Mobilizing for a zero carbon America:

Jobs, jobs, jobs, and more jobs

A Jobs and Employment Study Report

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with help from
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For release : July 29, 2020

Summary

Total decarbonization of America's energy system is often portrayed as being inconsistent with economic growth, particularly with respect to job opportunities for those currently working in more traditional energy industries. This report, based on an extensive industrial and engineering analysis of what such a decarbonization would entail, demonstrates that aggressive decarbonization would create, rather than destroy, many millions of well–paying American jobs. These jobs will be highly distributed geographically and difficult to off-shore. The opportunity to create even more jobs by becoming an exporter of clean energy technologies would increase the number of jobs.

Where most studies look at decarbonization in specific individual sectors such as transportation, the electricity grid, or buildings — and mostly only on the supply side — we build a model of the interactions of all sectors, both supply and demand, in a rapid and total decarbonization. The maximum speed at which the transition can occur is dictated by the speed at which productive capacity in critical industries is built out. We call this the "mobilization period," akin to the "arsenal of democracy" mobilization in service of winning WWII. Under our model, this period is followed by a prolonged stretch of deployment at close to 100% adoption rates. After this deployment period, the economy settles into a "new normal state" that provides steady growth, replacement, and maintenance of a 100% clean energy system.

This maximum feasible rate of decarbonization substantially decarbonizes the power, transportation, building, and industrial sectors in the U.S. by 2035. This is commensurate

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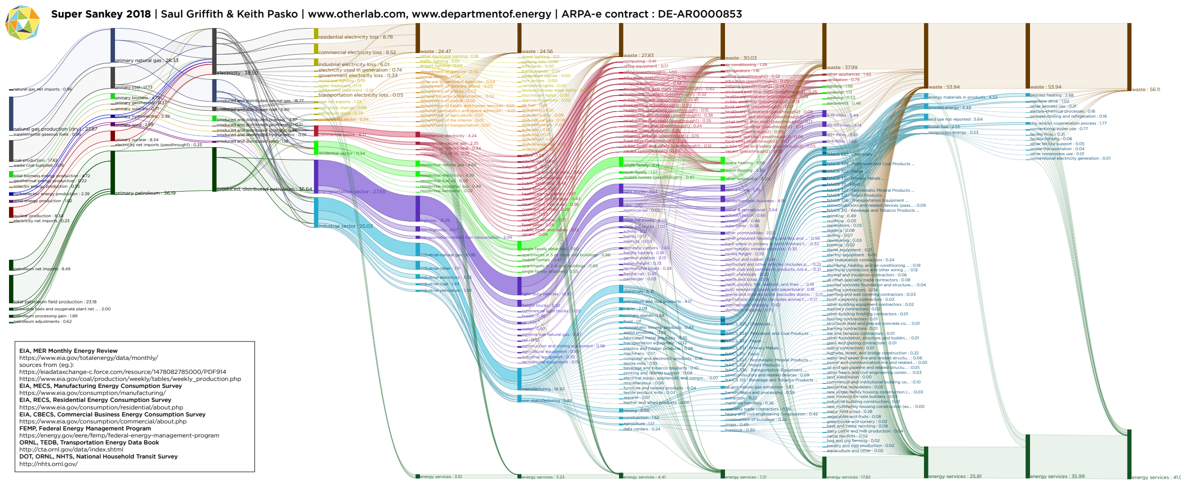

Figure 1: *A high resolution Sankey flow diagram of all US energy flows.*

with a global target of limiting warming to between 1.5° C/2.7° F and 2° C/3.6° F . Decarbonizing on this time frame produces around 25 million peak new jobs[1], tapering off to about 5 million sustained new jobs, in addition to the current jobs supported by the energy industry. While not the principal objective of this study, we also can project that with the right regulatory environment, and while paying good wages for energy sector jobs, we can still predict significantly lower energy costs for consumers, with an average household saving of 1,000–2,000 dollars per year[2].

Methodology

In 2018, Otherlab worked under ARPA-e (Department of Energy) contract DE-AR0000853 to conduct a highly granular energy flow analysis of the American energy system, identifying every energy flow in the American economy, from supply through demand, that could be determined from public data[3]. These flows can be seen in Figure 1. This study builds on that tool to develop fully decarbonized future energy scenarios. This study maps out a decarbonization pathway consistent with the most rapid rates of industrial transition in U.S. history [2]. The scenario utilizes only existing technology commercially available today. The scenario does not assume retirement of current assets before amortization of original capital costs — known colloquially as "early retirements" — though agrees with the analysis that early retirement of our heaviest emitters has enormous advantages in speeding our decarbonization and limiting cumulative emissions. The pathway is almost entirely focused on electrification, the exception being 5-10 Quads of non–electrical energy sources coming from an upper–bound utilization of our total identified biofuel potential as determined in

[1]This figure represents a best estimate, with the caveat that counting clean energy jobs 'cleanly' is notoriously difficult, see for example [1].

[2]The authors detail this and other analyses in an upcoming book
textitElectrify Everything, planned to be published with MIT Press in 2021. A summary handbook is available in the interim at www.rewiringamerica.com

[3]All of the data can be visualized, searched, and downloaded at www.departmentof.energy

the DOE "billion ton" report [3][4]. Hydrogen or other synthetic fuels (which are generated from electricity) are deployed for a few high–temperature applications. The scenario does not rely on any deployment of carbon capture and storage (CCS)[5], and all primary energy sources are net zero. We do not assume significant efficiency or behavioral changes, but rely on technology transformation instead. High electrification of the economy can be shown to reduce our primary energy needs by more than 50% (from ∼98 Quads down to ∼42) using only the inherent efficiency of electric vehicles over internal combustion engines (ICEs), of heat pumps over combustion heat sources, and on a smaller scale of LEDs over incandescents. From this model we build a "machines-up" account of the decarbonization transition, counting each specific piece of equipment required to make the transition. This accounting includes solar panels, heat pumps, and electric dryers, and also electrifying equipment that can be used for energy storage such as hot water heaters and electric vehicles. The jobs analysis presented here is grounded in the physical machines and equipment built for the decarbonization transition. The new machinery and equipment are priced against the fossil alternative (e.g. $30,000 electric vehicle (EV) vs. $20,000 internal-combustion engine (ICE) vehicle) and the resulting difference is established as the cost incurred for the changeover. These costs are then used to calculate direct, indirect, and induced jobs, using standard economic methods based on data from IMPLAN. We compare this economic job creation estimation with existing estimates of energy jobs, engineering estimates of jobs created, and with historically analogous projects of this level of ambition to confirm the reality of the very large number of jobs that this model projects.

Analysis Summary

- The maximum feasible transition (MFT) involves two primary stages: (i) an aggressive WWII–style production ramp–up of 3–5 years, followed by (ii) an intensive deployment of decarbonized infrastructure[6] and technology up to 2035. This includes supply–side generation technologies as well as demand–side technologies such as electric vehicles and building heat electrification.

- MFT also calls for close to 100% adoption of decarbonized technology when fossil machines reach retirement age. This is fairly simple to imagine: when someone's car reaches retirement age, it is replaced with an electric vehicle. When a natural gas plant is retired, it is replaced with nuclear or renewables.

- An MFT approach would create as many as 25 million net new jobs at peak.

- Every American household would accrue savings of $1,000–2,000 per year due to lower, more predictable energy prices.

[4] This is sufficient to run all aviation (≈ 2 Quads), non fossil mining and construction equipment (≈ 0.5 Quads), on-farm diesel (≈ 0.6 Quads) and a good portion of freight trucking (≈ 5.5 Quads)

[5] While "tech neutral" and politically seductive, the cost of CCS puts all fossil fuel sources at a severe cost disadvantage to wind and solar. Further, a CCS-heavy scenario assumes we have enough places to reliably sequester this carbon, which is impractical to say the least.

[6] We use a broad definition of infrastructure encompassing all machinery that generates, stores, or can shift electrical loads. This means including EV's, home HVAC, and the like as 21st century infrastructure.

- The government spending portion for such a transition is $300bN per year for 10 years for an approximate total of $3 trillion.
- This decarbonization pathway is commensurate with a global climate target of limiting warming to between 1.5° C/2.7° F and 2° C/3.6° F – assuming there is no significant deployment of carbon dioxide removal, that other major manufacturing nations (China, Germany, Japan, and South Korea) all follow suit in short order (within a decade), and that some nations are unlikely or unable to decarbonize quickly and are slower to respond.
- The job creation and the costs of such an ambitious nation–building project turn out to be similar in size and scope and new employment opportunities to the mobilization of U.S. industry for WWII.

Decarbonization

This study articulates a decarbonization strategy from the ground up. It provides an engineering account of what machines and infrastructure need to be replaced economy–wide, and on what timeline. This analysis is based on an assessment of the physical industrial setting – that is, rather than set emissions-reductions targets for various points in time and work backwards from there, as most models do, our approach looks at what machines and equipment currently exist and models the resulting "bottom-up" decarbonization pathway that follows. This approach demonstrates and illustrates the sort of transition that is possible and beneficial for first–mover economies that act rapidly and concertedly.

Figure 3 illustrates the decarbonization pathways for various climate targets. The pathways highlight the question of so–called committed emissions, the carbon emissions that will be emitted by machinery and infrastructure already in place through their useful lifetime [4]. What we can see from these simplified charts is that close to 100% adoption rates of decarbonized technology at end–of–life replacement are required for pathways commensurate with limiting warming to under 2° C/3.6° F . End of life–time replacement can be illustrated in a straightforward manner. When a car reaches retirement age, it is replaced with an electric one. When a coal plant is retired [7], it is replaced with nuclear or renewables.

In order to create a very specific estimate of jobs created by an energy system transition, we use detailed energy data to model out a pathway to completely decarbonize all energy related emissions in the U.S. The energy sector addresses ∼85% of emissions, with the remaining emissions coming from agriculture [5] and some esoteric industrial emissions. As per Figure 4 we move sector by sector through the economy and use existing technologies that can eliminate carbon emissions in that sector. We then estimate the future energy flow required to service that sector. No efficiency measures are assumed other than the inherent efficiencies of the substitution technologies. As an example it is assumed that nearly all vehicles will be electrified and that because the electricity is coming from renewables and

[7] Early retirement of our heaviest emitters is the only proven way we can improve our climate outlook, but today has proven very politically unpopular, at least partly because of the perception of lost jobs.

