, we need to view climate through the lens of economics.

Climate harm arises from the collective carbon dioxide emissions of eight billion people. One person's own carbon dioxide is too small to be relevant; therefore, no one benefits from reducing their own emissions. Instead, each individual prefers the other eight billion people reduce theirs. Economists refer to this situation as a “prisoner's dilemma problem.” According to economic theory, our fundamental strategy of using social pressure to solve the climate problem is destined to fail.

## Making Green Cost Less Than Carbon

In theory, R&D and mass production could reduce the cost of green energy to levels below carbon-based energy. This would incentivize nations to adopt green technologies, to be more economically competitive, to keep voters employed.

*It is possible this is the only way to solve the carbon dioxide emissions problem.*

Unfortunately, the U.S. government estimates persistent green energy sources (i.e., not solar, not wind) to remain more expensive than carbon-based sources over the next 30 years.

## The Saturation Problem

In many regions, the cost of electricity from a solar farm or wind farm is less than the fossil fuel it replaces. In other words, green costs less than carbon. However, if one continues to build solar/wind farms, they eventually reach “saturation,” which entails green supply exceeding electricity demand. At this point, electricity is discarded and construction stops. To decarbonize further, more persistent sources of green energy are needed. These include nuclear power, geothermal, solar/wind with battery storage, etc. These provide electricity when the wind does not blow and the sun does not shine, yet at a higher cost.

## 30-Year Decarbonization

In theory, a region could steadily reduce carbon dioxide emissions by approximately 1/30$^{th}$ per year over 30 years, in lowest-cost order. Under this approach, power companies would be required to size solar and wind farm construction to meet each year's emission-reduction target. Initially, the costs would be minimal, as solar and wind are comparably priced with fossil fuels. However, after five to seven years, saturation would occur, and decarbonization costs would increase. Moreover, if prisoner's dilemma applies, few would decarbonize further.

In other words, if you believe prisoner's dilemma, and you believe U.S. government estimates for future green energy costs, then roughly 20% of global carbon dioxide is likely to be decarbonized, yet not more.

For details on 30-year decarbonization costs, click here.

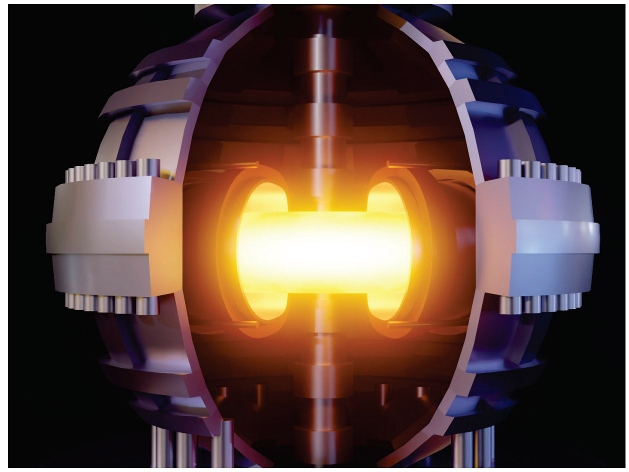
## More R&D

In conclusion, a *surge* in R&D is needed to reduce the cost of persistent green energy beyond current projections made by the U.S. government. This would help prepare for the day when solar and wind power saturate. The cost of this additional R&D would be small compared to the $4,000B spent globally each year on fossil fuel, and compared to the cost of climate harm.

Yet what might be developed? Let's explore.

# 4. Commercial Fusion

There are two primary types of nuclear power: fission and fusion.



Fission is the traditional form that generates electricity with uranium fuel. 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 within a donut-shaped reactor, as illustrated here.

## Commercial Fusion

Some scientists believe fusion power will not become commercially viable for another 20 years. However, a multi-billion dollar R&D initiative, overseen by the world's top scientists, could potentially accelerate development.

TCL defines "commercial fusion" as generating electricity with fusion at a cost below that of fossil fuel based electricity. This is sometimes referred to as "economic fusion", and it requires the fusion machine to operate reliably for extended periods, without failure, while keeping costs low.

If green energy were cheaper than fossil fuels, nations would have a powerful incentive to decarbonize, to save money, to remain competitive, to keep voters employed. In other words, cheaper green energy could potentially solve the carbon dioxide emissions problem.

Current fusion machines take years to construct and operate for seconds to minutes per experiment. Many scientists hope this will lead to economic fusion within a few decades. Alternatively, a surge of funding in key areas could potentially change this trajectory.

## Fusion Moonshot

Harm from climate change is likely to cost trillions of dollars; therefore, it is reasonable for governments and foundations to allocate billions of dollars to achieve economic fusion within several years. While this might seem unrealistic, consider the remarkable number of "gadgets" the U.S. designed and manufactured between 1939 and 1945.

In 1961, President Kennedy declared his goal to land a man on the moon by the end of the decade. In response, a program was established and funded. In theory, a similar approach could be applied to economic fusion.

But how might our society tackle fusion R&D differently? Let's explore.

## Tokamak vs. Stellarator

The tokamak and the stellarator are two fusion designs that could potentially produce large amounts of electricity in the near future. The tokamak features a donut-like shape, while the stellarator is more bumpy.

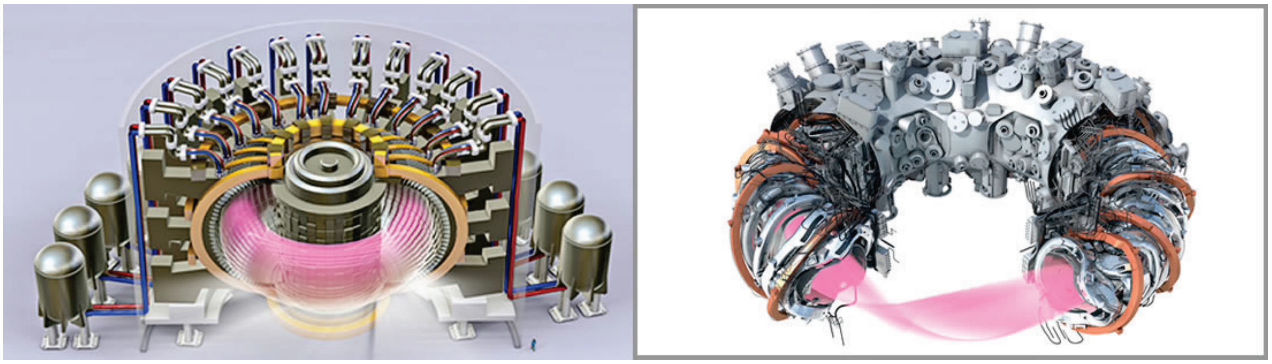


*Figure 4.1: Tokamak (left) and stellarator (right).*

These two approaches to fusion might seem to differ by bumpiness. However, upon careful inspection, one might notice additional gadgetry in the middle of the tokamak. This is used to maintain an extraordinarily high current—approximately 10 million amperes—within the plasma.

Sustaining such currents is no small feat. For context, a typical household vacuum cleaner draws about 10 amps, making tokamak currents equivalent to a million vacuum cleaners operating simultaneously. If a "disruption" occurs and this current inadvertently contacts the containment vessel wall, severe damage can result. Tokamaks must contend with this risk; however, plasma in stellarators do not have these currents, and are therefore easier to maintain.

## Damage is Bad

Damage within high-energy fusion devices is especially problematic because internal components typically become radioactive during operation. Radioactivity results from neutron activation and from the absorption of radioactive tritium gas into surfaces, which later outgas. As a result, human contact with these components must be avoided for many years after the reactor begins operation.

If ITER, a major tokamak project, experiences damage after starting high-energy operations (expected around 2034), repairs might be impossible due to radioactivity hazards. In other words, due to worker safety, the site might need to be abandoned—despite its roughly 50-year construction period.

## Cost Advantages of Stellarators

Cost models estimate the cost to generate electricity with a tokamak and with a stellarator, and according to Princeton Plasma Physics Laboratory (PPPL) Director Steven Cowley, "stellarator cost models beat tokamak every time—but it is at a very low technology level."

In other words, stellarators are less expensive. Their cost advantages stem from several factors: (a) they do not require the central gadgetry found in tokamaks, (b) they avoid the need to periodically replace central magnets damaged by neutrons, (c) they are not prone to disruptions that damage internal surfaces, and (d) they require less external microwave power to sustain the plasma.

## Making Electricity

The heat from a fusion reactor core needs to be moved outward, to create steam, to press on fan turbine 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.

To produce electricity cost-effectively, the energy output from the plasma must exceed the energy input (plasma gain > 1), and the electrical power generated by the site must surpass the electrical power consumed (engineering gain > 1). This requires powerful magnets and adequate plasma confinement, both of which are reasonably well understood by scientists.

## First Wall

There are two primary methods for handling the plasma-facing "first wall." One involves flowing liquid directly in *front* of a metal plate, and the other involves flowing liquid *behind* a metal plate.

### Liquid Metal Wall

In theory, a roughly 0.5m thick layer of flowing molten lithium metal could cover the internal surface of the plasma containment chamber. This would be held in place by electric currents in the liquid metal itself.

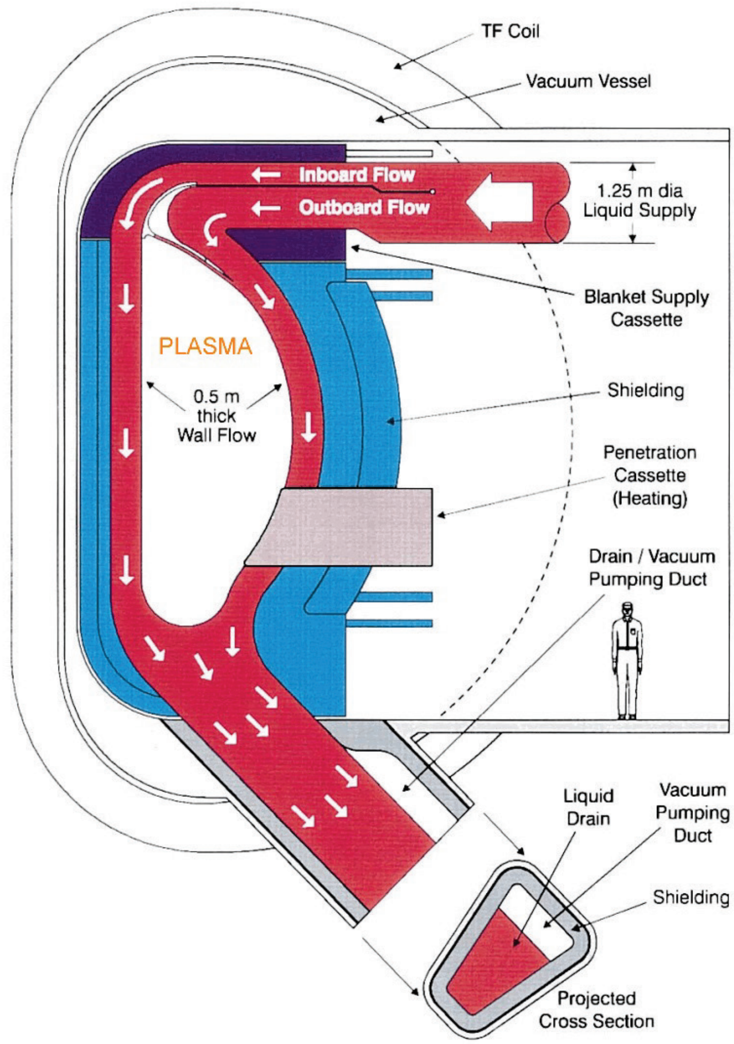



*Figure 4.2: Plasma radiates against liquid wall (red), held in place against metal plate (blue) by electrical currents and by magnet fields. This image first appeared in a 2001 paper by Dr. Mohamed Abdou.*

## Pushing Liquid Outward

As one might recall from physics class, a force is exerted on a current-carrying conductor in the presence of a magnetic field. In other words, one can embed posts within a fluid, move current between the posts, and maintain an evenly distributed wall of liquid by pushing it toward the plate, even if the plate is above the fluid.

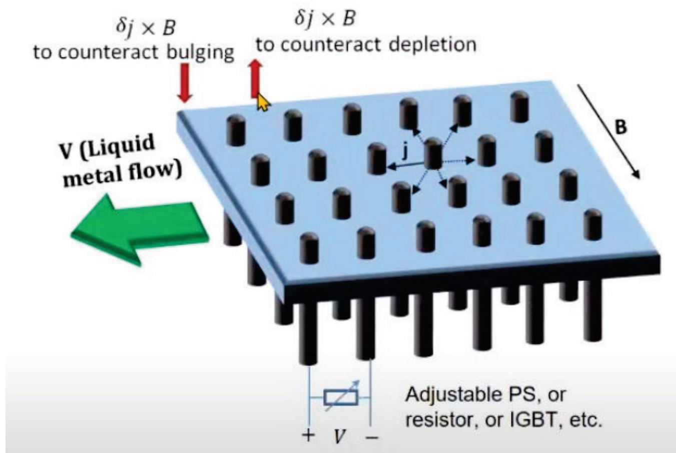



*Figure 4.3: Flowing liquid is pushed toward plate by surrounding magnetic field and by electrical currents between posts. Courtesy Renaissance Fusion.*

## Internal Cooling System

The alternative cooling method is to expose a thin (~2mm) metal plate to neutron radiation, and cool it by flowing molten liquid along its back surface. However, the neutrons cause the metal plate to become brittle, requiring replacement every one to five years. Frequent replacement necessitates disassembly, which is both challenging and expensive. Therefore, it is more cost-effective to protect the metal plate with a flowing liquid metal wall, and only assemble the machine *once* during its lifetime.

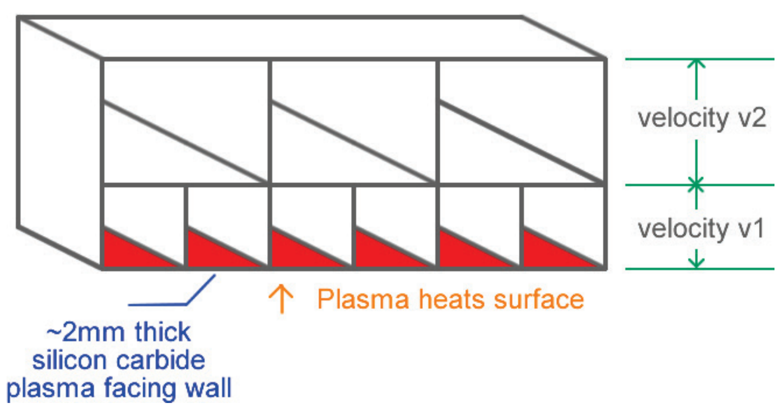



*Figure 4.4: Liquid flows in channels behind metal plate (red) and removes heat. Concept illustration by G. Weinreb.*

## Liquid Metal Wall vs. Internal Cooling System

There is a limit to how much power one can radiate against a metal plate. In theory, more power can be radiated against a wall of flowing liquid metal. Additionally, increasing the power per square meter of internal wall surface area reduces the reactor's physical size for a fixed amount of total power. This is good, since smaller physical size costs less to build.

In summary, a flowing liquid metal wall offers substantial advantages: improved heat removal, avoid component embrittlement, avoid neutron activation, smaller reactor size, and no disassembly—all resulting in lower costs. Nevertheless, liquid metal wall technology is relatively new, and more experiments are needed to validate feasibility and identify optimal materials, both liquid and solid. This area of research should be prioritized, as it could significantly influence reactor designs.

For details, see liquid metal wall video, tutorial, design and theory.

