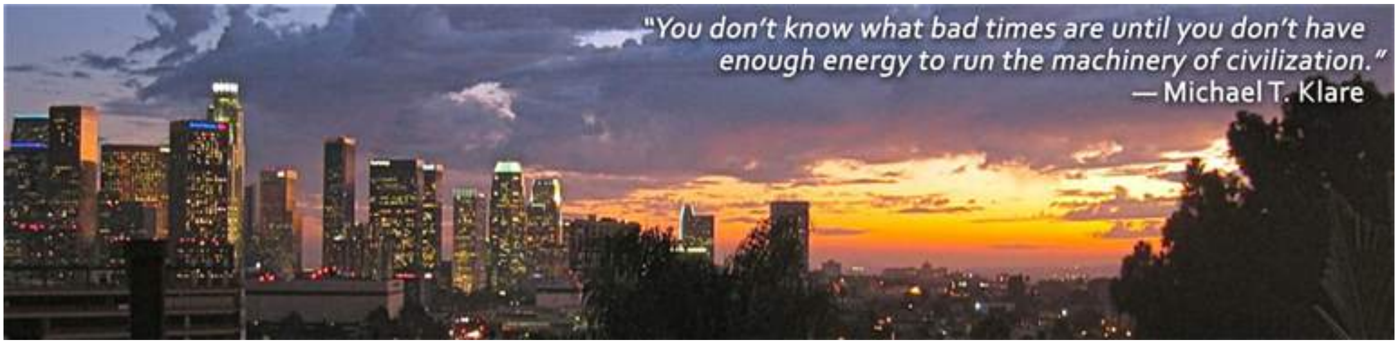


ROADMAP TO NOWHERE

The Myth of Powering the Nation
With Renewable Energy

by

Mike Conley and Tim Maloney
December 2017

A commentary on the 2015 landmark paper:

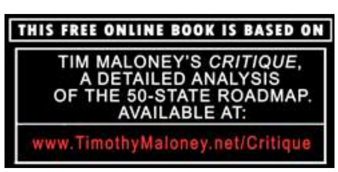
100% Clean and Renewable Wind, Water, and Sunlight (WWS)
All-sector Energy Roadmaps for the 50 United States

by Mark Jacobson, Mark Delucchi, et al

(We read it so you don't have to.)

Renewables have captured the public's imagination,
but can they actually be scaled up
to power the entire nation?

This book will challenge everything
you thought you knew
about renewable energy . . .



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Chapter One

A word before we begin

This book is not an argument against renwable energy.

It's an argument against a particular idea that many people believe about renewable energy, which doesn't seem to square with the facts:

> *The idea that renewables could actually power the entire nation – electricity, heating, transportation, industry, shipping, the works – and do it so well that we won't need power plants that run on actual fuel.*

Since our preferred source of clean energy is nuclear fuel, we framed our rebuttal by comparing an all-renewables grid with an all-nuclear grid.

Both, of course, are hypothetical scenarios, since neither grid will ever exist in its pure form. In the real world, and in the very real future, nuclear will be the best option for some scenarios, and renewables for others.

So just to be clear: we don't have a beef with renewables. Other than the claim that they can be scaled up to power the entire national grid.

You can't get there from here

Extraordinary claims require extraordinary evidence.

In our view, the claim that the United States, much less the entire world, can be adequately powered by 100% renewable energy is extraordinary, indeed.

The claim that we can have an all-renewables grid with no backup from fueled power plants, and practically no energy storage, is even more extraordinary.

To confirm or dispel our doubts, we ran the numbers on the industry's most highly regarded proposal, the Solutions Project's 50-State Roadmap.[1]

Short answer: It's not a solution. Long answer follows.

The Solutions Project is an environmental group with a bold vision to power the world with 100% renewable energy, through an aggressive buildout of WWS systems (wind, water, and sunlight) and a simultaneous phase-out of fossil and nuclear power.

The public face of the project is professor Mark Z. Jacobson, PhD, a civil engineer helming Stanford's Atmosphere and Energy Program.

The project's website[2] presents 50 detailed "roadmaps" to complete the U.S. portion of their global vision by 2050, with a custom blend of renewable systems for each state's geography and weather.

Their goal is laudable – a clean, green global civilization by mid-century – but getting there is the problem.

The 50-State Roadmap has become the go-to bible for WWS advocates in any discussion of U.S. energy policy.

Their goal is laudable – a clean, green global civilization by mid-century. Getting there is the problem. And replacing carbon-free nuclear power with carbon-backed renewables is not the solution.

This book shows you why.

The Roadmap

The 132-page plan details the equipment required (solar panels, wind turbines, etc.) for each state's participation in the national strategy. The feasibility, resource availability, and practicality of the nationwide scheme are simply assumed.

Mass energy storage plays a big role in most large-scale WWS strategies. Various scenarios range from powering the entire grid for 4 hours, up to an entire day.

In contrast, the tiny amount of storage in the Roadmap would only provide the equivalent of around 1.5 hours of nationwide power consumption.

The basic strategy of a wind or solar farm is the same as any actual farm: Make hay while the sun shines, use what you need, then store the rest for later or sell it.

The Roadmap takes a different approach:

- If we build enough wind and solar farms in enough places, they should all be able to back each other up – when it's cloudy in one place, it'll be windy in another.
- With a nationwide network of interconnected wind and solar farms, we won't have to rely on mass quantities of energy storage, or backup from fueled power plants.
- Just in case, we can place a small amount of energy in storage, to be used for smoothing out the occasional unexpected peak loads.
- Our fueled power plants (coal, gas, and nuclear) will become obsolete, so we'll shut them down as the buildout proceeds.

At least, that's the plan.

While enthusiasm for the Roadmap is strong, we wonder if advocates have actually read the fine print, because the more you pencil it out the sketchier it seems.

After reviewing the entire proposal, it's our conclusion that the Roadmap is deeply flawed. We'll show you exactly how and why.

This is more than an academic argument. The long-term energy plans of towns, cities and states are being actively shaped around this popular proposal, and underwritten (for now) with substantial state and federal incentives.

So we all need to know if the proposal is sound. Particularly since the Roadmap has become a national meme, as if it were a well-proven, highly workable, ultimately affordable, and entirely do-able national project. Even though it's not.

As nuclear power fans, we felt the best way to understand a 100% renewables grid was to compare and contrast it with a 100%-nuclear grid.

Before the renewables fans who are reading this become too annoyed, we should clarify something right here and now:

We all want the same thing.

We all want enough carbon-free energy to power the planet, reduce pollution, reverse ocean acidification and mitigate Global Warming. We're on the same team.

Because we are, we feel obligated to explain to our fellow environmentalists in particular, and our fellow human beings in general, why it is highly unlikely that the Roadmap will take us where we need to go, especially in the time we have to act.

As appealing as it may seem at first blush, the Roadmap is, unfortunately, an expensive, complex, inefficient, and ultimately unworkable idea. If not in principle, then certainly in practice.

Don't take our word for it. Twenty-one top climate experts, led by Dr. Christopher Clack, formerly with CIRES (Cooperative Institute for Research in Environmental Sciences) at the University of Colorado, have reached the same conclusion, in an eye-opening analysis we call the Clack Evaluation.[3]

Their paper has focused even greater attention on the Roadmap, which will hopefully promote a productive dialogue. We'll explore their key finding in Chapter Ten.

It is their view – and ours – that the Roadmap will get us nowhere fast.

Buckle up

There are some major potholes in the Roadmap, and we'll be driving over the biggest ones we found. First off, the sheer scale of the project verges on fantasy:

- A half million giant 5-MW wind turbines on acreage equal to New York state, Pennsylvania, Vermont and New Hampshire, and in open sea regions equal to West Virginia
- Billions of solar panels on land equivalent to Maryland and Rhode Island
- Concentrated Solar Power (CSP) on land equivalent to Connecticut
- Rooftop solar on 75 million homes and nearly 3 million businesses

And all of it covering 131,200 square miles (that's *miles*, mind you, not acres), not counting the roofs and the offshore region. The number would be even larger if we accepted the National Renewable Energy Laboratory's land estimates for wind and solar at face value.

In 2009, NREL examined 172 modern wind farms across the nation, and in 2013 they compiled land-use data for 66 large PV solar farms. According to their numbers, U.S. onshore wind will need 4X the land the Roadmap calls for,[4] and 2X the land that the Roadmap estimates for solar.[5]

We should note that the Roadmap plans on siting 70% of its onshore wind on the wide-open spaces of the Great Plains (we're just using east coast states for easy visual comparisons.) So to be more than fair, we based our calculations[6] on placing that 70% on the most ideal acreage possible.

We'll explain our other gimmes as we move along. However, we did take issue with the Roadmap's solar land estimate. We'll explain why when we get there.

But even with all the gimmes, the numbers *still* don't add up.

The Roadmap claims that with enough wind and solar, in a wide enough variety of weather zones, a self-supporting, fuel-free, 100% WWS grid could actually power the nation on a dependable basis. And that it can all be built in 35 years.

We disagree on both counts, and more. So do the aforementioned experts, whose criticisms and pro-nuclear views have been rejected by Dr. Jacobson.

The key to understanding our approach (and theirs) is that we aren't anti-renewables, we're pro-math. And a 100% renewables grid is an idea that just doesn't scale up.

The best way to show how and why that's true is to compare it to a technology that – if you had to choose just one technology – actually *can* be scaled up: an all-nuclear grid.

Heavy equipment

Wind and solar gear can last from 10–40 years: about 10 years for offshore wind turbines, 25 years for onshore turbines, and up to 40 years for solar panels.

A 40-year solar refurbishment schedule would mean the recycling and replacement of 1.23 million square meters of worn-out panels, every single day, rain or shine – forever*.*

This means that nearly 500,000 giant wind turbines, both onshore and off-, will need a major overhaul before the Roadmap's 35-year buildout is even complete.

It also means that 5 years after completion, we'll have to start recycling and replacing the solar panels – all 18 billion square meters' worth.[7] That's billion with a B.

A 40-year solar refurbishment schedule would mean the recycling and replacement of 1.23 million square meters of worn-out panels, every single day, rain or shine – *forever.*[8]

That's close to China's total daily volume of PV panel production. And the only thing all of that mining, fabricating, installing and recycling would do is sustain the solar portion of the 2050 national grid, not expand it.

Sustaining our fleet of wind turbines won't be any easier. With 342,000 onshore and 156,000 offshore, we'll have to initiate a major overhaul on more than 80 giant wind turbines every single day. That's in addition to swapping out all those solar panels.

In contrast, an all-nuclear grid composed of, say, 6,000 Small Modular Reactors (SMRs), each one generating 250 megawatts for a 7-year runtime, would require less than three reactor swap-outs per day (about 70 a month).

Think "nuclear battery": Factory-built SMRs will be fully sealed, self-contained units, about the size of a city bus and transportable by highway or rail. The fresh reactor is installed and the spent reactor is taken to a central facility for service and refueling.

Maintaining our 2050 national grid could be as simple as swapping out 2.3 Small Modular Reactors per day. Or, we could swap out 1.23 million square meters of panel instead, and initiate a major overhaul on 80 giant wind turbines. Every single day.

So quite aside from the Roadmap's technical shortcomings (several of which we'll explore), sobering questions arise:

- Can we actually pull it off?
- Do we have the money, land, labor, factories and resources?
- Equally important: Do we have the political will?

Even if the answer is yes to all three, and even if the Roadmap could actually work, and even if we could actually build it in 35 years:

- Is it really the best choice we have?

When you come to a fork in the road, take it." – Yogi Berra

At this critical juncture in history, our energy choices may well determine the survival of civilization as we know it. And even if we do get our act together in time, we'll still be in for a rough ride.

While going carbon-free is something our energy sector absolutely must accomplish, the Roadmap is such a big project that the entire nation will have to get on board or it won't get done. So consensus is king. Which raises an interesting point:

Advocates of the Roadmap tend to be politically left of center, which is fine. But they couldn't even get Bernie nominated, much less Hillary elected.

So do these same advocates really think they can convince the American public – 47% of whom voted for a person who claims that global warming is a Chinese hoax – to sign off on a long-term monetary commitment that's nearly the size of a second military budget? For thirty-five years?

Or just as daunting: Do they really think they can convince Capitol Hill to re-purpose the bulk of our military budget to fight a war on climate change?

We don't think so, either.

An inconvenient yardstick

In principle, enough renewables in enough places should provide the energy we need. But in practice, would the Roadmap actually work? Or would it be a lateral move from pipelines to pipe dreams?

The main issues that concern us are:

- The intermittent nature of WWS systems
- The risk of relying on a fuel-free grid with no substantial backup
- The lack of adequate mass energy storage
- The World War Two-scale mobilization lasting 35 years
- The wildly optimistic buildout schedule
- The mind-boggling amount of land
- The eye-popping price tag

Cleaning up our energy act is not an option – there is no Planet B. But can we do it as the Roadmap suggests, without tanking the economy in the process? And if that's a real concern (and it is) the follow-up question is:

Will we actually cut the check?

It's a key question, because the bare-bones Roadmap, without sufficient backup or storage, will cost at least **$15.2 Trillion**. That's Trillion with a T.[9] (By the way, professor Jacobson agrees with this price.[10])

> *... the bare-bones Roadmap, without sufficient backup or storage, will cost at least **$15.2 Trillion**. That's Trillion with a T.*

A modest 4 hours of pumped hydro all-grid energy storage – the cheapest mass energy storage that currently exists – would raise the price to $16.5 Trillion.

> NERD NOTE: Storage would never be used to energize the entire grid at any one moment. The hypothetical scenario is simply used as a basis of comparison between various energy storage options.

Discretionary spending is the money that Congress decides how to spend, by passing various appropriations bills. It currently totals about $1.1 Trillion a year.

The cost of the bare-bones Roadmap is equal to 14 years of all U.S. discretionary spending. Spread out over 35 years, it would constitute about 40% of all discretionary spending.

However, if the cost of an all-nuclear grid were spread out over the same 35 years, the yearly outlay could be as little as what we currently spend on SNAP, the federal food stamp program. That's if the upcoming Generation-IV reactors come online as predicted, in the next few decades.

Or we could start today with a national buildout of existing Generation-III technology, and have an all-nuclear grid in probably 20 years, at less than half the cost of the bare-bones Roadmap, on a tiny sliver of the land.

Speaking of land: If you think the Roadmap is pricey, wait till you see the land requirements (which we left out of our cost calculations), not to mention all the fresh water we'll need for the pumped hydro.

In fact, with just 4 hours of pumped-hydro energy storage (the cheapest energy storage by far), the Roadmap's price breaks down to over $471 Billion a year for 35 years.[11]

That's over 80% of our military budget, and over 60% of our social safety net. Year in and year out, for more than three decades.

That's what the Roadmap is proposing. On over 130,000 square miles of land, and more than 75 million rooftops.

And make no mistake, we have to decide and we have to act – not now, not right now, but right freaking now, because the clock is ticking. In fact, according to the Roadmap, we're already 2 years behind schedule.

So if we're really serious about becoming a 100% WWS nation, it comes down to four options:

- Gut the military budget
- Gut the social safety net
- Print the money
- Some combination of the above

For 35 years. And anyone who tells you different is either blowing smoke or seriously misinformed.

The fifth option: Go nuclear!

We'll be comparing the Roadmap's hypothetical all-renewables grid with an equally hypothetical all-nuclear grid, with each grid totaling 1,515 GWs of new-build power plants (we'll explain the 1,515 as we go along.) An all-nuclear grid would cost somewhere between $3 Trillion and $9 Trillion, depending on the reactors used.[12]

An all-nuclear grid would cost somewhere between $3 and $9 Trillion, depending on the reactors used.

In an ideal world, Generation-IV reactors would come online in the next decade. In the real world, expect to build at least the first half of an all-nuclear grid with existing Gen-III reactor technology.

A $3 Trillion, a 1,515-GW grid breaks down to about $2 an installed watt.[13] That's the speculated price per watt of our favorite Gen-IV reactor design, the MSR (Molten Salt Reactor).

From what we can determine, the Roadmap won't work unless it has substantial fueled backup, or massive amounts of cheap energy storage – something that would require a technical revolution.

Just to be clear:

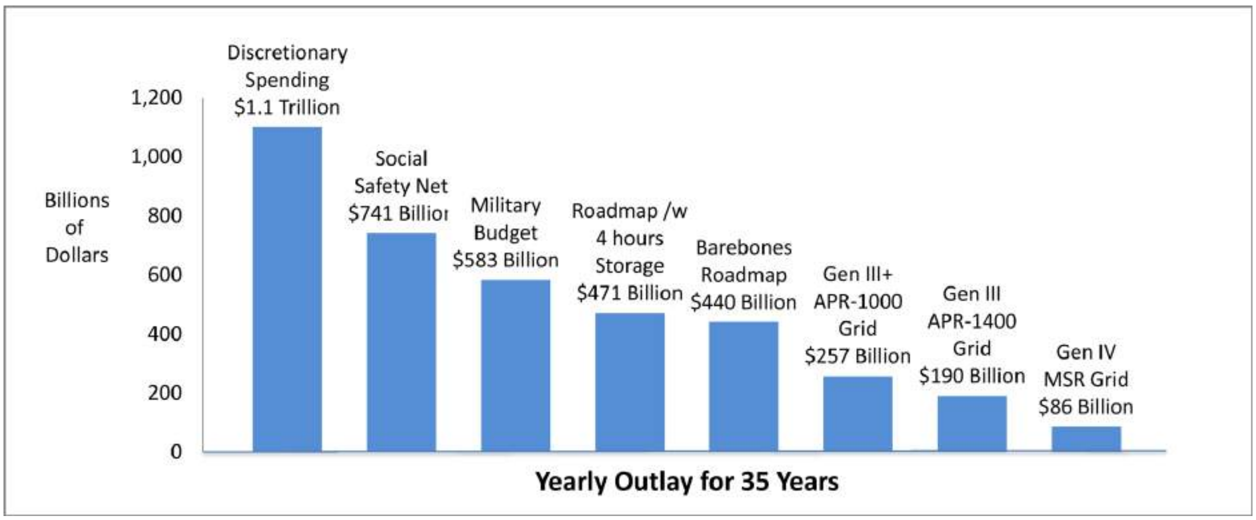
- Backup is extra generating capacity on standby that can come to the rescue on short notice.
- Storage holds a supply of energy that's already been generated, or a supply of fuel from which energy can be generated on demand.

The key feature of backup and storage is that either or both can be quickly brought online, and their power dispatched to wherever it's needed, to support the inevitable lapses and shortfalls of renewable energy production.

MSR is a proven and tested technology that was shelved during the Cold War, because a Molten Salt Reactor is just about useless for making weapons material. The technology is actively being revived and updated for commercial production – China has 700 engineers and scientists working on MSR science, borrowing heavily from our original research at Oak Ridge National Labs in the 1960s and '70s.

Advances have been made in mass energy storage, but the sheer scale of what would be needed to stabilize the grid just isn't there. And as we will show, the Roadmap simply will not work without it, unless we factor in substantial and sustained backup from traditional power plants, such as natural gas.

So we felt justified bringing our favorite reactor concept into the mix as the best-of-all-worlds scenario for our hypothetical all-nuclear grid. But as you will see, our rebuttal to the Roadmap stands entirely on its own with already existing Gen-III technology.



The $6.7 Trillion price tag would be for a national fleet of Generation-III APRs (Advanced Pressurized Reactors.) South Korea's KEPCO is currently building four APR-1400s (1,400 megawatts) in the United Arab Emirates for about $4.40 an average watt. The first one was finished on time and on budget.[14]

In their home country, KEPCO (Korea Electric Power Company) claims an installed cost of $2.50 a watt, which is significantly less than a new coal plant's $3–$3.50 a watt.[15]

The Roadmap's "Supplemental Information" section[16] implies that the price of an all-nuclear grid would be more expensive, at $9 Trillion. But that's using the new Generation III+ AP (Advanced Passive) reactors.[17] (Like any high-tech industry, nuclear has its own alphabet soup.)

But KEPCO has shown that old school Gen-III designs can already be built for much less.[18] This is reflected in our $6.7 Trillion price tag for a nationwide Gen-III grid.

Make nuclear cheap again

KEPCO's standardized design allows for a rapid national buildout. In fact, they completed the first of their four reactors in the UAE before the plant's new personnel could finish their training.

In sharp contrast, every power reactor that's ever been built in the United States has been a custom design, incorporating the latest innovations. Sometimes these changes were introduced in mid-project, causing expensive challenges and delays.

The upside of this approach is that our nuclear industry's product and performance has constantly improved. The downside is that our reactor fleet is an expensive collection of hand-built hypercars.

To power the entire country, we'll need a fleet of cheap, safe, and reliable mass-produced sedans. Reactor technology has matured to where this is entirely feasible.

As the name implies, the new Generation III+ AP-1000 (Advanced Passive) reactor takes an evolutionary step forward from Gen-III, with passive safety features that automatically keep the reactor from overheating after a shutdown.

The AP will be assembled on site using factory-built modules. Prices will drop and schedules will accelerate as more units are built and the learning curve kicks in.[19]

But the first of anything you build, even if it's a standardized design, is a one-of-a-kind custom project. So stuff happens – supply chain problems put our first AP-1000 project into an over-schedule / over-budget tailspin.[20] Despite the issues at Vogtle, Georgia, the South Koreans in the UAE have shown that standardization saves time and money.

While the Generation III+ AP is the most advanced reactor we can actually build right now, Gen-IV reactors are the future of nuclear power. We're especially impressed with the Molten Salt Reactor (MSR), one of eight Gen-IV designs now being developed.

A peer-reviewed energy innovation study shows that five of the eight Gen-IV designs will be as cheap or cheaper than a Gen-III+ AP reactor, two of them substantially so.[21]

To get the information they needed for an accurate analysis, the authors of the study kept corporate identities anonymous. It lists the eight companies and their reactors, but it doesn't reveal which set of results goes with which company or which reactor.

But we figured out that at least one of the two lowest-cost Gen-IV reactors is an MSR. We're guessing that both of them are, but here's what we actually know:

The two cheapest reactors in the study have a construction cost of right around $1.20 per watt. And according to ThorCon, an American MSR company, their manufacturing (construction) cost for molten salt reactors will be $1.20 a watt.[22]

So there you go.

The overall capital cost for both reactors at the low end of the price spread is projected to be $2 an installed watt ($1.20 of which is construction cost.) We'll be using $2 a watt as our benchmark price for Molten Salt Reactors – the safest reactor, with the lowest capital and operating costs.

Even so, the strength of our argument isn't built on the MSR, or any other Gen-IV reactor. There is an equally strong case to be made for an all-nuclear grid of old school Gen-IIIs, a mature and well-proven technology.

Indeed, if we had followed the wishes of president John F. Kennedy, we would have had a nationwide Gen-III nuclear grid in place by the year 2000.[23]

The ability to achieve a national clean-energy grid already exists with Gen-III reactors. Gen-IV would simply improve the performance, efficiency, and safety of the best carbon-free energy technology we already have.

"Come now, let us reason together . . . " – Isaiah 1:18

A fair comparison of renewables and nuclear clearly shows that, if a choice has to be made between one hypothetical grid over the other, nuclear would be a far superior technology for powering the nation.

And since fuel (nuclear or otherwise) is, in essence, a cheap, stable, and compact form of energy storage, the pivotal issue of mass storage – the holy grail of renewable energy – is rendered moot.

As we see it, a national all-renewables strategy is only being considered because the public has developed an overblown fear of radiation, largely generated by disinformation, sensational media, and the occasional outright lie.[24]

Fukushima is a perfect example: No one died from the meltdowns, and no one is expected to in the years ahead. Nevertheless, nuclear fear is what drove the news cycle, not the 20,000 lives that were actually lost in the earthquake and tsunami.

For the last several decades, this deep-seated radiophobia has been directly responsible for an overabundance of caution towards nuclear power.

In the wake of Three Mile Island, Chernobyl, 9/11 and Fukushima, the nuclear industry's excessive defense-in-depth approach to reactor construction has nearly priced their product out of the market.

In fact, no other energy source is regulated anywhere *near* the standards that have been set for nuclear power, in spite of its superior safety and reliability.

As George Monbiot famously wrote in the days after Fukushima, "While nuclear causes calamities when it goes wrong, coal causes calamities when it goes right, and coal goes right a lot more often than nuclear goes wrong."

Indeed, living near a nuclear power plant subjects you to less radioactivity than eating one banana per week.[25]

Fear-based protocols, in response to the political pressures of a misinformed populace, have guaranteed spiraling prices and failed projects, which only encourage anti-nuclear arguments.

On a level playing field, with appropriate safeguards and standardized designs, and with science and engineering as the final arbiters, reactors can come in on time and on budget, while being built to the highest international standards. Nuclear is indeed competitive with fossil fuel, if it's allowed to compete under the same rules.

The true nature of things

Advocates of renewable energy may be uncomfortable reading this book, but sometimes facts are uncomfortable things. We know we're challenging some deeply held beliefs, and rest assured we have a few of our own.

Mother Nature doesn't give a damn about anyone's favorite technology.

To put things in perspective, here's something we said elsewhere that should be kept in mind by anyone proposing a national energy solution, including ourselves:

" . . . please understand that when it gets right down to it, Mother Nature doesn't give a damn about anyone's favorite technology.

"She doesn't care if some people think that nuclear power is awesome, or if others think it's the work of the devil. And she doesn't care if some people think that global warming is settled science, or if others think that it's an anti-capitalist con game concocted by liberal academics angling for grant money.

"She frankly doesn't care what anyone thinks, hopes, or believes. All she cares about is objective reality, quantified by math and explored by science, both disciplines guided by a diligent respect for the true nature of things. . . ."

From our 2016 paper: "Wind and Solar's Achilles' Heel –
The Meltdown at Porter Ranch"[26]

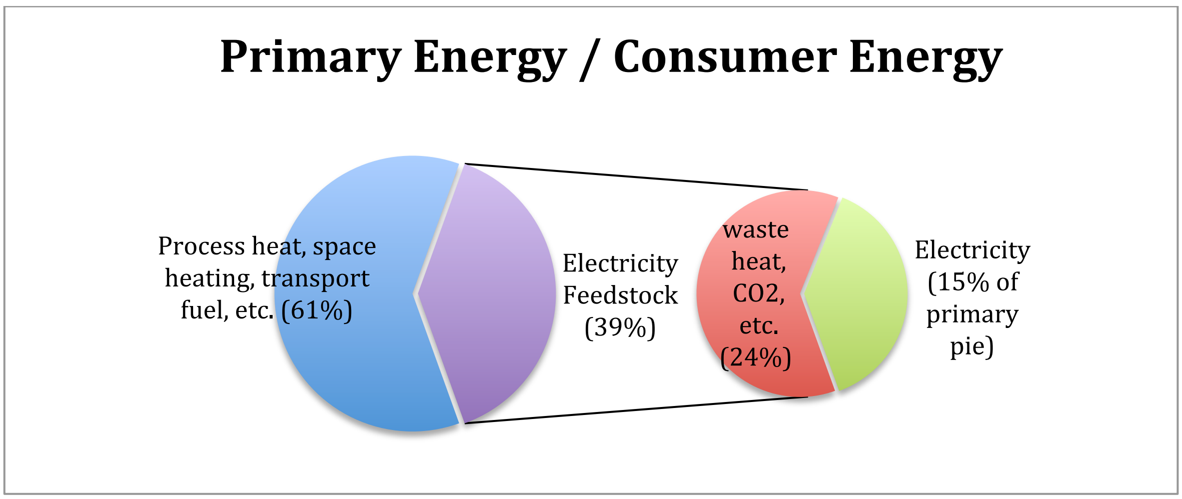
CHAPTER TWO

The big idea

Burning stuff is a grossly inefficient way to generate power.

Because this is so, the Roadmap proposes that we do much more than just clean up our electric power production, which now requires 39% of the primary energy we consume, mostly derived from burning fossil fuel.[1]

Primary energy refers to *all* the energy we use, not just electricity, and regardless of how it's produced. So even though electricity is only 15% of our *consumer* energy pie,[2] it takes 39% of our *primary* energy pie (mostly derived from fossil fuel) to generate that 15%. The rest is lost as waste heat.



The Roadmap aims to reduce this inefficiency by producing all of our primary energy in the form of WWS-generated electricity. Which, in principle, is a great idea (the electricity part, not the WWS part.)

So the Roadmap is about a lot more than just keeping the lights on. It also covers transportation, cooking, heating and cooling – anything that involves energy, including process heat (the high temperatures used to make steel, concrete, etc.)

With enough clean electricity, we can free ourselves from fossil fuel without immediately junking every vehicle we have and switching to EVs (electric vehicles):

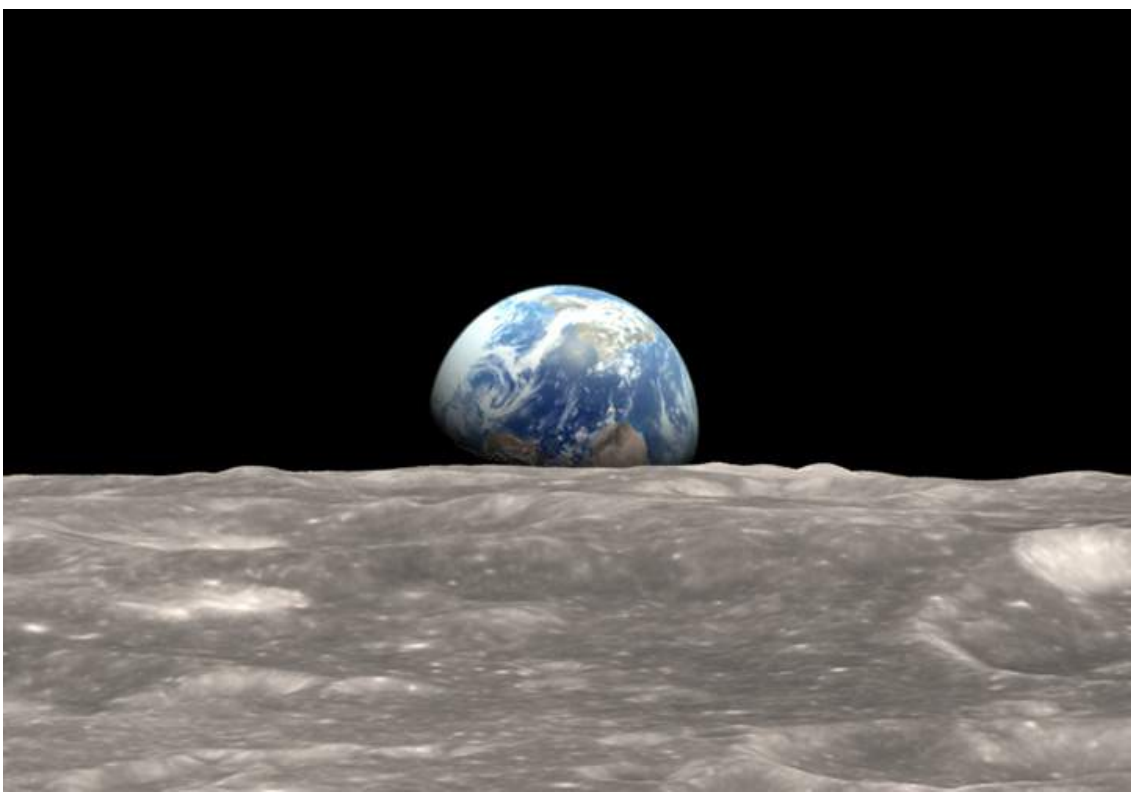
Electricity, water and CO_2 (captured from the atmosphere or smokestacks) can be used to synthesize carbon-neutral liquid fuels (synfuel), to get the full life cycle out of our existing fossil-fueled vehicles and their supporting infrastructure.

Today's carbon fuel infrastructure is more than just the drillers, refiners, and end-consumers. It also includes everything in between: Virtually all transport and shipping by air and sea, and the millions of fossil vehicles on the road, as well as the fuel storage, distribution, repair, parts and maintenance needed to service them. The trick is to exploit these assets as cleanly as we can.

If we had an abundance of cheap, clean energy, we could make synfuel for our fast-response gas turbines, the hot-rod power plants that respond to unforeseen peak loads on the grid. We may have to, if we're still using them to balance the grid when we finally run out of methane (natural gas.)

At our current rate of consumption, we'll run out of methane in less than a century. If we replace all of our coal power with methane power, it could happen in 50 years. Even quicker if we start exporting the stuff. And just as soon as we build a fleet of LNG tankers (liquefied natural gas), we will.

All hands on deck!



"There are no passengers on Spaceship Earth. We are all crew." [3]
– Marshall McLuhan

The task of our generation is to make an informed decision on the best way to get to a sustainable, zero-carbon world, and to act on that decision "with vigor!" as President John F. Kennedy used to say.

Unfortunately, making that decision entails wading through some rather science-y stuff. It also means shedding a lot of preconceptions, prejudice, and tribalism.

The "renewables vs. nuclear" divide has often been split along political lines, with lefties / greens all in for renewables while demonizing nuclear power.

That's gradually changing. In fact, many of the nuclear advocates and scientists we personally know are either centrists or left of center, and some are even social democrats. Very few of them could be considered right-wingers or free marketeers.

But regardless of your politics or ideology, there are two things to keep in mind:

- Science is (or should be) above politics.
- Belief is a barrier to understanding.

Science is (or should be) above politics.

Belief is a barrier to understanding.

We've tried to make our analysis as fair and painless as possible, because something this big and this important shouldn't be left to the Powers That Be. It's up to all of us to make an informed decision.

For that to happen, the basic knowledge of what it takes to cleanly and adequately power the nation, and the world, should be conveyed in the most non-partisan and user-friendly way possible.

Some quick notes

The Roadmap includes a few gigawatts of geothermal, tidal and wave power, but over 95% of its primary energy would come from:

- Onshore wind
- Offshore wind
- Utility-scale PV (photovoltaic) solar
- Residential rooftop PV solar
- Commercial / government rooftop PV solar
- Concentrated solar power (CSP) with overnight thermal storage

In a separate critique,[4] we detailed every aspect of the Roadmap – what it would take to fabricate, install, and maintain each type of WWS system for a 60-year period, which is today's conservative estimate for the lifespan of a nuclear reactor.

When reactors were first being licensed, 40 years was considered reasonable. But now, 40 years later, inspections have shown that reactor components can easily last 60 years, and with some standard refurbishment, 80 years and perhaps 100. But to be more than fair, we'll use 60 years as our benchmark.[5]

As we mentioned, most energy experts agree that a national renewables grid would need a tremendous amount of energy storage, fueled backup, or both.

The exact amount of each is in dispute, but adequate storage alone would likely require much more than the token 4 hrs mentioned above, and cost several trillion.

The Roadmap is unusual among WWS schemes in that it largely ignores mass storage, and completely ignores backup.

The $15.2 Trillion price for the bare-bones Roadmap also leaves out the new transmission corridors required to connect its 50,000-plus wind and solar farms to the national grid.

... deploying the right reactors would require virtually no new transmission corridors, since many of the reactors would simply replace our existing fossil plants.

