Transitioning to a net-zero carbon America: *Jobs, jobs, jobs, and more jobs*

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with thanks to
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Summary

This white paper looks at what it would take to mobilize the U.S. economy for the task of near-complete decarbonization by 2035. This is commensurate with a climate target of limiting warming to between 1.5° C and 2° C (2.7° F and 3.6° F). No doubt this is an ambitious analysis, but we feel compelled to propose in detail how to attempt this goal and what it would mean for American energy prices and the American workforce. We model an ambitious ramp–up of manufacturing and installation capacity in the first 3–5 years of the project, appropriate for building the manufacturing and workforce capacity for the aggressive build–out of infrastructure in the decade that follows. We find it likely that such a project creates between 10 and 40 million net jobs. We also find we can save every American household $1,000–2,000 per year. Using existing models of government investment, we find the required spending for this radical program is probably capped around $300bN per year for 10 years.

A specific decarbonization plan

Figure 1 shows just how dramatic decarbonization pathways now need to be to hit any reasonable climate target. The problem is that no matter what policy is instated today, it takes time to adopt decarbonized technology. In fact, the machinery and infrastructure that already exist carry "committed emissions", the greenhouse gasses that will be emitted while these machines live out their useful lifetimes [1]. These simplified charts show that we now need close to 100% adoption rates of decarbonized technology at end-of-life replacement hit an acceptable climate outcome. This is fairly simple to imagine. When someone's car

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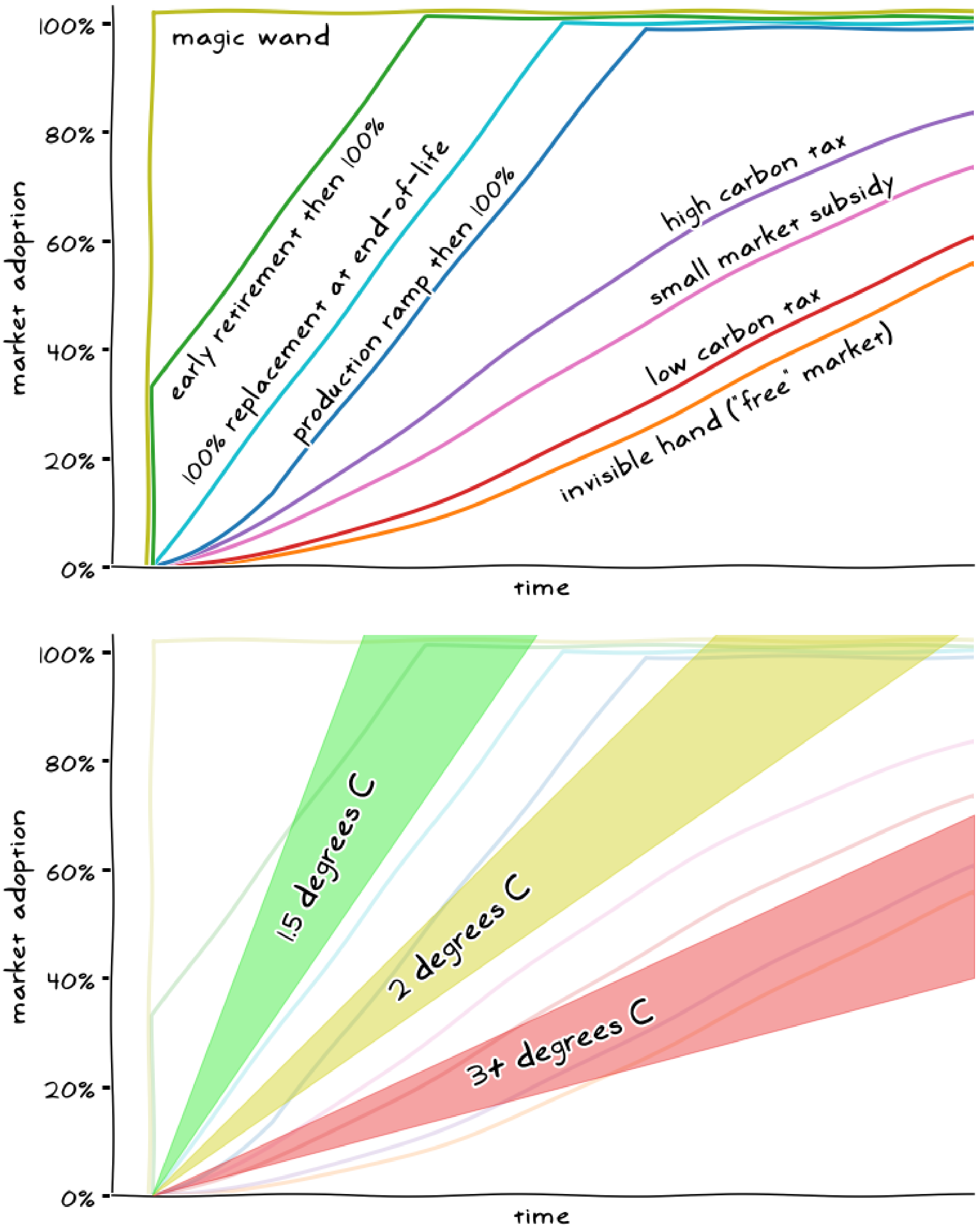

Figure 1: *Mitigation curves required to hit a climate target in terms of the adoption rates of decarbonized technology solutions. Time is up for slow rate–of–adoption free market solutions. The question becomes: Which set of incentives or regulations are best to speed up action? The only pathways that 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.*

