How a Government Could Solve the Climate Change Problem for $10B/yr

By Glenn Weinreb, Director, The Manhattan 2 Project, gWeinreb (at) Manhattan2.org, Oct 6, 2021

Executive Summary

This document explains how a government could spend $10B-per-year to solve the climate change problem. In summary, this money is used to:

- Develop factories that mass produce Generation 4 nuclear reactors.
- Develop factories that mass produce equipment that makes green hydrogen gas (H_2), and green liquid ammonia (NH_3).
- Automate the construction of nuclear reactor buildings and sites.
- Develop a super-sized transportation system that moves large and heavy cargo from factories to nuclear power stations, via extra wide rail.

The $10B/yr initiative automates, to the extent required, to make green energy cheaper than carbon-based fuels. This gets us worldwide decarbonization, since customers will buy green to save money. And this gets us capital market participation, which means banks and bond markets will pay for green energy power stations, and factories that supply them. Economic principles state that customers favor lowest cost products, and capital markets follow customers.

The $10B/yr initiative pays for the first factory of each type. And these are made both economically and technically transparent. This means everyone is given access to all drawings and financial data, which makes it easy to copy. This is the lowest cost way to facilitate global decarbonization. The gov't gives instead of sells for selfish reasons -- they do not want harm to come to their shores from climate change. Making a design public causes components to become commodities, which means prices are driven down to parts cost, plus processing cost, plus factory overhead, plus a small profit. We need this to make green energy cheaper than non-green. The $10B/yr automation cost is justified, by saving more than this, when the world builds ~$10T of green energy power stations over 25 years, to replace carbon-based fuels.

Each year the world consumes 583 EJ of heat energy, which corresponds to 56,000 TWh of electricity at 35% efficiency[12]. To solve our climate change problem, we need to replace this with a source of energy that does not emit CO_2. The 583 EJ/yr corresponds to:

- 13,500 [Hoover Dams](), a large hydroelectric dam in Nevada[12]
- 22,600 [London Arrays](), a wind farm with 175 large windmills[12]
- 21-times more than the world's current installed base of 400 GWe of nuclear power[14]

When decarbonizing, one can think of this as the "problem size". Global CO_2 emissions are increasing because the world is not building green energy generation capacity that matches the problem size. News reports on the London Array do not explain that the world needs 22K of these; and that the number of global opportunities with shallow windy water close to shore are less than 22K.

Solar, wind and hydro are "resource constrained", which means they need land conducive to the task to be somewhat cost-effective. Hydro needs sloped land with running water and bedrock to support a dam. Windmills need windy land away from people, or windy shallow offshore water close to land. Solar farms need low cost storage, which does not exist; and cheap cleared sunny land close to population. In all three cases, we run out of opportunities as we build, which means costs eventually go up, and people stop building.

Nuclear power is *not* resource constrained, which is good. However, nuclear has three big challenges: (a) the public is not comfortable with nuclear safety risks, (b) electricity from nuclear cost more than electricity from coal or natural gas, and (c) we would need 8,400 nuclear reactors at 1 GWe each to globally decarbonize. This is 21-times more than our current installed base of 400 GWe, and building just one reactor is exhausting.

Our plan is for the world to build hydroelectric power, solar farms, and windfarms until limitations cause costs to become unacceptable; and get the balance from cost-reduced Generation 4 nuclear power. To mitigate nuclear safety risks, we utilize Generation 4, whose nuclear fuel turns off when it gets too hot.

As a next step, we propose a government set up an initiative to solve the climate change problem, as summarized below:

Proposed: <u>Global Decarbonization Initiative</u>

Mission: Solve Climate Change Problem.

Funding: $10B/yr from gov't.

Mandate:

1) Automate the manufacture of equipment that makes green electricity, green hydrogen, and green ammonia.
2) Develop new systems that transport large cargo between factories and power stations.
3) Automate construction of power station sites.
4) Do the above to the extent required to make green energy cheaper than non-green.

Strategy: Develop one factory of each type and give all technology away for free so that capital markets globally fund the building of factories, and building of power stations, driven by customer demand to save money on cheaper green energy.

Next Step: Gov't publishes a plan for how it will decarbonize the world to zero emissions via a $10B/yr initiative. If desired, begin with this plan, edit in any way & rename at no charge.

In summary, we need green energy to be cheaper than carbon-based fuels to facilitate world decarbonization. And to make it cheaper, we need automation. And to justify automation, we need a plan that explains how the gov't can decarbonize the entire world to zero emissions, for the cost of the automation.

And the document you are currently reading, can be considered a first draft of that plan.

Always begin with plan.

Chapter 1) Global Decarbonization Plan

Plan Requirements

When making a plan, one begins with a set of requirements that are given to a design team, who develop a solution. This is evaluated by others, reworked and ultimately accepted. In our case, requirements are as follows:

1. Develop a plan for how the United States Government can decarbonize the world. A CO_2 molecule emitted from Austria is just as harmful as one that shoots out of Atlanta; therefore the mission is to decarbonize globally.
2. Spend at most $10B/yr of gov't money. Relying on more money is not helpful since brute force decarbonization entails more money than we have, especially worldwide.
3. Do not rely on resources we do not have. This includes rare earth materials, cheap cleared land, gov't money, consumer demand for higher priced green living, and political will.
4. Reduce global emissions to 20% of current levels by 2050 (i.e. a 5-fold reduction). Focus on the easiest first, and avoid difficult-to-decarbonize areas.
5. Assume consumers favor the lowest cost product, even if it emits more CO_2. Also, assume the global population does not consider climate change, and decarbonization, a priority. Make decarbonization somewhat easy; otherwise, it will not get done.
6. Write in a style that a layperson can understand.

We will now present a plan that meets the above requirements. We invite others to evaluate, discuss, and improve. We are serious, and consider this to be something we can actually accomplish. We will begin with a brief summary of green energy, which is energy that does not emit CO_2.

Green Energy 101

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

An "energy carrier" is a substance that moves energy from a source to a consumer. The four big carriers of green energy are electricity, piped hydrogen gas, ammonia liquid, and heat in a pipe. To produce green energy carriers, one needs a source that does not emit CO_2; such is wind, solar, hydro or nuclear.

Hydrogen gas (H_2) moves easily in a pipe, provided one has a pipe. However, it does not transport in a vehicle easily, or store easily, due to -253°C temperature when a liquid, and 700 ATM pressure (10K PSI) when compressed as a gas in a tank. Electricity does not store easily either; therefore, if you want green storage or transport via truck, train or ship via lowest cost; you are probably looking at tanked liquid ammonia.

Ammonia is NH_3, which means it is hydrogen with one nitrogen atom. Ammonia can be burned directly, or one can remove the nitrogen atom to make hydrogen, and then utilize hydrogen. If you feed hydrogen gas into a fuel cell, you can convert to electricity. Ammonia in a tank needs to be refrigerated to -33°C at 1 atm pressure, or pressurized to 10 atm at room temperature, and is therefore cumbersome; however, we have much experience with this since we use it to make fertilizer. Adding or subtracting a nitrogen atom costs some money, yet if you want green storage at lowest cost, this is probably it.

One can transfer green heat from a nuclear reactor to a heat driven process ~1km away via a pipe that carries a hot gas or hot liquid. One can then use the green heat to make things like hydrogen, ammonia, materials, etc.

In summary, green energy involves sources, carriers, and storage:

Sources of Green Energy:	Solar panels, hydroelectric dams, windmills and nuclear power plants.
Carriers of Green Energy:	Electricity traveling in a wire, heat traveling in a pipe, green hydrogen gas traveling in a pipe, and green liquid ammonia traveling in a pipe.
Storage of Green Energy:	Liquid ammonia in a tank.

National Cheaper Goals

As we mentioned previously, our plan is to make green cheaper than non-green, and then let consumers go green to save money. This leads to our proposed National Cheaper Goals, listed below. World leaders need to state that achieving these are of national importance and their gov't is willing to do whatever it takes to achieve them (within reason).

1. Green electricity must be cheaper than non-green electricity (typically generated with coal or natural gas).
2. Green heat must be cheaper than non-green heat.
3. Piped green hydrogen gas (H_2) must be cheaper than heating oil, coal and piped natural gas (CH_4); per unit energy.
4. Tanked liquid green ammonia (NH_3) must be cheaper than coal, natural gas, and oil; per unit energy.

If we provide methods for achieving these goals to businesses, they would then use them to take market share away from existing suppliers of CO_2 emitting energy. In other words, gov't does not need to decarbonize, only spend tens of billions of dollars to develop and publish methods to make cheaper green energy. Markets will then do the rest.

Chapter 2) Reduce Cost of Green Energy with Factory Automation

Build an Automated Factory that Makes Generation 4 Nuclear Reactors

The following two PO's would significantly reduce green energy costs:

1. Purchase the design of a Generation 4 high temperature modular nuclear reactor and make all technology free and open, which means anyone can copy, modify and utilize at no charge. This would include the design of the specialized equipment that forms fuel particles and fuel capsules, and inspects, since we want to reduce those costs as well. A high temperature enables one to drive chemical processes such as hydrogen production.

2. Purchase the design of a factory that mass produces transportable sub-assemblies used in the above standard design; and make the design of the factory itself free and open.

These PO's would establish one design as the de facto global standard, until the same treatment was provided to a different design.

Normally, gov't does not play a leadership role in reforming an industry. However, to get through climate change at minimal cost, they might need to. If uncomfortable with this role, they can delegate to a team that manages the process, perhaps inside or outside of gov't, perhaps led by a former US Secretary of Energy, or former director of a national laboratory.

In theory, a nuclear reactor design company could publicly *declare* pricing for the above two PO's via a press release; and include pricing for 10, 100 and 1000 reactors. The larger quantities would require a factory that mass produces sub-assemblies that are transported to reactor sites by truck, rail or ship. They could also publish what they consider to be a good global decarbonization plan, perhaps starting with our plan and editing to their satisfaction, at no charge.

Build an Automated Factory that makes Nuclear Reactors Every Five Years

There are several different Generation 4 technologies, some of which are still in development. Therefore, a reasonable strategy is to start today with a commercially available system in what we call Gen 4 Package #1 (Gen4P1). And then do this again with another two PO's in Package #2 (Gen4P2), with more advanced technology, perhaps five later. And keep going with additional packages, perhaps every 5 to 25 years.

An example of an operating Generation 4 high temperature reactor is the Chinese HTR-PM (click for video). The American Xe-100 is similar (click for video), yet is not running commercially. Both systems are uranium pebble with helium gas.

An example of newer technology that is still under development is thorium molten salt (MSR). This has several advantages, such as reduced fuel cost, shorter-lasting nuclear waste, and less pressure in reactor vessel. Researchers are currently tackling MSR challenges, such as internal surfaces that need better corrosion resistance when exposed to high temperature salt.

When COVID-19 struck, the US Gov't distributed R&D money quickly. They could potentially do the same with $100M, or more, to work on MSR. Researchers working on corrosion do not necessarily need to touch a nuclear reactor since they can simulate properties using software, and test small samples (e.g. 10x10cm) in a laboratory test chamber. Also, they can develop support equipment that looks for corrosion.

Materials that resist high temperature salt can be used in equipment other than MSR, since we also need to convert heat to electricity, convert heat/water/electricity to hydrogen, and convert hydrogen/air/electricity to ammonia.

Gen 4 Package #1 would enable us achieve Cheaper Goal #1, which is to make green electricity cheaper than non-green. This is extremely important for multiple reasons:

- Enables us to decarbonize the electricity sector, which is 42% of global CO_2 emissions[6].
- Enables us to replace fossil fuel powered appliances with electricity.
- Causes $540B/yr global investment capital to divert from non-green electricity to green.
- Enables the world to stay busy while we develop the newer Package #2 technology, which results in further cost reduction, which leads to achieving more goals, which leads to more decarbonization.

Build an Automated Factory that makes Hydrogen Production Equipment Every Five Years

To meet Cheaper Goals #3 and #4, we need to reduce the cost of equipment that makes hydrogen and ammonia. With these materials we can do the same as above, and issue two PO's.

Shipyards might be competitive with this since they are already set up to work with large steel structures, tanks, piping and welding. Also, a factory outside a shipyard could potentially be set up with similar equipment, and be just as competitive. If both relied on the same set of suppliers, their operations might be similar. For example, they might both buy from the same company that uses robots to weld together pipes in a sub-assembly.

A Hydrogen Package #1 (H_2P1) would probably utilize commercially available technology, such as high temperature electrolysis[9]. A Hydrogen Package #2 (H_2P2) might utilize newer technology, such as sulfur-Iodine, perhaps several years later.

Today's nuclear driven high temperature electrolysis technology makes electricity first, and then converts to hydrogen. Approximately 58% is lost when electricity is made via nuclear, and another 10% when hydrogen is made, for a total loss of 70% (30% efficiency) [11].

Tomorrow's sulfur-Iodine technology converts heat directly from nuclear reactor to hydrogen with a 53% loss, and then recaptures some for a total loss of approximately 43% (57% efficiency)[8]. If more is recaptured, then one could improve further. This means that a Hydrogen Package #2 should be able to increase hydrogen output by a factor of two or more, given the same sized nuclear reactor. Making this work requires developing components that better resist corrosion at high temperatures. And if a gov't leader established the National Cheaper Goals, this type of research would probably receive priority attention.

Mass Produce Nuclear Reactors like a Car

A car company must design a car, and also design a factory that makes the car. The factory contains multiple stations that each implement an assembly operation. Factory engineers program robots and design custom electro-mechanical equipment to assemble and test. The engineering that goes into designing a factory is significantly more than the engineering that goes into designing a car. The test jigs are often more complicated than the things they test. This involves engineering, and it costs money, yet if spread out over many production units, is affordable. The good news is you only need to do your engineering once, and then you can manufacture at low cost.

Each factory has a supply chain, which means it relies on other specialized companies to provide items that match each supplier's capabilities. For example, a car factory does not make tires, and instead buys from a tire company, such as Firestone.

We need to do nuclear like a car.

A factory that makes Generation 4 would need suppliers as well, including: printed circuit board assembly, systems integrator that combines electronics into cabinets, fabrication of large metal components via molding and machining, and thermochemical plant assembly. Interacting with suppliers requires engineering. For example, if a supplier builds your printed circuit boards, you need to supply them with the design files and a test jig that tests the final product.

A factory makes things themselves, has other factories make things, and buys off-the-shelf products (e.g. a tiny nut). All items do not need to hit a factory's dock, since they can be drop shipped directly from the supplier, to the end user. For example, a Generation 4 factory might have a molder of large pipes ship directly to the nuclear power site. The Generation 4 factory, molder, and customer would not necessarily need to be physically close -- they could reside thousands of miles from each other.

In nuclear industry lingo, we are referring to "mass production" (each factory makes many reactors), "standardization" (multiple factories make the same design), "free and open" (anyone can use the same design at no cost), "modular" (sub-assemblies transported via truck/rail/ship), "factory-made" (factory makes components), and "commoditization" (multiple companies make the same part). All of these contribute to another industry term: "cost reduction".

These ideas have been discussed for many years yet never implemented primarily for two reasons. Commercial grade Generation 4 is a new thing and is being made available for the first time in 2021. And secondly, this requires leadership from gov't, and gov't tends to only go big when under immense pressure.

Nations are Nervous about Nuclear

The public is nervous about nuclear power, and for good reason. However, to solve the climate change problem, we need to reconsider nuclear. More specifically, we need to update our thinking from "nuclear is bad" to "older nuclear is bad".

With older nuclear, a meltdown occurs if circulation stops. Alternatively, with newer Generation 4, this does not occur due to what is called a negative temperature coefficient fuel. This means that as fuel temperature increases, the amount of energy produced decreases. In other words, if you stop circulation, the fuel heats up, reaches an equilibrium temperature, and then the temperature stops increasing. Equilibrium is reached before components change state, which means before solids melt into a liquid, or before a liquid burns into a gas. In other words, nothing dramatic occurs when a Generation 4 reactor breaks.

Chapter 3) Spend Money Wisely

Fix Climate Change with $10B/yr of Automation Engineering

We are looking at gov't spending $10B/yr to achieve the cheaper green energy goals. This includes paying for the designs of factories that mass produce nuclear reactors, hydrogen production equipment and ammonia production equipment. More specifically we:

- Buy the design of a Generation 4 high temperature nuclear reactor and give the design away for free to establish it as a global standard (Gen4P1).
- Fund the development of a factory that mass produces the standard nuclear reactor, and give the design of the factory away for free, to reduce the cost of manufacturing 8,400GWe of nuclear power worldwide. This is 21 times more than the world's current set of reactors, and therefore requires mass production.
- Do the same as above with equipment that makes hydrogen gas (H_2P1), and liquid ammonia (NH_3P1).

Gov't also funds the development of free and open systems that automate and transport, including:

- Develop an automated system that moves super-sized cargo from factory to final site via rail, crane and ship. This includes developing a transparent factory that mass produces ships, cranes railcars and rail construction/maintenance equipment used by the new super-sized transportation system.
- Develop an automated system that assembles super-sized rebar and forms mounted on a jig.
- Develop an automated system that assembles super-sized hydrogen and ammonia production equipment, possibly on transportable units 12m x 12m x 96m in size.
- Develop automated systems for transporting, processing, and dispensing large amounts of concrete. Support parallel dispensing, to decrease time to construct buildings.
- Develop factory-made thermal storage systems, and automated installation equipment.
- Develop an automated excavation system.

Gov't funds the development of standardized nuclear infrastructure, including:

- Develop standardized reactor building with containment cavities that support upgradeable plug-in reactor packages.
- Develop standardized green energy production site that makes electricity, hydrogen and ammonia; and includes a network of heat pipes for processing of other materials.
- Develop federal green energy production zone with streamlined regulation.