This alone would kick up the price by an additional $0.5 Trillion or more, based on a rough average of 10 miles of new connector lines per farm to link the facility to the main trunk line (the actual grid), at the lowball price of $1 Million a mile.[6]

Another thing left out of the Roadmap is a nationwide HVDC (high voltage / direct current) transmission network. It's something that most renewables advocates agree would be a key element in a national WWS grid.

The intermittent spurts of energy produced by wind and solar can cause serious frequency disturbances on the existing ac (alternating current) grid. And the greater wind and solar's penetration becomes, the greater those disturbances will be.

The counter-measures will likely be expensive, and they may not even work – we won't really know until we try them.

A direct-current grid would have none of these issues, and would greatly reduce line loss as well – typically 5% of ac energy is lost over long-distance transmission.

An HVDC grid, in parallel with our ac grid, is actually quite feasible by running underground cables along existing state and federal rights-of-way, such as highways and railroads.[7]

A national HVDC grid could probably be built for $100–$200 Billion, which is nothing to sneeze at. But in the $15 Trillion grand scheme of things, it's chump change.

In contrast, deploying the right reactors would require virtually no new transmission corridors, since many of the reactors would simply replace our existing fossil plants.

And since most Generation IV reactors won't need water cooling, they could be sited virtually anywhere. That would eliminate many of our existing corridors, returning the land to the communities they run through.

Last point: Our prices are based on the latest industry and government figures, without tax breaks, rebates, or any other thumbs on the scale. Our focus is on what the Roadmap would cost the nation, not the subsidized homeowner.

With all that out of the way, here are the bottom lines up front:

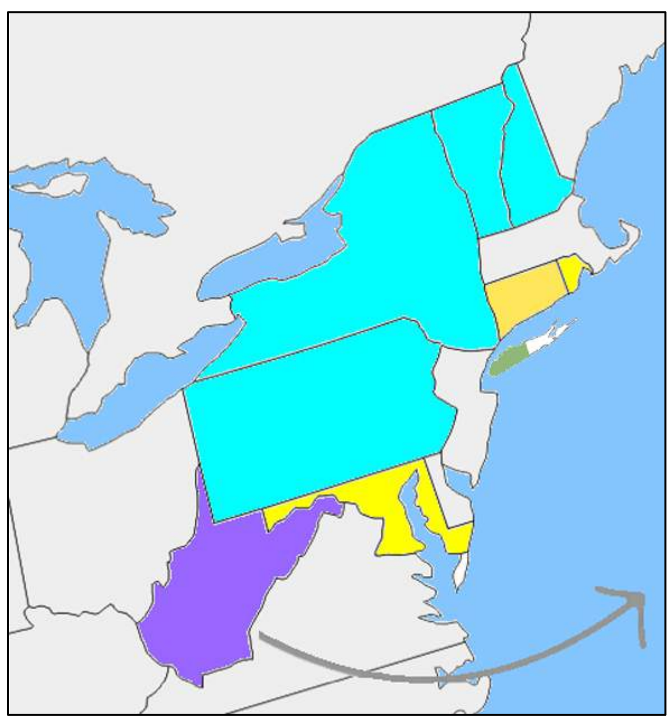
Generating all U.S. primary energy by 2050 with renewables

- Land for photovoltaic solar equal to Maryland and Rhode Island
- Land for concentrated solar power equal to Connecticut
- Land for onshore wind larger than New York state, Pennsylvania, Vermont and New Hampshire
- An offshore wind region larger than West Virginia
- Our existing hydroelectric dams (upgraded to 3% of grid)
- Over 140 GWs of hydrogen production for heavy vehicles (problematic)
- 4.38% overbuild of all WWS systems (inadequate)
- Our existing pumped hydro storage (inadequate)

Bare-bones cost: **$15.2 Trillion**

With 4 hrs of additional pumped hydro: **$16.5 Trillion**

(Onshore wind in blue, offshore wind in purple, solar in yellow.)

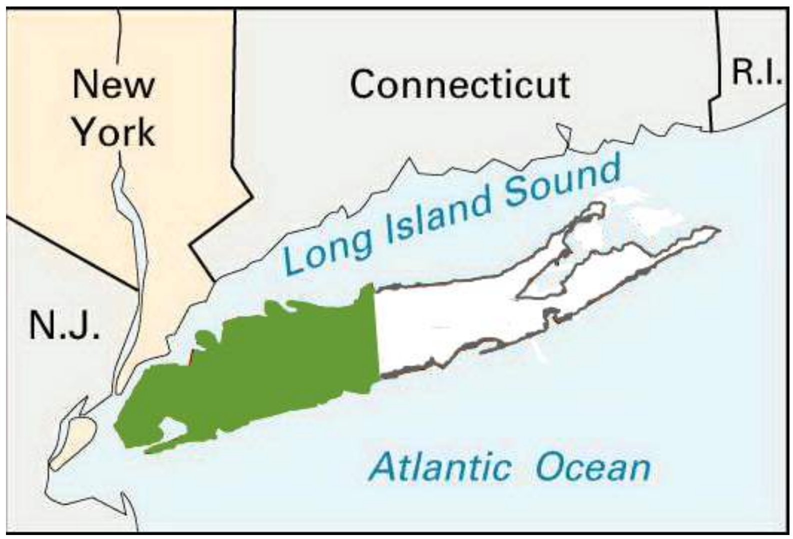


Generating all U.S. primary energy by 2050 with nuclear power

- Land equal to half of Long Island (including full security perimeters)
- $9 Trillion with Generation III+ AP (Advanced Passive) Reactors
- $6.7 Trillion with Generation III APR (Advanced Pressurized) Reactors based on South Korea's price for U.A.E.
- $3 Trillion with Generation IV Molten Salt Reactors
- Existing hydroelectric dams (upgraded to 3% of grid)
- Existing pumped hydro (to match the Roadmap, but superfluous)
- 18 months (minimum) of all-grid storage, in the form of reactor fuel

Total cost (depending on the reactors used): **$3 Trillion – $9 Trillion**

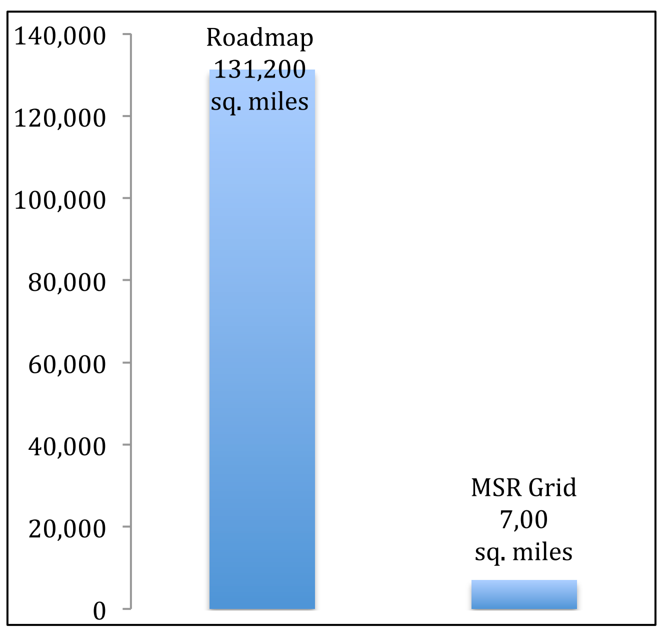
(Land for all-nuclear grid in green.)



Whichever reactors we use, a nuclear grid would be roughly 20–45% of the cost of the Roadmap, on less than 1% of the land, with 18 months of built-in storage – the fuel in each reactor.

If we go with small, factory-built reactors, a national nuclear buildout could be accomplished in 10 years.[8] At the low end of the reactor price spread, the MSR, or Molten Salt Reactor, is our preferred technology.

It's also the safest.



The reactor for people who don't like reactors

The liquid-fuel, meltdown-proof, air-cooled MSR was co-invented by Alvin Weinberg, who previously developed the solid fuel, water-cooled, high-pressure Light Water Reactor (LWR).

Weinberg's LWR began operating in the 1950s, and when it powered the submarine *USS Nautilus*, both the sub and the reactor became global sensations. From then on, nearly every reactor on earth has been a variation of the basic LWR concept.

But Weinberg had an even better idea.

By the 1960s, he was telling Washington that the new MSR would be a much more efficient, and far safer, reactor. Except by that time, an entire global industry had been built around the LWR and nobody wanted to hear it.

It was the Cold War, and we wanted a reactor that could easily produce plutonium for bombs and electricity for power. The LWR can do both, but not the MSR. While it's the best reactor for making power, it's not a reactor for making bomb material.

So despite 17,000 hours of flawless testing at Oak Ridge National Lab, the MSR was shelved in the 1970s and Weinberg was forced to retire.

> *Nuclear waste is wasted fuel. But it's only waste if you don't use it.*

He spent the rest of his life advocating for safe civilian power produced by the small, unpressurized, fuel-efficient MSR.

Not only did it feature minimal waste, but it could also be configured to run on the "spent" fuel from his LWR design. (Nuclear waste is wasted fuel. But it's only waste if you don't use it.) And best of all, MSRs can't have a meltdown – no matter what.

> NERD NOTE: Liquid-fuel MSRs are physically incapable of melting down, as in "the laws of physics." The reason is simple:
>
> *How do you melt a liquid?*
>
> If the unpressurized molten salt leaks out, it cools and solidifies like lava on the beach, with its radioactive particles held in a chemical lockdown.
>
> And though the material would be highly radioactive, *it wouldn't go anywhere*. Visualize a spill from a concrete truck.

> The mess would be measured in square meters, not square kilometers. We'd have a contaminated reactor building, not a contaminated countryside.
>
> A Molten Salt Reactor solves the biggest drawback of nuclear power – contamination. It also solves the second biggest drawback – waste.
>
> MSRs can utilize the residual energy in the "spent" fuel of other reactors. That unexploited energy is what makes nuclear "waste" such a long-lived problem.
>
> Exploiting this energy reduces the storage timespan of the residual material to about 300 years.

After gathering dust for 45 years, MSR technology is finally being revived in the U.S., China, Canada, the EU, and elsewhere. Expect the first MSRs to be in commercial operation by the mid-2020s.

Specially designed Gen IV reactors will actually be able to breed (produce) more nuclear fuel than they use. Others will be able to run on spent fuel, and still others will use natural (unenriched) uranium as fuel. An abundance of cheap, clean and reliable carbon-free energy will be readily available.

Thorium, which you may have heard of, is a popular candidate for fueling MSR breeder reactors. A common and slightly radioactive mineral found all over the world, thorium transmutes to (turns into) uranium fuel inside a reactor's core.[9]

A promising first-generation MSR design by ThorCon proposes a fuel load of half uranium and half thorium.[10] A second-generation dual-fluid MSR design called a LFTR ("lifter" – Liquid Fluoride Thorium Reactor) will use an initial kick-start load of uranium, but from then on all refuels would be 100% thorium.[11]

Thorium requires no enrichment, and is easily isolated with simple, low-tech chemistry. There's plenty of the stuff, generously distributed all over the world – there is no Middle East of thorium. It's even in Miami's beach sand at 12 ppm (parts per million): A pickup truck of sand has enough thorium to power the city for a day.

Ironically, thorium is also found in the waste stream of the wind turbine industry. In the process of mining one tonne of neodymium for the generator of a single 5-MW wind turbine, the mine throws out one-half to three-quarters of a tonne of thorium.

That's enough fuel to power a U.S. city of 500,000 for one year. A 5-MW wind turbine might power a village of perhaps 1,000. If it's a windy day.

These advantages and more make nuclear a true renewable energy, with enough carbon-free fuel to power the entire planet, at our current rate of energy consumption, for literally thousands of years. Or until we figure out fusion; whichever comes first.

Rube Goldberg and the Fukushima Syndrome

If you're convinced that nuclear power is off the table in any discussion of clean energy, here's a thought experiment that may give you another perspective:

- Pretend that nuclear power has one of the lowest death rates per terawatt-hour of any form of mass energy production in history, including hydroelectric, solar and wind.[12]
- Further pretend that nuclear energy doesn't emit greenhouse gases, that the volume of waste is small and easily managed, and can be recycled for more rounds of fuel.
- Also pretend that no one died from the meltdowns at Three Mile Island and Fukushima, and that no one is likely to in the years ahead.
- Now pretend that there's enough fuel to power the planet for centuries.
- Finally, pretend that no one will ever build a reactor like Chernobyl again.

Holding those ideas in mind, how attractive does wind and solar seem to you now?

Particularly since everything in the foregoing list is true.

... the interest in large-scale renewable energy is the direct result of a misinformed aversion to nuclear power.

In our view, the interest in large-scale renewable energy is the direct result of a misinformed aversion to nuclear power. In the absence of that hyper-inflated fear, renewables would never be seriously considered as a viable solution for powering the grid.

Instead of refining and improving the simple, clean, safe and compact technology of splitting atoms to release their stored energy, the Roadmap offers a complex, inefficient, sprawling and expensive Rube Goldberg scheme to power the nation.

Rube Goldberg was a wildly popular humorist of the early 20th Century, whose syndicated newspaper cartoons depicted intricate, silly, and laughably inefficient contraptions to perform the tasks of modern life. You've probably seen his work before. In this context, it's worth another look:[13]

From our perspective, WWS schemes to power the nation amount to a ginormous self-operating napkin.

We're happy to explain why, but the Roadmap is so complex and interwoven that we'll have to unpack it and show you all the pieces to get our point across.

The roadmap ahead

The following chapters provide what we hope to be an easy and entertaining overview, not only of the Roadmap's major components, but equally important, the broader context in which the Roadmap should be considered.

As our analysis unfolds, you'll see that we give the Roadmap the best possible advantage at every turn. To cite one example: its solar estimates are based on the 134-watt PV panel available at the time (2013–2015), but we used the newest (2017) high-performance 160-watt panel, which is now favored by Dr. Jacobson. [14]

The only thing in the Roadmap we didn't use was its land estimate for solar farms. We think it's an error, and we'll explain how we came to that conclusion.

Since energy is the lifeblood of our modern world, the consequences of pursuing an unworkable strategy could be downright catastrophic. So this is important stuff.

As Michael Klare once said, "You don't know what bad times are until you don't have enough energy to run the machinery of civilization.[15]

> *"You don't know what bad times are until you don't have enough energy to run the machinery of civilization."*
> *– Michael Klare*

On that cheery note, let's proceed.

And if it all becomes annoyingly intricate at times, don't blame us. The Roadmap calls for 1,515 GWs of new-build renewables[16] on a whopping 131,200 square miles[17] and millions of rooftops. But our "roadmap" for powering the nation is simple:

- Install 1,515 gigawatts of small, factory-built Molten Salt Reactors precisely where the power is needed.
- Beef up our transmission corridors as required.
- Dismantle the unnecessary corridors.
- Break out the beers.

Since small, cheap, air-cooled and meltdown-proof MSRs could be installed anywhere, even in the harshest desert, our roadmap is entirely feasible. And most of our long-distance transmission corridors would become a thing of the past.

One standardized MSR per day could roll off the assembly line like a Learjet, be transported by ship, truck or rail, and installed wherever it's needed.[18]

We figure ten years tops for the entire buildout, with no need to import any raw material or equipment, and for much less money than we spent invading the Middle East to make the world safe for oil.

But first, let's explore the Roadmap, because the advantages of an all-nuclear grid can best be appreciated by a thorough examination of the alternative.

We tried to make our analysis as pleasant as possible, but at the end of the day there's no real shortcut for getting a handle on their far-ranging proposal.

We read the whole thing so you don't have to, but unless you absorb the salient points it'll always be Dr. Jacobson's word against ours.

We don't want that, he certainly doesn't, and neither should you.

CHAPTER THREE

To be perfectly clear

We do think that small-scale renewables can be a clean and effective solution for off-grid and undeveloped regions. But in developed areas, the grid is expected to perform as reliably as our water, sewer, fire and police "utilities": they serve us 99.9+% of the year, night and day, rain or shine.

When you try to scale WWS technologies to run a factory, hospital or town, much less a city, state or country, the notion becomes more hopelessly impractical the more you think it through.

For starters, here's a big reason why:

Energy Density

Energy must be collected and directed to do work.

Mother Nature has already gathered and stored her energy in substances we call fuel – stable, portable stuff from which we can extract the energy we need, when and where we need it.

WWS advocates don't seem to fully appreciate these two essential points:

- Fuel is energy storage
- Renewables are fuel-free systems

That's worth repeating:

- Fuel *is* storage
- Renewables are *fuel-free* systems

> *Fuel is storage.*
>
> *Renewables are fuel-free systems.*

Burn those points into your brain, and renewables will be a lot easier to understand.

Thus far, civilization has advanced by exploiting ever more energy-dense fuels: Wood, coal, petroleum, gas and nuclear.

Fossil fuel takes about 100 million years to form, as carbon-rich organic material is drawn into the earth's crust by the motion of tectonic plates, where it's heated under pressure to form coal, petroleum and natural gas.

While fossil fuels are some of the most energy-dense substances we use, nuclear fuel is a million times denser.

Its heavy atoms were formed in the supernova shockwaves of dying stars, where small atoms were fused into larger ones, becoming trace elements in the stardust that coalesced into planets.

These oversized atoms can be thought of as tiny fusion batteries, retaining some of the ancient energy that formed them billions of years ago. Nuclear fission is the process of splitting these unstable atoms to exploit their stored energy.

In fact, over half the heat in the earth's core comes from the radioactive decay of thorium, uranium, and potassium-40, along with some naturally occurring fission. That heat, plus friction, and the residual heat from earth's formation, keeps the outer core's rotating mass molten, or melted.[1]

The constant circulation of this liquid metal creates our magnetic shield. This shield is what prevents the solar wind from destroying our atmosphere. That's what happened to Mars eons ago, when its core cooled and solidified.

So whatever misgivings you may have about nuclear material, realize that life on planet Earth wouldn't exist without it.

Energy, power and storage

Before we get too deep in the weeds, we should clarify some terms:

- *Energy* is the ability to do work that can change the physical world.
- *Work* is utilizing energy to exert *force,* resulting in motion.
- *Power* is the rate at which energy can be used to cause physical change.

Pour some gasoline on the sidewalk and light the fumes. [Disclaimer: Don't try this at home, or anywhere else for that matter.]

The ball of flame that sets your hair on fire also releases the gasoline's stored (potential) chemical *energy.*

The combustive energy dissipates as an undirected *force*, jostling the air around the flame. We experience this jostling (kinetic energy) as heat, or first-degree burns.

Burn that same gasoline (plus oxygen, of course) in a car's engine, and what was potential heat energy now produces explosive force that pushes down on the pistons. Their motion is successfully applied force doing *work*.

Doing it over and over again for an extended period of time is how the engine generates the steady *power* to move the car. The potential energy stored in the gasoline has now become the kinetic energy of the moving vehicle.

Some of the potential energy in the fuel is wasted as exhaust heat and mechanical friction. This applies to any power source.

The period of time that the engine can propel the car depends upon two things: How much energy (gasoline) is stored in the tank, divided by how much of that energy is used per unit of time. Energy ÷ time = power.

Energy, power, and storage are the three interlocking parameters that any power plant must contend with, whether they use actual fuel or not.

... wind, water, and sunlight are regarded as less-dense forms of fuel.

Except they're not really fuels at all.

Reinventing the waterwheel

The recent interest in renewables appears to be a reversal of the historical trend toward more energy density, in the sense that wind, water, and sunlight are regarded as less-dense forms of fuel.

Except they're not really fuels at all.

Renewables are fuel-free systems that exploit ambient natural phenomena by gathering and concentrating diffuse and variable bits of energy from the environment.

But the light and motion they exploit are not stable, storable, or transportable. That light and motion must either be utilized on the spot to make energy, or converted into something that can be stored for later use, typically as the electricity in a battery or the water in a reservoir.

That conversion will always entail a loss of energy. And while this stored energy can be loosely thought of as fuel, its wind, water and sunlight precursors cannot.

An example is the potential energy of an elevated reservoir. The water isn't actually fuel; the reservoir is simply storing the energy that was used to pump the water uphill.

Implementing the Roadmap would easily dwarf our industrial mobilization for World War Two, and last nearly nine times as long: 35 years instead of 4 years.

Most of that energy is re-generated when the water flows back downhill through the same reversible turbines, with about 20% of the energy lost in the round trip.[2]

The scope of the problem

Implementing the Roadmap would easily dwarf our industrial mobilization for World War Two, and last nearly nine times as long: 35 years instead of 4 years.

Even so, we'll probably still need to import a massive amount of wind and solar equipment – if it's available. And that's a big IF.

Because if the rest of the world embarks on their own Roadmap, which the Solutions Project recommends, no major exporter (read: China) will be able to keep up with global demand, and may stop exporting altogether to build their own national WWS grid.

Long story short: Everybody will be on their own.

Nevertheless, Dr. Jacobson and his colleagues have just released a Global Roadmap for the 139 countries that generate 99% of the world's carbon energy.[3] As you read through our examination of his 50-state U.S. Roadmap, it will be easy to see that their global roadmap is doomed to be just as impractical.

To stop and reverse anthropogenic (human-caused) global warming and ocean acidification, the entire world must replace the fossil fuel it uses with a reliable and "renewable" (read: inexhaustible) source of carbon-free power.

We strongly suggest nuclear energy, the next step in fuel's historical evolution of big punch / tiny package. Renewables are all about tiny punch / big package.

... nuclear energy [is] the next step in fuel's historical evolution of big punch / tiny package. Renewables are all about tiny punch / big package.

The notion of running the country on fuel-free renewables may sound like an elegant solution to pollution and climate change, but WWS advocates should keep three fundamentals firmly in mind:

- The gargantuan amount of on-demand energy our nation needs
- The scale of the project they're proposing to produce that energy
- The environmental impacts and resource consumption that would result

The U.S. has just 4.4% of the world's population, but we currently consume 18% of the world's energy – about 4X average global consumption.[4]

An all-renewables U.S. electric grid would be the largest construction project in history, by far. And the most expensive – like we said, nearly equal to an entire second military budget for 35 years, and that's without adequate backup or storage.

Another way of looking at it: The bare-bones Roadmap would cost three times what the U.S. spent, in constant dollars, on World War Two and the Iraq War *combined.*

Wind and solar systems capture diffuse and ambient energy to generate power. Which means that vast tracts of land and boatloads of equipment will be needed to gather and concentrate the energy into a useable form.

... the bare-bones Roadmap would cost three times what the U.S. spent, in constant dollars, on World War Two and the Iraq War combined.

And if it's not used on the spot, or if there's not enough to satisfy demand, backup and storage will be needed to ensure an adequate supply, and that will require even more land, equipment and resources.

And even then, the entire Rube Goldberg scheme will only generate a reliable flow of power if the weather cooperates.

Not as easy as it sounds

Wind, water and solar are not, and never can be, independent, consistent, and dependable sources of power.

While their "fuel" is free and renewable, gathering and exploiting the energy that results is expensive. And, their intermittent nature greatly complicates the effort and cost.

Wind, water and sunlight ebb and flow, come and go. Harnessing them as a source of power requires converting enough of their motion and light to energize the grid.

Hoover Dam is mighty impressive, and its massive turbo-generators are a sight to behold. But what's often overlooked are the tens of thousands of square miles needed to gather the rain that eventually flows into Lake Mead, its artificial reservoir.

Also overlooked are the downstream effects: Northwest Mexico was once a lush delta of verdant farmland, before the U.S. dammed the Colorado. Now it's a desert wasteland.

The same principle applies to solar and wind. Vast tracts of land and a stupendous inventory of equipment placed on that land would be needed to collect and concentrate the fitful energy of wind and sunlight.

That energy can either be exploited in real time, or stored for later use – *if* we can afford an adequate means of storage (more on this later.)

Like any form of renewable energy, hydro power is also at Mother Nature's mercy, though the effects play out in slow motion. As the drought increases, Lake Mead drops inch by inch, gradually decreasing the output and reliability of Hoover Dam.

Currently, the power production of U.S. dams is down about 20% since the mid-1990s. They now generate just 6% of domestic electricity.[5]

Our increased awareness of the environmental and ecological impact of dams and reservoirs, including the methane released from their algae blooms and drowned flora, is making dams increasingly unpopular.

In some cases, the greenhouse effect of methane from a dam's reservoir, or a pumped hydro system's reservoir, can actually be worse than if the same electricity was produced by fossil fuel.

Water scarcity is another issue. Indeed, as our drought unfolds, hydro may eventually become as unreliable – and impractical – as wind and solar.

CHAPTER FOUR

An exercise in utility

A utility-scale power plant can be relied upon to deliver power as needed, day in and day out. The standard of the industry is 99.9% uptime. That's what the word utility means, and the same concept holds true for water, sanitation, fire, police, etc.

... [power plants] should be decoupled from the environment as much as possible.

There is no renewable energy system that comes anywhere close to this standard, without adequate backup or storage.

Renewable advocates like to tell you that the wind is always blowing somewhere, which is true as far as it goes.

But it doesn't go very far, because until we have enough wind farms in Somewhere, Kansas and Somewhere, Wyoming and Somewhere Else offshore, we won't have a self-supporting renewables grid.

Ideally, utility-scale power plants should be independent sources of rock-solid, reliable power, free from the vagaries of weather, climate, season, or time of day, and under the operator's control at all times. In a word, they should be decoupled from the environment as much as possible.[1]

Since renewables are weather dependent, they can't be separated from the environment. Like the weather they rely upon, renewables are *interdependent, variable, and intermittent,* unless they're having a real good day.

Just like crops, wind and solar systems depend upon the whims of Mother Nature. And just like modern agriculture, the variables can be reduced but rarely eliminated.

As climate change evolves, the weather will be ever more difficult to predict. Which is a problem, because wind and solar farms are more like actual green leafy plants than any traditional power plant we have.

Just like crops, wind and solar systems depend upon the whims of Mother Nature. And just like modern agriculture, the variables can be reduced but rarely eliminated.

Irrigation, crop rotation, fertilizer and pest control enable the mass production and consumption of crops. In the same way, backup and storage enable the mass production and consumption of renewable energy.

But at this point in time, and for the foreseeable future, practical energy storage technology for a nationwide 100% renewables grid simply does not exist. And the technology that does exist can't be scaled up without bankrupting the nation.

Adequate backup technology exists, but most of it is in the exact form of energy production that renewables advocates seek to eliminate: Fast-start or always-on fossil-fueled power plants.

The Roadmap envisions a nationwide network of *inter*-dependent plants (as distinct from *in*-dependent), each one oversized to compensate for its low capacity factor (see below), so the plants that are having a good day might back up their less fortunate fellows.

However, without adequate storage or backup, WWS farms can't be thought of as actual utility power plants, unless they're members of a widespread, interconnected and self-supporting nationwide renewables fleet.

Which is a dubious proposition, because that same interconnected, interdependent nationwide fleet has to actually be able to back itself up. Which has never been tested at scale.

Nevertheless, that's the strategy behind the Roadmap: Build enough farms in a variety of weather zones, and they should, in theory, be able to back each other up.

This helps explain why the Roadmap calls for WWS in all 50 states. The other big reason may be politics:

Taking a cue from the defense industry, a WWS facility in every state would guarantee access and influence with local legislators. Or at least a seat at the table.

Training wheels

As we said, the industry standard for utility plants is 99.9% uptime. Renewables are fundamentally incapable of meeting this standard, due to the intermittent nature of wind, water, and sunlight. So they can't be considered true utilities without massive (and massively expensive) amounts of backup and storage.

In lieu of adequate storage, the Roadmap's wind and solar will need external backup from coal, gas, nuclear, or pumped hydro during most of the 35-year buildout, to serve as training wheels until there are enough renewables in enough regions to back each other up.

Baseload plants are IN-dependent.

Renewables plants are INTER-dependent.

This highlights one of the major advantages of a fueled ("always-on") baseload grid over a fuel-free WWS grid:

- Baseload plants are *IN*-dependent.
- Renewables plants are *INTER*-dependent.

Coal, gas, hydro and nuclear plants can operate on their own, independent of any other power plant. But WWS plants need training wheels, until there are enough of them to get their collective act together and (hopefully) roll with the big boys.

For these reasons and more, comparing always-on baseload plants with intermittent renewables can be an apples-and-oranges situation.

We can't actually replace a reactor with a wind or solar farm unless that farm has sufficient backup or storage. Augmentation options for a renewables plant include:

- Pumped hydro, grid-scale batteries (which don't exist), or other mass energy storage systems
- Traditional baseload plants (coal, nuclear, gas, hydro, etc.)
- Fast-start "peaker" plants (gas, diesel, propane, etc.)
- Other wind or solar farms that are having a better day

Oversize it!

We use the term *oversize* to refer to building a wind or solar farm with a much larger *nameplate rating* than the average power it's expected to produce.

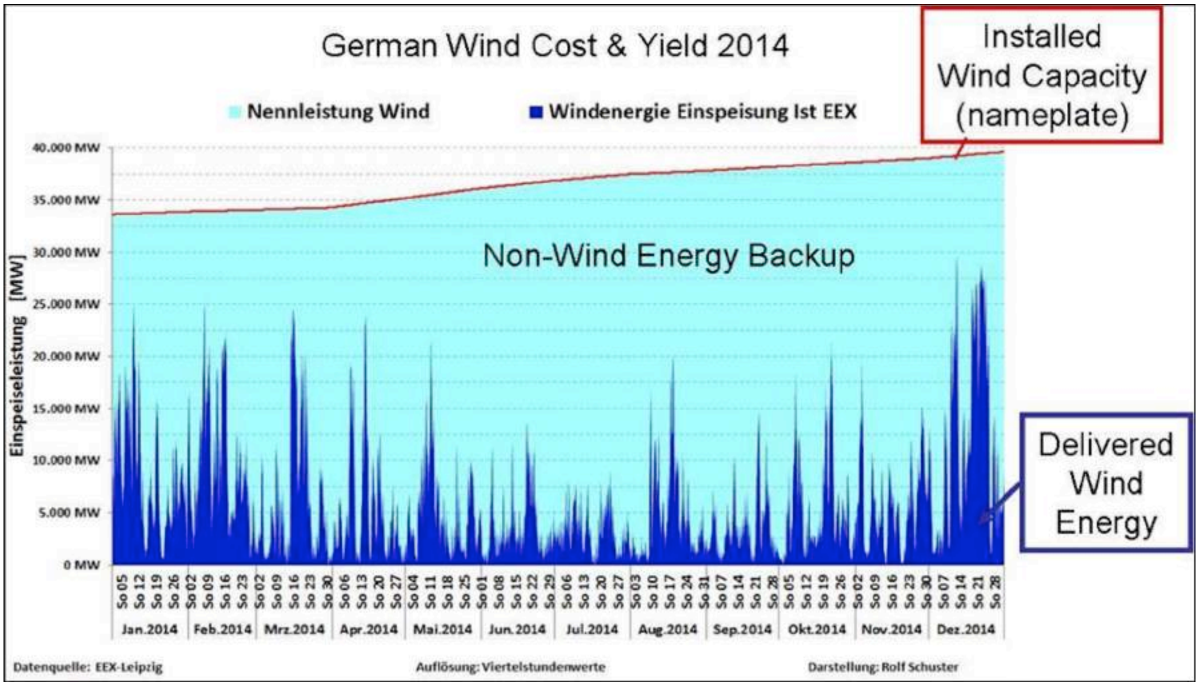
Nameplate rating refers to the peak, or highest, output of a power generator, traditionally stamped on its nameplate and often called its *peak capacity*. Which, when it comes to wind and solar, might only happen for a few minutes a day.

(Sorry to throw all these terms at you at once, but hang in there . . .)

Because the weather varies and because the sun tends to set every day, a renewables farm will, on average, generate just 1/5th to 1/3rd of its peak capacity, meaning the most power the farm can produce under ideal (sunny or windy) conditions.

Over the course of a year, a U.S. solar or wind farm's *capacity factor* (average output) is only 20–35% of its peak.[2]

To give you a good visual between the installed capacity and the actual performance of most renewable systems, here's the installed capacity of German wind in 2014 (light blue), and the power that was actually delivered by those wind machines in that same year (dark blue):



For a 1-GW solar farm with a 20% capacity factor to actually deliver a yearly average of one gigawatt, you have to oversize the farm by 5 times.

That is, you have to build it as a 5-GW power plant, so it can deliver a yearly average of one gig with a 20% CF (capacity factor).

If that's not enough to make it perform as advertised – and it typically isn't, due to seasonal variations (more on this later) – you have to back it up with external power or energy storage. Or both. Or we shouldn't even be calling it a 1-GW power plant (more on this later, also too.)

Since non-fuel forms of energy storage (batteries, reservoirs, etc.) are expensive, the Roadmap's approach is to build wind and solar in a variety of weather zones instead.

> NERD NOTE: Capacity factor (CF) is the total amount of energy that is actually produced by a power plant over the course of a year, divided by the greatest amount of energy that it could possibly produce under ideal conditions in that same year.
>
> For a wind or solar farm, ideal conditions means that the equipment is clean and in perfect condition, and the wind is always blowing at the perfect speed or the sun is always overhead in a cloudless sky.

> Which of course is impossible. So the CF of any WWS power plant will always be a fraction much less than 1, and is usually expressed as a percent. For example, a CF of 0.20 is a CF of 20%.

Due to wind and solar's naturally low capacity factors, a typical solar farm should be oversized by about 5X, and a typical wind farm by 3X (2.5X for offshore wind.)

That way, the underproduction of one farm can be compensated by the overproduction of another farm – if the weather cooperates over yonder.

And in the absence of storage, the farm over yonder that's having a good day has to be able to send its excess energy somewhere else.

The only alternative is to unplug their solar panels, or feather their turbine blades so they don't catch the wind. Either of which is a sin, given the money, subsidies, and resources spent on building and maintaining the typical renewables farm.

Sorry to beat this to death, but most people don't think it through. They just blithely assume that the one-gigawatt farm sold to their community will routinely deliver an average of one gigawatt.

The problem is, they were sold a 1,000-horsepower monster truck that averages 200 horses over the course of a year.

Truthiness in advertising

Industry professionals and savvy WWS advocates are well aware of the fact that a 1,000-MW solar farm in a 20% average capacity region (which is just about everywhere on earth) is actually a 200-MW farm in need of some serious backup.

But they don't make this perfectly clear to the general public or legislators, or even to most dedicated environmentalists, who think their community has a shiny new 1,000-MW farm.

That may seem like a forgivable bit of sales puffery ("your mileage may vary"), but when an industry is promoting a radical new energy paradigm for the entire nation – indeed, for the entire planet – the failure to clear up such a common misconception amounts to a massive form of deceptive advertising.

One admirable thing about the Roadmap is that the wind and solar it's calling for is based on average, not peak, capacity. So when the Roadmap proposes a 1,591-GW national grid, realize that it isn't calling for a wind and solar capacity of 1,591 GWs.

It's actually proposing that we build 3–5 times that amount to deliver an average of 1,591 GWs, on the presumption that the farms will be able to back each other up in real-world conditions, year after year, with no storage to speak of.