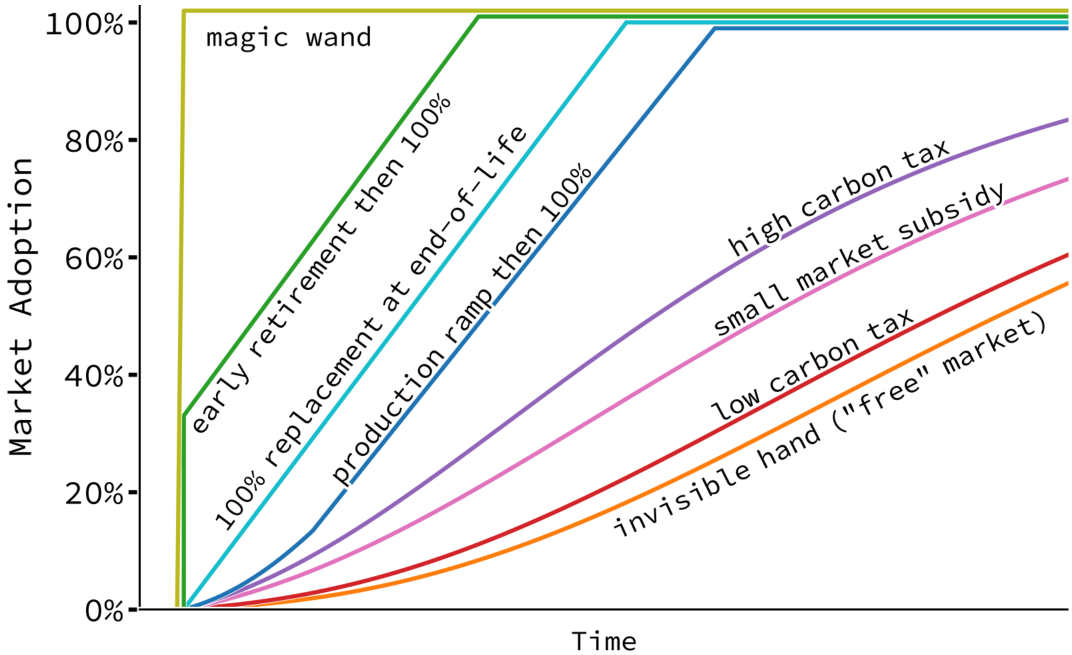

Figure 2: *Market adoption is the measure of penetration of a new technology. With 100% adoption of clean energy technologies we could be living carbon-free. The rate at which we get to 100% adoption will determine what global climate change we will get. We can contextualize different mechanisms for motivating increased market adoption where the "invisible hand", or a purely free market, is the slowest, and a magic wand that overnight changes all of our infrastructure to clean is the fastest.*

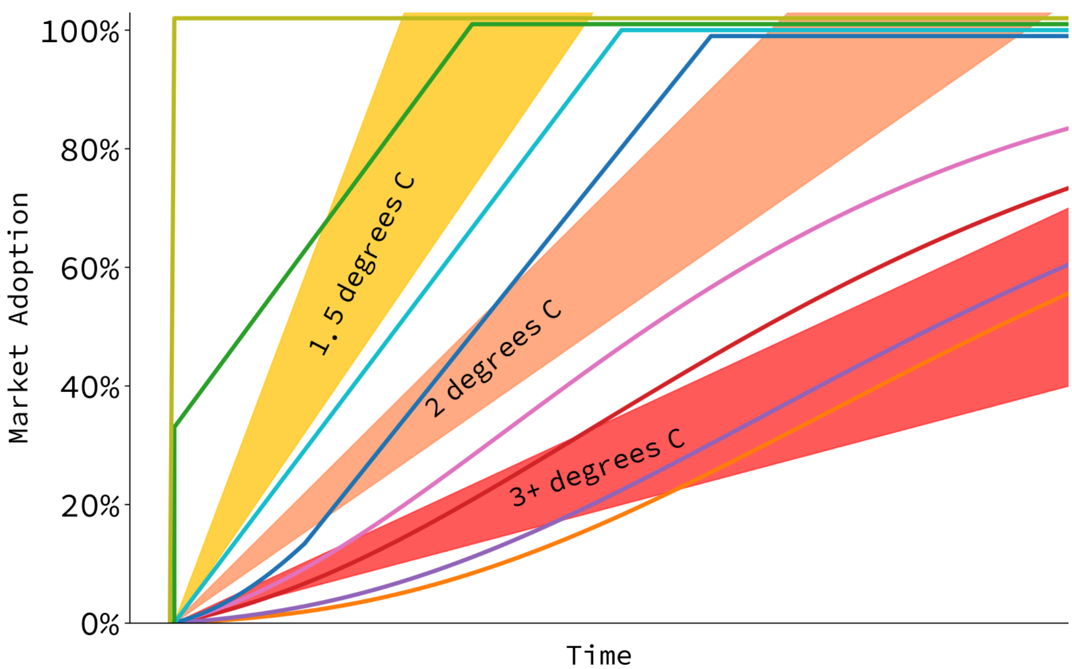

Figure 3: *Time is up for slow rate-of-adoption free market solutions. The question becomes: Which set of incentives or regulations are best to speed up action? The only pathways that stay under 2° C/3.6° F involve close to 100% adoption rates of decarbonized technologies at the end of life of all fossil fuel burning machines.*

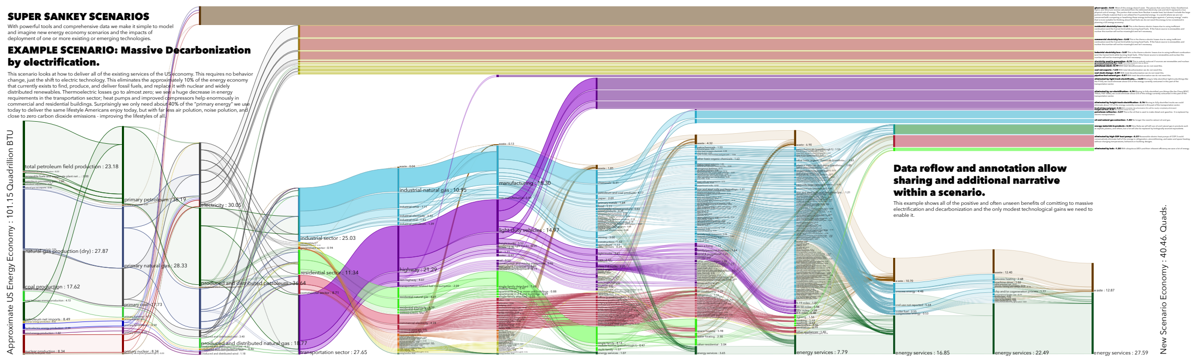

Figure 4: *A Sankey flow diagram of all US energy flows (based on 2018 data) where we have modeled out the primary energy reductions of electrification. This model gives a clear viewpoint on a total decarbonization strategy that does not rely on the invention of any new technology.*

nuclear, it will eliminate 16 quads of primary energy[8]; similarly, by producing all of our electricity with non-combustion sources, we eliminate 25 quads of thermo-electric losses. Electrification of buildings and the elimination of energy used to find, mine, and refine fossil fuels offer similarly large savings. It is found that the US only requires 40-50%[9] of its current energy needs by this high electrification pathway. It is assumed that biofuels or (something like) renewably generated hydrogen will be used in some of the small but difficult to decarbonize sectors such as long-distance aviation and steelmaking. This much electrification would mean the U.S. would need between 1,500 and 2,000 GW of net delivered electricity – between 3 and 4 times the current average of around 450GW. We assume the majority of this electricity will be produced with solar and wind, along with a doubling of the current nuclear electricity fleet from 100GW to 200GW. The decarbonization pathway we model is highly electrified.

This specific model of complete energy system decarbonization allows for a ground-up jobs estimate — based on knowing which machines and infrastructure need to be replaced with emission–free electrical machines and infrastructure[10]. The model does not assume much by way of efficiency apart from the inherent efficiencies of the electrical machinery replacing the fossil equipment. Similarly we don't assume any behavioral change, rather relying on technology transformation. This translates as replacing gas—powered pick-up trucks with electric pick—up trucks, and natural gas burning furnaces with electric heat pumps.

In short the model assumes:

- A highly electrified economy that reduces total primary energy need down to around 45-50 Quads (from 100).

[8]One *Quad* is one quadrillion (10^{15}) British Thermal Units (BTUs). For reference, today we use about 100 Quads to run the U.S.

[9]This is consistent with the highly electrified pathway outlined in [6].

[10]This method of thinking was first proposed by Koomey in chapter 3 of "Cold Cash, Cool Climate" and described as "Working forward towards a goal" — meaning choose your target, then figure out how to get there. This is in contrast with much analysis which begins with some version of the question "what is politically possible?".

- The great majority of that energy with renewable and nuclear electricity (1,500GW of new delivered electrical power).
- Near total electrification of transportation.
- Biofuels or electrically generated fuels will be used for aviation and some mining, freight, and construction equipment.
- The model accounts for capital expenditure to decarbonize industrial processes.
- Very high penetration of distributed (rooftop and community) resources is assumed, accounting for around 25% of energy supply and a high degree of the storage capacity.

The end result of the modeling effort is this:

- Decarbonizing America on this time frame produces as many as 25 million new jobs (at peak), tapering off to about 5 million sustained jobs, roughly double the number of jobs supported directly, and indirectly, by the current energy industry.
- The total government share of the expense is likely only $250-350 billion per year, with the total public and private spending over 20 years at about 20-25 trillion dollars.
- With appropriate regulatory policies and implementation, energy costs will be lower and the average household will save $1,000–2,000 per year.
- The majority of jobs that are created will be highly distributed throughout the economy. High–paying jobs are located in every zip code.

Estimating jobs

The effect of any decarbonization approach on the quantity and quality of available jobs is necessarily critical, both in terms of the ability to adopt and implement any such approach and its effect on people's lives. This consideration is only heightened in a post– COVID–19 world.

The MFT decarbonization model outlined here is well-suited to meet this challenge. Unemployment currently stands at a level higher than any point in time since the Great Depression [9]. For context and comparison we can look at the long-term history of unemployment in the US in Figure 5. At the height of the Great Depression more than 20% of Americans were unemployed. The public works and jobs programs undertaken under the administration of President Franklin Roosevelt made progress in addressing employment starting in 1935, but it wasn't until the war that the job situation changed significantly. Once the mobilization of American industry to manufacture war materials for WWII kicked in, the unemployment rate plummeted from north of 15% to 2–3% in a year or so.