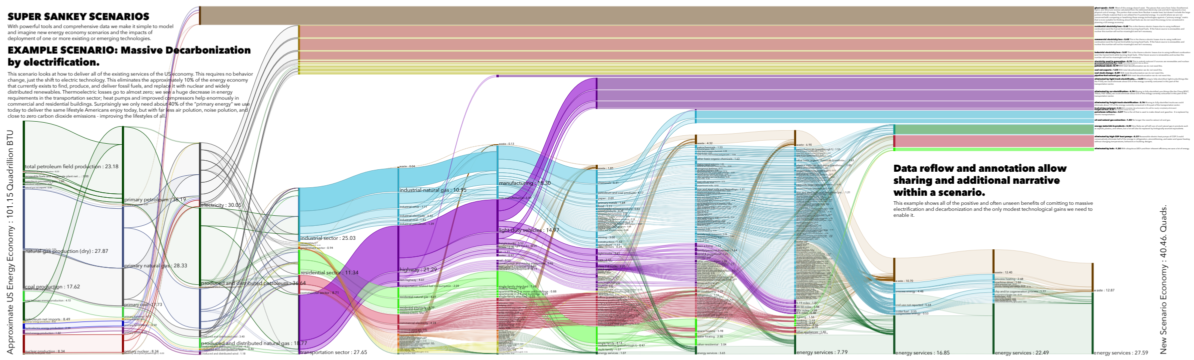

Figure 2: *A sankey flow diagram of all US energy flows (based on 2018 data) where we have modelled out the primary energy reductions of electrification. This model gives a clear viewpoint on a total decarbonization strategy that does not rely on the invention of any new technology.*

reaches retirement age, it is replaced with an electric one. When a coal plant is retired, it is replaced with nuclear or renewables.

In order to create a very specific estimate of jobs created by such 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. This addresses 90% of emissions, where the remainder comes from agriculture [2]. We move sector–by–sector through the economy, using existing technologies to decarbonize that sector and estimating the future energy flow required to service that sector. No efficiency measures are assumed other than the inherent efficiencies of the substitution technologies. For example, we assume that nearly all vehicles will be electrified, and because the electricity is coming from renewables and nuclear, it will eliminate 16 quads[1] of the primary energy we use today to run our vehicles. Similarly, by producing all of our electricity with non–carbon sources, we eliminate 25 quads of thermoelectric losses. Electrification of buildings and the elimination of energy used to find, mine, and refine, fossil fuels offer similarly large savings. All told, in this highly electrified pathway the US only requires 40-50% of its current energy needs. For the few things that are still difficult to electrify like long–distance flights and steel–making, we assume biofuels or renewably–generated hydrogen will be used. 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. 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.

Having this specific model of energy system decarbonization allows us to build our jobs estimates from the ground up — based on knowing which machines and infrastructure we need to replace with emissions–free electrical machines and infrastructure. We do not assume much in way of efficiency or behavioral change, but rather lean heavily on technology transformation. This means replacing gas–powered pick–up trucks with electric pick–up trucks, and natural gas burning furnaces with heat pumps. In short:

- We model a highly–electrified economy that reduces total primary energy needs to around 45-50 Quads (from 100).

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

- We provide the great majority of that energy with renewable and nuclear electricity (1,500GW of new delivered electrical power).
- We model almost total electrification of transportation.
- The model assumes biofuels 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 40 million new jobs during the transition, tapering off to about 18 million sustained jobs, roughly double the number of jobs supported by the current energy industry.
- The total government share of the expense is likely only $250-350bN per year, with the total public and private spending over 20 years at about 25-30 trillion dollars.
- With the right regulatory environment and implementation, energy costs will be lower than today and the average household will save 1,000–2,000 dollars per year.
- The majority of jobs that are created will be highly distributed throughout the economy, with high–paying jobs in every zip-code.

Without a doubt this report will be criticized for being naive, or politically impossible. We begin with the assumption that people believe addressing climate change is impossible, and that it is impossible to address it without audacious plans that push the limits of traditional markets. For this reason we do not begin with an economic analysis, but rather build the model of what needs to be done from the ground up. An engineering account of what machines and infrastructure need to be replaced economy–wide, and on what time–line. Not only does this base the analysis in a physical reality, but it actually demonstrates that addressing climate change quickly is possible and highly beneficial for the economies that act boldly, concertedly, and first.

Estimating jobs created in a 100% clean energy transition

We wish that decarbonizing simply for the sake of having a better planet to live on would be enough incentive to get it done. But people are rightfully cautious about the impacts this decarbonization might have on the economy. And, of course, any proposal to transform the world by decarbonizing and overhauling the energy sector needs to reassure people that they won't lose their jobs — or even better, that they will get new jobs that pay more and are more satisfying.

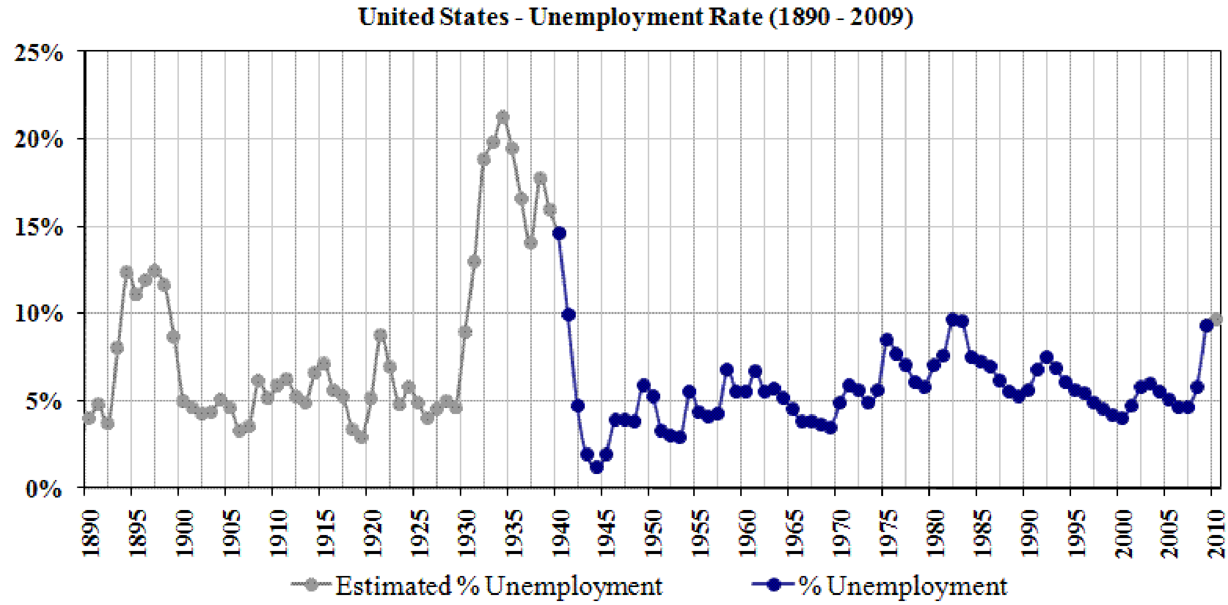

Figure 3: *The estimated U.S. Unemployment rate from 1890 to 2010. 1890–1930 data from [3], 1930–1940 data from [4], 1940–2009 data from Bureau of Labor Statistics [5].*