Due to the yawning gap between average and peak capacities, the Roadmap won't result in a self-supporting, nationwide network of fuel-free power plants until the 35-year buildout is nearly complete.

... the Roadmap won't result in a self-supporting, nationwide network of fuel-free power plants until the 35-year buildout is nearly complete.

A substantial amount of wind and solar will have to be built, in a variety of weather zones, before true interdependence starts to emerge. Until then, the wind and solar farms that are up and running will need training wheels.

Since coal is *verboten,* and nuclear is the work of the devil, and since we can't build more rivers or call rain down from the sky, the only acceptable backup for the first half of the buildout, if not longer, is:

Natural Gas – the polite term for methane

> *"We need about 3,000 feet of altitude, we need flat land, we need 300 days of sunlight, and we need to be near a gas pipe. Because for all of these big utility-scale solar plants – whether it's wind or solar – everybody is looking at gas as the supplementary fuel. The plants that we're building, the wind plants and the solar plants, are gas plants."* [3]
>
> – Robert F. Kennedy, Jr.
> Environmental activist
>
> Member of the board of Bright Source
> Developers of the Ivanpah Solar-Thermal Station
> On the California / Nevada border

"The plants that we're building, the wind plants and the solar plants, are gas plants." – Robert F. Kennedy, Jr. Environmental activist

As luck would have it, Mr. Kennedy's Ivanpah plant has had to burn 62% more methane than originally forecast by the builders, due to the unpredictability of relying on Mother Nature for energy.

In fact, Ivanpah has been burning so much methane that they're facing the ironic prospect of paying a carbon tax.[4] Let that sink in for a moment:

A solar plant that's so dirty, it has to pay a penalty for polluting the environment.

Burning natural gas for energy produces half the CO_2 of coal, which is a good thing. But if it leaks before you burn it, it has 84X the GWP (global warming potential) of CO_2 for its first 20 years in the atmosphere.[5]

If it makes you feel any better, methane's GWP mellows out over a 100-year span to "only" 28X, as the molecule breaks down and combines with oxygen to form CO_2 and water vapor.

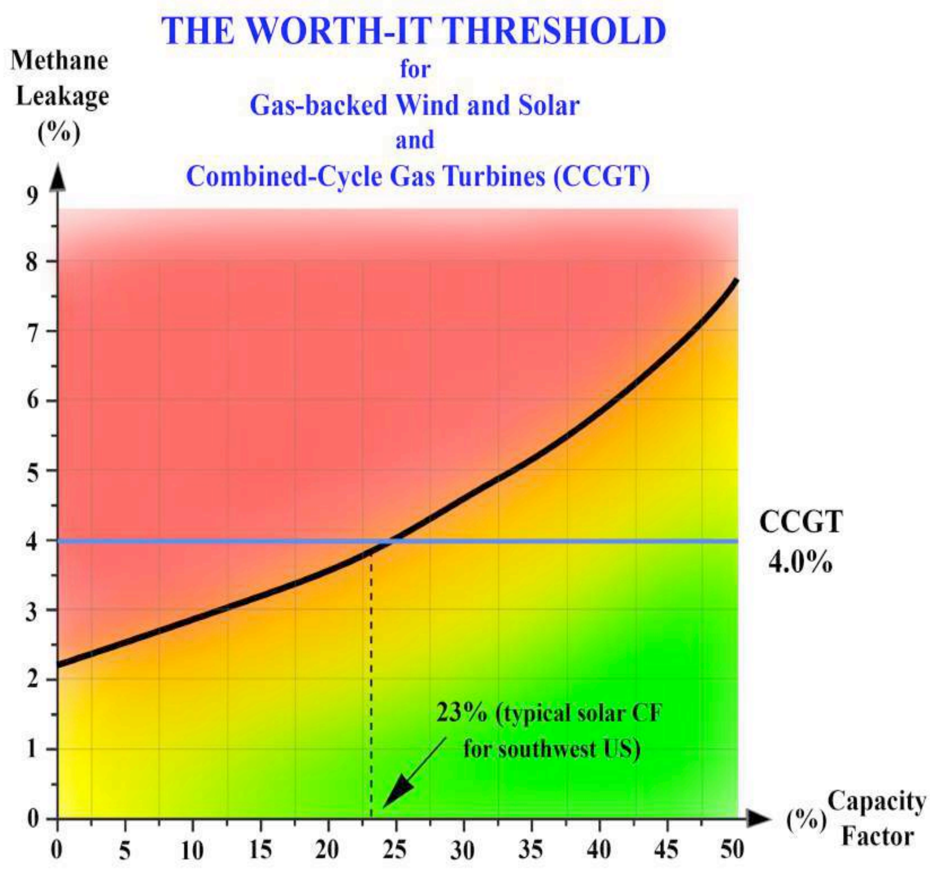
But since the next 20 years are the most critical in the fight against global warming, 84X is the number to focus on.

Like any gas, methane is an escape artist – remember the Porter Ranch leak? Using it as a bridge fuel to a clean, green future is a double-edged sword.

... a 4% leak makes any gas plant, or the average gas-backed wind or solar farm, as bad for the climate as a coal plant.

In fact, a 4% leak makes any gas plant, or the average gas-backed wind or solar farm, as bad for the climate as a coal plant. We call it the "Worth-It Threshold."

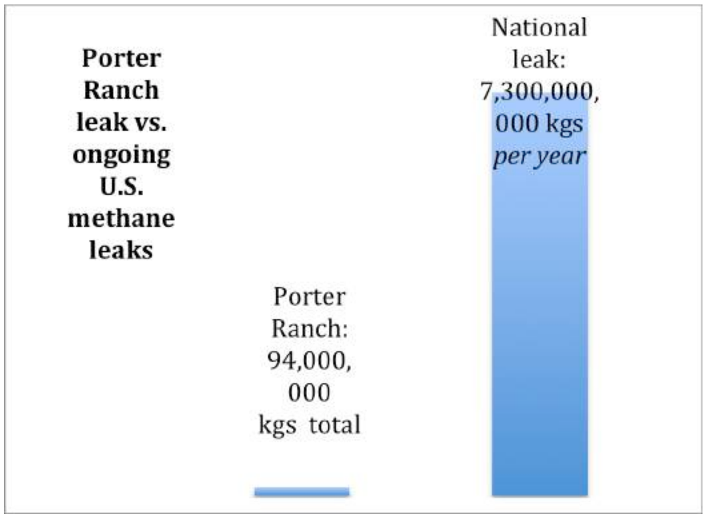
That low number may sound like a wild claim, but in our 2016 paper "Wind and Solar's Achilles' Heel – the Meltdown at Porter Ranch" we have clearly shown it to be true, with some surprisingly simple high-school chemistry and math.[6] (If anyone can disprove our formulas, please let us know.) Here's a graph from that paper:



Meanwhile, back at the ranch

To put Porter Ranch in perspective, its contribution to global warming was the equivalent of burning about 300 million gallons of gasoline,[7] essentially wiping out the climate benefits from an entire year of California's wind and solar.[8]

To further put it in perspective, the ongoing, business-as-usual national leak rate of the U.S. natural gas industry, according to the industry's own estimate, is equal to more than 75 unplugged, continuous, year-round Porter Ranch leaks.[9]



Even so, the gas industry claims a mere 1.6% national leak rate,[10] despite the fact that the EPA, using the latest in detection equipment, has found leaks up to 9%.[11]

But the industry's low number is alarming enough – see the above graph.

Since methane has such a powerful GWP, a 1.6% leak rate wipes out 40% of the climate benefits we hope to derive from gas-backed wind and solar: 1.6 is 40% of 4, and 4% is the Worth-It Threshold for gas-backed renewables.

As RFK Jr correctly points out, virtually all of our large wind and solar farms are backed by gas. What he doesn't mention is that with a 4% leak in the methane infrastructure, gas-backed renewables simply aren't worth the trouble.

In fact, you might as well be burning coal for all the good it'll do (global-warming-wise, not total-pollution-wise: Methane is a *lot* cleaner than coal.)

As more renewables come online, their intermittent energy is having a greater impact on grid stability. Whenever clouds pass overhead or the wind dies down, backup or storage has to kick in to take up the slack, and do so within seconds.

Although it's true that natural gas turbines can respond faster and easier than most reactors, there wouldn't be much need for their heroic interventions if the intermittent energy of WWS wasn't mandated to become a major part of our energy mix, and if it wasn't prioritized to be used first.

Right this way, your table's waiting

State governments should require that wind and solar come to the party with their own backup and storage. But WWS advocates and lobbyists have successfully pushed "priority dispatch" policies that give renewable energy precedence over any other form of production.

This leaves the twin problems of backup and storage for others to solve. In California, for example, any renewable power that's generated, no matter how fleeting, is given priority to be consumed first.

> *A "renewables first" policy is like designating the fast lane of a freeway for bicycles.*

This poses a major and growing problem for utility companies, since the grid was designed to import, synchronize, and dispatch the steady flows of high-quality energy generated by fueled plants and hydro.

A "renewables first" policy is like designating the fast lane of a freeway for bicycles.

Our existing Gen III reactors were designed to run flat-out for months at a time, day in and day out – the baseload behemoths of the grid. But with the increasing penetration of low-quality energy from renewables, more and more of our run-steady power plants are being called upon to act like fast-response backup systems.

Which poses a problem for these legacy plants: Ramping them up and down several times a day, on short notice, subjects them to stresses they were never designed to handle.

What gets lost (or dismissed) in the debate over carbon-free energy is that new reactors like the AP and the MSR are *all-load* plants, not just baseload plants.

Gen III+ and Gen IV reactors will be able to ramp up, or down, at power increments as fast as 5% per minute. That flexibility, plus some fast-response backups like hydroelectric dams, pumped hydro reservoirs, and gas turbines could power the grid.

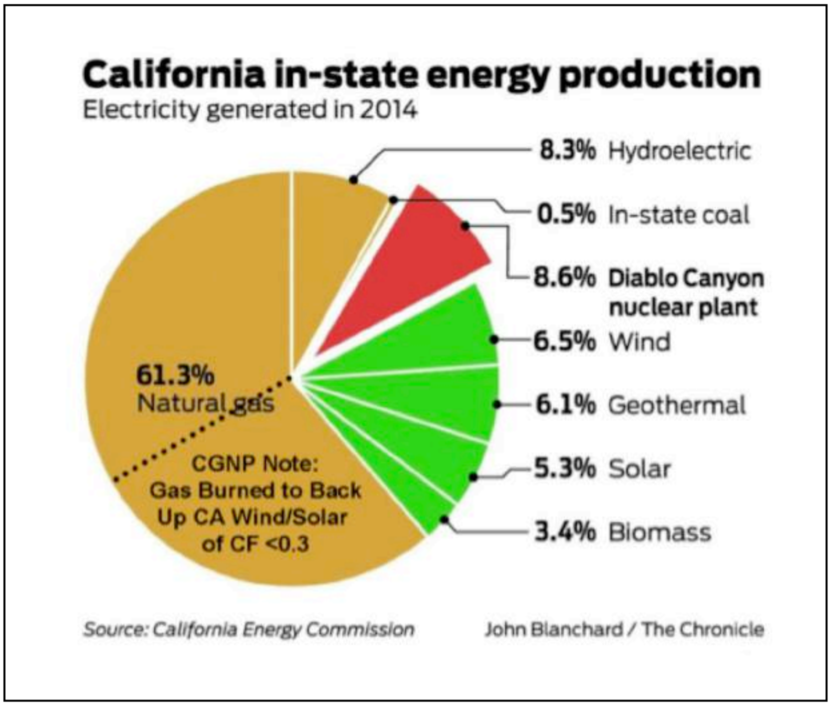
But our existing reactors aren't that flexible. So the "solution" (actually, the anti-nuclear excuse) is self-evident: Replace all reactors with natural gas plants.

This unfortunate decision obscures the larger point: If California had never embarked on a wind and solar buildout, a carbon-free fleet of new and existing reactors could anchor their entire grid, and power the state's pumped hydro for unexpected peak loads. Reactors could even power synfuel (synthetic fuel) factories to make carbon-neutral fuel for whatever backup gas plants they still need.

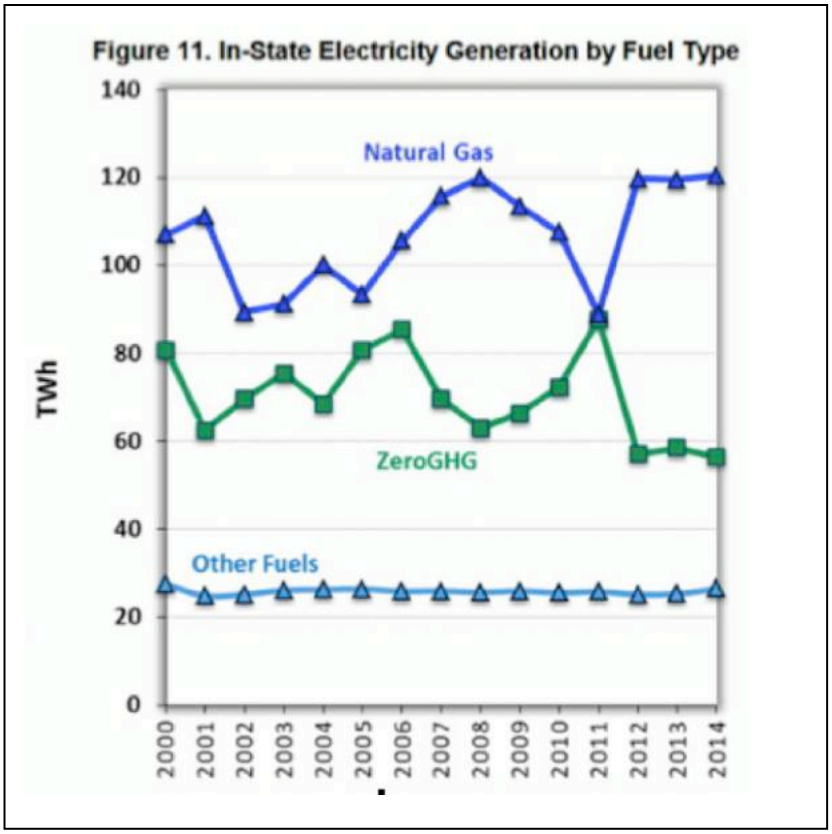
The truth is, California doesn't have to shut down their existing reactors to go green. What they really need to do is expand and modernize their nuclear fleet.

The state has created their own problem, and now they're "solving" it by getting rid of something that already works like a champ – the Diablo Canyon nuclear plant, which reliably generates 8.6% of California's electricity.

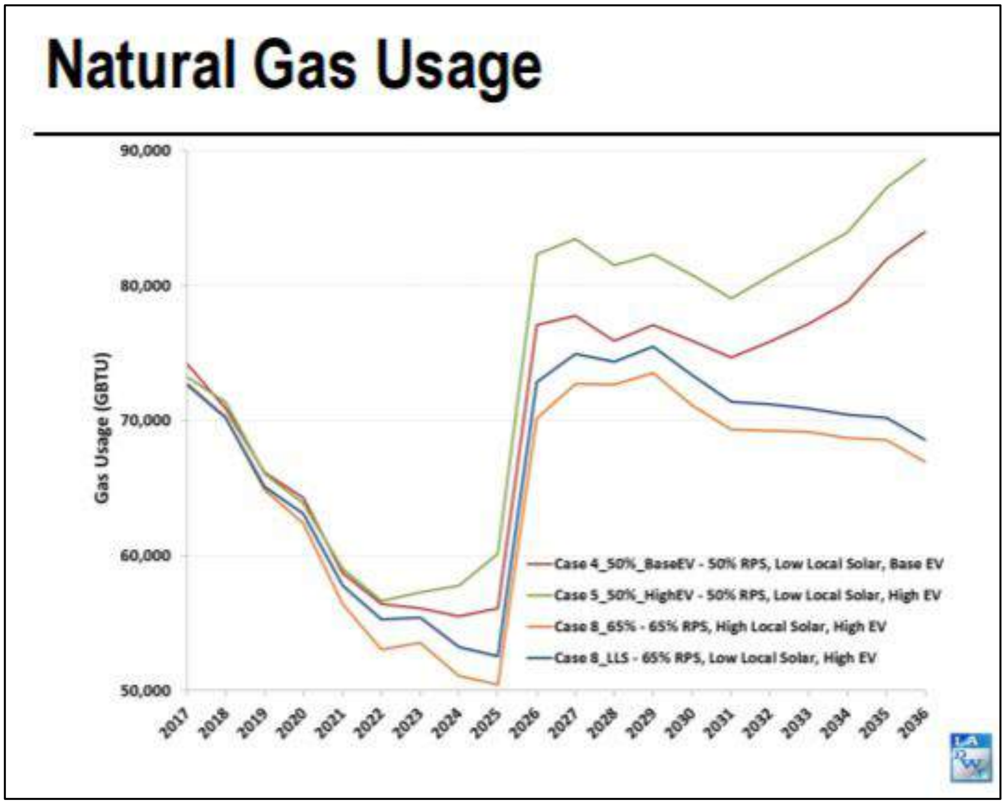
Californians for Green Nuclear Power (CGNP) has shown that nearly half the natural gas burned in CA for energy is now being used to back up wind and solar:[12]



CGNP has also shown that when SONGS was shuttered in 2011 (the San Onofre Nuclear Generating Station), California's natural gas use sharply increased, while their zero-greenhouse-gas electric production plummeted:



In 2017, the Los Angeles Department of Water and Power (LADWP) published their projection of a sharp increase in natural gas use, if the so-called bellwether state of California shuts down the Diablo Canyon Power Plant (DCPP) in 2025, and replaces it with a fleet of gas-fired plants, to back up their wind and solar:



Now that San Onofre is shuttered, Diablo Canyon is California's last zero-emissions fueled power plant. But anti-nuke groups have persuaded Sacramento that fuel-free renewables are the way to go.

Even though the direct result of implementing their "green" ideology over science-based reality will be a *net increase* in greenhouse gases, from methane combustion and leakage.[13]

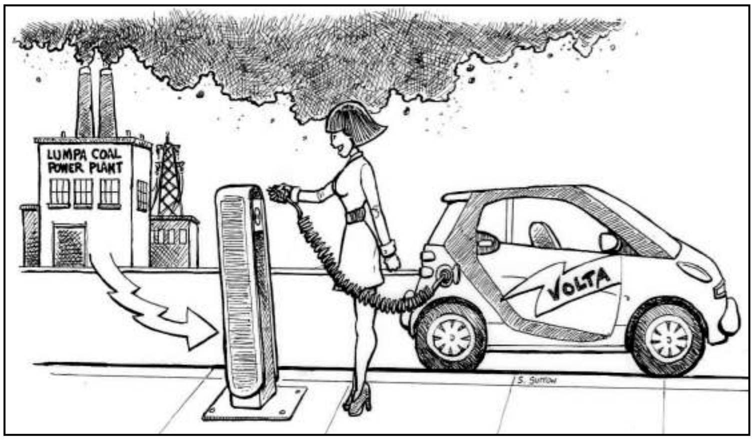
Compounding this irony, a sizeable chunk of the climate benefits that California *thinks* it's getting from the renewables industry, is actually being wiped out by leaks from an entirely different industry – the politically-incorrect fossil industry that fracks and extracts the methane California relies upon to back up their fossil-free renewables.

(To be fair, California's gas leak rate is lower than the national average. So their natural gas industry is "only" wiping out one-third of the state's WWS climate benefits, not the 40% average experienced nationally.)

And how exactly is this comedy of errors supposed to mitigate global warming? We don't know, either.

¿Quién es mas verde? [14]

Renewables advocates like to cop a greener-than-thou attitude, but we're not overly impressed. When you drive an EV, your tailpipe's down at the power plant.



With anemic capacity factors of 20–35%, the WWS farms they envision powering the nation would effectively be gas plants supplemented with renewables.

That is, until that happy day when we finally have thousands of WWS plants scattered hither and yon (linked by thousands of miles of new transmission lines), that can back each other up without relying on gas training wheels.

Without that backup, the farms will be one-fifth to one-third as productive as their advocates claim. And either way, the plants will have to be refurbished every 10–40 years.[15] Plus, there's the whole storage thing.

Not being up front on these fundamental issues can make a sensible conversation on energy choices far more difficult than it needs to be.

In theory, a tipping point should eventually occur when enough farms in enough regions start backing each other up. But the longer it takes to reach that point, the more methane we'll have to frack, leak and burn.

Another problem with blowing through our natural gas reserves is that we don't use methane just for electric power. We also use it to make fertilizer, plastic, pesticides, synthetic fabrics and pharmaceuticals.

Substitutes for methane can be found, but consuming mass quantities of a non-renewable resource to build a renewable energy system is a Faustian bargain that should give us pause.

P2G – a (possible) breath of fresh air

Power to Gas (P2G) is a new technology that may be worth watching. With P2G, the overproduction of a wind or solar farm that would otherwise be wasted in the absence of batteries or pumped hydro can now be used to produce methane, to store the energy for later use. Like we've been saying, fuel is storage.

In an industrial P2G system, water is electrically split into oxygen and hydrogen. The oxygen is released to the atmosphere and the hydrogen, combined with CO_2 that was scrubbed from a smoke stack or harvested from the atmosphere, is fed to microorganisms that excrete methane.

While it's not carbon-free, P2G methane is carbon-neutral, since the carbon released by burning it was either harvested from the atmosphere, or would have wound up in the atmosphere anyway as power plant smog.

> NERD NOTE: Burning a mixture of methane (CH_4) and oxygen (O_2) produces heat, water vapor (H_2O), and carbon dioxide (CO_2).

Power-2-Gas methane is less harmful than methane extracted from the ground, since the additional CO_2 from burning newly extracted natural gas would further disrupt the planet's Carbon Cycle.

P2G methane doesn't disrupt the Cycle all that much, since it re-uses the CO_2 that came from the prior burning of extracted fuel. But since any energy conversion results in a loss, the ultimate effect would be more carbon in the atmosphere.

The technology is still being tested, so don't hold your breath. In fact, a cursory glance suggests that the process may only return about 25% of the energy fed into it. Which, by the way, is the same return on energy we get from electrically isolating hydrogen for vehicle fuel (more on that later.)

In the absence of any other mass energy storage technology, P2G (and hydrogen) are better than nothing. Not by much, but still . . .

Even so, there are three points about P2G methane to keep in mind:

- It's (mostly) carbon-neutral, not carbon-free
- Like any combustion, burning methane for electric power wastes most of the chemical energy released in the process
- Like natural methane, a 4% leak of P2G would make the renewables it backs up as bad for the climate as a coal plant

Global Weirding

Messing with the Carbon Cycle is the disruption in the term Anthropogenic Climate Disruption (ACD).

When you dig up a gazillion tons of carbon fuel in 150 years (a geologic blink of an eye) and burn it, weird things start happening to the climate. That's because some of the carbon dioxide released in the combustion process will remain in the atmosphere for 100 years or more, trapping heat.

But this extra CO_2 doesn't just warm the atmosphere, which is one of the flimsiest substances on earth. Nearly all of the excess atmospheric heat (94%) is being absorbed by the oceans, which cover 70% of the globe.[16]

That's why it's called global warming, not atmospheric warming.

And even if you don't "believe" in all of this global warming stuff (or even if you do, but think that a warmer climate and more atmospheric CO_2 would be beneficial for crops and other flora), you should know that the oceans aren't just absorbing heat from the atmosphere.

They're also absorbing a lot of this excess CO_2. Which isn't surprising, since the oceans already absorb atmospheric CO_2 as a normal part of the planet's Carbon Cycle.

Ocean acidification is global warming's evil twin.

The problem is, with all the extra CO_2 we've been adding to the atmosphere, the oceans are absorbing far more than they can process, becoming more acidic (less alkaline) as a result.

Ocean acidification is global warming's evil twin.

Even now, the increasing acidity of seawater is destroying the phytoplankton at the base of the oceanic food chain, by dissolving their calcium carbonate shells. Drop a piece of chalk (fossilized phytoplankton) into a mildly acidic liquid like vinegar or carbonated water, and watch what happens.[17]

... the choice is clear: reverse our carbon emissions, or acquire a taste for jellyfish.

Acidification is a huge problem, because no little critters for the fish to eat = no fish for us to eat, and no more whales to watch. Since the oceans provide about 15% of humanity's dietary protein, the choice is clear: Reverse our carbon emissions, or acquire a taste for jellyfish.

Even more worrisome: Oceanic phytoplankton excretes about half of the world's supply of atmospheric oxygen.[18]

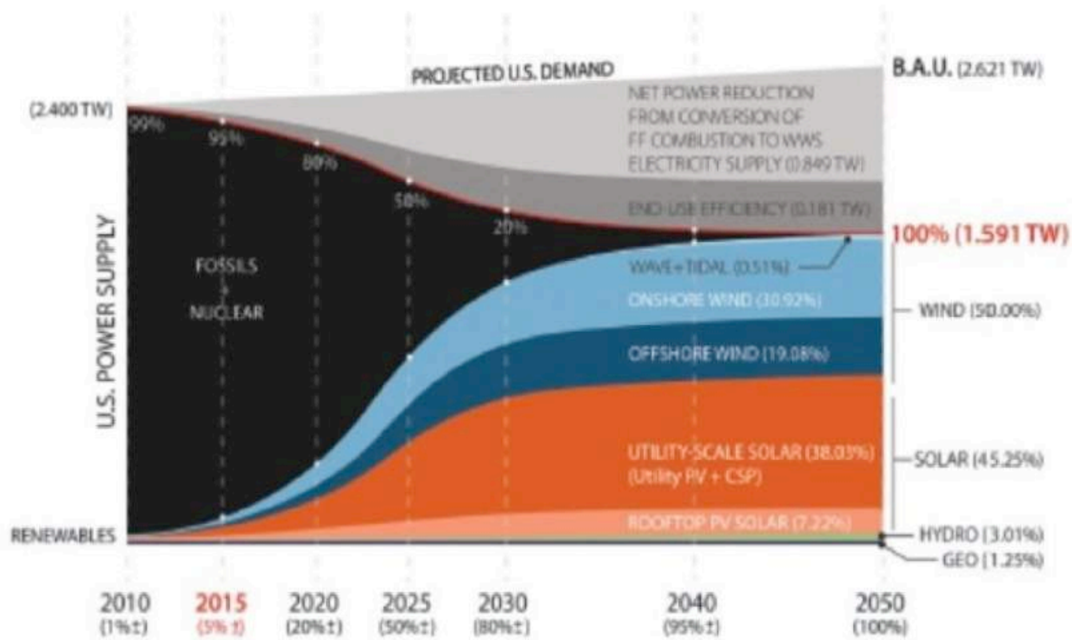
So completely aside from the issues of smog, acid rain, global warming and climate change, if you're partial to breathing air and if you enjoy seafood . . .

CHAPTER FIVE

Whistling in the dark with the lights on

The Roadmap has a slick graph that depicts a completely unrealistic buildout schedule. It calls for more than half of the buildout in the first ten years (2015–2025), and another 25% of the buildout in the following five years.[1]

That's 15 years to build more than three-quarters of a $15.2 Trillion, nationwide, fuel-free renewables grid.



The 35-year Roadmap would entail manufacturing (or importing) and installing:

- 496,000 5-MW wind machines
- 18 billion square meters of PV panels
- 50,000-plus wind and solar farms
- 75 million residential rooftop systems
- 2.7 million commercial rooftop systems

On 131,200 square miles, not counting the rooftops.[2]

Nuts and bolts

To execute the Roadmap, the entire country would have to shift to a war footing and stay hard on it for over three decades. And like we said, if other countries follow suit and overseas fabricators can't fill our orders, we'll have to make our own gear.

Which is a *lot* of stuff. Yes, we stepped up for World War II, and yes we can do it again. But can we keep it up for 35 years?

Yes, we stepped up for World War II, and yes we can do it again. But can we keep it up for 35 years?

And do some of it two or even three times over? Because remember, the buildout will last longer than the wind turbines, and nearly as long as the solar panels.

So even when the buildout is complete, it'll never end.

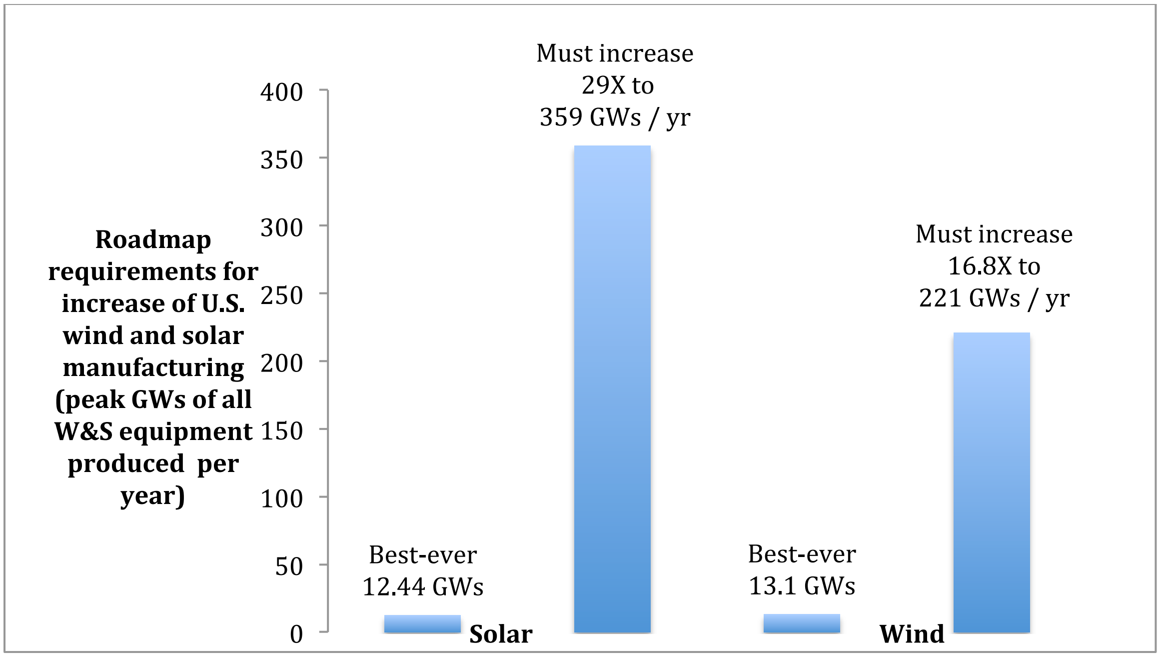
Like our military-industrial complex, born in the cradle of WW II and still going strong, we'll have to keep fabricating, installing, and recycling 1.23 million square meters of PV panels every single day – *forever* – just to keep the Roadmap working.[3]

Fabricating and installing that many panels each day would be difficult enough. Recycling the old panels that the new ones replace would become a polluting, resource-intensive industry unto itself, involving a series of mechanical, thermal, and chemical processes, each with its own energy requirement and waste stream.[4]

And don't forget, we'll also have to refurbish all of the 340,000 onshore turbines every 15–20 years (gearboxes, generators and blades), and do the same with the 156,000 offshore turbines every 10 years because of their harsh marine environment.

The U.S. doesn't have anywhere *near* the industrial capacity to get this done.

For example, just to stay on-track with the Roadmap's second 5-year portion (the period 2020–2025), we'll have to exceed our best year ever in PV panel production by almost 29X, and our best year ever in wind turbine production by nearly 17X, based on U.S. production totals for 2016: [5]



Dozens of factories will have to be built overnight, and we'll have to run them three shifts a day. That may seem like a good thing, since it would be a national jobs program that can't be beat.

But it could also amount to biting off more than we can chew. Because if we can't ramp up that much and that fast, we'll find ourselves hemorrhaging money with nothing much to show for it.

Public morale will falter, and the mobilization will seem more like the home front during the Vietnam War than World War II, with all the political turmoil, protests and culture wars that came with it.

And keep in mind, the longer it takes to get mobilized, the more those Xes go up.

So despite the optimistic curves in the Roadmap's graph, the buildout will actually be a constant scramble to catch up for three exhausting decades.

As of this writing (autumn 2017), we're already two years behind schedule.

Low energy? You might have a mineral deficiency

Copper and silver are just two of the critical minerals used to fabricate wind turbines, PV panels, and the parabolic (curved) mirrors for CSP solar.

We currently import a third of our copper and most of our silver. Imports would necessarily skyrocket if we make our own Roadmap gear. And even if we had the equipment made overseas, those countries would still have to mine or import the material themselves.

So how much copper and silver would we need for our nation's Roadmap?

The copper industry says that PV solar needs about 5 tonnes per MW, and wind turbines need about 3 tonnes.[6] Panel makers say they'll soon be reducing their silver consumption to 13 mgs (milligrams) per dc watt.[7] By pure coincidence, CSP's parabolic mirrors need 13 mgs per ac watt.[8]

Doing the math, the U.S. Roadmap will need 24.4 million tonnes of copper[9] and 51,300 tonnes of silver.[10] And that's not counting the copper for the tens of thousands of miles of new transmission lines. Or mirrors for CSP backup systems.

We'll assume that all the copper and silver in our worn-out panels and turbines will be recycled for the new panels and turbines needed to maintain the Roadmap. Regardless, our sudden increase in demand, along with the decline in ore grade that typically occurs with each new dig, would result in rising prices and bottlenecks around the world.

The material, however, *does* exist, even if it doesn't exist here. So the U.S. Roadmap, in theory, could actually be built. But there's a catch:

If the Roadmap goes global, the worldwide buildout will consume about one-third of the world's proven copper reserves[11], along with 90% of proven silver reserves[12] – meaning the copper and silver that we know for sure is still in the ground.

New silverware and silver jewelry would have to be banned. And mirror technology would have to be revamped – silver, the best reflector of visible light, has been used for centuries. The list goes on: Electrical contacts, batteries, printed circuits, etc.

At the current rate of silver consumption for all industrial products that aren't solar panels, the world would blow through the final 10% of global silver reserves in 4 years. Entire product lines would have to be re-thought. Things will change bigly.

Monopolizing one-third of the world's copper would be just as bad, putting a serious kink in global supply chains and jacking up prices around the world. And we haven't even factored in the transmission wires to connect the hundreds of thousands of new wind and solar farms to their respective national grids.

A global Roadmap would quickly become a victim of its own excess – strip-mining the planet, and carpeting it with wind and solar farms, is not going to save the world. Or us.

The 1,591-GW grid*†

(*Batteries not included. †Backup is optional at extra cost.)

The Roadmap contends that an all-electric grid could power the nation – electricity, transportation, heating, industrial processes, the works – with an average (not nameplate / peak) capacity of 1,591 GWs.

We'll take the estimate as a given.

If everything goes according to plan, smart grid technology will manage all of this extra juice (about 3.4X of what's now on the national grid) by sending power to wherever it's needed on a second-by-second basis, adroitly balancing our national supply and demand.

The Roadmap also recommends using LoadMatch, a grid integration computer model, for predicting the amount and availability of power every 30 seconds across the entire grid.

Sounds amazing, but we have our doubts, because no matter how precisely the grid is managed, it'll essentially be a fuel-free system with virtually no backup or storage, and entirely dependent on our ever-changing weather.