It is useful to note that the WWII buildup included not only a decrease in unemployment of around 15% (of a 53 million person 1939 labor force), or around ∼8 million jobs, but also an increase in the labor force of 18% which represented another ∼9.5 million jobs. This was

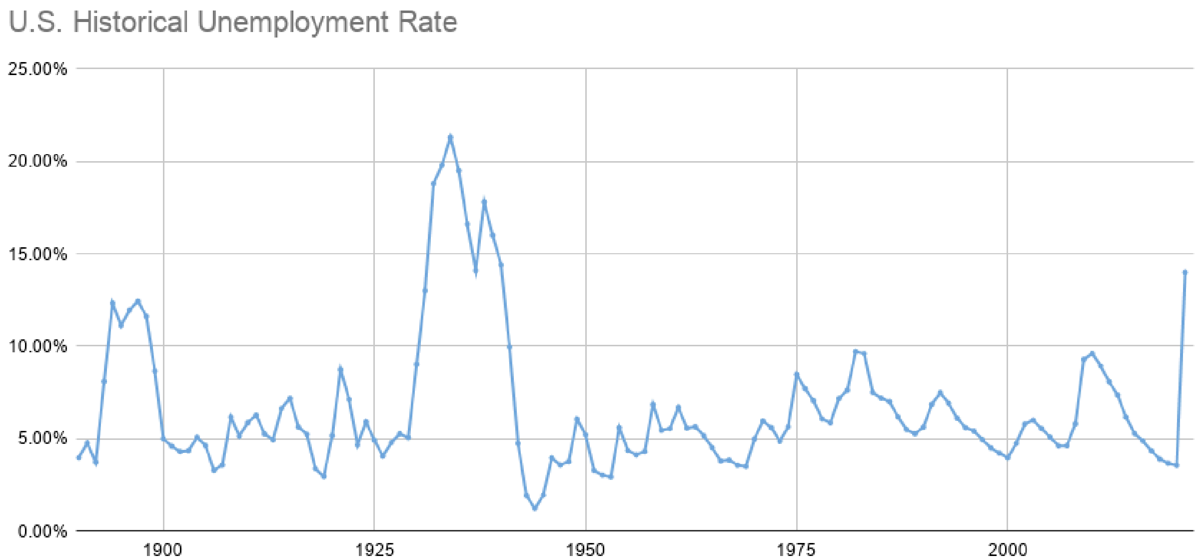

Figure 5: *The estimated U.S. Unemployment rate from 1890 to 2020. 1890–1930 data from [7], 1930–1940 data from [8], 1940–2020 data from Bureau of Labor Statistics [9].*

an addition of 17.5 million new jobs, which is useful to put the estimates in this paper of 25 million peak new jobs in a labor pool of 150 million people in perspective.

This real–world experience illustrates the employment potential of a rapid transition to a clean energy economy. Probably the only viable project of the scale necessary to reignite economic growth and return to full employment is decarbonizing America's energy system. This is equally true in many other countries in the world.

Below is a more detailed analysis of the job-creation opportunities associated with a rapid transition to a clean energy economy.

Job Creation Drivers in Transition to a Clean Economy.

Increasing employment under the transition to a zero–carbon is driven by the requirement for more labor in manufacturing, installation, and maintenance of renewables than their counterpart fossil fuel technologies. It takes more people to install and keep a wind farm running than it does to drill a well and keep it pumping for the same amount of energy over time. Renewables get their fuels for free, whereas fossil fuels cost money. It takes more labor and maintenance to access those free renewable fuels. This is a very desirable tradeoff in an economy with massive unemployment.

The double—edged sword explicit in any jobs analysis is that if there are more jobs, then the energy will be more expensive. But higher up—front jobs for building the infrastructure for free "fuels" in the future means many more jobs in the short term, more sustained jobs in the longer term, and lower energy costs almost immediately (if the appropriate financing and regulatory policies are enacted).

Calculating accurate estimates of job creation due to investments in decarbonization is

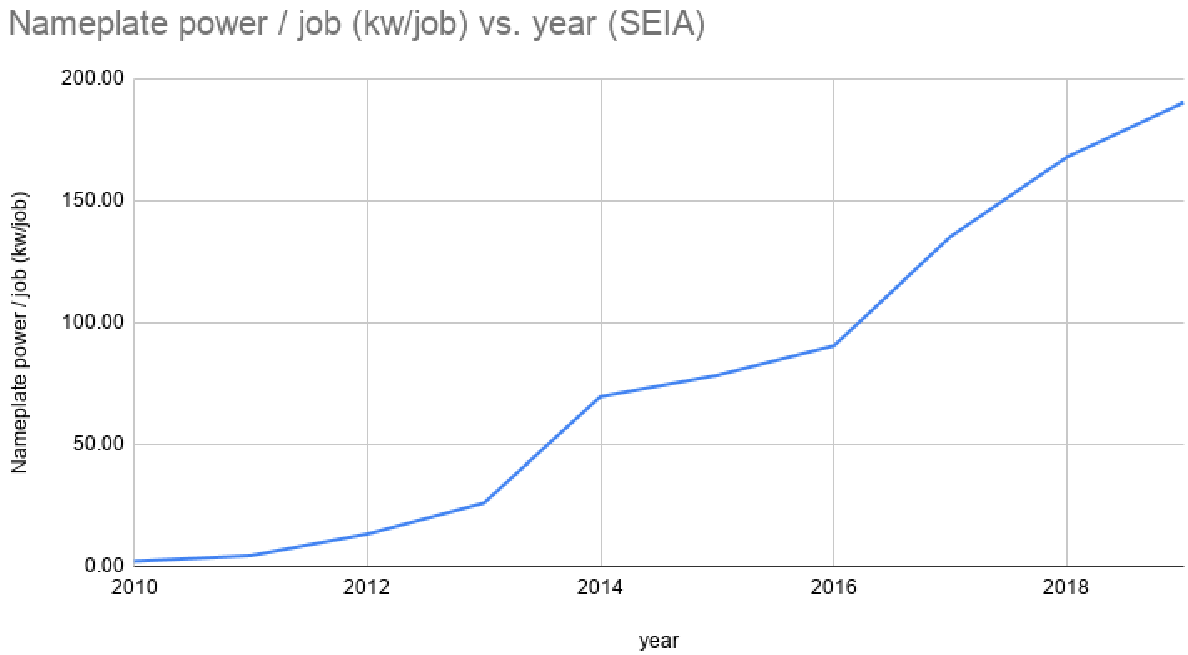

Figure 6: *Estimates of employment per kW of nameplate installed capacity from 2010-2019, from [10] and [11].*

challenging. As an example, consider the commonly-used method of assuming a fixed ratio of jobs per unit of electricity for a given technology. This allows us to estimate the number of jobs created by an investment by extrapolating this fixed ratio. In Figure 6, we plot the number of jobs per kilowatt of installed solar photovoltaics, using data from the Solar Energy Industries Association (SEIA) [10] and from the U.S. Energy Information Administration's Electric Power Montly report [11]. We can see that over the period from 2010 to 2019 this ratio did not, in fact, stay constant. Instead, it increased by nearly two orders of magnitude due to the learning rate of the industry.

As we can see, blindly applying fixed ratios of job creation is problematic, but extrapolating from the trend is slightly more reasonable. If we naively assumed 100% of our power would be supplied by solar, and that it is installed over 20 years, this implies more than a million direct jobs for this component alone.

Wind energy creates fewer jobs per kilowatt than solar, and a similar analysis using American Wind Energy Association (AWEA) data would suggest around 0.5 million sustainable-forever jobs if we supplied all of the U.S. energy needs with wind generated electricity.

Multipliers from jobs meta–analysis applied to this decarbonization strategy

Given the unreliability of the trade industry estimates and the unrealistic nature of supplying all energy from a single source, the next best method uses meta–studies of job estimates to synthesize across multiple sources. For instance, from the data of [1] we can estimate

New Capacity (GW)	Type	Multiplier	Jobs
500	Industrial solar	0.23	1,007,400
150	Rooftop / Solar	0.87	1,143,180
100	Nuclear	0.14	122,640
700	Wind	0.17	1,042,440
50	Hydro	0.27	118,260
100	Bio-fuels	0.21	183,960
1600			**3,617,880**

Table 1: *Estimate of supply side jobs using data of [1].*

jobs/GWh on the energy supply side in our decarbonization scenario, shown in Table 1.

That's more than 3.6 million *direct* jobs on the supply side, before counting the demand-side portions of the scenario.

Even before adding more details, we might then ask, how does this compare to the existing energy industry? What we'll find out next is that only counting the supply side, this is already double the number of direct jobs in the existing energy industries.

Current Energy Industry Jobs

The Bureau of Labor Statistics (BLS) maintains excellent publicly available data on jobs in their "Current Employment Statistics" monthly reports[12]. We arrange it in Figure 7 as a treemap that breaks down the big categories into increasingly small ones — answering the question that Richard Scarry [13] sought to answer in his famous children's book *What do people do all day?*[11].

What immediately stands out as we write this are the very large categories of jobs susceptible to a pandemic like the novel coronavirus: 17 million jobs in leisure and hospitality, 16 million people in retail trade, 12 million people in public and private education. We can see why a pandemic requiring social isolation causes so much unemployment so quickly. Energy jobs are easily identified by pulling the jobs related to energy out of this same dataset. We show them in Table 2.

What is immediately apparent is just how few people are directly employed by the energy industry —– about 2.7 million if you count gas station convenience stores jobs, and about 1.8 million if you leave those out. The largest number of people employed in fossil fuels from this perspective are the nearly one million working in gas stations. However, convenience stores also sell snacks and sundries, so we don't completely categorize them as energy industry employees; convenience stores sell 80% of the gas in this country.

Next, we can identify the jobs in coal mining — around 50,000 — and compare that to, for example , the 450,000 people who work in hair styling and barber shops, the 370,000 who work in golf clubs, or the more than 10,000,000 who work in restaurants.

The BLS data is based on North American Industry Coding System (NAICS) codes.

[11] For the data-inclined, the Bureau of Labor Statistics does keep marvelous numbers on time use beyond employment in their Time Use Survey dataset.

Job category	**Number of Jobs**	**Fossil?**
Fossil fuel electric power generation	83,200	Y
Nuclear and other electric power generation	61,300	
Electric bulk power transmission and control	25,300	
Electric power distribution	212,700	
Natural gas distribution	110,600	Y
Pipeline transportation	51,100	Y
Gasoline stations with convenience stores	**851,800**	
Other gasoline stations	101,400	Y
Oil and gas pipeline construction	152,400	Y
Power and communication system construction	216,500	
Petroleum	102,800	Y
Petroleum refineries	68,600	Y
Electric power and specialty transformers	28,400	
Electricity and signal testing instruments	370	
Turbine and power transmission equipment	99,200	
Mining and oil and gas field machinery	69,500	Y
Oil and gas extraction	155,800	Y
Support activities for oil and gas operations	247,800	Y
Bituminous coal and lignite surface mining	22,800	Y
Bituminous coal underground mining and anthracite mining	28,300	Y
Total	**2,689,870**	
Total without gas station convenience stores	**1,838,070**	
FOSSIL ONLY	**1,194,300**	

