Interregional Transmission, Economic Development and Workforce Opportunities

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Introduction

"There is no transition without transmission."

Transmission represents a pivotal organ of America's broader energy infrastructure as it is responsible for the transferring of electricity from power plants to local distribution networks and ultimately to consumers. Transmission acts as the critical link that enables the flow of energy across vast distances, ensuring that demand is met across urban and rural areas alike. And, with the increasing integration of renewable energy sources and the push for a more resilient and sustainable grid, transmission infrastructure must evolve to handle not only the current demands but also the future challenges posed by a rapidly changing energy landscape (Office of Policy, US Department of Energy, 4/22).

Despite its critical importance to the functioning of the American economy broadly, and energy systems specifically, the economic benefits of transmission are underemphasized and the workforce that services the transmission energy—and the macrogrid more broadly—faces a myriad of difficulties like recruiting and retaining diverse talent.

Surfacing the benefits of robust transmission and the opportunities for an expanded transmission workforce highlights substantial economic benefits both to the economy as a whole but also to particular localities where transmission is or will be built. Additionally, like the grid workforce, the transformer manufacturing sector—a critical part of the transmission development pipeline—is confronting significant challenges, including a heavy reliance on overseas production and a critical shortage of skilled workers in key areas such as welding, coil winding, and testing. The sector has also seen a decline in electrical engineers, as many are attracted to careers in other fields like computer science.

This paper reviews first the broad and specific impacts of transmission buildout on the US economy. Transmission enables other industries to thrive and be competitive via access to low-cost clean energy. These broader economic impacts are important–but as shown in the New England Clean Energy Connect (NECEC) case–can also quite debated, with opponents to transmission projects casting doubt on economic benefit projections. The second section focuses specifically on the workforce for transmission. We discuss the broad range of jobs that are part of building out transmission along with a variety of current constraints and future opportunities.

By focusing both on the economic and workforce development benefits of transmission we ground our analysis in people and communities. Discussions of the economic benefits of transmission are too often impersonal. Expanding transmission is not simply a technocratic engineering exercise but is also an investment in people, communities and the vitality of the United States.

Broad Estimated Economic Impacts

Grid Expansion and Economic Growth Estimates

New investment in interregional transmission lines will bring widespread economic benefits. The short-term benefits are the jobs and GDP created by constructing such extensive infrastructure (Jinglin and Frayer, 5/2018). The medium-term benefits of interregional transmission lines come in the form of more efficient electric markets — one study cites the possibility of $180 billion in electricity savings (Brinkman et al., 2021). These benefits have further positive impacts on industries that rely on affordable, dependable electricity (Wang, 06/2018). This memo will focus on the United States, but estimates of large economic impacts from integrated regional grids are not limited to the United States.[4]

Transmission lines make electricity markets more efficient by connecting consumers to cheaper electricity sources. In the United States in 2022, the share of final energy consumption from electricity was around 16% (Our World in Data, 2023). This is expected to only increase over time as more renewable energy sources are brought online and more processes are electrified, such as heating and cooling and industrial processes discussed below. Given the importance of electricity as an input, a key driver of broader economic growth will be the price of electricity.

In the current fragmented U.S. grid, there are opportunities for significant cost savings by strengthening the transmission connections between different regions. When regional electric grids are insufficiently connected, congestion costs arise. These costs describe a situation in which consumers must choose a more expensive source of electricity over a cheaper source because the cheaper source is inaccessible to the market without more transmission capacity. From 2021 to 2022, congestion costs jumped from almost $14 billion to more than $22 billion (Doying, Goggin, Sherman, 07/2023). Even as global conflicts forced up the price of fossil fuel prices, many regions were unable to access cheaper renewable energy, because their grids didn't have sufficient transmission access to those generating sites. As the U.S. comes to rely more on renewable energy, these costs will continue to increase. That's partly because renewable energy will offer cheaper alternatives — but there's no guarantee that consumers will be able to access those alternatives.

Another clear way to understand cost savings on the price of electricity is to look at the amount of renewable energy that has to be curtailed because there is insufficient transmission capacity (Davis, Hausman, and Rose, 2023). Curtailment limits supply, which in turn limits the potential for price decreases even if the marginal cost of energy production from renewables is low. Several regional grids have seen curtailments increase in recent years (Davis, Hausman, and Rose, 2023).[1] Failing to solve curtailment with new interregional transmission lines will force utilities to overbuild renewable energy generation to achieve the same energy production goals. This too will entail much greater energy costs.

If the U.S transitions to 100% renewable energy by 2050, it will cost an extra $1 trillion to do so without an extensive, interconnected national electric grid (Lew et al. 12/2021).

Alternatively, building more transmission lines between regions can result in significant savings. Under a 50% renewable energy goal, the benefit ratio of connecting the east and west electric grids with new interregional transmission lines is 2.5, and under an 85% renewable goal, that benefit ratio rises to 2.9, saving $4.5 to $29 billion over 35 years (Acevedo 06/2021). A more connected national grid will be able to exchange energy resources at their low costs, connecting high demand to high supply.

One analysis examines how the scale of interregional transmission buildout drastically affects the price of electricity in future economies. Under a 100% renewable energy economy, an interregional, nationally-optimized transmission system reduces electricity prices by 46%, compared to a grid-optimized state-by-state (Brown & Butterand, 2021). If each state planned its own grid, and didn't build any additional power lines across their borders, the price of energy would be an average of $134 MWh. But if states agreed to nationally-optimized plans, and built the electric grid to be most efficient on a national scale, the average price of electricity would be $74 MWh (Brown, 2021). These price effects are due to a mismatch between supply and demand. Regions that are naturally abundant in solar or wind energy, for example, often consume less energy compared to areas with more economic activity. Better transmission minimizes these discrepancies across regions which in turn lowers costs dramatically.

There are several real examples of this. The TransWest transmission line, costing $3 billion, is estimated to save more than $9.5 billion over the next 50 years (Brinkman, 2021). The MISO utility estimated that their $10.4 billion investments in thousands of miles of new transmission will save $37 billion over the next 20 years (MISO 2023). National Grid's new Twin States transmission line will save more than $8.3 billion in the first 12 years alone, as it brings Canadian hydropower to New England markets (PR Newswire 10/2023). Arkolakis and Walsh (08/2023) estimates that 4 significant transmission lines, costing $10 billion, could save $1.5

[1] Combined with particular policy mixes, this can lead to negative prices (Seel et.al, 2021.)

billion GDP a year. These specific examples are part of a larger opportunity for cost savings. The impact of transmission lines will vary depending on the markets they impact, but the implied price effects and impact on economic growth are substantial.

In turn, electricity savings make a significant impact on the rest of economic activity. Saving $1 million in electricity costs tends to create 8-11 jobs in that electricity market, and boost regional GDP by around $1.5 million (Wang, 2018).

Specific Economic Sector Growth

Next we analyze a set of specific economic sectors to consider the impact of increased transmission on growth in these sectors. As the service, residential, and transportation sectors electrify, they will benefit from increased transmission capacity, to make electricity cheaper and more reliable. But in the following paragraphs we focus especially on the relationship between the industrial sector and the electric grid. We cover data centers, heavy industry, the fossil fuel sector, and the nascent carbon capture sector. These industries are major sources of local and national revenue. They are also increasingly the main drivers of growth in electricity demand. In 2023, grid planners almost doubled the five-year national forecast for electricity demand, from 2.6% to 4.7% growth, and identified new manufacturing and data center facilities as responsible for the uptick (Wilson and Zimmerman, 12/2023*)*. It's unclear whether the U.S grid can meet these demands. So we have evaluated how new transmission lines will impact sustainable growth in these industries.

Data Centers

Data centers provide huge and growing economic benefits to local and state governments, and are key to growing AI technology. But a lack of transmission capacity is a bottleneck to their rapid development.

Data centers are the specialized facilities where organizations store their computer systems, servers, and networking equipment; they are the physical infrastructure where data is stored and processed, and where digital services are conducted. In our booming digital age, data centers are a major source of revenue for local and state governments and generated more than $2 trillion in economic activity between 2017 and 2021 (PwC and Data Center Coalition, 09/2023). A typical data center employs more than 150 workers, contributing more than $30 million to local economies, and paying $1.1 million in public revenue to local and state governments (U.S Chamber of Commerce 06/2017). In northern Virginia, which has the greatest concentration of data centers in the US, the industry employed 45,000 workers, contributing $174 million to the state government and $1 billion to local governments (Northern Virginia Technology Council 2023).