8,400GWe of nuclear power would cost approximately $10.6T, and reducing this cost is imperative since if it is too high, capital markets will not participate. And spending $250B over 25 years to reduce $10.6T is reasonable ($10B x 25yrs).

An economist would say that what is more reasonable is to calculate productivity gains for each $1B of R&D, and multiply these by $10.6T to calculate the optimal amount of R&D to minimize total cost. The engineer would then say that is all fine, in theory, yet we don't know the productivity vs. R&D curve, and will therefore end up guessing no matter what we do.

One advantage of having a global decarbonization plan is one can look at what needs to be done over ~25 years, and also look at engineering that reduces total costs. Without a plan, this engineering cannot be justified, and without engineering, total costs are prohibitively expensive. In other words, there is no way to survive climate change without a global decarbonization plan.

World Capital Markets invest $423B/yr over 25 years

We will now run through the numbers to see what it would take to replace the 583 EJ of world energy consumption with cost-reduced nuclear power[12]. To simplify, we assume energy consumption growth is zero, and ignore other complexities.

We assume the average cost of a green energy nuclear power plant to be $1250/kWe. With this plant, one could produce any combination of electricity, hydrogen and ammonia. This cost does not include ammonia storage tanks, hydrogen distribution pipes, and many other costs associated with decarbonization. For reference, the cost of a nuclear power plant in China is currently $2,000/kWe. Anyone is welcome to download, copy, and rework our calculations.

In summary, after significant cost reduction, we could replace energy consumption with nuclear power over 25 years at the following cost per year: $423B worldwide, $82B for the USA, $82B for China, $73B for Europe and $20B for India. This would be paid for mostly with bonds, since power plants make money, and this money can pay back loans. The $423B/yr is in the range of the current $540B/yr that is invested globally in energy infrastructure, mostly for CO_2 emitting initiatives. Also, we can scale up solar, wind and hydro to the point where limitations lead to unacceptable costs.

If one reactor building provides 0.8GWe of power, then this would entail constructing 68 reactor buildings each year in the USA over 25 years, for example (1713/25). Getting this done at low cost would require mass production and standardization, as discussed previously.

		World	USA	China	Europe	India	Other
World Heat Energy Consumption per Yr	EJ/yr	583.6	94.7	141.5	83.9	33.8	229.7
> BP Statistical Review, World Heat Energy, 2019	TWhr/yr	162,100	26,300	39,300	23,300	9,400	63,800
> Corresponding electricity at 35% efficiency	TWhr/yr	56,735	9,205	13,755	8,155	3,290	22,330
	% of Total	100.0%	16.2%	24.2%	14.4%	5.8%	39.4%
Energy from Nuclear Reactor Per Yr	kWh/kWe	8,059					
> Amount of time operational	CF (%)	92%					
> Heat to Electrical Efficiency	kWe/kWt	42%					
> Annual heat energy per year, per GWe	EJ/GWe	0.069					
# of 1GWe Reactors	GWe	8,448	1,371	2,048	1,214	490	3,325
# of 1GWt Reactors	GWt	20,114	3,263	4,877	2,891	1,166	7,917
Size of Each Reactor Building, typical	GWe	0.80	0.80	0.80	0.80	0.80	0.80
# of 0.8GWe Reactor Buildings		10,560	1,713	2,560	1,518	612	4,156
CapEx (Nuclear + H2 + NH3)	$/kWe	$1,250	$1,500	$1,000	$1,500	$1,000	$1,250
Total Cost	$T	10.6	2.1	2.0	1.8	0.5	4.2
# of years	yrs	25	25	25	25	25	25
Nuclear Power Built each Year	GWe/yr	338	55	82	49	20	133
Cost Per Year to Build Nuclear + H2 + NH3	$B/yr	423	82	82	73	20	166

Build Solar, Wind and Hydro -- Until Too Costly

We can build solar, wind and hydro until costs exceed what consumers are willing to spend.

- **Solar Farms:** These need cheap cleared sunny land to generate electricity at low cost; and this is only available in some regions (e.g. TX, NV, AZ, FL, and NM). We can expect regions conducive to solar farms to scale up until customers shed at midday.
- **Residential Solar:** We can add when convenient and when reasonably priced; however, we eventually bump into constraints such as limited roof space in high population density areas. Single-family homes can often make use of solar cost effectively; however, cold regions typically augment with an external energy source for building heat.
- **Windmills:** These need high winds and offset from population. We exploit easiest first, yet eventually run out of low cost opportunities.
- **Hydroelectric Dams:** Cost is a function of land geometry. We exploit easiest first, and eventually run out of reasonably priced opportunities.

Decarbonization Sectors: Easiest First

One can divide decarbonization into multiple sectors, where we list them in order of how easy they are to implement, with easiest first:

1. **Electricity:** This is easiest since one can place a Generation 4 plant anywhere along a power wire, with no modification at consumer. 42% of global CO_2 emissions is from electricity generation; therefore, this is an easy way to make significant progress in a relatively short period of time.

2. **Transition from fossil fuels to electricity when convenient:** Replace carbon-based fuels with green electricity when convenient. For example, natural gas HVAC furnace fails and is replaced with an electricity driven heat pump, of similar cost.

3. **Transition from fossil fuels to cheaper green fuels when convenient:** Consumers go green when green is cheaper, and when it is easy to convert.
4. **Supply cheap process heat directly from Gen 4 Reactor:** Heat from a nuclear reactor supplies heat-driven < ~750°C processes, cheaper than coal and natural gas.
5. **Difficult to Decarbonize (D2D):** This involves areas that are avoided by consumers due to being too costly, too difficult, or too uninteresting.

The first four sectors would probably eliminate two-thirds or more of global CO_2 emissions over 10 to 20 years, driven by capital markets, and the desire to save money by buying cheaper green. During this time, R&D and additional green cost reduction chips away at the more difficult areas.

In sectors #2 and #3 we add the term "when convenient" to emphasize we are focusing on the easiest first. If not convenient, the task ends up in sector #5, which will not get done anyway (since not convenient). For now, we ignore #5, and focus on #1 through #4. Easiest first.

Suggested Next Steps

Below is a list of suggested next steps:

- World leaders consider adding an Energy Finance Czar and Nuclear Energy Czar to their team.
- World leaders read our proposed decarbonization plan, copy, edit to their satisfaction, produce their own version, publish, and tweet with a link.
- World leaders consider setting up a Global Decarbonization Initiative that is responsible for implementing their Global Decarbonization Plan.
- Foundations consider setting up a Global Decarbonization R&D Initiative at their favorite university to develop free and open technology identified in this plan.
- For associated materials visit: www.manhattan2.org/global-decarbonization-initiative
  Anyone can copy, edit and rename any file at this website at no charge. To avoid plagiarism, add the following attribution: *This is based on … originally published by … on date ….*

Chapter 4) Government & Billionaires

Restructure Government to Handle Decarbonization

Gov't leaders should consider approaching decarbonization in the same way one approaches a chess board, where issuing a PO is one move on the board. They could ask their top people about the possible moves (PO's) and potential outcomes for each. They can advance with each move, control the center of the board, and advance further. A few moves could potentially have a profound impact.

If they find decarbonization difficult, they are probably doing it wrong. Difficult is when one spends $3B on an initiative that decarbonizes 1/15,000th of world energy demand, which is too small to have an impact. One needs to look at the whole board and see what moves are needed to get to zero CO_2 emissions. To do this, one needs a plan. If you are a gov't leader and you are reading this, you can ask your energy minister to draft a global decarbonization plan within 30 days. If they are not sure what that is, you can have them read this document. They can start with ours, and modified in any way, at no charge.

To help with this chessboard, the gov't could add two key positions:

- **Nuclear Energy Czar (NEC):** Authority over nuclear power regulation, R&D, standardization, mass production, and green energy production zones.
- **Energy Finance Czar (EFC):** Authority over a gov't decarbonization budget, energy taxes, energy infrastructure debt, and demand right-of-way for electrical power wires and hydrogen piping.

Ideally, the EFC and NEC are brilliant, experienced, and trusted individuals. A former US Energy Secretary might make a good NEC, and a former US Treasury Secretary might make a good EFC. With the right authority, they could potentially decarbonize the world.

Gates, Musk, Bezos, Bloomberg, and Buffet

Multiple billionaires have expressed interest in helping to solve the climate change problem. Each would probably not want to pay for the entire $10B/yr initiative themselves since it involves too many entities out of their control. However, they might be willing to pledge a portion with conditions that encourage others to participate. Below are example conditions that one might attach to a pledge:

- The gov't must create the position of Energy Finance Czar and Nuclear Energy Czar.
- The gov't must set up a $10B/yr Manhattan-sized development effort that exclusively supports automation engineering, which makes green energy cheaper than non-green.

It would be helpful if multiple business titans got personally involved, even with a relatively small $100M contribution. However, it's not their money that we need. It is their brains. They know how to set up production, and structure global operations more than the typical university professor or gov't employee. Their contribution would buy them influence; however it is *we* that need *their* influence.

Perhaps they would like to buy the world a factory that is technically and economically transparent, enabling others to easily copy, to reduce green energy costs?

Or write their own global decarbonization plan and hand to their foundation. If they wanted, they could begin with ours, at no charge.

Perhaps Joe would let Jeff, Bill, and Mike run his Global Decarbonization Initiative? Jeff knows automation, Bill knows computers, and Mike knows markets. Together they could do great things, provided they were given the right authorities.

Alternatively, Elon could probably solve the climate change problem on his lunch break since he has direct experience with factory automation, transportation, construction, robotics, machine vision, automated movement, and sequencing of programmed operations.

It is scary how much Jeff, Bill, Mike and Elon's expertise match what we need to solve the climate change problem. Very few people probably realize this. They are the Henry Fords of this day with computers and automation, and that is what we need, given a 13k Hoover Dam sized problem.

Chapter 5) Automate Super-Sized Construction

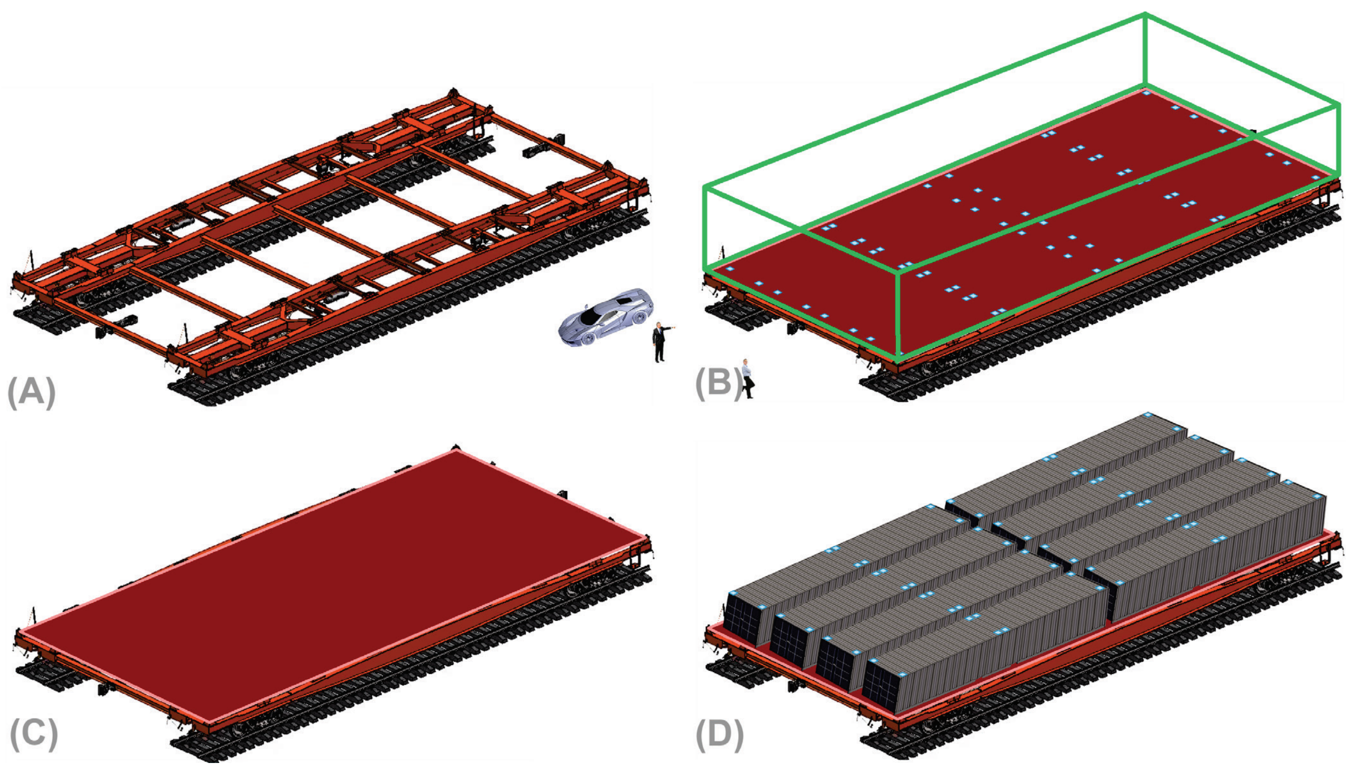
Develop Super-Sized Transportation System

We currently have a standard for shipping containers that supports stacking, moving, and transport by ship, rail and truck. Each container is typically 2.4m x 2.6m x 12.2m in size, and includes features in corners that support stacking.

Nuclear reactors and support equipment are much larger, as shown in this video of the 3.2GWe Hinkley Point C nuclear power station. Subsequently, to better connect factory production with the reactor site, we need to develop a super-sized container-like system that supports cargo significantly larger than the standard shipping container.

This is important, since factory-made sub-assemblies, forms for concrete, and the concrete itself are massive. And we need to keep local USA/Europe costs down; otherwise, we will not meet our cheaper goals. And if we don't meet our goals, capital markets will not fund production. Therefore, we need to develop a cheap way to move large and heavy items between factory and site.

Below are illustrations of a concept that might meet our needs. Image A shows an extra-wide 12m x 24m flat-top railcar that rolls on two pairs of standard rails. This could move large cargo from factory to nearby ship, and from ship to nearby construction site. Image B shows 12m x 24m x 2m cargo that could potentially stack on ship, lift by crane, and mount on flat-top railcar. Image C shows a steel platform for irregularly shaped cargo, such as earth moving equipment, or rebar with forms. And Image D shows multiple containers, which could potentially stack in layers.



This system supports super-sized shipping containers that are 6m, 12m, or 24m long; and 2.4m, 5.4m, 8.4m or 11.4m wide; in any combination. Image B shows mounting points that match these sizes.

Previously, the nuclear industry considered factory-made "modular" to be limited by what one can move on a 2-lane road. However, with super-sized transportation, the industry would rethink what one can do with modular.

Automate Super-Sized Rail

We need a new and automated extra-wide rail system that supports moving large objects from factories to energy production zones. Below is an example concept that might meet our needs.

SuperCargo: Our proposed system moves super-sized cargo via a combination of ship and rail. Each moveable unit, called SuperCargo, is 12m wide, 1 to 12m high, 24m to 96m long, and up to 2000 tons in weight.

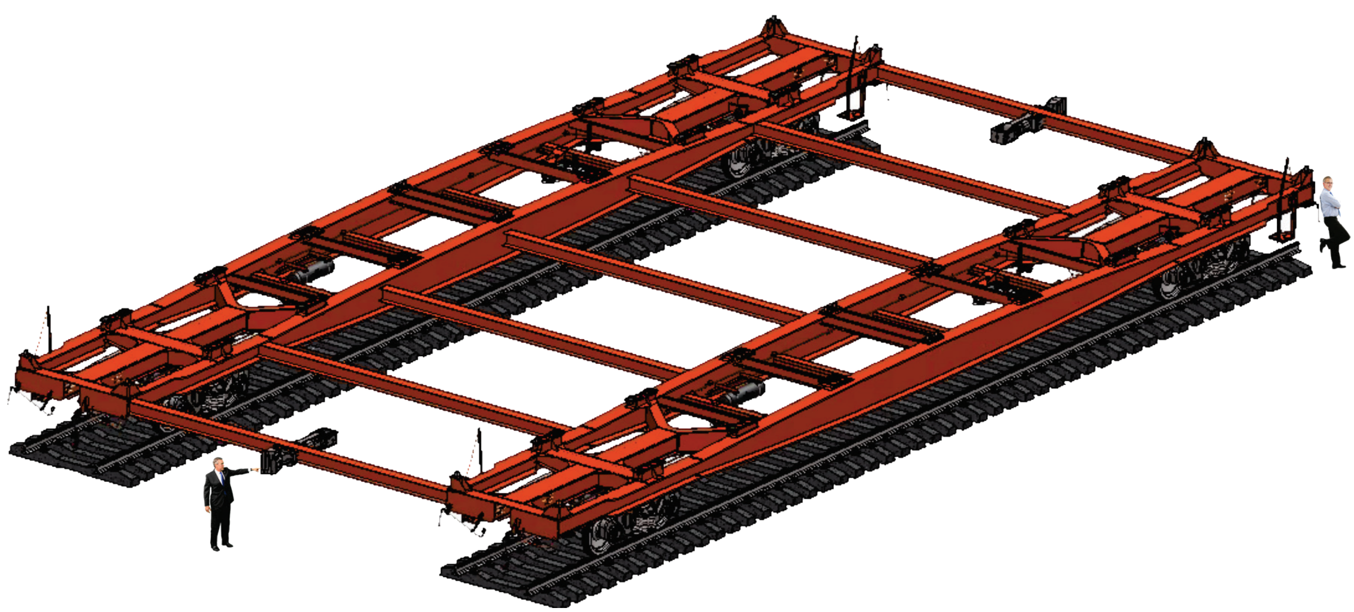
Factory to Site: One moves SuperCargo from a factory to a dock via 12m wide rail, and then from dock to ship via crane or roll-on/roll-off. Ship travels to a dock close to the construction site, SuperCargo offloads from the ship, and then moves to the construction site via 12m wide rail.