## Magnet Making Machines

Fusion devices contain large, expensive magnets whose cost could be reduced by developing specialized machines capable of: (a) producing superconducting REBCO-like tape more quickly and at a lower cost, (b) print wide 2cm to 300cm conductors onto a rotating tube, (c) print narrow 0.2cm to 2cm conductors directly onto a rotating tube, and (d) print conductors directly onto a magnet baseplate.

## 3D Magnet Printing

Stellarators require irregularly shaped magnets to confine plasma, and these magnets are expensive to fabricate using traditional methods. In theory, these magnets could be made by placing alternating layers of superconductor and “insulator” onto a rotating tube via an additive process such as ion deposition. For example, one might place five irregular shaped magnets onto each of 12 tubes, and place a large magnet at the end of each tube—as illustrated lower-right. This could potentially reduce stellarator cost. Therefore, it is reasonable to dramatically increase funding for the development of 3D magnet printing machines. For details, see this video.

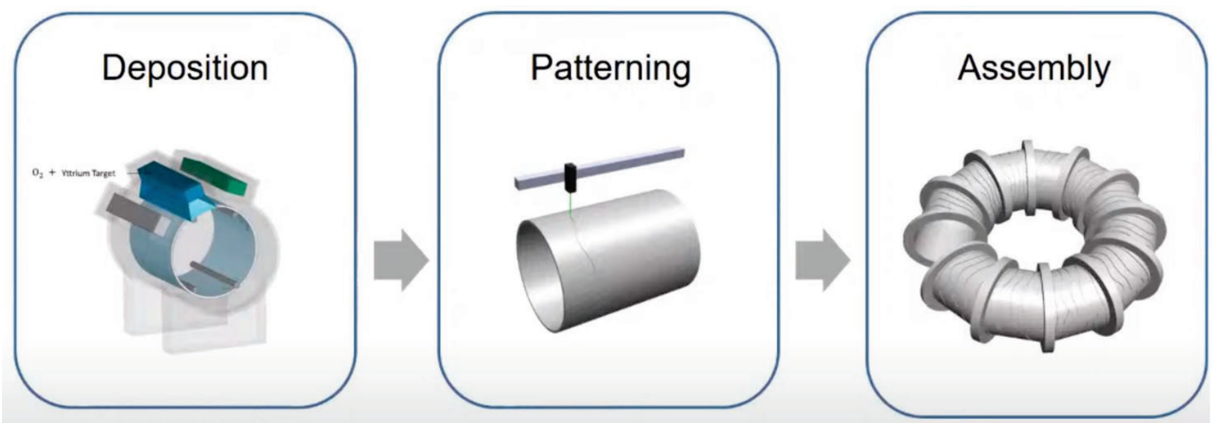



*Figure 4.5: 3D magnet printing. Courtesy Renaissance Fusion.*

## Paper Only Designs

In theory, researchers can design a commercial fusion machine entirely on paper, and publish their work. This has been done. For example, the Volpe/Frost P1 design is expected to generate $1GW_e$ of electrical power at a cost of \$50/MWh, with an estimated site cost of \$5 billion. Also, if one doubles the site cost to \$10 billion, and doubles the reactor diameter, the electricity cost decreases 2-fold, to \$25/MWh. This is less than fossil fuel-based electricity. These figures represent first-of-a-kind (FOAK) costs, which are expected to decrease by 20% to 40% as additional units are built. Magnet costs account for ≤18% of the total, with the remaining expenses distributed across the facility. For a closer look at a fusion facility, check out this tour of the SPARC site.

For more details on the Volpe/Frost design, refer to their 2024 paper, design summary, energy diagram, cost breakdown, YouTube video, and cost model. This design incorporates new innovations, such as liquid metal wall and 3D magnet printing. However, as noted earlier, these technologies have yet to be validated in a working fusion machine.

The work by MIT and Commonwealth Fusion Systems (CFS) is also noteworthy. However their papers refer to a more expensive approach that does not include liquid metal walls. As a result, their machine requires disassembly every one to five years, which is expensive. For a summary of parameters that describe a fusion machine, click here.

## Parallel, not Serial

The fusion research community is operating under the assumption continuously-operating fusion machines will not appear soon. As a result, relatively little funding has been directed toward developing the equipment required for continuous operation. For instance, specialized systems are needed to separate exhaust gases (such as helium, tritium, and deuterium) and extract tritium from a stream of liquid lithium. To accelerate commercial fusion R&D, all subsystems must be developed concurrently, supported by equipment that tests these systems at maximum power for months.

## High-Power Long-Duration Experiments

Plasma in a commercial fusion machine would emit high levels of neutron radiation continuously over years, and this would have a significant effect on both liquids and solids within the first one to two meters of the chamber wall. While these effects have been estimated, they have not yet been measured. To validate these estimates, a high-power neutron source is needed to expose candidate materials to radiation for weeks to months (e.g., > 1 MW/m$^2$). Building such a facility is a significant challenge. Currently, the closest example is the billion-dollar IFMIF test facility, which is currently under construction. However, it is not expected to be operational until the 2030s—too late for those seeking relief from climate change.

What is urgently needed is an experimental fusion reactor that tests candidate materials and subsystems for long durations. This machine would not need to be large, efficient, or cost-effective. Instead, it would need to be built quickly to guide other designs and influence funding decisions. Ideally, this system would de-risk key technologies such as shielding solid components with liquid metal walls, separating helium from deuterium/tritium, extracting tritium from liquid lithium, implementing neutron multiplication, avoiding neutron activation, managing high neutron wall loading, and removing large amounts of heat over extended periods. Also, multiple experimental reactors might be needed to explore different approaches.

The most promising facility for testing is the Chinese Comprehensive Research Facility for Fusion Technology (CRAFT). However, achieving commercial fusion within a few years would require significantly more funding for a facility like this.

Let's recap. Current experimental fusion reactors operate for seconds to minutes. To accelerate the path to commercial fusion, multiple *experimental* reactors would be needed that support continuous operation. These would each cost approximately $2 billion. After achieving high-power, long-duration fusion, engineers could focus on designing a fusion machine that generates low-cost electricity.

## Computer Aided Design

In theory, manufacturing engineers could develop software capable of generating detailed fusion designs based on a set of key parameters. With sufficient funding and resources, such software could produce comprehensive drawings for every component on site, including drawings for casting molds, assembly instructions, and cost models. This capability would streamline the process of designing and constructing both experimental and commercial fusion reactors, significantly reducing development time.

The United States has approximately 300,000 mechanical engineers, while China has over a million. Similar numbers of electrical engineers are available in both countries. In theory, more engineers could be mobilized to support commercial fusion R&D.

## Government Support

The U.S. government currently allocates approximately $800 million annually to basic fusion research, supporting programs such as PPPL, ITER, and DIII. In theory, a *new* initiative could be launched to achieve economic fusion through a top-down approach, led by the world's leading scientists. Such an initiative would integrate plasma physics, manufacturing engineering, and cost analysis to achieve an objective such as *achieve economic fusion within several years*. Priority would be given to de-risking key technologies, such as liquid metal walls and 3D-printed magnets.

## Open Fusion

Companies and research laboratories often avoid sharing developed materials, fearing that open review could negatively impact their funding. However, achieving commercial fusion within a few years may require a shift toward greater transparency. Sharing experimental data and materials online for open review could accelerate progress by identifying and addressing problems more quickly. In theory, climate money could pay test laboratories, such as China's CRAFT, to share ("collaboration"). It could also fund scientists and engineers to conduct R&D and publish open-source materials online, maximizing the climate benefit per dollar spent.

## Fusion Companies are not Aiming to Fix the Climate Problem

TCL hopes to generate electricity from fusion at a cost lower than fossil fuels—a breakthrough that could significantly impact the climate crisis. However, most fusion companies have a different focus. Their primary goal is to develop a single fusion machine, potentially in the 2030s, capable of producing electricity at a cost much higher than that of fossil fuel-based electricity. This single machine would be paid for by investors, rather than by the typical electricity customer.

In other words, it is easier to build a fusion machine that generates electricity at $150/MWh, funded by investors, than to build one that generates electricity at $30/MWh, funded by consumers. While fusion companies are concentrating on the former, climate-focused funding is looking at the latter, at an accelerated timeline, and at a higher funding level.

## The Lab's Role

TCL dramatically increases funding for key technologies needed to achieve economic fusion within a few years.

## R&D Funds: Economic Fusion (EF)

- R&D Fund: **Liquid Metal Wall R&D**
  Support liquid metal wall research and development (e.g., design experiments, write proposals, fund proposals).
- R&D Fund: **Wide Tube Magnet Printing R&D**
  Support the development of machines that print wide 2cm to 300cm REBCO-like tape directly onto a rotating tube.
- R&D Fund: **Narrow Tube Magnet Printing R&D**
  Support the development of machines that print narrow 0.2cm to 2cm REBCO-like tape directly onto a rotating tube.
- R&D Fund: **Baseplate Magnet Printing R&D**
  Support the development of machines that print REBCO-like tape directly onto a magnet baseplate.
- R&D Fund: **Exhaust Gas Processing R&D**
  Support the development of equipment that separates exhaust gases (e.g., deuterium, tritium, helium).
- R&D Fund: **Liquid Lithium Processing R&D**
  Support the development of equipment that extracts tritium gas from a stream of liquid lithium.
- R&D Fund: **Experimental Tokamak with Liquid Metal Wall Design**
  Support the design of an experimental D-T tokamak with liquid metal wall that runs continuously at maximum power for months. Cost, size, and efficiency are not a priority.
- R&D Fund: **Experimental Stellarator Design**
  Support the design of an *experimental* stellarator with liquid metal wall and 3D-printed tube magnets. Cost, size, and efficiency are not a priority.
- R&D Fund: **Economic Stellarator Design**
  Support the design of a commercial stellarator that produces electricity at a cost less than U.S. natural gas-based electricity.

# 5. Automated Nuclear Power Construction

The costs of nuclear fission power could theoretically be reduced through measures such as building standardized reactors ("design one, build many"), automating site construction, relying heavily on factory-made subassemblies ("modularity"), and developing a new transportation system that moves large subassemblies from factories to power plant sites.

The traditional form of nuclear fission power is not popular in many nations due to meltdown risk. In theory, this can be resolved with advanced reactors that do not melt down, when not cooled. For instance, the nuclear fuel in China's HTR-PM reactor includes an additive that reduces output power when cooling is lost, preventing the fuel from melting. This additional safety increases costs ~20%. However, additional cost-reduction could make this more tolerable.

Nuclear waste can also be reduced by spending more money. For example, allocating approximately 10% of the wholesale electricity cost to advanced waste processing could significantly decrease both the volume and the longevity of nuclear waste.

## Nuclear Power Markets

China and South Korea have constructed many nuclear reactors over recent decades, gaining expertise that allows them to build at relatively low costs. Conversely, the United States and Europe have been less active, resulting in less proficiency and higher costs. However, this lack of experience is not permanent. If nuclear power was used to solve the carbon dioxide problem, more construction would result in more proficiency and lower costs. Also, if construction was automated, this would naturally occur first in regions that are comfortable with nuclear power, and eventually spread to nations who are less comfortable.

## Basic Concepts of Nuclear Power

Large nuclear power facilities typically host between three and six reactors, with each reactor commonly producing approximately one billion watts of electricity (1 $GW_e$). Given that an average U.S. household consumes about 1,000 watts, a single reactor can supply electricity to roughly one million homes. Additionally, the process of generating electricity from nuclear reactors typically requires about 2.5 watts of heat (2.5 $W_t$) to produce 1 watt of electricity (1 $W_e$).

## Decarbonization Problem Size

We know how much energy is consumed worldwide each year, and we know how much is produced by a large 1 $GW_e$ nuclear reactor. To get a sense of decarbonization problem size, we can divide these two numbers to calculate how many 1 $GW_e$ reactors would be needed to replace global energy. The math works out to about 9,000 $GW_e$ of nuclear power. This refers to *all* energy, not just electricity.

## The Nuclear Solution

If, for example, nuclear power were used to decarbonize 50% of global energy over the next 30 years, approximately 150 $GW_e$ of nuclear power would be constructed worldwide each year (50% × 9,000 $GW_e$ ÷ 30 years). This would entail building 41 $GW_e$ per year in China, 23 $GW_e$ per year in the U.S., and 19 $GW_e$ per year in Europe.

Over a 30-year span, China alone would add approximately 1,250 $GW_e$ of nuclear capacity. If distributed across roughly 240 sites, each site would support approximately 5 $GW_e$ (1,250 ÷ 240).

Current nuclear construction rates are about 7 $GW_e$ per year in China, 0.15 $GW_e$ per year in the U.S., and 0.17 $GW_e$ per year in Europe. Therefore, to replace 50% of global energy over 30 years, annual construction rates would need to increase approximately 6-fold in China, 150-fold in the U.S., and 100-fold in Europe.

Calculations used in this chapter can be accessed here. For simplicity, they assume zero economic growth.

## Nuclear Economics

The cost of new nuclear reactors in China is currently around $2 per watt ($2/W). In contrast, reactors in the U.S. and Europe are significantly more expensive, primarily due to less construction experience, rather than higher labor costs (as labor represents only a small fraction of total costs). Thus, reactor costs in the U.S. and Europe would likely approach Chinese levels if construction volumes were similarly high, adjusted for labor cost differences.

If global nuclear construction were scaled up to 150 $GW_e$ per year, then cost-reduction due to automated construction could potentially offset the additional cost of higher quality (e.g., less meltdown risk, less waste). In other words, the $2/W cost could potentially continue, with 150 $GW_e$ of annual construction costing $300B per year ($2/W × 150 $GW_e$). While this is a rough estimate, it provides a general sense of costs in a world more reliant on fission power.

We can compare a $300B per year nuclear cost with the annual cost of half of fossil fuel. Present global fossil fuel spending is around $4,000B per year. This includes $2,500B for oil (based on ~35 billion barrels annually at ~$70 per barrel), $1,000B for coal, and $500B for natural gas. While nuclear reactors are not a direct replacement, we see that $300B per year for new nuclear reactors, is less than $2,000B per year for half of fossil fuel.

## Site Construction

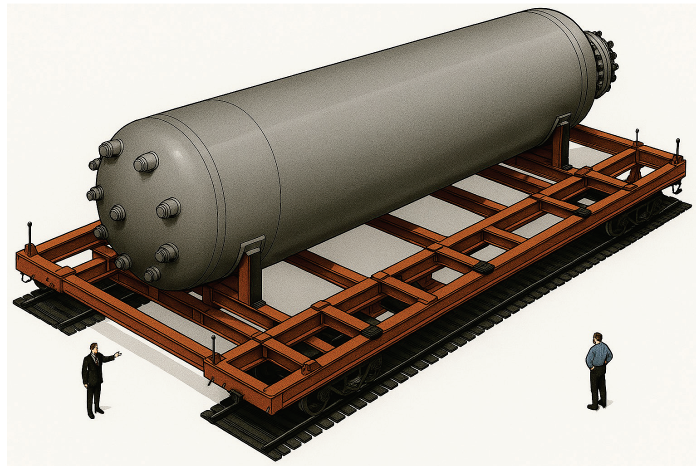
The nuclear reactor vessel itself accounts for only a small fraction of total nuclear site costs. For example, the HTR-PM reactor vessel cost only 2% of total site cost in China. This works out to 5 pennies per Watt of capacity {$2.30 x 2%}.

The majority of expenses arise from excavation, concrete pouring, and rebar installation. These costs could potentially be reduced through: (a) developing equipment that automates site construction, (b) building factories that make large subassemblies, and (c) creating equipment that transports subassemblies from factory to site.