To power their financially rewarding services, data centers require abundant electricity. Currently, the sector consumes 22 GW nationally, but consumption is estimated to rise to 33 GW in only a few years (Wilson 03/2023). In Virginia, energy consumption jumped 28% between 2022-2023, an increase caused largely by new data center operations Anderson and Sweeney, 2023).

The mid-Atlantic region so far produces sufficient electricity to power these data centers. But the regional utility, Dominion, has had to call for delays in the construction of new data centers because of insufficient transmission line capacity to deliver that electricity (Wilson, 2023). In 2018, one Amazon data center was delayed until the technology company helped pay to bury a contested transmission line that was necessary for the new site (Prince William Times, Washington Post, 03/2018). For two months in 2022, the utility stopped interconnecting new data centers to the grid, in order to better plan how to expand transmission capacity. Dominion has since managed to connect all data centers seeking electricity. However, the industry is worried about powering its plants in the future. At the recent Data Center World conference, keynote speaker Chris Crosby claimed that “the most critical issue now is transmission…the number one thing we can do is build more high voltage transmission lines” (Data Center Frontier, 05/2023). The most likely sites for new data centers, from Texas to California to Iowa, are the sites with great access to renewable energy and excellent transmission capacity. Meta, which recently announced plans to double the size of its data center in rural Utah—a project which will collectively employ over 2,000 people in its lifetime—and power it entirely through renewable energy, will depend on sufficient transmission to succeed (Semerad, 2022). Utilities are planning for the future to keep up with the pace of proposed construction.

This challenge will only become more significant as technology companies invest in artificial intelligence. The use of AI models requires 2-3 times more energy than the current data center uses. Training AI models require 5-7 times more energy than current uses (Anderson and Sweeney, 2023). Experts from all realms agree that AI will be a massively growing industry in the coming decades. The recent Grid Strategies report suggests that powering generative AI could require as much as 7.5% of U.S electricity by 2030 (Wilson and Zimmerman, 12/2023). However, companies may have trouble developing and especially deploying AI at scale if they don’t have the abundant electricity to do it.

Heavy Industry

Heavy industries are an economic bedrock in many regions of the United States. In Indiana and Michigan, for example, manufacturing contributes 29 and 19 percent of the gross state product, respectively (Foster, Navaho, Sun Hon Ng, 2020, p.4). What’s more, manufacturing is key to reaching national goals, from clean energy to the future of computing. To keep these domestic industries thriving, for national objectives and for local prosperity, the U.S. must ensure that these industries have access to steady, cheap electricity. That will be ever more important in a rapidly decarbonizing future, where industries will be relying less on fossil fuels and more on electricity. Already as of 2023, 200 new clean energy manufacturing facilities have been announced, catalyzed by the Inflation Reduction Act. As a result, new “near-term load growth” has already been observed in the southeast, and is expected in the Midwest and southwest regions as well (Wilson and Zimmerman, 12/2023). New transmission is necessary to power these factories and the industrial transformations to come.

Steel

Despite declines over time, the iron and steel industry remains an important contributor to the US economy.[2] It is also extremely energy intensive. Nevertheless, steel production is a remarkable case of increased energy efficiency, with the energy required to produce a ton of crude steel having dropped by 60% since 1960. Technologies like electric arc furnaces make for greater efficiency. But energy still represents 20-40% of the total cost of steel production (World Steel Association, 04/2021) . As steel producers decarbonize and electrify more of their processes, that figure could rise. Energy prices could be a bottleneck, blocking advanced steel production; a congested grid could limit the electricity supply available to a manufacturing center. That's why abundant cheap electricity is key to keeping steel production affordable, especially in a decarbonized future. Essential to securing low electricity prices, in turn, is an extensive grid that can deliver the cheapest clean electricity.

The need for new transmission lines to enable steel production is already evident. Steel Dynamics recently invested $1.2 billion in Mississippi to build a new steel production site, including a cutting edge, low-carbon bio-carbon manufacturing facility (White, WJTV News, 10/2023). This is the largest economic investment in Mississippi's history. At the same time, the Mississippi utility has proposed dramatic new investments in transmission infrastructure across the state (MISO 10/2023). The Steel Dynamics investment will create 1,000 jobs paying an average of $93,000. This job growth is only possible if the factory can access dependable, affordable electricity. Transmission buildout is necessary to accompany steel production.

Aluminum

Aluminum, valuable for its conductivity, malleability and light weight, is the second most commonly utilized metal after steel (Rocky Mountain Institute, 12/23). Useful across a wide array of sectors, aluminum is a crucial input into a range of renewable energy technologies, which in turn require manufacturing and generate economic benefits (Moreira, 03/2023).

Aluminum production involves extracting, refining, and electrolyzing mineral ores; it's an energy-intensive industry with substantial electricity needs (DOE, 02/2007). The industry also has large contributions to the US economy. In 2019, the primary aluminum production industry contributed $174 billion to the economy and employed 162,000 workers directly and 692,000 indirectly (Foster et al., 2020). But primary aluminum production was at one time even more

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[2] According to an economic impact study by the American Iron and Steel Institute, the iron and steel industry added more than $206 billion directly to the US economy with 386,753 jobs for American workers in its production, processing, and distribution. Including the indirect employment and industry output that is a result of these primary processes…iron and steel are estimated to make a total economic impact of over $500 billion and almost 2 million jobs" (Foster, Nabahe, and Ng, p.11).

prosperous. In 2000 the US was the world's leader in primary aluminum production. Now it is the ninth largest producer, at only 2% of global primary aluminum production (Watson, 2022).

A major reason for this manufacturing decline is energy costs. 40% of the cost of primary aluminum comes from the cost of its energy inputs. In the last two decades, this kind of aluminum production relocated to Russia, Canada, UAE, and other countries with cheaper — often not cleaner — sources of energy. China accounts for over half of global primary aluminum smelting (Energy Information Administration, 09/2017).

Since 2018, when America imposed a 10% trade tariff on aluminum imports, the industry has recovered some revenue and production (Hersch and Scott, 05/2021). But going forward, the future of the industry is uncertain. This is a chance to decarbonize[3] and rebuild the domestic aluminum industry via cheaper energy inputs that can be facilitated through transmission expansion. To do so, manufacturers must have access to abundant, affordable electricity.

Paper

In 2018 the paper and pulp industry employed approximately 360,000 workers and contributed $57 billion to the US economy. It is the manufacturing sector with the third highest consumption of energy, behind chemical and petroleum products (Foster et al., 2020). In 2006, the paper industry spent around $7.5 billion on energy costs, equal to "roughly 20% of the total material cost," writes one report from the Lawrence Berkeley National Laboratory (Kramer, Masanet, Worrell, 2009). $4.7 billion of this investment was for fuels, and $2.8 billion was for electricity. But the latter figure will continue to rise as manufacturers decarbonize by electrifying their processes (Furszyfer Del Rio, et al., 2022). Companies in the European Union are already experimenting with using electrified heat pumps for the drying stage of production instead of using fossil fuels. U.S. manufacturers are the second largest producer of paper products in the world. If they wish to decarbonize their processes while staying competitive on a global stage, it's crucial that paper manufacturers have access to abundant, affordable, dependable electricity.

Renewable Energy Jobs

A lack of transmission is one of the greatest bottlenecks to renewable energy expansion: almost 2000 gigawatts of already-built renewable energy has been stranded without a grid interconnection because there's not enough transmission capacity to deliver it to consumers (Wayner, et al., 2023).

Accordingly, building new transmission lines — especially high voltage lines across distinct grids — will enable new renewable energy generation to flourish. Grid Strategies estimates that with a

[3] Aluminum production contributes to around 2% of global greenhouse gas emissions (Rocky Mountain Institute, 12/23).

$64 billion investment in 36 shovel-ready transmission projects, there could be an increase of 2 million jobs in the wind and solar industries (Wilson et al., 9/2023).

Fossil Sector

The Permian Shale Boom of 2018 required record use of electricity in West Texas. Due to the huge demand, the regional grid became congested (Handy, 4/2018). Electricity prices were rising and state operators were having trouble delivering sufficient electricity to meet demand. So state planners rapidly built new transmission lines — more than $200 million worth — to enable the industry to continue to grow (Hedden, 2019). The new transmission lines secured a sufficient supply of electricity so that the shale extraction operators could use abundant electricity. The fossil fuel sector itself can be energy-intensive and unless sufficient transmission lines connect them to other, cheaper energy resources, they can be constrained by costs. This trend is evident in Wyoming's extraction industry wherein electricity cost increases, such as the proposed hike by Rocky Mountain Power, could significantly impact production and operational sustainability, which is currently flourishing as a result of low electricity rates (Bleizeffer, 2023).