Short Distances: Since we are working with oddly spaced rails, distance from factory to shore, and from shore to construction site, is less than 10 miles in most cases. And if in an urban or crowded area, it might be on the order of 100's of meters.

SuperRail: Two parallel pairs of standard rail, spaced 12m apart is a "SuperRail".

SuperTrain: A SuperTrain is any number of railcars that link together and roll on SuperRail. A more descriptive term might be "SuperWide Train", yet this does not sound as good as "SuperTrain", which should not be confused with a TV show from the 1970's.

SuperRailcar: Each flat-top SuperRailcar is 12m wide and 24m long, as illustrated below.



Multiple railcars join to form a SuperTrain, which is propelled by a small locomotive, or an internal propulsion system embedded in a railcar (e.g. battery powered motors). Railcars can be made cheap and light, or costly and heavy. Cargo 24m to 96m in length mount on top of one to four flat-top railcars.

Width: We set railcar width to a fixed 12m since this corresponds to the width of a small ship or barge. Roads are too narrow for 12m; subsequently, when transporting on land, we use rail. 12m refers to the width of the railcar, which ~1.5m greater than Track Spacing (distance between centers).

Length: SuperCargo supports multiple quantized lengths that correspond to standard 24m long railcars linked together end to end. This means each SuperCargo is one of four fixed lengths: 24, 48, 72, or 96m.

Height and Weight: SuperCargo height and weight are variable.

Non-Standard Cargo: Cargo that is smaller than a standard size is transported in a standard sized bin or platform. For example, an 8m x 16m part might be transported in a 12m x 24m bin, which sits on a flat top SuperRailcar.

SuperCrane: A "SuperCrane" moves SuperCargo between dock and ship. Typical crane lifting capacity ranges from 100 tons to 2000 tons.

SuperShip: A "SuperShip" is a ship or barge that moves SuperCargo over water. When rolling SuperTrains between ship and land, a ballast tank on ship/barge aligns height to that of dock. Rolling large cargo on parallel rails between ship and shore is not unprecedented, as one can see from this video of 1500 ton ZPMC Cranes being rolled.

SuperTrain Software: SuperShip, SuperCrane, and SuperRailcars all contain computers with common software that coordinates operations.

Automation: System is automated, as much as reasonably possible, to the extent required to move cargo from factory floor to final resting place, without human intervention. When automatic control is engaged, humans monitor; otherwise humans operate manually.

Networked Equipment Boxes: Railcars, cranes, ships and barges include cavities for equipment boxes in all four corners of each machine, sized at approximately 0.5m x 0.5m x 0.3m per cavity. Equipment boxes coordinate and automate, as needed. They contain networked computers, communications transceivers, cameras, lights, and radar.

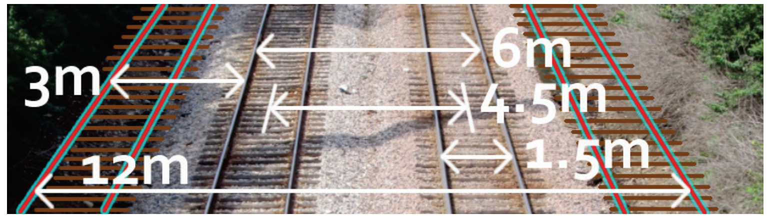
Application: System supports constructing 8,400GWe of nuclear power, along with associated hydrogen and ammonia production equipment, at lowest cost.

Constraints: Software manages constraints, such as: maximum weight supported by machine, minimum turning radius of rail, ship to shore ramp angles, ship movement at dock, water height, and maximum pivot supported under railcars, etc.

Stacking: Features similar to shipping container twistlocks secure SuperCargo to SuperTrains, secure SuperCargo to SuperShips, and secure stacked SuperCargo blocks to each other. SuperCargo optionally supports stacking additional SuperCargo above.

SuperJumble: A SuperJumble is multiple blocks of SuperCargo stacked on a ship, or stacked on multiple parallel railcars. Each SuperCargo block is of variable length, height and weight; therefore, software calculates how to best fit these together into a SuperJumble.

Making Use of Land Around Existing Track: In some cases, engineers might make use of land around existing track. One could add track at both left and right, as illustrated here; or, use one of the existing tracks, and add an additional track 12m away. Regulators might accept less clearance around tracks, if maximum train speed is reduced.



If one rolls on local tracks, then local Track Gauge (~1.5m distance between rails) might not match other locations. Subsequently, one might keep specially gauged railcars on matching tracks; or, change bogies as needed (i.e. set of wheels under train).

If engineers make use of land around current track, they might need to rip up existing rails and rebuild from scratch, to meet all requirements. However, this would cost little when working with short distances between ports, and nearby industrial zones with cheap land. In all cases, local engineers would need to figure out how to move large and heavy cargo between a SuperRail capable docks, and nearby cheap land.

Develop SuperTrack Construction/Maintenance Equipment: Engineers develop 12m wide track construction and maintenance equipment that resides on top of 12m x 24m SuperRailcars. These would control planarity and distance among four rails. Also, in some cases, engineers might adapt existing track equipment to work with extra-wide double-rail.

Mass Produce SuperRail Equipment: Engineers build a transparent factory that mass produces SuperRailcars, SuperCranes, SuperShips, and SuperRail construction/maintenance equipment. Transparent in the sense that all factory documents are made available to others, to facilitate cheaper green energy. Ships and large cranes would mostly likely be built in a shipyard setting, since they are uniquely suited to work with large steel structures.

SRA SuperRail Automation Inc.
Super-sized ship & shore support systems

Existing Double-Rail Systems: Below is an example of an existing multiple rail transporter that moves 200 ton structures. Photo on the left is recent; whereas the photo on the right was taken by Author Weinreb in 1976. For details, google search: nrao VLA transporter.

Automate Super-Sized Rebar and Forms

Rebar steel rods are embedded in concrete along with a variety of mounting brackets and other hardware. Forms at wall external surfaces, often made of plywood, control wet concrete after being poured. Rebar, form walls, and embedded hardware could all be mounted on a steel jig via robots in a factory. One could then lift via crane, transport via SuperTrain, disconnect jig, and return jig to factory. A jig is needed since if you lift a delicate heavy structure, it will deform. Alternatively, engineers might consider permanent flat steel plate at wall surface, weld to rebar, and lift without a jig.

Nuclear reactor concrete containment cylinders on the order of 14m diameter and 36m height might surround the nuclear reactor vessel. In theory, a factory could assemble the rebar and forms that make this cylinder, mount within a 16m x 16m x 38m sized jig/frame, and ship to the final site. One could do the same for wall segments on the order of 12m x 24m x 1m in size that are transported in a stacked configuration. A building with eight reactor cavities would require approximately 430 of these 12m x 24m x 1m wall assemblies, for example. In theory, one could build at a fast pace given factory-made units that install under programmatic control in a sequence.

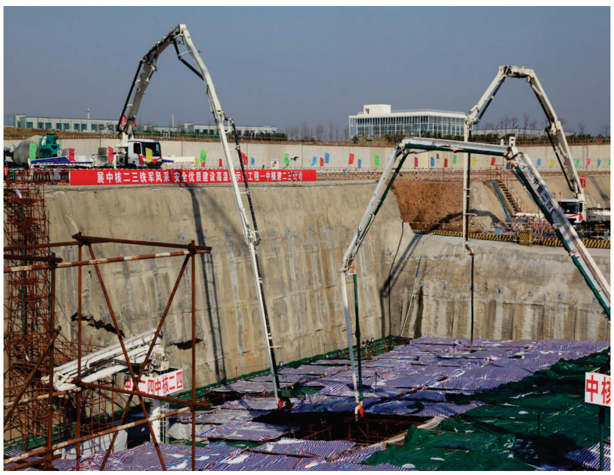
If a factory that makes cars with robots cost $1B, then a factory that makes rebar/form assemblies with robots might be of similar cost. The Government could support this, as part of the $10B/yr fund, and give the design away for free, to make green energy cheaper. Subsequently, multiple factories with no R&D budget could compete and drive down costs for each rebar/form assembly, via free and open global standardization.

Modular concrete and rebar construction is not new, as noted in NRC document #ML1214. However, global standardization, factory assembly via robots, R&D paid for by an external party, and super-sized transport is unprecedented.

Shipyards tend to have equipment and expertise suitable to working with super-sized structures. Alternatively, a factory outside a shipyard, with similar equipment, might be just as competitive. Automated robots tend to increase productivity; therefore, the facility with the most robots might win, wherever that is.

Automate Super-sized Excavation

Nuclear reactor sites often excavate large amounts of earth for buildings, an example of which is illustrated below-left. Oversized earth moving equipment, illustrated below-right, can reduce cost, provided they are easily transported.



An extra wide rail system could support oversized *fully assembled* rollable equipment with the help of an on-site ramp, as illustrated below. The HD-785-8 dump truck is 12m long, 6m wide, 5m tall, and weighs 80 tons; and the PC-2000-11 excavator is 17m long, 8m wide, 7m tall, and weighs 225 tons, for example. Both are commonly used in large surface mines, and can move earth quickly.

Computer programmers could further reduce cost if given multiple powered cavities (e.g. 0.5m x 0.5m x 0.3m) in all earth moving equipment, along with cavities at fixed positions throughout the site. They would place equipment boxes into these cavities, network them together, and run similar software on each. They could then identify objects, coordinate, and automate.

At first, one might want a human in each machine to monitor. However, after a trial period, one human might view multiple machines and shut down the entire system if it goes awry. Running expensive equipment 24 hours a day, 7 days a week, would reduce idle time, and therefore reduce cost.

Automate Super-Sized Concrete

Nuclear reactor buildings require a significant amount of concrete. For example, the typical 1GWe reactor consumes 75K m^3 of concrete (200K tons) [13]. The raw material itself works out to $21M total, at $300/$m^3$ for dry concrete ($300 x 75e3), and corresponds to 5300 large truckloads at 14m^3 per load.

Concrete SuperTrains with several 12m x 24m railcars could possibly reduce costs. Each railcar could be dedicated to a specific task, such as: mixing water with dry material, storing dry material and water in bins, and pumping wet concrete via distribution booms.

Engineers can explore developing an automated concrete storage and processing ship/barge that provides wet concrete to specialized 12m x 24m railcars. These would transport material a short distance before dispensing via boom.

Multiple automated Concrete SuperTrains at each site could dispense concrete in parallel, at rates faster than we are accustomed. Timing is crucial since wet concrete dries over time. For this reason, computers would need to accurately sequence mixing and deployment. This would be easy to do, provided they had an understanding of the geometry being built, an understanding of the entire site, and had control over the machines.

If one pours incorrectly in some way, it can be expensive to remedy. Therefore, one would want many cameras that inspect during a pour, and stop pumping as needed.

Automatic Concrete Inc.
Super-Sized Processing & Deployment

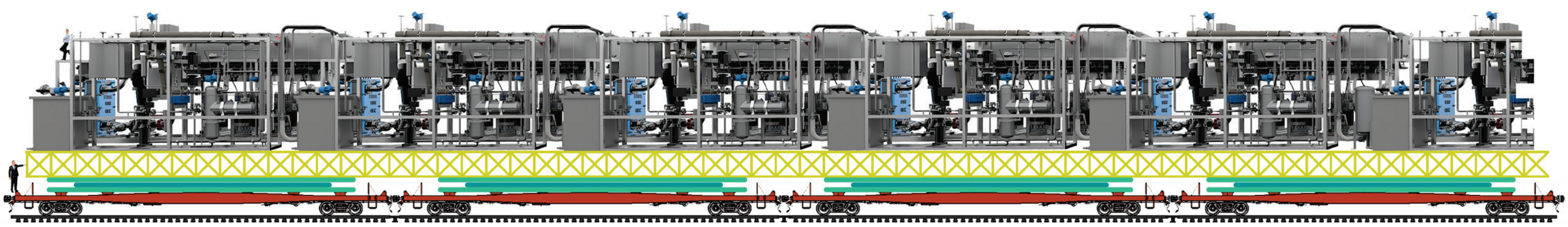
Engineers develop automated concrete processing equipment, and build a transparent factory that mass produces the equipment, to facilitate cheaper green energy.

In summary, there are many different ways of working with concrete, and given a generous engineering budget, and super-sized automated transportation system, engineers can explore many possibilities.

Automate Construction of Super-Sized Hydrogen & Ammonia Processing Equipment

To make hydrogen and ammonia, one needs a massive jumble of steel pipes, tanks, pumps, and machines. The chemical engineering details are not important -- let's just think of this as a big pile of heavy metal stuff. If one assembles this on site, one component at a time, it is costly. Alternatively, to reduce cost, factory robots could build processing equipment that reside within assemblies 12m wide, ≤ 12m high, and 24m to 96m long.

In theory, one could place rails on a factory floor, position flatbed cars on the rails, create a 12m x 96m platform, build a structure on that platform with robots, and transport to the final site via rail and ship. During transport, the platform might reside on a truss that stays straight while on curved rail, aided by an underlying mechanism that supports lateral movement, as illustrated below. Jacks under truss might lift slightly before mounting the platform on the final foundation. Jacks could also maintain truss rigidity while train goes over a small hill, or dips. To get a sense of how big this is, take note of four flatbed rail cars under truss, and above rail, in the illustration below.



A small robot costs approximately $20K, and a large robot costs more like $100K. If one places 50 small and 20 large robots in a factory, for example, then the total cost would be $3M, which is low relative to the cost of the structure being assembled. These could all work in parallel, to build quickly.

Managing components is just as complicated as assembly, if not more so. Components need to be moved from delivery truck to warehouse, maintained, and then moved from warehouse to factory floor. Amazon is an example of a company that has pioneered warehouse automation with a combination of machine vision, conveyor belts and automated machines. Many of our components would be heavier than your typical Amazon package. And, in some cases, they would require processing before being used. For example, a factory might have many specialized processing stations where raw material is brought in to station, worked on, and scrap is returned to the warehouse. For example, one station might cut pipe, bend, weld flanges to ends, visually inspect, test under pressure, and add barcode label.

Building a factory involves a massive amount of engineering. For example, if you have 1000 engineers at $300K each (fully loaded expenses), and they work for 3 years, then your total cost is $0.9B (1000 x 3 x 300e3). This is feasible if it reduces the cost of a $10.6T project. In comparison, the typical automobile factory cost $0.1B to $5B.

Recall that our plan is for gov't to finance the development of factory mass production, and give the engineering away for free, to reduce the cost of building $10.6T worth of green energy equipment, and to make green energy cheaper than non-green. Alternatively, if a company funded the programming of the robots and then used it for themselves, they would not be implementing the plan that gets us to zero. It would be important for people managing the $10B/yr fund to not confuse these two, and have their fund diverted.

A labor union leader might prefer assembly *without* robots; however, we need to drive down costs to meet our cheaper goals. And building 8,400GWe reactors, along with decarbonization infrastructure, is a massive effort that will probably lead to labor shortages, even if we have robots every step along the way.

Automation Operating System (OS)

To coordinate and automate, engineers network together equipment boxes that contain computers and cameras. Each box would be on the order of 0.5m x 0.5m x 0.3m in size, and reside in both fixed positions, as well as mobile positions within machines.

Fixed positions view the following kinds of scenes: ship approaching dock, multiple machines excavating earth, several machines constructing a building, a boom pouring concrete, a factory floor, the top of a nuclear reactor building, and inside an elevator shaft. Mobile positions entail multiple equipment boxes in each of: ships, barges, railcars, cranes, elevators, dump trucks, earth excavators, and concrete processing equipment.

All equipment boxes would contain the *same* software, perhaps called "Automation OS". This would make coordination easy, which would make automation easy.

Software receives images, identifies objects, calculates their position, calculates their movement and places information into a database which is shared on the network. This means that each computer has access to the entire scene of information. Computers also have the option of doing control, such as moving a crane, railcar, ship, elevator, truck, or excavator.

The system supports complex operations, such as moving cargo from the factory floor to the final resting position in a nuclear reactor building. Or excavating a large amount of earth under a nuclear reactor building. Or sequencing hundreds of placements of rebar/forms assemblies to construct a building.

This might sound a bit complicated, yet hardware and software products already exist that do much of this. What has been missing is a place for software engineers to place their equipment, standards that define how the various elements interact, and common software at all positions.

This software would need to be free and open in order for it to gain acceptance, since companies and countries do not like to be controlled by others.