In a post COVID–19 world, this is even more critical. Thirty million people in the U.S. lost their jobs between February and May of 2020. In April 2020, at nearly 15%, the unemployment is the highest it has been since the Great Depression [5]. For context and comparison we can look at the long term history of unemployment in the US in Figure 3. At the height of the Great Depression more than 20% were unemployed. FDR'S public works and jobs programs made real progress 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.

The good news should be shouted from the rooftops: a rapid transition to a clean energy economy will create more, better–paying, jobs. There might even be so many jobs that we'll need to employ robots to do them. Probably the only project imaginable that could put everyone back to work in this terrible employment environment is decarbonizing America's energy system. This is equally true in many other countries in the world.

So here we will take a look at a number of ways of estimating how many jobs a clean energy economy can create.

The shortest argument for why there will be more jobs

The shortest argument that switching to a zero–carbon world will mean more jobs for all of us comes from understand this: decarbonization technologies require more labor in manufacturing, installation and maintenance than 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.

The double–edged sword in this argument 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 pretty much immediately. That's providing we get the financing and regulatory environment right.

According to the Solar Energy Industry Association (SEIA) there were 240,000 jobs in solar in 2018, and in that same year 13GW(DC) of capacity were installed. Accounting for a capacity factor of 0.25, this means around 13kW of net generation are installed per job created. If you were to multiply that job creation number out sufficiently to satisfy building out the 2,000GW of electricity we'll need, that would be more than 150 million job–years. If we installed them over 20 years, (and assume this is the natural replacement rate) that's more than 7.5 million direct sustainable jobs into the future, and that's only on the supply side.

Current Energy Industry Jobs

Let's begin our analysis with a closer look at the state of play. The Bureau of Labor Statistics (BLS) keeps excellent publicly–available data on jobs in their "Current Employment Statistics" monthly reports [6]. We arrange it in Figure 4 as a Sankey diagram[2] that breaks down the big categories into increasingly small ones, answering the question that Richard Scarry [7] sought to answer in his famous children's book *What do people do all day?*

What immediately stands out as we write this are the very large categories of jobs susceptible to a pandemic like the 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.

But what about energy jobs? We can pull the easily–identified jobs related to energy out of this same dataset. We show them in Table 1.

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, 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. But we need to remember convenience stores also sell us hot dogs, cigarettes and lottery tickets, so we probably shouldn't completely categorize them as energy industry employees; convenience stores sell 80% of the gas in this country.

Next, we can see just how few jobs there are in coal mining — around 50,000 — and compare that to, say, 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. 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

[2] Who doesn't love the opportunity to create another Sankey diagram!