Carbon Capture

Some industrial processes, such as the production of concrete or chemicals, are very difficult to electrify. The easiest solution may be to use point-capture technology to remove the carbon pollution (IEA Berghout 2/2021). But carbon capture is energy intensive. Energy costs have been from 33-50% of the total operating costs of carbon capture technology (Butterworth 2023). If electricity prices are on the high end of the $74-134 MW/hr range, it may be difficult for these heavy industries that rely on carbon capture to stay competitive on the world stage.

Direct air facilities, similar but distinct from point capture, use giant fans and filters to remove carbon from the open air. Several of the first DAC sites are being constructed across the states, with help from a $3.5 billion federal investment, and facilities like these could be key to removing the residual emissions from hard-to-decarbonize industries like concrete production (DOE, 2022). But DAC facilities are also energy intensive: removing 1 ton of carbon requires 22 to 1500 kW, and this electricity must be low or zero carbon to have a meaningful decarbonization impact. That's why DAC facility site selection places high emphasis on access to abundant, cheap, low carbon electricity. At the present, that means DAC sites must be located near to plentiful renewable energy. But models of future decades show that DAC facilities could be sited at a distance from renewable energy, as long as transmission lines link together the electric grid and provide abundant, cheap, clean energy to those sites (Abramson, McFarlane, et al., 2023). The Rhodium Group estimates that the construction of an average DAC facility would create more than 1200 jobs, and that its operation would employ more than 300 people (Jones, et al., 2023). Any region that seeks these economic benefits must also have a well-connected, energy abundant electric grid.

Green hydrogen production is in a very similar position to DAC facilities. Green hydrogen is produced using renewable energy. So green hydrogen production facilities must either be located at the same site as renewable energy production, or have access to abundant, cheap, clean electricity. The hydrogen production facilities proposed as of 2023 will require 3.6 gW of electricity, and these sites are only the beginning of prediction production (Wilson et al., 2023). Regions that seek the economic benefits of hydrogen production might ensure co-location to vast renewable energy resources, or an extended grid that has access to cheap and abundant clean electricity.

Landowner revenue models

Building out transmission requires working with local landowners to gain access. However, there is no standardized system in place for transmission rights-of-way negotiations between landowners and state-commissioned utility companies. Negotiations are handled on a case-by-case basis and are influenced by a myriad of factors including developer policies, state and local regulations, and increasingly, landowner preferences. All such negotiations however incorporate appraisal, a valuation of the land that is translated into landowner compensation; a common principle of this appraisal process is that the compensation is based on what the owner has lost, not the value of the new use of the land (Berry, 2013).

The most common revenue model for landowners is easement, which grants a lasting permission for an entity (usually a utility company) to utilize someone else's land or property to construct and upkeep a transmission line on the property. The landowners receive compensation for this easement and retain the ability to use their land for various activities, though there are certain limitations outlined in the contract. Although easement is widespread, alternative revenue models also exist. **Table 1** outlines alternative models to landowner compensation.

Compensating landowners fairly is an inherently difficult task. and often unfairly values the land in question. For one, many compensation models undercompensate landowners because they do not consider “anthropocentric valuations” which includes “personal preferences, emotional sentiment, community bonds, or suitability of land for particular uses.” (Gerstle, 2014). Secondly, poor compensation has the potential to create substantial financial costs for the state in the case that landowners challenge compensation amounts in court (ex: in Garden Grove, California, a property initially valued at $640,000 (in 2000) was later acquired by the city for $1,070,000 plus $620,000 in attorney's fees after a legal challenge by the landowner) (Gerstle, 2014).

Beyond speaking to the political and legal challenges of building transmission, compensation models can help drive local economic growth in much the same way that rents from renewables or mining/oil/gas extraction can inject revenue into local communities. In the case of royalty payment models, for instance, these local economic benefits can also be long term as they persist throughout the course of the transmission line’s lifetime. While the value proposition discussed here focuses on economic growth due to transmission, this is economic growth directly due to the value of providing land for transmission.

Table 1. Landowner Compensation Models for Transmission Rights-of-Way

Compensation Model	Description	Example	Reference
Damage Payments	Payments made to individual landowners on the basis of damages (to business or assets)	Montana-Alberta Tie Line; landowners affected by the transmission line were offered compensation for lost crop production (they were also paid annual pole payments ~$200/pole, see row below).	Berry, 2013
Annual Per-Pole Payments	Utilities pay a fee for each pole they use to string electric lines or communications cables on the land of individual landowners	For landowners affected by the Rock Island Clean Line, landowners were given the choice between one-time payments or annual-payments, both on the basis of pole usage.	Berry, 2013
Landowner Association	Groups of landowners are represented by a single association, who collectively bargain for association preferred compensation	Rocky Mountain Farmers Union (RMFU) represents family farmers and ranchers in Wyoming, Colorado, and New Mexico and negotiates directly with utilities.	Berry, 2013
Rapid Response Team for Transmission	The RRTT was a 2011 initiative by the Obama administration to fast-track federal permitting across agencies for seven transmission projects.	Since 2011, two of the seven projects have been built; one of the seven projects has been under construction; three of the sevens projects have been cleared for construction only in the fall of 2023, including SunZia and TransWest; one of the projects was canceled entirely.	Berry, 2013; Storrow, 2022
Buy the Farm	Landowners can select to have the utility purchase the entire property over which a transmission line will pass.	Minnesota is the only state with a "buy the farm" statute–Xcel Energy has utilized this statute in previous rights-of-way matters.	Berry, 2013
Royalty Payments	Landowners are paid royalty compensation for right-of-ways. Costs come out to .00099 cents / kw.	Cornerstone TansCo LLC uses this approach and has never had to use eminent domain to secure land.	Berry, 2013
Special Purpose Development Corporation	Landowners are given the choice to trade their land for an equally valuable number of shares in what's known as a Special Purpose Development Corporation. This entity is created solely to assemble and sell land parcels to the developer. This policy theoretically gives the landowners more collective leverage to negotiate for more desirable deals.	The policy has been proposed by the Center for Rural Affairs and has not yet been enacted.	Winn, 2014
Land Assembly District	Especially useful for fragmented parcels. Landowners assemble into a common organization that negotiates with developers. The united organization can use eminent domain to override minority voices of its members.		Gerstle, 2014
Land Readjustment	Landowners collectively agree to redevelop their land. In	This approach has been used in	Gerstle, 2014

	the framework described by Gerstle it takes 25% of landowners to begin proceedings, under which a public body holds hearings. If no significant objections arise, the developing campaign seeks the consent of a majority of landowners. After several back and forth elections between an established board, public body, and landowners, a development plan is established, and landowners receive shares or other payment	urbanization processes across the world.	Hong and Needham, 2007
Equity Model Limited Liability Corporation	This method is very similar to the SPDC. Landowners receive shares in an LLC created by the developer. They can later sell their shares, or simply enjoy the flow of money from their shares.	Proposed in 2010 by developer Ralph Basile.	Gerstle, 2014
Transmission Corridor District	First the planning agency plans several routes, divided into specific segments. Then it must seek the support of 25% of those landowners of a segment, or else that segment is disqualified from the development process. Then at least 10% of landowners vote to elect a board, which negotiates with the developer. Then the developer needs at least 50% of the landowners' support. Then the developer wins easement rights as part of a special purpose vehicle entity. The landowners receive tradable shares in that entity as compensation, and dissenting landowners receive FMV payments. Representatives from the route segment boards continue to represent the landowners.	This policy has been proposed by Gerstle but is not yet in practice.	Gerstle, 2014

Grid Resiliency for Economic Resiliency

New investments in long-distance, high-voltage transmission infrastructure would also reduce the risk of disastrous blackouts that wreak economic havoc. For example, “to meet the projected energy demand in 2035, the Southwest region — including Nevada — will need between 2.3 and 4.7 gigawatts of additional interregional transfer capacity to maintain electricity reliability during extreme weather events, according to a recent US Department of Energy Report (DOE 10/2023). That means the Southwest would need to increase its transfer capacity with the Plains region by 914% relative to what’s available now” (Nevada Current, 10/31/2023). This means that on a day with the worst possible weather conditions — say, cloudy and extremely hot — the Southwest electricity market would need 914% more transmission infrastructure to receive sufficient electricity from the Plains to meet its energy demand. This is just one regional example. Estimates of the economic cost of energy interruptions vary but are nonetheless substantial (Sanstad et al., 11/2020; Macmillan 05/2023; Shuai 2018).[4] The temporary loss of energy is not just damaging to people’s health and safety. It’s financially crippling, because it’s costly to interrupt business and have to restart industrial processes, and because these blackouts can cover such large areas at once. Avoiding 1 hour of blackout can save $.6 - $1 billion for affected areas (Wang, et al., 06/2018, p.22).