Even more amazing, the 1,591-GW average was derived by simulations that Dr. Jacobson and his colleagues had LoadMatch perform for the years 2050 through 2055.[13]

Think that through:

A $15.2 Trillion national WWS buildout, embraced by millions of renewables advocates, was determined with the aid of a computer model that purports to predict the nation's weather, region by region (not the climate, mind you, but the weather), every 30 seconds . . .

For a 6-year period 35 years in the future.

Peering into the future through a 35-year fog bank, and claiming to read the details of a distant shore, is dicey indeed.

Future trippin'

Peering into the future through a 35-year fog bank, and claiming to read the details of a distant shore, takes a certain amount of chutzpah.

Nevertheless, the authors of the Roadmap are confident that a fuel-free national grid is not only achievable, but predictable to the gigawatt.

While computer modeling is improving by leaps and bounds, the accuracy of any model's output depends upon the accuracy – and applicability – of the input.

The only way to make accurate long-term weather predictions is by extrapolating historical data, and that data is proving to be less and less applicable as climate change disrupts our weather patterns.

Which means that any long-term bets on the weather are long shots at best.

Looking into the past to see the future only works if baseline conditions remain largely intact. But global weather conditions are becoming ever more unpredictable, and doing so at an ever-increasing rate.

Smart grid technology and LoadMatch will supposedly enable us to build up to the grid capacity we need, then add on a mere 4.38% overbuild (69.7 extra GWs) and call it a day.

So much better than the 150% overbuild[14] the U.S. resorted to in the dark days of the 20th Century, before computers made everything run like a Swiss watch . . .

We disagree.

If backup is like training wheels, then overbuild is like spare tires. And anyway, a Swiss watch runs like a Swiss watch without any help from a computer.

Overbuild, as distinct from oversize (yes, there is a difference)

Oversize has to do with power plants. Overbuild has to do with the entire grid.

We walked you through oversizing, which is a new thing in the energy business. Before renewables came along, a power plant was expected to produce exactly what its nameplate said when the thing was tuned up and running at full capacity: A 1-GW plant has always been relied upon to crank out one gig, on demand.

Even so, we still built a lot more power plants than we strictly need, just for just in case. Using thousands of "always-on" baseload plants (coal, gas, hydro and nuclear) we built a 1,167-GW national electric grid – not primary energy, mind you, just electricity.

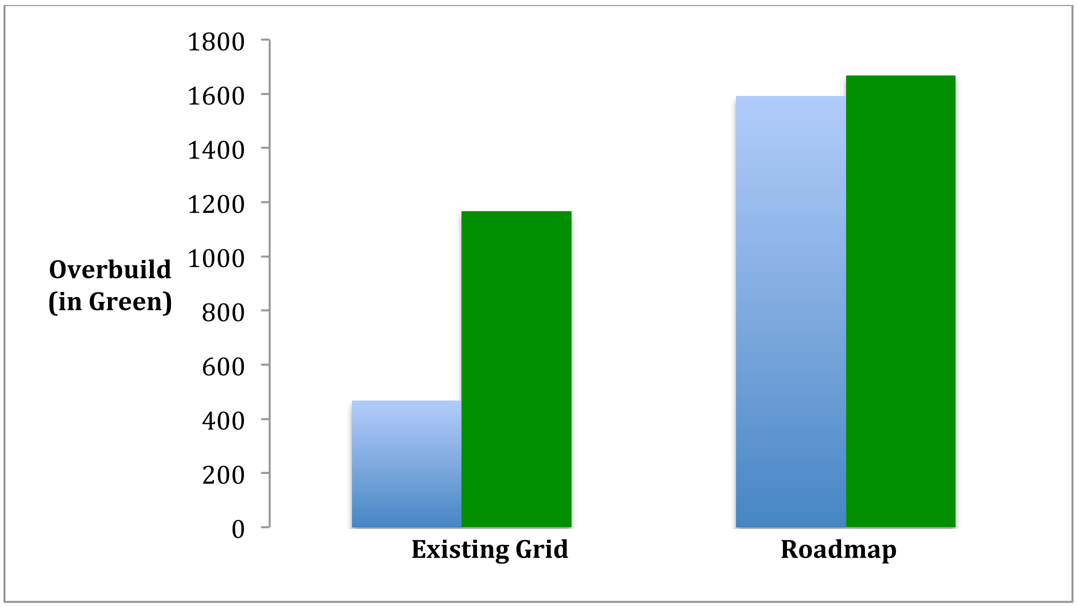
That's an overbuild of 2.5X our annual average electrical demand of 467 GWs.[15] Another way of saying it: Our current safety margin is 150% above demand.

That's how we've kept the lights on 99.9% of the time for more than a century.

Call it overkill if you like, but the idea is sound. So is the idea of converting to an all-electric society. Better living through electricity! Go, USA! However . . .

If you're driving into unexplored territory, you're probably going to pop some tires. Reliability rules, and overbuild is a low-tech, nearly foolproof way of getting down the road. Buy the best tires you can afford, but always carry a spare. Or two. (Even armored limos with run-flat tires carry a spare.)

But the Roadmap chucks all of that Nervous Nelly stuff out the window, because LoadMatch. Which is why the Roadmap's total grid overbuild (as distinct from oversizing each farm) amounts to 69.7 GWs, or just 4.38% above and beyond the basic 2050 grid:



That's not an overbuild of 4.38 *times*, mind you, but 4.38 *percent*.

For an interdependent – and weather-dependent – fuel-free national grid, into which we'll plug every blessed thing in the country. And all of it load-balanced to a T with a computer program, and a dinky little 69.7-GW spare tire for good luck.

Green elephants with training wheels

Back in the day, before elephants were on the endangered list, they were sometimes used in metaphors for comic effect: When a person was drunk they saw pink elephants.

A white elephant was something you wouldn't dare get rid of, even though it was utterly useless and destroyed your finances. The term comes from a time when Thai royalty would gift the rare creatures to especially annoying patrons. The patrons couldn't refuse a royal gift, even though they knew it would ruin their lives.

Utility-scale wind and solar farms could easily become green elephants, even with an endless supply of free "fuel" gifted to us by Mother Nature.

She's mighty annoyed by what we've done to the planet, so we're atoning for our sins by humbly accepting her bounty – no matter how inefficient and wasteful a national renewables grid may prove to be.

That may seem over the top, but we wanted to get your attention, to emphasize an important distinction between a fueled grid and a fuel-free grid:

- If we launch a buildout of fuel-powered baseload plants (coal, gas or nuclear) and abandon it halfway through, we would still have a collection of fully functioning, independent power plants.
- If we launch the Roadmap and abandon it halfway through, we would have a herd of green elephants that will always need training wheels.

All or nothing

The Green Elephant Scenario is one of the biggest drawbacks of a 100% national WWS grid: It's an all-or-nothing proposition. Because that's what interdependency is all about – it only works if all (or nearly all) of the pieces are in place and functioning.

... one of the biggest drawbacks of a 100% national WWS grid: it's an all-or-nothing proposition.

If we start the buildout, we'll need to complete the entire project to ensure that each renewables plant has the best possible chance of having enough fuel-free backup.

For that to happen, tens of thousands of wind and solar farms will have to be placed in the widest possible variety of advantageous weather zones. And they'll all have to be completed, or alternative sites will have to be found.

And then, even if we *do* build the whole thing, the Roadmap may still not prove to be fully self-supporting. It's entirely possible that training wheels in the form of traditional fueled power plants will still be needed.

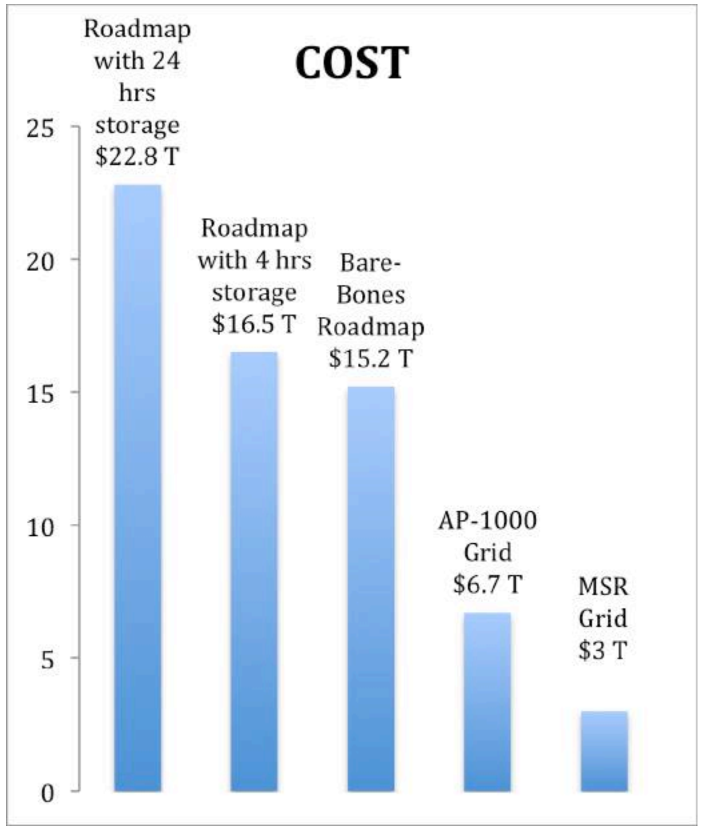
We won't really know if the Roadmap will work as advertised until we actually build it. And once we do, we'll have to *make* it work. The reason is simple:

We can't afford to waste that much money, time, land, and resources, then change our minds and move on to something else. Aside from using fast-start gas turbines or traditional baseload plants that can operate 24 / 7, and aside from oversizing every wind and solar plant we build, the only reliable way to back up the inherently unreliable performance of renewables is with mass energy storage.

24 hours of energy storage could easily cost another $7.6 Trillion.

We walked you through P2G. In the next few pages, we'll be addressing energy storage in the form of grid-scale batteries and pumped hydro. We'll also cover hydrogen, which is being considered as a carbon-free fuel for heavy transportation and process heat.

The bare-bones Roadmap treats adequate storage as an externality. Which is one way to keep the sticker price down: 24 hours of energy storage could easily cost another $7.6 Trillion. The price chart deserves another look:



Of all the WWS plants called for in the Roadmap's 1,591-GW plan, only 7.3% of them (116 GWs) will have their own on-site storage, and it'll be just enough to get them through the night. *If* it was a sunny day.

CSP: Sunshine in a straw

Concentrated solar power (CSP) is a clever solar technology with a bit of built-in storage – just for over night and pretty much just for itself, but it's a step in the right direction. (More of a gesture than an actual step, but still . . .)

Instead of photovoltaic solar panels, which convert sunlight to electricity, CSP uses simple curved mirrors to heat a pipe of molten (melted) salt, which is used to boil water to run a turbine to generate power.

Since molten salt retains a tremendous amount of heat, some of the salt can be stored in insulated tanks to produce power when the sun goes down – if it was a sunny day.[16]

If not, then the CSP plant has to be backed up by another plant, or plants. And even if it *was* a sunny day, the stored energy will only last till morning.

Not to change the subject, but a Molten Salt Reactor's fuel salt is totally different: It stays molten because the atomic fuel in the salt is actively producing heat.

Since there's nothing in CSP's molten salt to generate its own heat, storing its solar energy in salt tanks is like storing water in a leaky bucket – it'll probably be gone by morning. But no biggie, you can just heat up the salt again the next day.

If it's sunny.

CHAPTER SIX

A fuel-free lifestyle and the quest for the holy grail

Aside from a handful of CSP plants comprising 7.3% of the basic 2050 grid, and another handful comprising the grid's entire 4.38% overbuild, none of the Roadmap's farms will have any built-in training wheels.

External backup or energy storage would be the only reliable ways to make the Roadmap's fuel-free grid work.

Cheap storage is the holy grail of renewable energy, the long sought game-changer that will finally put renewables on par with traditional baseload systems.

With enough cheap storage, the bits and bursts of energy gathered from wind and solar can be collected and later released in a smooth, steady stream that mimics the dependable power we rely upon for modern life.

But the Roadmap has a better idea: *Eliminate* the need for storage. With enough oversized farms in enough locations backing each other up, who needs storage?

This is an adventurous proposition, because the light and motion that make renewables work isn't under human control and never will be, unless and until the energy we make with it can be transferred to a storable medium.

Our existing grid has a 2.5X overbuild, consisting of fossil, nuclear, and hydro plants. All these systems have storage in the form of actual fuel, or in the potential energy of elevated water. And though drought is eroding our hydro capacity, we still have plenty of fossil and nuclear fuel on hand.

Traditional power plants extract energy from their fuel supply (a load of coal, a fuel tank, a fuel rod, or a reservoir of water) and generate power with that energy day and night.

Fuel (or elevated water) enables these plants to adjust their output, sometimes within minutes, to respond to predictable peak loads.

Renewables, not so much.

Traditional power plants extract energy from their fuel supply (a load of coal, a fuel tank, a fuel rod, or a reservoir of water) and generate power with that energy day and night.

Gridmasters of the 21st-and-a-half century

Overbuilding the grid is all about how much extra generating capacity (fuel or hydro) can be reliably brought into service with adequate lead time.

The operative concept is "reliability," but the Roadmap dispenses with this old-school notion. Its 4.38% overbuild of extra CSP farms will rely strictly on sunshine – if and when it's available.

As you can imagine, this may not suffice to ensure grid stability. For example, California needs to find 607 additional MWs per minute every afternoon, as the sun's energy fades past its midpoint and solar production declines.

So let's play gridmaster, and examine the quantity of extra power potentially available in 2050, to see just how wobbly the grid might be without training wheels.

First off, the Roadmap calls for adding 19.2 GWs to our dammed hydro production, from our current 28.7 GWs, for a new peak capacity of 47.9 GWs (3% of the 2050 grid). This will be done by upgrading the turbines and extending operating hours.

However, the turbines in our large dams weren't designed to be ramped up and down as fast-response backups, even if they were upgraded. So we're guessing that the Roadmap's expansion of our hydro dams would probably include the installation of additional, fast-start hydro turbines.

It's just our speculation, but our large existing dam turbines would most likely function as they always have, providing both baseload and what Europe calls *intermediate load* – power that can be slowly ramped up and down to meet predictable daily and seasonal demand. The newly installed turbines would be fast-start models to respond to unexpected peak loads.

We'll also have our existing 22 GWs (peak capacity) of pumped hydro storage, which can run for about 12 hours – if the reservoirs are full. Which means the Roadmap, through no fault of its own, will actually inherit a tiny amount of storage. And we'll also have the Roadmap's 69.7 GWs of overbuild CSP.

Our intrepid gridmasters of 2050 will therefore have the following options:

- 19.2 GWs of backup power from expanded hydro capacity
- 22 GWs of pumped hydro for 12 hrs (if we can fill the reservoirs)
- 69.7 GWs (4.38% of grid) from overbuild CSP (if it was a sunny day)

That's a theoretical blue-sky maximum of 110.9 GWs (about 7% of the grid.) Which is great, until we have an extended period of unfavorable weather.

And that's the Roadmap's entire backup for the 2050 grid. We recommend more.

Cargo Cult

Staking out a patch of wilderness and waiting for energy to come along is what we call a Cargo Cult approach to power.

> *Staking out a patch of wilderness and waiting for energy to come along is what we call a Cargo Cult approach to power.*

In World War II, remote Pacific Islanders marveled at the bounty that washed ashore from torpedoed cargo ships. As far as they knew, they must have finally thrown the right virgin in the right volcano, because all of a sudden the gods were sending them tons of free goodies.

Mother Nature sends us an inexhaustible bounty of wind, waves, tide and sunlight. WWS "islands" catch this light and motion and make electric power.

But if we can't use the power as soon as it's made, we have to store it or dump it. At least cargo-cult Spam had a shelf life.

Lithium-ion batteries are mentioned in the Roadmap's footnotes, but they aren't formally factored in, probably because they're prohibitively expensive and haven't been tested at scale.

In any case, those that are on the market are only warrantied for 10 years. So even if prices drop like a rock, their lifespans will have to grow by 6X to match a reactor's.

But the battery guys aren't about to give up.

Big-ass batteries

In July of 2017, Elon Musk promised to build a 100-MW lithium-ion battery in 100 days, to store the excess production of a South Australian wind farm.[1]

If he makes his self-imposed 100-day deadline, the price is $50 Million. If he misses the deadline, it's free. (No worries – he can afford it.)

Existing Li-ion battery technology enables a storage capacity of one kWhr with about 77 grams of lithium metal.[2] So Musk's battery will contain about 10 tons of lithium.[3]

That is one big-ass battery. But it's still not big enough – like everything else in the field of renewables, *it's a nice idea that doesn't scale*.

One hour of energy storage for the Roadmap's 1,591-GW grid would require over 122,000 tonnes of lithium (77 tonnes per GW-hr × 1,591.)

That's more than 3 times the total global production of lithium in 2016, which was 36,000 tonnes.[4] Flip the numbers around:

All the lithium mined on planet Earth in 2016 would provide a whopping 18 minutes of all-grid storage for the 2050 Roadmap (36,000 tonnes ÷ 122,000 tonnes = 0.3. And 0.3 hrs = 18 minutes.)

But wait! There's less!

Liquid-flow batteries have been generating considerable interest in renewables circles as a possible solution to mass energy storage. Don't get too excited.

The battery consists of two tanks of different electrolyte solutions (dissolved minerals.) The liquids are pumped into a divided chamber (the two solutions never touch) to produce a flow of dc (direct current) electricity.

The liquids are returned to their tanks, and the system is recharged for another round, using surplus electricity from a wind or solar farm (when it's available.)

Vanadium oxide is the electrolyte mineral of choice. Unlike a solid lithium battery, which eventually wears down and must be dismantled to recycle the material, a vanadium electrolyte solution can be used over and over again.

Problem is, a grand total of just 79,400 metric tonnes of vanadium were mined last year, over half of it in China. And they used 90% of it for making steel, not batteries.

Aside from resource availability, the problem with flow batteries is energy density: Vanadium electrolyte solution can only store 0.36 MW-hrs per tonne of vanadium, compared to lithium's storage capacity of 13 MW-hrs per tonne. That's a 36:1 ratio.

And, the round-trip efficiency of a flow battery is about 75%, compared to a lithium battery's 90%. But here's the real deal breaker:

If all 79,400 tonnes of vanadium that was mined worldwide in 2015 were used to make electrolyte solution for one big-ass flow battery, it would store about *one minute* of all-grid storage.[5]

Back to the drawing board.

UTES (no, not the tribe . . .)

Underground Thermal Energy Storage (UTES) is mostly done in the form of borehole energy storage (BHES).

Basically, borehole is just a residential heat pump writ large and enhanced with thermal solar panels, those black plastic rooftop panels that heat circulating water.

The hot water is sent through a network of underground pipes and the surrounding soil retains the heat, which can later be retrieved for space heating.

Since different soils retain heat with varying degrees of efficiency, borehole is a site-dependent technology. But it works well enough that the authors of the Roadmap chose it for the bulk of our heating needs.

Sounds boring, but space heating is a sizable slice of our energy pie, currently consuming about 10% of primary energy.[6]

(Remember, primary energy is *all* the energy we use: For air, land, and sea transportation; for construction, industrial process heat, space heating, etc., as well as electricity.)

The Roadmap removes space heating from the 2050 primary energy pie because it'll be produced independently of the grid, using borehole rather than grid electricity.

Fair enough – for our all-nuclear grid we've done the same.

With improved efficiency and building insulation, the Roadmap estimates that our national space heating requirements will drop to just 7.2% of our total primary energy, down from the approximately 10% that space heating now consumes (mostly natural gas and heating oil.) That 7.2% amounts to 114.7 GWs, derived from heat, not electricity.

Good old H_2O

Like a hydroelectric dam, pumped hydro (PHES, or Pumped Hydro Energy Storage) generates energy from the force of falling water.

A superior storage system, pumped hydro comprises nearly 99% of all mass energy storage in the world. The U.S. currently has a peak capacity of 22 GWs, which is about 2% of our grid's total peak power.[7]

> *... pumped hydro doesn't generate its own electricity. Rather, it stores and re-generates (most of) the energy that was used to fill its reservoir in the first place.*

Essentially, pumped hydro acts like a dam: Pump water uphill when you have the power to spare, and let it run back down through the same reversible turbines when you need the power to satisfy electric demand.

The round-trip efficiency is about 80%: If you use 100 megawatt-hours to pump up the hydro, you'll get 80-ish MW-hrs back.

Unlike our existing hydroelectric dams, our pumped hydro reservoirs aren't factored into the 2050 grid. Probably because, strictly speaking, pumped hydro doesn't generate its own electricity. Rather, it stores and re-generates (most of) the energy that was used to fill its reservoir in the first place.

Prices may vary

When it comes to mass energy storage, pumped hydro is the gold standard that has to be matched or beaten by other non-fuel storage technologies. And it's as low-tech and reliable as gravity.

Like borehole, the cost and efficiency of pumped hydro is site-dependent. If there's a dammable, high-elevation valley nearby, or an abandoned watertight mine, you're in luck. Otherwise, you'll have to build two reservoirs, not one.

This is one reason why pumped hydro prices vary from a few pennies per installed watt-hour, to well over a dollar. To be more than fair, we'll calculate pumped hydro for the 2050 grid based on the lowest quintile: $0.20 per watt-hour of stored energy. It'll be interesting to see if P2G can match or beat that $0.20.

So why did we call out a price per "installed watt" for a fueled power plant, if we called out a price per "installed watt-hour" for storage?

Because any fueled generator can continuously produce power at its nameplate rating as long as it has fuel. But storage can only deliver a finite amount of energy before it has to be recharged, refueled, or refilled.

Unlike the heat stored in CSP's molten salt, pumped hydro energy doesn't fade away, unless the water evaporates or the reservoir leaks. Which is why fresh water is a must: A saltwater leak would be catastrophic to the local flora. That's why ancient armies would sow their enemy's fields with salt.

The drawbacks of large-scale pumped hydro are the gargantuan amounts of water required, and the evaporative loss that's bound to occur. Not to mention the permanent inundation of habitable land.

The drawbacks of large-scale pumped hydro are the gargantuan amounts of water required, and the evaporative loss that's bound to occur.

In these days of severe drought, fresh water is a major concern – especially in the southwest U.S., where most of our solar farms would be.

To put the volume of water in perspective, it would take almost 135 days of America's total fresh water consumption (irrigation, industry, tap water, the works) to store one day of power at 1,591 GWs, or one "grid day".

So that's off the table.

We'll explain how we arrived at 135 days in the section "One ESB" below. But first:

Another shameless plug for our favorite technology

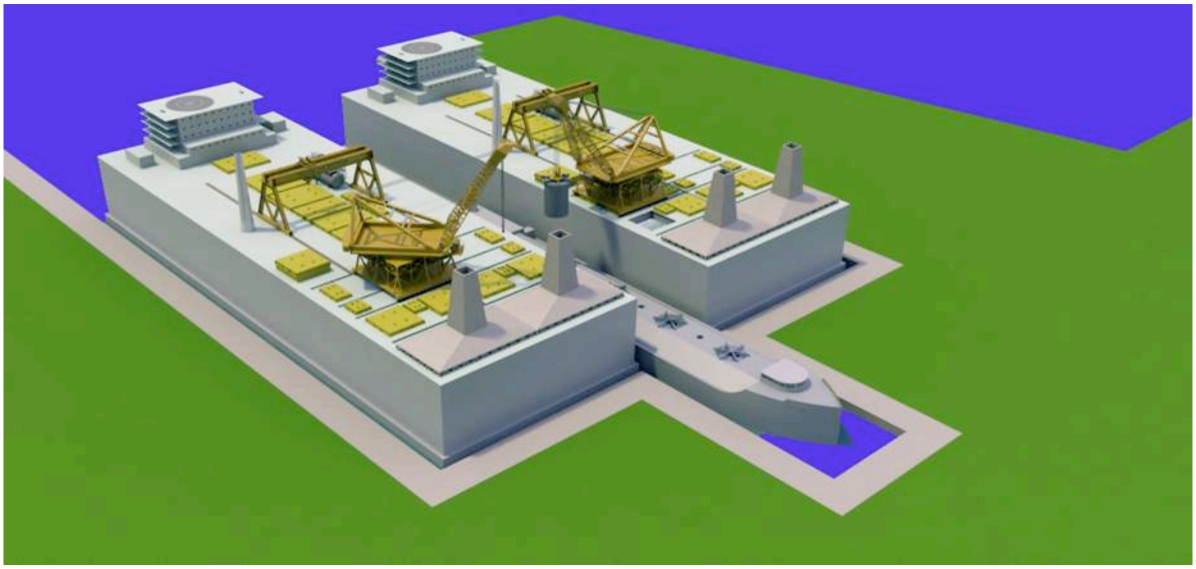
The general consensus of MSR engineers is that Molten Salt Reactors can be built for an average cost of $2.00 an installed watt, which would make them substantially cheaper than a coal plant.[8]

The reactors of an all-nuclear grid could generate about 550 grid days of power (18 months) before refueling. And that's if we use traditional solid-fuel reactors.

Liquid-fuel Molten Salt Reactors would be even better, since an MSR can be refueled while it's running by pouring in more fuel salt.

> *... [a Molten Salt Reactor] can be refueled while it's running by pouring in more fuel salt.*

Like most other Gen IV reactors, a pair of small MSRs would enable switching from one reactor to the other, so the first one can be taken back to the factory for service and refueling.[9] ThorCon's twin 500-MW reactors will feature continuous electrical production, 24 / 7, year in and year out. A fresh reactor will come online as a spent reactor is shut down and shipped back to the factory.



This eliminates the downtime that is ordinarily backed up by the rest of the fleet, meaning the entire collection of power plants that generate power for the grid.

Since an MSR can run non-stop for 4–10 years before it needs to be serviced, the ability to refuel on the fly, and / or the ability to switch to a fresh on-site reactor, are two major advantages that give Gen IV reactors a capacity factor that will probably exceed 99%.

Of all the Gen IVs, we feel the MSR is the solution for our energy needs, featuring:

- 99% uptime
- Cheaper than a coal plant
- An endless supply of cheap fuel
- The physical impossibility of a meltdown
- No spread of contamination in case of a malfunction
- The ability to operate exactly where the power is needed
- The ability to use "waste" (including weapons) as a secondary fuel

We now return to our regularly scheduled program.

One ESB

We coined the term "ESB" to refer to the volume of one Empire State Building – the amount of falling water required to generate 250 MW-hrs of electric energy.

A 100-meter drop provides a good pressure head, like the standpipe in a skyscraper. Which is what inspired the term.

Imagine if the Empire State Building was made entirely of water, like the water snake in *The Abyss*.[10] Now picture that water draining by gravity through a bank of hydro-turbines in the basement.

That's one ESB.

Under perfect conditions (i.e., with 100%-efficient machinery), 917,400 cubic meters of water, falling 100 meters, would be all the water you need: That much water has a kinetic energy capable of producing 250 MW-hrs of electric energy.[11]

But in real-world conditions, hydro turbine-generator efficiency is about 90%. So the *actual* water volume required to generate 250 MW-hrs is 1,020,000 m^3 (917,400 ÷ 0.90 = 1,020,000.)

The *ideal* water volume of 917,400 m^3 is roughly equal to the visible part of the Empire State Building, which is 900,000 cubic meters. The entire structure, including the basement, comes to 1,100,000 m^3. So the ESB acronym works in either case.

Of course, a reservoir would never be shaped like that. We're just trying to give you a good visual on the volume of water required.

The rule of thumb is: One ESB = 250 MW-hrs

Drop one ESB in one hour and you generate 250 MWs. Drop it in 5 hours and you get 50 MWs for five hours. Drop it in 10 hours and you get 25 MWs for 10 hours. Et cetera. The rule of thumb is: "One ESB = 250 MW-hrs."

> NERD NOTE: One tonne (1,000 kilograms) of pure water has the volume of one cubic meter, and weighs slightly more than 2,200 lbs in the English system of measurement.
>
> (And no, tonne is not pronounced "tonay" or "tunny." A tonne is a tonne.)
>
> In the U.S., a tonne is often called a "metric ton" to distinguish it from a 2,000-lb U.S. ton, which is sometimes called a "short ton". At 2,200 lbs, a metric ton is also called a "long ton".
>
> *Weight* is gravity's pull on mass. So we're actually talking about a *mass* of water with a volume of one cubic meter, which just so happens to weigh about 2,200 lbs on this planet. The same mass of water would weigh more, or less, on another world.
>
> All these labels and numbers might seem confusing, but that's because we in the U.S. adopted the antiquated measurements of inches, feet, yards and pounds from England, while the rest of the world adopted the metric system.
>
> Science uses the metric system because all metric measurements – volume, energy, mass, distance, force, work, power, etc. – fit together like Legos in a simple, elegant, and logical framework. And it all comes back to the weight and volume of water.[12]
>
> They don't call this a water planet for nothing.

Pump up the hydro[13]

At the rate of 1,020,000 m^3 for 250 MW-hrs, we would need about 156 billion cubic meters of water (that's 156 cubic *kilometers*) to generate one grid-day of power.

> *[We would need] about 156 billion cubic meters of water (that's 156* cubic kilometers*) to generate one grid-day of power.*
>
> *That's ... 152,700 ESBs...*

In 2010, the U.S. consumed about 421 cubic kilometers of fresh water. Which means that one grid-day of pumped-hydro energy production requires the fresh water consumption of the entire nation for nearly 135 days.[14]

Even at the bargain-basement price of $0.20 per installed watt-hour, twenty-four hours of pumped hydro for the entire 1,591-GW grid would cost $7.6 Trillion.[15] Plus you'll need enough fresh water, and the land to build the reservoirs.

Keep in mind, prices will vary depending on site conditions. But even with the most favorable conditions, one grid day of storage (a prudent insurance policy) would balloon the cost of the Roadmap to nearly $23 Trillion.

That's a lot of money, and a lot of water – 152,700 ESBs to be exact. If the entire island of Manhattan was carpeted with a solid mass of Empire State Buildings, built window-to-window, you would need 19 Manhattan Islands to accommodate that many ESBs.

All of which is ridiculous. So let's explore a (slightly) more reasonable scenario:

WWS advocates say that with a smartly managed grid, wind and solar farms will only need a few hours' storage. Since the number 4 has been bandied about, let's do the math:

Four hours is 1/6th of a day, which comes to about 23 days of total U.S. fresh water use. Which is still ridiculous.

Granted, the entire electric grid would never have to be backed up all at once, even for 4 hours. But with a major interruption like the Northeast Blackout of August 2003, a substantial portion might need backup for a day or more. These things add up.

In our view, a mere four hours of all-grid backup is pretty darn optimistic for a fuel-free grid. Our existing grid has a safety margin of 150%, and virtually all the power plants we have, including our backup systems, are powered by fuel or hydro, with plenty of extra fuel on hand.

Even then, we *still* have the occasional wide-area blackout. Nevertheless, the authors of the Roadmap are confident that we can enjoy a clean and green fuel-free future, utilizing geographic sweet spots in all 50 states. Distributing, diversifying, and interconnecting our 50,000-plus WWS farms would (hopefully) ensure that the bulk of them would never be idle at the same time, and would always be able to back each other up.

Which looks great on paper, until you look out the window.

CHAPTER SEVEN

The new abnormal

In September 2016, tropical storm Hermine barreled out of the Caribbean and plowed through northern Florida, then parked off the Carolina coast for several wet, miserable days.

Meteorologists were baffled; the storm's behavior was starkly different from anything in the historical record.

A few months later, they were caught flat-footed a second time when Hurricane Matthew came due north between Haiti and Cuba, churned along the east coast of Florida, and swamped the Carolinas all over again.

As we write this (autumn 2017), Hurricane Harvey has just dumped over four *feet* of rain on Houston, our national petroleum hub. Then Hurricane Irma chewed up the Virgin Islands and Florida, and Hurricane Maria wiped out Puerto Rico.

Global warming isn't causing more storms. But it is making the storms that do exist more intense and much wetter: Warm water evaporates easier, and warm air holds more water. Which means more rain when it rains, and more snow when it snows.

There is a sobering graphic from the Washington Post that's worth seeing. We call it "Thirty Cubic Miles of Harvey." And nobody knew how bad it would be until *three days* before it hit. Check this out:[1]

Historical records are becoming less and less predictive, and as climate change progresses we can expect more and more surprises, along with more and more damaged wind and solar equipment. Like the solar farms in the Virgin Islands, or what's left of them. Here's one of several shredded by the 2017 hurricanes:[2]

Puerto Rico's wind farms didn't fare much better. Check out this video:[3]

> *...since wind and solar are weather-dependent, how can we depend on them if we can't depend on the weather?*

And yet, renewables fans are proposing that the island's power grid should be rebuilt with wind and solar.

In stark contrast, the two reactors at STP (the South Texas Project nuclear plant) operated at full capacity before, during, and after Hurricane Harvey, despite 130 mph winds, a sustained storm surge, and 60 inches of rain.[4]

The plant sustained zero damage, same as the Turkey Point nuclear plant south of Miami, and the St. Lucie nuclear plant up the coast. Florida Light and Power chose to shut their plants down for the storm, and that was their choice.

But just like the South Texas plant, Turkey Point and St. Lucie sustained no damage, and were back online shortly after the hurricane. All of which raises an interesting question:

Since wind and solar are weather-dependent,
how can we depend on them
if we can't depend on the weather?

Especially in a world of global warming, where storms will be wetter and wilder as the years roll on, as more heat energy is pumped into the oceans and atmosphere.

With a rapidly changing climate, is it wise to base the siting and stability of our entire national grid on historical weather charts? Particularly when the equipment is so vulnerable to unfavorable weather?

Stripped down to basics, that's what the Roadmap seems to be proposing, with over 50,000 wind and solar farms in thousands of sweet spots around the country.

Any of which could turn sour in the decades to come, or be flattened by a storm.

> *... we are nowhere* near *being able to dial in precise predictions about long-term weather, cloud, and wind patterns.*
>
> *Climate, yes, but weather, no.*

"Any way the wind blows, doesn't really matter to me." – Freddy Mercury

Well, it should, because climate change will also change our long-term wind patterns. Remember the Polar Vortex in early 2014?

The Jet Stream suddenly changed course and we were completely blind-sided, even with our libraries of historical weather data. The anomaly stuck around for weeks, altering wind and sun patterns in the lower 48 and pushing freezing temperatures as far south as Tampa.

At first frostbitten blush, a freight train of Arctic air roaring down from Canada seems to fly in the face of global warming theory. While some scientists contend that the two aren't related, those who do see a connection explain it like this:

Melting sea ice lowers the albedo effect of the Arctic, reflecting less sunlight back into space. The darker, open water absorbs more heat, which warms the polar atmosphere above, causing the Jet Stream to behave erratically.[4]

Regardless of warming's ultimate effect on the Vortex, it's a virtual certainty that all global climate data is herding in the same general direction, with a lot of unpredictable jostling going on.