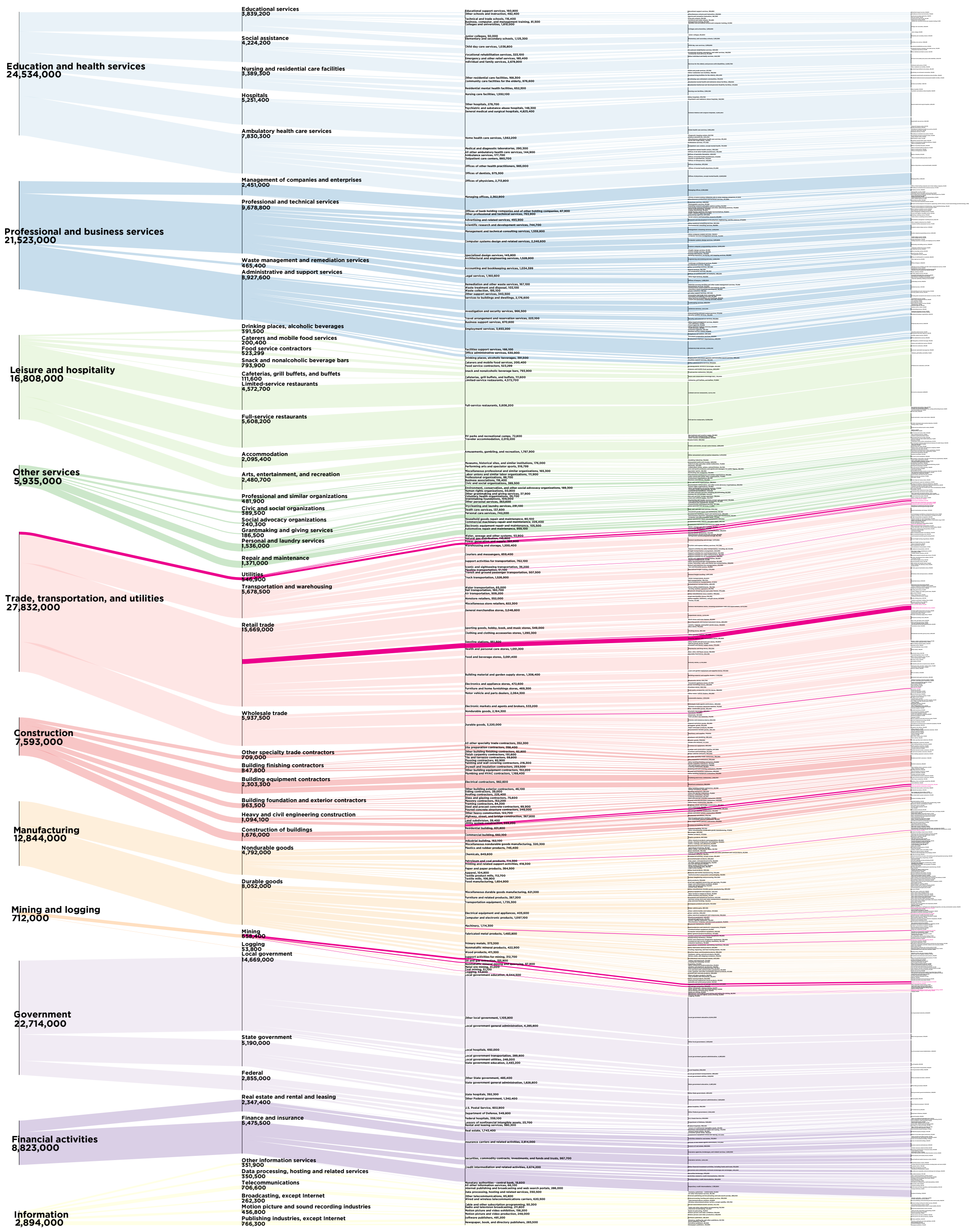

Figure 4: *All US jobs, Pre-COVID-19. Data from [6]. Get out your glasses!*

Job category	**Number of Jobs**
Fossil fuel electric power generation	83,200
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
Pipeline transportation	51,100
Gasoline stations with convenience stores	**851,800**
Other gasoline stations	101,400
Oil and gas pipeline construction	152,400
Power and communication system construction	216,500
Petroleum	102,800
Petroleum refineries	68,600
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
Oil and gas extraction	155,800
Support activities for oil and gas operations	247,800
Bituminous coal and lignite surface mining	22,800
Bituminous coal underground mining and anthracite mining	28,300
Total	2,689,870
Total without gas station convenience stores	1,838,070

Table 1: *2019 US jobs related to the energy economy, from [6]*

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 rennovations.

Given these limitations, we can take a look at a deeper study of energy industry jobs.

USEER — A better estimate?

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)[8]. 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)[3] *"to reform existing data collection systems to provide consistent and complete definitions and quantification of energy jobs across all sectors of the economy."* [9]

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 2.

We can see the first outline here of why there will be more jobs in a decarbonized economy. Let's assume that there will be the same number of motor vehicle jobs, just that those cars will be electric. The other giant category, energy efficiency jobs, is going to boom. This includes all of the HVAC system upgrades we'll need — the replacement of any hot water heater or furnace that burns fossil fuels with something like a heat pump, better insulation and windows for our homes, and electrified cooking appliances.

What we really want to see is whether electrifying the country will create more jobs than we will lose in the fossil fuel sector. According to USEER, "fuels" employs about 1.15 million people, whereas electric power generation, transmission, distribution, and storage employs 3.3 million people. We learned earlier that to electrify all of our activities we would need to deliver 3-4 times as much electricity. In a very crude analysis, the 1.15 million jobs lost in the fossil fuels sector alone would be offset by a gain of 9.9–13.2 million jobs in the expanded electricity sector. It should be noted that this is a big underestimate, as studies have already shown that per unit of delivered electricity, solar and wind employ more people than fossil fuel–generated electricity, so this number would be even higher. This would be 8–10 million genuinely new jobs as a crude estimate, not including all of the related jobs created by making so many new jobs — the jobs that economists call indirect jobs, and induced jobs.

[3]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 [9] and [10].

Job category	Number of Jobs
fuels	1,149,000
electric power generation	897,000
transmission, distribution and storage	2,400,000
energy efficiency	2,380,000
motor vehicles	2,550,000
Total	9,376,000
Total (- Motor Vehicles)	6,826,000

Table 2: *USEER estimate of total energy industry jobs 2016 [8]*

How economists estimate jobs, and how many jobs an economist would forecast

What we have looked at so far is not how economists estimate jobs and job creation. We called an expert for guidance on the methodology economists use to answer questions like this. Skip Laitner is an economist who has been answering just such questions for decades. In fact it was one of his proteges who created the Job and Economic Development Impact (JEDI) models that the National Renewable Energy Labs (NREL) uses to estimate job creation in the wind, solar, and other renewables industries [11].

The economist's view is that you can estimate the jobs created by understanding how much economic activity will occur (in millions of dollars), using estimates based on historical job creation in different industries per dollar. The economist 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 associated with the direct jobs, and with servicing. 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 methodology then is pretty simple. (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 [12]. (3) Calculate indirect jobs and induced jobs as multipliers of this number that can be simply be figured out.

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 have to phase out coal mining and find jobs for those 50,000 miners, but we don't phase 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 is required to make sure we are not double–counting jobs and that we are fairly counting the eliminated or transitioned jobs.

The hardest task is the first task of defining what we are going to build, then we can address how much it will cost. With an engineer's mindset, we'll do this from the bottom up, and consequently this is 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 [13, 14].

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. **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.

6. **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.

Generation type	$GW_{nameplate}$	**$/W**	Millions of $ 2017
WIND	1500	$1.48	$2,215,500
SOLAR - rooftop	1000	$1.5	$1,500,000
SOLAR - industrial	1500	$1.38	$2,070,000
HYDRO	75	$2	$150,000
NUCLEAR	100	$3	$300,000
GEO	50	$4	$200,000
BIO	100	$2	$200,000

Table 3: *New primary energy (Nominal installed capacity to which capacity factors must be applied) that will deliver approximately 1500 net new GW of electricity*

7. **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.

8. **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 time–frames 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 3 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 I 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 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!

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

Table 4: *New Transmission and Distribution*

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 honesty 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 4. 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 5. We must account for replacing all of the equipment that currently uses fossil fuels. As 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. 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 methodoloy we outlined at the beginning of this whitepaper, 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[4].