Table 2: *January 2020 US jobs related to the energy economy, from BLS[12]*

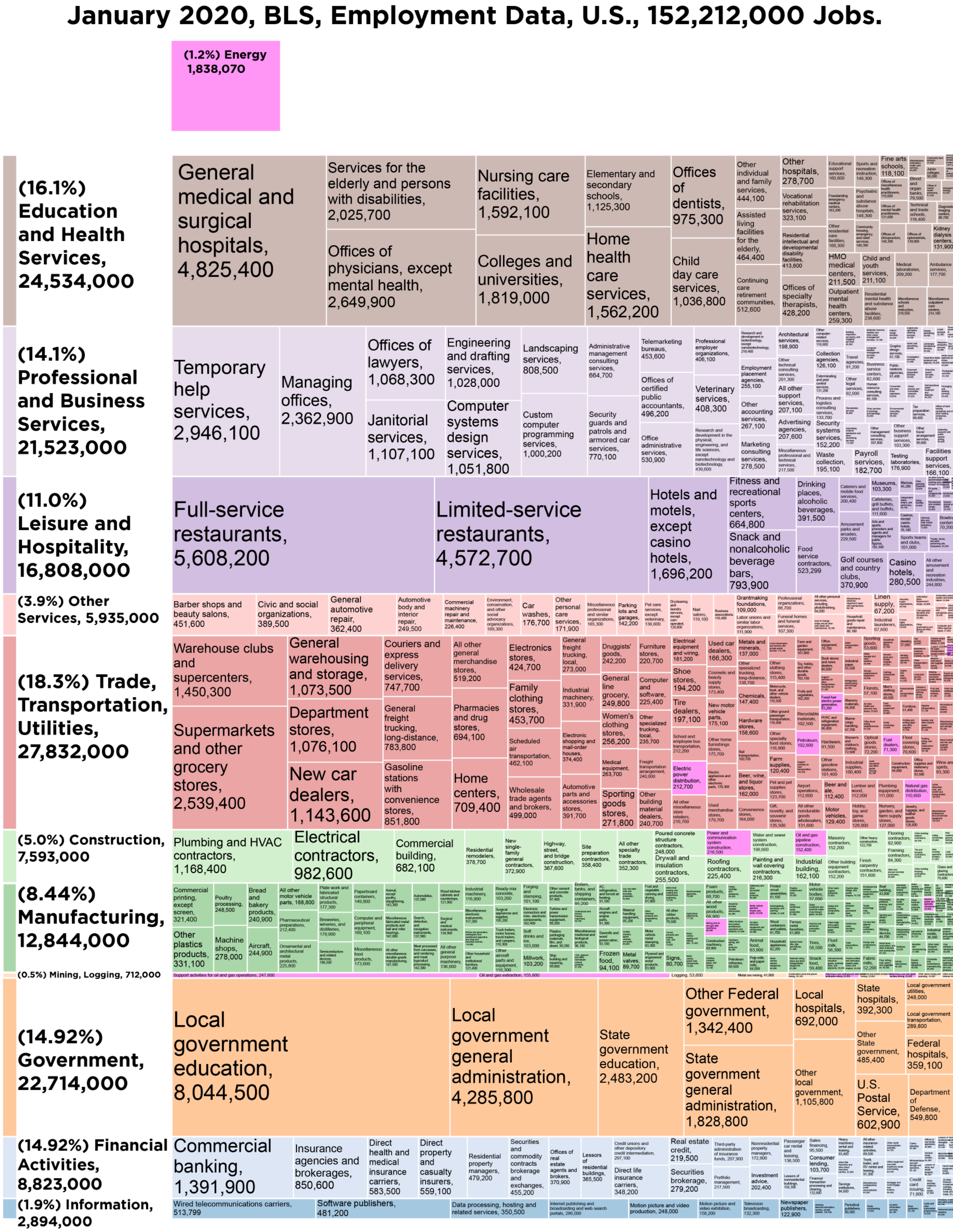

Figure 7: *All US jobs, Pre-COVID-19. Data from [12]. Get out your glasses!*

Job category	**Current Jobs**	**Heuristic of future jobs**
Fuels	1,149,000	∼150,000
Electric power generation	897,000	∼2,300,000
Transmission, distribution and storage	2,400,000	∼6,000,000
Energy efficiency	2,380,000	∼4,400,000
Motor vehicles	2,550,000	∼2,000,000
Total	9,376,000	14,850,000

Table 3: *USEER estimate of total energy industry jobs 2016 [14]*

Many federal data sets are arranged by this coding system, including energy surveys such as the Manufacturing Energy Consumption Survey (MECS). It is important to note that many jobs don't fit perfectly into these buckets, and categories of jobs change over time. Further confounding the data is that people might spend a small part of their day doing energy work, and the rest of their day doing construction; consider a small town electrical installer who sometimes does solar panels and energy efficiency retrofits like heat pump water heaters, but also does hot tub installations and wiring for non-energy related home renovations. Given these limitations, we can take a look at a deeper study of energy industry jobs.

USEER Estimates

Since 2015, The National Association of State Energy Officials (NASEO) and the Energy Futures Initiative (EFI) have produced the U.S. Energy and Employment Report (USEER)[14].

This report is compiled from a comprehensive survey of industries and individuals throughout the energy economy, and builds a comprehensive outlook on jobs from the resulting data. The USEER came about in 2016 after the DOE recommended reviewing how we count energy jobs in the 2015 first installment of the Quadrennial Energy Review (QER)[12] *"to reform existing data collection systems to provide consistent and complete definitions and quantification of energy jobs across all sectors of the economy."*[15]

The USEER breaks down energy into five different energy sectors: the "traditional," which include (1) fuels (1,149,000 jobs), (2) electric power generation (897,000), and (3) transmission, distribution and storage (2,400,000). The other two are (4) energy efficiency (2,380,000) and (5) motor vehicles (2,550,000). In 2020 the first 4 sectors employed 6.8 million Americans, or 4.6% of a workforce of 149 million. For reference, that is similar to the total number of people who work in finance and insurance (6.5 million). If we include those who work in motor vehicles under energy jobs, it is close to 9.4 million. The summary is presented in Table 3.

We can heuristically discuss each of these categories, and reason whether the number of jobs in those categories increases or decreases as we decarbonize.

The fuels category obviously decreases, but not to zero, as natural gas and to a lesser extent oil are used in substantial amounts in the plastics and fertilizer industries. A small amount of natural gas for seasonal peaker plants is also likely to stay on the grid for reliability

[12]The Quadrennial Energy Review is surprisingly readable, has great charts and images, and would be a great start for anyone wanting to develop an energy information hobby :) See [15] and [16].

reasons. Let's suggest this number might decrease by 80%, to around 150,000 (transitioning out around 1 million jobs).

Electric power generation is set to increase 3 to 4 times, which if applied as a multiplier on current electric power generation jobs gives an additional 1.8–2.7 million jobs. As a sanity check, we see this is in rough agreement with the solar energy industry example above.

Transmission, distribution, and storage also need to increase 3-4 times. That's another 4.8–7.2 million new jobs.

Energy efficiency is ill-defined currently, but we know that we need to do a huge number of end–use technology transformations for stove–tops, hot water heaters, furnaces, and the necessary home and commercial electrical upgrades (breaker boxes, etc) to make it possible. This is in addition to weatherization and existing efficiency jobs. It is hard to imagine that this category doesn't double or more given the pace of transformation required suggesting an increase of at least 2 million new jobs.

Finally, we consider motor vehicles – a fraught category. We know that electric vehicles should require less maintenance, because they have fewer components and fluids to replace. In contrast, they also weigh more, which typically correlates to more assembly labor. Most industry pundits believe there will be fewer jobs in an electrified automotive industry, but it is too early to tell just how many. Expanding factory automation is likely to be as significant a driver of job reduction in this sector as the change in technology from ICEs to EVs, whether or not we decarbonize. If we assume a reduction of 20% that's around 500,000 fewer jobs. Aggressively scaling U.S. production of EVs could allow the country to command more of the global vehicle export industry, more than offsetting hypothetical losses due to converting the vehicle fleet to electric.

Adding up the changes in this very gross estimate, we see around 1.5 million jobs transitioning out, replaced by as many as 10 million new jobs transitioning in.

We can see from these sector-specific, simplistic analyses that we can expect total employment in the energy industry to increase substantially, but just how substantially is beyond the scope and accuracy of these types of estimates. We provide them here as a framing for the more rigorous econometric analysis that we undertook which is a more traditional way of estimating job creation from macro–economic interventions.

A detailed econometric jobs forecast

Our analysis employs traditional economic models to estimate jobs and job creation, such as the Job and Economic Development Impact (JEDI) models employed by the National Renewable Energy Labs (NREL), to estimate job creation in the wind, solar, and other renewables industries[17].

Under this approach, job creation is estimated by understanding how much economic activity will occur (in millions of dollars), using estimates based on historical job creation in different industries per dollar. This econometric approach also takes a more expansive view of jobs, which includes (1) direct jobs (similar to those we counted earlier), which are jobs that are concretely and specifically in energy; (2) indirect or supply chain jobs, which are the jobs that support and service the direct jobs. A direct job might be installing natural gas pipelines, and an indirect job related to that is making the steel for the pipes, or the valves and pumps for the pipeline. Induced jobs (3) are the jobs that are created in a community around the direct and indirect jobs. These are the people employed in the restaurants, schools, local retail stores, and other facilities that service the direct and indirect jobs. The woman installing wind farms gets a handsome pay check that she'll spend a good portion of in her local economy employing butchers and bakers and LED makers.

The application of the methodology then is pretty straightforward. (1) Estimate the amount of money it will take to build all of the things we need to decarbonize the economy. (2) Use the ratio of direct jobs per million dollars spent for that economic sector. This number is calculated by looking at the employment statistics by industry sector over time, and comparing it to the economic activity in the sector over time. A specialist company called Implan develops and maintains databases of this kind [18]. (3) Calculate indirect jobs and induced jobs as multipliers of this number.

By example, $1,000,000 (2017 dollars) spent in construction creates 5.38 direct jobs, 3.87 indirect jobs, and 10.22 induced jobs. That is 19.77 jobs created per million dollars. This can tell you the *gross* number of new jobs. The *net* number of jobs must subtract out jobs that will be lost, or pre-existing jobs that overlap or will be absorbed by the new activity. We must find career transitions for the phased out coal mining and find jobs for those 50,000 miners, whereas we are not phasing out the 2,500,000 jobs in the auto industry, as they'll be redirected to electric vehicles and other net-zero carbon vehicle options. Careful and methodical accounting was undertaken to make sure we are not double-counting jobs and that we include the eliminated or transitioned jobs.

The first task is defining what we need to build, then we can address how much it will cost. This calculation is from an engineering approach, from the bottom up, and consequently this report offers one of the most detailed estimates of what it takes to decarbonize ever presented.

Remember that we will need somewhere between 1500 and 2000 GW of new electricity capacity on the supply side to decarbonize. That will need millions of miles of new and upgraded transmission and distribution to get to the end user. Finally on the demand side we'll need to electrify our 250 million vehicles, 130 million households, 6 million trucks, all of our manufacturing and industrial processes, and 5.5 million commercial buildings covering 90 billion square feet.

For the purposes of this analysis, and to help make sure we don't double-count anything, we'll divide the work into 8 large categories.

1. **Supply Build-Out:** The new-generation capacity for everything that will be electric and additional biofuel capacity for those things (like aviation) that won't. We base the build-out on costs of build-out in 2017, and with a goal of 1500 new GigaWatts (net) of zero-emission infrastructure to add to the existing 300GW.

2. **Transmission and Distribution Build-Out:** This category is the new long-distance transmission lines, and the extra capacity for local distribution required to connect the new supply. The costs are based on known GW-miles/year of existing infrastructure [19, 20].

3. **Household Electrification:** These are all of the components of a national electrification strategy that are connected to households. It includes the appliance upgrades, and electric vehicle upgrades appropriate to complete decarbonization of all households.