Because this is so, we are nowhere *near* being able to dial in precise predictions about long-term weather, cloud, and wind patterns. Climate, yes, but weather, no. Which is precisely why 100% reliance on a fuel-free, weather-dependent grid would be a folly of historic proportions.

And yet, here are millions of sincere, die-hard WWS advocates, who accept the science on climate change (indeed, who have great respect for Science Itself), and have nevertheless embraced a multi-trillion-dollar strategy, the feasibility of which will utterly depend upon accurate long-term weather forecasting – not the climate, mind you, but the weather – in a future of ever-growing climate disruption.

The difference between a WWS grid and a nuclear grid couldn't be more clear:

- Each Generation IV reactor will be small, stable, factory-built and easily replaced – an independent power plant unto itself.
- The Roadmap is a sprawling, interconnected nationwide project that will only work as envisioned if all (or nearly all) of its power plants are up and functioning.

Given the Roadmap's cost, interdependency, and scale, it had *better* last a long time, and it better work. Which means that nearly every farm will have to be kept up. That includes the farms in states that might lose interest in renewables.

Maintaining those farms could prove to be difficult if local opinion turns against the technologies. Being on state or federal land, sovereignty sentiments will undoubtedly clash with eminent domain, a conflict that's right up the radical right's alley.

What if an entire region of the country backs out of the Roadmap? Could the Roadmap be re-drawn to work with the states that stay in the program?

Nobody knows, until we go down that road and see who's in and who's out.

And even if everyone hangs in there, and the Roadmap is built, and even if it *does* work, its success still might not be enough to inspire proper maintenance.

The last thing we'll need is a herd of green elephants with training wheels, eating us out of house and home.

Eisenhower's national highway system was a great idea that worked like gangbusters, and there's no doubt in anyone's mind that it's still a vital part of our infrastructure. Even so, it's starting to crumble after a half century of neglect.

Why should we assume that the Roadmap's upkeep would be any different, even if it's a great idea (which it's not)? And especially if we break the bank in the process of finding out?

By the time we realize our mistake, we'll also be saddled with the hellacious expense that unmitigated climate change is sure to impose.

The last thing we'll need is a herd of green elephants with training wheels, eating us out of house and home. If there's one key take-away from this book (besides fuel = storage) it's this:

The long-term success of a fuel-free, weather-dependent energy system depends upon accurate long-term weather prediction. Which no longer exists.

Running aground on Cargo Cult Reef

Wind and solar farms aren't just weather dependent. They also operate on narrow margins of utility: Even a mild long-term change in the weather could render a farm, or an entire cluster of farms, essentially useless.

What if our wind-blown Northern Tier becomes the Northern Doldrums? What if Texas becomes the Monsoon State?

Floating offshore wind turbines have been developed that can be moved to chase the wind – if the seabed in the new sweet spot is conducive to anchoring the rigs.

Floating wind rigs are all well and good, but moving an onshore wind farm, or a solar farm, would be out of the question. The expense would easily wipe out the farm's already-meager EROEI – the Energy Returned On Energy Invested.

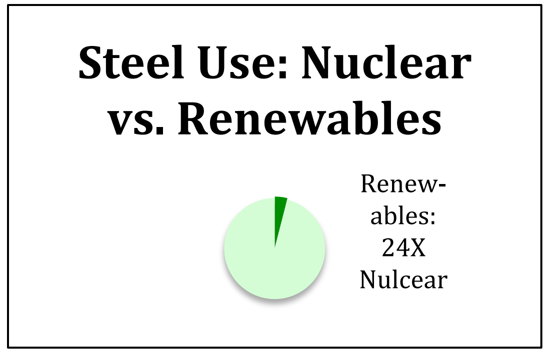
The flip side of average capacity is underproduction: if a farm's capacity factor is 20% it ... is underproducing by 80%.

Stranded assets are another factor to consider when comparing energy systems: How much labor and resources are sitting idle?

The flip side of average capacity is under-production: If a farm's capacity factor is 20%, it can be said that the farm is underproducing by 80%. But there's more to it than that – 80% of the labor and material invested in the farm are stranded as well.

And a low capacity factor isn't the only way to strand assets. Equipment that operates at peak performance can still be a waste. "Steel-per-megawatt" is a good yardstick: A megawatt peak of wind power requires nearly 8X the steel of a megawatt peak of nuclear.[5]

But since wind typically has one-third the capacity factor of nuclear, the actual steel-per-megawatt gap between the two technologies is more like 24X.



Even a whopping 40% capacity factor at a state-of-the-art wind farm still amounts to 60% stranded assets, which is still a waste of resources.

As rich and powerful as this nation is, we don't have an endless supply of labor, material, and money. Or time, for that matter.

When you're powering a country of 320 million people, these things add up.[6]

Casting our fate to the wind (and the courts)

A permanent weather shift could markedly degrade the long-term productivity of wind and solar in a wide geographic area.

Political flare-ups are likely to follow, when a fiercely independent region finds itself exporting gigawatt after gigawatt, to another region whose long-term weather luck has gone sour and stayed that way.

Some might call it Energy Welfare. Brexit comes to mind. So does Texit.

The nationwide, we're-all-in-this-together Kumbaya grid proposed in the Roadmap would make every region utterly dependent on each other – whether they like it or not.

The nationwide, we're-all-in-this-together Kumbaya grid proposed in the Roadmap would make every region utterly dependent on each other – whether they like it or not.

When the public realizes what energy interdependence actually entails, the anti-collective streak in American politics could cripple the entire project.

There's been some intense bickering lately over the management of federal land, and we'll wager that most members of the Sagebrush Revolution aren't real big renewables fans. As outlandish as their tactics were, expect more, since a lot of the buildout would occupy state and federal land fifty miles from nowhere.

And being fifty miles from nowhere, wind and solar farms will need new connecting corridors to the main trunk (the actual grid.) Many of those corridors will have to run through private property. Lawsuits and eminent-domain battles will delay some projects for years.

It's already happening in Germany, where their state-sponsored buildout of wind and solar (*Energiewende*) is meeting vocal resistance from property owners, particularly in scenic regions.[7]

In our hyper-litigious American culture, drawn-out court battles could dwarf the estimated $1 Million per mile for the new wires and towers.

And that's quite aside from the ruckus we can expect from efforts to save migratory birds, desert critters and oceanfront views. While desert turtles might have trouble finding a good lawyer, the critters dwelling in seaside mansions have them on retainer.[8]

In contrast, Generation 4 reactors could actually eliminate most transmission corridors. That's because most Gen IV reactors won't need a body of water for cooling, which means they can be placed wherever power is needed.

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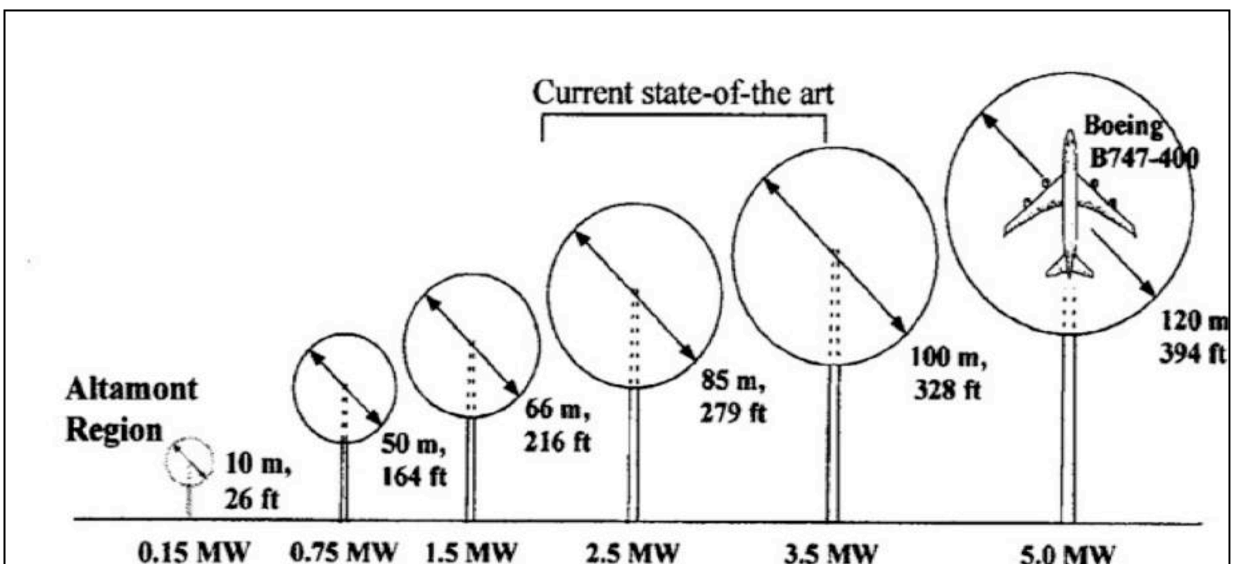
Selling off corridor real estate could be a nice perk for the electric utilities, helping to defray the cost of switching to nuclear power. It would also allow formerly divided communities to reconnect and expand in place.

As we pointed out, this would be especially attractive to urban and suburban agencies tasked with finding environmentally friendly solutions to the challenges of density and livability.
And if we don't have to see a conga line of transmission towers traipsing across the fruited plain, so much the better (wind and solar farms don't exactly enhance the landscape, either.)

The more you think it through, the more obvious it becomes: The scale of the Roadmap is so enormous, its footprint so large, and its impact so invasive, that the actual construction of the farms – as daunting as the national project would be – might be the easiest part of the buildout.



Go big or go home

Sorry, but the Roadmap is not going to be cobbled together by a distributed network of artisanal power cooperatives.

In fact, the BLM (Bureau of Land Management) wants to initiate competitive bidding to award federal land for renewables, which up to now has been granted on a first come / first served basis.

Since low EROEIs mean narrow profit margins, competitive bidding on wind and solar acreage could eliminate all but the biggest deep-pocket outfits.

General Electric makes wind turbines, gas turbines, and nuclear reactors.

So do GE hobbits make the wind turbines, while GE orcs make the gas turbines and reactors?

That won't sit well with the renewables crowd, since one of their emotional selling points is freedom from the evil clutches of Big Energy. Which has always puzzled us:

General Electric makes wind turbines, gas turbines, and nuclear reactors. So do GE hobbits make the wind turbines, while GE orcs make the gas turbines and reactors?

Another emotional selling point they like to use is freedom from Big Energy's evil octopus of a national grid, through the generation of distributed local power.

Even though, in a WWS-powered world, a reliable renewables grid (even a local one) would depend upon viable grid-scale batteries (which don't exist, and likely never will), or a nationwide network of tens of thousands of other wind and solar farms, with thousands of miles of new transmission corridors, to back each other up and deliver power to their local markets.

Fortune 500 companies, billion-dollar construction firms, and defense contractors are the only outfits with enough resources, engineering talent, and financing to get the job done. While rooftop solar can be a decentralized and local (if intermittent) approach to carbon-free power for remote or off-grid areas, it won't run the country.

The politically incorrect truth is:

A nationwide, carbon-free, renewables grid
would be the very essence *of Big Energy.*

Industrializing nature

While most cities and towns haven't been built in the most windacious places, wind farms will have to be. Long-distance transmission will be an integral part of a national renewables paradigm.

While it's hard to calculate the total impact on the Roadmap, long-distance ac (alternating current) transmission lines from rural wind or solar farms can have a line loss approaching 5% or more, reducing their net delivered power.

To ensure connectivity, and to mitigate the unavoidable loss from long-distance transmission, there's been talk of building a "loss-less" (actually low-loss) HVDC national transmission grid (high voltage direct current) in parallel with our existing ac grid.

HVDC would enable any power plant to transmit long distance with minimal loss, and have its power converted to ac at the destination. In fact, HVDC already provides electric transmission from the Columbia River on the Washington / Oregon border to Southern California, a distance of more than 1,000 kilometers.

Regardless of how ac power is generated, the line loss for ac transmission is the same. So this isn't just an issue for wind and solar – an all-nuclear grid could benefit from HVDC as well. But with renewable's low EROEIs, line loss is a particularly important factor in assessing their ultimate worth.

Like we said, with over 50,000 wind and solar farms required for an all-renewables grid,[9] we'll probably need 500,000 miles or more of new transmission lines, at an average of about ten miles per farm, to move power from the farms to our long-distance trunk lines. That's a *lot* of copper.

... with over 50,000 wind and solar farms required for an all-renewables grid, we'll probably need 500,000 miles or more of new transmission lines...

In the near future, we will also have to upgrade our long-distance ac grid to accommodate the Roadmap's much greater power level. This would be an entirely separate expenditure, and even *more* copper.

Eventual construction by mid-century of a national HVDC grid, would be yet another separate undertaking.

Calm down

The foregoing litany of hassles is completely aside from the fact that as global warming increases, there will likely be a 15% calming of worldwide wind by mid-century.[10]

Which will require 15% more wind turbines (which means 15% more money, material and land) to compensate for this reduction of "free fuel."

To be more than fair, we didn't factor wind calming into the bare-bones price tag. Mostly because no one can say exactly how the calming will play out. But since the poles are warming faster than the equator, calming is likely to occur.[11]

That's because two things generate wind: The rotation of the earth (which is unlikely to change), and a temperature difference between two large masses of air.

As the Arctic warms, the temperature difference between the Arctic air mass and the Canadian air mass is reduced. Overall calming, and a shift in wind patterns, will likely result. (The Polar Vortex, the Northern Doldrums . . .)

So whatever long-term generating capacity we're hoping to get from the half-million wind turbines recommended by the Roadmap, we should probably curb our enthusiasm by 15%. Or build 15% more.

And build a parallel HVDC grid for good measure.

CHAPTER EIGHT

"It's a gas, gas, gas!" – Mick Jagger

Folded into the Roadmap is something you don't notice until you read the fine print:

More than 10% of the electricity generated by the Roadmap (182.6 out of 1,591 GWs) will be used to isolate hydrogen gas, which is done by electrolyzing fresh water.[1]

As we mentioned, fuel is storage. Indeed, one tactic of the Roadmap involves using any excess renewable energy to isolate hydrogen for fuel.

Most of the hydrogen (made with 141.4 GWs) will be used to power long-haul trucking; buses; rail transportation and freight; and large-scale waterborne freight and transport. Their on-board fuel cells will use compressed hydrogen to produce electricity to power these large vehicles.

The rest of the hydrogen (made with 41.2 GWs) will be used for process heat, the high temperatures used in industrial processes, by combining the hydrogen with atmospheric oxygen and burning it.

Since those long-haul and heavy-transport GWs would be 9% of our primary energy pie, this is worth exploring in detail.

> NERD NOTE: Hydrogen is isolated by splitting water molecules (H_2O) in electric-powered electrolyzers. The oxygen is released to the atmosphere and the hydrogen is stored in pressurized tanks.
>
> The hydrogen can then be used to make heat by burning it in a combustion chamber. Alternatively, the hydrogen can be used to make some electricity (along with a lot of heat) by running it through a fuel cell.
>
> In either case, it has to be mixed with oxygen from the atmosphere – the same amount of oxygen that was released when the hydrogen was isolated.

Burning hydrogen for process heat is a good idea – when mixed with atmospheric oxygen, it's a high-temperature, squeaky-clean and totally green combustive fuel.

Hydrogen fuel cells, however, are far less efficient. In the process of making electricity, they squander most of the hydrogen's potential energy as waste heat.

Even so, fuel cells play an important role in the Roadmap. And to be honest, they would probably play the same or similar role in an all-nuclear grid.

But still, when you see how these things work . . .

Rube Goldberg must be smiling down from heaven

A hydrogen vehicle is something that would have made Mr. Goldberg proud:

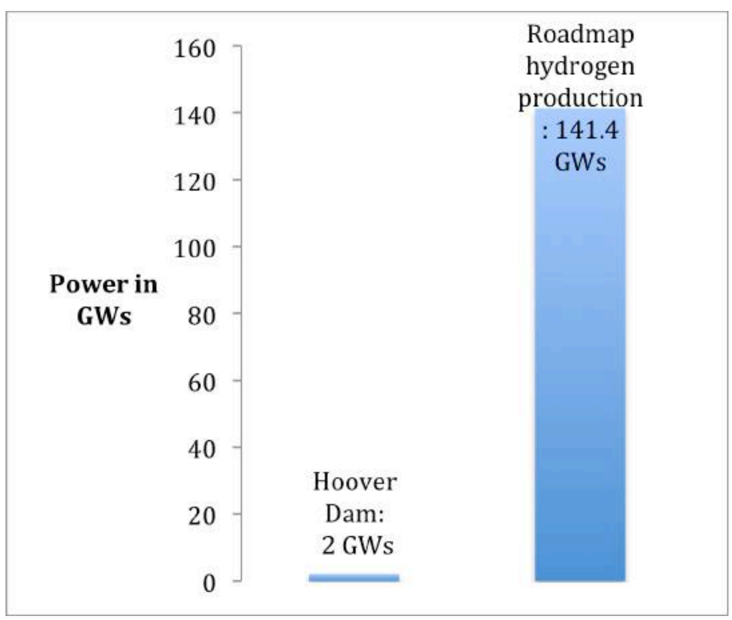
Instead of using electricity to power an EV (electric vehicle), the electricity is used to power an electrolyzer at an H_2 gas production plant.

The electrolyzer sheds copious amounts of waste heat in the process of destroying fresh water to isolate hydrogen, which is then used to fuel a hydrogen vehicle. Which is actually an electric vehicle (EV) with a bunch of hydrogen stuff bolted on.

To be clear: A hydrogen vehicle is an EV with an onboard fuel cell. The fuel cell grabs oxygen from the atmosphere, and combines it with hydrogen from the vehicle's pressurized gas tank, to make heat, water vapor, and electricity to power the EV.

When the process is complete, the water vapor is released out the tailpipe. The heat is wasted as well, in the same way that an internal combustion engine sheds heat as it operates.

In fact, only 26% of the original amount of energy (that was used to split the water to isolate the hydrogen) is ultimately re-generated by the onboard fuel cell, to power the vehicle's electric motor.[2]



Pretty clever, huh?

We'll grant you that it's a pollution-free system, with an endearing Goldbegrian charm, but there are several problems with the scheme, particularly if it's done at scale. And 141.4 GWs qualifies as scale:

Hoover Dam has a peak capacity of "only" 2 GWs, so this hydrogen vehicle thing is Big Stuff. We're talking more than 70 Hoover Dam's worth of power.

Six days on the road

In spite of wasting a lot of primary energy, hydrogen power is still an attractive idea for commercial transportation, where vehicle range, cargo volume, cargo weight, and refueling times combine to affect the bottom line.

A battery-powered class 8 (big rig) tractor-trailer has a range of 60–120 miles, and takes hours to recharge. That's fine for shuffling containers at a cargo port, or taking short hops from port to warehouse. Battery exchange could reduce downtime to a matter of minutes, by using a forklift to swap out a pallet of on-board batteries.

But maximizing cargo volume is what long-haul trucking and freight are all about. That same big rig could go 800–1,200 miles on a tank of hydrogen, and take just 15 minutes to refuel.

The batteries that would be needed to give a big rig the same range as its hydrogen-fueled twin would eat up precious cargo space, to where the numbers don't pencil out for long-haul trucking.

So hydrogen fuel does have its advantages. However, isolating all that hydrogen would do more than just gobble up 141.4 gigawatts, and squandering most of it as waste heat.

It would *also* destroy a lot of fresh water that can't be directly recovered: About 250 ESBs per year, or about 5 hrs of our annual national fresh water use.[3]

In the big picture, that may not seem like much, but those ESBs would add up as the years roll on. True, it's all released as water vapor and will eventually come back to Earth somewhere or other as rain. But still, that's a lot of fresh water to re-purpose in a thirsty world.

So that's the pickle between battery vs. hydrogen rigs. Our guess is that hydrogen will win out as the fuel of choice for long-haul, and for large-scale waterborne freight as well.

Here's why: Reducing precious cargo space in our freight and transport fleets, to accommodate a load of heavy onboard batteries, would be a drag on our domestic economy. Since 70% of our commerce involves consumer goods, delivered by truck, ship, and rail, it's cheaper to build power plants to isolate the hydrogen instead.

"Waste not, want not." – Benjamin Franklin, electrical pioneer

Imagine 105.2 GWs squandered as waste heat. Ben would have a fit.

That's a *lot* of energy, especially when you're gathering it from intermittent spurts of wind and sunlight. To put it in perspective:

Imagine 53 Hoover Dams shedding all their energy as waste heat, in the process of destroying 250 ESBs per year to isolate the hydrogen to move our freight and cargo.

If we're going to waste that much energy, the least we could do is make sure that generating the energy is easy, cheap and reliable, with a small footprint. That's where nuclear energy shines.

Another option for powering heavy transportation, including aircraft, is synfuel. Though it's (almost) carbon-neutral rather than carbon-free, synfuel does have its advantages:

It can be stored, piped, and distributed by our existing fossil infrastructure, and it could power our existing trucks and ships without having to swap out the engines.

Synfuel can also be used in hybrid-electric big rigs, by powering an on-board turbine that generates electricity, giving the vehicle similar range, weight, and cargo capacities as a hydrogen rig.

Then there'd be all that water we wouldn't have to destroy, or desalinate. But there's a hitch:

The challenge of making synfuel is to harvest enough CO_2 from the atmosphere. And thus far, carbon-capture systems haven't been ready for prime time. But they're working on it. And cheap, abundant nuclear power would go a long way toward making the idea feasible – yet another argument for an all-nuclear grid.

Ammonia has also been proposed as an alternative fuel, but the danger of an ammonia cloud released in a traffic accident should give everyone pause.

As you can see, there is no easy solution for carbon-free long-haul trucking, short of turning the rigs into giant slot cars (slot trucks, actually.[4])

A more practical solution may be using induction to charge the vehicle on the fly, essentially a giant version of a wireless cellphone charger embedded in the roadway.[5] But thus far, the transportation sector is leaning toward hydrogen for heavy transport and freight.

CHAPTER NINE

To review (trigger warning: *numbers!*)

The Roadmap's fuel-free grid for 2050 will consist of:

- 1,591 GWs of WWS-generated electricity
- 114.6 GWs of non-electric UTES space heating[1]
- 69.7 GWs of CSP overbuild[2]

Since wave, tidal and geothermal systems are practically non-existent in the U.S. at present, and will only amount to 1.76% of the Roadmap, we've left them out of this discussion.

The 1,591 GWs will also include our existing renewables:

- 47.9 GW of hydro dams (up from our current 28.7 GWs)[3]
- 21.8 GWs of onshore wind
- 4.4 GWs of solar
- 1.9 GWs of geothermal[4]

That's 76 GWs. So at the end of the day, the Roadmap is actually calling for 1,515 GWs of new-build renewables.

That's where we get our 1,515-GW nuclear grid.

And don't forget, the entire backup for the Roadmap's fuel-free national grid would be maybe 7-ish percent of total power, depending on what's available to our intrepid gridmasters on short notice.

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2050 will be here before you know it

As the buildout proceeds and our oversized farms start backing each other up, they will gradually shed their natural gas training wheels until backup and storage become quaint memories.

Interdependent, fuel-free and self-supporting, our clean, green, smart grid will be balanced to a computerized T, despite the vagaries of a changing climate . . .

At least, that's the plan. Some things are worth repeating:

- Our existing grid, primarily energized by baseload (always-on) power plants running on actual fuel, has an overbuild factor of 2.5X, or 150% above our average consumption.
- Fuel = storage. A cord of wood; a load of coal; a water reservoir; a fuel tank or a fuel rod, all essentially act like batteries, in the sense that energy can be extracted on demand and converted to a reliable flow of electric power.
- The Roadmap proposes that we drop our overbuild from 150% to 4.38%, and reduce our reliance on fuel to a nice round number: *Zero.*

> *The Roadmap proposes that we drop our overbuild from 150% to 4.38%, and reduce our reliance on actual fuel down to a nice round number:* zero.

As you may have guessed by now, we think the entire enterprise is ill-advised. Because even if LoadMatch is a flawless suite of software, and even if the smart grid is a screaming genius, *stuff happens.*

Wasn't tomorrow wonderful?

Sorry to pop your bubble, but this rosy vision of a fuel-free future is, to quote Eric Cartman, "a bunch of tree-huggin' hippie crap."

Don't get us wrong – we love trees. And hippies. But in our view, We the People are not going to entrust our national grid to the caprice of Mother Nature without substantial backup, overbuild and storage.

Some WWS fans discount the importance of baseload, and some even dismiss the importance of the grid itself, which is quite odd considering that the renewables they favor will only work in the way they hope if all the farms and rooftops are interconnected by an enhanced and expanded national grid.

A reality check will quickly confirm that our daily lives, and nearly every aspect of business, commerce and industry, are structured around a reliable supply of cheap, high-quality, on-demand energy – in any weather, any time of day or night.

> *A reality check will quickly confirm that our daily lives, and nearly every aspect of business, commerce and industry, are structured around a reliable supply of cheap, high-quality, on-demand energy.*

An advanced society requires a robust grid, delivering silky-smooth power over 99% of the time. So if the completed Roadmap doesn't work as planned, we'll have to make it work with massive overbuild, backup or storage, or some combination thereof.

This presents two problems: Our existing backup technology involves burning methane, and our existing non-fuel storage methods (batteries, pumped hydro, etc.) are completely impractical for the price and scale involved.

Furthermore, we can't assume that a cheap and scalable storage technology will magically appear if we embark on the Roadmap. Good karma doesn't necessarily work that way.

Maybe a fabulous storage solution will reveal itself, and maybe it won't. But the stakes are too high to take a flying leap, and hope that something comes along to save our butts.

This isn't like putting a man on the moon, where we figured it out as we boldly went, inventing Tang and Velcro along the way.

Yes, we pulled off the moonshot, and yes, it did wonders for our national mojo, but it wasn't an existential necessity.

We could have failed in the attempt, and it wouldn't have jeopardized the economy, or our prospects for a livable future.

We're not betting the farm, we're betting the planet

The Roadmap is a fantastically expensive, 35-year nationwide mobilization to fundamentally restructure our entire supply of primary energy.

Addressing our energy needs is nowhere near as glamorous as a moonshot, but it's something we absolutely *cannot* afford to screw up.

Which means that we have to evaluate the feasibility of any proposed solution based on existing technology, and that technology's foreseeable improvements. Which is why we use pumped hydro as our benchmark to evaluate other storage technologies.

A low storage price ($0.20 per installed watt-hour) is one thing, but figuring out how much storage we'll need is quite another. Because like we said, there's no way of knowing how well the Roadmap will actually work, and what augmentation it will need, until a sizeable portion is built and tested over time.

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Germany's track record of renewable energy production gives us some sobering hints[5], but we won't really know how things will work for us until we try it over here.

While Germany is large for a European country, and while it's frequently cited as proof that large-scale renewables can work, it's only the size of Montana. The U.S. is larger than all of Europe, with a much wider variety of landscape and weather.

But even with our considerable advantages and wide-open spaces, can we actually build a fuel-free, self-supporting national grid that needs less than 5% storage? And if we can't, how much backup and storage will we need?

No one can rightly say unless the entire grid, and the weather it would likely encounter, can be accurately modeled over time. Which the authors of the Roadmap contend they have done, even though climate change makes long-term weather prediction a shot in the dark at a moving target.

The consequences of taking the wrong fork in the road, on such a vital issue as powering the entire national grid, could hobble our ability to get back on track. So even though we must act, we must first choose carefully.

Decisions, decisions . . .

One of the many drawbacks of the Roadmap is that it's an all-or-nothing proposition. Which means that it will either become a vital and enduring part of our national infrastructure, or a horrifically expensive herd of green elephants trampling the countryside.

Since it's an undisputed fact that fuel can reliably power the nation, you would think that the response to climate change would be a transition to carbon-free fuel, rather than a transition to fuel-free systems.

... you would think that the response to climate change would be a transition to carbon-free fuel, rather than a transition to fuel-free energy systems.

We contend that the overblown fear of radiation and contamination – and the overblown costs that result – are the main reasons why this self-evident solution isn't being pursued.[6]

Indeed, the carbon-free fuel of choice comes down to nuclear energy, since there isn't anywhere *near* enough hydroelectric potential in the U.S. to do the job (you'll get a great perspective on this in the next chapter.)

The Roadmap, however, proposes an aggressive transition to a fuel-free paradigm. This is so radically different from what we have now – or what we could have with an all-nuclear grid – that it can't even be compared to changing horses in mid-stream.

It's more like changing to a beast we haven't ridden before, while charging into the future at a breakneck gallop. And if the stunt doesn't work we'll land on our wallet, so hard that we might not be able to get back on the horse.

CHAPTER TEN

If things don't go according to plan . . .

We will have to expand storage, or backup, or both. By how much is anyone's guess, and since anyone includes us, we'll give it a shot. Let's start with storage.

At pumped hydro's $0.20 per installed watt-hour, we'll be spending $1.27 Trillion for 4 hours of all-grid storage. That's 1,591 GWs for 4 hours, or 6,364 GW-hours.

Aside from the preposterous amount of fresh water required (Remember those 23 days of fresh water consumption?) the price is somewhat reasonable, as far as non-fuel storage goes.

What's unreasonable is the whole idea of energy storage backing up a fuel-free national grid. As you can see, even the best and cheapest technology doesn't scale without a significant disruption to another vital utility – our national water supply.

Quite aside from that pesky problem, $1.27 Trillion is nearly half the cost of an entire Molten Salt Reactor grid. And that is our main issue with renewables:

The numbers simply aren't there.

For the cost of just 4 hrs backup for a WWS grid (which probably wouldn't be enough), we could build nearly ***half*** of an entire national MSR grid.

> *For the cost of just 4 hrs backup for a WWS grid (which probably wouldn't be enough), we could build nearly* half *of an entire national MSR grid.*

And unlike a renewables farm, each reactor would be a fully independent power plant, placed exactly where we need it, with 18 months of storage built right in, and plenty more where that came from.

While it's true that big-ass batteries are being developed, assuming that they can be scaled up to support the grid is exactly that: *an assumption*.

And like they say in the world of construction, where simple mistakes can injure and kill: "Assume" makes an a-s-s out of u and me.

All of which means that overbuilding our generating capacity is the only halfway-realistic option. As we pointed out, our existing fueled grid has an overbuild factor of 2.5X. In our view, it's foolish to consider anything less for renewables.

But since the Roadmap's authors are so confident of their modeling, perhaps they would consider a modest 1.5X overbuild (one and a half times the bare-bones grid.) That comes to $22.8 Trillion – not including backup and storage.

And keep in mind, that also includes 1.5X the land, or more than 196,800 square miles, up from 131,200. Then there are all the extra transmission corridors, and the copper wire, plus an additional offshore region half the size of West Virginia.

And, we'll need to replace (and recycle) 1.85 million m^2 per day of worn-out panels, up from 1.23 million m^2 – forever. Plus there'll be all those extra panel and turbine factories, when we're already two years behind schedule, and the clock is ticking.

Remember those best-year-ever Xes? They'll go up by 1.5X, too: Wind turbine production would have to ramp up from 17X to about 25X, and panel production from 29X to 43X.

Then there's the price: A modest 1.5X buildout (with virtually no storage) would require a yearly outlay of $651 Billion for 35 years. That's higher than our 2018 military budget, and nearly as large as our social safety net.

Adding a WWS buildout to the federal budget, even the bare-bones Roadmap of "just" $15.2 Trillion, is something that Washington is unlikely to do, no matter which party is in charge. But it was fun to pencil out.

Are we over-making our point? Perhaps. But just to overdo it a little bit more, there's something else to consider that blows up all of our tidy guesstimates.

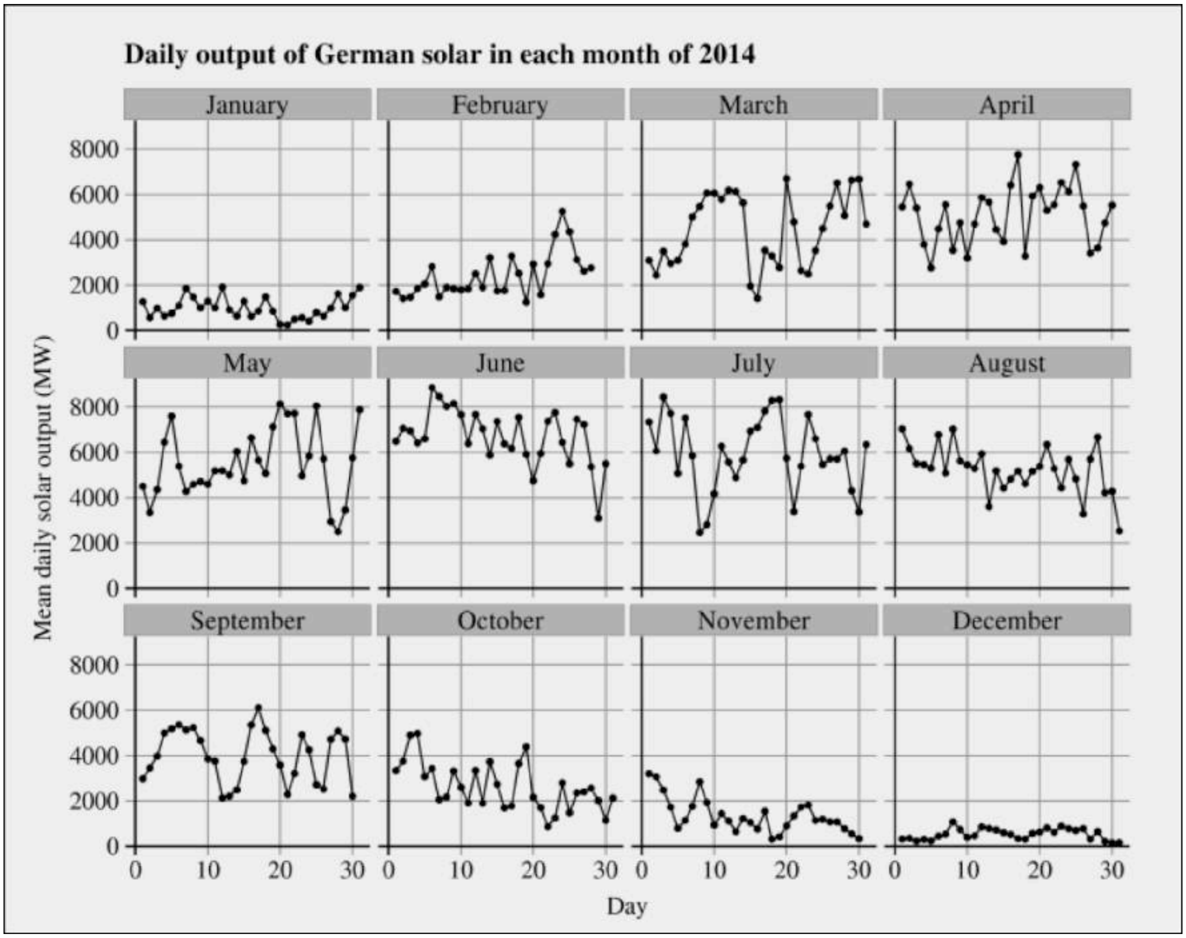
... after a long summer of high-capacity days, the winter production of an entire region's solar farms can dwindle to a trickle for weeks or even months.