Automation OS Foundation

Free Construction Automation Software

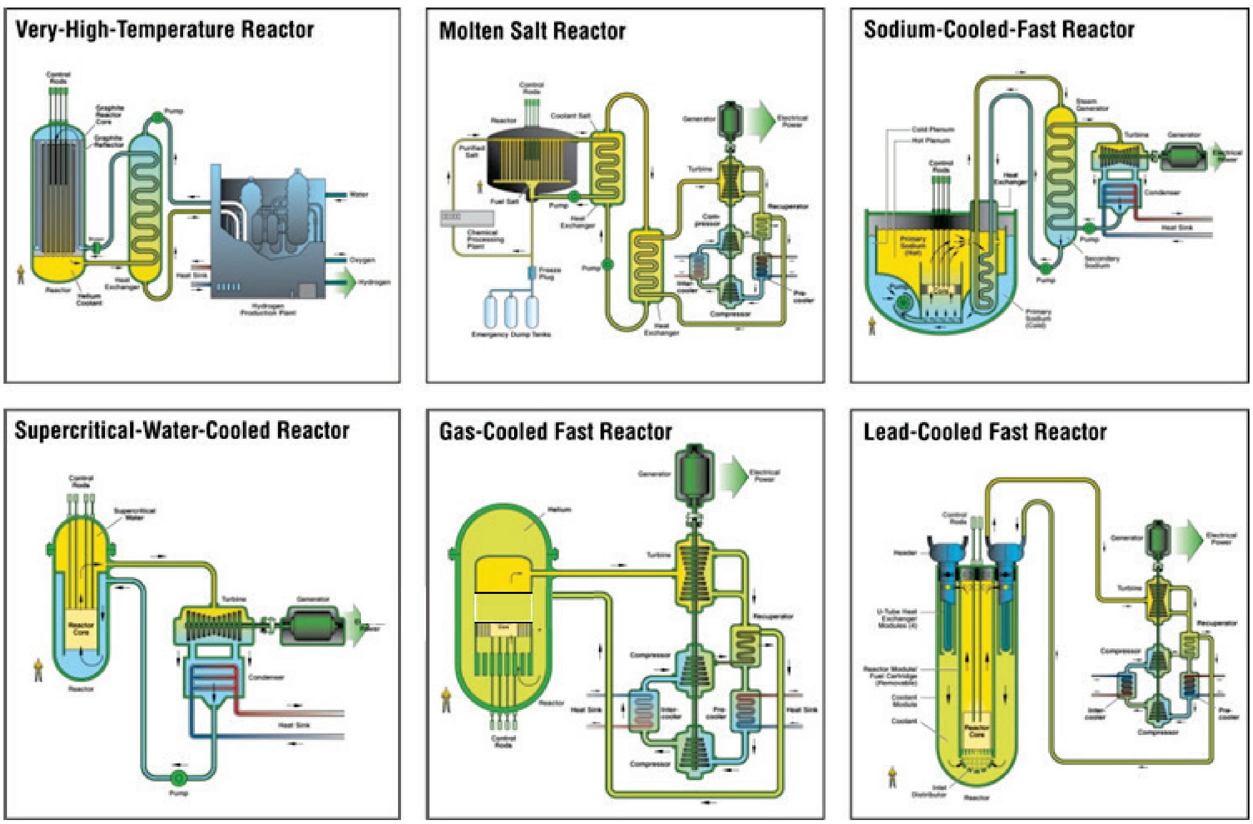
Much automation could be implemented with a tiny percentage of the $10B/yr engineering budget, provided software engineers were given cavities for their boxes, given responsibility for the entire scene, and required to place the same base software into each box.

Plug-in a Nuclear Reactor like a Light Bulb

Previously, we talked about modular factory-made nuclear packages (e.g. Gen4P1) that are transported from factory, to reactor site, via a super-sized transportation system.

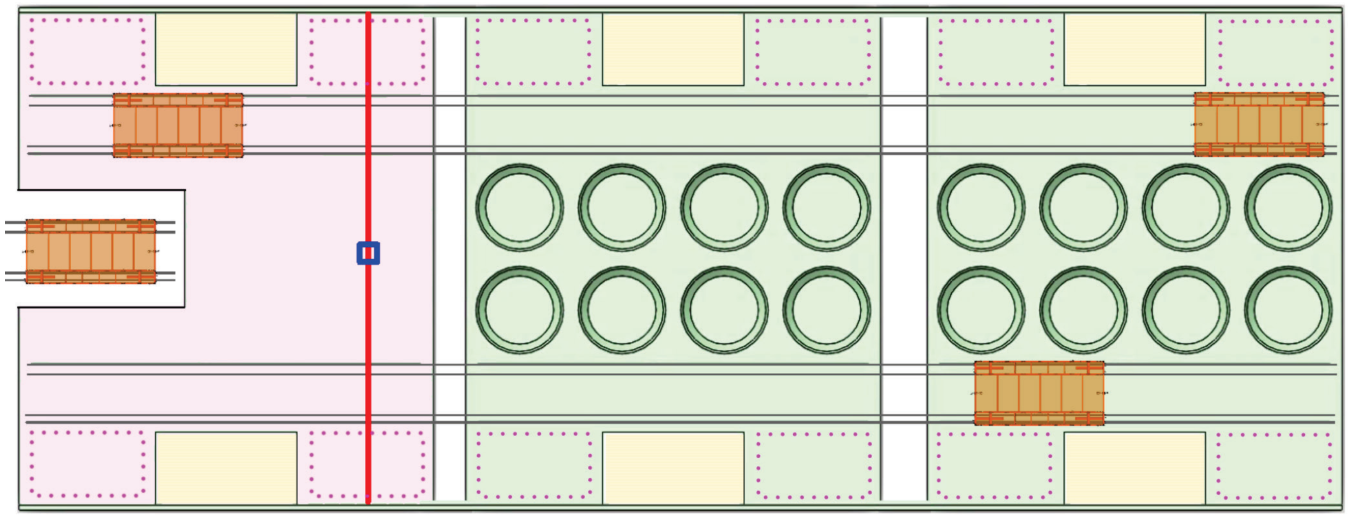
Packages both install, and also uninstall. And after being removed, one can install a newer package, perhaps with more output power. If one starts with 100MWe per silo, and doubles output power via three upgrades over 100 years, for example, they would be looking at 200MWe, 400MWe, and 800MWe per silo. Building owners would be inclined to upgrade, if it saved them money.

The Generation IV Forum (GIF) defines six different types of Generation IV reactors, illustrated below, and we would want the standard nuclear building to support all types.

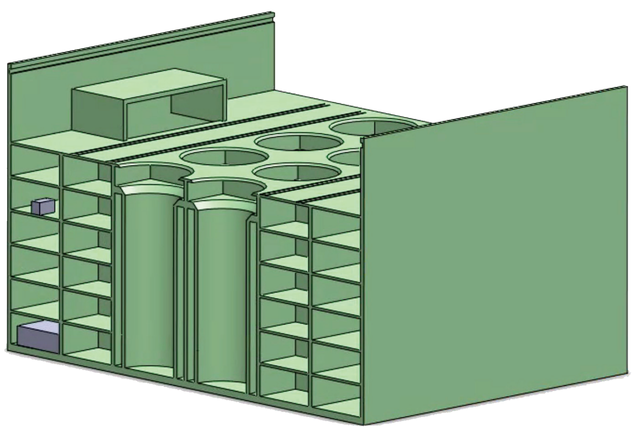


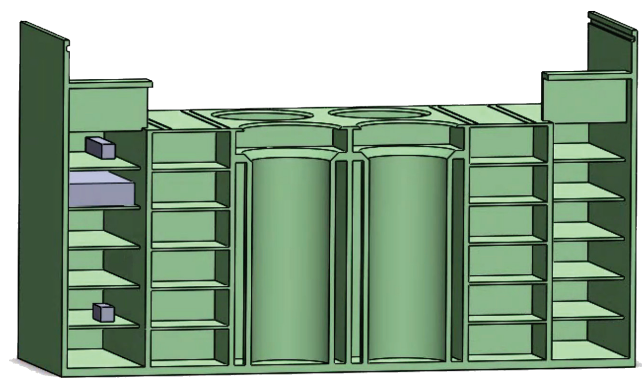
To facilitate fitting factory-made packages into a standard nuclear building, nuclear engineers would define two rooms of a specific size. For example, they might have a 36m tall containment cylinder with an internal diameter of 14m, and 1.25m thick walls. And a rectangular room 12m x 24m in size, with 6m ceilings, for equipment. We will refer to the cylinder as the "silo", and the room as a "berth". An example nuclear package might include: four components that install into one containment silo, three standard sized shipping containers with equipment that are placed into one berth, and two 12m x 24m super-sized pieces of equipment that each install into a berth. The new transportation system moves a package's components from factory, to final resting place in the building, via a combination of automated rail, ship, crane, and elevator.

An example of a building that supports this concept is illustrated below.



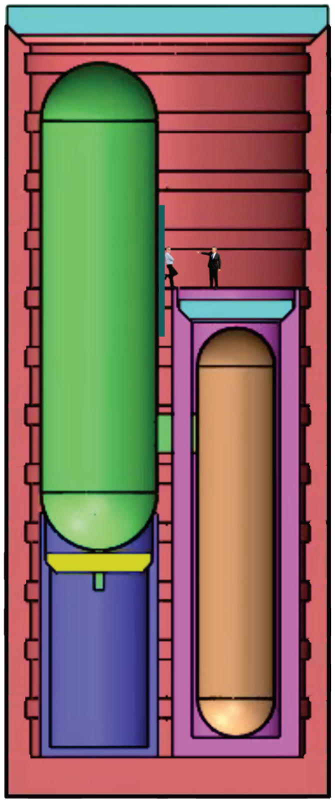
A common building unit resides at the left, and any number of 8-silo building units are added to the right. A gantry crane moves cargo horizontally, for purposes of installing package components, and supporting daily operations. Nearby electrical buildings, not shown, convert steam to electricity. Extra wide rail is placed on the upper level to help move cargo, and to support specialized rolling platforms.

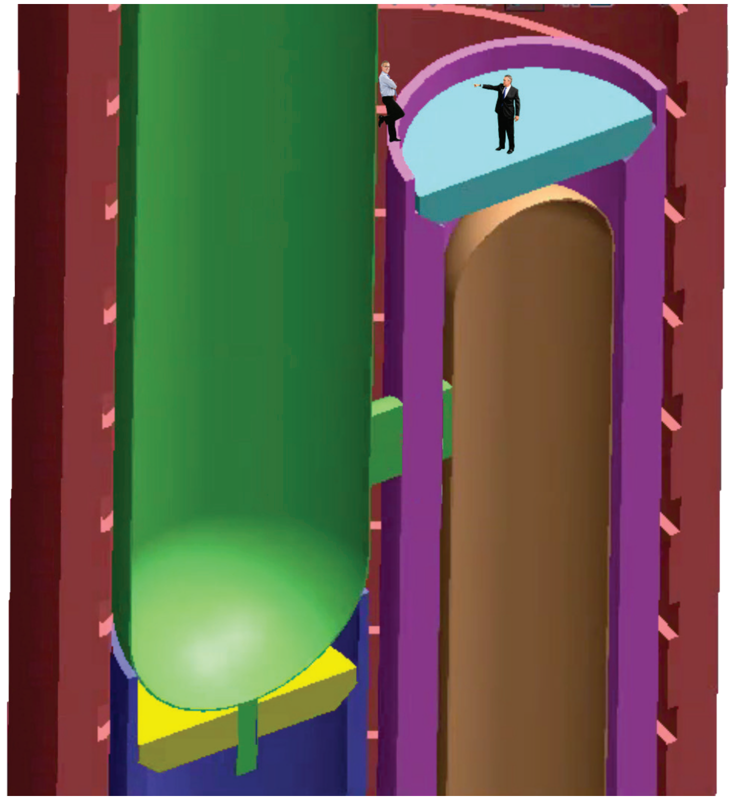




Containment Silo Supports Different Nuclear Packages

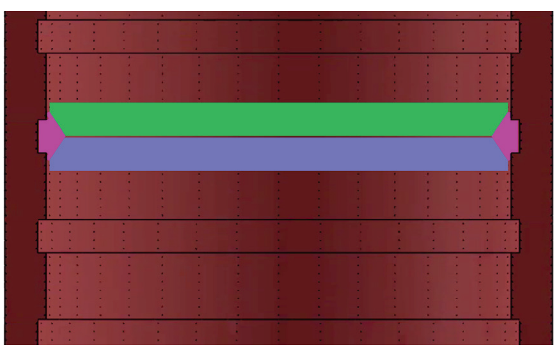
Nuclear packages include multiple components that install into each containment silo. For example, a 250MWt pebble bed gas cooled package might position a 6m x 25m reactor vessel on top of a molded concrete pedestal that houses pebble processing equipment, and place a 4m x 21m steam generator into its own 5m diameter by 23m tall 740 ton concrete chamber, as illustrated below. Complex shapes made of concrete and rebar can be fabricated with a low-cost molding process, and dropped-in by crane.

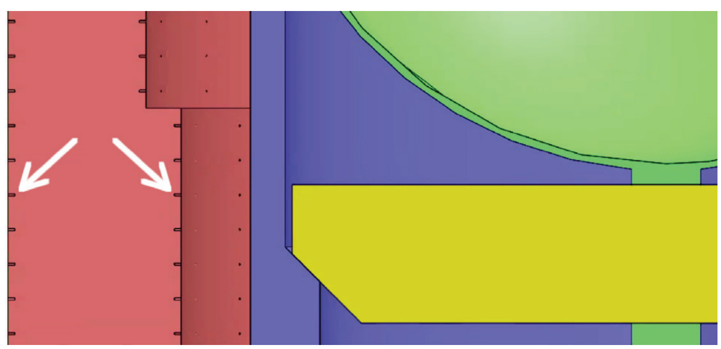




Upon careful inspection of the above illustrations, one might notice recessed areas in the silo internal surface, positioned vertically every 3m. These mate with optional concrete disks that isolate regions vertically within each silo, illustrated below-left. For example, one might place a reactor vessel in the upper 18m, and an isolated steam generator in the lower 18m (or visa-versa). A 1.25m thick 14m diameter concrete disc, for example, weighs 510 tons, and could be handled by a crane.

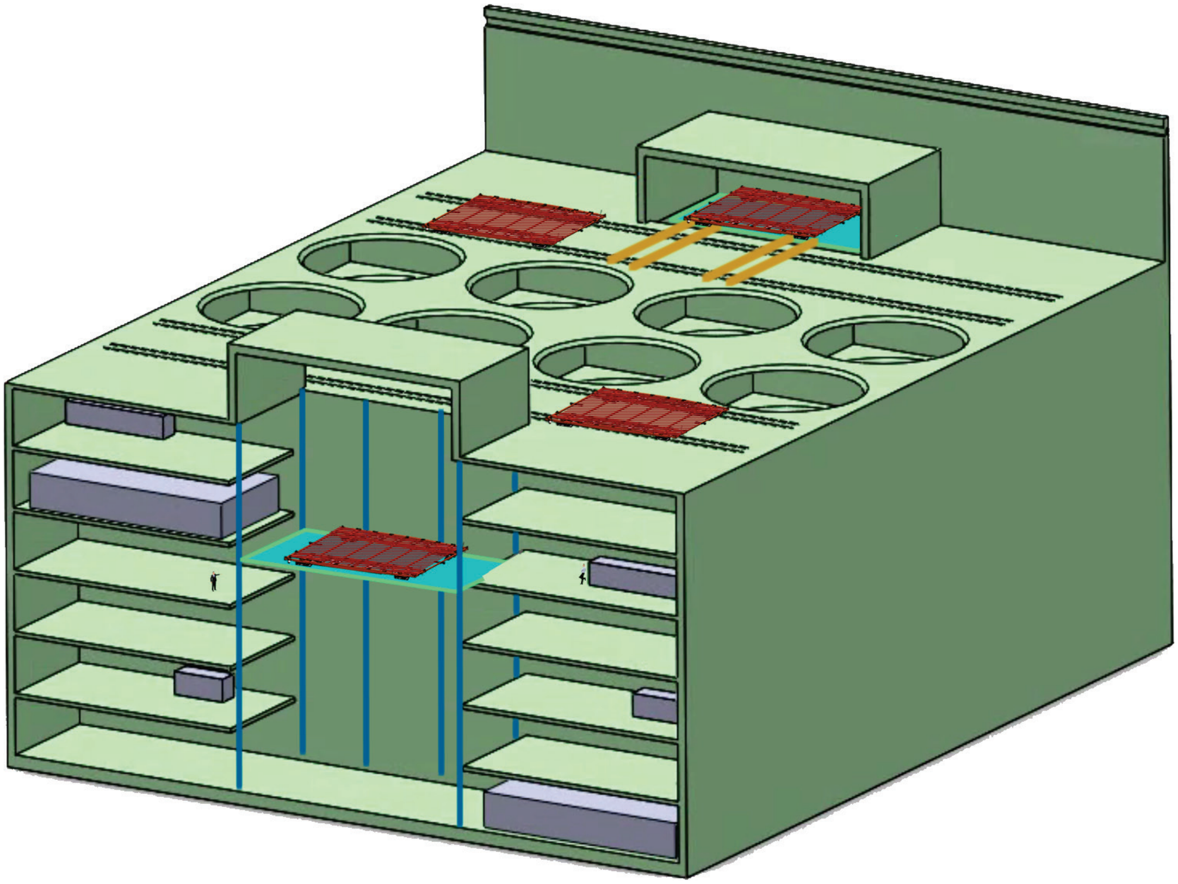
Arrays of threaded anchors in silo internal and external surfaces, illustrated below-right, support mounting brackets included with each nuclear package. Ports in the silo wall, not shown, allow pipes to gain access to the containment area.



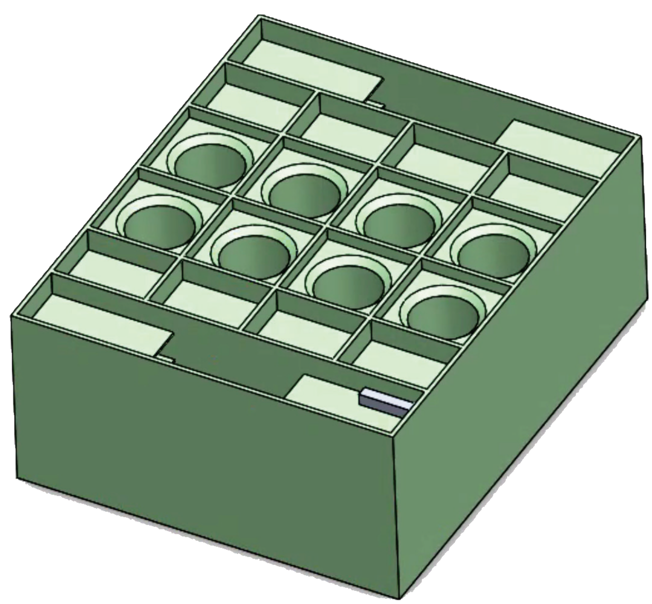


Nuclear Berthing System

Each 8-silo building unit maintains 28 berths, where each berth is a rectangular room 12m x 24m x 6m in size. Seven berths stack vertically in each of the four building corners. An elevator-like mechanism moves cargo down a large vertical shaft, and then slides cargo left or right, as illustrated below. More specifically, the elevator itself is very simple, and it moves a specialized Berthing Railcar (BR) within the vertical shaft. Complicated mechanisms that move and install cargo are built into each BR. Each nuclear package might include its own specialized BR that installs its components into the building.