## Design One, Build Many

Engaging in a lengthy nuclear reactor design and certification process is unnecessary. Instead, one can copy an existing design. China's HTR-PM is a reasonable candidate since it is probably the safest commercially operating nuclear fission reactor in the world. In particular, it does not melt down if not cooled; its fuel and coolant do not react with air or water; and its helium gas coolant is not radioactive. In the event coolant is lost, the core radiates heat outward to the metal containment vessel, which then radiates heat to the concrete containment chamber, which conducts heat to bedrock. The HTR-PM reactor took 20 years to develop and repeating this process is not necessary.

## New Transportation System



In theory, a new transportation system could be developed to move large and heavy loads over land and water, to better connect factories to nuclear power sites. For example, a 12m wide by 24m long railcar on double-rails could potentially transport: (a) large nuclear reactor components, (b) bins of concrete, (c) concrete forms, (d) rebar subassemblies, and (e) large automated construction equipment.

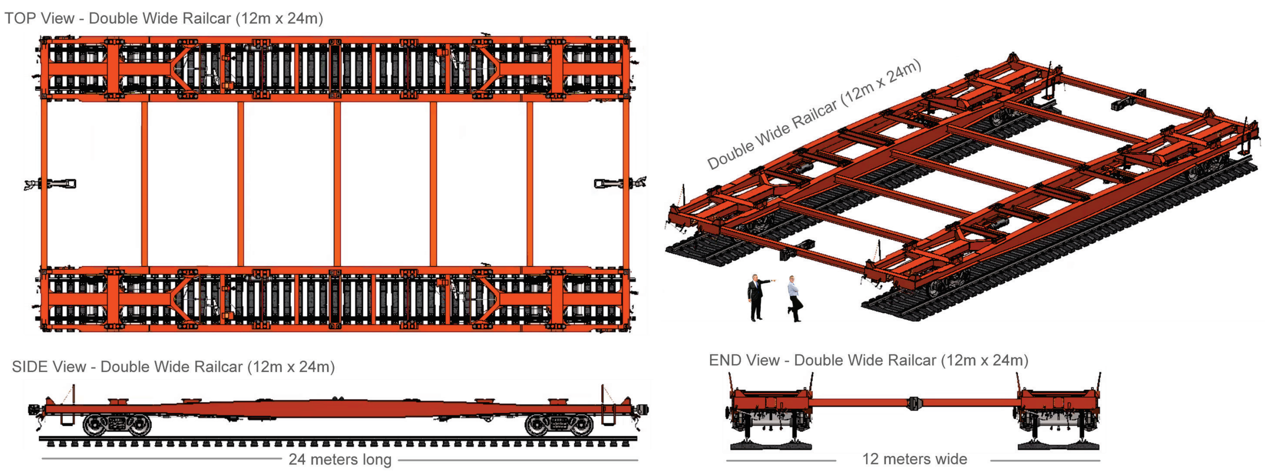



*Figure 5.1: Double-width railcar. Concept illustration by G. Weinreb.*

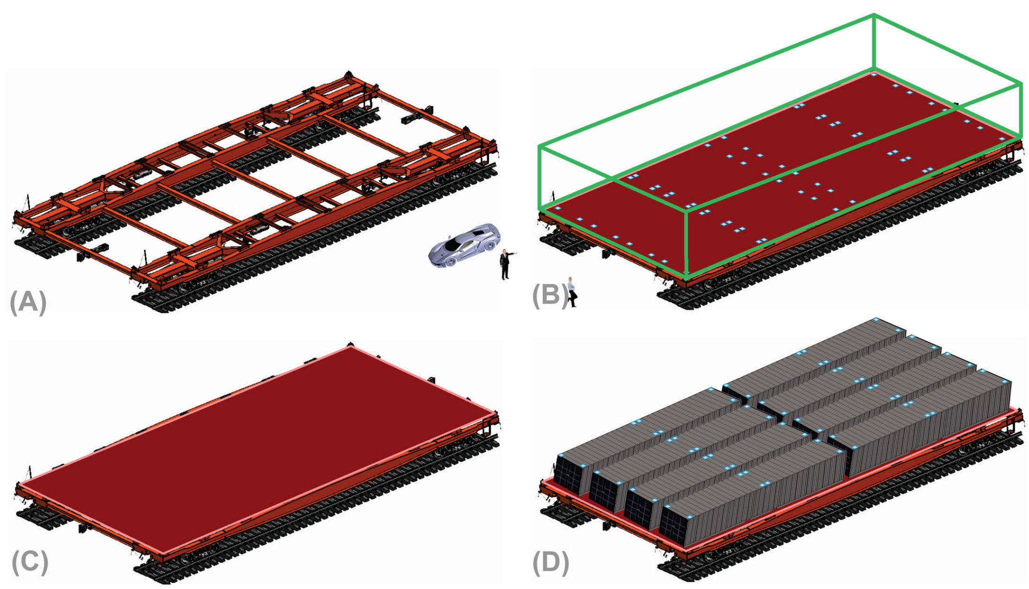



*Figure 5.2: A large railcar could be adapted to support: (A) base frame, (B) large container, (C) flat working surface, and (D) multiple shipping containers.*

## Chemical Processing Platforms

Large platforms of chemical processing equipment could theoretically be co-located with nuclear power plants, and powered by heat transported through pipes carrying steam or molten salt. For instance, platforms measuring 12m wide by 96m long could be transported via double-rail and positioned side-by-side near the reactor (Fig 5.3). Site-wide efficiency could be maximized by capturing unused heat and redirecting it to generate electricity, produce chemicals, or increase the temperature of thermal storage. In theory, platforms of chemical processing equipment could support the production of common chemicals, including hydrogen gas, liquid ammonia, methanol, ethylene, sulfuric acid, chlorine, caustic soda, and cement.

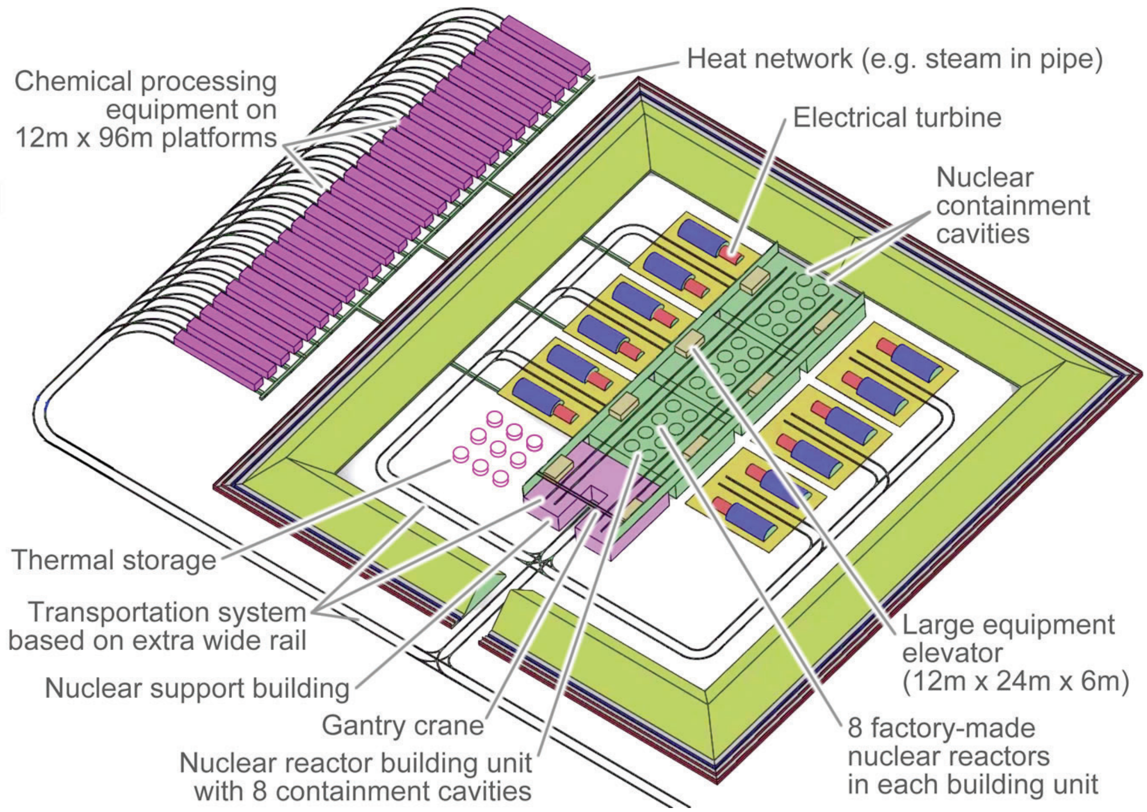



*Figure 5.3: Nuclear reactors co-located with multiple platforms of chemical processing equipment. Concept illustration by G. Weinreb.*

## Chemical Processing Yard

In theory, chemical processing platforms could be positioned side-by-side, as shown below. In this illustration, platforms are shown in green, pipes carrying heat from the nuclear reactors are shown in blue, underground tunnels that support pipes in between platforms are shown in light violet, and underground tunnels that support moving material into and out of the chemical processing platforms are shown in light purple.

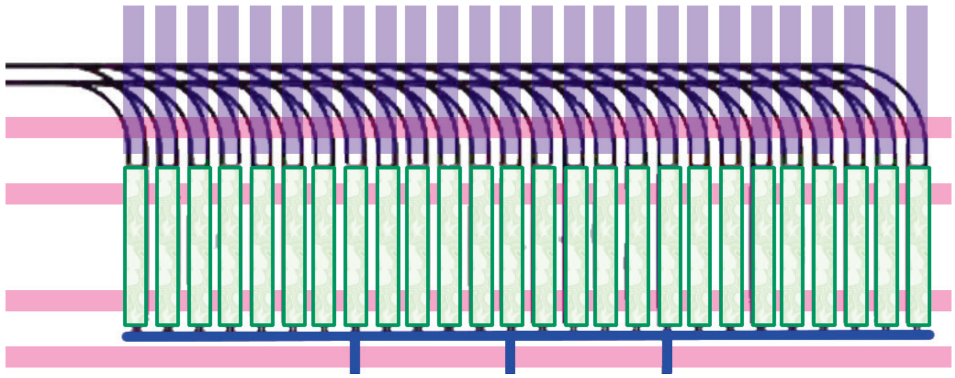


*Figure 5.4: Chemical processing yard consists of processing platforms side-by-side.*

There are two primary approaches to underground tunnel construction. One method involves manufacturing precast concrete modules at an off-site factory, transporting them to the site, and joining them with more concrete. Alternatively, rebar cages and forms could be assembled off-site, transported to the site, and then filled with wet concrete. Specialized equipment and factories could be developed that support both methods.

## Platform Transporter

In theory, equipment could be developed that moves 12m × 96m platforms across land via double-rail, and across water via specially built ships. To prevent bending when traveling over hills or around curves, these platforms could be mounted on a ridged truss supported by jacks between the truss and railcars, as illustrated below.

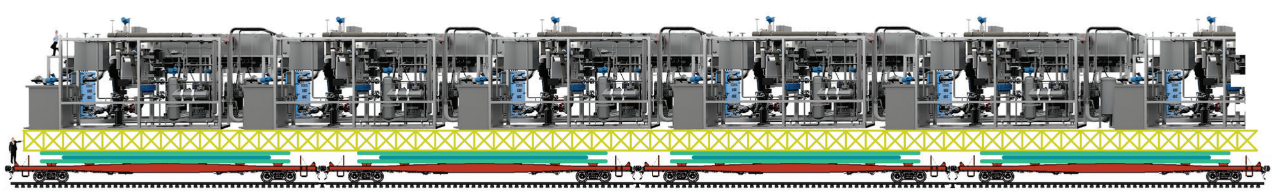


*Figure 5.5: Concept illustration of chemical processing platform transported on a rigid truss, mounted on four double-width railcars.*

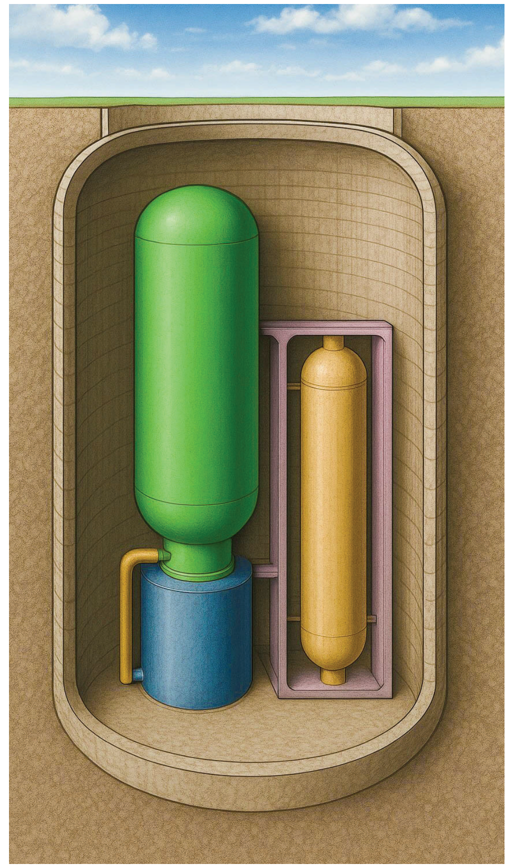
## Thermal Storage

When electricity demand is low, nuclear reactors can increase the temperature of a hot liquid in a thermal storage tank; and when electricity demand is high, the stored energy can be used to make electricity. In other words, to minimize costs, thermal storage can bridge the gap between fluctuating demand and constant supply. Also, thermal storage can minimize waste heat by consuming it when available at a temperature higher than the storage temperature. In theory, R&D could reduce thermal storage costs by supporting the development of equipment that automates the construction of thermal storage tanks.

## R&D Funds: Automated Nuclear Power Construction (ANP)

- R&D Fund: **Nuclear Power Automated Construction R&D**
  Support the development of custom machines that automate the construction of nuclear fission power plants.
- R&D Fund: **Automated Thermal Storage Construction R&D**
  Support the development of custom machines that build thermal storage tanks (e.g., large factory-made subassemblies are joined on-site by custom machines).
- R&D Fund: **Chemical Processing Platform Design**
  Support the development of large chemical processing platforms (e.g., 12m × 96m) that produce common chemicals.
- R&D Fund: **Chemical Processing Platform Factory Design**
  Support the development of an automated *factory* that builds large chemical processing platforms.
- R&D Fund: **Chemical Processing Site Design**
  Support the development of chemical processing yards which support multiple platforms.
- R&D Fund: **Chemical Processing Platform Standards Development**
  Support the development of plug-and-play standards that define how heat sources (e.g., fission reactors) connect to adjacent platforms of chemical processing equipment.
- R&D Fund: **Chemical Processing Platform Transportation R&D**
  Support the creation of a transportation system that moves large platforms of chemical processing equipment from factories to power generation sites.
- R&D Fund: **Double-Rail Transportation R&D**
  Support the development of equipment that supports double-rail transportation (e.g., railcars, special purpose-built ships, equipment that moves cargo from ship to shore, and interconnection standards).
- R&D Fund: **Double-Rail Concrete Processing R&D**
  Support the development of concrete processing equipment that resides on double-railcars (e.g., machines that mix water, gravel and dry cement; along with bins/tanks that contain these ingredients).

# 6. Underground Nuclear Power



Nuclear fission reactors typically require significant amounts of concrete and rebar, in part because they need to withstand attacks from missiles and airplanes. In principle, these costs could be reduced by placing the reactor vessel underground, inside a concrete-lined chamber, surrounded by bedrock. Achieving this affordably would probably require the development of specialized machines that automate: excavation, installation of concrete lining, and assembly of reactor components.