'Tis the season

If you recall, capacity factor (CF) is a *yearly* average.

It's a big-picture number which obscures the fact that after a long summer of high-capacity days, the winter production of an entire region's WWS farms can dwindle to a trickle for weeks or even months.

For example, check out Germany's pitiful winter solar statistics: [1]



Sluggish performance can sometimes last for weeks on end. Their "solution" has been to keep burning lignite (brown coal), the dirtiest coal there is.

Here at home, if a polar vortex comes swooping out of nowhere when we're already in a seasonal slump, the wind farms that would normally back up our socked-in solar farms could be stuck in the doldrums as well.

The Roadmap projects thatit will need 1,300 GWs of all hydro power (dammed hydro plus pumped storage) in January 2055. Even though the buildout will only produce 105 GWs from dammed hydro...

Remember way back in Chapter One, where we mentioned the Clack Evaluation? The analysis of the Roadmap written by 21 top climate experts?[2]

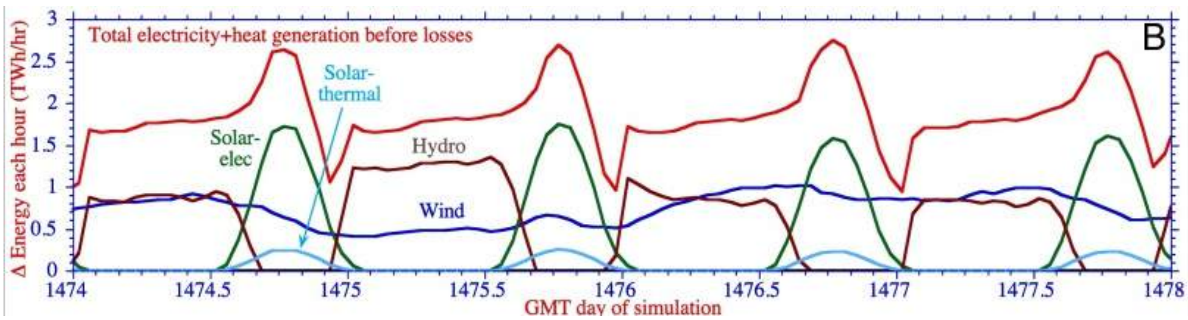
Here's the big take-away from their report:

The Roadmap projects that it will need 1,300 GWs of hydro power (dammed hydro plus pumped storage) in January 2055. Even though the buildout will only produce 105 GWs from dammed hydro.

That buildout, plus our existing 22 GWs of pumped hydro, will total 127 GWs of maximum production, if we turn on all the spigots at once – less than 10% of the 1,300 GWs we'll need.

Like we said, the numbers don't work.

Dr. Clack and his colleagues extracted the following graph from the Roadmap's supporting study, which utilized LoadMatch's computer modeling projections:[3]



The numbers across the bottom of the graph are days 1,474 through 1,477 of the 6-year simulation that Dr. Jacobson and his colleagues ran on the years 2050–2056. (The ".5" numbers are high noon of each day.)

The top wavy red line is the total power that the model says we'll need during those four days in mid-January of 2055.

According to the Roadmap, our 2055 power demand will be supplied by the four technologies plotted on the graph below the top line: Solar electric (PV), solar-thermal (CSP), hydro and wind.

Note clearly that the big brown terawatt-sized square humps in the graph are modeling projections of hydro *demand*, as distinct from the hydro the Roadmap would actually *supply*. It's what we'll need, not necessarily what we'll have.

All four renewables must contribute their share of power as marked on the graph, or else we'll end up short. And from what we (and Clack *et al*) can determine, the Roadmap's hydro contribution would come up 90% short in the darkest days of winter.

Here's where it gets interesting

Let's examine those big brown humps more closely. Our dammed hydroelectric generating capacity in 2015 was 79 GWp (p = peak, as in "maximum production.")[4] At a generous 36% capacity factor, that's 28.7 GWs average.

As we pointed out in Chapter 6, the Roadmap calls for expanding our hydroelectric annual average (not peak) production from that 28.7 GWs average to 47.9 GWs average, a factor of 1.66X.

This expansion is supposed to be accomplished by adding additional turbines to our large dams, along with increasing the operating hours of the existing turbines.

It is unclear from the Roadmap what portion of the 1.66X increase will ~~be~~ come from the new turbines. If we assume that half the new turbines will generate half the extra power, their share of the increase would be 1.33X. This 50-50 scenario would raise our national dammed hydro capacity to 105 GWp (1.33 × 79 = 105.)

And don't forget, we'll still have our existing 22 GW of pumped hydro. So that storage, plus the increase to 105 GW from the new turbines, totals 127 GWs. Hold that thought.

Now look at the writing along the graph's vertical axis: "Energy each hour (TWh/hr)." That means the hour-by-hour production rate of the entire grid, measured in terawatts. (A terawatt is a trillion watts.)

Now look at the power curves plotted on the graph. Notice that the highest brown hydro hump (on day 1,475) rises to 1.3 TW, which is 1,300 GWs.

The problem is, we'll only have 127 GWs of maximum hydro capacity to respond to that demand. And that's if our 50-50 scenario is even roughly accurate.

Like we said earlier, the total supply of hydro power would be less than 10% of the 1,300 GWs demand for same.

And note clearly that the big brown hydro humps on those four consecutive days in mid-January of 2055 aren't just momentary spikes. Quite the contrary: They are continuous 12-hour demands, from about midnight through the lunch hour. In mid-winter.

The 90% shortfall (about 1,200-ish GWs) will simply be unavailable. Because remember, an integral part of the Roadmap is to decommission all of our fueled power plants by 2050. By 2055, the United States will be a fuel-free zone.

First, the Solutions Project claims to predict the weather 35 years in the future. And then, *their own chart* shows that we will only have 10% of the hydro we need.

The truth is, we'll never have anywhere *near* 1,300 GWs (1.3 terawatts) of hydro, even if we wanted it. Because that much hydro power would require the flow and volume of nearly 100 Mississippi Rivers (no, that's not a typo.[5])

And unfortunately, we can't build more rivers.

Dr. Jacobson has responded to the Clack Evaluation point-by-point, and Dr. Clack has replied.[6] Expect the debate to continue, because even if the Roadmap had no other issues, this by itself is a fundamental flaw.

Oddly enough, the Roadmap does offer a remedy if natural gas doesn't turn out to be the backup hero that renewables need, a strategy that's euphemistically called Demand Response, or DR. We prefer to call it:

Tough love through power rationing

Stripped of all the happy talk, Demand Response boils down to the re-scheduling or postponing of private, public, commercial and industrial activity in response to an energy shortage. In California, they call it a "flex alert."

This would be accomplished by reducing power consumption as availability dictates, up to and including outright shutdowns if demand can't be responded to. (To be fair, a demand for power can always be responded to: A shutdown is a response to a demand.)

We'll all have to learn how to make hay while the sun shines.

DR boils down to: It's a cloudy day and the flags don't flap – no juice for you!

The externalized cost of DR to our industrial sector isn't part of the Roadmap, but it could easily run into billions of dollars: If a factory can't get enough electricity from nine to five, they'll have to invest in extra machinery to make up for lost production when the lights come back on.

We'll all have to learn how to make hay while the sun shines.

The Roadmap aims to minimize DR downtime by siting enough farms in enough locales, based on the accumulated wisdom of historical weather patterns, with the expectation that past trends will likely continue, in spite of climate change.

They warn you in the stock market that past trends are not indicative of future results. You would think that with a changing climate, this pithy caveat would find wider application. Because just like the stock market, the weather is a notoriously fickle beast.

And because it is, how can we expect to keep the lights on without actual fuel or other means of storage, if (or rather, when) the proverbial black swan flies north for the winter instead of south?

Relying on a fuel-free, weather-dependent grid, with virtually no overbuild, backup or storage, is a recipe for national disaster.

And the price tag for a WWS grid with adequate overbuild, backup and storage is a recipe for national bankruptcy.

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Which is why, if for no other reason (and as you have seen, there are several), the Roadmap is doomed to failure.

The whole enchilada (with green sauce)

Our existing grid, with over 8,000 electric power plants[7] is thought to be the largest and most complex machine in the world. The Roadmap proposes to grow the machine by nearly 7X, and expand its carrying capacity by 3.4X.[8]

While the Roadmap doesn't call out specific wind farm sizes, we'll venture a guess that the new farms would probably average 500 MWs (our existing wind farms average 135 MWs.) With the amount of wind called for in the Roadmap, that comes to 4,842 new onshore and offshore wind facilities.

The Roadmap does call out the number of new solar farms: 48,753. So new wind and solar farms for 2050 could amount to perhaps 53,600 large plants, plus an additional 1,364 CSP plants for overbuild.

Since the Roadmap calls for a shutdown of fossil and nuclear, the only remnants of our current grid would be our existing wind and solar and our 1,756 hydro dams.

Add those plants to the Roadmap's new wind and solar facilities, and we're up to something like 58,000 plants.

But wait! There's more!

The Roadmap also calls for 75 million residential rooftop solar systems and 2.7 million commercial rooftop systems. And all of these systems, large and small, from farm to rooftop, are supposed to sing "Kumbaya" in perfect harmony 24 / 7 / 365.

In principle, it's a compelling idea: Since electric-driven systems are far more energy efficient than fossil-driven systems, a 100% electric paradigm would be a great way to conserve energy, even with a growing population.

And though we applaud the goal of an all-electric primary energy grid, we're leery of the proposed means of production, especially but not limited to its cost, complexity and practicality.

With the massive buildout the Roadmap has in mind, our manufacturing base will have to mushroom overnight, and those factories will have to be plugged into a rock-solid, reliable grid, running 24 / 7, to accommodate the nationwide mobilization.

Ensuring stable, high-quality power during a 35-year buildout, especially when that buildout is coupled with a simultaneous shutdown of fossil and nuclear, will require massive volumes of natural gas, for at least the first half of the project, if not more.

The growing instability of Germany's grid is a cautionary tale. Their factories have had to purchase expensive backup batteries and generators to smooth the many destabilizing incidents caused by wind and solar's penetration of their national grid.

When an injection-mold factory suffers a power glitch, for example, the computerized machinery resets and the plastic dries in the molds. It's an expensive, icky, time-consuming mess.

Interventions by Germany's gridmasters used to be just a handful of incidents a year. Now they're up to more than 1,000 per annum, with no let-up in sight.

The industrial base of our own buildout will encounter similar issues, unless each new WWS farm contributing power to the grid has an excellent set of training wheels.

This underscores the point that wind and solar can't produce enough reliable power to enable their own paradigm shift, an irony that should not be overlooked.

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Energy feudalism

A thought may have occurred to you: The Roadmap would be a huge jobs program.

Pretty much – the pyramids were weekend warrior projects in comparison. But even though the Roadmap would generate millions more jobs than an all-nuclear grid, we don't see that as much of a selling point, despite being widely touted as such.

In fact, we see it as a major disincentive. We should explain . . .

Until about 1800, virtually all labor was performed by humans and other beasts of burden. Indeed, prior to mechanized farm equipment, it took 20 humans to raise enough food for 22 humans.

The extra two humans were the nobility and the privileged; everyone else was the underclass and tied to the land.

Today, only 1–2% of our populace is involved in agriculture. This frees the rest of the country to get on with the other important work that goes into building and maintaining an advanced civilization.

In our view, the same criteria should apply to the energy sector, and for much the same reason:

Assembling a massive work force devoted to building and maintaining the national grid depicted in the Roadmap would amount to energy feudalism. Indeed, it would be far better for the country if energy required as little labor as agriculture.

There's so much important work to do! Something as rudimentary as keeping the lights on shouldn't consume our resources, land and labor. To cite just one example, the U.S. needs to repair or rebuild nearly 60,000 bridges.[9]

> ... a clean, efficient, and reliable grid built and run by a tiny sliver of the work force would free us to do a lot more than produce enough power so we could produce more power.

If we didn't have anything else that needs doing, the Roadmap might be all right as a jobs program to keep a restless population occupied, which some archeologists think the pyramids were mostly about.

But we desperately need to repair and augment our entire national infrastructure, not just the energy sector. And though we'll need a lot of clean energy to get the job done, most of the work should be devoted to actually rebuilding the country.

In the same way that agricultural advances have freed us for other tasks, a clean, efficient, and reliable grid built and run by a tiny sliver of the work force would free us to do a lot more than produce enough power so we could produce more power.

We're not hamsters, or serfs.

"Everything counts in large amounts." – Depeche Mode

The Roadmap would be the largest construction project in history: The pyramids, the Great Wall of China, Three Gorges Dam, nothing even comes close. And we're just talking about the U.S. portion of the Solutions Project's ultimate vision: A WWS-powered world.

We'll confine our analysis to the Roadmap's U.S. wind and solar systems, which would comprise over 95% of our national WWS fleet.

Once our dams are upgraded, they'll constitute 3% of the fleet. But geothermal, wave, and tidal will essentially be decimal dust.

Bottom line: The Roadmap will live or die on the performance of wind and solar.

CHAPTER ELEVEN: SOLAR

The sunny side of the street

Our 60-year price tags, and our land projections for the Roadmap's PV (photovoltaic) systems, are based on the latest NREL numbers (National Renewable Energy Laboratory) from September 2016.

Our prices include the original panel installation, with foundations, mounting racks and labor, plus one full replacement of all panels and three replacements of all inverters, including labor, based on SunPower's standard of a 40-year average lifetime for their panels.[1]

Inverters are the gizmos that transform a panel's dc current into grid-ready ac current, and last about 10,000 on-off cycles. With perpetually clear skies, an inverter would only cycle once a day and last about 27 years.

But in the real world, clouds happen. Three interruptions (cycles) a day reduces an inverter's lifespan to 9 years, which means 6–7 replacements in a 60-year span.

To be more than fair, we presumed that our solar farms would be sited in the very best locales, and figured on just three replacements in 60 years.

The Roadmap implies three different capacity factors expected for residential rooftop, commercial rooftop, and utility PV (big solar farms), but they're all right around 21%.

Which is pretty darn optimistic, since actual rooftop solar capacity factors in the U.S. are currently in the mid-teens.[2] But since the Roadmap is probably anticipating technical improvements and optimum siting, we'll go with their numbers.

Utility PV solar, and commercial rooftop solar, use various sized panels, but the technology is the same – they just use more or less solar cells per panel. So we'll be calculating how many square meters (m^2) of panel are needed for each system, rather than how many panels.

To be more than fair . . .

We'll use the latest (2016) PV panel efficiency, which is substantially better than the 2013 model used in the Roadmap.

The authors of the Roadmap have always favored the SunPower E20 series, which now produces more watts. [3] From the Roadmap's Table 2, we've deduced that the panel used in their 2013 calculations delivers a peak performance of 134 watts-ac (watts of alternating current) per square meter, after the inverter changes it from dc to ac.

We'll be using SunPower's 2016 model E20-435, which cranks out a blistering 160 watts-ac / m^2 after dc-ac inversion.[4]

We'll also apply a 28% price discount to all utility PV systems, and a 23% discount to all PV rooftop systems. Both discounts are based on NREL's latest near-future cost projections.[5]

Despite the specious claim that Moore's Law can be applied to solar panels, improvements in photovoltaic manufacturing, installation, and conversion efficiency are flattening out.

Interestingly enough, the greatest portion of these NREL discounts don't come from a reduction in panel cost, but from a reduction in the BOS cost (Balance Of System, meaning everything but the panels): A 21% reduction for utility PV BOS, and a 15% reduction for rooftop BOS.

We know what you're thinking: If efficiency keeps improving and the costs keep dropping, won't our calculations be out of date as quickly as the Roadmap's?

Not really. Despite the specious claim that Moore's Law[6] can be applied to solar panels, improvements in photovoltaic manufacturing, installation, and conversion efficiency (see nerd note below) are flattening out. [7]

Most of the recent cost improvements in solar have come from manufacturing and installation, rather than increases in panel efficiency. But there are some hopeful manufacturers with the ambitious goal of improving a panel's conversion efficiency from its present in-the-field average of less than 17% to a dazzling 25%.[8]

In spite of the fact that many physicists believe this would require a dramatic technical breakthrough, we've factored the hoped-for 25% conversion efficiency into our cost calculations anyway.

However, we didn't reduce our land calculations. That's because there's no way of knowing if 25% efficiency will ever be achieved, and if so, when. Land has to be reserved decades in advance, or other development may gobble it up. So we based our land calculations on the industry's present-day conversion efficiency.

[NERD NOTE: Conversion efficiency is the panel's ability to convert a percentage of the sun's energy falling on the panel into dc electricity.

Don't confuse Conversion Efficiency with Capacity Factor, which is the total energy (in watt-hrs) that is *actually* produced by a panel in a 365-day period.

This is expressed as a percentage of total energy that *could* have been produced under impossibly perfect conditions in ~~during~~ that same period of time: A sunny, cloudless sky, 24 hrs a day, for an entire year.

Capacity Factor depends ~~up~~on a ~~the~~ panel's location. Conversion Efficiency depends ~~up~~on solar cell design and fabrication.]

So to be *way* more than fair, we'll be using:

- The latest 160-watt (ac) panels
- An assumed 25% solar-to-electric conversion efficiency breakthrough (which would up the 160-watts ac performance to nearly 200 watts)
- 28% discount for utility PV costs
- 23% discount for rooftop PV costs

We think you'll agree that if we bent over backwards by any more than that, we'd fall out of our chairs. But even with all these gimmes, we'll still show you how PV solar would be an expensive and ineffective way to power the nation.

Before we dig into the digits, however, there's one last thing we should address: A number in the Roadmap's Table 2[9] that makes their total solar farm footprint much smaller than it could possibly be.

Even if it's just a typo, it deserves to be mentioned.

Elbow room

The technical term is "packing factor" and the idea is simple: How much wind or solar gear can you pack into a given patch of land for maximum power production?

With wind and solar's meager EROEIs (Energy Returned on Energy Invested), it's vitally important that no panel is ever in shadow and that every turbine's propeller can catch a fresh breeze.

In the world of solar energy, fixed-mount (stationary) PV panels need a little less room than single-axis track-mount panels, which are motorized to follow the sun.

Taking both mounting methods into account, the average solar packing factor for the continental U.S. is about 40%: One square kilometer (1 million square meters) of a solar field will have 400,000 square meters of panel surface.

Packing factor is ultimately determined by latitude: Since panels have to face the sun, they're tilted to compensate for how far north or south they are from the equator. At 45º latitude, panels are tilted at 45º. At the equator (0º latitude), they're parallel to the ground.

In either case, the panels cast a shadow, below the panels at the equator or behind the panels when they're north or south of the equator. And the farther from the equator, the longer the shadow.

The shadow area becomes the service path, the area between the solar arrays (long racks of panels) where installers and maintenance personnel can move about.

The problem is, column 7 of row 9 in Table 2 of the Roadmap (we *told* you we read the whole thing!) implies a packing factor of close to 100%. That means that all utility PV panels would have to be packed side by side, with almost no maintenance paths and no room for shadows.

Which of course is impossible, unless we move everything down to the equator, and do the maintenance from beneath the panels, and string an HVDC cable up to our southern border. Not a likely scenario.

So it sure seems like a typo, but regardless, it greatly reduces the Roadmap's estimate for the amount of land needed for its multitude of utility PV farms.

We wanted to walk you through the weeds on this because our estimate of total land needed for utility PV is much more than the acreage called for in the Roadmap.

☼☼☼

Alrighty, then!
After that 25,000-word preamble,
let's run the numbers . . .

☼☼ ☼

Green acres – PV solar farms

The Roadmap calls for 2,326,000 MWp-ac (megawatts peak of alternating current) generated by 46,480 PV farms. That requires 14.5 billion m^2 (square meters) of 160-watt ac panels, on land slightly greater than Maryland and Rhode Island, with a 40% packing factor.[10]

Granted, Maryland and Rhode Island aren't big states, and in any case most of our solar would be in the southwest deserts. (Remember, we're just using eastern states for illustration purposes, because they happen to be the right size for easy visual comparison.)

NREL's cost for utility PV is $1.75 an installed watt.[11] Panels are 44% of the installation price, and inverters 7% and labor 9%, totaling 60% of initial cost.[12]

The rest is for racks, wiring, grid connection, etc. One panel replacement and three inverter replacements (for a 60-year comparison to nuclear) adds 80% to the original price.[13]

The Roadmap's utility PV solar breaks down as follows:

- 14.5 billion m^2 of panels
- Initial installation: $4.1 Trillion[14]
- With one panel replacement and three inverter replacements: $7.4 Trillion[15]
- Minus 28% (NREL's utility PV future discount), 60-year cost = **$5.3 Trillion**

According to the Roadmap, our utility PV farms in 2050 would deliver 488.9 GWs average, or 30.7% of the 1,591-GW grid, for 34.9% of total cost.

Utility PV quick numbers:

- *490 GWs*
- *31% of grid*
- *35% of cost*

Not such a bad deal. But there are major feasibility issues to consider, which we'll explore in the PV summary below.

Up on the roof

The Roadmap calls for rooftop solar on more than 75 million homes, averaging a modest 5 kWp (five kilowatts peak) per installation.

We have about 100 million single-family homes and mobile homes in the U.S., so that's 3 out of 4 dwellings.

Since only 700,000 U.S. homes currently have panels, this would be a goldmine for local contractors. Even though their skills and effort would be better utilized by rebuilding the rest of our national infrastructure.

One big problem with rooftop solar is that all panels have to face south. Finding 75 million south-facing residential rooftops with unobstructed exposures might be a challenge. And cutting trees to eliminate shade can be environmentally worse than having no panels at all.

That's largely why the BOS cost of residential solar is higher: The racking is rarely a straight run, like it is on a flat commercial roof or on open ground.

But there's an even bigger problem:

Residential solar is a big, fat waste of money

Sorry, but it had to be said.

We know how popular rooftop solar is, and since it is so popular, we'll walk you through the numbers so you'll understand how we arrived at our admittedly unpopular conclusion.

When the homeowner doesn't pay full boat, their fellow taxpayers have to kick in the balance.

One thing to keep in mind as we proceed: We're discussing *actual costs*, without the good-deal discounts a homeowner can snag with rebates and tax credits.

While residential solar can seem like a bargain to the consumer, we're focused on the actual cost to the nation as a whole. When the homeowner doesn't pay full boat, their fellow taxpayers have to kick in the balance.

There is no free lunch, even in "Solartopia."[16]

First off, rooftop PV is traditionally expressed in terms of direct current, not alternating current like utility (big farm) solar. That's probably because dc numbers are bigger – inverting from dc to ac always entails a loss of power.

And, big numbers sound better in a sales pitch to the low-information homeowner. So if you ever peruse the back pages of the Roadmap, heads up on that, or the numbers won't make sense.

The Roadmap calls for 379,500 MWp-dc (megawatts peak of direct current) from residential rooftop solar. But since inverting from dc to ac loses 15% of the energy, residential systems would actually deliver a cumulative net of 322,600 MWp-ac. (See what we mean about the numbers?)

Generating that much power would require more than 2 billion m^2 of 160 watt-ac panels (2,016,093,709 to be exact, but who's counting?)According to NREL, sloped-roof residential is $2.93 an installed watt (dc),[17] which pencils out to $1.1 Trillion for the initial installation.[18]

Panels and inverters are just 38% of total price,[19] because the BOS cost (racks, wiring, etc.) and the soft costs like permits, interest, and insurance are pricier for residential work.

One panel replacement and four inverter replacements add about 71% to the original cost.[20] Since both commercial and residential rooftop systems must contend with shade from trees, buildings, and other obstructions, their inverters cycle more often and thus wear out faster.

The Roadmap's residential solar breaks down as follows:

- 2 billion m^2 of panels
- Initial installation: $1.1 Trillion
- With one panel replacement and four inverter replacements: $1.9 Trillion[21]
- Minus 23% (NREL's rooftop future discount), 60-year cost = **$1.5 Trillion**

According to the Roadmap, rooftop residential would deliver 63.3 GWs, or 3.98% of the 1,591-GW grid, for 9.9% of the cost.

Residential PV quick numbers:

- *63 GWs*
- *4% of grid*
- *10% of cost*

Like we said, it's a big, fat waste of money.

Which rankles the hell out of the pro-nuclear (read: pro-math) crowd. And here's why:

That same $1.5 Trillion, which would fund less than 4% of a 1,591-GW all-renewables grid, could fund half of an entire Molten Salt Reactor grid.

Which is something that our nation could easily afford, and actually accomplish, in the time we have to act.

Big roof = mo' betta (but not by much)

Commercial, industrial, and government rooftops are tantalizing territory for solar expansion, but the numbers are nearly as dismal as they are for residential systems.

NREL says that flat-roof systems cost $2.13 per installed watt (dc).[22] The Roadmap calls for 276,500 MWp-dc from commercial rooftop systems, which inverts down to 235,000 MWp-ac.

Since the BOS cost and soft costs are less for commercial work, panels and inverters make up 46% of total price.[23] One panel replacement and four inverter replacements adds 78%.[24]

The Roadmap's commercial rooftop solar breaks down as follows:

- 1.5 billion m^2 of panels
- Initial installation: $590 Billion[25]
- One panel replacement and four inverter replacements: $1,050 Billion[26]
- Minus 23% (NREL's rooftop future discount), 60-year cost = **$810 Billion**

According to the Roadmap, commercial rooftop PV would deliver 51.4 GWs, or 3.24% of the 1,591-GW grid for 5.7% of the cost.

Commercial PV quick numbers:

- *51 GWs*
- *3% of grid*
- *6% of cost*

Not quite as bad as residential rooftop, but it's still a bad idea.

PV summary

Over the conservative 60-year life of a reactor, the Roadmap would need 36 billion square meters of high-performance 160-watt panels. Here's how we arrived at that number:

- Utility PV: 14.5 billion
- Residential: 2 billion
- Commercial: 1.5 billion
- Sub-total: 18 billion
- With one panel replacement: 18 + 18 = **36 Billion m^2 of panels**

Even with factoring in NREL's future cost discounts – which partially depend upon improved panel conversion efficiency – the 60-year cost for PV would still be **$7.6 Trillion.**[27]

That's 38% of the grid for 50% of the cost. Which isn't such a hot deal. And like we said, there are major feasibility issues (see below).

All PV Solar quick numbers:

- *605 GWs*
- *38% of grid*
- *50% of cost*

The Roadmap requires the installation of 18 billion m^2 of panels, over three-quarters of which would have to be racked and operating in the first 15 years of the buildout.

Which, if we had started on time, would be the years 2015–2030. (To keep things simple, we'll just use the years in the Roadmap's snazzy graphic.)

Installing 13.5 billion square meters in fifteen years comes to 2.47 million m^2 a day for 5,475 days (15 years), rain or shine.

In the remaining twenty years of the Roadmap (2030–2050), we could kick back and install the last 25% of the panels (4.5 billion m^2) at the leisurely rate of 616,400 m^2 a day.

Then we can chill for five years, until the panel party starts all over again. And when it does, it'll never end.

Treading water

Assuming that SunPower's panels will actually last 40 years[28], and further assuming that their technology becomes the industry standard, the nation's panel industry could actually take a break for 5 years after the buildout, and use the downtime to gear up for a future of replacing and recycling 1.23 million m^2 per day, rain or shine, forever.

And mind you, all that busy work won't expand our power grid – it'll just maintain what we've already built.

As we said, if the buildout can be likened to a 35-year mobilization of World War II proportions, then maintaining an all-renewables grid would be like an endless Cold War, waged against global warming by a renewable-industrial complex.

... maintaining an all-renewables grid would be like an endless Cold War, waged against global warming by a renewable-industrial complex.

Also keep in mind that if Dr. Jacobson's dream comes true, and the entire industrialized world embarks on their own Roadmaps, there's a very good chance that we will have to do all of our panel manufacturing and recycling right here at home, including the inverters.

Quite aside from the challenge of ramping up our manufacturing base (17X for wind and 29X for solar[29]), there are serious doubts that most Americans would tolerate the mining and waste involved in extracting and refining the raw materials.[30]

And we haven't even discussed wind machines.

Mining and refining wind's rare earth requirements (approximately one tonne of neodymium magnets per 5-MW generator)[31] has been making a hellacious mess in China. They control 95% of the world's rare earth production, and have few pollution controls on the industry.

The environmental costs are downright ghastly,[32] and yet it's been comfortably out of sight of the world's WWS advocates, who by and large have ignored the situation. (We don't pollute – China does it for us.)

But as we pointed out, if the Roadmap gets implemented around the world, as Dr. Jacobson and his colleagues hope, we will have to fabricate most or all of our own PV panels and wind turbines The envionmental impacts of the domestic mining, manufacturing and recycling would be substantial and ongoing.

If and when domestic production skyrockets, stringent pollution controls will significantly drive up the cost of a homegrown Roadmap. Which, to be more than fair, we haven't factored into our calculations.

Before we get into wind, there's one other solar system we need to visit:

CSP Solar

We saved concentrated solar power for last because it's such an oddball: At 7.3% of the bare-bones fleet, it's the only wind or solar technology with built-in backup (just for over night and just for itself, but still . . .)

And completely aside from the fleet CSP, a separate contingent of CSP farms will constitute the entirety of the Roadmap's 4.38% overbuild.

Fleet CSP will generate 227,300 MWp-ac, contributing 116 GWs to the 1,591 grid, or 7.3% of total power.

Overbuild CSP will generate 136,400 MWp-ac producing 69.7 GWs, equal to 4.38% of the grid.

Taken together, they'll generate a total of 363,700 MWp for an average of 185.7 GWs, with the advantage that they can operate after sundown.

(By the way, if you use these numbers to calculate CSP's capacity factor, you'll get a misleading figure of 51%. It's really about half that value. The reason for the discrepancy is that CSP farms play fast and loose with their numbers.[33])

One drawback of CSP is that the land requirement is 2.4X of what's needed for utility PV solar. We used the Andasol CSP plant in southern Spain as a basis of comparison, since it's been up and running for a while and our own CSP plants are brand new. Our CSP should get similar results for land density: 0.039 km^2 / MWp-ac.[34]

Which means that the Roadmap's fleet CSP, plus its overbuild CSP, will need a grand total of 14,200 km^2 of land, or a smidgen more than Connecticut.

Cost estimates for CSP vary, depending on how much storage the plant would have. Table S-14 of the Roadmap gives a range of costs, including projected future discounts, which we've boiled down to a long-term average of $5.94 per Wp-ac.[35]

That's substantially less than Andasol's price of $8.00 (USD) per watt. But we'll go with the Roadmap's lower number and chalk it up to American ingenuity

Since simple curved mirrors and clean molten salt should last for decades, no replacement costs are anticipated.

Fleet CSP will generate 7.3% of the grid, and cost $1.35 Trillion.

Overbuild CSP would equal 4.38% of the grid, and cost $810 Billion.

Total CSP (fleet + overbuild) would be 363,700 MWs, and cost **$2.16 Trillion.**

Fleet CSP quick numbers:

- *116 GWs*
- *7% of grid*
- *9% of cost*

Overbuild CSP quick numbers:

- *70 GWs*
- *Equal to 4% of grid*
- *5% of cost*

Not as good a bargain as PV solar, but CSP can work after sundown – if it was a sunny day.

CHAPTER TWELVE: WIND

"It's always amazed me that anyone would suggest or believe that the world's flimsiest fluid [air] could be harvested for energy by the engineer's least efficient convertor – a propeller."

– Dr. Alex Cannara (advanced degrees in math and engineering)

Onshore wind: It's all over the map

Since wind needs lots of elbow room, determining the actual land requirement is an important bit of penciling. We call it "land density" – the amount of land needed per X amount of energy produced.

Since a wind turbine has a tiny footprint (the base of the tower) but needs lots of elbow room for its blades to catch a fresh breeze, land density is the proper method of wind farm land estimation.

And while it's true that a wind farm can be planted in a wheat field, the greater truth is that wind companies are harvesting wind, not wheat. So the rationale of wind's "real" footprint being just the base of the towers, is misleading.

One of our gimmes for onshore wind is that we accept that 70% of it would be on sweet spots in the midwest. But the remaining 30% would take up far more land than than an entire national nuclear footprint.

Although not directly stated in the Roadmap, its land density for wind can be derived as 0.089 km^2 / MWp.[1] In an email we received from Dr. Jacobson, he confirmed the 0.089 value we deduced from his paper.[2]

That number is about one-quarter of NREL's estimation of 0.345 km^2, from their 2009 survey of U.S. wind farms.

In other words, the Roadmap claims that wind can produce 4X the power per square kilometer that NREL says it can.

Part of this wild discrepancy is because NREL took into account the irregular terrain (creek beds, odd property shapes, etc.) they encountered in their analysis in 2009. Another part is due to the fact that wind technology has improved.

Even so, the only way the Roadmap's number could work is by siting their wind farms on flat, ideal, wide-open spaces.

To be more than fair, we'll go with the Roadmap's density estimate for onshore wind. But as dense as the Roadmap can lay out its wind farms, it still needs nearly 6X the land for its PV solar, which weighs in at a svelte 0.016 km^2 per MWp.[3]

> [NERD NOTE: For all you foot-and-inch types, there are 2.59 square kilometers (km^2) in a square mile.]

~~So~~ While the Roadmap's land for PV solar is equal to Maryland and Rhode Island (literally every square foot of land in both states), its land estimate for onshore wind is a bit larger New York state, while its area for offshore wind is a bit larger than West Virginia.

If you trust NREL's land-for-wind estimates better than the Roadmap's (as we do), figure on New York, Pennsylvania, Vermont and New Hampshire for onshore wind.

Elbow room on the lone prairie

The Roadmap calls for 1,701,000 MWp of onshore wind. With an expected capacity factor of 28.9%, onshore wind will generate 492 GWs average, or 30.9% of the 1,591-GW grid.[4]

By 2015, we already had 73,400 MWp installed. So we'll need to fabricate (and / or import) 1,627,600 MWs more.

Their plan is to use the humongous new 5-MW turbines. That comes to 325,500 more onshore spinners.

With more moving parts than a solar panel, an onshore wind assembly will only last 10–25 years before the propellers and the mechanical contents of the nacelle (the housing atop the tower) will need to be refurbished. But the tower and foundation should last as long as a reactor.

With more moving parts than a solar panel, an onshore wind assembly will only last 10–25 years before the propellers and the mechanical contents of the nacelle (the housing atop the tower) need to be refurbished.

In 2014, the U.S. DoE (Department of Energy) estimated that 2-MWp wind assemblies cost about $1.71 per installed Wp (peak watt).[5]

Factoring in economies of scale and engineering advances, we've applied a 20% discount to the fabrication and installation of the Roadmap's proposed 5-MW monsters. So anticipate $1.37 / Wp for wind during the buildout.

Two turbine refurbishment companies, one in Europe and one in the U.S., have told us that a complete overhaul, including rebuilding or replacing the blades, averages 10% of initial cost.