Nuclear packages are transported in the following standard sized containers: 6m or 13m standard shipping container, 2x/3x/4x width of standard 6m or 13m container, and 12m x 24m sized platform. For example, one might place a diesel powered generator in a standard shipping container, and an auxiliary control room into a 12m x 12m container.

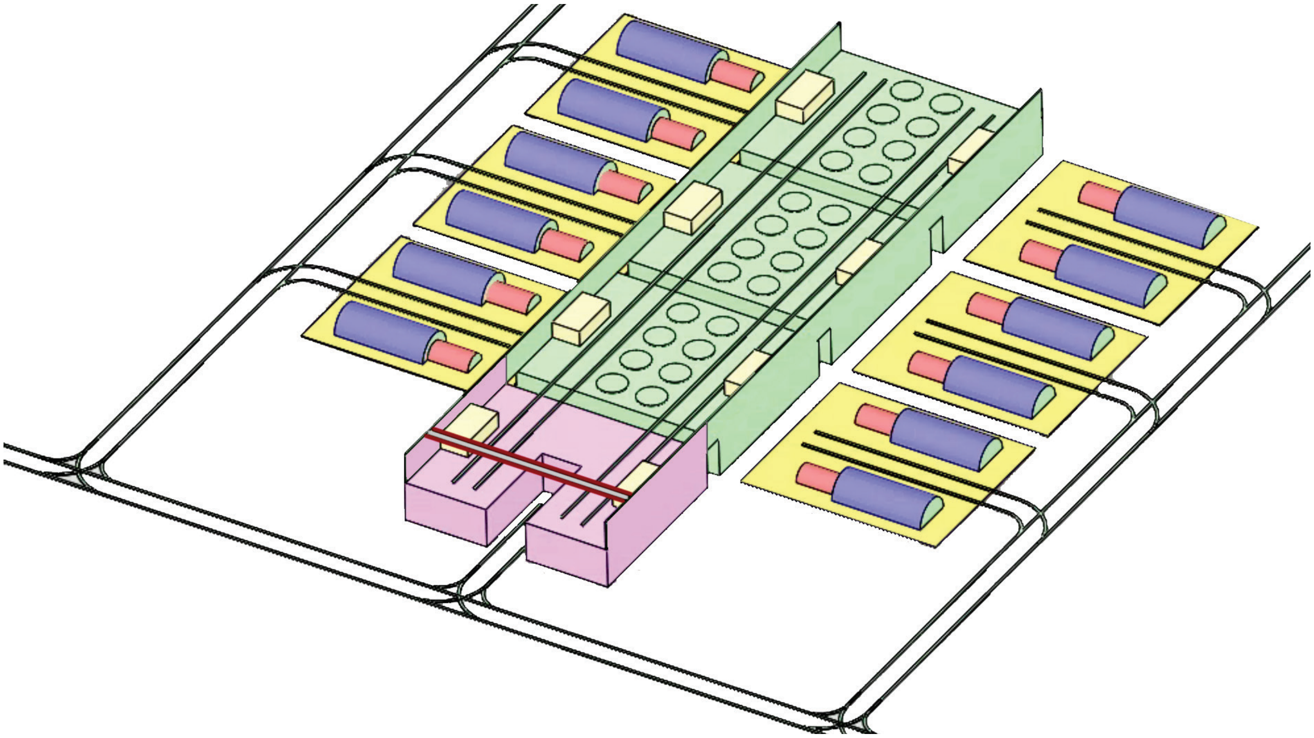


Engineers can also explore transporting fully formed concrete. For example, 15K ton concrete caissons are commonly moved via several techniques, as shown in this video.

The disadvantage of a flexible building is it uses more concrete and rebar than a structure sized to a specific nuclear design. The 8-silo building unit, shown here, consumes 88K m^3 of concrete (232K tons). This corresponds to concrete material cost of \$26M at \$300/m^3. Normally, nuclear sites cost much more than this. However, if we automate rebar, forms, concrete, and excavation; we can potentially build oversized and flexible buildings at low cost.

Converting Steam-to-Electricity

Adjacent to nuclear buildings are non-hardened buildings, illustrated below, that convert pressurized steam to electricity. Not shown are walls and roof of electrical buildings, roof of nuclear buildings, and condensers.

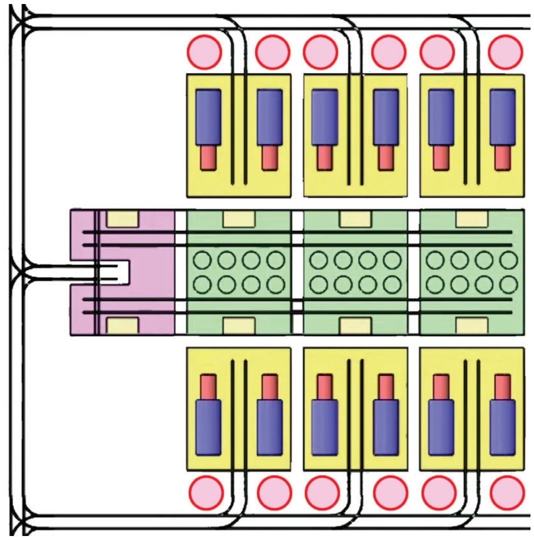


Illustrated above are turbines of 1.7GWe size, which are large, yet would transport on extra-wide rail. The SST-6000 is an example of a 1.2GWe turbine from Siemens; and the Arabelle 1700 is an example of a 1.7GWe turbine from GE. Pictured below are typical turbines.

If each reactor silo produced 100MWe, 200MWe, 400MWe, and 800MWe via upgrades; this would correspond to 400MWe, 800MWe, 1600MWe, and 3200MWe at each electrical building; which is large, yet manageable.

Making use of Thermal Storage

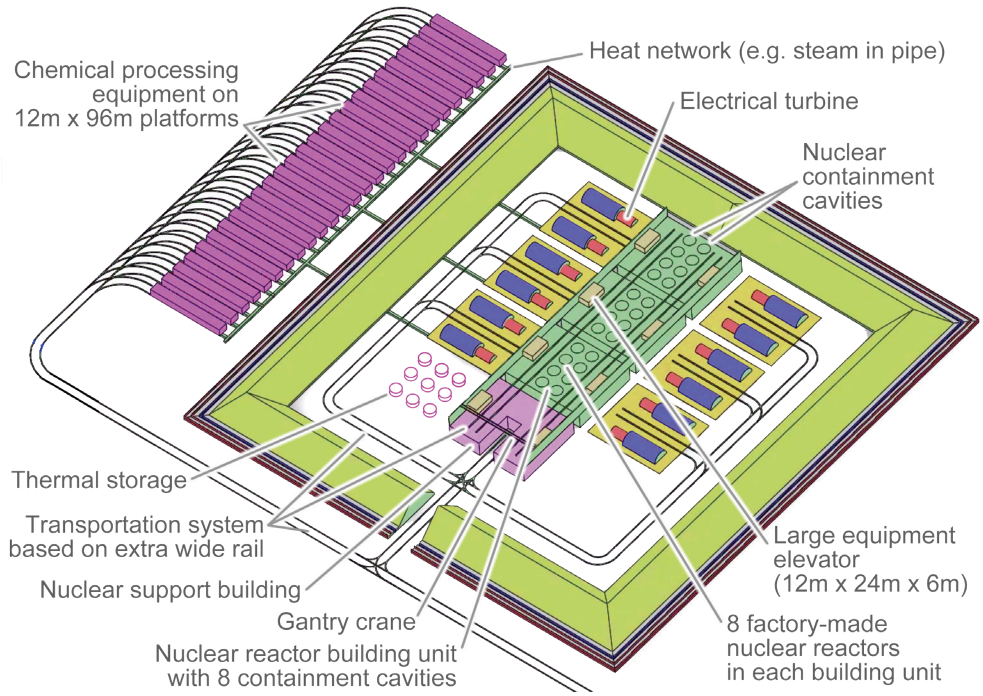
One technique for balancing load is to pump thermal energy into a tank of molten salt at night, when electricity demand is low, and later utilize the stored energy when demand is high. For example, let's assume energy demand during the day is 1.5GWe, during the night is 0.5GWe, and averages 1.0GWe over 24hrs. To satisfy peak demand, one might size their nuclear reactor at 1.5GWe, and disregard excess capacity at night. Alternatively, a 1.0GWe reactor could store 0.5GWe at night, and produce 1.5GWe total during the day. Cylindrical tanks 40m tall by 30m diameter, illustrated to the right in red, could store 0.5GWe for 12hours, given several million dollars of salt in each tank. This would probably cost less than adding 0.5GWe of nuclear power, especially if the thermal storage equipment was mass produced in a factory.



The standard site could be set up to support adding thermal storage at any time, if not during original construction.

Engineers could design a factory that mass produces thermal storage tanks, where factory-made subassemblies are transported via extra-wide rail. Also, engineers could explore specialized automated machines, perhaps mounted on wide rail, that excavate 30m diameter holes for standard sized tanks. There are a variety of techniques for soil stabilization during deep shaft construction, as shown in video1 and video2. Alternatively, engineers initially excavate the entire site down to bedrock, and build tanks and buildings on top of exposed bedrock. In theory, a super-sized transportation system could transport 30m x 40m cylinders in *multiple segments*, where each segment is in the range of ≤1000 tons and 40m length, for example.

In summary, factory mass production and site automation could enable one to obtain more energy via thermal storage, at low cost.



Making use of Cheap Green Heat

Rows of processing equipment, illustrated to the right, could be positioned near nuclear reactors to convert heat and electricity to hydrogen gas, liquid ammonia, cement, glass, plastic, etc.

In this concept, processing equipment is mounted on 12m wide by ≤96m long factory-made platforms that rest side-by-side, after being transported by extra-wide rail. Mobility allows them to be upgraded, and also allows one to reduce cost via factory mass production. For protection, an earth berm, fencing, and anti-vehicle trench surround nuclear buildings.

Maximizing Efficiency while Balancing Load

To minimize the cost of green energy, one needs to minimize heat losses while ensuring that supply meets demand for items being made (e.g. electricity, hydrogen). To maximize efficiency, one can capture "lost" heat via heat exchangers and use it in some way. One has several options: (a) feed heat back into a system and consume it in real-time, (b) feed heat into a steam generator and make electricity, (c) move heat into thermal storage and use it later. If one has multiple thermal storage tanks on-site, and each is at a different temperature (e.g. 150°C, 300°C, 600°C), then a computer can move heat into a tank of its choosing, and utilize to support varying demand. Also, one could focus on making and storing liquid ammonia when demand for other items is low.

Working with Decay Heat

When nuclear reactors turn off, they typically produce decay heat for days to weeks on the order of 3% to 0.5% of their maximum output. An 8-silo building rated for 100MWe/silo would produce 60MWt-per-building at 3%, for example (250MWt/silo, 2GWt/building, 2G x 3%). If one upgrades three times, and double capacity each time, building total might be 480MWt one minute after shutdown (16G x 3%), and 200MWt one hour after shutdown (16G x 1.3%).

Generation 4 nuclear fuel with a negative temperature coefficient will produce less energy than this if it is not cooled; however, we would prefer to not stress and test that system. Our first choice is the primary cooling system keeps fuel cool; however, if that fails, a secondary cooling system might be helpful. This entails three steps: (a) getting heat out of the reactor core, (b) transporting it, and (c) sinking it into a mass that heats up. This is a little complicated; however, we will touch on a few points to give one a sense of how this works.

If one places 8 tanks of water on the lowest floor, and 8 tanks on the highest floor, where each is 12m x 24m x 4m, it would take 2.7days to boil this water given 200MWt of energy, for example. Physically higher is helpful when using gravity and convection to move water; whereas lower is more protected. To support any duration, one could circulate outside water into these tanks from a lake, river or ocean. Or, place vertical aluminum fins on the building's external surface, and use these to conduct heat to the atmosphere indefinitely. This would require pumping a hot gas or fluid through piping attached to fins. If one pushed 200MWt into 2m x 16m fins on all four walls spaced every 1m, they could move approximately 200MWt with 250°C at fin surfaces, for example. Alternatively, one could pump 200MWt into 210K tons of building concrete for 12hours, and heat it up 50°C. Or pump heat into large tanks of salt that are also used for load balancing, discussed previously.

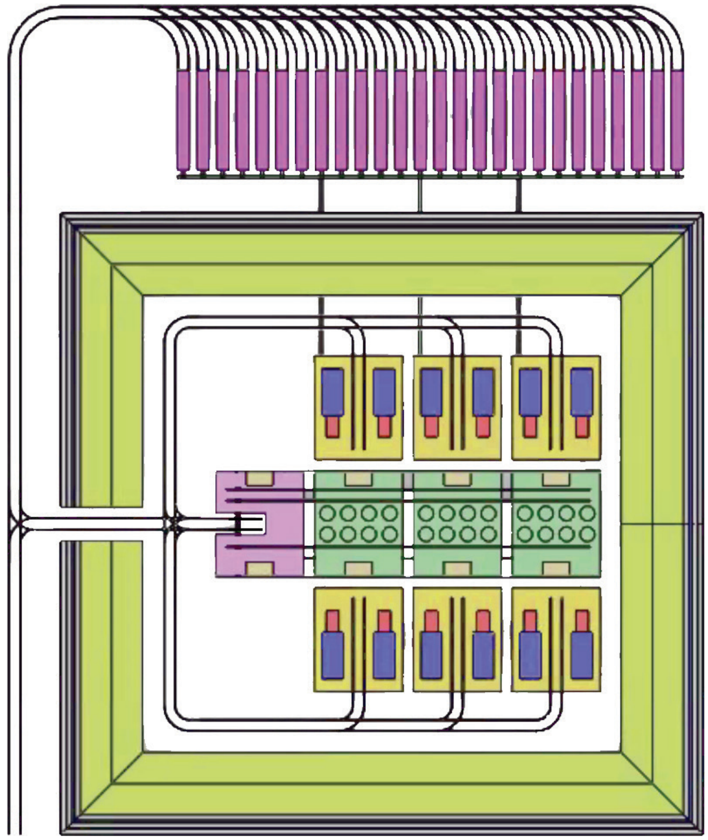
Conduction between reactor vessel external metal surface, and containment cavity internal concrete surface is limited. For, example, if 1m of air exists between 6m x 25m vessel surface, and concrete 1m away, then only 0.004MWt would conduct through air given 300°C between surfaces. Moving heat via heat radiation is better. In this example, one would get an additional 2MWt transfer via heat radiation (7m*3.14*25m*0.64ε*5.6e-8*((300.0°C+273°C) ^4)).

Heat conduction through concrete is minimal. For, example, if one moves heat 1m down a 14m diameter 1.25m thick concrete cylinder, and 300°C exists across this span, then only 0.012MWt would move.

To do a good job of moving heat out of a reactor core, one needs to pass a fluid or gas through the reactor vessel core. Or, attach fins and piping to reactor vessel external surface, and flow a coolant through that piping.

One would need many backup power generators, pumps, and fans to support moving heat via gas and/or fluid, in ducts and pipes. If all of these fail, then the Generation 4's negative temperature coefficient fuel is the last line of defense. This entails having the fuel heat up to a tolerable temperature, and then slowly dropping in temperature; even with no electricity, no coolant, and no circulation. This is made possible with material mixed into the nuclear fuel that turns off the fission reaction when its temperature exceeds normal operation. Older generation nuclear fuel does not have this feature, and is therefore at risk of meltdown.

Standardized Site Design



Previously we talked about factory-made standardized nuclear reactor packages, standardized hydrogen gas production packages, and standardized ammonia production packages. Global standardization entails designs that are made available to the public, which facilitates multiple factories who manufacture each transportable sub-assembly, which reduces costs.

Nuclear packages install into containment silos and into 12m x 24m berths. And packages that process heat install on 12m x 96m foundations, described previously. One can utilize multiple packages to obtain large capacities. For example, 16 packages of Gen4P1, 8 packages of H_2P1 and 8 packages of NH_3P1 might be placed at one site.

One could characterize a site with notation that describes packages and their quantities. For example, the above case might be described as "16-Gen4P1, 8-H_2P1, 8-NH_3P1".

Site design specifies things like roads, conduits, security, fencing, position of 12m wide rail, position of building units, and position of heat processing equipment. Software could produce drawings and other documents given the list of packages and their quantities. Site standardization would provide the following benefits:

- Reduce site design costs and time.
- Streamline regulatory certification process.
- Streamline quoting and contracting process.
- Simplify decision making process for gov't and power company executives.

Also, site owners could deviate from the standard site, if desired.

Federal Green Energy Production Zones

Local regulators and local opportunists could potentially drive up costs; therefore, they would need to be controlled if we wanted to achieve our cheaper goals. A remedy would be to establish federally controlled green energy production zones that support nuclear reactors, heat-driven processing, and green energy storage.

Additionally, federal law could provide to the EFC (Energy Finance Czar) the authority to demand right of way for hydrogen piping between green energy production zones and nearby heavy industry (e.g. cement factory).