## Rethinking Nuclear Fission

It typically cost more to build underground. However, this might not hold true for gas-cooled nuclear fission reactors that are built with machines that automate construction.

Traditional reactors are cooled with pressurized water; however, several advanced designs instead use helium gas.

Gas carries less heat per unit volume compared to water, and therefore gas-cooled reactors are physically larger than their water-cooled counterparts. Consequently, their nuclear fuel is more spread out, which helps them not melt when not cooled. More specifically, in the event coolant is lost in a gas-cooled reactor, decay heat is moved via radiation to concrete chamber walls, to bedrock, without melting. Alternately, water-cooled reactors are dependent on external systems that must be protected against airplane attack, significantly driving up costs. For details, see this video.

## Automated Excavation and Concrete Installation

A cost-effective underground approach would involve developing specialized machinery that excavates in bedrock and installs a concrete lining. Rebar and formwork assemblies could be prefabricated within a factory, transported to the site, lowered into the excavated cavity, and then filled with wet concrete.

## Concrete Example

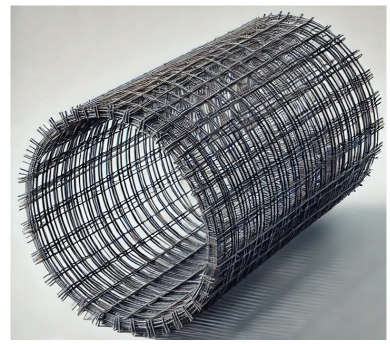
Let's examine some numbers to get a better sense of this. An example of a commercially operating gas-cooled reactor is the HTR-PM, with a 24m tall by 7m diameter reactor vessel, and a 22m tall by 4.5m diameter heat exchanger (drawing). In theory, these could be arranged side-by-side or stacked vertically, and the containment structure shape could either be cylindrical or rectangular.

Assuming a vertical arrangement, let's position the reactor vessel and heat exchanger within a 50m-deep cylindrical chamber, 12m in diameter. According to the math, a 1m thick concrete lining would weighing approximately 2,700 metric tons.

Standard railcars typically support around 125 tons, and their capacity can be increased with more axels. Thus, double-width railcars should be able to support several hundred tons, or more weight with more axels.

A bin measuring 20m × 10m × 1m weighs 200 tons when filled with water, 288 tons when filled with dry cement powder, and 320 tons when filled with dry aggregate gravel. Therefore, roughly 14 double-width railcars of material would be needed to make the concrete lining described above.

## Concrete Strategy



There are two primary methods for concrete construction: precast segments and on-site casting. The first approach involves molding large concrete segments with protruding rebar at an off-site factory, transporting to the construction site, and then joining with wet concrete. The second approach entails manufacturing rebar cages and formwork in a factory, transporting to the site, and pouring wet concrete to form a solid structure. In theory, custom machines could be developed that support both methods.

## Excavation

There are two primary methods for excavating bedrock: blasting and mechanical excavation. Blasting uses explosives to fracture rock, while mechanical excavation uses machinery to cut and remove material in a controlled manner. Costs can vary significantly, reaching up to approximately $250 per cubic meter of rock. However, based on calculations, bedrock excavation would cost less than 2% of total site costs.

## Excavation Support

Custom machines are needed to break bedrock, remove debris, install a concrete lining, and install nuclear components. This would probably require a gantry-like crane system that lowers custom machines into an excavation, an example of which is shown below. In this illustration, the cylinder-shaped excavation is depicted in blue, and a custom machine being lowered into the excavation is shown in orange.

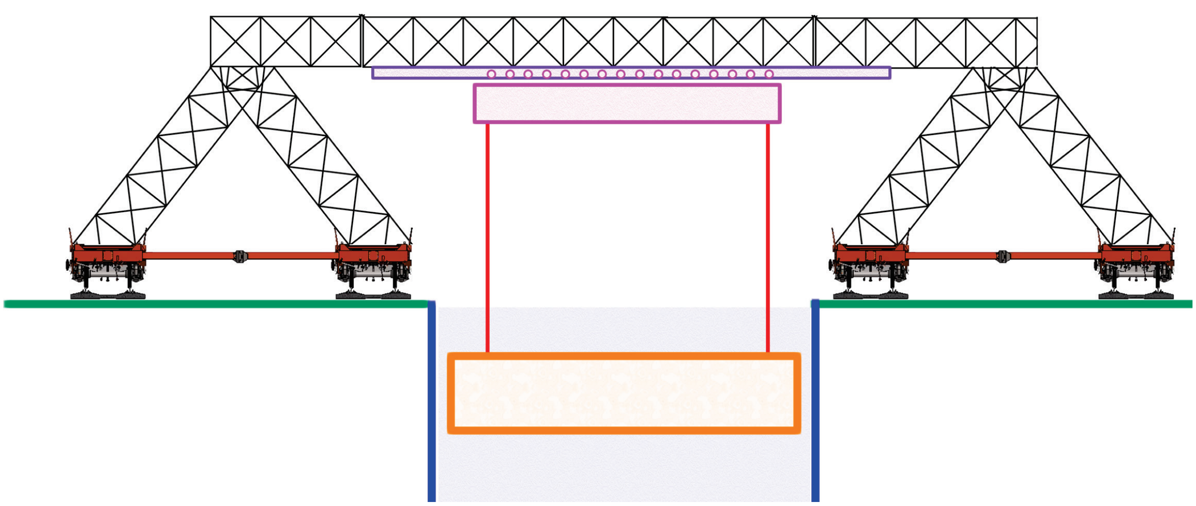


*Figure 6.1: Gantry-like crane supports excavation.*

Custom machines would perform several key functions: (a) excavation support, including breaking and removing bedrock; (b) concrete lining installation, such as placing rebar cages and pouring wet concrete; and (c) installation of subassemblies. These machines would operate within the excavation under the control of the gantry crane system, enabling precise placement and sequencing of tasks.

## Gantry-Like Crane

In theory, a truss mounted on two synchronized railcars could span the excavation and implement a crane system. A trolley could move along the truss to enable Y-axis movement, railcars could provide motion along the X-axis, and motorized hoists could provide Z-axis vertical positioning.

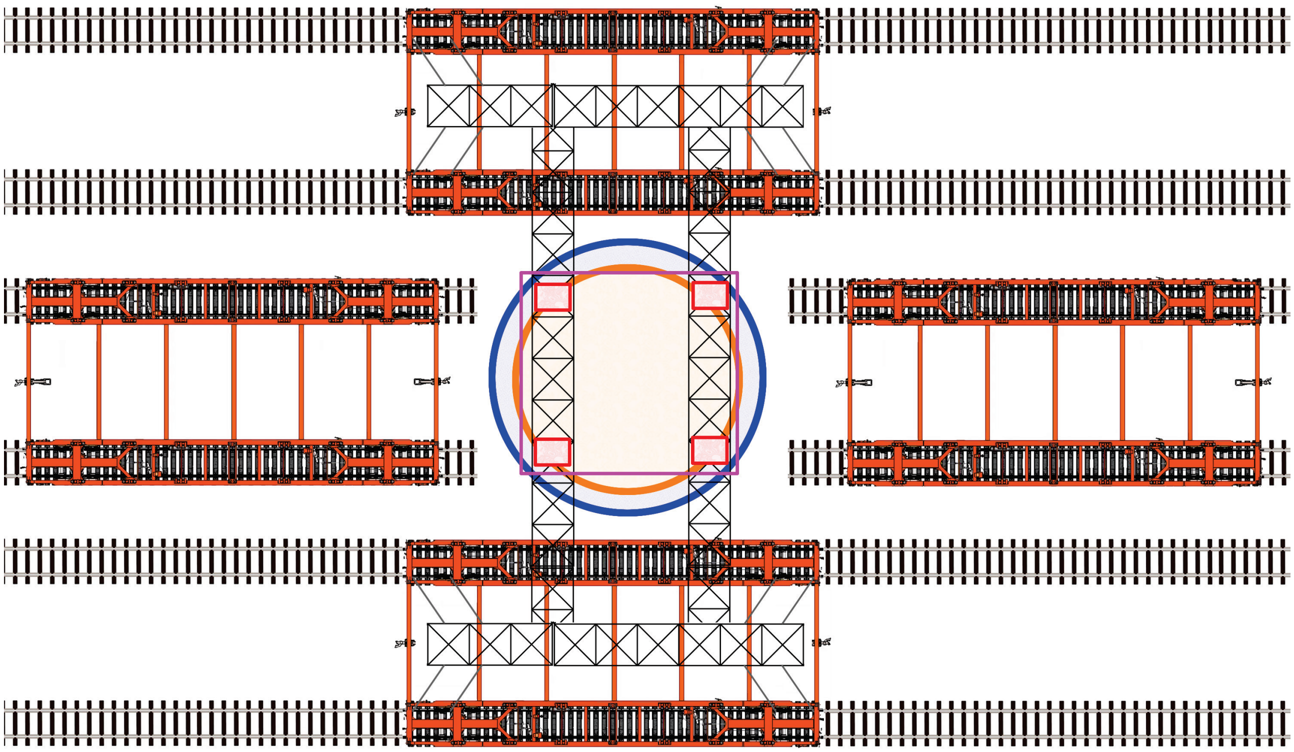


*Figure 6.2: Top view of excavation.*

In the above concept, additional railcars support material handling and machine exchange. For example, a rock removal machine could be retrieved from one support car, lowered into the excavation, and used to transport material via conveyor to a bin on another support railcar.

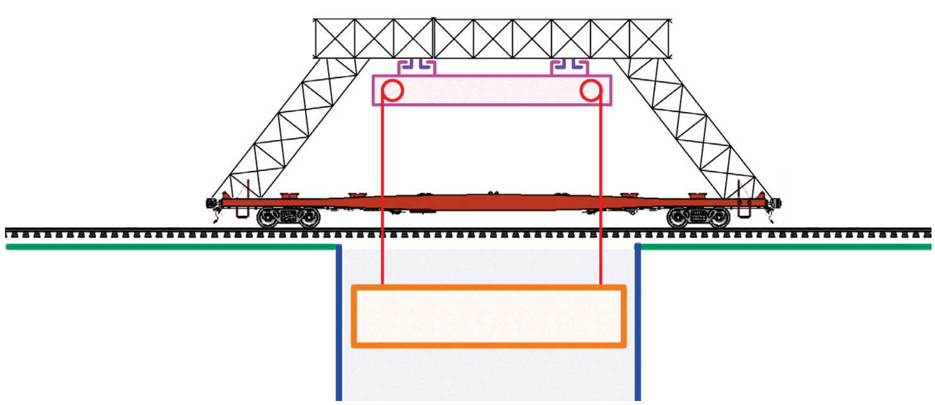
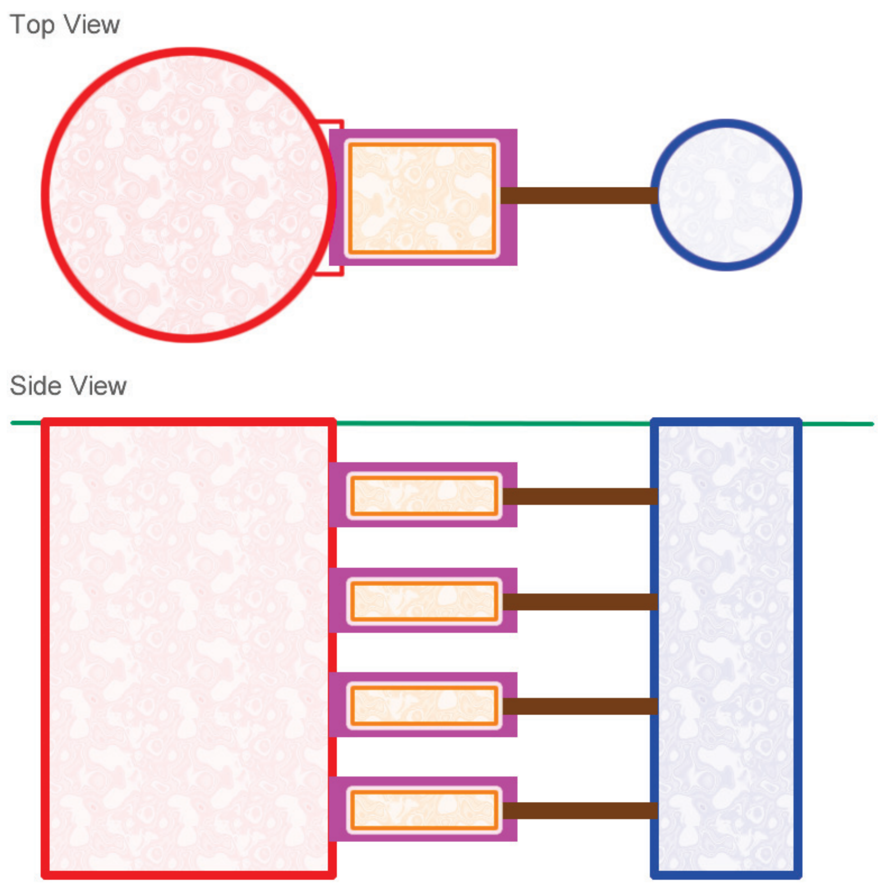


*Figure 6.3: Side view of gantry-crane.*

## Nuclear Containment

The primary functions of the containment structure are to withstand airplane attacks and to contain radiation under pressure in the event of system failure. To hold pressure, a dome-shaped seal could be bolted to the top; and to protect against attack, a retractable concrete block could be placed above it.

## Support Equipment




Nuclear reactors require various support systems, including pumps, electrical power generators, monitoring instruments, control systems, and nuclear fuel storage. In theory, these could be housed in a separate "equipment excavation," while reactor vessels and heat exchangers are kept in "power excavations."

Support systems could be preassembled within factory-made metal enclosures that are transported to the site, lowered into the equipment excavation, and slid into pre-positioned concrete boxes.

This is illustrated here with power excavations shown in blue, equipment excavations shown in red, concrete boxes shown in violet, metal equipment boxes shown in orange, and connecting tunnels shown in brown.

In theory, a custom machine could excavate rectangular chambers in the side of the equipment excavation. A second machine could install factory-made concrete boxes to prevent bedrock collapse. A third machine could pump wet concrete between bedrock and concrete boxes to affix in place. And a forth machine could install metal equipment boxes.

## Site Design

To reduce costs, multiple power excavations could be positioned around a single central equipment excavation, as shown below.