Commercial Buildings

We will need to upgrade commercial buildings as well, and we will include public electric car charging infrastructure here. For commercial buildings the calculations are made using

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

Number	**Item**	**Cost Decarbonized solution**	**Cost incumbent**	**MegaDollars**
Home Appliances				
90,000,000	HP water heaters	1,600	1,130	42,300
100,000,000	load centers	2,000	0	200,000
80,000,000	HP furnace	7,500	4,000	280,000
100,000,000	home car chargers	1,500	0	150,000
80,000,000	induction ranges	1,200	1,000	16,000
80,000,000	home battery electric	3,000	0	240,000
80,000,000	home battery thermal	1,000	0	80,000
50,000,000	Electric Dryer	1,200	1,100	5,000
Vehicles				
250,000,000	Light duty vehicles	38,000	32,000	1,500,000
Home Retrofits				
1,200,000,000	LED Lightbulbs (/bulb)	2	1	1,200
120,000,000,000	hydronic heat (/sqft)	10	0	1,200,000
240,000,000,000	window retro (/sqft)	7	0	1,680,000
240,000,000,000	insulation retro (/sqft)	2	0	480,000
240,000,000,000	electric retro (/sqft)	2.5	0	600,000

Table 5: *Upgrading our homes and our vehicles*

Sq.Ft (of 90,000,000,000 total)	Item	Cost / sq.ft	MegaDollars
75,000,000,000	HVAC	20	$1,500,000
60,000,000,000	Lighting	5	$300,000
40,000,000,000	Cooking	1	$90,000
80,000,000,000	Water	1	$160,000
50,000,000,000	Refrigeration	2	$100,000
50,000,000	world car chargers	6,000	$300,000

Table 6: *Upgrading our commercial buildings and charging stations*

gross estimates of the per square foot price of upgrading things like the HVAC systems. We can see these top line estimates in Table 6.

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 come up with a very gross estimate we look at the 2019 United States Census Bureau's "U.S. Capital Spending Patterns 2008-2017" [15]. We will take the 2017 capital expenditures by industry sector, and assume during the period we are changing over the capital equipment (10 years) we'll spend 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 7. We have also added in the electrification or upgrade to renewable biodiesel for trucks in this industrial sector.

Research and Development

For a gross estimate we can begin with analagous existing federal R&D spending. We can then imagine how much similar spending we might dedicate 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 [16]. Let's add a number like that to 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 [17]. The NSF does fundamental science for the large part, exploratory work that creates total new avenues and solutions, not just cost reductions. We need that kind of spending if we are going to change the game for 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

Industry Sector	**2017 Cap–Ex Spend, ($Millions)**	**Decarbonize Multiplier**	**New MegaDollars**
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 7: *Upgrading our Industrial Capital Equipment*

Agency	New budget	Old budget	Net New Spending
DARPA	$3,400	$3,400 [16]	$0
ARPA-e	$4,000	$366 [18]	$3,634
NSF	$10,000	$8,000 [17]	$2,000
EERE	$6,800	$2,400 [18]	$4,400
EIA	$250	$125 [18]	$125
New R & D Spending			**$10,159**

Table 8: *New Federal Research and Development Spending*

heavy lifting of near–term response will be, and hence for this exercise we raise the budget from $2.4bN to $6.8bN [18]. 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 add it all up, and we'll need 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.

This shouldn't be taken as a recommendation on exactly how to spend the money, 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 give us some of the breakthrough technologies that would make it much easier to address the climate problem.

Education and Training

We can already see that the numbers of new jobs will be so great we'll need huge amounts of 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 [19] and dedicate a similar amount to new vocational training specific to the energy industry jobs that we need filled. Someone will have to train an awful lot of electrical technicians as only one example of all of the new jobs.

Finance jobs

This type of program obviously involves a lot of monetary transactions and a lot of borrowing and repayment. What is the jobs creation effect of that? We can use a very simple cost analysis to produce the first cut rough estimate. 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. In all cases we try to align these annual spends towards an emissions trajectory that 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 would mean 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. Annualized spending such as R&D and training are treated as such. We use established 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 9.

As per the typical methodology of economists, we convert the dollar amounts in Table 9 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 5 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. It is far away and certainly technology and automation could change the number enormously, but 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. The highest of these 3 numbers is (3), which totals 1,092,900 direct jobs, for a total of 14,552,699 jobs. We also consider existing non–carbon, non–fossil, energy jobs in the same manner, where the existing 643,770 jobs become 8,572,231 with the same jobs multipliers. All of these jobs are graphed in Figure 6. We can see the tapering out of the fossil–related jobs through 2040, and the fact that they are more than compensated for with the enormous number of new jobs in the new energy economy. It won't be easy for everyone, but with appropriate re–training and early–retirement programs and plenty of empathy this should be a more than manageable transition.

Who is going to pay for all of these jobs?

We should emphasize once again the potential double–edged sword of these calculations. Politically, job creation is something that all political parties are in favor of, just as they

Sector	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
SUPPLY BUILDout	$0	$173	$346	$519	$519	$519	$519	$519	$519	$519	$519	$519
GRID BUILDOUT	$0	$50	$100	$150	$150	$150	$150	$150	$150	$150	$150	$150
HOUSEHOLD ELECTRIFICATION	$0	$63	$127	$191	$254	$318	$318	$318	$318	$318	$206	$204
HOUSEHOLD EFFICIENCY	$0	$47	$99	$151	$202	$254	$254	$254	$254	$254	$254	$254
COMMERCIAL SECTOR	$0	$115	$138	$161	$184	$197	$196	$196	$195	$194	$174	$173
INDUSTRIAL SECTOR	$0	$47	$93	$140	$187	$233	$233	$233	$233	$233	$233	$233
ENERGY R&D	$0	$2	$5	$10	$10	$10	$10	$10	$10	$10	$10	$10
EDUCATION AND TRAINING	$0	$4	$7	$16	$16	$16	$16	$16	$16	$16	$16	$16
TOTAL	$0	$495	$903	$1,311	$1,496	$1,671	$1,670	$1,670	$1,669	$1,668	$1,536	$1,533

Table 9: *Total Cost of Capital, training, and build-out of a zero-carbon US economy in $bN 2017 dollars.*