To further control opportunists, a list of attack vectors could be compiled by surveying experienced project managers, and a defense against each type of attack could be codified into federal law. This might sound silly, yet if we do the math on how much this cost, we see it is enormous, especially in Europe and the USA, and therefore threatens our cheaper goals.

Standardization Ensures Pieces Fit Together

To get everything to fit together, all participants must use the same drawings. This is referred to as "standardization"; and to standardize, engineers from China, Europe and the USA must agree on one set of drawings. To do this, different concepts are presented to the industry by multiple parties; and ultimately, a group of engineers from different companies meet to develop a final design. This is called a "standards body meeting", and it is here that all numbers are reworked to the satisfaction of the participants. For example, they might favor a 10m x 30m containment cavity instead of a 14m x 36m cavity.

We refer to the word "standard" throughout this document, which means multiple participants have agreed to utilize the same design.

Many of the ideas in this document are *suggestions* for a standards body. We have no authority over the participants -- they ultimately decide what they want to do. Our role is to suggest concepts.

Chapter 7) Generation 4 Factory 1

Generation 4 Factory 1 becomes Ground Zero for Global Decarbonization

The factory purchase order (Gen4P1 PO #2) buys a factory that is both economically and technically transparent. This means energy executives, nuclear engineers, energy analysts (which drive capital markets) and regulators from all countries can visit to examine design, production, operations, logistics and finance. This factory becomes ground zero for decarbonizing the planet. Its goal is not to maximize revenue, but instead to maximize decarbonization. As we noted previously, if we want to decarbonize globally, we need to provide a method for achieving the cheaper goals. Making this one factory transparent is that method. After this, we let capital markets drive decarbonization.

This factory is only the tip of the decarbonization iceberg, since the world needs to make many copies of this factory to get this done. For example, to decarbonize globally, we would need 10 of these factories operating over 25 years at 33GWe/yr per factory (10 x 33 x 25 = 8400GWe) [12].

Also, as discussed previously, this first factory is engineering heavy, which means it needs to do significant engineering to support assembly and test. Later factories would copy the engineering, and focus primarily on production and coordination of suppliers. Their cost would be lower since engineering is expensive.

Cheaper Green Energy, Inc.

Legally, the issuers of the Factory PO would end up with a corporation that controls the factory, and the issuers of the PO would own stock in that corporation. Technically this "factory" is really a company that mass produces Generation 4 reactors. A public relations person might casually mention it is not necessary to place the word "nuclear" in the organization name.

CGE Cheaper Green Energy, Inc

Enabling Markets To Fix Climate Change

Alternatively, one might consider making this a foundation since it helps others manufacture, as opposed to trying to grab market share away from those that it helps.

Since this is a big project, the headquarters would probably be a campus with multiple buildings. And since we want others to copy, we would want to make it easy to visit. For example, issuers of the Factory PO might require ≤ 45min public transport between a large int'l airport and hotel; and another ≤ 15min public transport between hotel and campus.

To encourage participation, the campus might sponsor a free on-site monthly symposium where others visit, give talks, discuss, and learn. These could be recorded and made public via YouTube, to facilitate cheaper green energy.

The campus would perform engineering, coordinate suppliers, provide laboratory space, and do some manufacturing. An example engineering project might be to develop a system that tests a manufactured device that attaches to the reactor.

Sub-assemblies that consume significant amounts of factory floor space or storage space might be offset from headquarters in a more remote area with cheap land. And production of physically large sub-assemblies might be fabricated at any global location, and shipped directly to customers.

Set Up USA, Europe and China

If multiple governments paid for the Factory PO, they might require an independent campus be set up in each of their respective countries. Design materials could be shared among campuses; therefore, engineering of each device would only be done once. Also, each campus might be required to independently support production via their own set of suppliers, some of which would be in-country.

If we had multiple campuses, they would need to be controlled by *one* corporation; otherwise, they would fight. More specifically, they would block others from entering their region by differentiating the standard design into localized versions, get their version certified by regulators, and discourage other versions from being certified.

If the Factory PO was given to the China National Nuclear Corporation (CNNC), for example, they might be required to set up multiple campuses in multiple regions to the extent that they each independently manufactured at a minimum rate. CNNC is the largest builder of reactors worldwide and they currently own the design of an operational Generation 4 high temperature reactor. Americans at first glance might be uncomfortable with the Chinese playing this role. However, America would end up with a factory in the United States, run by Americans, with design files not controlled by Chinese, and the ability to make cheaper green energy -- which is probably acceptable.

Chapter 8) Working with Green Energy

Tanked Ammonia

If one country wanted to decarbonize another country, they could, in theory, park a ship off their coast loaded with liquid ammonia cheaper than coal, natural gas and oil; per unit energy. Flooding the world market with cheaper green ammonia is probably the easiest way to gain Paris compliance. Instead of persuasion, one could rely on a consumer's desire to save money. However, moving toward ammonia would require massive new infrastructure that includes pipes, storage tanks, terminals for ships, and retrofit at consumer. According to our calculations, beating oil and gasoline with cheaper green energy is somewhat easy, while, beating natural gas and coal is an immense challenge.

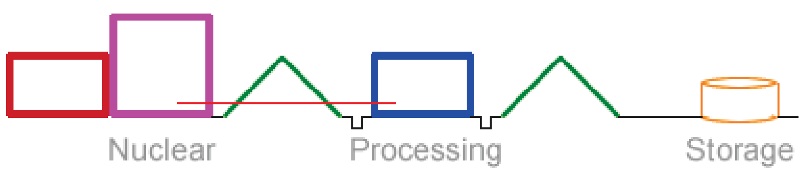
Using Direct Heat from Nuclear Reactor

Coal and natural gas are often burned to create heat to make cement, glass, metals, plastics, hydrogen, and other materials. In Cheaper Goal #2, we want to create heat without emitting CO_2, and have it cost less than heat from fossil fuels. More specifically, we want to pump a hot gas or hot liquid in a loop of pipe, between reactor and processing equipment. For example, one might transport heat via 700°C steam at 100 ATM pressure in a 500m loop.

Alternatively, one could first make piped hydrogen gas (Cheaper Goal #3) or tanked ammonia (Cheaper Goal #4), and then have that make heat; however additional steps increase cost. If one wants green heat to be cheaper than non-green, then in some cases, the only way is direct heat from the reactor.

Manufacturing processes are typically *not* co-located with nuclear, due to concerns over security and safety. However, due to climate change risks, Generation 4 safety improvements, and the need to get green heat cheaper than non-green, a re-think is warranted.

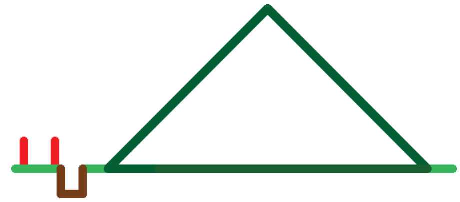
In theory, regulators could define multiple zones, one for nuclear reactor, one for heat driven processes, and one for storage; and require that an explosion in one zone not affect others. Earth berms (green in illustration), excavation, and offset distances can help isolate.



Energy contained in storage tanks could produce a large explosion, and would therefore require sizable offset distances. A large bulldozer costs $200/hr and can move 500m^3 of soil per hour ($0.40/m^3). Therefore, a berm 30m high x 60m wide x 500m long would require 450k m^3 of soil at an excavation cost of $160K, for example.

To expedite co-locating nuclear with green heat driven processes, regulators could offer a handbook that explains acceptable design practices, and include example drawings and calculations. To encourage further, they could offer free seminars, YouTube videos, on-line discussions, periodic open zoom meetings, free consultations, etc. Gov't can be helpful, if set up to do so.

Cheap Protection



For protection, two fences could block people, a ditch could block vehicles, an earth berm could block explosive force, and a radar-driven-gun could engage low and high flying airplanes. To make air defense visually more appealing, one could place both gun and multiple radars under one dome made of thin fabric or plastic. One might favor a missile over a gun due to increased range; however, guns are more effective against imminent low altitude attacks, and are less likely to accidentally engage a distant non-imminent threat.

For more protection, engineers might pile dirt on top of the nuclear building, at relatively little cost. If bedrock is down 30m, and building on bedrock is 50m tall, then 20m would be above grade, for example. Perhaps nuclear power in the future will look more like a small grassy knoll with a tree on top to mark entrance?

Beating the Gas out of Cars

If the green car was cheaper than the gasoline car, and drivers replaced at the same rate as today (100M/yr), we could convert the existing fleet (2.5B total) in 25 years without asking drivers to spend more money, which they would probably accept.

To beat gas, we can explore cheap green liquid ammonia that powers fuel cells, which produces electricity, which turns motors, which turns wheels. And we can also explore standardized swappable low-range cheap plug-in EV batteries that use fewer rare earth materials.

Liquid ammonia has three big challenges: (a) it consumes three times more volume relative to gasoline per unit energy, (b) it needs to be chilled to -33°C at 1 atm pressure or pressurized to 10 atm at room temperature, and (c) ammonia vapor needs to be kept out of noses. To maintain refrigeration, ammonia-based vehicles would need to maintain constant communication with a central authority, and if refrigeration failed, a service vehicle would need to visit to either repair or remove ammonia. A plug-in swappable standard refrigeration hardware unit used by all vehicles might make automated replacement easier. A refrigeration maintenance system would ultimately add to the total cost of ownership.

The good news is that liquid ammonia fuel made with Generation 4 should be cheaper than gasoline, per unit energy. And a fuel cell's 50% efficiency is better than an internal combustion engine's 25% efficiency. Also, one can explore combusting hydrogen, as explained in this video. In summary, if engineers can get the total cost of ownership for an ammonia-based car to be less than a gasoline-based car, it might be viable.

Currently, proprietary batteries are installed in each EV car and are periodically charged. Alternatively, one could have a standard plug-in battery, where all cars use the same form, and are swapped with a fresh battery in less than 60 seconds. Car owners would pay for the energy consumed and wear on the battery. Cavities would be dug out at key locations and a mechanism would be dropped in via crane that implements charging, storage and swap. Cars would position themselves over the mechanism, and the swap would occur automatically. Swap mechanisms might be positioned next to highway on/off ramps, and next to frequented establishments. For example, the corner next to your local drug store might be convenient. If swap is easy and fast, then shorter range batteries would become more acceptable; and these tend to be cheaper and use fewer rare earth materials.

Installing swap chambers or liquid ammonia refueling infrastructure would be an enormous undertaking.

Currently, gov't observes that EV battery prices have dropped over the past few years, extrapolates forward, and declares this as the transportation decarbonization plan. However, this might not work due to rare earth constraints. Subsequently, we should consider investing heavily in transportation that is cheaper than gas and is not resource constrained. For example, gov't could invest $10M/yr over 3 years for each of the following R&D initiatives:

- Design swappable plug-in battery infrastructure.
- Design ammonia-based car.
- Design an automated ammonia refueling station.
- Design a standardized plug-in ammonia refrigeration unit & tank.
- Design an automated city-wide ammonia refrigeration monitoring and maintenance system.

In summary, engineers need to figure out how to build 2,500,000 cheap green cars over ~25 years.

Beating the Gas out of Buildings

If we flood the market with low cost green electricity, then natural gas-fired building heat and hot water could transition to electrical heat pumps. One could explore piping hydrogen gas to buildings; however, installing new hydrogen piping, or converting natural gas piping to hydrogen involves digging up streets, which is a massive undertaking.

An easier approach is to first deploy a source of cheap green electricity. And then declare a cessation of natural gas service 15 years or so later, and a ban on installing new natural gas equipment effective immediately. Subsequently, homeowners would have 15 years to upgrade to electric heat pump, which does the same thing as a natural gas fired furnace connected to an A/C unit, yet costs less money to buy and install[7]. In many cases, building owners would wait for non-green equipment to fail, and go green when they replace it. This would enable them to decarbonize without incurring significant costs, which would be politically feasible.

In summary, to decarbonize heating/air conditioning, we first need a source of cheap green electricity, and then we can have building owners slowly replace gas furnaces to save money. The green equipment is cheaper because a heat pump that gives you heat is similar to an air conditioner that runs in reverse, and when you buy a gas furnace, you are also paying for an adjacent A/C unit.

Chapter 9) Develop Big Systems That Reduce CO_2

In theory, the world could develop large and complicated CO_2 reduction systems that are "Too Big". Too big in the sense that one company cannot afford to develop them. However, if funded by foundations or gov't, these might move forward. A small percentage of the $10B/yr budget, perhaps 1%, could be directed to Energy Systems R&D, to reduce the number of nuclear reactors we build. If we do this over five years at a total cost of $0.5B (5yrs x 10B x 1%), and this reduces CO_2 emissions by 1%, we would save $106B ($10.6T x 1%). Below are examples of systems that are too big for one company to develop, that also could significantly reduce CO_2 emissions:

A) **Solar Skins:** In theory, we should be able to wrap a building roof and wall surfaces with solar skins, at a cost less than traditional treatments. In the case of residential homes, this would entail attaching solar material directly to plywood, at a cost less than installing side wood clapboards and roof shingles. This would require complicated machines that fabricate custom pieces that wrap windows and install. For details, click here.

B) **Mechanization of Solar on Soil:** Develop mechanized systems for coating large amounts of land with solar in a manner similar to how agricultural tractors maintain large swaths of land. Also, explore placing solar material directly onto soil and dramatically reducing material usage for each Watt of electricity produced. For details, click here.

C) **Smart Building:** Place a processor into all building devices and network them together with reliable wired communication (i.e. data wire in power cable). Devices include: light switches, light sockets, motors that move thermal covers over windows, pumps that move water from thermal storage tanks to radiator valves, radiator valves, motorized dampers within ducts, motorized dampers at vent openings, fans within ducts, large appliances, thermostats, temperature sensors, occupancy sensors, and fire detectors, etc. In this initiative, we design devices and write software that reduces climate change via several techniques. For details, click here.

D) **Window Thermal Cover:** Create automated window thermal covers which deploy when the room is unoccupied. Thermal covers attach to smart building network. For details, click here.

E) **Next Generation HVAC:** Develop standardized plug-and-play modules that provide more control over air in a building. This includes: motorized dampers in ducts, fans in ducts, valves on radiators, routing thermal storage water, routing 60°F ground source water, etc. Modules connect to smart building network. For details, click here.

F) **Automated Articulating Arm:** Develop truck mounted articulating arm components that support construction and upgrades that reduce CO_2. For details, click here.

G) **Automated Market Place:** Develop website-based automated market places that support construction and upgrade projects that reduce CO_2; making use of above data. For details, click here.

H) **Automated Data Access:** In order to automate building construction and upgrade projects, software is written that collects, maintains and coordinates architectural drawings, laser scans of existing structures, photography, and ground penetrating radar data. For details, click here.

I) **Big Solar Architecture:** Architects explore ways of providing large surfaces for solar, on and around a building. For details, click here.

J) **Consolidate Building Complexity into Factory-Made Modules:** Researchers explore ways of consolidating additional building complexity into factory made modules that drop in via crane. For details, click here.

K) **Automated Ground Source Installation:** Develop automated systems for installing ground source piping. For details, click here.

L) **Standard Electric Vehicle Battery:** Develop swappable electric vehicle battery and support systems. For details, click here.

Chapter 10) Green Energy Strategy

Achieving Cheaper Goals are *required* to Globally Decarbonize

World leaders declaring the cheaper goals of national importance might be the most consequential acts of their careers. This is because we need this to make decarbonization easy. More specifically:

- Easy to pay for green energy power stations since capital markets will pick up the tab.
- Easy to build factories that mass produce green energy generation equipment since we can commission companies to build factories at relative low cost.
- Easy to automate construction of green energy power stations since we can hire engineers to focus on standard building designs and standard site designs.
- Easy to afford a $10B/yr decarbonization initiative since it reduces cost of $10T worth of green energy equipment by more than the $10B/yr automation cost.

As mentioned previously, this is based on green energy being cheaper than carbon-based fuels, which is mostly made possible with automation and with gov't regulation that controls opportunists. In other words, decarbonization is mostly an automation and gov't regulation problem.

Cost Uncertainty

Our estimates for cost-reduced nuclear power are uncertain since accuracy cannot be obtained without deployment. If we are off by a factor of two, for example, this would amount to $164B/yr for the USA, which is still affordable ($82B x 2). However, this increase would threaten our cheaper green energy goals, which drives customers, which drives capital markets that invest in infrastructure. In other words, affording 8,400GWe of nuclear power is probably not the hardest part of decarbonization. The hardest part is achieving the required cost reduction to make green energy cheaper. This means we need *all* cost reduction measures, not just a few.

Unintended Side-Effects

Our efforts to decarbonize might have unintended side-effects, several of which are summarized below.

- If we automate construction, then the building of cities might accelerate and cause an increase in global energy demand. Ultimately, we might end up with a race between the building of green energy supply, and growing energy demand.
- If green energy is cheaper than non-green, then the supply of non-green might increase relative to demand of non-green, which would cause the price of non-green to drop, which would make it more difficult to make green cheaper than non-green. For example, if no one wants natural gas, then the price of natural gas will drop and make it more difficult for the price of green hydrogen to be less than the price of natural gas, per unit energy.
- It is not clear how automation effects the unemployment rate. Thus far, it has not led to an increase, yet the future is uncertain.
- Nuclear has several big issues. These include high costs, meltdown risk, nuclear waste, and proliferation risk. Each of these can be mitigated, yet only to an extent, as summarized below.