The 2021 Texas Winter Storm Uri is one tragic and disastrous example of an unexpected blackout event that harmed people and cost the state billions of dollars. Many generating systems failed during the extreme cold temperatures. But a fundamental fault of the crisis was the state’s lack of interconnection with other electricity markets. It couldn’t receive emergency electricity from other regions. Going forward, greater transmission interconnections are crucial to reducing the risk of blackouts, for Texas, and for every state. As the nation increasingly transitions to renewable energy, interregional transmission and grid updates will keep the flow of electricity for people, businesses, and industry.

International Competitiveness

Transmission infrastructure acts as a backbone for U.S. industrial excellence. It is key to dependable, affordable production across sectors. Lack of transmission, in turn, acts as a bottleneck, delaying development and reducing competitiveness on a global stage.

The U.S. could be an export leader, selling products made with clean electricity to markets across the world. But domestic manufacturing cannot be internationally competitive without a 21st-century grid to deliver cheap power. The nation can only bring substantial aluminum production back to the U.S., for example, if it can be powered at low costs and low emissions. The same is true across industries. Manufacturers are designing clean ways to produce steel, aluminum, paper, and other products, and developing carbon capture to clean up the dirtiest sectors (IEA 2022). And for manufacturing sectors that are internationally traded, carbon tariffs

[4] An online tool provides one window into these costs, https://icecalculator.com/home.

such as the European Union's Carbon Border Adjustment Mechanism will drive up the prices of products that do not decarbonize production.[5] Internet based businesses that serve global customers rely on infrastructure and data centers, and so these in turn also rely on a dependable electric grid.

An efficient grid is crucial for U.S. renewable energy development, which will only thrive alongside modern transmission to bring it to markets. But these other more widespread benefits of transmission investment–here international competitiveness–are often overlooked. Transmission infrastructure is a foundation for domestic industry, and key to competitiveness on a global stage. Domestic industries will lose their competitiveness without dependable, affordable energy; transmission lines are the crucial backbone of a strong internationally competitive economy.

Workforce

To accelerate a transition towards net zero and the broad-scale electrification of every sector, the development of a workforce dedicated to the planning, construction, and maintenance of the macrogrid, herein referred to as the grid workforce, will be essential. The grid workforce is incredibly diverse in the wide gamut of occupations it encompasses, including traditional jobs like lineworkers and adjacent jobs like energy compliance specialists. Some of these jobs are require a more mobile workforce, such as those who install towers and hoist lines. As mentioned in the Grainbelt Express chapter, this can lead some to oppose projects as there might be little local economic workforce utilized (see Gazmararian and Tingley 2023 on this general point). However, other jobs require less mobility and local communities can benefit from adjacent economic development opportunities like those discussed above.

However, grid related jobs are often treated monolithically, hindering our understanding of the increasingly complex dynamics of this sector of the economy.

Occupational Variety

The building, servicing, and maintenance of the transmission grid has created a vast array of occupations directly and adjacently related to the grid, representing a microcosm of the diverse energy workforce. Work related to the grid includes the traditional jobs in grid work (ex: lineworkers and transformer specialists) as well as those in associated fields such as cable manufacturing and legal counsel, all of which collectively support the functioning and growth of energy infrastructure. It is important to delineate and characterize the diversity of jobs related specifically to the grid. Although considerable research has outlined the range of jobs related to energy at-large, less focus has been placed on the grid; for instance, the Bureau of Labor Statistics does not specifically calculate employment and wage data for grid occupations.

[5] US manufacturers will not be nearly as opposed to CBAM compared to their competitors in China (Hoenig 2023). However, this is in part due to relative carbon intensity that further electrification will help.

Importantly, however, the grid is the heart of the United States' efforts towards electrification and accordingly, a detailed and accurate characterization of the labor involved in maintaining the grid is paramount.

The grid encompasses a myriad of disparate yet inherently interconnected occupations, ranging from electrical engineers to power-plant operators. **Table 2** highlights this diversity, and categorizes occupations into distinct categories and sub-categories.

Table 2

Category	Sub-Category	Occupations	Example of Employer
Core Grid Operations & Maintenance	Engineering & Development	Electrical Engineers, Protection Engineers, Grid System Analysts	GridSME (hires Electrical Engineers, Protection Engineers)
	Operations	Power Plant Operators, Substation Operators, Grid Operators, Control Room Operators	Duke Energy (hires Power Plant Operators, Grid System Analysts)
	On-The-Ground Work	Transmission and Distribution Line Workers, Utility Linemen, Maintenance Technicians, Meter Installers and Readers	Pacific Gas and Electric Company (PG&E) (hires Transmission and Distribution Line Workers, Utility Linemen)
Grid Planning & Policy	Environmental and Land Planning	Environmental Planners, Land Acquisition Specialists	HDR Inc. (hires Environmental Planners, Land Acquisition Specialists)
	Regulatory and Compliance	Regulatory Affairs Specialists, Safety Inspectors	Southern Company (hires Regulatory Affairs Specialists, Safety Inspectors)
	Policy and Research	Energy Policy Analysts, Research Scientists, Energy Economists	National Renewable Energy Laboratory (NREL) (hires Energy Policy Analysts, Research Scientists)
Customer & Public Relations	Service and Support	Utility Customer Service Representatives, Public Relations Specialists	Xcel Energy (hires Utility Customer Service Representatives)
	Field Work	Meter Installers and Readers	Florida Power & Light Company (hires Meter Installers and Readers)
Technology & Innovation	Renewable Integration	Renewable Energy Specialists	National Grid Renewables (hires Renewable Energy Specialists)
	Storage Solutions	Energy Storage Specialists	AES Energy Storage (hires Energy Storage Specialists)
	Cybersecurity	Cybersecurity Experts	Waterfall Security (hires energy-focused Cybersecurity Experts)
	Mapping and Planning	GIS Specialists	Environmental Systems Research Institute (Esri) (hires GIS Specialists)
Administrative & Support Roles	Logistics	Logistics and Supply Chain Managers	FedEx Supply Chain (hires Logistics and Supply Chain Managers)
	Training	Training & Development Specialists	Electric Power Research Institute (EPRI) (hires Training & Development Specialists)
	Legal	Energy Lawyers & Litigators	Latham & Watkins LLP (has a renowned practice in energy law and

			hires Energy Lawyers & Litigators)

The diversity of employment in the grid workforce is the product of two factors. Firstly, like much of the United States energy sector, the grid itself is highly interconnected and necessitates expertise and labor across various sectors of the economy. Secondly, the grid itself requires swift adaptation to emerging trends in the economy as a whole (ex: greater integration with renewable energy and in recent years, utilization of artificial intelligence and machine learning to drive results) and hence demands a widely skilled and flexible workforce.

In recent years, the 'electrify everything' movement has given rise to calls highlighting a pressing need for more electricians. Yet, as is obvious from the diversity of jobs required to sustain the grid, electricians represent only a fraction of the occupations in the grid workforce. This trend of grid workforce homogenization—the imprecise grouping of occupations related to the grid—is particularly evident in the high and ultra-high voltage domains, wherein different occupations such as lineworkers, tower construction specialists, and transformer manufacturing and installation experts play pivotal, yet often poorly defined and delineated roles. Although high-voltage workers often undergo similar training to their low and standard-voltage counterparts, their occupation also requires specialized training and certification to safely operate at higher voltages and utilizes highly specialized tools like highly-insulated cable tools. Finally, alongside these technical disparities, these roles are also confronted with distinct regulatory issues, such as compliance with OSHA's Electrical Safety Standards (29 CFR 1910.269), which specifically regulates electric power generation, transmission, and distribution work, setting forth specific practices for high-voltage work.

Finally, adjacent to the core jobs of the grid are a range of complementary occupations that are integral to the overall functioning of the sector, including but not limited to the manufacturing of cables, the production of steel for towers, and roles in management and legal counsel. Each of these roles is essential in sustaining the intricate framework of the modern electrification movement and warrants distinct recognition and understanding in academic and professional discussions surrounding the ongoing transition to electrification.