For a 60-year lifespan of the Roadmap's onshore wind:

- Initial installation for new onshore wind: $2.2 Trillion
- With two overhauls: **$2.6 Trillion**

Onshore wind has the best value of any WWS system in the Roadmap: 30.9% of total energy, for 17.1% of total cost. A nearly two-for-one bang for the buck.

Onshore Wind quick numbers:

- *490 GWs*
- *31% of grid*
- *17% of cost*

Offshore wind

A 2011 IRENA study (International Renewable ENergy Agency) concluded that offshore wind is twice the cost of onshore systems.[6] That's $2.74 per installed Wp, with the same 20% discount that we applied to onshore.

The Roadmap calls for 780,900 MWp of offshore wind, with a brisk capacity factor of 38.8%, that would generate a yearly average of 304 GWs, or 19.1% of the grid.[7]

But in the harsh marine environment, mechanical equipment and blades only last about 10–15 years. So three overhauls, not two, will be needed over 60 years.

We have generously ballparked the overhauls at just 10% of initial cost, the same as onshore wind, even though offshore turbines are serviced at sea.[8]

- Initial installation: $2.1 Trillion
- With three overhauls: **$2.73 Trillion**

Though it's not the same bargain as onshore wind, offshore still has more bang for the buck than solar: 19.1% of total energy, for 18% of total cost.

Offshore Wind quick numbers:

- *305 GWs*
- *19% of grid*
- *18% of cost*

Wind summary

Wind will comprise 50% of the Roadmap's 2050 grid: 30.9% from onshore, and 19.1% from offshore, for a 60-year price tag of **$5.33 Trillion.**

That's half the grid's total power, for one-third of the grid's total price. Pretty good deal. In fact, some might say it's tempting to just power the entire grid with wind alone. But there's a catch:

While onshore wind is the best bargain on the menu, the amount of land it gobbles up makes it utterly impractical as a silver bullet to power the entire country, even if we could afford the energy storage – which we can't.

Even with a wind density factor of 0.089 km^2 / MWp, it would take 489,600 km^2 to generate the Roadmap's entire 1,591-GWs average with onshore wind.

That's 189,000 square miles, equal to every square foot of Florida, Georgia, South Carolina, and half of North Carolina . . .

Sorry, ~~but~~ that just ain't gonna happen. Even way out west.

FINAL REMARKS

In case you weren't keeping score . . .

We gave the Roadmap fourteen gimmes:

- We set the lifespan of a reactor at a conservative 60 years.
- We calculated pumped hydro at the lowest quintile of $0.20 an installed watt-hour.
- In our mineral calculations, we didn't include copper for transmission wires and silver for the curved mirrors of the overbuild CSP farms.
- We assumed that solar farms would be sited in the very best locales, to keep inverter replacements down to 3 swap-outs in 60 years.
- We accepted the Roadmap's 21% capacity factor for rooftop PV solar, even though the current CF for U.S. rooftop is in the mid-teens.
- We assumed a 25% solar-to-electric conversion efficiency, even though the industry is currently averaging about 17%.
- We used the latest 160-watt / 40-year hot-rod panel, and presumed that it would become the industry standard.
- We applied a 28% future discount to utility PV, and a 23% future discount to rooftop PV.
- We used the Roadmap's land density estimation for wind, even though it's one-fourth of the NREL estimate. And mind you, NREL based their estimate on what they found at dozens of actual, operating U.S. wind farms.
- We didn't apply a premium to the cost of refurbishing the Roadmap's 156,000 offshore wind turbines, even though it will clearly be more expensive than refurbishing onshore turbines.
- We didn't beat up the solar industry for its toxic waste stream, even though the daily fabrication and recycling of 1.23 million square meters of PV panels would make a major mess.
- We also didn't beat up the wind industry for its toxic waste in China. Even though solar and wind waste makes nuclear "waste" pale in comparison.
- We didn't apply a premium to U.S. domestic wind and solar fabrication costs.
- We went with the Roadmap's much lower price for CSP, rather than the real-world costs encounted in Andasol, Spain.

And after all that, the Roadmap *still* doesn't pencil out. Like we said, were not pro-nuclear, we're pro-math.

(Actually, we're pro-nuclear *because* we're pro-math.)

How can the U.S., in good conscience, commit to such an expensive and unproven scheme as the Roadmap? When it doesn't even hang together on paper?

As we see it, there are two reasons why the Roadmap has become so popular:

a) the public doesn't fully understand what it would actually entail, and / or:
b) their fear and loathing of all things nuclear make renewables seem like the only option to save the planet.

Hopefully, we've put a big dent in (a). And Part Two of this book will hopefully put an even bigger dent in (b).

Oops. We forgot to tell you, but this is Part One of an upcoming book titled *Power to the Planet.* Part Two will be an in-depth (and entertaining) exploration of nuclear energy and nuclear reactors, with an emphasis on our favorite reactor.

Plus we'll address every halfway sensible objection to nuclear power that we can find. And some of the crazy ones, too. So watch this space. In the meantime, check out the links in the end notes.

But most of all, stay engaged, speak up, and do yourself (and everyone else) a favor – think long and hard about what you've read here. But most important:

Be willing to change your mind.

Fight truth decay!

If you haven't guessed by now, we're both politically left of center. And yes, we did say that science should be above politics. So why are we even bringing it up?

Because tribalism and partisanship are killing us.

In our experience, too many lefties are stubbornly irrational about nuclear energy, and too many righties are stubbornly irrational about AGW (anthropogenic global warming.)

To admonish the folks on our side of the aisle: A liberal (as distinct from a doctrinaire leftie) is by definition open to new ideas. As the British philosopher and mathematician Bertrand Russell once said:

"The essence of the Liberal outlook lies not in what *opinions are held,*
but in how *they are held: Instead of being held dogmatically,*
they are held tentatively, and with a consciousness that
new evidence may at any moment lead to their abandonment."

John Maynard Keynes put it more bluntly. A Cambridge-educated economist whose ideas were favored by president Franklin Roosevelt, Keynes responded to an antagonistic politician with these immortal words:

"When the facts change, I change my mind. What do you do, sir?"

The wild rumors of a million deaths from Chernobyl, and of Fukushima poisoning the entire Pacific Ocean, are as provably false as the wild rumors that Saddam Hussein was in cahoots with al-Qaeda, and had a direct connection to 9/11.

Fear mongering, misleading statements, weasel words, cherry-picked facts and outright lies have no political affiliation.

Small world, big planet

Humans have always had tribal minds. The problem is, we now have a global reach.

Bits of our trash wash up on someone else's beach, no matter how diligently we try to recycle. We just *think* we throw our trash away. But in truth, there is no "away."

We're all right here, on a small, crowded, and rapidly warming planet, with a populace that uses the oceans and the atmosphere as trashcans.

By the way, there is a practical and well-developed technology to reduce any form of trash down to its component atoms: Plastic, for example, reduces to elemental carbon, oxygen, hydrogen, etc. But powering enough plasma-arc furnaces[1] to effectively address the world's trash will require terawatts of clean, cheap energy.

This is not a drill

Published in August 2017, a sobering meta-study[2] concludes that we only have a 5% chance of keeping global warming below 2 degrees Celsius, unless we put climate change at the forefront of our concerns, and keep it there.

The paper strongly urges severe reductions in carbon emissions, to avoid even greater temperature rise. We've already released enough excess carbon to guarantee a rough ride for the next several centuries.

It's baked in the cake. So we need to do two things at once:

- Rapidly reduce the volume of carbon we're dumping into the atmosphere and oceans, with the ultimate goal of zero emissions.
- Actively *remove* excess carbon from the atmosphere and the oceans, until we restore the planet's heat budget.

How to accomplish the first one is obvious: Switch to a clean energy paradigm ASAP. Something with, say, a one-decade buildout (nuclear comes to mind . . .)

But realize that the only thing rapid carbon reduction will accomplish is to take the edge off a tough situation. We also need to *reverse* the damage we've done.

To do that, we must capture the billions of tonnes of carbon we've dumped into the atmosphere and oceans, and put it back where we got it – the crust of the earth.

The environmental imperative of getting to zero emissions, and then actively reversing our carbon footprint, will create global industries demanding terawatts of cheap, clean, reliable power. That's *in addition to* the power needed to cleanly recycle our trash.

And we have to do all the above while we're generating enough energy to run the machinery of civilization.

After 150 years of making a mess, Mother Nature wants us to start cleaning up after ourselves. Otherwise she'll do it for us. And we won't like it if she does.

Power to the planet!

There is a school of thought that says we need to power down civilization. While it's true that we as individuals should consume less energy, we as a global civilization of more than 7 billion people actually need to power up.

Simply put: The world needs all the clean, carbon-free energy it can get.

But there's a catch: That energy source will have to be cheaper than coal, and just as reliable. Or the world will keep right on using coal.

Nuclear fission can generate all the carbon-free energy the world needs, with enough left over to deal with our trash and actively reduce our carbon backlog.

The solution exists – without reinventing the waterwheel, or hoping the weather cooperates, or relying on a herd of green elephants with training wheels. Nuclear power is a well-proven, scalable technology that can be deployed in the time we have to act.

The new Gen III+ reactors offer substantial improvements in efficiency, safety, standardization, and ease of construction. And the upcoming Gen IV reactors are material in case of a malfunction.

We favor the MSR in particular because we feel it's the best Gen IV design to fulfill these requirements. Proponents of other designs will beg to differ, but good people can disagree. That's why they make Chevys and Fords.

The road ahead will be rough. But a steady supply of clean, cheap and abundant energy will significantly enhance our ability to adapt to climate change, and mitigate its worst effects, by restoring the energy budget of the planet and the pH level of the oceans.[3]

This is the challenge of our era, and will always be our legacy. That includes all of us, because there are no passengers on Spaceship Earth. We are all crew.

Go nuclear or go extinct.

END NOTES

CHAPTER ONE

1. http://web.stanford.edu/group/efmh/jacobson/Articles/I/USStatesWWS.pdf
   "Roadmap." Originally published in the journal *Energy & Environmental Science*

2. http://www.thesolutionsproject.org

3. http://www.pnas.org/content/114/26/6722.full *"Clack Evaluation."*

4. http://www.timothymaloney.net/Critique_of_100_WWS_Plan.html "*Critique*"
   (This paper by Tim Maloney is the basis of *Roadmap to Nowhere.*)

   See internal footnote # 33. It refers to:

   http://www.nrel.gov/docs/fy09osti/45834.pdf

   Land-Use Requirements of Modern Wind Power Plants in the United States. See Page 10, Table 1, Average Area Requirements row, Total Area column: 100 hectare units (ha) = 1 km^2. 34.5 ha / MWp **= 0.345 km^2 / MWp** capacity-weighted average per NREL study in 2009.

   Ibid. Chapter One End Note #1. *Roadmap*. See:

   Table 2, row 1, column 4: 1,701,000 MWp nameplate capacity of existing plus new plants. 1,701,000 MWp × 0.345 km^2 / MWp = 586,800 km^2 total area for onshore wind, per NREL data (without taking into account capacity weighting of future new construction on clear flat land.)

   Table 2, row 1, column 5: 3.59% existing, so 96.41% new construction. 0.9641 × 1,701,000 MW = 1,640,000 MW new construction, using 5-MW wind turbines.

   When NREL made its survey in 2009, such giant 5-MW wind turbines did not exist. Using larger / taller turbines can result in an improved land density value. This is part of the Roadmap's strategy.

   Note clearly that when NREL made its survey in 2009, these giant 5-MW turbines didn't even exist. So using larger machines result in more energy production per acre, which is the Roadmap's strategy. Hence the improved land density numbers.

Row 1, column 8: 1.5912% × 9.162e6 km2 (US total land area) = 145,800 km^2 for new onshore wind construction. Anticipated new land-use density with 5-MW giant wind turbines: 145,800 km^2 ÷ 1,640,000 MW = **0.089 km^2 / MWp** (0.0889).

So on the face of it, there is a discrepancy factor of 3.9X between NREL's and the Roadmap's land usage. [0.345 km^2 ÷ 0.089 km^2 = 3.9]

Alternatively: Total onshore wind area: 145,800 km^2 ÷ 0.9641 = 151,200 km^2 per *Roadmap*. Or 1,701,000 MW × 0.0889 km^2 / MW = 151,200 km^2.

NREL total wind area ÷ *Roadmap* total wind area: 586,800 km^2 ÷ 151,200 km^2 = 3.9X factor of difference.

5. *Ibid*. Chapter One End Note #2. *Critique.* See internal footnote # 22.7. Round to 160W-ac / m^2 for discussion & estimation.

   Also see: http://www.nrel.gov/docs/fy13osti/56290.pdf

   See page 12, Sec. 4.2.1: Evaluation of PV Packing Factors. Page 13, Figure 7, Capacity-weighted average packing factor for PV projects. Fixed (mount) column: 47% packing factor (PF). 1-axis (tracking) column: 34% packing factor (PF).

   Average = 40.5%, round to 40% for discussion & estimation.

   Ibid. Chapter One End Note #1. *Roadmap*. See Table 2, row 9, column 4: 2,326,000e6 W.

   2,326,000e6 W ÷ 160 W / m^2 ÷ 1e6 m2 / km^2 = 14.54e3 km^2 total PV panel area. Land area is PV panel area ÷ PF: 14.54e3 km^2 ÷ 0.40 = 36,300 km^2 total land area for utility-scale PV solar, per NREL-derived data.

   Table 2, row 9, column 7: 0.18973% of 9.162e6 km^2 US total land area = 17,400 km^2 land area for utility PV solar, per *Roadmap*.

   NREL total PV solar area ÷ *Roadmap* total PV solar area: 36,300 km^2 ÷ 17,400 km^2 = 2.1X factor of difference.

6. http://www.thesolutionsproject.org/resource/50-state-visions-infographics/

   Step 1. Click to download 50states_PDFs_all. In the Downloads folder, unzip and open the folder named 50states_PDFs_all.

   Step 2. Double-click the Adobe Acrobat PDF icons for the 11 “great plains” states: North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, Minnesota, Iowa, Missouri, Illinois, and Indiana.

Upon viewing each state's info graphic, record on paper the state's name and its percentage of Primary Energy to be provided by onshore wind. Do this on lined paper with seven drawn columns. Percent of PRI NRG from onshore wind goes in the column second from the left (column 2).

Step 3. Find each state's Primary Energy consumption in the year 2013 by entering in your browser bar:

https://knoema.com/atlas/United-States-of-America/North-Dakota/Energy-consumption

Record the large-font number at upper-left, which is North Dakota's PRI NRG in units of billions of BTUs. In your column 3, write about 4 significant digits.

On a calculator move the decimal point 6 places to the left to express in units of quadrillion BTUs, called Quads, unit-symbol Q. Do not write it on the paper. Multiply by the conversion factor 293 TWh /Q to convert to terawatt-hour units of Primary Energy. Record in column 4.

Repeat this process 10 more times by replacing "North-Dakota" with the other states' names in the browser bar. (South-Dakota is hyphenated.)

Step 4. Multiply each state's 2013 Primary Energy in column 4 by the following factors to obtain its estimated Primary Energy demand in year 2050, per the Roadmap's expectation of energy reduction.

Write all 11 of the factors into column 5 before starting. These factors were obtained from the Roadmap's Table 1, column 8, "% change in end-use power".

ND = 0.631; SD = 0.709; NE = 0.707; KS = 0.625; OK = 0.615; TX = 0.598; MN = 0.646; IA = 0.717; MO = 0.596; IL = 0.619; IN = 0.628.

Record the multiplication results in column 6.

Step 5. Multiply each state's estimated PRI NRG in column 6 by its onshore wind percentage from column 2. Record the result in column 7. That gives each state's onshore wind-supplied energy in year 2050, expressed in TWh units.

Step 6. Add all 11 states' wind consumption to obtain 3038 TWh in year 2050.

Then divide 3038 TWh by 4309 TWh to obtain 0.705, rounded to **70%**. This is the portion of the nation's onshore wind that will be located on open flat ground.

The value 4309 TWh is obtained from the Roadmap's Table 2, onshore wind row, 30.92% in column 3. Multiply 30.92% × 13,937 TWh to obtain 4309 TWh. The value 13,937 TWh /year is the Roadmap's standard-demand load, namely 1591 GW, converted into annual TWh energy units by multiplying by 8760 hours /yr.

Step 7. With 70% of 2050's onshore wind capacity located on flat land where the minimum land usage value 0.089 km^2 /MW pertains, that leaves 30% in harder locations where the NREL study's 0.345 km^2 /MW pertains. Calculate the weighted average of those two values as:

0.70 × 0.089 km^2 + 0.30 × 0.345 km^2 = 0.166 km^2 /MW. Round to **0.17 km^2 /MW** as the best estimate and working figure for onshore wind discussion.

Comparison to the Roadmap's simple optimism gives a **discrepancy factor of about 2X**. [0.17 km^2 ÷ 0.089 km^2 = 1.9]

7. *Ibid.* Chapter One End Note #1. *Roadmap.* See frame 8 of PDF, journal page 2098. This is the Roadmap's Table 2, row 9, which covers Solar PV utility plants:

   2,326,000e6 Wp-ac ÷ 160 Wp-ac / m^2 [power rating of SunPower series E panel] = 14.5 billion m^2 for utility PV panels.

   Table 2, row 7 covers residential roof PV: 379,500e6 Wp-dc ÷ 186 Wp-dc / m^2 [SunPower series E panel] = 2.0 billion m^2 for residential PV panels.

   Table 2, row 8 covers commercial roof PV: 276,500e6 Wp-dc ÷ 186 Wp-dc / m^2 = 1.5 billion m^2 for commercial PV panels.

   All three PV solar systems: 14.5 + 2.0 + 1.5 = 18 billion m^2 of panel area.

8. *Ibid.* Refer to 14.5e9 m^2 of utility PV panels. Rooftop PV solar: 379,500e6 W-dc (residential) + 276,500e6 W-dc (commercial) = 656,000e6 W-dc combined.

   Sunpower dc power density: 158 Wp-ac / m^2 ÷ 85% conversion eff. = 186 Wp-dc / m^2.

   Rooftop panel area: 656,000e6 Wdc ÷ 186 W / m^2 = 3.5e9 m^2 of rooftop PV panels. Combined utility & rooftop: 14.5e9 m^2 + 3.5e9 m^2 = 18.0e9 m^2 total panel area.

   Replaced over 40-year lifetime: 18.0e9 m^2 ÷ 40 yr ÷ 365 days = 1.23e6 m^2 per day.

9. *Ibid.* Chapter One End Note # 2. *Critique.* To determine the cost of the Roadmap, search in *Critique* for:

"Total W&S build-out cost"
"Money cost Utility PV Solar"
"Money cost Residential PV Solar"
"Money cost Commercial PV Solar"
"All three PV solar categories combined"
"Money cost Onshore Wind"
"Money cost Offshore Wind"
"Money cost CSP Solar"

10. http://www.youtube.com/watch?v=yEHf5K9AQjY at 44:55

11. *Ibid.* Chapter One End Note #1. Roadmap. See frame 7, journal p. 2097, bottom row, column 3:

a) 1591 GWavg total end-use power in 2050
b) 1591 GWavg × 4 hours = 6.36e12 W-hr of energy storage

Unit cost = $0.20 / W-hr

See also:

http://reneweconomy.com.au/pumped-hydro-the-forgotten-storage-solution-47248/

See the 7th paragraph:

6.36e12 W-hr × $0.20 / W h-r = $1.27 trillion construction cost for PHES
$15.2 T (from End Note #3) + $1.27 T = $16.5 Trillion

$16.5 Trillion ÷ 35 years = $471 Billion / year

12. *Ibid*. Chapter One End Note # 2. *Critique.* See internal footnote No. 65.5:

a) Average cost of KEPCO-UAE project is $22.7 billion
b) $22.7 B ÷ 5600 MWp = $4.05 / Wp
c) $4.05 ÷ 92% CF = $4.41 / Wavg for KEPCO Gen 3+ APRs

Cost of 1,515 GWavg APR nuclear fleet: 1,515 GW × $4.41 / W = $6.7 trillion

Also, see internal footnote No. 66:

a) Near-term and future cost estimate of US Gen 3+ AP (Advanced Passive) reactors = $5.53 / Wp
b) $5.53 ÷ 92% CF = $6.01 / Wavg
1,515 GWavg required of Gen-3+ AP fleet × $6.01 / W = $9.1 trillion for Gen-3+ Advanced Passive technology.

13. http://innovationreform.org/wp-content/uploads/2017/07/Advanced-Nuclear-Reactors-Cost-Study.pdf

Page 10, Figure 4. Capital Cost Results. Project the rightmost two bars (MSRs) to vertical axis, at about $2000 /kW = $2 /W.

14. https://www.thenational.ae/uae/government/construction-of-uae-s-first-nuclear-reactor-complete-but-operation-delayed-to-2018-1.42360

15. https://www.eia.gov/analysis/studies/powerplants/capitalcost/ See:

Table 1: Supercritical coal (no Carbon Capture & Storage)
Table 2: Advanced Pulverized coal (no CCS)

16. *Ibid.* Chapter One End Note #1. *Roadmap*. Supplemental Information (SI) section begins at Frame 28. See Table S14 on pages 66 & 67 of SI (Frames 93 & 94).

17. *Ibid*. Chapter One End Note #2. *Critique.* See internal footnote No. 66:

a) Near-term and future cost estimate of US Gen 3+ AP (Advanced Passive) reactors = $5.53 / Wp
b) $5.53 ÷ 92% CF = $6.01 / Wavg

1,515 GWavg required of Gen-3+ AP fleet × $6.01 / W = $9.1 trillion for Gen-3+ Advanced Passive technology.

18. https://www.vox.com/2016/2/29/11132930/nuclear-power-costs-us-france-korea

19. *Ibid*. See Figure 10 in the section "South Korea Actually Lowered Costs." Notice that overnight construction costs have declined since 1980.

20. http://www.environmentalprogress.org/big-news/2017/2/13/why-its-big-bet-on-westinghouse-nuclear-bankrupted-toshiba

21. *Ibid*. Chapter One End Note #12. Compare the bar heights to $4 / MWp (shown as $4,000 / kW), the approximate KEPCO price for the U.A.E. project.

22. *Ibid.* End Note #12, Chapter One. See Page 10, Figure 4: "Capital Cost Results." Project the top of the two rightmost vertical bars (one of them is the ThorCon MSR) to the vertical axis. They're both at about $2000 / kW = $2 / Watt.

    Of that $2000 / kW capital cost for complete installation, about $1000 to $1200 /kW ($1.00 to $1.20 /W) is for direct construction /manufacturing cost. That cost is shown by the red portion of the vertical bars.

    https://aris.iaea.org/PDF/ARISThorCon9.pdf See page 21, sub-section "Low Costs."

23. http://energyfromthorium.com/pdf/CivilianNuclearPower.pdf

24. http://www.environmentalprogress.org/big-news/2017/6/12/atomic-humanism-as-radical-innovation-2017-keynote-address-to-the-american-nuclear-society

25. https://www.youtube.com/watch?v=2yBePJrKmws&t=206s

    At 3 minutes, 20 seconds: Vermont Yankee protesters eating bananas. See also:

    https://www.youtube.com/watch?v=LjQpvTg8i7k

26. http://www.dailykos.com/story/2016/03/18/1503359/-Wind-and-Solar-s-Fukushima-The-Methane-Meltdown-at-Porter-Ranch. See section "An Inconvenient Truth 2.0"

CHAPTER TWO

1. https://www.eia.gov/totalenergy/data/monthly/pdf/flow/css_2016_energy.pdf

2. https://www.eia.gov/totalenergy/data/monthly/pdf/flow/electricity.pdf
   consumed to generate electricity = 38.52 Quads
   Gross generation of electricity = 14.69 Q
   Generation efficiency = 14.69 Q ÷ 38.52 Q = 0.38
   0.38 × [39% of PRI NRG] = 15% of PRI NRG

3. http://www.goodreads.com/quotes/32944-there-are-no-passengers-on-spaceship-earth-we-are-all

4. http://www.timothymaloney.net/Critique_of_100_WWS_Plan.html *Critique.*

5. https://www.nrc.gov/docs/ML1034/ML103490041.pdf

Generic Aging Lessons Learned (GALL) report, Nuclear Regulatory Commission, frame 602, page × E1-2

6. https://www.wecc.biz/Reliability/2014_TEPPC_Transmission_CapCost_Report_B+V.pdf page 2-3, Table 2-1

7. http://www.pnas.org/content/114/26/6722.full

8. http://thorconpower.com/docs/domsr.pdf See page 17, 4th paragraph:
"A big shipyard . . . could easily manufacture 100 one-GW-e ThorCons per year."
So two big shipyards = 200 GWavg annually. Therefore 1,515 GW ÷ 200 GW / year = 7.6 years.

9. http://www.huffingtonpost.com/victor-stenger/lftr-a-longterm-energy-so_b_1192584.html See p. 307, Figure 3

10. http://thorconpower.com/docs/domsr.pdf

11. https://en.wikipedia.org/wiki/Liquid_fluoride_thorium_reactor

12. http://boingboing.net/2017/07/31/nuclear-energy-is-the-safest-m.html

https://www.nextbigfuture.com/2011/03/deaths-per-twh-by-energy-source.html

13. https://www.cbsnews.com/pictures/the-wacky-inventions-of-rube-goldberg/4/

14. https://us.sunpower.com/sites/sunpower/files/media-library/data-sheets/ds-e20-series-327-residential-solar-panels.pdf

See also *Ibid.* Chapter Two End Note #4. *Critique.* Search for "Land Use Utility PV Solar", then see 15th paragraph. Also see internal FN 22.5.

15. http://www.tomdispatch.com/post/175621/tomgram%3A_michael_klare,_a_thermonuclear_energy_bomb_in_christmas_wrappings/

16. From Chapter One End Note #5, we take the value of 1,591 GWs, minus the following:

a) Existing wind production of 21.8 GWavg in 2015 (*Critique* FN 67.3), with
b) Existing solar production of 4.4 GWavg in 2015 (*Critique* FN 67.7), with
c) Expected hydro production of 47.9 GWavg in 2050 (Roadmap, Table 2, row 5, 3.01%).
d) Expected geothermal production of 2.0 GWavg in 2050 (Roadmap, Table 2,

row 4, 1.25%).

Therefore 1,591 GWs - [21.8 GW + 4.4 GW + 47.9 GW + 2.0GW] = 1,515 GWs

17. https://web.stanford.edu/group/efmh/jacobson/Articles/I/USStatesWWS.pdf
Roadmap. From Table 2, row 9:

2,326,000 MWp-ac ÷ 160 Wp-ac / m^2 = 14.5e9 m^2 of solar panels.
To calculate PV land area divide by packing factor PF = 0.40 (40%). Obtain 36.3e9 m^2 = 36,300 km^2 land area; or 14,000 sq mi for utility PV solar farms.

Use the onshore wind farm density of 0.17 km^2 / MW, derived in Chapter 1, end note #5. From *Roadmap* Table 2, row 1: Wind capacity is 1,701,000 MW × 0.17 km^2 / MW = 289,200 km^2 land area; or 111,700 sq mi.

Combined PV & onshore wind = 14,000 + 111,700 = 125,700 sq mi for wind & PV solar.

Use the CSP land density of 0.039 km^2 / MWp that describes the Andasol CSP farm in Spain (see *Critique* footnote No. 86). In the Roadmap's Table 2, rows 10 and 11, CSP capacity = 227,300 + 136,400 = 363,700 MWp. Multiply by 0.039 km^2 / MW to obtain 14,200 km^2, or 5,500 sq mi for utility CSP farms.

Total onshore wind and solar: 125,700 + 5,500 = 131,200 sq mi

18. *Ibid.* Chapter Two End Note #11. See page 15 ff

CHAPTER THREE

1. https://www.livescience.com/15084-radioactive-decay-increases-earths-heat.html
2. http://energystoragesense.com/pumped-hydroelectric-storage-phs/
3. http://web.stanford.edu/group/efmh/jacobson/Articles/I/CountriesWWS.pdf
4. https://www.eia.gov/tools/faqs/faq.php?id=87&t=1
5. https://www.eia.gov/tools/faqs/faq.php?id=427&t=3

   See 5th line in list: "hydro power"

CHAPTER FOUR

1. http://www.ecomodernism.org/

   Download the Manifesto pdf.

2. http://www.timothymaloney.net/Critique_of_100_WWS_Plan.html *Critique.*

   See internal footnote No. 12

3. https://www.youtube.com/watch?v=qcm1gmPL50s

4. http://www.pe.com/2017/01/23/ivanpah-solar-plant-built-to-limit-greenhouse-gases-is-burning-more-natural-gas/

5. https://en.wikipedia.org/wiki/Global_warming_potential

6. https://www.dailykos.com/stories/2016/03/18/1503359/-Wind-and-Solar-s-Fukushima-The-Methane-Meltdown-at-Porter-Ranch

7. https://www.kcet.org/redefine/socalgas-aliso-canyon-leak-a-disaster-for-climate

   37,000 tonnes methane leaked is equivalent to annual emissions of 195,000 passenger cars.

   Total amount of methane leaked from Porter Ranch was 94,000 tonnes, according to CARB. By proportion, 94,000 tonnes / 37,000 t = 2.54. Multiply 195,000 cars × 2.54 = 495,000 cars. Assume 12,000 miles / yr @ 20 miles / gal; 495,000 cars × 12,000 mi / yr ÷ 20 mi / gallon = 297 million gallons of gasoline.

8. Carbon-free electric generation avoids about 405 kg CO_2 emission per megawatt-hour of production, assuming that it replaces natural gas-fueled Combined Cycle Gas Turbine (CCGT) electric plants.

   California wind and solar produced 20 million MW-hrs in 2013 (stated as 20 billion kW-hrs in the fourth paragraph).

   https://www.forbes.com/sites/jamesconca/2014/10/02/are-california-carbon-goals-kaput/

   Therefore California's wind and solar avoided 405 kg CO_2 / MW-hr × 20 million MW-hr = 8.1e9 kg CO_2 = 8.1 million tonnes CO_2 avoided in 2013.

Per California Air Resources Board (CARB) the Porter Ranch total emission was 94,000 tonnes of methane. At a GWP of 84X, that's 7.9 million tonnes of CO_2 equivalent (CO_2-e).

7.9 million tonnes ÷ 8.1 million tonnes avoided = 98%. Therefore nearly one year's worth of emissions benefit was wasted by Porter Ranch.

9. http://www.theenergycollective.com/energy-post/2375967/wind-and-solars-achilles-heel-what-the-methane-meltdown-at-porter-ranch-means-for-the-energy-transition

See: "From Sea to Shining Sea."

10. http://blogs.edf.org/energyexchange/2013/01/04/measuring-fugitive-methane-emissions/

See 4th paragraph.

11. *Ibid*. See 1st paragraph.
12. http://cgnp.org/
13. http://www.sandiegouniontribune.com/sdut-diablocanyon-naturalgas-2016jul03-story.html
14. http://norewardisworththis.tumblr.com/post/64845798933/snl-quien-es-mas-macho-sketch-from-21719
15. http://windpower.sandia.gov/other/080983.pdf

    See Page 16.

    https://us.sunpower.com/sites/sunpower/files/media-library/data-sheets/ds-e20-series-327-residential-solar-panels.pdf

    See Page 2, note 4.

16. http://onlinelibrary.wiley.com/doi/10.1029/2012GL051106/abstract
17. https://www.youtube.com/watch?v=xuttOKcTPQs
18. http://news.nationalgeographic.com/news/2004/06/0607_040607_phytoplankton.html

CHAPTER FIVE

1. http://www.timothymaloney.net/Critique_of_100_WWS_Plan.html *Critique.*

2. https://web.stanford.edu/group/efmh/jacobson/Articles/I/USStatesWWS.pdf
   Roadmap.

   See table 2, row 9: 2,326,000 MWp-ac ÷ 160 Wp-ac / m^2 = 14.5e9 m^2 of solar panels. To calculate PV land area, divide by packing factor PF = 0.40 (40%). Obtain 36.3e9 m^2 = 36,300 km^2 land area, or 14,000 sq mi for utility PV solar farms.

   Use the onshore wind farm density of 0.17 km^2 /MW, derived in Ch. 1, End Note #5. From *Roadmap* Table 2, row 1: Wind capacity 1,701,000 MWp × 0.17 km^2 / MW = 289,200 km^2 land area, or 111,700 sq mi.

   Combined PV & onshore wind = 14,000 + 111,700 = 125,700 sq mi for wind & PV solar.
   Using the CSP land density of 0.039 km^2 / MWp that describes the Andasol CSP farm in Spain: https://en.wikipedia.org/wiki/Andasol_Solar_Power_Station
   Andasol's land area is 5.85 km^2. Its nominal power rating is 150 MWp. 5.85 ÷ 150 = 0.039 km^2 / MWp.)

   In the Roadmap's Table 2, rows 10 and 11, CSP capacity: 227,300 + 136,400 = 363,700 MWp. Multiply by 0.039 km^2 / MW to obtain 14,200 km^2; or 5,500 sq mi for utility CSP farms.

   Total onshore wind and solar: 125,700 + 5,500 = 131,200 sq mi.

3. 18 billion m^2 of panels ÷ 14,600 days in 40 years = 1.23 million m^2 / day

4. http://www.scmp.com/news/china/society/article/2104162/chinas-ageing-solar-panels-are-going-be-big-environmental-problem

   http://www.environmentalprogress.org/big-news/2017/6/21/are-we-headed-for-a-solar-waste-crisis

5. *Ibid*. Chapter 5 End Note #1 *Critique.* Search for "intends to ramp up our solar".

6. https://en.wikipedia.org/wiki/Copper_in_renewable_energy

Refer to the table “Copper usage in renewal energy generation”. Power values are expressed in terms of peak capacity. In Photovoltaics row, columns 2 and 4:

350 kilotonnes Cu ÷ 70 GWp cumulative installed PV solar = 350e3 tonnes ÷ 70e3 MWp = 5 tonnes Cu / MWp

In Wind row, columns 2 and 4:

714 kilotonnes Cu ÷ 238 GWp cumulative installed wind = 3 tonnes Cu / MWp

7. http://www.itrpv.net/Reports/Downloads/2016/

Refer to Fig. 8 on page 11, Frame 13. The data point for 2016 indicates 95 milligrams of silver per cell (crystalline silicon technology). Assuming power rating of 3.1 watts per cell, the usage of silver is 95 mg ÷ 3.1 W = 31 mg /W.

The data point for 2026 indicates 40 milligrams of silver per PV cell. 40 mg /cell ÷ 3.1 W /cell = 13 mg /W.

The reference PV unit is SunPower Co. module E20-435, containing 128 cells. Module power rating = 401 Wdc under PTC (Photovoltaics for Utility-Scale Test Conditions, often referred to as Practical Test Conditions). 401 W ÷ 128 cells = 3.1 Wdc /cell. Its 435 W nominal rating refers to STC - Standard Test Conditions (laboratory).

8.

fossilhub.org/wpcontent/uploads/2014/03/Pihl_etal2012_ConcSolarPower_materials.pdf

If the link does not work, copy and paste URL into browser: "Material constraints for concentrating solar thermal power." See table 3 on page 5. 13 tonnes silver per GWac = 13e6 g / 1e9 W = 13e–3 g / W = 13 mg / Wac

Alternate: (pay-wall unless registered)

http://www.sciencedirect.com/science/article/pii/S036054421200374X
See Frame 5.