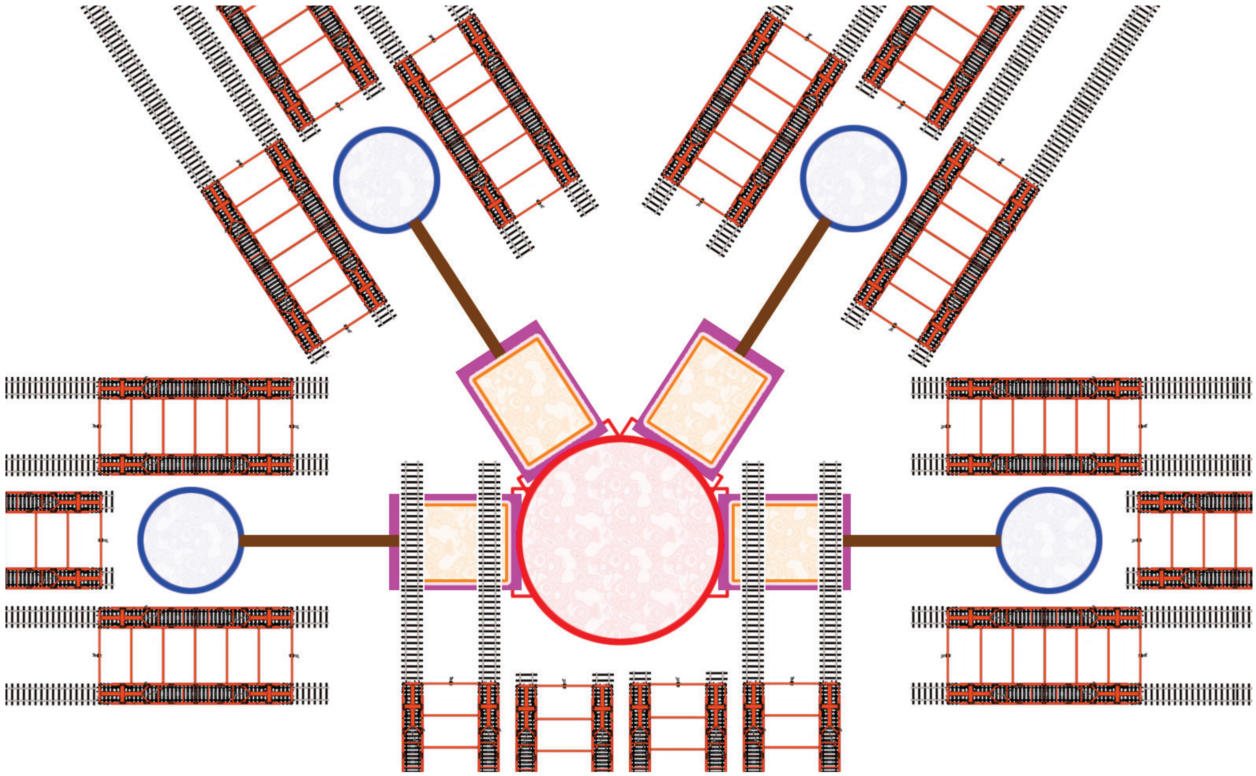
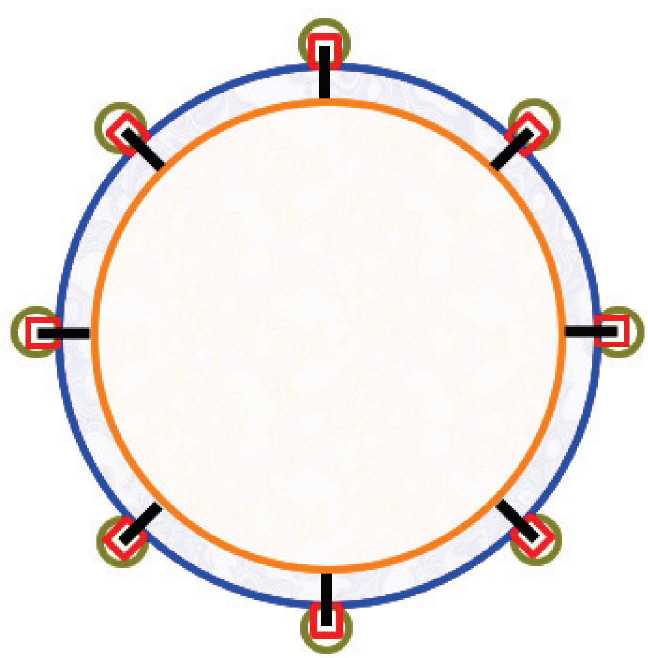


*Figure 6.4: Top view of nuclear power system. Concept illustration by G. Weinreb.*

A preliminary estimate finds this approach would consume 9-times less concrete-per-unit-electricity than Vogtle 4, and 26-times less concrete-per-unit-electricity than Hinkley C. In other words, less concrete is needed when mission-critical infrastructure is kept close to gas-cooled reactors.

## Excavation Alignment



Excavation might begin by drilling multiple ~1m diameter pilot holes outside the excavation, as shown here. Rails could be installed in these holes to guide custom machines that break rock and remove rock. Wheels on the machines could slide within the rails to ensure alignment. In this illustration, the excavated cylinder is shown in blue, pilot holes are shown in gold, rails are shown in red, wheels are shown in black, and the custom machine is shown in orange.

## Precision Excavation

Traditional excavation methods are often imprecise, while a surface accurate to ±1 cm might be preferred. Therefore, crude excavation methods might be used to remove bulk material, followed by more precise methods. For example, a custom machine with a rotating cutting head could be used to refine the excavated surface to a higher precision, as shown in Fig 6.5. In this illustration, a custom machine is shown in orange, a rotating assembly in green, a bearing in yellow, and cutting heads in red.

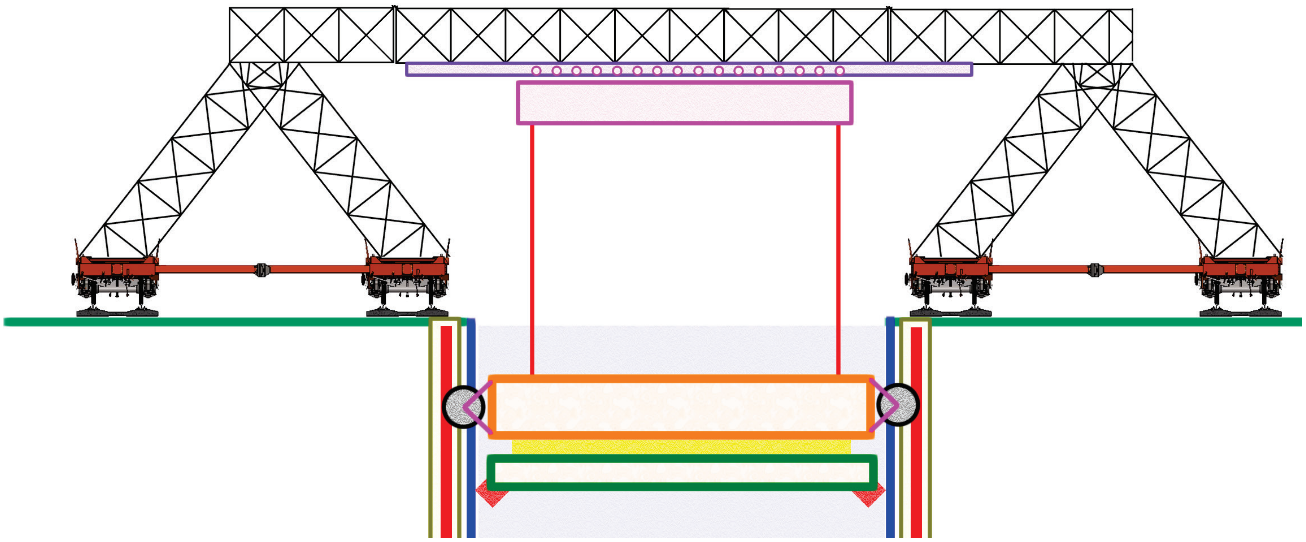


*Figure 6.5: Side view of precision excavation machine.*

## Power Generation

Heat from nuclear reactors creates steam, which presses on fan turbine blades, which produces electricity. The electrical turbine could be located either above ground, or below ground within the equipment excavation. In theory, custom machines could support both methods.

## Robot Support

In theory, AI-based robots could oversee nuclear site construction, factory construction, and factory production.

## R&D Funds: Underground Nuclear Power (UNP)

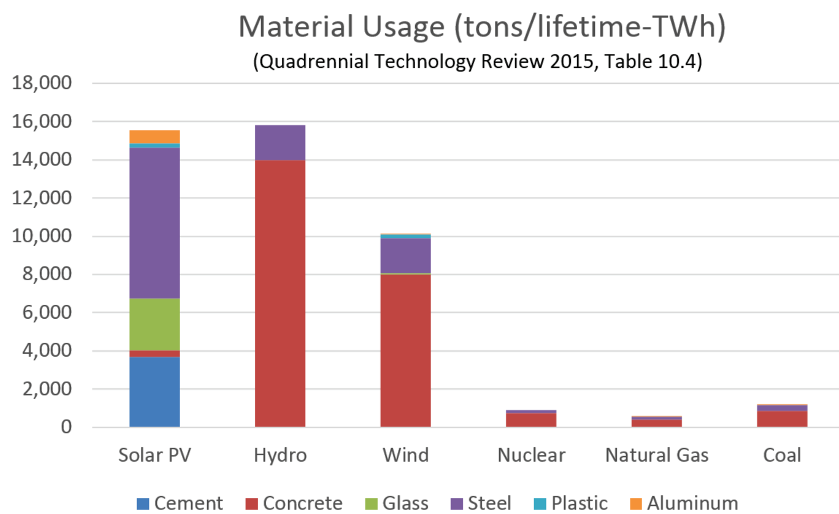
- R&D Fund: **UNP Site Design**
  Support the design of nuclear power plants that embed gas-cooled fission reactors in bedrock, and automate site construction.

- R&D Fund: **UNP Automated Construction R&D**
  Support the development of custom machines that excavate, install concrete linings, install concrete boxes, install equipment boxes, and install nuclear reactor components.

# 7. 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.

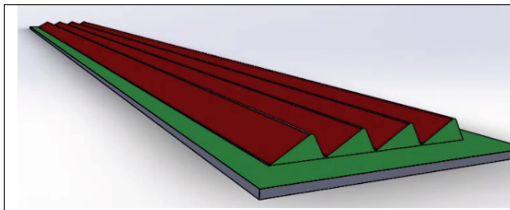
## Solar Direct to Soil

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 × 100m (6 × 300ft) carpet onto a surface. Prior to installation, the land would be shaped with earth-moving equipment under computer control.

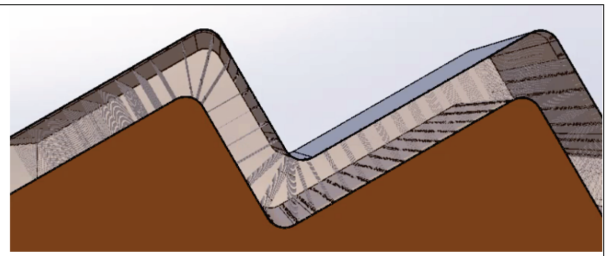
Initially, this might seem like a bad idea. However, there are good reasons for going to ground, such as significantly less material usage. Engineers could explore various techniques for overcoming challenges such as soil erosion, upward pressure due to wind, and keeping solar material clean.

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.

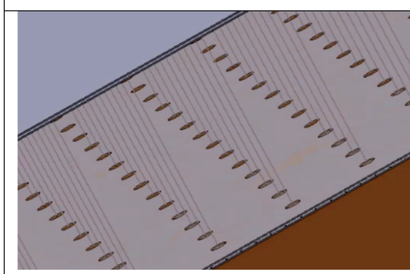
The above-ground layer might be similar to flat flexible plastic with an embedded steel wire mesh. To hold in place, installation machinery might install a parallel layer of material underground, perhaps 50cm (20") below the top above-ground layer. The above-ground layer might connect to the underground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



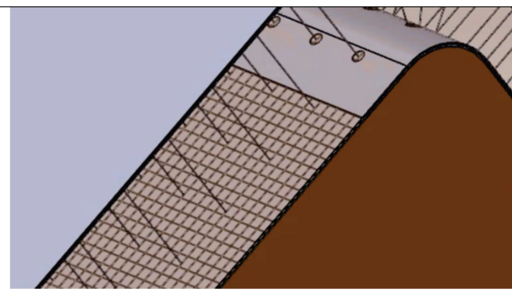
*Multiple rows of flexible solar material are placed directly onto soil (e.g. 2m x 100m per row, shown in red). Entire bed is covered with solid material to control soil erosion from rain and wind. Skirt along outer perimeter (green) controls erosion near rows.*



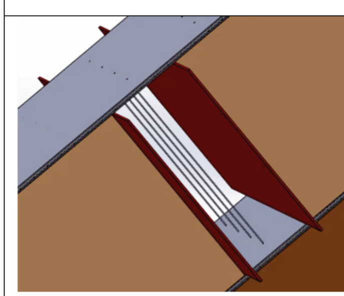
*Metal links connect above-ground solar layer to below-ground anchoring layer. Not shown is soil between two layers.*



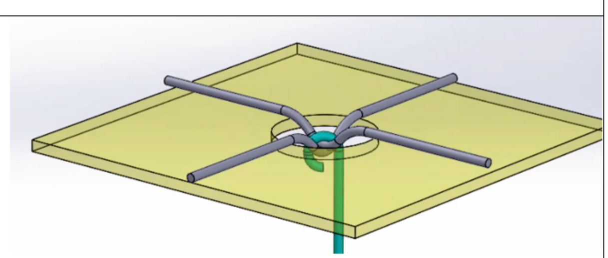
*Vertical metal links connect above-ground solar layer to below ground anchoring layer. Load is transferred to the weight of the soil (not shown) between two layers. This keeps top layer in place when wind creates negative pressure.*



*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 7.1. Thin-film solar direct to soil (concept illustration by Weinreb).*

## Region Differences

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 multiple-decade simulations and wind tunnel testing to ensure that soil movement due to wind and rain is acceptable.

## Thin-Film Plastic vs Silicon Solar Cells

Traditional solar farms use sheets of glass, and metal frames, to protect delicate silicon-based solar cells. Also, over the last 20 years, their costs have been driven down via mass production.

Alternatively, thin-film solar material mounted on rolls of plastic is currently expensive, due to less economies of scale. However, if mass produced via roll-to-roll processing, costs would be more competitive.

## Custom Machines

Placing thin-film solar material directly onto soil would require the development of custom machines that shape the land, install the material, clean the material, and fabricate the material in a factory. Some of these machines might look similar to existing equipment, shown here.

*Figure 7.2. Earth-moving vehicles and agricultural sprinkler system.*

## R&D Funds: Solar Direct to Soil (SDS)

- R&D Fund: **SDS Weather Modeling Research**
  Support the development of models that estimate the following parameters for every location on Earth: temperature, humidity, wind, precipitation, solar radiation, airborne particulate matter (such as dust), and surface debris accumulation (such as thin layers of solidified mud).
- R&D Fund: **SDS Material Manufacturing R&D**
  Support the development of roll-to-roll processing machines that fabricate SDS material.
- R&D Fund: **SDS Material Installation R&D**
  Support the development of machines that install SDS material.
- R&D Fund: **SDS Material Cleaning R&D**
  Support the development of machines that clean SDS material.
- R&D Fund: **SDS Material Removal R&D**
  Support the development of machines that remove SDS material.
- R&D Fund: **SDS Standards Development**
  Support the development of interconnection standards that define how SDS components connect mechanically, electrically and with data communications.
- R&D Fund: **SDS Site Preparation R&D**
  Support the development of site preparation techniques (e.g., automated earth moving machines).
- R&D Fund: **SDS Water Handling Research**
  Support research in rain water handling (e.g., dispose in-place, flow to tank, flow to pond, etc.).
- R&D Fund: **SDS Material Anchoring Research**
  Support the development of material anchoring techniques (e.g., underground anchoring layer holds above-ground material in place).

## Further Reading

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

# 8. Swappable Car Battery

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

The equipment cost-per-charge is determined by the equipment cost divided by the number of charges. Therefore, the cost-per-charge is high when the number of charges is low. This causes fast charging to typically cost three times more than slow charging at home. This, along with charging inconvenience, causes EV owners to rarely fast charge.