Representation and Diversity

Unions

In the ongoing developments and projects associated with the electrical grid, several key unions are prominently involved, playing crucial roles in advancing the objectives of these initiatives. These unions include the North America's Building Trades Unions (NABTU), the Utility Workers Union of America (UWUA), the International Brotherhood of Electrical Workers (IBEW), the International Association of Bridge, Structural, Ornamental, and Reinforcing Iron Workers, the Laborers' International Union of North America (LIUNA), the United Mine Workers, and the International Union of Operating Engineers. Two notable projects, the NE Clean Energy Connect and the Cardinal-Hickory Creek Transmission Line, are noteworthy for employing hundreds of union members, thereby fostering an employee-centric approach to electrical project development.

Veterans

In recent years, there has been a growing acknowledgment of the untapped potential veterans bring to the table. Organizations such as Troops in Energy Jobs and Veterans in Energy have taken the mantle to facilitate the transition of veterans into the energy workforce. Furthermore, the relevance of integrating veterans into these projects is being recognized by several organizations, like National Grid which employs over 700 veterans as of November 2020 (National Grid, 2020). Veterans' specialized experiences and proficiencies are considered valuable in augmenting the diverse pool of talents required to realize the goals of modern electrification projects. There also exist programs, like Power4Vets, which are focused on supporting veterans by training and credentialing them for jobs servicing the grid.

Racial and Sociodemographic Disparities

Many aspects of the clean energy economy have representation gaps when it comes to women and persons of color. The extent of this for grid related jobs is unclear, though there is a strong chance that it mimics other parts of the broader industry. This hence misses opportunities for innovation, collaboration, and diverse perspectives that these groups bring. While advances in unionization for grid occupations and greater inclusion of veterans into the grid workforce e.g., initiative like Get Into Energy) stand as positive advances to enhance the diversity and employment in the grid workforce, there is much work to be done in regards to bolstering the sector's employment opportunities and access to these opportunities. In a proactive move to redress the broad imbalances, partnerships between stakeholders and Historically Black Colleges and Universities (HBCUs) and other institutions that serve minority populations are underway (e.g., https://hbcucleanenergy.org/category/solar-energy/). These collaborations aim to create pathways for these underrepresented groups, ensuring they become vital contributors to the energy sector.

Employment: Needs, Challenges, and Impacts

When studying the workforce of the US grid, many studies proffer broad generalizations about job opportunities, often grouping diverse employment categories and lumping in categories that include production jobs.

According to the Americans for a Clean Energy Grid, the construction of twenty-two identified transmission projects holds the potential to create approximately 240,000 direct jobs (Goggin, Gramlich, and Skelly, 2021). Furthermore, the American Council on Renewable Energy estimates that the implementation of an investment tax credit for regionally significant transmission lines could create an estimated 600,000 transmission-related jobs (Goggin and

Gramlich, 2021). Additionally, this policy initiative could potentially facilitate the creation of at least 330,000 more transmission jobs associated with projects that are evaluated based on their odds of success. These projections underscore the substantial impact that developments in the macrogrid can have in fostering employment opportunities and driving economic advancement via grid modernization and development.

Although some of these jobs will inevitably be short-term construction and planning roles, a substantial portion of transmission jobs will provide workers with durable employment. Indeed, according to the National Renewable Energy Laboratory, 12% of the jobs related to a transmission project from Wyoming to Colorado were long-term (NREL, 2013). Moreover, many transmission jobs, short and long term, are union jobs that pay prevailing market wages. In short, the employment opportunities present in transmission expansion are durable and valuable, to economies and individuals alike.

Workforce challenges have emerged as a critical area of concern as the grid expands, especially in the context of transmission and distribution construction. Before the COVID-19 pandemic, employers in transmission and distribution construction reported experiencing more difficulties in hiring compared to their utility counterparts. However, starting in 2020, utility employers witnessed a sharp increase in recruitment challenges (Foster et al., 2021). An executive from Xcel Energy provided insight into this issue, stating, “Xcel has generally hired around 1000 new employees a year for the past five years; however, in the past 6 months, we have found it increasingly difficult to find people who are willing to work far from their homes, even for only short periods at a time.”

From a training perspective, there are elements of optimism within the sector. A prevalent assessment among industry experts is that the existing workforce training system—which includes building trades apprenticeship programs in the construction industry, utility intern and apprenticeship programs, the community college system, and advanced degree colleges—is sufficiently robust. This network is deemed more than capable of providing a skilled workforce to facilitate the significant ramp-up in the deployment of renewable energy, energy efficiency, and smart grid technologies, thereby addressing the needs of a rapidly advancing sector. For example, Georgia Power’s recruitment of electrical line workers from a training program that raised retention rates from 75 to 93 percent, while reducing initial training costs by over 30 percent (Foster et al., 2021). Another example is the Wisconsin Regional Training Partnership where industry, schools and unions work together to create technical training programs that have resulted in high participant wages.

However, despite the readiness of the training system, numerous challenges persist. As noted by Foster et al. (2021), “there are clearly larger systemic issues…lack of industry-standard curricula, close coordination between affected industry partners such as the construction and utility industries, and access to pre-apprenticeship programs.” These challenges underscore the need for industry stakeholders to foster closer collaborations and address these systemic barriers to progress effectively. These barriers are not just hindrances to achieving full employment in this sector, but also major impediments to the progress of grid projects at large.

The benefits of expanding the transmission workforce are not restricted to the economic benefits of transmission itself. Rather, as consistent and long-term employment opportunities in the transmission workforce grow, there will be a commensurate economic multiplier effect that promotes economic growth in local communities, primarily through the creation of other jobs. Indeed, the forward and backward linkages of transmission labor are immense; according to a 2019 report from the Economic Policy Institute, the economic multiplier of every 100 jobs in the transmission sector is 560 total indirect jobs (supplier and induced jobs) (Bivens, 2019). Hence, prioritizing the transmission workforce, which has strong economic tethers to overall employment, will be an essential aspect of increasing economic growth broadly.

Expanding The Workforce

To ameliorate the gaps between grid workforce needs and individual access to workforce jobs, various training programs have sprouted in recent years. For example, the formulation of partnerships with rural educational institutions is a strategic initiative aimed at broadening access to specialized education in underrepresented regions. Similarly, collaboration with private firms for the provision of online education is gaining momentum, exemplified by initiatives aimed at upskilling low-voltage workers for occasional high-voltage tasks. Finally, the introduction of licensure layering, such as a lineman license and a Commercial Driver's License (CDL), is being integrated into training programs to equip professionals with multifaceted competencies.

Line burial

Another tool used to expand the grid workforce has been the implementation of line burial. Importantly, line burial represents a more considerable financial investment compared to traditional overhead lines. In Oklahoma, for instance, the cost of line burial was cited as the primary barrier to its implementation, alongside other logistical considerations such as right-of-way disputes and the difficulty of finding leaks should they occur (Terry-Cobo, 2022). However, line burial *has* been strategically implemented in numerous high-voltage projects of late, a notable example being the Champlain Hudson Power Express (Willson, 2023).

In addition to many of its aesthetic and safety benefits, anecdotal evidence also suggests that line burial garners more acceptance within certain political geographies, potentially mitigating community opposition and regulatory obstacles. In the UK, for instance, strong empirical evidence suggests that there is strong support from citizens for line burial projects (Cotton and Devine-Wright, 2011). In Germany, SuedLink, a 700 km transmission line that is entirely underground, is projected to be operational in 2027, suggesting the slow but certain growth of this transmission method globally (Renewable Energy World, 2021).

Doing line burial necessitates the adoption of diverse lines and construction methods, such as digging and the application of concrete. This diversity in implementation techniques, in turn, broadens the spectrum of workforce skills required, encompassing a variety of specializations and expertise. Line burial involves various construction techniques, including trenching, horizontal directional drilling, and the use of specialized equipment to lay cables and pipes beneath the surface, requiring workers to be proficient in operating a variety of machinery (OHSA, 2018). In addition to these technical skills, a strong understanding of engineering principles, particularly soil mechanics, is essential as different soil types present unique challenges during the burial process. Workers must assess soil conditions, adjusting their techniques to ensure the integrity of the buried lines. The application of concrete to encase and protect utility lines is another critical aspect, demanding skills in mixing, pouring, and understanding how environmental conditions affect the curing process. Coordination with other utility services is often required, necessitating strong communication and collaboration skills to work effectively as part of a team, avoid disruptions to existing services, and ensure worksite safety (NextGen Highways, 2022). In summary, the shift towards line burial is expanding the required skill set of the workforce, encompassing a variety of technical, practical, and interpersonal capabilities.