- <u>Cost</u>: Electricity from nuclear currently costs more than electricity from coal or natural gas. To improve, one can reduce cost with factory mass production, and automated site construction.
- <u>Meltdown Risk</u>: Most existing nuclear power plants are at risk of meltdown. To avoid this for new ones, one can use newer fuels that do not melt down, even with no coolant, due to additives that attenuate energy output when fuel becomes too hot
- <u>Waste</u>: Most nuclear reactors produce waste that lasts 100,000 years. To improve, one can work with newer designs that produce less waste, or waste that lasts 300 years.
- <u>Proliferation Risk</u>: There is a concern that more nuclear power plants will increase proliferation risk (i.e. risk of bomb). To reduce this risk, one can work with nuclear fuels that are not easily refined into weapons grade material. However, even with proliferation-resistant fuels, some risk remains. After the climate change problem has passed, one might observe that we traded climate change risk for proliferation risk.

Align Business Interests

A nuclear company such as China's CNNC could potentially set up production like this themselves, without the discussed PO's, possibly contingent on receiving a large order.

However, many countries will resist buying from an outsider since this would lead to monopoly power over their energy industry by a foreign entity. A company with mass production would have lower costs and could capture significant market share. Also, after being certified by regulators in each country, certification for additional units would be easy, providing additional competitive advantage.

If a company like CNNC wanted to participate heavily in the US and European markets, they would need to make peace with the respective governments. And the two PO's would probably align interests to the extent required to make that happen. We will now illustrate this with a hypothetical conversation between the CEO of the China Nuclear Company, and the President of the United States:

CEO: "I am concerned this planet is going to end up a potato chip floating through space if I don't mass produce my Gen 4."

JOE: "Building Gen 4 is fine, yet my friends and I don't want to be controlled by China."

CEO: "Ok, what is the best we can do, from my point of view?"

JOE: "Make the design free and open so that no one owns it and you don't control anyone".

CEO: "That is fine, but I would need to recover my R&D costs, and I would want to be able to sell production units to anyone. And, by the way Mr. President, to be frank, you suck at manufacturing, and therefore free and open will not save you".

JOE: "I need you to compete globally; otherwise you will end up with monopoly power and jack prices. I can create plenty of American jobs that require on-site presence, such as building construction. I don't mind paying for your R&D, provided the price is reasonable. And by the way, I am trying to suck less by getting access to a decent Gen 4."

Maximize Profit or Maximize Decarbonization?

If the standard nuclear reactor design was owned by a company, they would maximize profit. Alternatively, if owned by no one, the price would be set by manufacturing costs plus a little profit (8% is typical).

The difference between the price of cheaper green energy and the price of carbon-based energy is the amount of money a customer saves if they switch to green. Divide this by the amount of money it takes to convert and you get a payback period in years. The lower this is, the more customers that switch, and the more capital that diverts toward green. In other words, if you want to maximize decarbonization, you want green energy to be as cheap as possible, not just 1% less than non-green.

If a company owned the standard nuclear reactor design, they would have monopoly power and would therefore control price. To maximize profit, they would price a tiny bit under non-green. Alternatively, if one wants to maximize decarbonization, they would want multiple companies to compete, which would drive price down and maximize conversion to green. In summary, supplying the design to others via free and open blocks monopoly power, and therefore maximizes decarbonization. Ultimately, governments are faced with the question, "Do you want to maximize global decarbonization, or do you want to have a company maximize profit?"

If you are a company who owns a reactor design then your first choice is called "proprietary platform play". This is when others standardize on your platform, which leads to monopoly power and high profit. This is a fantasy of most business executives; however, it is seldom achieved since others resist having their profit controlled by someone else. A Generation 4 company's second choice would be to sell their design at an acceptable price and have it become free and open, and also link to their own suppliers to gain an advantage when supplying the market. And the third choice entails a *competitor's* design becoming the cost-reduced standard, which might lead to your own design being defunded internally due to an inability to compete and make money.

Existing Transportation Systems

Transport of equipment is not expensive relative to total project costs. Many items can be transported via railcar (70tons, 23m x 4m x 3m) or truck (30tons, 17m x 4m x 3m). However, a nuclear reactor vessel is large, and might therefore involve special treatment. For example, one could partially disassemble, to some extent. Or install multiple small reactor vessels into one large building. For example, the proposed HTR-PM600 places six reactor vessels (250MWt, 6m x 25m) into one 1.5GWt building.

With the help of special equipment, one can transport 6m (18ft) wide objects on a two-lane road for dozens of miles. This video shows an example of this with a 225ton 50m x 6.5m cylinder. Both the X-Energy Xe-100 (200mWt, 23m x 5m) and NuScale NPM (250MWt, 25m x 5m) envision similar transport, as described here.

Also, one can transport very heavy items, at additional cost. This video shows transporting the SONGS-1 reactor vessel (1.3GWt, 770tons, 15m x 6m) via rail and self-propelled modular transporter (SPMT), for example.

Chapter 11) Today's Decarbonization is Not Working

The Paris Agreement was set up in 2015 to decrease worldwide CO_2 emissions; however, emissions are increasing, primarily because we confuse CO_2 reduction with a plan that gets us to zero emissions. The world does not have a plan, and subsequently dabbles in projects that are tiny relative to the size of the problem.

Hydro Does Not Scale as Needed

Hoover Dam is a hydroelectric plant that generates 0.015 EJ of electrical energy per year. This required 2.5million cubic-meters of concrete, which is 0.17M truckloads at 14m^2 per load. If we replaced the world's 583 EJ of annual heat energy consumption with these dams, we would need 13,500 of them, which would require 1.9 billion total loads of concrete (583 x 35% / 0.015, 0.17e6 x 11.3e3)[12]. However, as we add hydro, we run out of locations with geometry similar to that around Hoover Dam. In other words, even if we wanted to scale hydro to 583 EJ, and had no problem with 1.9 billion loads of concrete, we still could not do this.

Wind Does Not Scale as Needed

The London Array is 175 large windmills off the coast of England that cost $2.5B and generates 0.009 EJ of electrical energy per year. If we replaced the world's 583 EJ of annual heat energy consumption with multiple London Arrays, we would need 22.6K of them at a total cost of $56T (583 x 35% / 0.009, $2.5B x 22.6e3)[12]. However, as we add London Arrays, we run out of locations with favorable water depth, distance to shore, and high wind velocities. In other words, even if we wanted to scale offshore wind to 583 EJ, we could not.

Energy from wind increases with the cube of the wind velocity. For example, 20mph wind has 8-times more energy than 10mph ($8 = (20/10)^3$). This means you need windy areas, which are somewhat rare. Also, windmills make noise and therefore need to be kept far from people. As a remedy, we sometimes place offshore, yet this is expensive, especially in deeper water, and water further from the coast. In summary, cost effective windmill opportunities are limited.

Solar does Not Scale as Needed

Solar is similar to hydro in that we go after the easiest first. This is often sunny desert with cheap cleared land; and in these cases, we can build to the extent that we shed electricity in the middle of a sunny day. This means we supply 100% of the needs of a nearby city, and throw away excess electricity since we don't have enough consumers. We can try to transmit elsewhere, yet we incur losses as we move electricity over long distances. In other words, we can scale solar up to an extent, yet we eventually run out of regions conducive to the tasks.

Solar produces electricity approximately 25% of the time in a sunny region, which leaves 18 hours a day uncovered. And since energy does not store easily, this only satisfies a portion of our needs. One can try to make hydrogen gas from solar, yet this costs approximately $4/kg, which is 10-times more than natural gas, per unit energy.

Today's Electric Car Might Not Scale as Needed

Today 2.5 billion cars are on the world's roads and 100M are manufactured each year worldwide. Only 2% of those manufactured are electric (EV), due to gas costing less. To fully replace the existing fleet, we would need EV to be cheaper than gas, to drive adoption, and we would need to increase EV production 50-fold, to 100M/yr, and build EV for 25 years ($2.5B / (2M x 50)). EV batteries use rare lithium, cobalt and nickel; and it is not clear where we would get these, and at what price, if we increased consumption dramatically. In other words, lithium based electric cars might be resource limited.

Nuclear Scales, yet Is Currently Unpopular and Costly

Nuclear is not a walk in the park either. This video of the Hinkley Point C nuclear site shows what 3.2GWe looks like. To get 583 EJ of energy from this type of nuclear power, we would need 2,600 of these massive sites at $32.6B each, for a total cost of $84T (8429 / 3.2)[12]. Consumers, governments, and capital markets consider this too costly; subsequently, we would need significant cost reduction to make this financially acceptable. Also, as one can see from the Hinkley Wikipedia article, this 3.2GWe project has been a source of stress for all parties. Therefore, if the world built many of these, we would need to streamline operations, to avoid fatigue.

Nuclear scales, which means one can build additional plants and costs do not increase. Understanding this is crucial, since decarbonizing via other means, at the scale and price needed, is probably impossible.

Failing to Decarbonize will Result in Death

Also, there is the option of *not* decarbonizing. However, all climate models show this leads to massive harm this century in Europe, USA and China. We should all be aware that the world's current plan, in effect, is to do nothing, based on the fact that CO_2 emissions are increasing. This might feel counterintuitive since we observe windmills and solar farms on the news. However, when we do the math, we see current efforts are small relative to our 13K Hoover Dam or 22K London Array sized problem.

Chapter 12) Green Energy Economics

Achieving Cheaper Goals depends on Time, Place and Technology

Our Cheaper Goals entail green energy being cheaper than non-green, which is directly affected by non-green price. And non-green price vary with time, and with location. For example, in May 2021, coal was $57/ton in the USA, and $82/ton in China. Also, green energy costs tend to decrease over time due to new technology, and cost reduction measures. For this reason, we can expect to achieve cheaper goals at a different time, for each location.

The Economics of China's Nuclear Power

The table below shows wholesale cost-per-unit-energy ($/GJ) of existing carbon-based energy, along with the cost of hydrogen and ammonia made with direct heat from a nuclear reactor in China. This later approach is still in development; therefore, their costs are estimated. Also, if many nuclear reactors where built, these costs would decrease, perhaps 2-fold. If one wants to solve the climate change problem, consider focusing here.

In summary, nuclear reactors in China could create cheap heat for manufacturing in China, create cheap piped hydrogen for use in China, and create cheap ammonia for export. And after ammonia is exported, it could be converted to hydrogen, or it could be pushed into an ammonia-based fuel cell to produce electricity.

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

Cheaper Goal #1 - Green Electricity ($/kWh)

We will now run the numbers and see what it takes to achieve Cheaper Goal #1, which is to make green electricity cheaper than non-green. This would enable us to decarbonize the electricity sector, which is 42% of global CO_2 emissions. We compare dollars per kWh for each option, where kWh is a unit of electricity. Anyone is welcome to download, copy, and modify our calculations at no charge.

The initial cost to build equipment is referred to as the "Capital Expense" (CapEx). In the case of nuclear power, this is the cost to build the reactor and the associated equipment. We assume our Gen 4 Package #1 cost-cutting measures CapEx down by a factor of two relative to the current China reactor price. We do not have an accurate calculation of this factor since we have not yet built the factory; therefore, we stay conservative with the low number two. This means that the total China CapEx drops from $2K/kWe to $1K/kWe[2].

The total CapEx is the sum of several primary components: cost of factory-made sub-assemblies, transportation costs, import duty, cost to construct building/site, and cost of local assembly. We estimate the total USA/Europe CapEx to be $0.5K/kWe higher than the China CapEx due to higher local costs. Subsequently, the total USA/Europe Gen4P1 CapEx would be $1.5K/kWe. The current USA/Europe CapEx is $6K/kWe; therefore, this new price would have a seismic effect on their respective energy industries, and decarbonization strategies[1].

Also, we assume that a second round of cost cutting measures (Gen4P2) reduces CapEx further by 30% to \$1.0K/kWe for USA/Europe, and \$0.7K/kWe for China.

We will now look at USA electricity costs from various sources, based on the USA National Renewable Energy Lab (NREL) 2019 ATB year 2022 model[1]. In summary, electricity from mass produced nuclear is cheaper than other options that emit CO_2, even in Gen 4 Package #1. This means we can achieve Cheaper Goal #1, which means we can decarbonize electricity.

The red numbers in the below table show fossil fuel prices (USA, 2019, wholesale), the green numbers show predicted Generation 4 green electricity costs, and the blue numbers show the cost of electricity generated from solar, wind and hydro. Energy prices fluctuate with time and with place, as shown in this Wikipedia page. We assume heat to electricity conversion efficiency is 42%, which is typical with a high temperature reactor[11].

Cost data for utility scale wind, solar and hydro are good; however, this is misleading since it suggests you can buy at these rates, which you often cannot. One runs into resource constraints, as discussed previously. Nuclear, on the other hand, can scale up to any volume.

"China Soon" refers to an HTR-PM nuclear power plant which produces electricity, hydrogen via sulfur-iodine, and ammonia via a 65% efficient hydrogen-to-ammonia process. This does not exist however, will probably appear in the not-so-distant future.

Source	Type	Electricity Cost (LCOE, \$/kWh)[1]	CO_2 Emissions (LBs/MMBtu)	Expenses (\$/kW-Yr)	Nuclear Plant CapEx (\$/kWe)[1]	Fuel Cost[1]
Nuclear	Gen4P1 Usa/Europe	\$0.028	0	\$75	\$1,500	\$0.65/MMBtu, \$0.007/kWh
	Gen4P1 China	\$0.021	0	\$50	\$1,000	\$0.65/MMBtu, \$0.005/kWh
	Gen4P2 Usa/Europe	\$0.017	0	\$53	\$700	\$0.33/MMBtu, \$0.003/kWh
	Gen4P2 China	\$0.013	0	\$35	\$500	"
	Usa/Europe Today	\$0.066	0	\$101	\$6,000	\$0.65/MMBtu, \$0.007/kWh
	China Soon (HTR-PM)	\$0.034	0	\$73	\$2,400	\$0.65/MMBtu, \$0.005/kWh
Coal	IGCC-Constant CF	\$0.070	210		\$4,200	\$2.1/MMBtu, \$50/ton, \$0.018/kWh
	CCS 90%-Constant CF	\$0.140	21		\$6,000	\$2.1/MMBtu, \$50/ton, \$0.023/kWh
Natural Gas	CC, constant CF	\$0.032	117		\$1,000	\$3.4/Mcf, \$0.021/kWh
	CC-CCS, constant CF	\$0.053	11		\$2,300	\$3.4/Mcf , \$0.025/kWh
Solar	Chicago Utility PV	\$0.040	0		\$1,100	
	Los Angeles Utility PV	\$0.050	0		"	
Wind	On shore, TRG4	\$0.034	0		\$1,600	
	Off shore fixed TRG4	\$0.110	0		\$4,100	
Hydro	NPD 3	\$0.052	0		\$4,100	

Cheaper Goal #2 - Green Heat (\$/MMBtu)

We will now run the numbers and see what it takes to achieve Cheaper Goal #2, which is to make green heat cheaper than non-green. This is similar to electricity, yet instead we look at the cost of the heat output of a Generation 4 reactor before it is converted to electricity, and compare with the internal energy content of non-green fuel. We assume the electricity Generation equipment is in place, since one might want electricity from time to time, instead of redirect heat. We compare dollars per million BTU for each option (MMBtu), where BTU is a unit of heat. The below table shows the cost of heat from non-green sources. We want our green heat to be cheaper than these.

	Natural Gas (CH4)	Coal, Anthracite	Gasoline	Diesel	Ethanol	Crude Oil	Heating Oil
$/MMBtu (internal energy)	$3.06	$2.19	$17.19	$15.09	$27.04	$9.42	$13.39

Below is the cost of Generation 4 heat in a pipe. Green beats liquid fossil fuels and natural gas in Gen 4 Package #1, which is good. And green heat beats heat from coal in Gen 4 Package #2.

Type of Nuclear	Heat Cost (LCOE, $/MMBtu)[1]	Heat Cost (LCOE, $/GJ)	Expenses ($/kW-Yr)	Nuclear Plant CapEx ($/kWe)[1]	Fuel Cost[1]
Gen4P1 Usa/Europe	$3.43	$3.25	$75	$1,500	$0.65/MMBtu, $0.007/kWh
Gen4P1 China	$2.60	$2.46	$50	$1,000	$0.65/MMBtu, $0.005/kWh
Gen4P2 Usa/Europe	$2.05	$1.94	$53	$700	$0.33/MMBtu, $0.003/kWh
Gen4P2 China	$1.60	$1.52	$35	$500	"
Usa/Europe Today	$6.27	$5.94	$101	$6,000	$0.65/MMBtu, $0.007/kWh
China Soon (HTR-PM)	$4.21	$3.99	$73	$2,400	$0.65/MMBtu, $0.005/kWh

The above table assumes a zero cost for the equipment that converts the non-green fuel to heat, since it depends on the process that requires heat. Also, we assume regulators are making it easy to attach non-nuclear grade equipment to a network of heat pipes driven by a nuclear reactor.

Cheaper Goal #3 - Piped Green Hydrogen ($/GJ)

We will now run the numbers and see what it takes to achieve Cheaper Goal #3, which is to make piped green hydrogen cheaper than heating oil, coal and piped natural gas; per unit energy. We are looking at gas flowing in a pipe, which is different from storing energy in a tank, as mentioned previously. Piping gas requires a network of pipes between supplier and multiple consumers, which is only convenient in some cases. A feasible scenario would be a nuclear reactor in the vicinity of heavy industry within an industrial zone. If you want to store instead of flow energy in a pipe, then consider cheaper goal #4, discussed later.

A joule is a unit of energy and one billion joules is called a gigajoule (GJ). If one looks at the cost of energy for different common non-green fuels, they will see coal and natural gas are cheap ($2 to $3/GJ); whereas others are relatively higher ($12 to $25/GJ), as shown below. Also, non-green ammonia is high at $21/GJ ($400/ton).

To make hydrogen we use high temperature electrolysis which is commercially available today at $750/kWe. We assume we can drop this to $300/kWe via cost reduction program H_2P1 and we assume we drop this further to $200/kWe via H_2P2. Also, we assume we lose 5% from high temperature electrolysis (95% efficiency), and 10% due to servicing of equipment (90% CF).