## The Power Problem

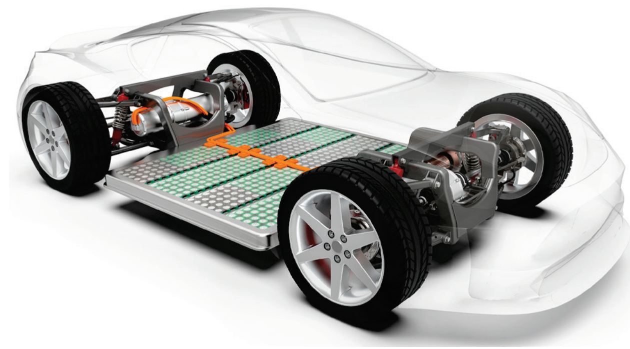
The greatest challenge with fast charging cannot be seen. It is electrical power. The typical 50kWh EV battery consumes 100kW of power when charging in 30 minutes (100kW × 0.5h). This is the same amount of power drawn by 80 U.S. homes on average. In other words, supporting large amounts of power is expensive,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

Charging stations are often located at shopping malls and hotels since they have access to large amounts of power. 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.

## Swappable Standardized Battery

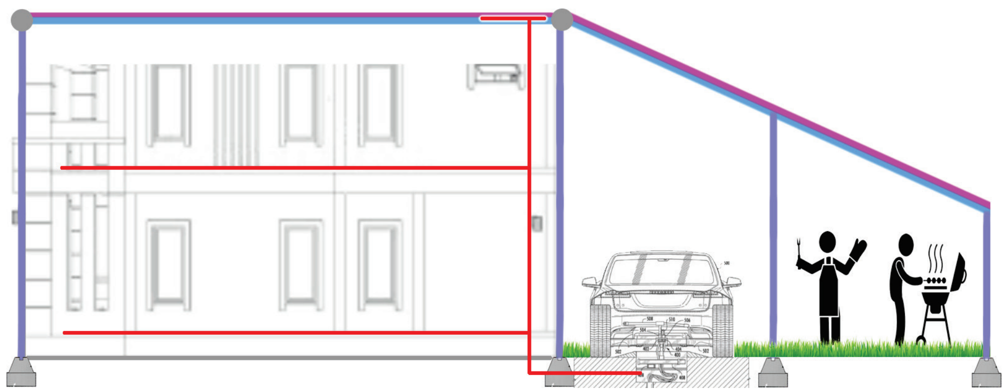

There is one way to resolve all of the problems alluded to above. It is a standardized plug-in swappable EV battery. Currently, the world has mechanical and electrical standards that define batteries, and these enable us to power many products at a low cost.

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, car and swap station. This is not a new idea. For a video that discusses this, click here.



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 several minutes. Car owners would pay for electricity consumed and wear on the battery; and would pay less when using lower-cost batteries.

Batteries that can only slow-charge cost 2 to 3 times less per mile than batteries that can fast-charge. This is due to supporting more charge cycles, due to internal chemistry. Therefore, those who drive less than 150 miles (250 km) per day and never fast-charge could swap in a small slow-charge-only battery, and save money. Alternatively, for long trips, one could swap in an expensive high-range fast-charge battery; or swap more often.



Also, homes could install swap chambers in their driveway with multiple batteries, as illustrated here. These could be charged by solar during the day, power the house at night, and swap with cars as needed.

## Swap Costs Less

Batteries sitting in swap stations could charge anytime over multiple days. This would reduce costs for multiple reasons: (a) they could charge at night when electricity is cheap, (b) they could charge when solar farms and wind farms are producing power, (c) they could charge slowly and avoid expensive fast-charging hardware, (d) they could be placed near large power cables at shopping malls and buy electricity at the commercial rate which is 30% less than residential, and (e) manufacturers of cars, batteries and swap hardware could compete and drive down costs.

## Chicken and Egg

Swappable EV batteries present a classic “chicken and egg” problem: automakers are hesitant to participate without an established network of swap stations, and investors are reluctant to fund swap stations without a significant number of compatible vehicles.

Nio is an example of a swappable EV manufacturer that has resolved this conundrum. On an annual basis they: (a) garner over $8 billion in revenue, (b) manufacture hundreds of thousands of swappable EVs, and (c) install thousands of battery swap stations. Their success is due largely to Chinese government policies that encourage electric vehicles, and a willingness of affluent EV owners to pay more for convenience.

## Standards Development

If multiple EV manufacturers shared batteries and swap stations, then standards would be needed that define: (a) how batteries mechanically and electrically attach to cars and swap stations, (b) how batteries communicate with cars, and (c) how cars communicate with swap stations.

Automakers would not be inclined to invest in a swappable battery controlled by a competitor. Therefore, standards development would probably require the involvement of a neutral entity, such as a foundation or a government body.

Governments are already investing in EV charging infrastructure; therefore, they might be inclined to allocate a small portion to support standards development. More specifically, they might support the design, prototype and testing of: (a) swappable batteries, (b) swap mechanisms, (c) swap stations, (d) battery handling machines, and (e) battery transportation infrastructure. To encourage widespread adoption, developed technology could be disseminated free and open.

## Economic Strategy

Regions that import significant amounts of oil, such as China and Europe, would probably lead the way since EVs reduce dependence on foreign oil. In contrast, the U.S. produces oil, and is therefore less interested in EVs. However, as adoption increased in regions fond of EVs, economies of scale would drive down costs, eventually making swap more attractive to regions less supportive of EVs.

To press forward, a government or foundation would probably need to fund the development of a free and open swappable EV battery standard.

## R&D Funds: Swappable EV Battery (SEVB)

- R&D Fund: **SEVB Mechanical Standards Development**
  Support the development of standards that define how the various SEVB components fit together mechanically.

- R&D Fund: **SEVB Electrical Standards Development**
  Support the development of standards that define how the various SEVB components connect electrically.

- R&D Fund: **SEVB Communications Standards Development**
  Support the development of standards that define how the various SEVB components communicate.

- R&D Fund: **SEVB Swap Station R&D**
  Support the design, prototype and testing of swap stations.

# 9. Next Generation Building Automation & Control


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 could save money, increase comfort, and reduce energy consumption via multiple techniques. For example, this could help control the temperature of each room, and help move heat from one room to another.

## Open Source Operating System

To facilitate global acceptance and ensure bug-free operation, the same free and open operating system software would probably be needed on all devices. 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 flips a physical wall light switch, the communication between the switch and the ceiling bulb is operational ≥ 99.999% of the time (commonly referred to as 'five nines'). This gets little attention, yet is important. Occupants typically do not tolerate less reliability from 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 ensure high reliability, a communications data wire would probably be needed in power cables within walls. Fortunately, it would cost little to add this to new buildings.

## Light and Heavy Devices

To reduce costs, devices could be divided into two categories: 'Light' and 'Heavy'. 'Light' might consume less than 20W and include bulbs, switches, sensors, and small motors; while 'Heavy' supports 110/220VAC outlets, HVAC equipment, and appliances. From a cabling perspective, 'Light' might be supported by 48VDC power and one communications wire; while 'Heavy' is supported by 110/220VAC power and two data wires.


*Figure 9.1: In theory, buildings could be supported by two power/data networks, one for large loads, and one for small.*

Most devices in a building are 'Light' and could use lower voltages and lower power to save money via multiple techniques. These include smaller cables, less conduit, fewer safety requirements, and less expensive microcontroller power supplies.

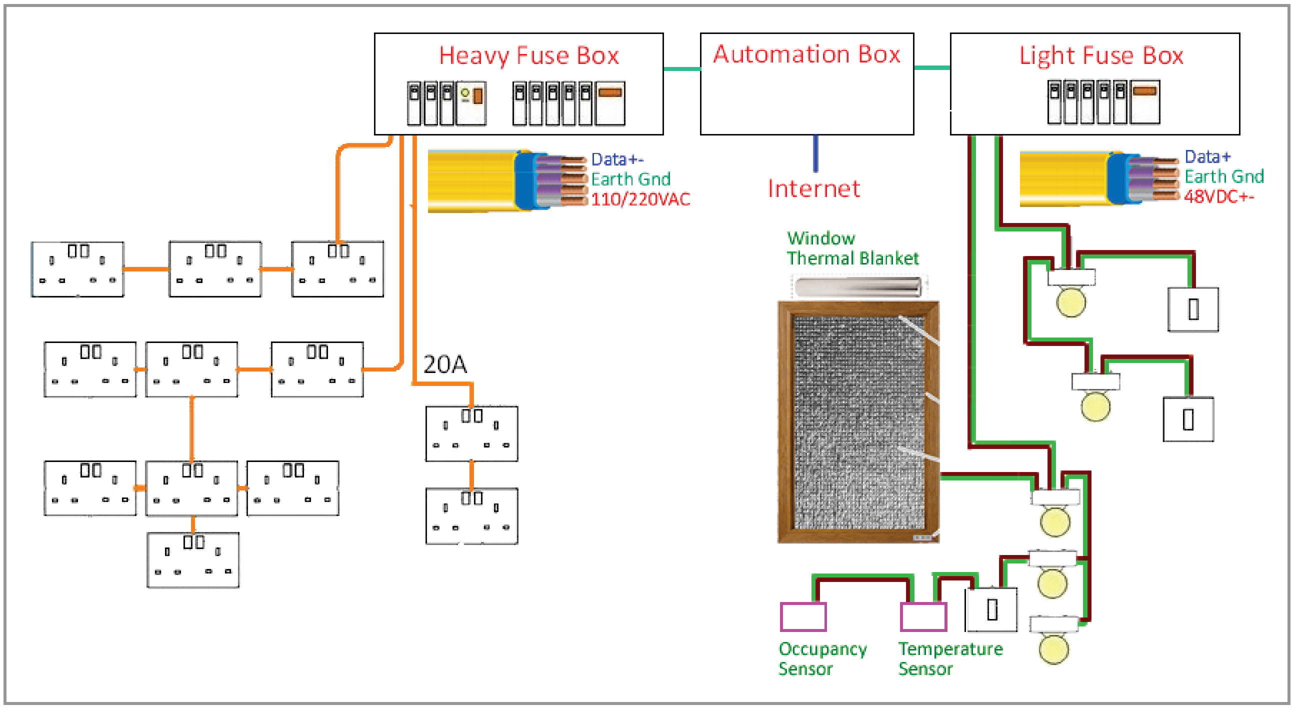



*Figure 9.2: In theory, a data wire could be added to power cables in newly constructed buildings to enable reliable device communication.*

## Plug-and-Play Standards

To support plug-and-play operation, standards are needed that define how devices connect electrically, mechanically, and with data communications. Before these are proposed, components would need to be designed, prototyped, tested, debugged, and improved. This might cost 10's to 100's of millions of dollars given the size of the system.

So who might fund this initiative, and how might it be structured to meet the satisfaction of the various participants? Nations resist being controlled by external entities, and therefore might require new standards be based on free and open technology. Companies cannot afford to give their money to their competitors, and governments rarely provide leadership. Therefore, a foundation looking to save the planet from climate change might be required. The Gates Foundation is uniquely suited since Bill has experience developing networks, devices, operating systems and standards (e.g., UPnP).

## System Requirements

TCL supports the development of a next generation building automation and control system that meets the following of requirements:

- The system supports device-to-device communication for purposes of automation and control within residential and commercial buildings. Devices include HVAC equipment, water heaters, appliances, control panels, motorized dampers and fans in ducts, motorized valves in radiators, thermal storage tanks, solar panel electronics, motors that move thermal covers over windows, occupancy sensors, temperature sensors, and fire detectors.

- The system supports: (a) managing the above list of devices, (b) regulating the temperature in each room, (c) transferring heat from one room to another, and (d) transferring heat between thermal storage, ground sources, appliances, and rooms.
- Any device can communicate with any other device within a house-sized structure. Typical data rates are 30K bits/second with ≥ 99.999% reliability (i.e., percent of data packets that are delivered without error). System does *not* support audio, video, or computer data; which is typically transmitted via wireless or powerline communication at higher data rates and with less reliability.
- Electrical power and communications standards are developed that support next generation 'Light' and 'Heavy' power/data cables embedded in walls. 'Light' includes two 48VDC power wires, one data wire, and one earth ground wire; while 'Heavy' includes two 110/220VAC power wires, two data wires, and one earth ground wire. The earth ground wire normally does not carry current, and instead supports RFI shielding and safety against power shorting to case. Devices must not incur damage if a power wire shorts to a data wire.
- Mechanical, electrical and software standards are developed that define replaceable standardized plug-in hardware modules. Open-source designs are published to reduce costs via commoditization, and to reduce risk of replacement parts not being available. Original module manufacturers are not likely to maintain production over a building's lifetime; and building owners understand a building will lose value if cannot be maintained; therefore, standardized commoditized replaceable modules are needed to facilitate system acceptance.
- To easily add sockets to power/data cables, a standardized clamshell clamp socket is developed along with a motorized hand-tool that mills plastic to expose conductors and turn bolts (ref 4.13).
- To support module replacement without additional user interaction, an eeprom memory IC is embedded in each socket, and programmed with physical location and module settings.
- Module sockets expose an additional diagnostic connector to help maintain the system over the building's lifetime. A custom cable with in-line electronics connects this diagnostics connector to a smartphone USB connector, allowing software to identify sources of failure (e.g., no power, data wire shorted or open), and suggest remedy (e.g., replace module, probe a different socket).
- Data protocol is CANbus since it is the only one-wire communications system embedded in low-cost microcontrollers. Devices mostly sleep in low-power mode, and are woken up when the CANbus data line asserts, and the device's ID is recognized.
- Physical layer signaling standards are developed for both 'Light' and 'Heavy' networks (ref 4.1). For example, 'Light' devices might signal by shorting a current limited data line to ground, and 'Heavy' devices might signal with opto-couplers to support large voltage drops between devices. Physical wiring topology is a tree and therefore does not support transmission line termination. Therefore, rise/fall times need to be long to avoid ringing (e.g., 3µSec).

- All devices are required to use the same free and open operating system software. Developers begin with the free BuildingBus OS, and improve as needed. This was written by Weinreb, who has developed approximately 30 automation and control systems over the last 45 years. For details, see the BuildingBus Software Development Guide, and Hardware Development Guide.
- Each power cable terminates at a fuse within a utility box; and each data wire terminates at an adjacent automation box. The latter is connected to the internet.
- Each power/data cable maintains a set of devices that signal along the same data wire, and each of these devices support an optional sub-network of devices, each with their own data wire. Also, each sub-network device supports an optional sub-sub-network, for further isolation. Ultimately, a 3 number physical address identifies each device (i.e., 0…15 network number, 0…31 sub-network number, 0…15 sub-sub-network number) and the BuildingBus software supports routing data packets from any device to any other device within this three-layer hierarchy. In other words, within a house-sized structure, any device can talk to any other device, with isolation and reliability.
- A low-cost, low-power communication system with ≥ 99.999% reliability is developed that enables 110/220VAC outlets to communicate with plugged-in appliances through their power cords (ref 4.13.6). Communication is supported after user powers appliance off via a low quiescent power supply. Note that 3V/1mA power costs less than 5 pennies per year.
- A system is developed that supports standardized communication between buildings and the electrical power company. This supports building heat decarbonization, the broadcast of electricity price, the broadcast of $CO_2$ emissions per unit of electricity, etc.
- A standardized system is developed that supports next generation LED lightbulbs in smart light sockets.
- Software is developed that helps electrical engineers specify devices when buildings are designed, helps electricians install modules, helps identify failures, and helps occupants live in comfort.

## R&D Funds: Next Generation Building Automation & Control (NGBAC)

- R&D Fund: **NGBAC Operating System Development**
  Support the development of an open source operating system that runs on all devices.
- R&D Fund: **NGBAC User Interface Software Development**
  Support the development of 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.
- R&D Fund: **Standardized Plug-in Hardware Module Development**
  Support the development of standardized plug-in hardware modules, module sockets, socket-to-cable interface (ref 4.13), diagnostic tools, and installation tools.
- R&D Fund: **Light Power Cable Standards Development**

Support the development of standards that govern 'Light' power cables with data wire support.