Transformers, Grid Structures, and Grid Monitoring

Transformers are used to convert electricity to different voltages along the trek between where it is generated to where it is consumed. These steps are crucial for maintaining the efficient transmission of energy. The manufacturing sector of transformers is currently grappling with substantial challenges, most prominently the fact that approximately 80% of transformers are manufactured abroad (US Department of Commerce, 2020). In fact, only eight US-based companies currently manufacture transformers domestically (Behr, 2022). Moreover, the transformers which *are* currently servicing the grid are being used up to 15 years beyond their lifespan (US Department of Commerce, 2020) and obtaining new transformers is also challenging as the time to procure new transformers is between 20 to 39 months (US Department of Commerce, 2020; Walton, 2022). Finally, increasingly catastrophic climate events, like hurricanes, tornados, fires, and floods have depleted already limited reserves of transformers (Rodriguez and Cavert, 2023).

This scenario is intensified by significant workforce shortages in crucial areas such as welding, coil winding, and transformer testing. Particularly, the shortage of welders is extremely acute, with the absence of a unified representation or a single union complicating the efficient matching of supply and demand for skilled labor in this domain. Additionally, the field is experiencing a notable depletion in the availability of electrical engineers, a trend attributed to the diversion of prospective talent towards computer science and related disciplines (Rodriguez and Cavert, 2023). This multifaceted workforce shortage necessitates urgent and comprehensive strategies to bolster both the availability and the diversity of skills within the domestic transformer manufacturing sector.

Transformers and transmission lines are supported by transmission towers, which are a key employment stimulus in the energy sector. Transmission towers bolster employment through manufacturing and maintenance jobs, both of which are long term employment opportunities. The transmission tower industry—which constitutes roughly 21% of electricity transmission and distribution market revenues worldwide—has an estimated compound annual growth rate of 5.6%, indicating substantial need for such infrastructure in the buildout of transmission lines in the US and globally (Statista, 2022). The manufacturing of transmission towers, which requires about 40 to 60 thousand pounds of steel per tower (and is hence a strong source of steel demand), has a strong domestic presence and is expanding (Abel, Parfomak, and Shea, 2004; AISI, n.d.). Most recently, the creation of a transmission tower production facility in Indiana is expected to create 200 full-time jobs and support Indiana's growing energy ecosystem (Nucor, 2023). Transmission towers, although durable, are susceptible to physical weathering and are vulnerable to domestic and foreign threats, both physical and in cyberspace (Abel, Parfomak, and Shea, 2004). Hence, the maintenance and protection of transmission towers will also require specialized and technical labor expertise.

Finally, the modernization of the electrical grid is also creating a diverse array of new employment opportunities, reflective of advancements in technology and evolving industry needs. With the advent of remote sensing technologies, such as Unmanned Aerial Vehicles (UAV) and even satellites, new specialized roles are emerging to leverage these technologies for enhanced grid monitoring and management (TC Energy, 2022). Furthermore, the integration of artificial intelligence and machine learning-based tools is creating novel positions focused on optimizing grid performance and reliability through computational approaches. All of these opportunities largely await training programs in higher education or elsewhere to prepare workers for this new industry.

Policy: Past, Present, and Future

A significant implication of the Inflation Reduction Act, 2022 (IRA) is its stimulation of demand for transmission projects, which includes $2 billion earmarked for transmission facility financing, $760 million in grants earmarked to facilitate the siting of interstate transmission lines, and another $100 million for interregional electricity transmission planning and modeling (Sections 50151, 50152, and 50153 IRA). Yet, despite the financial and structural support to enhance transmission development over the next two decades, the IRA still leaves many questions unanswered about how transmission development will operate under its passage.

For instance, the direct loan provision of Section 50151 stipulates that in order to be eligible for a direct loan, a transmission project must be located in a National Interest Electric Transmission Corridor (NIETC), a designation which does not currently exist (Vann, 2020). Similarly, the grants outlined in Section 50152 depend on the siting authority agreeing to make a final decision on a transmission project within two years, potentially creating bureaucratic challenges to the provision's implementation should a decision not be reached within the window (Lawson, 2022). Additionally, the investment support in the form of Investment Tax Credits, which was initially anticipated for transmission projects, was eventually dropped from the final version of the IRA (Zaifman, Schaff, and Mitchell, 2022). In addition to this, interconnection credits for projects larger than 5MW are missing from the legislation (Zhang, 2023). Finally, the enticing prevailing wage and apprentice program credit increments (that provide a five-fold increase of the base credit rate) that are available for other energy projects (ex: solar and wind facilities) are absent for transmission projects (IRS, Accessed 2023). In short, despite being an important step forward, the IRA is not sufficient in and of itself to help America reach its goals in energy transmission.

There are a myriad of other recent developments in energy financing at the federal level that seem to be promising in financing transmission and the grid workforce. In October of 2023, for example, the Biden-Harris administration announced an unprecedented $3.46 billion investment in strengthening the nation's power grid (U.S. Department of Energy, 2023). Part of President Biden's Investing in America agenda, this investment sets the stage for significant job creation and enhancement of worker conditions across the utility sector. With the allocation of funds to 58 transformative projects spanning 44 states, the initiative is poised to create a surge in employment opportunities, ensuring job security and fostering workforce stability. The strong collaboration with the International Brotherhood of Electrical Workers (IBEW) in 75% of these projects exemplifies a clear commitment to not just creating jobs, but ensuring that these are high-quality union jobs.

This strategic investment is also targeted towards areas that have been traditionally underserved, ensuring that the benefits of job creation and workforce development reach communities that need them the most. The emphasis on projects that support the President's Justice40 Initiative guarantees that at least 40% of the overall benefits of these projects are channeled to disadvantaged communities, ensuring a more equitable distribution of employment opportunities (The White House, 2022). Furthermore, with a substantial number of projects focusing on modernizing aging infrastructure, workers will have the opportunity to engage with and learn from cutting-edge technologies and innovative practices. This exposure is invaluable, as it ensures that the workforce is not only meeting the current demands of the industry but is also being prepared for future challenges and advancements in the energy sector.

The investment goes hand-in-hand with Biden's recent creation of the American Climate Corps (ACC). The ACC carries an aim of equipping a new, diverse generation with essential skills for burgeoning careers in climate mitigation and clean energy. The program is designed to train and employ around 20,000 individuals, emphasizing the establishment of long-term career pathways in collaboration with unions and various educational institutions. It extends opportunities to a broad demographic of individuals, requiring little to no prior experience or college degrees for most positions, and ensures the incorporation of transferable skills and credentials (Yoder, 2023). In relation to the U.S. grid workforce, the ACC has the potential to be particularly salient, both imbuing the grid workforce with greater manpower and diversity. It remains to be seen whether the ACC will focus on the grid workforce.

Policy Recommendations

The preceding analysis sets up a number of potential policy recommendations that can take advantage of the economic development and workforce implications of expanding interregional transmission.

Financing prospects for grid build out would be improved if there were tax credits available for transmission, rather than just renewable energy generation. These were dropped from the Inflation Reduction Act in favor of other priorities. Legislative windows to consider this form of stimulus might be narrow or non-existent, but they remain a policy lever that could help drive build out.

Landowners–and the communities they live in–can and should benefit from transmission projects that run through their land. Ensuring this happens in transparent and consequential ways will reduce blockages that have stymied earlier efforts. State and Federal governments could create clear menus of options and guidance for local stakeholders that will negotiate with firms, as well skilled interlocutors that help parties on both sides of a project.

Policies that encourage domestic production of key components of the broader interregional grid technology stack, such as transformers, are another policy opportunity. Programs that stimulate more domestic production of these and other technologies, as well as building next generation technologies and systems, will help to improve the long term efficiency and resiliency of the grid. This requires innovations in educational systems ranging from community colleges to elite engineering schools, which will in turn create a new workforce.

Keeping track of detailed changes in the grid related workforce is an opportunity for the Bureau of Labor Statistics (BLS). Not all grid jobs are the same, and specific employment and wage data for grid-related occupations will better inform policy and training programs.

Finally, Congress should implement policies that encourage grid-related companies to partner with HBCUs, minority-serving institutions, and Veterans groups to create pathways for enhancing the diversity of the grid workforce. This could happen in a variety of ways, from spotlighting existing efforts and providing seed grants to private sector/education sector partnerships to broader tax and related incentive programs akin to those found in legislation like the Inflation Reduction Act.