4. **Household Efficiency:** These are the more traditional energy efficiency measures for upgrading U.S.residential building stock (insulation, double glazing, new wiring, LED lighting, hydronic heating loops) such that the appliances in Household Electrification can work more efficiently.

5. **Transportation Sector:** This accounts for the replacement of our personal, fleet,and commercial light-duty vehicles (∼250 million of them) and 6 million trucks.

6. **Commercial Sector:** These are the HVAC, lighting, water, and cooking retrofits required of the commercial building stock estimated on a $/sq.ft basis. We include public vehicle charging infrastructure under the commercial sector as we anticipate the majority to be in parking spaces adjacent to or located at commercial businesses. We include commercial freight trucking in this sector.

7. **Industrial Sector:** We very grossly estimate the increased capital spending required per industrial sector as a multiplier of the 2017 capital expenditure of U.S. industry to account for the electrification upgrades of process heat and other efficiency measures.

8. **Energy Research and Development:** The plan for decarbonization we outline does not require or reference technologies that do not yet exist; however the project certainly gets cheaper the more we invest in R&D. We use comparable existing R&D budgets from ARPA-e, DARPA, and NSF, to contemplate an annual spend appropriate to an aggressive U.S. decarbonization or energy-led economic recovery program. Energy R&D will be important, particularly in the hard-to-decarbonize sectors of industry, and if there is to be any near-term progress made on "game-changing" technologies such as advanced nuclear, fusion, a breakthrough battery, or carbon capture.

9. **Education and Training:** An enormous amount of education and retraining will be required to mobilize a workforce at this scale. We use the total existing trade and vocational training industry and its annual expenditures to grossly estimate this component.

Once we have each of these estimates, we'll add them up, reconcile the timeframes of all of the upgrades, and develop a schedule of jobs created per year under the assumption that we will do an aggressive 3-5 year ramp up of manufacturing and installation capacity, followed by a period of implementation with a goal of majority decarbonization by 2035 — commensurate with a goal of avoiding 2° C/3.6° F of warming.

Supply Build-Out

The new generation capacity we can guess at pretty well. In Table 4 we create an additional 1500 GW of new capacity, in addition to the 319 GW of net-zero-carbon capacity we already have.

The observant reader will notice that we use a very low cost of rooftop solar of $1.50. This is half of the current American cost ($3-3.20/W), and more in line with the costs in Australia — in fact, they vary between $1 and 1.25/W down-under. It would create more jobs if we used the current U.S. number, but it would make energy more expensive, and

Generation type	$GW_{nominal}$	**$/W**	Millions of $ 2017
WIND	1500	$1.48	$2,215,500
SOLAR - rooftop	1000	$1.50	$1,500,000
SOLAR - utility	1500	$1.38	$2,070,000
HYDRO	75	$2.00	$150,000
NUCLEAR	100	$3.00	$300,000
GEO	50	$4.00	$200,000
BIO	100	$2.00	$200,000

Table 4: *New primary energy (Nominal installed capacity to which capacity factors must be applied) that will deliver approximately 1500 net new GW of electricity, and additional biofuels*

Category	**GW of capacity**	**$M/GW/year**	Millions of $ 2017
Transmission	1000	21	$21,000
Distribution	1000	52	$52,000

Table 5: *New Transmission and Distribution*

that is not the goal. We want to create the lowest cost energy system we can, save our households money, and create jobs, but one immediately sees the tension in this approach to the analysis: if you want the answer to be more jobs, spend more money!

This, then, is the total work that needs to be done to decarbonize. It won't happen in a year, so we will need to decide upon the time period over which it is implemented to determine the annual jobs.

We will push on with as much clarity as we can about the cost of things.

Transmission and Distribution Build-Out

Much of this new generation capacity will need to be connected to the grid, and transmitted and distributed. Some of it is biofuels and much of it is rooftop solar that needs neither transmission or distribution. The other 1000 GW needs to be connected though.

We can use existing costs of transmission in millions of dollars per GW of capacity per year. Using the University of Texas, Austin, estimates, we get Table 5. This is an annualized estimate of the number of jobs based on estimates of the current annual costs per GW of capacity.

Household Electrification and Household Efficiency Retrofits

What do we need on the demand side? Let's look at our homes and vehicles first in Table 6. We must account for replacing all of the equipment that currently uses fossil fuels. For example we assume that hot water heaters that are mostly natural gas today are replaced by heat pump water heaters. We assume one per household, but that only about 3/4 of households need one, as many already have electric hot water systems. We assume most houses will need a new load center commensurate with increasing the electrical load in the household significantly. Similar logic is applied to the other appliances in the house.

Number of units (millions)	Item	Decarbonized cost ($)	Incumbent cost ($)	Transformation Cost (M$)
Appliances				
90	HP water heater	1,600	1,130	42,300
100	Load center	2,000	0	200,000
80	HP furnace	7,500	4,000	280,000
100	Home car charger	1,500	0	150,000
80	Induction range	1,200	1,000	16,000
80	Home battery electric	3,000	0	240,000
80	Home battery thermal	1,000	0	80,000
50	Electric Dryer	1,200	1,100	5,000
Retrofits				
1,200	LED Lightbulbs (/bulb)	2	1	1,200
Optional Efficiency Retrofits				
120,000	hydronic heat (/sqft)	10	0	1,200,000
240,000	window retro (/sqft)	7	0	1,680,000
240,000	insulation retro (/sqft)	2	0	480,000
240,000	electric retro (/sqft)	2.5	0	600,000

Table 6: *Upgrading our 120+ million homes. The Optional Efficiency Retrofits are not critical to our analysis.*

Number of units (millions)	Item	Decarbonized cost ($)	Incumbent cost ($)	Transformation Cost (M$)
250	Light duty vehicles	38,000	32,000	1,500,000
5	Freight Trucks	120,000	80,000	200,000

Table 7: *Upgrading our transportation fleet.*

It is assumed nearly every household will have at least one home car charger installed, for example. We include light-duty vehicles under household electrification as they are purchases made by the household, connected to the household, and will be integral to the "electrical infrastructure of the home." It is not strictly necessary by the methodology we outlined at the beginning of this white paper, but we assume a small number of traditional "efficiency" jobs — insulation and double-glazed windows as canonical examples. Another curious thing will become apparent — as LED lightbulbs are now so cheap and economically effective, and because they last so long, mass adoption will result in fewer net jobs[13].

Transportation:

As per Table 7 there are between 250 million and 263 million light-duty vehicles. There are 5.5-6 million trucks. We assume a $6,000 dollar price differential for EV's and a $40,000 dollar price differential for alt-fuel (but mostly electric) trucks.

[13] You can imagine what the nay-saying press will have to say about that!

Billion Sq.Ft (of 90 billion total)	Item	$ / sq.ft	Transformation cost (M$)
75	HVAC	20	1,500,000
60	Lighting	5	300,000
40	Cooking	1	90,000
80	Water	1	160,000
50	Refrigeration	2	100,000
Units (millions)	**Item**	**Unit cost ($)**	**Total cost (M$)**
50	car chargers	6,000	300,000

Table 8: *Upgrading our commercial buildings and charging stations*

Commercial Buildings

Upgrade of commercial buildings is required as well, and we will include public electric car charging infrastructure here. For commercial buildings the calculations are made using gross estimates of the per square foot price of upgrading things like the HVAC systems. We present these top line estimates in Table 8.

Industrial Sector

The final sector of the economy we need to consider is industry, which comprises manufacturing, mining, and agriculture, among others. It's more complicated to provide a cost estimate for a sector that is so varied. We know that we'll need new capital expenditures for upgrading steel mills to electric and hydrogen, aluminum smelters, and new ways of making pretty much everything to eliminate the oil, coal, and natural gas that power much of industry.

To produce a very gross estimate we look at the 2019 United States Census Bureau's "U.S. Capital Spending Patterns 2008-2017" [21]. We will take the 2017 capital expenditures by industry sector, and assume capital equipment is turned over during the 15-year mobilization and decarbonization periods (2020-2035) to calculate an expenditure as a multiple of the historic amount. We change this multiple for different sectors with a gross estimate of which will be more impacted. We look at this in Table 9.

Research and Development

For a gross estimate we can begin with analogous existing federal R&D spending. We then estimate how much similar spending might be dedicated to energy system renewal and decarbonization, including the material economy. Today DARPA, The Defense Advanced Research Program Agency — perhaps the most renowned R&D agency in the world for high-risk, high-return research — has a budget of $3.4bN annually [22]. We add a number like that to spending by an agency like ARPA-e, which is modeled on DARPA, but exists specifically to advance high-risk, applied research projects in energy. NSF, the National Science Foundation, currently has a budget of around 8bN [23]. The NSF does fundamental

Industry Sector	2017 Cap-Ex Spend (M$)	Decarbonized Multiplier	Decarbonized Spend (M$)
Forestry, fishing, & agricultural services	$4,746	1.25	$1,186
Mining	$132,875	1.25	$33,219
Utilities	$134,456	1.25	$33,614
Construction	$34,800	1.25	$8,700
Manufacturing	$248,349	2.00	$248,349
Wholesale trade	$42,710	1.10	$4,271
Retail trade	$91,747	1.05	$4,587
Transportation and warehousing	$110,729	1.05	$5,536
Information	$158,184	1.10	$15,818
Finance and insurance	$167,675	1.05	$8,384
Real estate and rental and leasing	$158,184	1.05	$7,909
Professional, scientific, & technical services	$37,964	1.05	$1,898
Management, companies & enterprises	$7,909	1.05	$395
Administrative & support & waste management	$26,891	1.05	$1,345
Educational services	$36,382	1.05	$1,819
Health care and social assistance	$104,401	1.05	$5,220
Arts, entertainment, and recreation	$22,146	1.05	$1,107
Accommodation and food services	$36,382	1.05	$1,819
Other services (except public administration)	$22,146	1.05	$1,107
Industries not elsewhere classified	$4,746	1.05	$237
TOTAL INDUSTRIAL UPGRADE ANNUALLY	$1,581,840		**$509,906**

Table 9: *Upgrading our Industrial Capital Equipment*

Agency	New budget	Old budget	Net new Spending
DARPA	$3,400	$3,400 [22]	$0
ARPA-e	$4,000	$366 [24]	$3,634
NSF	$10,000	$8,000 [23]	$2,000
EERE	$6,800	$2,400 [24]	$4,400
EIA	$250	$125 [24]	$125
New R&D spending			**$10,159**

Table 10: *New Federal Research and Development Spending*

science for the large part, exploratory work that creates total new avenues and solutions, not just cost reductions. That level of spending is required to develop viable applications of nuclear fission or fusion, develop low-cost carbon sequestration, improve agriculture, and find alternatives to plastics, cements, steel with carbon, and aluminum — all currently high carbon emitters. EERE is the Energy Efficiency and Renewable Energy office of the DOE. It is the most applied of these agencies, meaning the work is typically closer to market. It is where the heavy lifting of near-term response will be, and hence for this exercise we raise the budget from $2.4bN to $6.8bN [24]. Finally, the Energy Information Administration, which helps us know what we know about energy and carbon, will double its budget so that we can have increasingly-detailed knowledge about the right problems to solve. We sum up these numbers, and determine the pathway requires around $10bN annually in new federal R&D spending. This can be compared to the approximately $100bN that goes into all federal R&D programs annually.