- R&D Fund: **Heavy Power Cable Standards Development**
  Support the development of standards that govern 'Heavy' power cables with data wire support.
- R&D Fund: **NGBAC Master Controller Hardware and Software Development**
  Support development of master controllers (e.g., chassis next to fuse box that connects BuildingBus System to internet).
- R&D Fund: **NGBAC Router Hardware and Software Development**
  Support development of routers that reside between subnetworks.
- R&D Fund: **NGBAC Power Company Interface Standards Development**
  Support development of standards that connect NGBAC systems to power companies.
- R&D Fund: **Appliance Interface Standards Development**
  Support development of standards that connect 110/220VAC plug-in appliances to the NGBAC system (e.g., NFC between power cord plug and outlet, ref 4.13.6).
- R&D Fund: **Smart LED Bulb Standards Development**
  Support development of standards that govern next generation LED light bulbs and sockets (ref).
- R&D Fund: **Window Thermal Cover Standards Development**
  Support the development of mechanical and electrical standards that govern replaceable motorized window thermal covers (e.g., embedded in a wall next to a window, and slide out to physically cover the window when the room is not occupied, ref).
- R&D Fund: **Replaceable Fan Standards Development**
  Support the development of standards that govern replaceable fans embedded in HVAC ducts (ref).
- R&D Fund: **Replaceable Dampers Standards Development**
  Support the development of standards that govern replaceable dampers embedded in HVAC ducts (ref).

## 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

# 10. Reflecting Sunlight

We can solve the carbon dioxide problem by replacing fossil fuel with green energy. However, this alone probably will not resolve the problem of climate tipping points. We seem to be approaching these critical thresholds too quickly. Therefore, we probably need to reflect approximately 1% of sunlight back into outer space, to cool the planet. There are several ways to do this, one of which is called “stratospheric aerosol injection” (SAI). This involves spraying reflective gases or liquids into the upper atmosphere using airplanes.

The upper atmosphere is known as the stratosphere, while the lower atmosphere is called the troposphere. At the equator, the boundary between these layers occurs at an altitude of about 20 km (60k ft), whereas near the North and South Poles, this boundary is lower, at approximately 12 km (40k ft).

Existing aircraft can reach the stratosphere over the Polar Regions (e.g., at about 60°N or 60°S latitude), making it possible to cool these regions using SAI. However, cooling the entire planet would require injections to occur near the equator, at altitudes around 20 km (60k ft). We currently do not have large airplanes that fly to this height; however, they could be developed. In summary, we can cool the Polar Regions with existing aircraft, yet would need to develop new aircraft to cool the entire planet.

One possible injection material is sulfur dioxide gas ($SO_2$). Sulfur occurs naturally in coal and oil, and is therefore emitted into atmosphere upon combustion. In principle, it could be extracted before combustion, moved to an airplane, and emitted into the stratosphere instead of being emitted at ground level. Stratospheric sulfur stays aloft for one to two years, while sulfur emitted at low altitudes typically stays aloft for only hours to days. Therefore, shifting 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. Yet by how much?

Annually, fossil fuel combustion releases approximately 70 million tons of sulfur dioxide ($SO_2$) and 40,000 million tons of carbon dioxide ($CO_2$) into the atmosphere. Both contribute to ocean acidification, though the impact of $CO_2$ is significantly larger due to its greater quantity. Consequently, introducing $SO_2$ into the stratosphere for planetary cooling would likely have a negligible effect on ocean acidity. Another concern is harm to the ozone layer; however, initial assessments indicate this would be minimal.

Sulfur-based materials are not the only substances with reflective properties. For instance, calcium carbonate ($CaCO_3$), commonly known as chalk, exhibits similar reflective capabilities and interacts less with ozone. Further research is needed to understand the benefits and drawbacks of each candidate material.

## How Much Does this Cost?

To justify the expense of SAI, our society would need to compare the cost of cooling the planet, with the cost of not cooling the planet. One study suggests large-scale planet cooling would cost $18B a year. For comparison, the total value of New York City property is $1,400B—and this is just one coastal city that would be lost to sea level rise. If the U.S. paid half, planet cooling would cost each American $27 per year (50% × $18B ÷ 330 million people).

## Sulfur Cools the Planet

Sulfur injected into the stratosphere follows a different path than sulfur injected into the troposphere.

### Stratospheric Sulfur (“Aerosol-Radiation Effect”)

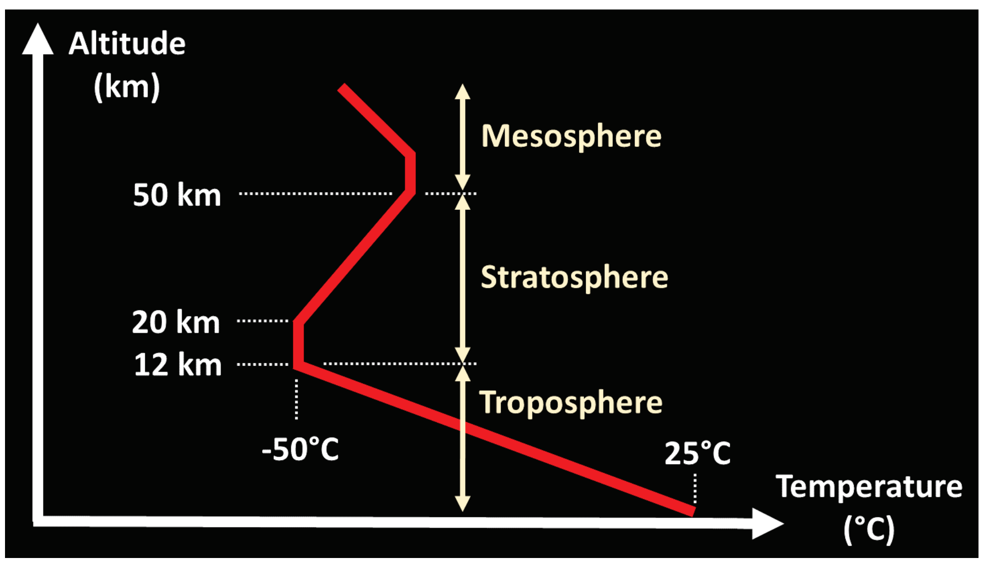
> Sulfur in the upper atmosphere (stratosphere) is rare; however, it is made possible via volcanic eruptions and SAI. When sulfur dioxide gas ($SO_2$) enters the stratosphere, it chemically reacts with water ($H_2O$) and oxygen ($O_2$) to form liquid sulfuric acid ($H_2SO_4$). This combines with water to produce tiny droplets that are typically composed of 50% sulfuric acid and 50% water. These droplets last for month to years, while reflecting sunlight back into outer space.

### Tropospheric Sulfur (“Aerosol-Cloud Effect”)

> Significant quantities of sulfur are already present in the lower atmosphere (troposphere), primarily due to fossil fuel combustion. However, this sulfur typically remains airborne for only hours to days because of rainfall and gravitational settling. In humid conditions, tiny sulfuric acid droplets grow into cloud droplets consisting mostly (≥ 99%) of water. Clouds with sulfur reflect more sunlight than clouds without, and therefore offset global warming with cooling.

## Atmospheric Temperature Gradient

Air temperature varies with altitude in unobvious ways, as shown in the graph below.




Altitude values in this illustration reflect the atmosphere near the equator. In contrast, these values are approximately 40% less when near the North Pole or South Pole.

As one can see, the atmosphere is relatively warm at ground level, and gets colder as one goes up. However, this reverses after one enters the stratosphere, since ozone in this region absorbs solar radiation, and causes temperatures to become warmer as one goes higher. In other words, there is a layer of relatively cold air in the lower portion of the stratosphere, and a layer of warmer air above it.

Also, warm air rises, which means that material injected in the lower stratosphere will go up, and not quickly fall to Earth due to gravity. Therefore, one gram of sulfur injected into the stratosphere will cool the planet more than one gram injected at ground level.

## Three Areas of SAI Operation

Increasing the reflectivity of the atmosphere involves three physical areas of operation:

- **SIA Research:** Physical experiments could be conducted in the stratosphere near the Polar Regions. For example, a specially equipped aircraft could inject reflective material at an altitude of around 14 km (43k ft) within the polar vortex, near the North Pole, while a second aircraft monitors properties of the material over days to weeks.
- **Cool the North and South Poles:** Approximately one-hundred modified Boeing 777 aircraft could disperse reflective materials close to the North and South Poles to block tipping points associated with Arctic and Antarctic sea ice loss, the Greenland Ice Sheet, the West Antarctic Ice Sheet, and disruptions to the AMOC (ref).
- **Cool the Entire Planet:** Custom-built high-altitude aircraft capable of reaching approximately 20 km (60k ft) altitude could disperse reflective materials near the equator, to cool the entire planet (ref1, ref2).

## The Lab's Role

Increasing the reflectivity of the atmosphere is a new field and there are many things we don't know. We don't know exactly what to inject, when, where and how. And we don't have an accurate assessment of costs, and adverse side effects. To resolve unknowns, TCL 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.

## R&D Funds: Reflecting Sunlight (SAI)

- **R&D Fund:** **SAI Experiment Development**
  Support the development of experiments and proposals that physically injects material into the arctic stratosphere, and monitors that material over days to weeks (Example SAI Experiment).
- **R&D Fund:** **Measure Aerosol Reflectivity**
  Support the development of experiments and proposals that measure how much sunlight reflects off aerosols, to reduce the size of the blue error bar in IPCC Ar6 Figure 7.6 (Example Aerosol Experiment).
- **R&D Fund:** **SAI Spray Hardware R&D**
  Support the development of spray equipment on airplanes (e.g., tanks, pumps, and nozzles).
- **R&D Fund:** **SAI Instrumentation R&D**
  Support the development of instruments that monitor injected material (e.g., LIDAR, UV/IR spectroscopy, radio wave measurements, direct sampling, and remote measurements).
- **R&D Fund:** **SAI Experimental Spray Plane R&D**
  Support the development of spray planes that conduct SAI experiments (e.g., modify an airplane to spray 10,000 kg of $SO_2$ gas at a 14km (43k ft) altitude near the North Pole).

- R&D Fund: **SAI Monitor Plane R&D**
  Support the development of monitoring aircraft that analyze injected material by flying through it, above it, and below it. This includes flying through material and analyzing direct samples, flying *above* material and comparing sunlight reflected off material with sunlight that does not pass through material, and flying *below* material and comparing sunlight that passes through material with sunlight that does not.

- R&D Fund: **Polar SAI Airplane R&D**
  Support the development of airplanes that conduct full scale SAI operations near the North and South Poles (e.g., Modify a Boeing 777).

- R&D Fund: **Equatorial SAI Airplane R&D**
  Support the development of new high-altitude aircraft (e.g., SAIL-01) specifically built to disperse material near the equator, at a ~20 km (60k ft) altitude, to cool the entire planet.

- R&D Fund: **SAI Airport Development**
  Support the development of automated airports that conduct full-scale SAI operations (ref).

- R&D Fund: **Automated SAI Refueling R&D**
  Support the development of automated equipment that refuels and reloads SAI airplanes between flights.

## 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
- Pandora's Toolbox: The Hopes and Hazards of Climate Intervention
- Solar Radiation Modification, EU Evidence Review, Dec 2024

# 11. Climate Science in Five Minutes

The following is a brief summary of climate science.

### The 1.5°C Problem

Several decades ago, climate scientists stated the world needs to avoid a 1.5°C global temperature increase, relative to 150 years ago, or “bad things” will happen. They implied we are to peak at 1.5°C, and then drop back down. Instead, we breached 1.5°C in 2023, and we are not cresting. Instead, we are warming rapidly.

Also, global $CO_2$ emissions would need to be close to zero at the point of cresting, to cause global temperatures to decrease. Instead, emissions are at their highest level, and are still increasing.

### The Failure of Decarbonization

It takes several decades to decarbonize to zero emissions; therefore, the world would have had to start decarbonizing roughly 30 years ago, to get to zero $CO_2$ emissions today. In other words, over the last several decades, our society failed to decarbonize.

### Sunlight Reflects Off Air Pollution

Sunlight reflects off man-made air pollution and back into outer space, offsetting global warming, with cooling.

### The 0.3°C Jump

In 2022 the average global temperature, relative to 150 years ago, was 1.2°C ; and over the next two years, it surged by 0.3°C, reaching 1.5°C.

For 40 years, between 1970 and 2010, global temperatures rose at a rate of about 0.18°C per decade. Therefore, a 0.3°C jump over a few years is unusual.

Top climate scientist James Hansen believes half the surge was due to El Nino, and half due to a reduction in air pollution. As noted previously, air pollution cools the planet; therefore, less pollution leads to more warming.

### Tipping Points

Tipping points are additional sources of global warming, which add to global warming already done by $CO_2$. An example is North Pole sea ice. It is one to two meters thick, and when it melts, sunlight is absorbed by sea water, instead of being reflected by sea ice—and this causes the temperature of the planet to increase.

Another example tipping point is the West Antarctic Ice Sheet. If this were to collapse, sea levels would rise multiple meters, and this would disrupt coastal areas.

Published studies suggest tipping points are likely to activate after global warming exceeds 1.5°C.

## Global Warming Components

Global warming is made up of multiple components that add together. These are roughly illustrated below. As one can see, some components increase global warming (red), whereas others decrease global warming (blue). These combine to produce total warming (green), which is the same as observed warming.

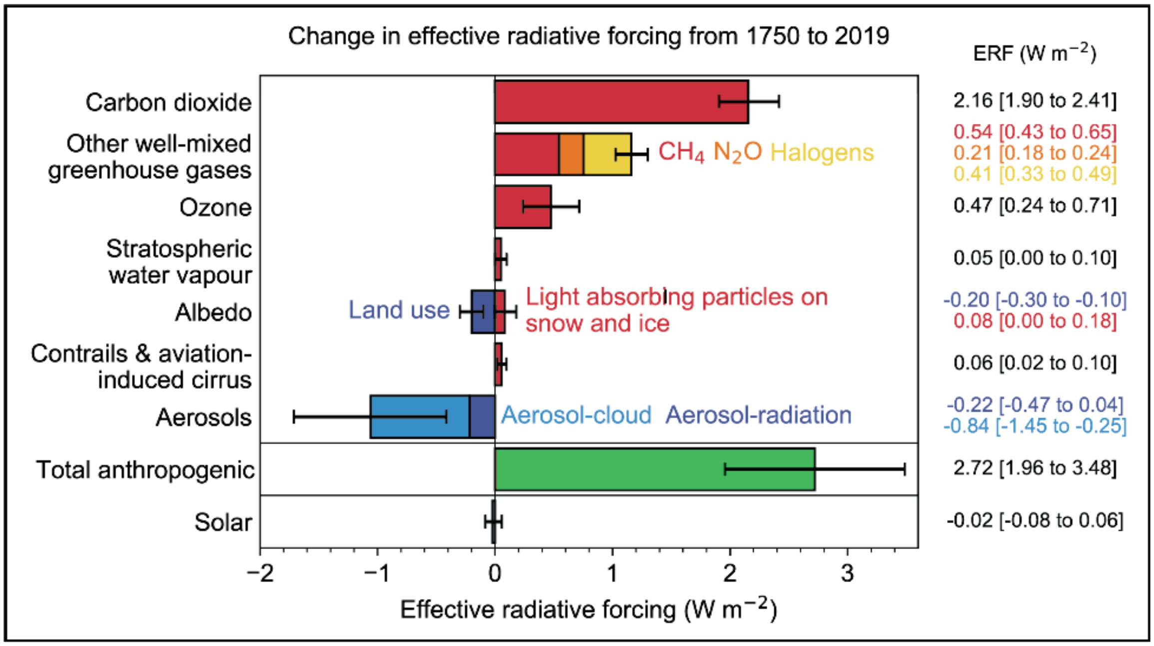



*Figure 11.1: Sources of global warming (red) and cooling (blue) in units of watts per square meter of Earth's surface area. Total actual warming (green) is observed with instruments. Source: IPCC's 6th Climate Report, Figure 7.6.*

## Global Cooling

Global cooling—represented by the blue bars in the above graphic—is caused by sunlight reflecting off particles and droplets in the atmosphere. These substances, known as aerosols, often originate from human-made air pollution.