References

1. Abel, Amy, Paul W. Parfomak, and Dana A. Shea, "Electric Utility Infrastructure Vulnerabilities: Transformers, Towers, and Terrorism." Congressional Research Service, April 9th, 2004. https://sgp.fas.org/crs/homesec/R42795.pdf
2. Abramson, McFarlane et al. "An Atlas of Direct Air Capture: Opportunities for Negative Emissions in the United States" (Carbon Solutions LLC & Great Plains Institute, March 2023).
3. AISI, "New & Expanding Demand For Steel In Energy." No Date. American Iron and Steel Institute. https://www.steel.org/steel-markets/energy/
4. Anderson, Jared, and Sweeney, Darren. “Power of AI: Surging datacenter load has Dominion bracing for AI’s added demand.” S&P Global, Market Intelligence, 10/17/2023.
5. Arcolakis Costas and Walsh Conor, "Clean Growth." NBER Working Paper No. w31615, August 2023. https://ssrn.com/abstract=4553618
6. Bain, Dominique; Buster, Grant; Draxl, Caroline; Das, Paritosh; Ho, Jonathan; Ibanez, Eduardo et al., "The North American Renewable Integration Study: A U.S. Perspective—Executive Summary." National Renewable Energy Laboratory, 2021. https://www.nrel.gov/docs/fy21osti/79224-ES.pdf
7. Baylin-Stern Adam and Berghout, Niehls. “Is Carbon Capture Too Expensive? – Analysis.” IEA, February 17, 2021.
8. Behr, Peter. "How a transformer shortage threatens the grid." E&E News Energy Wire, October 20th, 2022 https://www.eenews.net/articles/how-a-transformer-shortage-threatens-the-grid/
9. Berry, Alison. “Getting Right-of-way Right: Landowner Compensation for Electric Power Transmission Right-of-Way.” Lincoln Institute of Land Policy, 2013. https://www.lincolninst.edu/sites/default/files/pubfiles/2335_1675_Berry_WP13AB1.pdf
10. Bivens, Josh. "Updated employment multipliers for the U.S. economy." Economic Policy Institute, January 23, 2019. https://www.epi.org/publication/updated-employment-multipliers-for-the-u-s-economy/
11. Bleizeffer, Dustin. “Oil and Gas Leaders Say Electric Rate Hike Would Shrink Wyoming Production.” WyoFile, November 3, 2023.
12. Brinkman, Gregory, Dominique Bain, Grant Buster, Caroline Draxl, Paritosh Das, Jonathan Ho, Eduardo Ibanez et al., "The North American Renewable Integration Study: A U.S. Perspective—Executive Summary." National Renewable Energy Laboratory, 2021. https://www.nrel.gov/docs/fy21osti/79224-ES.pdf
13. Brown Patrick and Audun Butterud. “The Value of Interregional Coordination and Transmission in Decarbonizing the U.S Electricity System.” Joule 5, January 2021.
14. Butterworth Paul. “Carbon Capture Economics: Why $200 /TCO2 Is the Crucial Figure.” Sustainability.crugroup.com, March 20, 2023. https://sustainability.crugroup.com/insights-and-analysis/carbon-capture-economics-why-200-tco2-is-the-crucial-figure/
15. Data Center Frontier “The power problem: Transmission Issues Slow Data Center Growth” (2023).. Available at:

https://www.datacenterfrontier.com/energy/article/33005221/the-power-problem (Accessed: December 14, 2023).

16. Department of Energy, “National Transmission Needs Study,” October 2023.
17. DOE, "U.S Energy Requirements for Aluminum Production," February 2007. https://www.energy.gov/eere/amo/articles/us-energy-requirements-aluminum-production
18. DOE, “Biden-Harris administration announces $3.7 billion to kickstart America’s carbon dioxide removal industry,” December 13, 2022. https://www.energy.gov/articles/biden-harris-administration-announces-37-billion-kick-start-americas-carbon-dioxide
19. Doying, Richard; Goggin, Michael; Sherman, Abby. 2023. "Transmission Congestion Costs Rise Again in US RTOs." Grid Strategies. https://gridstrategiesllc.com/wp-content/uploads/2023/07/GS_Transmission-Congestion-Costs-in-the-U.S.-RTOs1.pdf
20. Energy Information Administration, "U.S Primary Aluminum Production Remains Low Despite Slow Increase in Prices," September 2017. https://www.eia.gov/todayinenergy/detail.php?id=32872
21. Energy Use in the Steel Industry, World Steel Making Association, April 2021.
22. Figueroa Acevedo et al, "Design and Valuation of High-Capacity HVDC Macrogrid Transmission for the Continental US," IEEE Transactions on Power Systems, July 2021.
23. Foster D., Nabahe S., and Sun Hon Ng B., "Energy and Manufacturing in the United States," MIT Center for Energy and Environmental Policy Research, 2020.
24. Foster David, Sade Nahbahe, and Benny Siu Hon Ng, "Energy Workforce Development in the 21st Century." MIT Center for Energy and Environmental Policy Research, September 2020. https://ceepr.mit.edu/wp-content/uploads/2021/09/The-Roosevelt-Project-WP-7.pdf
25. Furszyfer Del Rio, Dylan D.; Sovacool, Benjamin K.; Griffiths, Steve; Bazilian, Morgan; Kim, Jinsoo; Foley, Aoife M.; Rooney, David, "Decarbonizing the pulp and paper industry: A critical and systematic review of sociotechnical developments and policy options." Renewable and Sustainable Energy Reviews, Volume 167, 2022. https://doi.org/10.1016/j.rser.2022.112706
26. Gazmararian, Alexander, and Tingley, Dustin. "Uncertain Futures: How to Unlock the Climate Impasse." Cambridge University Press, 2023. https://www.uncertainfuturesbook.com
27. Gerstle Brandon, “Giving Landowners the Power: A Democratic Approach for Assembling Transmission Corridors.” Journal of Environmental Law & Litigation: Vol. 29 No. 3, 2014. https://scholarsbank.uoregon.edu/xmlui/bitstream/handle/1794/18644/Gerstle.pdf?sequence=1&isAllowed=y
28. Goggin Michael and Gramlich Rob, "Investment Tax Credit for Regionally Significant Electricity Transmission Lines." American Council on Renewable Energy, May 2021. https://acore.org/wp-content/uploads/2021/05/Investment-Tax-Credit-for-Regionally-Significant-Electricity-Transmission-Lines-ACORE.pdf
29. Goggin Michael, Gramlich Rob, Skelly Michael, "Transmission Projects Ready to Go: Plugging Into America's Untapped Renewable Resources." Americans for a Clean

Energy Grid, April 2021.
https://cleanenergygrid.org/wp-content/uploads/2019/04/Transmission-Projects-Ready-to-Go-Final.pdf
30. Handy Ryan Maye, "Another Sign of Permian Boom: Record Electricity Demand." Houston Chronicle, April 3, 2018.
31. Hedden Adrian, “Permian Basin Electrical Grid Continues to Grow amid Oil and Gas Boom.” Carlsbad Current-Argus, December 13, 2019.
32. Hersh, Adam, and Scott, Robert, "Aluminum Producing and Consuming Industries have Thrived under U.S Section 232 Import Measures." Economic Policy Institute, May 2021. https://www.epi.org/publication/aluminum-producing-and-consuming-industries-have-thrived-under-u-s-section-232-import-measures/
33. Hoenig, Daniel. 2023. "Potential CBAM Impacts on U.S. Industry," Climate Leadership Council, https://clcouncil.org/blog/potential-cbam-impacts-on-u-s-industry/
34. Hong Yu-hung and Barrie Needham. “Analyzing Land Readjustment : Economics Law and Collective Action.” Cambridge Mass: Lincoln Institute of Land Policy, 2007. https://www.lincolninst.edu/sites/default/files/pubfiles/analyzing-land-readjustment-full.pdf
35. Hong Yu-Hung and Needham Barry, “Analyzing Land Readjustment,” 2007.
36. IEA, "The world is entering a new age of clean technology manufacturing and countries’ industrial strategies will be key to success," 2022. https://www.iea.org/news/the-world-is-entering-a-new-age-of-clean-technology-manufacturing-and-countries-industrial-strategies-will-be-key-to-success
37. IRS, "Prevailing wage and apprenticeship requirements." Internal Revenue Service, September 1, 2023. https://www.irs.gov/credits-deductions/prevailing-wage-and-apprenticeship-requirements
38. Jinglin and Frayer, “Estimating Macroeconomic Benefits of Transmission Investment with the REMI PI+ Model,” London Economics International, May 2, 2018.
39. Jones W, Bower G, O’Rear E, King B, Pastorek N, “Direct Air Capture Workforce Development: Opportunities by Occupation.” Rhodium Group, October 2023. https://rhg.com/research/direct-air-capture-workforce-development/
40. Kramer, Klaas Jan, Masanet, Eric, and Worrell, Ernst. "Energy Efficiency Opportunities In the US Pulp and Paper Industry.” Lawrence Berkeley National Laboratory, 2009. https://www.osti.gov/servlets/purl/970818.
41. Lawson, Ashley. "Electricity Transmission Provisions in the Inflation Reduction Act of 2022." Congressional Research Service, August 23, 2022. https://crsreports.congress.gov/product/pdf/IN/IN11981
42. Lew; Bakke, Debra Jordan; Bloom, Aaron; Brown, Patrick; Caspary, Jay; Clack, Christopher; Miller, Nicholas et al. "Transmission planning for 100% clean electricity: Enabling clean affordable and reliable electricity." IEEE Power and Energy Magazine 19, no. 6 (2021): 56-66.
43. Lucas, Davis W.; Hausman, Catherine; Rose, Nancy L. "Transmission Impossible? Prospects for Decarbonizing the US Grid." Journal of Economic Perspectives 37 (4), 2023.