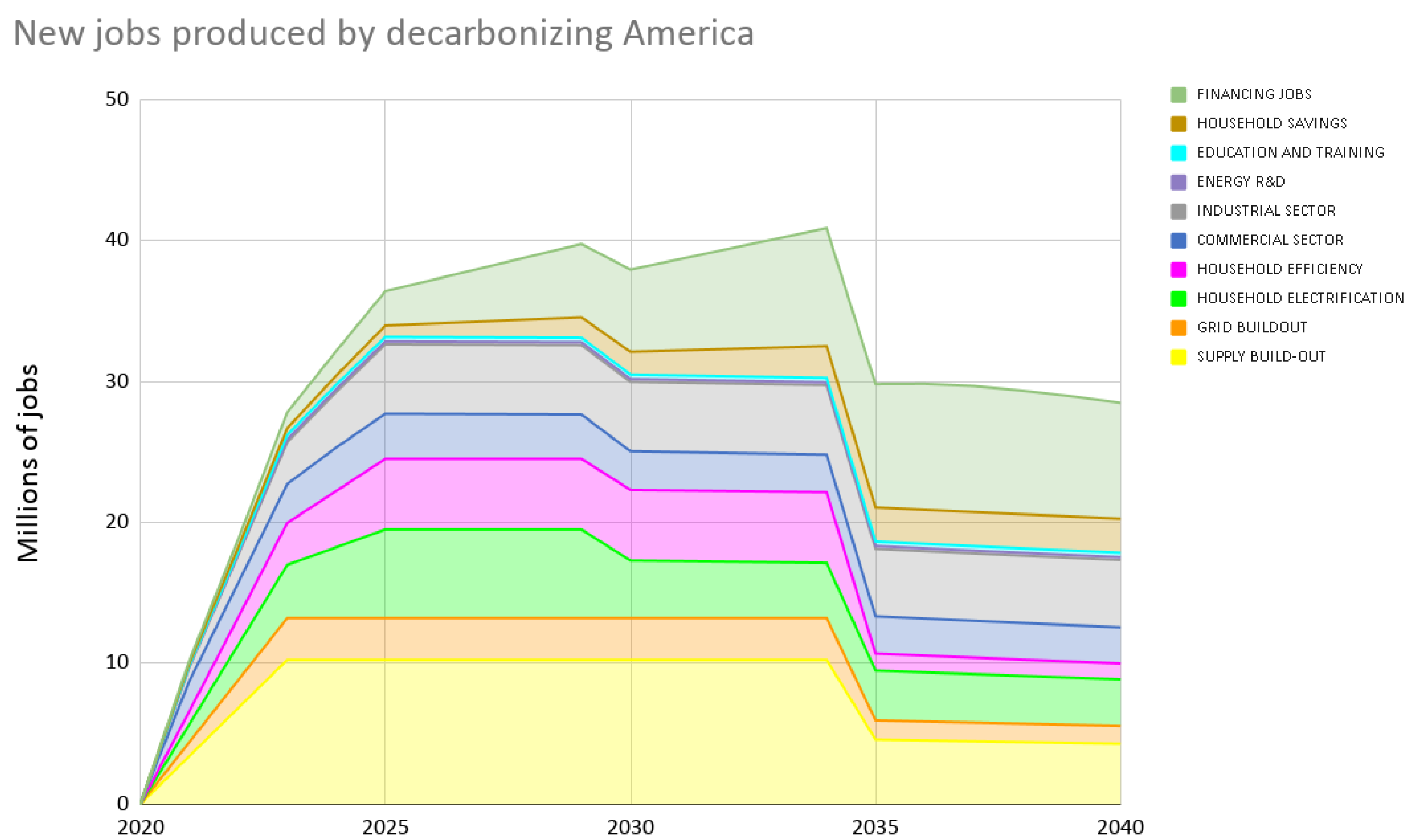

Figure 5: *Net new jobs created in a mobilization of the economy commensurate with a 2° C/3.6° F target.*