9.

http://thesolutionsproject.org/resource/transition-chart-to-100-clean-renewable-energy/

Download the sixth file, “Solutions-US-2015-Web”. Print that S-curve. It represents the building schedule for US wind, water, and solar equipment between years 2015 through 2050.

On the right-side vertical axis, combined solar furnishes 45.25% of 1591 GW total US power, or 720 GWavg for PV and CSP solar combined.

The Roadmap's implied capacity factor for PV solar in the U.S. is 21% so the total capacity of all US solar equipment must be: 720 GWavg ÷ 0.21 = 3,430 GWp-ac.

On the right-side vertical axis, repeat the same procedure for wind. Combined wind is 50.0% × 1591 GW, or 796 GWavg. The U.S. Roadmap has implied capacity factors of 29% for onshore wind and 39% for onshore wind. Their weighted average capacity factor is 33%. [Refer to the light blue (30.92%) and dark blue (19.08%) segments and calculate the weighted average of the two.]

Therefore, the total capacity of all U.S. wind equipment must be:

796 GWavg ÷ 0.33 = 2,410 GWp.

Copper requirements:

Solar: 3,430 GWp × 5 t /MWp = 17,200,000 t
Wind: 2,410 GWp × 3 t /MWp = 7,200,000 t
Combined W&S: 24,400,000 tonnes copper

10. The Roadmap's split between PV and standard fleet CSP is 84% /16%. (This does not count the supplementary CSP backup solar farms, equivalent to about 4% of standard fleet power, 1591 GW.)

So the PV /CSP split consists of 0.84 × 3,430 GWp-ac = 2,880 GWp-ac for PV, and 550 GWp-ac for CSP.

The photovoltaic cells themselves must have dc power capacity greater than 2,880 GW, to allow for 85% conversion efficiency of the electronic inverters that convert dc to grid-compatible ac. The U.S. PV infrastructure must have dc capacity given by 2,880 GWac ÷ 0.85 = 3,390 GWdc.

Silver consumption for U.S. PV solar cells in 2050 is given by 3,390 GWdc × 13 mg / Wdc = 44,100 tonnes. For standard fleet CSP, silver amount is 550 GW × 13 mg / Wac = 7,200 t.

Total silver for combined fleet solar: 44,100 t + 7,200 t = 51,300 tonnes.

11. https://minerals.usgs.gov/minerals/pubs/commodity/copper/mcs-2017-coppe.pdf

Refer to page 2. Units are thousands of tonnes. In Reserves column, world total = 720,000,000 tonnes of copper.

12. https://minerals.usgs.gov/minerals/pubs/commodity/silver/mcs-2017-silve.pdf

13. *Ibid.* Chapter Five End Note #2. *Roadmap.* See the Abstract.

14. *Ibid*. Chapter 5 End Note #1 *Critique.* See internal footnotes 9 and 11.

15. *Ibid*. *Critique.* See internal footnotes 9 and 10.

16. http://spectrum.ieee.org/green-tech/solar/a-tower-of-molten-salt-will-deliver-solar-power-after-sunset

CHAPTER SIX

1. https://www.gizmodo.com.au/2017/07/all-the-details-on-teslas-giant-australian-batteryt/

2. Our estimate of 77 grams of Li per kW-hr of battery storage is averaged from two sources:

   http://www.batteryeducation.com/2010/05/what-is-the-total-equivalent-lithium-content-of-my-battery.html

   A 10.8 volt (V), 8.8 amp-hour (Ah) Li-ion battery contains 7.9 grams (g) lithium.10.8 V × 8.8 coulombs / sec × 3,600 sec / h = 342e3 joules (J) energy content of battery. Conversion factor: 1 kWh = 3.6e6 J. 342e3 J × 1 kWh / 3.6e6 J = 0.095 kWh energy content of the battery. Therefore: 7.9 g Li / 0.095 kWh = 83 g lithium / kWh.

   Now click on:

   https://www.researchgate.net/post/What_is_the_content_of_pure_lithium_eg_kg_kWh_in_Li-ion_batteries_used_in_electric_vehicles

   Refer to derivation by Saeed Kazemiabnavi: lithium content = 0.0714 kg /kWh or 71 g lithium /kWh.

   Average the values 71 g and 83 g to obtain 77 g Li /kWh.

3. *Ibid.* Footnote #1. See 2nd paragraph:

100 MW / 129 MW-hrs refers to 129 megawatt-hours of energy storage (energy content, or energy "capacity"), with a maximum power output (discharge rate) of 100 megawatts. As usual, the word "capacity" is misused here to refer to peak power output.

129e6 W-hrs energy content × 77 g Li /1e3 W-hrs = 9.9e6 g Li, or 9.9 tonnes lithium.

4. https://en.wikipedia.org/wiki/List_of_countries_by_lithium_production

5. http://www.vanadiumcorp.com/targeted-products/vanadium/electrolyte

   See the 2nd image in the left column. Vanadium flow battery (VFB) storage capacity of 1,600 MW-hrs uses 8,000 tonnes of V_2O_5. Of that 8,000 tonnes, 4,480 tonnes is elemental vanadium.
   Vanadium atomic mass = 51, and oxygen atomic mass = 16. So, V_2O_5 molecular mass = (2 × 51) + (5 × 16) = (102 + 80) = 182. The vanadium portion = 102 ÷ 182 = 0.56. 8,000 tonnes × 0.56 = 4,480 tonnes elemental vanadium.

   VFB specific energy = 1,600e6 W-hrs ÷ 4.480e6 grams = 0.357 W-hrs / gram of vanadium. Alternatively, 2.8 grams / W-hrs of stored energy.

   http://investingnews.com/daily/resource-investing/industrial-metals-investing/vanadium-investing/world-class-vanadium-deposits/

   See section "Global production of vanadium totaled 79,400 tonnes in 2015."
   One grid-hour of energy storage is 1,591 GWs × 1 hour = 1,591e9 W-hrs.
   1591e9 W-hrs × 2.8 grams / W-hr = 4.45e12 grams of vanadium per grid-hour.

   World production of 79,400e6 grams ÷ 4.45e12 grams /grid-hour = 0.018 grid-hour, or about 1 minute. (So there.)

6. https://www.eia.gov/totalenergy/data/monthly/pdf/flow/css_2016_energy.pdf

7. http://energystorage.org/energy-storage/technologies/pumped-hydroelectric-storage

8. http://thorconpower.com/costing

   http://thorconpower.com/costing/bottom-line

   http://thorconpower.com/docs/exec_summary.pdf

   See: Frame 62, page 61.

9. http://thorconpower.com/docs/domsr.pdf

   See: page 6ff

10. https://www.youtube.com/watch?v=0MJkAoA1Nek

11. One cubic meter of water has mass (m) = 1000 kilograms (kg). Acceleration due to earth's gravity (g) = 9.81 meters / second per second (9.81 m / s^2). Force (F) [also called weight] = mass × acceleration = m × g. F = 1000 kg × 9.81 m / s^2 = 9.81e3 newtons (N). Kinetic energy (NRG) from falling 100 meters onto hydroturbine = F × distance = 9.81e3 N × 100 m = 981e3 joules (J) per cubic meter. Conversion factor: 1 watt-hour (Wh) = 3.6e3 J.

    Therefore:

    981e3 J per m3 of water / 3.6e3 J /Wh = 273 Wh of kinetic NRG per m3 of water.

    Ideally, 1 ESB = 917,400 m^3 (with 100% efficient machinery).

    273 W-hrs / m^3 × 917,400 m^3 = 250e6 W-hrs. Or 250 megawatt-hours per 1 ESB.

12. The metric system is an amazing, ingenious, brilliant, and stupid-simple method of measurement based on two everyday properties of a common substance that are exactly the same all over the world: *the weight and volume of water.*

    One cubic meter (m^3) of pure H_2O = one metric ton (~ 2,200 lbs) = 1,000 kilograms = 1,000 liters. And one liter = 1 kilogram (~ 2.2 lbs) = 1,000 grams = 1,000 cm^3 (cubic centimeters.) And one cm^3 of water = one gram, hence the word "kilogram," which means 1,000 grams. And a tonne is a million grams.

    You may have already deduced that metric linear measurements are related to the same volume of water: A meter is the length of one side of a one-tonne cube of water, and a centimeter is the length of one side of a one-gram cube of water.

    Metric energy measurements are based on another thing that's exactly the same all over the world: *the force of falling water.* One cubic centimeter (one gram) of water, falling for a distance of 100 meters (about 378 feet) has the energy equivalent of right around one "joule" (James Prescott Joule was a British physicist and brewer in the 1800s who figured a lot of this stuff out.)

    One joule per second = one watt. (Energy used or stored over time = power. A joule is energy, a watt is power.) A million grams (one tonne) falling 100 meters per second = a million joules per second = a million watts, or one megawatt (MW). One MW for 3,600 seconds (one hour) = one MWh (megawatt-hour.)

13. https://dothemath.ucsd.edu/2011/11/pump-up-the-storage/

14. To calculate the water needed for one "grid-day" of energy: 1,591e9 W × 24 hr = 38.2e12 W-hrs. 38.2e12 W-hrs per grid-day × 1,020,000 m^3 / 250e6 Wh = 156e9 m^3 of fresh water = one grid-day.

https://water.usgs.gov/watuse/wuto.html

U.S. annual water use = 397 million acre-feet per year, of which 86% was fresh water, so 341 million acre-feet. Multiply by conversion factor 1.233e-6 km^3 / acre-foot. Obtain 421 km^3 / year, or 421e9 m^3 / year

1,56e9 m^3 per grid-day / 421e9 m^3 water usage / year × 365 days per year = 135 days of fresh water usage for one grid-day.

15. 1,591 GWs × 24 hrs = 38.2 Terawatt hrs (trillion watt-hrs.) 38.2 trillion watts × $0.20 per W-hr = $7.64 Trillion.

CHAPTER SEVEN

1. https://www.washingtonpost.com/news/capital-weather-gang/wp/2017/08/30/harvey-has-unloaded-24-5-trillion-gallons-of-water-on-texas-and-louisiana/?utm_term=.65d47512c118

2. https://www.nytimes.com/2017/09/27/us/hurricane-maria-virgin-islands.html?hp&action=click&pgtype=Homepage&clickSource=story-heading&module=photo-spot-region&region=top-news&WT.nav=top-news&_r=0

https://www.scientificamerican.com/article/dreaded-polar-vortex-may-be-shifting/

3. https://www.youtube.com/watch?time_continue=8&v=1AAHJs-j3uw

4. https://www.reuters.com/article/us-storm-harvey-nuclearpower/south-texas-project-nuclear-plant-running-despite-harvey-idUSKCN1B92KG

5. http://www.climatecentral.org/blogs/closer-look-at-arctic-sea-ice-melt-and-extreme-weather-15013

https://insideclimatenews.org/news/27092017/polar-vortex-cold-snap-arctic-ice-loss-global-warming-climate-change

6. http://www.timothymaloney.net/Critique_of_100_WWS_Plan.html *Critique.*

Search for “115.6 tonnes / MWp”, or just “115.6”. Then search for “15,500 tonnes”. Divide that by 1,040 MW per reactor: 15,500 ÷ 1,040 = 14.9 tonnes / MWp. Then divide 115.6 t ÷ 14.9 t = 7.8.

7. *Ibid*. *Critique.* Search for “Factor of difference”.

8. http://www.spiegel.de/international/germany/wind-energy-encounters-problems-and-resistance-in-germany-a-910816.html

9. https://en.wikipedia.org/wiki/Cape_Wind - Controversy

10. https://web.stanford.edu/group/efmh/jacobson/Articles/I/USStatesWWS.pdf *Roadmap.*

    See Frame 8, journal page 2098, Table 2. Use columns 2 and 6, for rows 1, 2, 9 and 10.

11. http://www.meteo.mcgill.ca/~huardda/articles/greene10.pdf

    See pages 1594, 1595, 1599. See also:

    https://spectrum.ieee.org/green-tech/wind/a-less-mighty-wind

12. https://www.nasa.gov/topics/earth/features/warmingpoles.html

CHAPTER EIGHT

1. https://web.stanford.edu/group/efmh/jacobson/Articles/I/USStatesWWS.pdf *Roadmap.*

   See Frame 5, journal page 2095

2. http://www.timothymaloney.net/Critique_of_100_WWS_Plan.html *Critique.* Search for “Figure C”. See theFor the cost of just 4 hrs caption.

3. *Ibid*. *Critique.*

   Search for Figure C. Observe Figure C call-out of 30,000 m^3 water / hour. That means 24 hours / day, *forever*. 30,000 m^3 / hr × 8760 hr / year = 263e6 m^3 /yr.

Divide by U.S. annual fresh water usage of 421e9 m^3 / year: 263e6 ÷ 421e9 = 0.000 62. Multiply 0.000 62 × 8760 hours /yr = 5.4 hours.

4. https://www.youtube.com/watch?v=VgQQOZkdxag

5. http://www.caranddriver.com/features/going-wireless-how-induction-will-recharge-evs-on-the-fly-tech-dept

   http://witricity.com/

CHAPTER NINE

1. https://web.stanford.edu/group/efmh/jacobson/Articles/I/USStatesWWS.pdf *Roadmap.*

   Table 2, row 12, column 3

2. *Ibid.* Table 2, row 11, column 3

3. http://www.timothymaloney.net/Critique_of_100_WWS_Plan.html *Critique.*

   See internal footnote 67.5

4. *Ibid*. Chapter Nine End Note #1 *Roadmap*. Table 2, row 4, columns 3 and 5 for already installed geothermal.

5. http://www.environmentalprogress.org/big-news/2017/1/13/breaking-german-emissions-increase-in-2016-for-second-year-in-a-row-due-to-nuclear-closure

   Germany's installed (peak) wind capacity, versus actual (average) production:

   https://wryheat.wordpress.com/2015/02/12/german-wind-power-fails-a-cautionary-tale/

6. http://www.whoi.edu/page.do?pid=83397&tid=3622&cid=94989

   http://www.timothymaloney.net/Pacific_Ocean_damaged_by_Fukushima.html

   Search for "It's all the same"

https://www.propublica.org/article/even-in-worst-case-japans-nuclear-disaster-will-have-limited-reach

https://www.forbes.com/sites/jamesconca/2014/09/05/germans-boared-with-chernobyl-radiation/ - 475a7e5043b0

CHAPTER TEN

1. https://carboncounter.wordpress.com/2015/08/11/germany-will-never-run-on-solar-power-here-is-why/

2. http://www.pnas.org/content/114/26/6722.full

3. http://www.pnas.org/content/112/49/15060
Frame 5, page 15064, Figure 4B.

4. http://search.usa.gov/search?utf8=%E2%9C%93&affiliate=eia.doe.gov&query=existcapacity_annual.xls

   Then click on www.eia.gov . Open or Save the offered file. A spreadsheet doc will come up. Scroll to line 38,854 for the year 2015: "Hydroelectric." Go to column "Nameplate Capacity": 78,957 MW (79.0 GW).

5. https://www.nytimes.com/2017/06/20/business/energy-environment/renewable-energy-national-academy-matt-jacobson.html?_r=0
See paragraph 26 (but the entire article is worth reading, too.)

6. http://www.postcarbon.org/controversy-explodes-over-renewable-energy/

7. In 2015 there were 8,002 dedicated electricity-producing facilities in the U.S.

   http://www.eia.gov/electricity/annual/html/epa_04_01.html
See: "Total Sectors" section, row 2015.

8.

https://www.hbr.org/2017/04/the-3-stages-of-a-country-embracing-renewable-energy

10th paragraph: ". . . grid operators frequently have to intervene to keep the electricity grid in balance. For example, interventions in Germany's largest transmission grid operated by private company TenneT increased from fewer than 10 interventions per year in 2003 to almost 1,400 interventions in 2015."

13th paragraph: ". . . demand-response . . . temporarily switch off part of their electricity consumption—increasing the elasticity of demand to keep the grid balanced."

http://www.renewableenergyworld.com/news/2014/07/german-utilities-paid-to-stabilize-grid-due-to-increased-wind-and-solar.html

"Germany's push toward renewable energy is causing so many drops and surges from wind and solar power that more utilities than ever are receiving money from the grids to help stabilize the country's electricity network.

"Twenty power companies . . . add or cut electricity within seconds to keep the power system stable, double the number in September, according to data from the nation's four grid operators.

"Germany's drive to almost double power output from renewables by 2035 has seen one operator reporting five times as many potential disruptions . . . "

9.

http://www.artba.org/newsline/2015/04/03/61000-u-s-bridges-need-repair-new-study-finds/

CHAPTER ELEVEN

1.

https://us.sunpower.com/sites/sunpower/files/media-library/data-sheets/ds-e20-series-327-residential-solar-panels.pdf
See page 2.

2. http://www.timothymaloney.net/Critique_of_100_WWS_Plan.html *Critique.*
See internal footnotes 12 and 27

3. ttps://web.stanford.edu/group/efmh/jacobson/Articles/I/USStatesWWS.pdf
   Roadmap.
   See Table 2, footnote *d*.

   www.pnas.org/content/112/49/15060
   See Table 2, footnote *c*.

4. *Ibid.* Chapter Eleven End Note #2. *Critique*.

   Search for "About 160 W". See internal footnote 22.3.

5. *Ibid*. Chapter Eleven End Note #2. *Critique.*

   Search for "US Solar PV System Cost Benchmarks"; then search for "28%", then "23%"

   Also see: https://ourworldindata.org/grapher/number-of-patents-filed-for-renewable-energy-technologies

6. https://en.wikipedia.org/wiki/Moore%27s_law

   https://www.greentechmedia.com/articles/read/why-moores-law-doesnt-apply-to-clean-technologies

7. http://www.nrel.gov/docs/fy16osti/67142.pdf

   See graph on page 8.

8. *Ibid.* See graph on page 42: "Modeled Impacts of Module Efficiency on Total System Costs, 2016."

9. https://web.stanford.edu/group/efmh/jacobson/Articles/I/USStatesWWS.pdf
   Roadmap

   Table 2, row 9, column 7 states 0.18973% as the portion of US land required for utility solar PV farms.

   0.18973% × 9.162e6 km^2 total US area = 17,380 km^2 land area required for utility PV, asserted by the Roadmap.

   Referring to Table 2's column 4, using 160 W / m^2 SunPower PV panels specified by the Roadmap, the total panel area (not land area), is 2,326,000e6 W ÷ 160 W /square meter = 14.54e9 square meters of total panel area.

At U.S. average packing factor of 40%, the total land area required = total panel area ÷ 0.40: 14.54e9 m2 ÷ 0.40 = 36.35e9 m^2 = 36,350 km^2. This is 0.397% of total U.S. land.

Therefore the NREL / SunPower-derived land requirement for utility-scale PV solar is 2.1X greater than the Roadmap's assertion. [36,350 km^2 ÷ 17,380 km^2 = 2.1. Also 0.397% ÷ 0.18973% = 2.1.]

The Critique's treatment of this issue can be found by searching for "would occupy only 37,100".

The discrepancy between the Critique's 37,100 km^2 of land and 36,350 km^2 calculated here is due to the Critique's rounding of land density values to just two significant figures, namely 0.029 and 0.016 km^2 /MW.

10. To give you an idea of how we get our figures, here's the number crunching:

- 2,326,000 MWs ÷ 160 watts / m^2 = 14,537,500,000 m^2 of panels
- 14,537,500,000 m^2 = 14,537 km^2 (square kilometers)
- With 40% packing factor: 14,537 ÷ 0.40 = 36,343 km^2 of land
- Maryland = 32,131 km^2 / Rhode Island = 4,001 km^2
- 32,131 + 4,001 = 36,103 km^2 (240 km^2 less than required)

11. *Ibid.* Chapter Eleven End Notes #7

See Page 8, "Overall Model Results." Utility Scale PV cost values are at the right. 2016 fixed-tilt cost = $1.42 per dc watt. For ac divide by dc-to-ac conversion factor 0.83, the value assumed by NREL for ground-mounted PV facilities.

$1.42 /Wdc ÷ 0.83 = $1.71 / W-ac (for ground-mounted fixed-tilt in 2016)

Page 45, Conclusions (1), for single-axis tracking mount;
$1.49 / W-dc ÷ 0.83 = $1.79 / W-ac (for single-axis tracking in 2016)

$1.71 for fixed-tilt and $1.79 for tracking-mount, per ac watt. Combined average $1.75 per ac watt.

12. *Ibid*. Chapter Eleven End Note #7.

Page 8, Overall Model Results, Utility Scale PV: all dollar values are per dc watt. $1.42 for fixed-tilt and $1.49 for tracking-mount. Combined average $1.45 per dc watt.

See page 36, Utility Scale PV, Modeling Inputs. All dollar values are per dc watt:

Module Price:
$0.64 ÷ $1.42 = 45% for fixed mount
$0.64 ÷ $1.49 = 43% for tracking mount
44% average, for PV module cost portion.

Inverter Price:
$0.09 ÷ $1.42 = 6.3% for fixed mount
$0.10 ÷ $1.49 = 6.7% for tracking mount
6.5% average, for inverter cost portion; rounded to 7% in text.

Installation Labor: http://www.nrel.gov/docs/fy15osti/64746.pdf For 2015 installations, see page 29, Figure 21.

$0.16 /Wdc for fixed mount
$0.22 /Wdc for tracking mount
$0.19 /Wdc average, labor cost portion in 2015.

Labor cost declined by about one-third from 2015 to 2016. See NREL 2016 report (*Ibid*.), page 8, Utility Scale PV, at far right. Compare orange-color segments in the bar graphs for those two years. By comparison, estimate that $0.19 declined to about $0.13 /Wdc. $0.13 /Wdc ÷ $1.45 /Wdc = 9.0%, labor cost portion in 2016.

44% (module cost) + 6.5% (inverter cost) + 9% (labor cost) = 60% of initial cost of utility PV solar.

13. Assuming that initial labor cost of 9% divides as 5% for panels and 4% for inverters:

    1 PV panel replacement = 44% module + 5% labor = 49%
    3 inverter replacements = 3 × (6.5% parts + 4% labor) = 31%
    Lifetime replacement cost = 49% + 31% = 80%.

    Lifetime cost factor = 1.80X.

14. 2,326,000 million watts (MWs, or megawatts) × $1.75 /W = $4.1 trillion for initial installation at 2016 cost.

15. $4.1 trillion × 1.80 = $7.4 trillion lifetime cost, before NREL future discount.

16. http://solartopia.org

17. *Ibid*. Chapter Eleven End Note #7

Page 8, Overall Model Results: residential cost values are at the left. All values expressed in dc watts. (vertical scale factor = $0.11 /millimeter)

$2.93 / Wdc for residential solar in 2016.

18. 379,500 million watts × $2.93 / W = $1.1 trillion for initial installation at 2016 cost.

19. *Ibid*. Chapter Eleven End Note #7

p. 25, Residential PV. Modeling Inputs and Assumptions:
module + string inverter = $0.64 + $0.16 = $0.80 /Wdc
module: $0.64 ÷ $2.93 = 22%
inverter: $0.16 ÷ $2.93 = 6%

Pg. 8, bar graph; Scale orange segment for labor: 2.7 mm. Vertical scale factor = $0.11 per mm; installation labor = 2.7 mm × $0.11 / mm = $0.30 /Wdc
Labor: $0.30 ÷ $2.93 = 10%

module + string inverter + labor = $0.80 + $0.30 = $1.10 / W-dc
$1.10 ÷ $2.93 = 38%

20. Assuming that initial labor cost of 10% divides as 5% for panels and 5% for inverters:

1 PV panel replacement = 22% module + 5% labor = 27%
4 inverter replacements = 4 × (6% parts + 5% labor) = 44%
Lifetime replacement cost = 27% + 44% = 71%.

Lifetime cost factor = 1.71X.

21. $1.11 trillion × 1.71 = $1.90 trillion lifetime cost, before NREL future discount.

22. *Ibid*. Chapter Eleven End Note #7. See Page 8, section on "Overall Model Results." Commercial cost values are in the center. Values are expressed in dc watts. (Vertical scale factor = $0.11 /millimeter.) $2.13 / Wdc for commercial rooftop solar in 2016.

23. *Ibid*. Chapter Eleven End Note #7
See Page 31, Commercial PV "Modeling Inputs and Assumptions":

module + inverter = $0.64 + $0.13 = $0.77 /W-dc
module: $0.64 ÷ $2.13 = 30%
inverter: $0.13 ÷ $2.13 = 6.1%

See also Page 8, bar graph. Commercial cost values are in the center. If we scale the orange segment for labor, we get 1.8 mm. At $0.11 per mm. Installation labor = 1.8 mm × $0.11 / mm = $0.20 / W-dc. Labor: $0.20 ÷ $2.13 = 9.4%

module + inverter + labor = $0.64 + $0.13 + $0.20 = $0.97 / W-dc
$0.97 ÷ $2.13 = 46%

24. Assuming the initial labor cost of 9.4% divides evenly as 4.7% for panels and 4.7% for inverters:

1 PV panel replacement = 30% module + 4.7% labor = 34.7%
4 inverter replacements = 4 × (6.1% parts + 4.7% labor) = 43.2%
Lifetime replacement cost = 34.7% + 43.2% = 78%

Cost factor = 1.78X.

25. 276,500 million watts × $2.13 / W = $590 billion for initial installation at 2016 cost.

26. $590 billion × 1.78 = $1050 billion lifetime cost before NREL future discount.

27. Utility + residential + commercial = $5.3 T + $1.5 T + $0.8 T = $7.6 T, if NREL's future discount projection is borne out.

28. https://us.sunpower.com/sites/sunpower/files/media-library/data-sheets/ds-e20-series-327-residential-solar-panels.pdf

See page 2, reference No. 4: SunPower white paper titled “SunPower Module 40-Year Useful Life”, May 2015. Useful life [means] 99 out of 100 panels operating at more than 70% of rated power.

29. *Ibid*. Chapter Eleven End Note #2. *Critique.*

Search for “factor of 16.9”. Refer to internal footnote # 13. Then refer to “factor of 58” in internal footnote # 14.

30. See the "Material Requirements" chapter in "The Non-Solutions Project" by Mathijs Becker: https://www.amazon.com/non-solutions-project-Mathijs-Beckers/dp/1537673807

31. http://news.mit.edu/2012/rare-earth-alternative-energy-0409

32. http://www.bbc.com/future/story/20150402-the-worst-place-on-earth

33. A CSP farm's capacity factor is sometimes specified in the 40% or 50% range. That's an unrealistic range for actual solar insolation anywhere in the entire world, even in the sunniest locations. This spurious capacity factor has been conjured up by the solar industry with the following accounting gimmick:

Only *a portion* of a CSP farm supplies immediate electric energy to the grid. The rest of the farm's curved mirrors put heat energy directly into a pipe of molten salt, and the hot salt is stored in insulated tanks for later use.

But instead of adding up all the energy (electric + heat) produced by the entire farm, the solar operator only counts the "immediate electric energy" portion of the farm as the *total* peak power rating for *the entire farm*.

The farm's electric generating equipment and steam turbine are sized to handle just the amount of power produced by the immediate electric energy mirrors, and not the entire solar field, meaning the farm's entire collection of mirrors. The industry has coined the innocuous term "solar multiple" for this accounting gimmick.

Solar multiple is the ratio of all the mirrors in the solar field to the mirrors that are producing immediate electric energy. For example, a solar multiple of 1.5 means that in a 150-mirror CSP farm, 100 mirrors are counted *and 50 mirrors aren't*. This reduces the farm's declared peak-power rating. However, the material use and dollar cost to build the entire field relates to the entire solar field, and not just the counted mirrors.

As described, the 50 uncounted mirrors store the thermal energy that's intended to be used after sundown. The accounting trick makes it look on paper like the additional electric output obtained from the stored (and uncounted) thermal energy seems to be coming from less infrastructure than it really is.

This enables the industry to (falsely) quote a greater capacity factor of the CSP farm, for advertising and PR purposes.

34. https://en.wikipedia.org/wiki/Andasol_Solar_Power_Station

Andasol's land area is 5.85 km2. Its nominal power rating is 150 MWp. 5.85 ÷ 150 = 0.039 km2 /MWp.

35. *Ibid*. Chapter Eleven End Note #2. *Critique.*

Search for "$5.94". Refer to internal footnote 46.

CHAPTER TWELVE

1. https://web.stanford.edu/group/efmh/jacobson/Articles/I/USStatesWWS.pdf
   Roadmap.

   See table 2, row 1, columns 2, 6 and 8. U.S. land area is taken to be 9.162e6 km^2.

   1.5912% × 9.162e6 km^2 = 145,800 km^2; 5 MW × 328,000 turbines = 1.64e6 MW; 145,800 km^2 ÷ 1.64e6 MW = 0.089 km^2 / MWp assumed land density for wind.

2. On 10/20/16 11:32 PM, Timothy Maloney sent this message:

   Dear Dr. Jacobson,

   I am writing an article on renewable energy and need some clarification.

   For onshore wind the *100% clean and renewable WWS all-sector energy roadmaps for the 50 united States* shows 1.59% of US land area needed for spacing of new plants /devices. I take this to mean the entire area of a wind farm, what the National Renewable Energy Laboratory defines as Total Wind Plant Area in their 2009 technical report - *Land-Use Requirements of Modern Wind Power Plants in the United States.*

   NREL defines Total Wind Plant Area as "the total area of a wind power plant consisting of the area within a perimeter surrounding all the turbines in the project". [p.4, Sec. 2.2]

   172 large wind projects were evaluated in the NREL study, obtaining a clear specification of the Total Wind Plant Area for 161 of them [p.10, Table 1]. Their combined Total Area was 8778.9 km^2, with combined generating capacity of 25,438 MWac, giving an Average Area Requirement of 34.5 ha /MW, or 0.0345 km^2 /MW, shown at lower right in that table.

   The 100% WWS Roadmap, Table 2, states a target value of 1,701,000 MW, with 3.59% already built as of 2013. New buildout would therefore be 1,640,000 MW.

   With NREL's land-usage for actually existing large wind farms at 0.0345 km^2 /MW, the new land area required would be 565,800 km^2. That land area represents 6.18% of all US land, if Alaska is counted. This is about 4X greater than the 1.59% value for onshore wind in Table 2 of the Roadmap.

Perhaps the word “spacing” in Table 2 does not really refer to the Total Area occupied by large wind farms built in the US. Perhaps it refers instead to a theoretical model for flat land only, assuming a rectangular field with a turbine array spaced about 3 to 5 blade-diameters apart “sideways," and 10 diameters apart in the direction of prevailing wind.

Under that assumption, analysis models anticipate land usage of 0.13 to 0.20 km^2 /MW [p.15 of the NREL report]. The center value of that predicted range, 0.165 km^2 /MW, would yield new land requirement of 270,600 km^2, or 2.95% of total US area. Even this idealization is substantially greater than the 1.59% of US land area specified in Table 2.

Could you help me reconcile these discrepancies?

Thank you in advance.

Timothy Maloney

On 10/21/16 1:17 AM, Mark Z. Jacobson replied:

Dear Timothy,

Yes, I will address this below. Also, I checked out your "Critique" of our U.S. plan, and while I am flattered you have taken such an interest, I would suggest you go into the spreadsheets more to see exactly how things are calculated. For example, you claim that the U.S. average capacity factor of wind and solar applied to our generation capacity give a slight underestimate of our annual power output but you omit the fact that we are including offshore wind in our 2050 mix (none of which existed in the U.S. at the time of the report), and CFs are higher for offshore wind than onshore, and you averaged wind and solar CFs and different types of solar CFS, then multiplied an average number by a total capacity rather than multiplying individual CFs by individual capacities and summing the results. Also, you used recent values rather than 2050 values, which we use.

With regard to wind turbine spacing areas, we use the standard metric for wind turbine area requirement Area (km2) per turbine = aD × bD where D is turbine diameter (km), and a and b are constants representing the sidestream and upstream distance between turbines in an area. For onshore turbines, we used a=4, b=7 and for offshore, a=5 and b=10. For the 5-MW, D=126 m turbine we used, these translate into 0.44 km^2/turbine (0.089 km^2/MW) and 0.79 km^2/turbine (0.159 km^2/MW), respectively.

A recent study that will be published shortly by an independent group analyzing the spacing of more than 1000 operating turbines covering 44 onshore and offshore wind farms around the world found that the mean distance between turbine towers was 4.2D, giving an approximate mean area of turbines as A = 4.2D × 4.2D = 17.6 D^2, which is much less than what we used (28 D^2 and 50 D^2).

In other words, the spacing areas we estimated are larger than spacing based on real wind farm data (thus our results are conservative), which is opposite from the conclusion you draw from the NREL report.

There are three reasons for this.

1) NREL does not provide any calculation of actual average distances between turbines towers, which is the relevant method of performing this calculation because the reason turbines are spaced is to avoid interference of the wake of one turbine with the next. It is irrelevant to know the irregular outside perimeter of a property based on project applications (which is what NREL used), particularly since the outside may be far away from the last turbine actually installed or could lie in a creek bed far away from any turbines.

2) The NREL report acknowledges on page 15 that their method of calculation "Wind Plant Area" results in overestimates and gives several examples why.

3) On page 4 of the NREL report, they further acknowledge that the Wind Plant Area is "subjective in nature" and "the total area of a wind power plant could have a number of definitions." In their case, they define it based on project applications, which results in several of the overestimates given in (2) above.

On the other hand, the method based on data I described above relies on analyzing actual distances between turbine towers.

In sum, I believe our estimates overestimate rather than underestimate spacing area requirements based on real data.

This result is common sense as well, particularly as we go toward 1.7 million turbines in the U.S. Wind farm operators have an incentive to squeeze turbines as close together as possible to minimize transmission costs and land impacts, sacrificing some loss in capacity factor due to more interference.

Sincerely,
Mark Jacobson

3. http://www.timothymaloney.net/Critique_of_100_WWS_Plan.html *Critique.*

   Search for “NREL's 0.029 value becomes 0.016”.

4. *Ibid*. Chapter Twelve End Note #1. *Roadmap.* Table 2, row 1, column 3.
5. *Ibid*. Chapter Twelve End Note #2. *Critique.* See internal footnote 37.
6. *Ibid*. See internal footnote 41.
7. *Ibid*. Chapter Twelve End Note #1. *Roadmap*. Table 2, row 2, column 3.
8. *Ibid*. Chapter Twelve End Note #2. *Critique.*

   See internal footnote No. 40. See also:

   http://onlinelibrary.wiley.com/doi/10.1002/we.v20.2/issuetoc

   Wind Energy Feb. 2017, Volume 20, Issue 2, pages 361-378.

FINAL REMARKS

1. http://www.thesciencecouncil.com/pdfs/P4TP4U.pdf

   See Chapter Seven.

2. https://www.theguardian.com/environment/2017/jul/31/paris-climate-deal-2c-warming-study
3. https://en.wikipedia.org/wiki/Earth%27s_energy_budget