## Direct Warming from $CO_2$ (Absorption of Outgoing Infrared Radiation)

Sunlight warms the planet's surface after passing through $CO_2$ in atmosphere. The planet then emits infrared (IR) heat radiation back into outer space. $CO_2$ absorbs this *outgoing* IR radiation more than the *incoming* visible light, trapping heat and raising the average temperature of the planet.

## Indirect Warming from $CO_2$ (Climate Feedbacks)

After direct warming occurs, more warming occurs due to climate feedbacks. For example, initial warming melts sea ice, which leads to more sunlight being absorbed by ocean water, which leads to more warming. Other feedbacks include: (a) release of additional greenhouses gases (e.g., methane and $CO_2$) from thawing permafrost, and (b) increased water vapor in atmosphere (due to warmer air), which further traps heat.

## Climate Feedback Response Time

Climate feedbacks don't occur all at once—they unfold over time. After carbon dioxide enters the atmosphere, roughly one-third of the resulting warming occurs within the first five years, another third over the next 100 years, and the final third over the following 1,000 years.

This delayed response means the full effect of today's emissions will not be felt for generations. It also implies that a significant amount of future warming is already "locked in" due to past emissions.

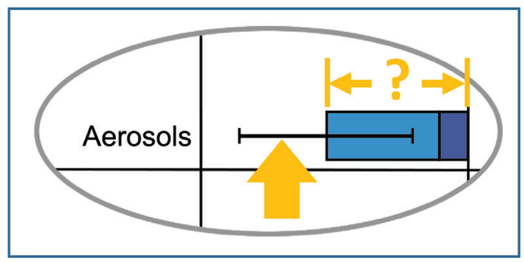
## $CO_2$ in Atmosphere

Hundreds of years ago, atmospheric $CO_2$ levels were about 280 parts per million (ppm). Today, they are around 425 ppm and are projected to reach 560 ppm by the year 2075—double the pre-industrial level.

## Earth Climate Sensitivity (ECS)

The amount of eventual warming (e.g., after 1000 years) that occurs after a doubling of $CO_2$ in atmosphere is referred to as the Earth Climate Sensitivity (ECS). Some scientists believe this is 3°C, whereas others think it is closer to 5°C. If ECS is high, then more tipping points will activate, and sooner.

## Global Cooling Uncertainty




What is fascinating about global cooling in the above graphic is the error bars. These tell us climate scientists do not know if this is a little, or a lot. If actual cooling is large, then climate models estimate ECS is high, and significant changes will occur to our planet over the next few decades. Otherwise, if actual cooling is small, climate models suggests ECS is low, and we have more time.

## Uncertainty Magnitude

Notice the size of the global cooling error bars relative to the amount of warming from 150 years' worth of carbon dioxide (i.e., red bar in Fig 11.1). It is about 80% of that level. In other words, the degree to which scientists do not understand global warming, based on cooling error bars, is enormous. This makes it difficult for national leaders to craft an appropriate response, since the severity of the problem is unknown, by climate scientists' own admission.

## Sense of Urgency

Some scientists believe the recent 0.3°C jump indicates global cooling is large and ECS is high. If this is true, it will probably be accepted by the wider scientific community within several years. If this occurs, the sense of urgency among national leaders will probably increase. However, many so-called decarbonization initiatives are not effective, or not cost-effective. Therefore, expanding them is not likely to have a significant impact.

Ultimately, interest in reflecting sunlight is likely to increase as it becomes clearer that: (a) decarbonization has failed, (b) the climate problem is worse than previously considered, and (c) global temperatures are accelerating upward.

# 12. Decarbonizing Electrical Power

On most home electric bills, electricity consumption is specified in units of kilowatt-hours (kWh). The typical U.S. home consumes 10,000 kWh each year, at 14 cents per kWh, for a total of $1,400 per year. Homeowners typically work with kWh units, while utilities typically work with megawatt-hour (MWh) units, which are 1000-times larger.

At one end of the U.S. grid are homeowners who pay $.14/kWh retail for generation plus transmission, while at the other end is power generation facilities that receive approximately $0.05/kWh wholesale for large volumes of electricity delivered to their front gates.

## Electricity Markets

Comparing the cost of electricity from different sources is challenging due to parameters that vary with time and place, such as interest rates and fuel costs. Also, power plants that run continuously at maximum power ("baseload") typically offer lower costs than facilities that vary through the day. Despite these challenges, we do our best to compare "apples with apples" in the below table. For details, click here.

| Energy Source | | Electricity Cost (LCOE) ($/MWh) | Construction ($/W) | Fuel Cost |
|---|---|---|---|---|
| Nuclear Fission Power | | $34 | $2.00 | $5/MWh nuclear fuel |
| USA | Coal | $36 | $1.50 | $45/ton coal |
| | Natural Gas | $29 | $0.82 | $3.10/MMBtu natural gas |
| China | Coal | $58 | $0.75 | $120/ton coal |
| | Natural Gas | $57 | $0.70 | $8.00/MMBtu natural gas |

*Figure 12.1: Cost of electricity from natural gas, coal, and $2/watt nuclear power.*

Some nations have low fossil fuel costs (e.g., USA, Russia) whereas others have high fossil fuel costs (e.g., China, Europe). As one can see from the above table, the cost of $2/W nuclear-based electricity in China is similar to that of fossil fuel when fuel prices are low (e.g., USA), and is less when fossil fuel prices are high (e.g., China).

## China's Solar Surge

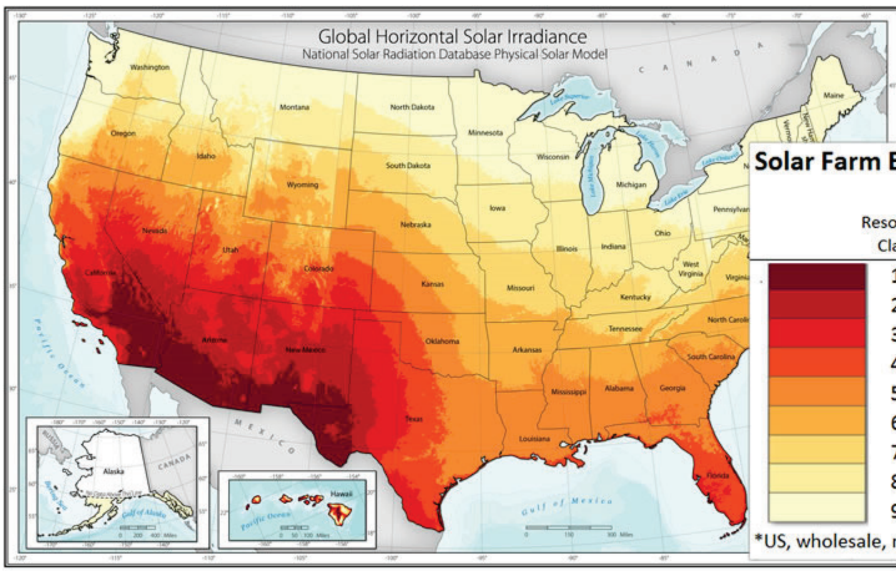
A coal shortage in China recently increased the cost of their coal-based electricity to the point where it's roughly twice the cost of their solar farm electricity. To reduce coal demand, reduce coal price, and save money, the Chinese built 277 GW of solar power in 2024. This is approximately 10-times more than that built in the U.S. over the same time period. Also, this is approximately 46-times more than China's nuclear construction (277 $GW_e$ ÷ 6 $GW_e$). At their current solar construction rates, they will reach saturation within several years, and stop building farms.

The Chinese are demonstrating that large amounts of solar are technically and economically feasible, and their large production volumes are driving down solar costs due to economies of scale. For reference, solar panels made in the U.S. cost approximately $170/kW more than solar panels made in China—which equates to $4/MWh more for electricity.

China's solar construction spree is *not* due to climate change. Instead, it is due to their high cost of fossil fuel, and a lack of local sources of oil and natural gas. Europe is similarly challenged, and is therefore interested in alternatives, such as renewables. In comparison, the U.S. has local low-cost sources of fossil fuel, and is therefore less inclined to go green.

## Solar Farms and Wind Farms

Some regions in the U.S. are more sunny, while others are more windy. As one might imagine, it cost less to generate electricity with a solar farm in a sunny region, and it cost less to generate electricity with a wind farm in a windy region. Yet by how much? The following tables show the wholesale cost of electricity from wind farms and solar farms built in the year 2025 and the year 2033, as estimated by the U.S. National Renewable Energy Laboratory (NREL).

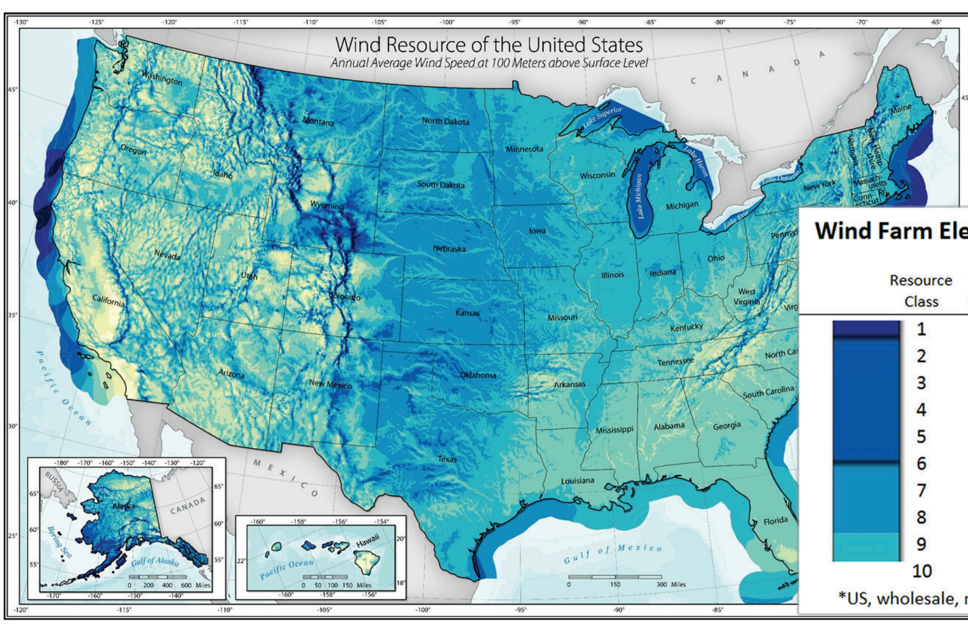



**Solar Farm Electricity Cost***

| Resource Class | Heat Energy (kWh/m$^2$/ Day) | AC Capacity Factor | Electricity Cost 2025 $/MWh | Electricity Cost 2033 $/MWh |
|---|---|---|---|---|
| 1 | > 5.75 | 32% | $39 | $25 |
| 2 | 5.5–5.75 | 31% | $41 | $26 |
| 3 | 5.25–5.5 | 29% | $43 | $27 |
| 4 | 5–5.25 | 28% | $45 | $28 |
| 5 | 4.75–5 | 27% | $47 | $30 |
| 6 | 4.5–4.75 | 25% | $50 | $31 |
| 7 | 4.25–4.5 | 24% | $52 | $33 |
| 8 | 4–4.25 | 23% | $54 | $34 |
| 9 | < 4 | 22% | $57 | $36 |

*US, wholesale, no tax credits, NREL 2024 data, Moderate

*Figure 12.2: This map shows the cost to generate electricity with a solar farm.*




**Wind Farm Electricity Cost***

| Resource Class | Wind Speed Range (m/s) | Capacity Factor % | Electricity Cost 2025 $/MWh | Electricity Cost 2033 $/MWh |
|---|---|---|---|---|
| 1 | > 9.0 | 51% | $29 | $23 |
| 2 | 8.8 - 9.0 | 48% | $31 | $25 |
| 3 | 8.6 - 8.8 | 47% | $32 | $25 |
| 4 | 8.4 - 8.6 | 45% | $32 | $26 |
| 5 | 8.1 - 8.4 | 44% | $34 | $27 |
| 6 | 7.6 - 8.1 | 42% | $35 | $28 |
| 7 | 7.1 - 7.6 | 38% | $39 | $32 |
| 8 | 6.5 - 7.1 | 35% | $45 | $35 |
| 9 | 5.9 - 6.5 | 34% | $49 | $40 |
| 10 | 1.7 - 5.9 | 26% | $72 | $55 |

*US, wholesale, no tax credits, NREL ATB 2024 data

*Figure 12.3: This map shows the cost to generate electricity with a wind farm.*

It tends to be windy at high altitudes; therefore, windmills are technically feasible in many areas. However, due to audio noise and other factors, they cannot be placed close to people. Therefore, they are typically set up in remote areas. For example, windmills for U.S. east coast cities are likely to reside 200 miles inland.

## Decarbonization Cost

When replacing fossil fuel based electricity with green electricity, the additional cost to the consumer is the cost of the green electricity (Fig 12.2 or Fig 12.3) minus the cost of the fossil fuel that is not burned plus variable costs (Fig 12.4). In other words, to calculate the cost to go green, subtract a red number from a green number in these figures.

| Fuel + VC ($/MWh) | Fuel+VC (¢/kWh) | % of US Electricity | Type of Power Plant |
|---|---|---|---|
| $25 | 2.5¢ | 38% | Natural Gas Combined Cycle |
| $32 | 3.2¢ | 8% | Natural Gas Steam Turbine |
| $39 | 3.9¢ | 4% | Natural Gas Combustion Turbine |
| $43 | 4.3¢ | 14% | Coal |

*Figure 12.4: Wholesale fuel cost plus variable cost at carbon based power plants. Source: NREL 2024 ATB*

## Conclusion

We rarely see nations decarbonize at large scales unless green energy costs less than fossil fuel. Also, the U.S. government is not projecting persistent green sources to cost less than carbon sources over the next 30 years. Therefore, a surge of R&D is needed to further drive down the cost of green energy other than solar and wind power.

# 13. Related Material

## Videos by Glenn Weinreb

**A Plan to Save the Planet (27-minute video)**
https://www.youtube.com/watch?v=9RY1943xlRI

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

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

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

**How to Resolve Climate Change at the Lowest Cost to Society (CS7)**
https://www.youtube.com/watch?v=VBSsRb4SeoI

**The Politics of Climate Change (CS5)**
https://www.youtube.com/watch?v=UJ72hDDguyc

**The Easiest Way for Government to Tackle Climate Change (CS3)**
https://www.youtube.com/watch?v=QvlOVtCi-qw

**YouTube Videos by Weinreb**
http://www.aplantosavetheplanet.org/climate-solution-videos

## Articles & Books by Glenn Weinreb

Climate solution articles by Weinreb: www.manhattan2.org/#articles

Free climate book: www.APlanToSaveThePlanet.org/pdf

## 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/lab

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