The discussion above is not offered as a recommendation on the best areas for R&D, and often new agencies will have a fresh take and less bureaucracy than old ones, but rather it illustrates the flavors and types and volumes of R&D spending that could deliver some of the breakthrough technologies that would make it easier to decarbonize in the short term and more cost effective in the long term.

Education and Training

From the analysis above it is apparent that the numbers of new jobs created will require major investments in education and training to make it possible to fill all of the jobs. As a very gross first estimate we can take the gross annual spending of trade and technical schools which is $16bN [25] and dedicate a similar amount to new vocational training specific to the energy industry jobs to be filled. Someone will have to train an awful lot of electrical technicians as only one example of all of the new jobs in this sector.

Finance jobs

This type of program will require a very large volume of monetary transactions, including borrowing and repayment. We use a very simple cost analysis to produce a first-cut rough estimate of the jobs creation in the finance sector. We take the total spending on this project and apply a net present value calculation based on a 20-year amortization and an interest rate of 4%. These annual interest expenditures are converted into a jobs number using the jobs multipliers or factors appropriate to the finance industry: 4.10 direct jobs / $Million, 3.49 indirect, 10.11 induced, and 17.70 in total.

Adding it all up

The spending from all of these categories can now be added together. We convert all spending into annualized expenditures. This is something like the fastest imaginable pathway to decarbonization without hobbling the economy — in fact, boosting it. The emissions trajectory associated with this level of ambition, if also subsequently carried out by the other major emitters[14], correlates to a 2° C/3.6° F world. In the case of the supply-side build-out this means that we assume an aggressive 3-5 year ramp up of capacity followed by a similarly aggressive 10-year build-out of the capacity. This implies near complete decarbonization of the supply side by 2035. On the demand side we largely try to replace things at the natural replacement rate implied by the natural lifetime of the incumbent technology. For example, water heaters last on average about 11 years, so we spread the spending out over that period. As such the great majority of the demand side will also be decarbonized by 2035. Annualized spending such as R&D and training are treated as such. We use established

[14] There is a first-mover advantage to the economies that act this decisively first in producing highly profitable export industries to serve the rest of the world. Proving the economics work for America would provide the majority of other nations with the impetus and a framework for their own decarbonization plans.

Sector	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Electricity supply	170	335	495	488	481	473	466	459	452	446
Grid	49	97	143	141	139	136	134	132	130	128
Residential	15	30	45	59	73	72	71	70	69	54
Residential efficiency	46	95	143	189	234	231	227	224	220	217
Commercial	111	130	149	166	177	175	172	170	167	135
Transportation	26	52	77	102	126	124	122	120	118	116
Industrial	45	90	133	175	216	213	209	206	203	200
R&D	2	4	10	10	10	10	10	10	10	10
Education/training	4	7	16	15	15	15	15	15	15	14
Finance	11	31	59	90	125	158	192	225	257	288
Total:	**482**	**875**	**1,273**	**1,440**	**1,598**	**1,610**	**1,622**	**1,633**	**1,645**	**1,612**

Table 11: *Total cost of capital, training, and build-out of a zero-carbon US economy in B$*$_{2017}$.

sector appropriate job multipliers to calculate the direct, indirect, and induced jobs in the new energy world implied.

The first 10 years of spending is broadly outlined in Table 11.

As per the typical methodology of economists, we convert the dollar amounts in Table 11 to direct, indirect, and induced jobs using indicative sector specific job coefficients. For the majority of these estimates we use the specific coefficients for construction industry of (1) direct: 5.68 Jobs per million dollars, (2) indirect: 3.87 jobs/$M, and (3) induced: 10.22 jobs/$M. This represents a total of nearly 20 jobs per million dollars spent. Figure 8 shows the rapid mobilization ramp-up as capacity is built to manufacture and install the necessary infrastructure. New jobs peak after this ramp at about 34 million. As would be expected, the jobs ramp down after the initial infrastructure build-out, and then stabilize long-term. After the build-out period bubble of jobs the number of jobs tapers off to the sustained jobs in the natural rate of turnover in replacement installations and operations and maintenance of the new energy economy, which we can see out to 2040. Technology and automation could change the number enormously — we modeled in an industrial cost reduction rate of 1.5% per year associated with industries still ramping up production in addition to the compounding 1.34% labor productivity improvements associated with mature industries. This cost reduction rate is likely higher in such a mobilization. From where we stand today we can assume the 2040 numbers as the approximate total number of new sustained jobs in a fully transitioned energy economy.

But this does not fully account for the jobs displaced or transitioned in this full decarbonization plan. We need to understand the direct, indirect, and induced jobs in the current fossil economy, and subtract those from our total. We have the choice of 3 different numbers: (1) We can take the estimate from the USEER study, or (2) we can take the direct fossil jobs in the BLS data and multiply by normalized indirect and induced job factors for the energy industry, or (3) take the same BLS data and use the indirect and induced job factors for the construction industry, which was the multiplier for all of the other jobs we analyzed. We chose (2), which totals 1,092,900 direct jobs, for a total of 11,141,090 jobs. We also consider existing non-carbon, non-fossil, energy jobs in the same manner, where the existing 643,770 jobs become 6,562,631 with the same jobs multipliers. All of these jobs are graphed in Figure 9. We can see the tapering out of the fossil-related jobs through 2040, and the

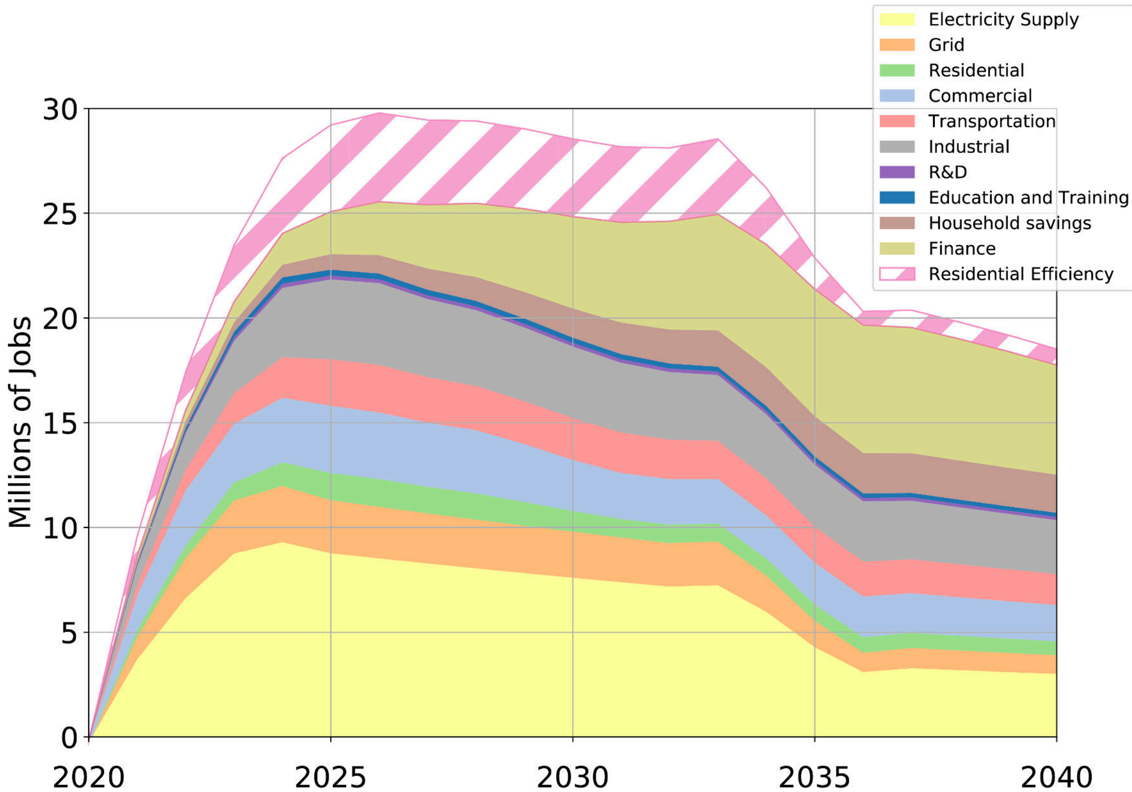

Figure 8: *New clean energy jobs created in a mobilization of the economy commensurate with a 2° C/3.6° F target. The "efficiency" jobs (pink stripes) are optional, and not necessary for decarbonization and not included in our total job count.*

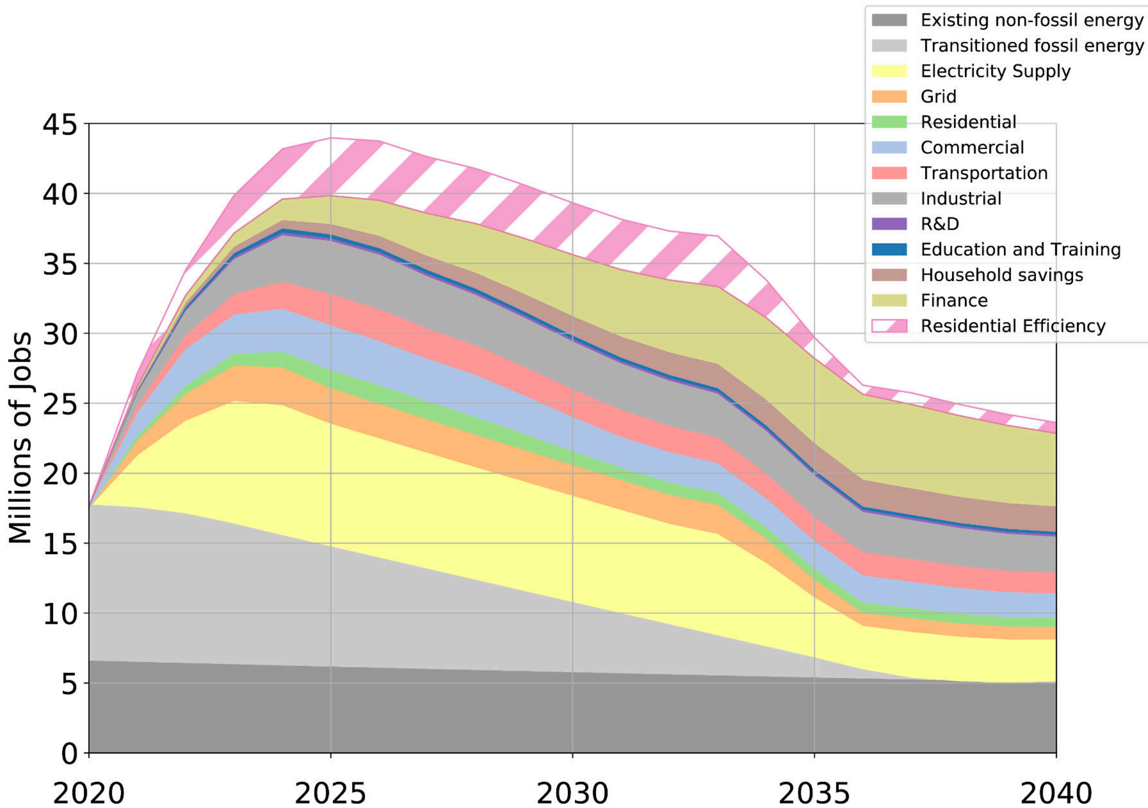

Figure 9: *Total jobs in energy through 2040 with a winding down of fossil fuels and decarbonization effort commensurate with a 2° C/3.6° F target. The "efficiency" jobs (pink stripes) are optional, and not necessary for decarbonization and not included in our total job count.*

fact that they are more than compensated for by the enormous number of new jobs in the new energy economy. It won't be easy for everyone, and given the vibrant economy we have enjoyed for a century underpinned by these fossil jobs, we believe the argument stands for treating very generously those who have worked in fossil with appropriate re-training and early-retirement programs. With plenty of empathy we should be capable of a manageable transition.