The below table shows dollars-per-unit energy ($/GJ) for common fossil fuels (USA, 2019, wholesale[1]), and also shows the hydrogen parity price ($/kg), which is the price needed for hydrogen to have the same amount of cost-per-unit-energy. For example, to beat $3.40/mcf natural gas, one would need green hydrogen priced at $0.45/kg.

			Natural Gas (CH4)	Coal, Anthracite	Gasoline	Diesel	Ethanol	Crude Oil	Heating Oil
Cost	cost		$3.40	$57.00	$2.12	$2.10	$2.34	$1.26	$1.80
	units		$/mcf	$/ton	$/gal	$/gal	$/gal	$/gal	$/gal
	source		nrel atb	nrel atb	eia whls	eia whls	cme eth	eia whls	eia whls
Cost/GJ	$/GJ		$3.19	$2.09	$16.38	$14.37	$25.76	$8.97	$12.75
Hydrogen Parity Price ($/kg)			$0.45	$0.29	$2.31	$2.03	$3.63	$1.27	$1.80

We now look at expected hydrogen costs given the previously discussed cost reduction programs. We are making hydrogen using nuclear power and water; which is different from the traditional method that utilizes natural gas.

Type of Nuclear	Hydrogen Cost (LCOE, $/kg)[1]	Hydrogen Cost (LCOE, $/GJ)	Expenses ($/kW-Yr)	H_2 Plant (CapEx $/kWe)	Nuclear Plant (CapEx $/kWe)[1]	Fuel Cost[1]
Gen4P1/H_2P1 Usa/Europe	$1.02	$7.22	$112	$300	$1,500	$0.65/MMBtu, $0.007/kWh
Gen4P1/H_2P1 China	$0.76	$5.39	$75	$225	$1,000	$0.65/MMBtu, $0.005/kWh
Gen4P2/H_2P2 Usa/Europe	$0.62	$4.42	$78	$200	$700	$0.33/MMBtu, $0.003/kWh
Gen4P2/H_2P2 China	$0.48	$3.40	$53	$150	$500	"
Usa/Europe Today	$2.27	$16.11	$151	$750	$6,000	$0.65/MMBtu, $0.007/kWh
China Soon (HTR-PM)	$1.26	$8.93	$113	$500	$2,400	$0.65/MMBtu, $0.005/kWh

Cost-reduced green hydrogen beats gasoline and oil, yet not natural gas and coal. After Package #2, green hydrogen gains parity with natural gas in China, yet loses to coal in China by a factor of 1.6, approximately. Below are several possible remedies:

- Gov't places their thumb on the scale and makes fossil fuels more costly, or green cheaper.
- Price of fossil fuels might be higher in some locations, and at some points in time.
- Explore additional cost reduction programs for green hydrogen.
- Do not use hydrogen gas and instead utilize green heat directly from a Gen 4 reactor via a heat pipe.
- Focus on easier to decarbonize areas for a while and hope newer technology comes along and helps us beat natural gas and coal with piped green hydrogen.
- It is possible that additional global standardization rounds (e.g. #3 and #4) of newer technology is needed to get green hydrogen and green ammonia closer to natural gas and coal.

Do not expect hydrogen from solar, wind or hydro to be cheaper than hydrogen from nuclear. Nuclear works at higher temperatures, which are more efficient. And, solar operates 25% of the time, which means equipment is idle 75% of time, which is costly. Nuclear runs 90% of the time, which is 3.6 times more than solar (90/25).

Cheaper Goal #4 - Tanked Green Ammonia ($/GJ)

We will now run the numbers to see what it takes to achieve Cheaper Goal #4, which is to make tanked liquid ammonia cheaper than coal, natural gas, and oil; per unit energy. We are looking at liquid stored in a tank, which requires an additional step after you get hydrogen flowing in a pipe. We assume this additional step causes 10% of energy to be lost, increases equipment costs, and increases operating costs. Also, this means our competition with fossil fuels is similar to hydrogen, yet is worse due to these additional costs.

The below table shows dollars-per-unit energy ($/GJ) for common fossil fuels (USA, 2019, wholesale[1]), and also shows the ammonia parity price ($/gal and $/ton), which is the price needed for ammonia to have the same amount of cost per unit energy. For example, to beat $3.40/mcf natural gas, one would need green ammonia priced at $54/ton.

			Natural Gas (CH4)	Coal, Anthracite	Gasoline	Diesel	Ethanol	Crude Oil	Heating Oil
Cost	cost		$3.40	$57.00	$2.12	$2.10	$2.34	$1.26	$1.80
	units		$/mcf	$/ton	$/gal	$/gal	$/gal	$/gal	$/gal
	source		nrel atb	nrel atb	eia whls	eia whls	cme eth	eia whls	eia whls
Cost/GJ			$3.19	$2.09	$16.38	$14.37	$25.76	$8.97	$12.75
Ammonia Parity		($/gal)	$0.14	$0.09	$0.71	$0.63	$1.12	$0.39	$0.55
Price		($/ton)	$54	$35	$278	$244	$437	$152	$216
		($/GJ)	$3.19	$2.09	$16.38	$14.37	$25.76	$8.97	$12.75

We now look at expected ammonia costs given the previously discussed cost reduction programs.

Type of Nuclear	Ammonia Cost (LCOE, $/ton)[1]	Ammonia Cost (LCOE, $/gal)	Ammonia Cost (LCOE, $/GJ)	Expenses ($/kW-Yr)	$H_2 + NH_3$ Plant (CapEx $/kWe)	Nuclear Plant (CapEx $/kWe)[1]	Fuel Cost[1]
Gen4P1/H_2P1 Usa/Europe	$207	$0.53	$12.21	$131	$450	$1,500	$0.65/MMBtu, $0.007/kWh
Gen4P1/H_2P1 China	$154	$0.39	$9.06	$88	$338	$1,000	$0.65/MMBtu, $0.005/kWh
Gen4P2/H_2P2 Usa/Europe	$128	$0.33	$7.53	$90	$300	$700	$0.33/MMBtu, $0.003/kWh
Gen4P2/H_2P2 China	$98	$0.25	$5.77	$62	$225	$500	"
Usa/Europe Today	$452	$1.16	$26.67	$176	$1125	$6,000	$0.65/MMBtu, $0.007/kWh
China Soon (HTR-PM)	$258	$0.65	$15.24	$133	$700	$2,400	$0.65/MMBtu, $0.005/kWh

As one can see, green ammonia is cheaper than liquid fossil fuels, per unit energy. However, it is more costly than natural gas by approximately 2-fold, and more costly than coal by approximately 3-fold after two rounds of cost reduction.

Coal and natural gas are used in four general areas: electricity Generation, building HVAC heat, < 750°C process heat, and > 750°C process heat. We can beat it in the first three via Generation 4 electricity, building furnace to electric heat pump conversion, and direct heat from Generation 4 reactor, respectively. And in the last area (> 750°C), we can pre-heat via direct Generation 4 reactor heat, and then use costly ammonia to get to the higher temperatures.

Our plan is not perfect, yet might be the best we can do, for now.

Chapter 13) Conclusion

Plan Summary

As we stated previously, we cannot decarbonize using only Solar, Hydro and Wind; due to costs that increase as we build more facilities, driven by resource limitations. Therefore, we have no choice but to rely heavily on nuclear power. A new type of nuclear, called Generation 4, resolves meltdown risks, and therefore costs do not increase as we build more power plants.

To replace the world's 583 EJ of energy consumption, we would need to build 8,400GWe of nuclear power. Capital markets and commercial companies are more efficient than gov't run projects, and political will to spend gov't money is limited; therefore, these would need to be funded by capital markets.

We observe that consumers select the lowest cost option, independent of how it relates to CO_2. Capital markets invest in creating infrastructure that supports consumer demand; therefore to divert capital spending toward green energy, such as building of 8,400GWe nuclear power, we need green energy to cost less than non-green.

To reduce green energy costs, we employ many cost-reduction measures:

- Free and open standardization of nuclear reactor and hydrogen/ammonia conversion equipment.
- Multiple manufacturers that make each sub-assembly and drive down costs.
- Development of super-sized transportation system that moves large and heavy objects. This includes developing a transparent factory that mass produces ships, cranes, railcars, and rail construction/maintenance equipment used by the new system.
- Development of robotic assembly of rebar and forms.
- Development of robotic assembly of nuclear and hydrogen/ammonia conversion sub-assemblies.
- Development of factory-made thermal storage systems and automated installation equipment.
- Establishment of federal green energy production zones.
- Establishment of energy finance and nuclear power czars with sweeping authority.
- Regulation that supports processes driven directly from nuclear reactor heat.
- Development of a standardized green energy site design.

Also, on top of all that, we need to give all engineering away for free, since each global participant cannot afford the massive amount of engineering required to significantly reduce the cost of manufacturing green energy production equipment. The good news is that the gov't could pay for this engineering with relatively little money, and put the world onto a gentle decarbonization path.

Who manages this? People like Elon Musk, Jeff Bezos, and Bill Gates built empires using the technology we need to solve the climate change problem. We are talking about computers, automation, machine vision, networks, software, mass production, factories, robotics, construction, and self-driving vehicles. They could probably solve the climate change problem on their lunch break, given a $10B/yr engineering budget, based on their experience. While eating their sandwiches, they could decide on what to automate, and then let engineers and markets do the rest.

Engineers must be given the right instructions. A reasonable assignment might be, "Build 8,400GWe of nuclear power over 25 years at a cost of $1250/KWe via factory mass production, given a generous $10B/yr engineering budget."

Alternatively, engineers might be told "build one reactor" or "build one $3B windfarm that produces 1/18,000th of 583 EJ world energy consumption". These will not get us to zero, and therefore waste valuable time and talent. Also, one can argue the $3B windfarm does harm because it gives us a false sense that we are tackling climate change. Reduce is not zero.

If anyone has another way to solve the climate change problem, they should explain how they plan to scale given resource limitations, and identify realistic sources of funding. If an alternate plan is not produced, then it is possible the concepts identified in this document are the only way to fix this.

Truth and Science

All of this might seem overwhelming, and it is. Yet this might also be the easiest way to decarbonize the planet in a reasonable period of time, without significant public money, and without increased energy prices.

President Biden stated the cornerstone of his presidency is *Truth* and *Science*. We could apply that here. Science entails developing a mathematical plan that decarbonizes the planet where the math is shared, checked, and rechecked for validity. And *Truth* entails basing the plan on accurate numbers, laws of economics, and laws of science.

Truth and *Science.*

Chapter 14) Reference

Atmospheric Science 101

When we increase the amount of CO_2 in the atmosphere (i.e. ppm), we quickly get an associated temperature increase relative to the beginning of industrialization, 200years ago. Temperature increase and CO_2 ppm level are in lock-step due to well-known and complicated physics that is beyond the scope of this discussion. Also, in lock-step, is the moisture level in soil, and the average reservoir water level. As we increase temperature, we quickly get an associated reduction in water, which affects food production.

If we did *not* stop CO_2 emission, we would see a 4 to 5°C temperature increase by 2100, which would result in death, in part due to something called "desertification". This is when land dries out to the point where it becomes a desert and produces little food. We don't want this; therefore, it is worth the effort to halt CO_2 emissions.

On the day we stop emitting CO_2, we lock-in for many years the ppm CO_2 level in the atmosphere. And we also lock-in the associated temperature increase, the amount of moisture in soil, and the average reservoir water level. These levels will revert back to where we started, when people traveled by horse and foot, yet slowly, perhaps by 50% over the next 1000 years.

Some of the harms from CO_2 occur quickly, whereas others are slow. For example, desertification is fast, and sea level rise is slow.

Increased temperature will cause the 1000's of meters of ice on Antarctica to melt over thousands of years. If fully melted, sea level will increase approximately 200 feet and claim coastal cities, in addition to half of Florida.

Sea level rise that occurs slowly does not need to be painful since building codes can avoid constructing buildings, as needed. A beautiful evacuation of Manhattan would entail no one being harmed, via building codes that encourage gentle migration before damage.

However, there are cases when sea level rise moves faster than people can adapt. For example, Bangladesh and South Vietnam land will go under water, perhaps within 100 years, and eliminate large amounts of land and food production, before people are ready to move.

In summary, if we do not stop emitting CO_2, we will turn much of China, Europe, India and the United States into deserts -- this century.

Energy Carriers

The following table shows energy-per-weight and energy-per-volume for common energy carriers. Only Hydrogen (H_2) and Ammonia (NH_3) do not emit CO_2 when burned.

		Ammonia (NH3)	Hydrogen (H2) 1atm	Hydrogen (H2) 700atm	Natural Gas (CH4) 1atm	Coal, Anthracite	Gasoline	Diesel	Ethanol	Crude Oil	Heating Oil
Specific Energy											
	MJ/kg	**18.6**	**141**	**141**	**53.6**	**30.0**	**46**	**45**	**30**	**41**	**46**
	GJ/kg	**0.0186**	**0.141**	**0.141**	**0.0536**	**0.03**	**0.046**	**0.045**	**0.03**	**0.041**	**0.046**
	kg/GJ	**53.76**	**7.09**	**7.09**	**18.66**	**33.33**	**21.74**	**22.22**	**33.33**	**24.39**	**21.74**
	ton/GJ	**0.059**	**0.008**	**0.008**	**0.021**	**0.037**	**0.024**	**0.024**	**0.037**	**0.027**	**0.024**
Energy Density											
	MJ/L	**11.5**	**0.012**	**5.300**	**0.0364**	**38.5**	**34.2**	**38.6**	**24**	**37.0**	**37.3**
	MJ/m^3	**11,500**	**11.9**	**5,300.0**	**36.4**	**38,500**	**34,200**	**38,600**	**24,000**	**37,000**	**37,300**
	MJ/ft^3	**329**	**0.339**	**151.429**	**1.040**	**1,100**	**977**	**1,103**	**686**	**1,057**	**1,066**
	MJ/gal	**44**	**0.045**	**20.063**	**0.138**	**146**	**129**	**146**	**91**	**140**	**141**
	GJ/gal	**0.044**	**0.00004**	**0.02006**	**0.00014**	**0.146**	**0.129**	**0.146**	**0.091**	**0.140**	**0.141**
	gal/MJ	**0.023**	**22.2**	**0.05**	**7.3**	**0.007**	**0.008**	**0.007**	**0.011**	**0.007**	**0.007**
	gal/GJ	**22.97**	**22,237**	**49.8**	**7,257**	**6.9**	**7.7**	**6.8**	**11.0**	**7.1**	**7.1**
	MCF/GJ				**0.94**						

Footnotes

[1]USA National Renewable Energy Lab 2019 ATB model

[2]World Nuclear Association reports China's CapEx is $1.7K/kWe for CPR-1000 and is $2.3K/kWe for AP1000. We use the average and estimate China's CapEx for new reactors at $2K/kWe.

[3]Global E&P investments by segment 2010-2019, Statista 2020 Report.

[4]Missing Link to a Livable Climate, How Hydrogen-Enabled Synthetic Fuels Can Help Deliver the Paris Goals, 2020, By Eric Ingersoll and Kirsty Gogan.

[5]Tracking the decoupling of electricity demand and associated CO2 emissions. www.iea.org. Report Retrieved 2019-09-21.

[6]Global Energy and CO_2 Status Report 2018, IEA Report.

[7]Rhodium Group table shows the net present value of an air-sourced heat pump versus a natural gas heater and an electric A/C in a new house. Costs are calculated using a 7 percent discount rate and current prices for electricity and natural gas as of summer 2019 and a 15-year life span for the heat pump. This is also presented in Ch8 of Bill Gate's 2021 Climate book.

[8]Energy optimization of a Sulfur–Iodine thermochemical nuclear hydrogen production cycle, June 2021 paper.

[9]First high-temp electrolyzer for efficient hydrogen production, May 2020 article.

[10]Transient Study on the HTR-PM with TINTE-vPower Coupling Code Package, 2019 paper.

[11]The Shandong Shidao Bay 200 MWe High-Temperature Gas-Cooled Reactor Pebble-Bed Module (HTR-PM) Demonstration Power Plant: An Engineering and Technological Innovation, 2016 paper. 210/500 = 42% efficiency.

[12]BP Statistical Review of World Energy, 2019 report states annual world energy consumption is 583 EJ/yr of heat energy, which is the same as 162,194TWh/yr of heat energy (1Wh = 3600 joules, 162e3 x 1e12 x 3600 / 1e18J/EJ). At 35% conversion, this corresponds to 56,600TWh/yr of electrical energy (204EJ = 583 x 35%, 56,600TWh = 5.66e16Wh = 204e18 / 3600). The London Array produces 2.5e12Wh/yr, and one would need 22,600 of these to produce 5.66e16Wh/yr (5.66e16 / 2.5e12). Hoover Dam produces 4.2e12Wh/yr, and one would need 13,500 of these to produce 5.66e16Wh/yr (5.66e16 / 4.2e12). A 1GWe nuclear power plant produces 8.06TWh/yr of electrical power if operating 92% of the time (1GWe x 92% x 24 x 365 / 1e3); and this corresponds to 0.0691EJ/yr of heat energy at 42% heat-to-electricity conversion efficiency ((3600 x 8.06e12 / 42%) / 1e18). One would need 8,400 of these to produce 583EJ/yr of heat energy (583 / 0.0691).

[13]Metal And Concrete Inputs for Several Nuclear Power Plants, 2005 report.

[14]Nuclear Share of Electricity Generation in 2019, IAEA Report. The world supplied 2,657TWh of electricity from nuclear power in 2019. One would need to increase this 21-fold to satisfy world's energy consumption of 56,600TWh (56,600 / 2,657)