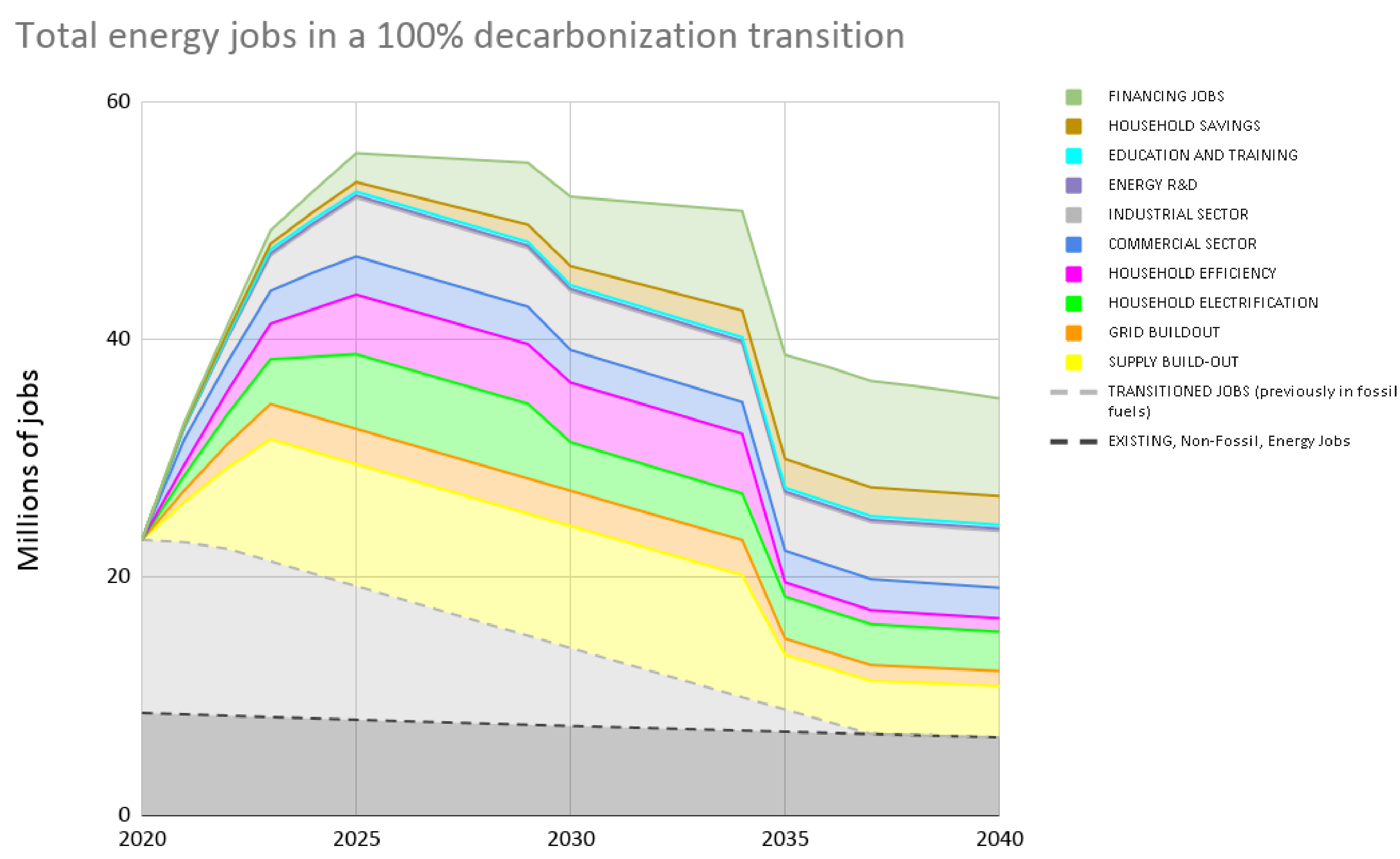

Figure 6: *Total jobs in energy through 2040 with a winding down of fossil fuels and decarbonization effort commensurate with a 2° C/3.6° F target.*

are both frightened of anything that sounds like jobs destroyed. 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 jobs that you want to create. For example, if I used 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 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 LED lighting results in spending less money and destroying jobs in these analyses. We must be careful on the side of the ledger that leads to headlines such as "study shows that installing LED lighting destroys jobs." We want job creation and we want clean cheap energy and cheapness is in conflict with jobs. This is why we began with the simplest argument that clean energy creates net jobs because what we would have paid for in fueling our fossil energy system in the future we can use 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 that the "spend money to create jobs" narrative means that we report the total cost of these programs, not the savings, and not the economic benefit. In the reductive headlines we saw around the Green New Deal, many articles proclaimed its great expense, and at times one could be forgiven for believing that proponents of various plans were just trying to spend the most money to create the best job creation headline. But back in the real world, the government would never 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 which 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 the interest rates available to the consumer.

So we need to 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 10 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 \$3 Trillion dollars of a total \$17.8 Trillion dollar investment. Not only will this transition save households money on their energy bills, improve air quality and health outcomes, reduce our emissions to zero and help address climate change, it won't cost the federal government nearly what we have been told to imagine it will. The roughly \$300 Billion dollars per year of government investment is similar to the amount we project households to save on their energy costs. It should be plainly stated that this is a win–win investment, provided we do it smartly.

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
INDUSTRIAL SECTOR	25%	subsidies / tax incentives
ENERGY R&D	50%	direct
EDUCATION AND TRAINING	50%	direct
FINANCE JOBS	0%	

Table 10: *Federal Portion by Sector*

What does history have to say about this?

Creating this many jobs, and doing it in quick order with a massive mobilization, is not without precedent. We did something quite similar in 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 look to the retroactive look at wartime production that was 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 7 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 8 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 us understand that if we shoot for a victory against climate change by a wartime–style mobilization of our industrial productivity, we stand to benefit enormously economically, and in terms of jobs and consumer well–being. Thankfully this time it can be done without the tragedy of sending young people into battles from which many would not return.

Holy Cow, That's a lot of jobs

Any effort to transform an economy as ambitious as that outlined here 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. In the most simplistic analysis only considering jobs in the energy industry we can see that decarbonization will produce around 10 million 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 18 million jobs, and an increase in people employed in energy from around 11 million to 35 million. Nearly 40 million jobs are created at the peak. As with WWII production one can expect that at this scale of manufacturing and mobilization,