Revenue supporting job creation.

We emphasize once again the potential double–edged sword of these calculations. Because this economics methodology for calculating jobs starts with "dollars in = jobs out" one must resist the temptation to just spend more money to create the number of desired jobs. For example, if this analysis were to use the existing cost of installation of rooftop solar in the U.S., $3.20/Watt, we create 3.5 million more jobs than if we use something more like the Australian price of $1.50/Watt. However, if we create those extra jobs, we increase the price of energy because of that extra labor. That potential conflict is everywhere in this analysis. Because LED lighting at this point in history is such an easy economic win — the bulbs last much more than ten times as long and are not nearly ten times more expensive, installing

Sector	Gov.Share	Precedent
SUPPLY BUILD-OUT	26%	RTC credit
GRID BUILDOUT	10%	Tax credit
HOUSEHOLD ELECTRIFICATION	25%	Rebates, loan guarantees
HOUSEHOLD EFFICIENCY	5%	Rebates, incentives
COMMERCIAL SECTOR	5%	tax incentives
TRANSPORTATION SECTOR	30%	Rebates, tax incentives
INDUSTRIAL SECTOR	25%	subsidies / tax incentives
ENERGY R&D	50%	direct
EDUCATION AND TRAINING	50%	direct
FINANCE JOBS	0%	

Table 12: *Estimating Federal contribution by sector*

LED lighting results in spending less money and destroying jobs in these analyses.

We are careful in this analysis to balance both sides of the ledger. This is why we began this analysis discussion with the heuristic of the primary economic driver of job creation on this pathway: it creates net jobs because what would have been paid for in fueling the fossil energy system in the future is used to invest in labor in the manufacturing and installation of a clean energy system that doesn't need fuel in the future.

The other edge of this sword is the temptation to report the total dollar investment required for this pathway, not the savings, and not the economic benefit. However, the government does not pay for the entire program. That is not how it worked in the Great Depression, nor how it worked in WWII. Government programs and incentives and loan guarantees can all be designed to leverage huge amounts of private sector money. Federal loan guarantees of mortgages that were invented in 1936 were designed to provide liquidity to local and regional banks without the government actually having to spend money, but merely guarantee mortgages to improve loan viability. So we now look at the costs of this type of mobilization effort and estimate which costs will be borne by the government and which by the private sector in this ambitious program. We can do a first pass on gross estimates of government vs. private investment by looking at historic methods for motivating the right investments in energy.

We can look in Table 12 for estimates of the government portion by sector. If we look at the first 10 years of spending, through 2031, the federal portion of the spending is $2.8 trillion dollars of a total $11.7 trillion dollar investment.

This transition save households money on their energy bills, improves air quality and health outcomes, reduces our emissions to near zero and helps with the global issue of addressing climate change. The roughly $300 billion dollars per year of government investment is similar to the amount we project households to save on their energy costs should we do this smartly[15].

[15] Doing it smartly is never guaranteed with this many interest groups, but hopefully the largest interest group of all, the American consumer and voter, will see the wisdom in building the nation's infrastructure to save every household money.

Historical Parallels

Job creation on this scale and at this pace is not without precedent. The U.S. followed a very similar path in mobilizing for WWII. Winning the war for the Allies had a total cost of around 1.5 1939 GDPs. Transitioning to a completely decarbonized energy system probably has a cost closer to just 1 2019 GDP of $22 Trillion. We can take a retroactive look at wartime production, recorded in *Wartime Production Statistics and the Reconversion Outlook, War Production Board, Oct 9, 1945*, to see that these projections that look enormous are not dissimilar in their effect on the economy as to what was seen in WWII. In Figure 10 we see the 60-70% expansion of manufacturing employment, the more than doubling of manufacturing output, and the other massive increases in construction and raw materials production required to feed this activity. Even more illustrative is Figure 11 which shows the economy-wide benefits of such an audacious project. An 18.3% increase in the labor force, a 63% increase in manufacturing employment, a 52% increase in Gross National Product, and a massive 58% increase in consumer spending, as so many more people had money in their pockets to spend. The war analogy is not perfect, but it helps in understanding that mobilization of our industrial capacity can drive the creation of millions of new jobs while protecting consumer well-being.

Sheer Scale

Any effort to transform an economy as ambitious as that outlined in this scenario is destined to strain the validity of models based on precedent and historical data. In spite of this, it is a very informative exercise to model this audacious transition to a more verdant and healthier world that protects citizens and environment alike.

Historically, industrialists have been able to estimate the cost reductions of technologies as they scale up according to scaling laws like Moore's law, or Swanson's law. These laws observe that costs reduce predictably with each doubling of the production capacity. If we use the 2019 global production capacity figures for a few of the critical technologies required for this project, we can see that we are a number of doublings away from being able to produce at the sustainable capacity required to provide global clean energy. EVs are on the most accelerated path, and we only need on order of 2-3 more doublings (4X-8X current production rates). For solar, wind, and batteries we are 3-4 more doublings (8X-16X). This has a couple of major consequences: the sheer scale of this project will reduce its cost enormously, and that will be both good for the consumers, but temper some of the higher jobs numbers in this report.

In the most simplistic analysis, only considering jobs in the energy industry, we can see that decarbonization will produce at steady state a few millions more direct jobs than what we are doing today with fossil fuels. In a more complete economic analysis based on the typical methodologies for modeling economy-wide job creation we see the net creation of around 23 million jobs at the peak settling at around 4-6 million more jobs at steady state (2040 and beyond). As with WWII production one can expect that at this scale of manufacturing and mobilization, many more innovations and a lot more automation will be invented and bought to the task, and no doubt this is an estimate on the high side. The

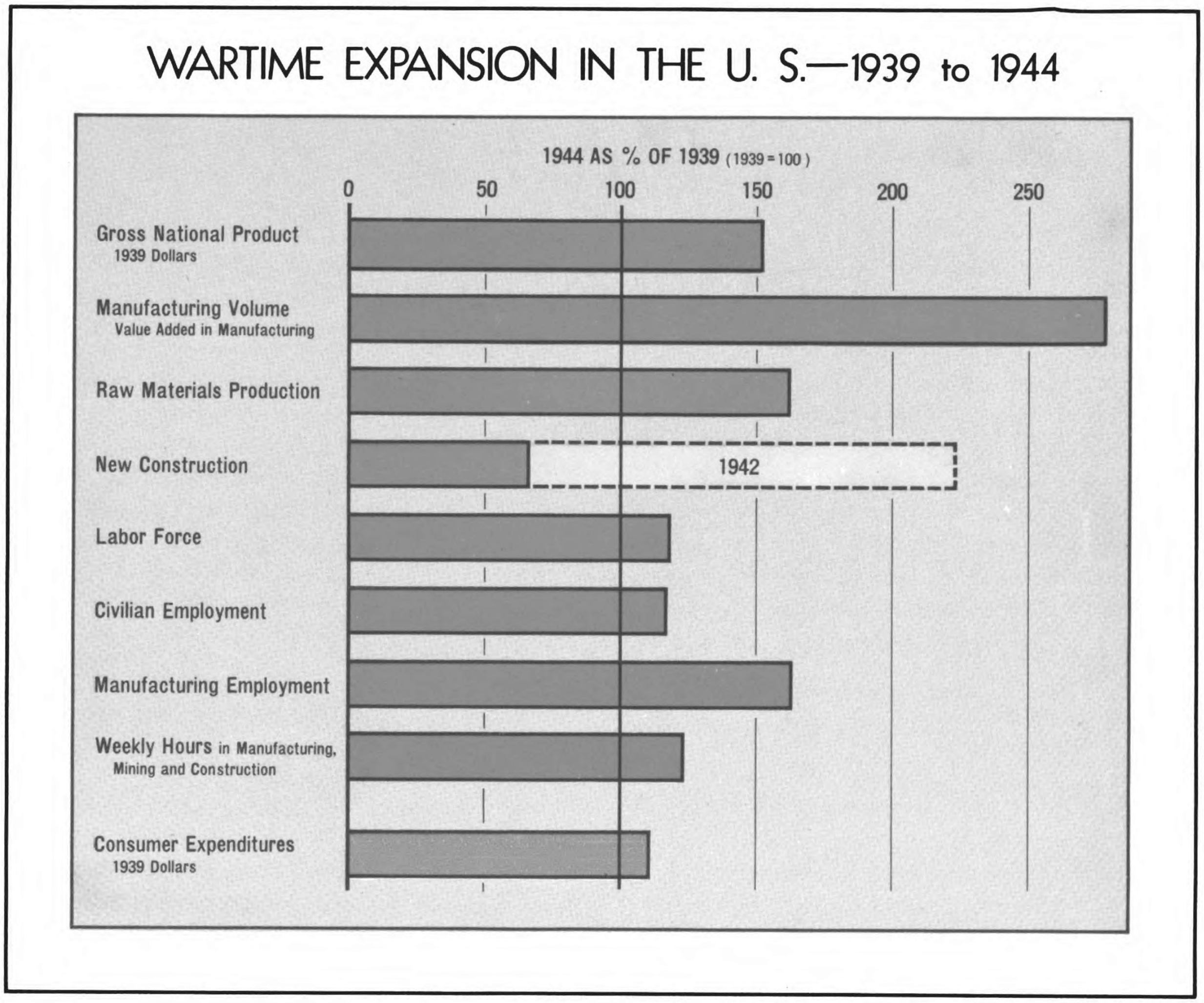

Figure 10: *Net new jobs created in a mobilization of the economy commensurate with a 2° C/3.6° F target.*