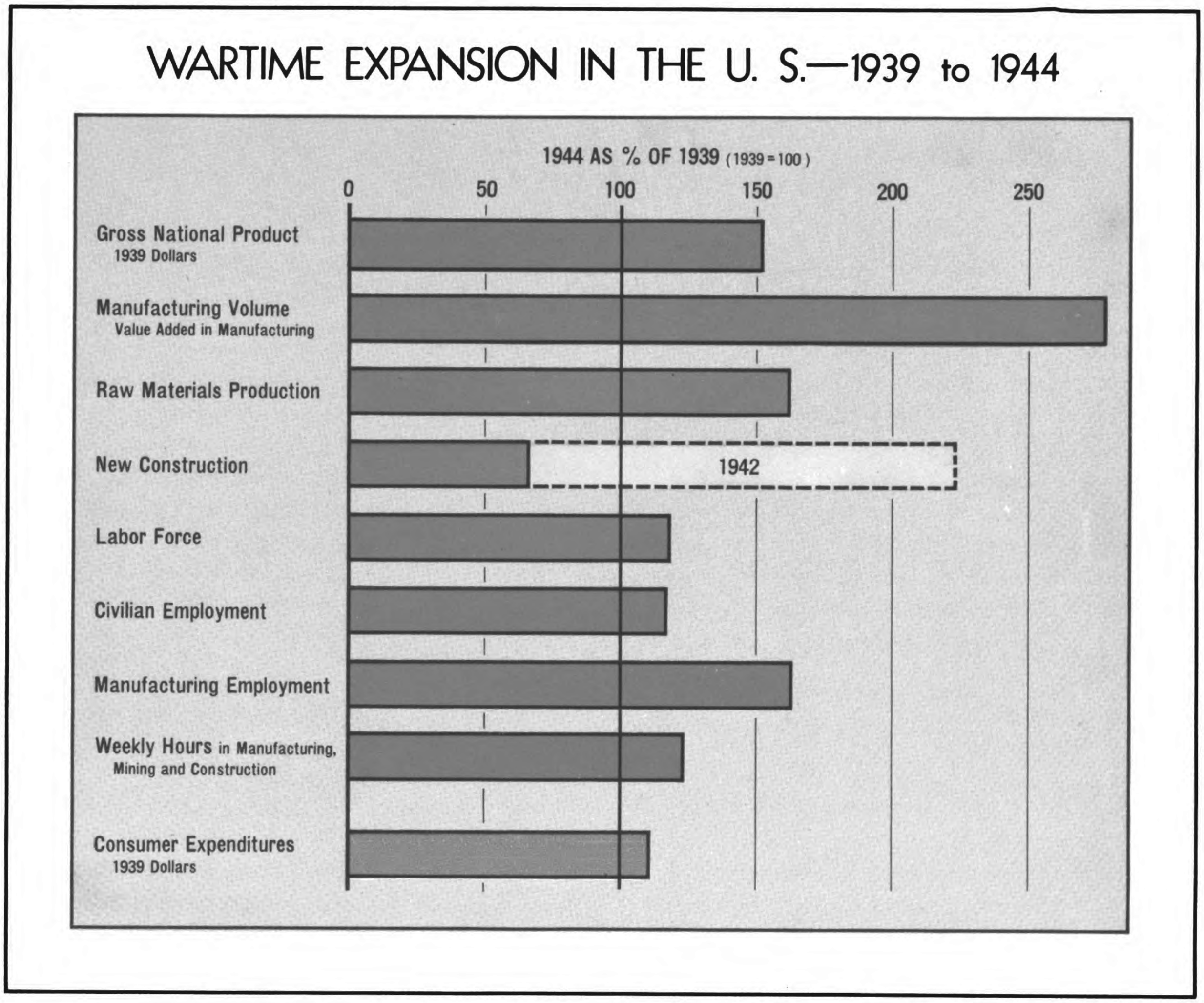

Figure 7: *Net new jobs created in a mobilization of the economy commensurate with a 2° C/3.6° F target.*

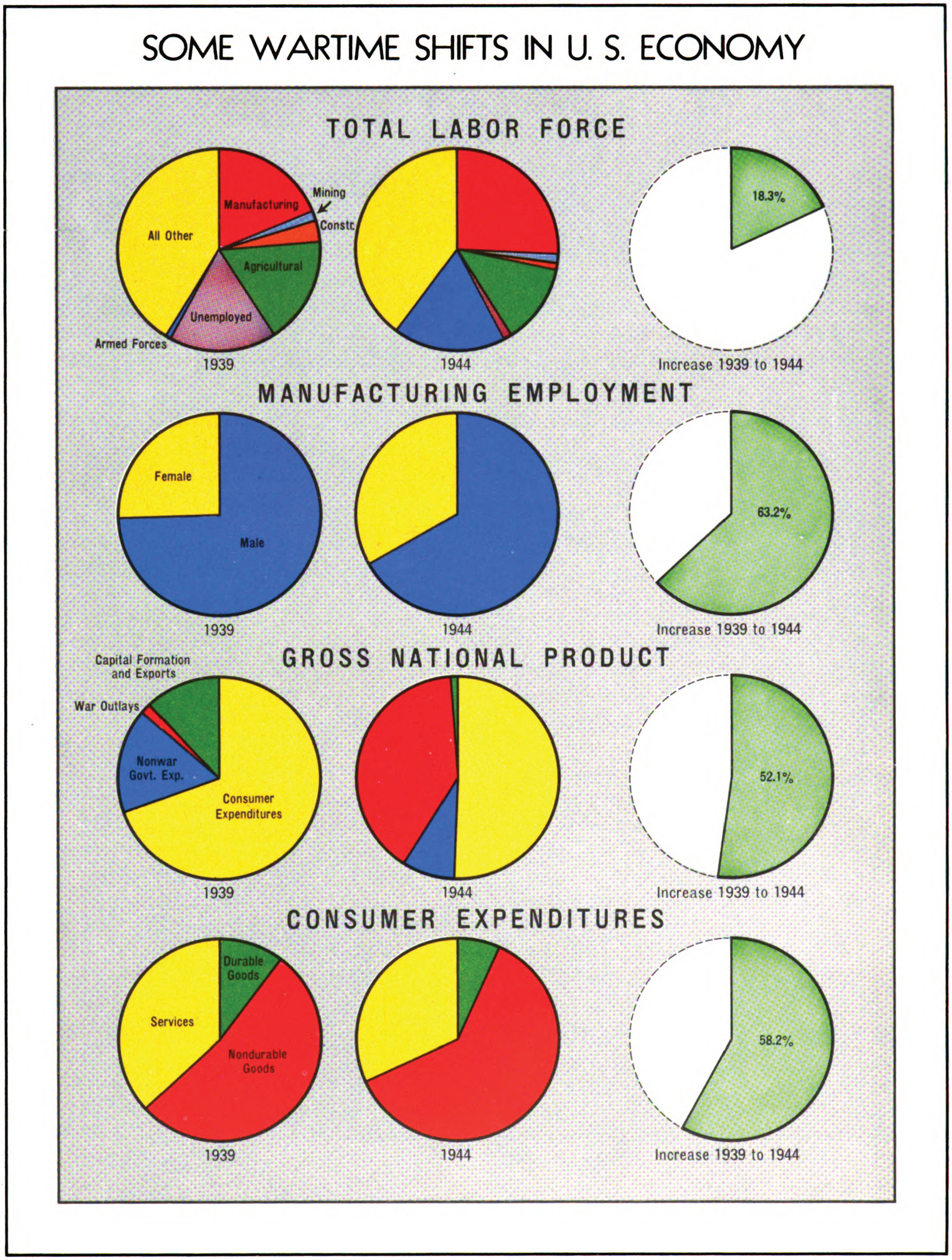

Figure 8: *Net new jobs created in a mobilization of the economy commensurate with a 2° C/3.6° F target.*

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 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. The reality is, however, that 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 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.

There will be so many jobs we'll need robots to do (the least rewarding of) them.

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