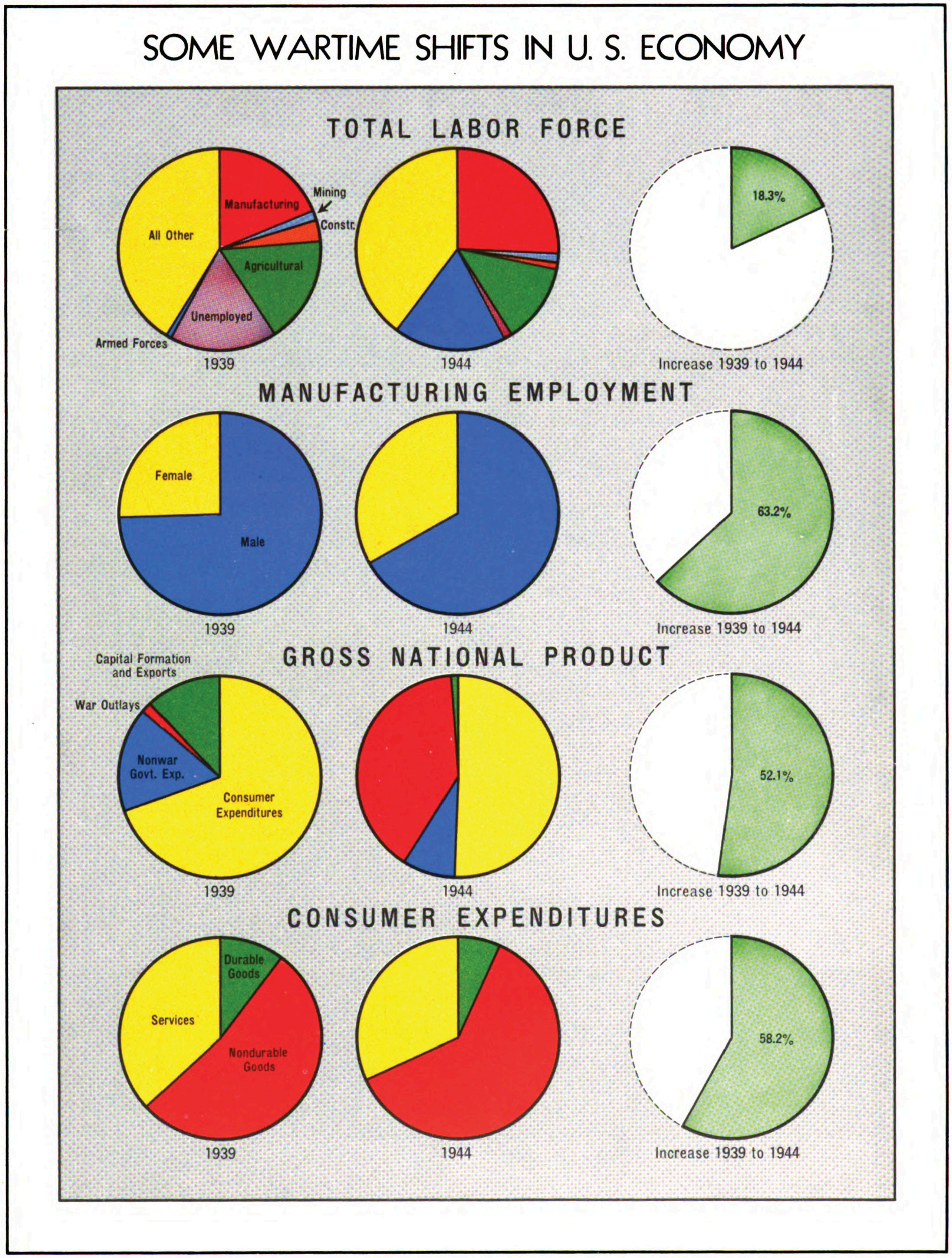

Figure 11: *Net new jobs created in a mobilization of the economy commensurate with a 2° C/3.6° F target.*

Estimation Source	Supply &/or Demand	**Jobs**	Direct &/or Indirect
Existing BLS data	Mostly Supply	2,600,000	Direct, some indirect
BLS without gas stations	Mostly Supply	1,800,000	Direct, some indirect
BLS Direct Fossil	Supply only	1,100,000	Direct
USEER	Supply and demand	6,000,000	Direct, Indirect, part time
Jobs/MWh studies	Supply only	4,000,000	Direct
Econometric Analysis	**Supply and demand**	**25,000,000**	**Direct, Indirect, Induced**
Econometric Analysis (w/ efficiency)	Supply and demand	30,000,000	Direct, Indirect, Induced
Econometric, sustained new 2040 jobs	Supply and demand	5,000,000	Direct, Indirect, Induced
WWII, Arsenal of Democracy	Neither	20,000,000	All jobs

Table 13: *Summary of various job estimation methods and number of jobs.*

good news is that with aggressive assumptions about automation and efficiency we would see even greater savings in household energy costs, and still with millions of new, well-paying jobs in the economy.

These estimates here use the current mix of domestic and imported manufacturing as per the data of 2017. With a more "Made in America" policy on the manufacturing side, this analysis would show even greater numbers of domestic jobs in manufacturing. However, the majority of jobs in this proposal to stimulate the American economy and lead the world in clean energy are construction and installation jobs that occur in every zip code. Installing rooftop solar, installing wind farms, replacing furnaces and hot water heaters — these are all jobs that cannot be shipped overseas. These are good jobs that play strongly to the productivity and industriousness of American workers in construction and the trades. A stimulus program along these lines will reap enormous rewards in precisely the areas of the economy that we have ignored for the past four decades: rural areas, small towns, and industrial manufacturing towns.

Summary of methods and results

Table 13 summarizes the data sources and methods, the scope (supply, demand, or both), job creation, and whether the scope is direct, indirect or induced jobs as calculated by different methods in this report.

Level of Decarbonization

What many people want to know is how much decarbonization is achieved by what policies. We have presented the Maximum Feasible Transition to zero carbon (MFT) model. This assumes a massive and rapid build up in industrial capacity akin to the Arsenal of Democracy for WWII. After this 5 year period we assume that industrial capacity is sufficient to meet a 100% adoption rate for all key carbon producing technologies, e.g. EV's, heat pump furnaces, heat pump water heaters, induction ranges, solar, wind and nuclear power plants, electric trucks, rooftop solar, etc.

It is beyond the scope of this modelling to determine the exact levels of decarbonization by sector. We can estimate decarbonization grossly, by understanding the lifetime of the current fossil powered equipment that will be replaced, and their gross replacement schedules. We can look to EIA data[26] for estimating the level of grid decarbonization over this timeframe by inferring which generation capacity will be replaced or retired. Limited studies of the histogram of vehicle ages[27], and of the age distributions of home appliances[28] can be used to guess at what portion of those machines can be replaced by 2035 on a 100% adoption rate schedule as per MFT.

A snapshot: Furnaces last on average around 15-20 years. Water heaters 10-12. Most power plants 30-50. Cars have an average age of 12 years, but as we know there are a lot of 25 year old cars on the road.

Hence we can very grossly estimate the following levels of decarbonization by sector for the year 2035, on the JOBS pathway:

- Residential 75-95%, limited by the retirement of natural gas heating (of hot water, air and food).
- Commercial 75-95%, limited by the retirement of natural gas heating (of water, air and food).
- Industrial 60-80%, limited by our capacity to invent the technologies to decarbonize the difficult to decarbonize sectors such as steel, aluminum, paper and pulp, and plastics.
- Transportation, 80-90%, limited by the long tail of older vehicles being kept on the road as well as non–highway transportation innovations in things like the decarbonization of flying.
- Electric grid, 70-80%, limited by the recently built natural gas plants, and any coal we can't retire for political reasons on this timeframe. The proportion of total electric grid will be much higher as we need to increase the output of the grid approximately 3–fold in this period to absorb the level of electrification of our vehicles, residences and businesses, and that extra capacity is assumed to be from new–build non–combustion sources.

To be clear, continuing down this pathway will decarbonize close to 100% of everything by 2050 and the levels above are professional estimates of best case adoption rates by 2035.

Acknowledgements

Valuable contributions to the methodology and economic analysis were made by Skip Laitner[16]. Contextual material on climate and excellent editing was added by Hunter Cutting[17]. Content and style reviews were made by Adam Zurofsky[18]. Critical edits making this a human-readable document were made by Laura Fraser.

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[17] Climate Nexus
[18] Rewiring America

End notes on this decarbonization pathway

1.5 degrees C of warming is the IPCC's aspirational target for climate change. This target does not consider at least three practical problems. First, since 2004 the IPCC has assumed significant negative emissions by carbon sequestration. We believe they are highly unlikely to be real as the energetics, kinetics and cost of carbon dioxide removal are so poor. We cannot rule out a breakthrough, but it is even more true that we shouldn't model it in as assumed [29]. It must be remembered that as a single man-made substance, humanity produces more CO2 than it does *all other materials combined*. In 2019 the US manufactured around 6.5 billion tons of agricultural products, fossil fuels, meta ores and non-metallic minerals. We emitted 6.7 billion tons of CO2.

Second, this 1.5° C/2.7° F target considers "committed emissions," or the emissions that will be emitted by infrastructure already built or planned to be built. This consideration is why early retirement is modeled in to emissions trajectories, as committed emissions already put us on a trajectory somewhere in the middle of 1.5° C/2.7° F and 2° C/3.6° F . This policy emphasis on early retirement of the heaviest emitters (coal) is good and sound policy, but often politically poisonous as it implies specifically abruptly closing down coal plants and mines. The implication of the committed emissions trajectories is that if every country in the world merely had 100% adoption rates of zero–carbon technology starting today, we would end up with around a 1.75 degree world.

Third, none of the targets we use consider the time required to ramp up the industries necessary to create the solutions. If we just look at electric vehicles, batteries, wind turbines, and solar modules, each need an increase in production quantity of one order of magnitude or greater. This is 3 or more doublings of the current capacities. Even with something akin to the U.S' WWII production ramp-up, but this time globally, this would take 5 or more years.

If the other major manufacturing nations, China, Germany, Japan, and South Korea all follow suit in short order, and if nations that are unlikely to decarbonize quickly due to their fossil reserves and politics (eg. Russia, Saudi Arabia, Brazil, Nigeria) are slower to respond, it is safe to say that this is probably the only strategy with technology that is known today that can hit a roughly 2 degree target given climate sensitivity uncertainties. Early retirement of our heaviest emitters (coal fired electricity) can improve this picture a little bit.

Additional Thoughts

Jobs vs. Cost

The traditional pathways to lowering the cost of manufactured goods is either through manufacturing automation, which negatively affects the labor market, or through off–shoring to a country with lower wage rates and fewer environmental regulations — both with negative societal outcomes. We want cheap energy, we want cheap goods, and we want well-paying jobs. There is an obvious conflict here between these things. Domestic manufacturing is probably the best pathway for any country looking to build these industries, but it is likely achieved with very high levels of automation. Fortunately this only affects the manufacturing job component, which is small compared to the installation and maintenance labor. Decreasing manufacturing jobs due to automation can be more than compensated with increasing export markets for the early national adopters of these categories of climate solutions.

6 days, 5 days, 4 days

America pioneered the cultural move from a 6-day work week to a 5-day work week through the middle of the 20th century. With enormous productivity improvements since the industrial revolution, this was possible without undue economic impact. A counter argument to those who oppose high levels of automation is that it could be our pathway to a 4-day work week. For why do we work if not to enable some leisure?

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