44. Macmillan, Madeline; Wilson, Kyle; Baik, Sunhee; Carvallo, Juan Pablo; Dubey, Anamika; Holland, Christine A. May 2023. “Shedding light on the economic costs of long-duration power outages.” Lawrence Berkeley National Laboratory.
45. Magnum Economics, March 2022. "The Impact of Data Centers on the State and Local Economies of Virginia." Northern Virginia Technology Council. https://www.nvtc.org/topics/data-center-and-cloud/report/
46. Mao, Shuai; Chengzhi, Wang; Shiwen, Yu; Hao, Gen; Jufang, Yu; Hui, Hou 2018. “Review on Economic Loss Assessment of Power Outages.” WTISG 2018.
47. Matthew, Cotton; Devine-Wright, Patrick. “Discourses of Energy Infrastructure Development: A Q-Method Study of Electricity Transmission Line Siting in the UK.” Environment and Planning A: Economy and Space, 2011. https://doi.org/10.1068/a43401
48. MISO, October 2023. "MTEP24 Expedited Project Review." https://cdn.misoenergy.org/20231011%20PAC%20Item%2004a%20Expedited%20Project%20Reviews630438.pdf
49. Moreira, Susana. March 2023. "Cost-competitive low-carbon aluminum is key to the energy transition." World Bank Blog.
50. National Grid. "A second career for army veteran." November 11th, 2020. https://www.nationalgrid.com/stories/community-spirit-stories/second-career-army-veteran
51. NextGen Highways. "Introduction to Buried High-Voltage Direct Current Transmission for Departments of Transportation." November 2022. https://nextgenhighways.org/wp-content/uploads/2023/01/NGH_Introduction-Buried-HVDC-Transmission-DOTs.pdf
52. NREL. "Economic Development from New Generation and Transmission in Wyoming and Colorado." National Renewable Energy Laboratory, March 2013. https://www.nrel.gov/docs/fy13osti/57635.pdf
53. NUCOR. "Nucor Announces Location for Second Utility Structures Production Facility." June 14, 2023. https://nucor.com/news-release/19931
54. Occupational Safety and Health Administration. "Standard 1910.269." United States Department of Labor - Occupational Safety and Health Administration, United States Department of Labor. https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.269_2
55. OHSA. "Avoiding Underground Utilities during Horizontal Directional Drilling Operations." Occupational Safety and Health Administration, March 13, 2018. https://www.osha.gov/sites/default/files/publications/shib031318.pdf
56. Olivo, Antonio, "Dominion Agrees to Bury Power Lines in Prince William Ending Legal Standoff." Washington Post, March 23, 2018. https://www.washingtonpost.com/local/virginia-politics/dominion-agrees-to-bury-power-lines-in-prince-william-ending-legal-standoff/2018/03/23/4d1e73ee-2e97-11e8-8688-e053ba58f1e4_story.html
57. Our World in Data, “Electricity as a share of primary energy," Available at: https://ourworldindata.org/grapher/electricity-as-a-share-of-primary-energy
58. Paul. “Carbon Capture Economics: Why $200/TCO2 Is the Crucial Figure.” Sustainability.crugroup.com, March 20, 2023.

59. PR Newswire, October 30, 2023. "Biden-Harris Administration selects National Grid's Twin States Clean Energy Link as part of $1.3 billion commitment to build out nation's transmission infrastructure." Morningstar.com
60. PwC, September 2023. "Economic Environmental and Social Impacts of Data Centers in the United States." Prepared for the Data Center Coalition. https://static1.squarespace.com/static/63a4849eab1c756a1d3e97b1/t/65048f92e74c956b68a419e4/1694797719030/Data+Center+Impact+Study+Executive+Summary.pdf
61. Renewable Energy World. "World's longest underground transmission line will transport wind energy to Germany's grid." September 8, 2021. https://www.renewableenergyworld.com/news/worlds-longest-underground-transmission-line-will-transport-wind-energy-to-germanys-grid/#gref
62. Rocky Mountain Institute, "Aluminum GHG Emissions Reporting Guide," 12/23.
63. Ryan Nicholas. 2021. "The Competitive Effects of Transmission Infrastructure in the Indian Electricity Market." American Economic Journal: Microeconomics 13 (2): 202-42.
64. Sanstad, Alan H., et al. "Electric Utility Valuations of Investments to Reduce the Risks of Long-Duration Widespread Power Interruptions Part I: Background." Sustainable and Resilient Infrastructure, vol. 8, no. sup1, 2023, pp. 311–22.
65. Seel, Joachim, Millstein, Dev, Mills, Andrew, Bolinger, Mark, Wiser, Ryan. "Plentiful Electricity Turns Wholesale Prices Negative." 2021. Advances in Applied Energy 4: 100073.
66. Semerad, T. (2022) 'big day' for Utah City as Facebook's parent firm plans to nearly double the size of its Data Center, The Salt Lake Tribune. Available at: https://www.sltrib.com/news/2022/09/30/facebooks-parent-firm-nearly/ (Accessed: December 14, 2023).
67. Solis, Jennifer. "New NV Transmission Will Slash Energy Costs, Says White House." Nevada Current, 10/2023
68. Statista. "Electricity transmission and distribution market revenue worldwide in 2021, with forecasts for 2025 and 2030, by product type (in billion U.S. dollars)." Chart. June 30, 2022. The Brainy Insights. https://www-statista-com.ezp-prod1.hul.harvard.edu/statistics/1350494/forecast-electricity-transmission-and-distribution-global-market-revenue-by-product-type/
69. Storrow, Benjamin. "Like Manchin, Obama tried to fast-track transmission. Nope." E&E News, CLIMATEWIRE, October 3rd, 2022, Accessed November 2023. https://www.eenews.net/articles/like-manchin-obama-tried-to-fast-track-transmission-nope/
70. TC Energy. "Drones, Unmanned Vehicles and (No) Fires, Oh My!" February 3rd, 2022. https://www.tcenergy.com/stories/2022/2022-02-02-drones-unmanned-vehicles-and-no-fires-oh-my/
71. Terry-Cobo, Sarah. "Weather Underground: Costs Deter Utilities in Oklahoma from Burying Electrical Lines." Journal Record, Jun 21, 2013. http://search.proquest.com.ezp-prod1.hul.harvard.edu/newspapers/weather-underground-costs-deter-utilities/docview/1371951828/se-2.
72. The White House. "Justice40 A Whole-Of-Government Initiative." Accessed November 2023. https://www.whitehouse.gov/environmentaljustice/justice40/

73. U.S Chamber of Commerce, June 2017. "Data Centers – Jobs and Opportunities in Communities Nationwide"
74. U.S Department of Commerce Bureau of Industry and Security Office of Technology Evaluation. "The Effect of Imports of Transformers and Transformer Components on the National Security." October 15th, 2020. https://www.bis.doc.gov/index.php/documents/section-232-investigations/2790-redacted-goes-report-20210723-ab-redacted/file
75. U.S Department of Energy, April 2022. "U.S Energy Requirements for Aluminum Production." https://www.energy.gov/eere/amo/articles/us-energy-requirements-aluminum-production DOE
76. U.S. Department of Energy, "Biden-Harris Administration Announces $3.5 Billion for Largest Ever Investment in America's Electric Grid, Deploying More Clean Energy, Lowering Costs, and Creating Union Jobs." October 18th, 2023. https://www.energy.gov/articles/biden-harris-administration-announces-35-billion-largest-ever-investment-americas-electric
77. Vann, Adam. "The Legal Framework of the Federal Power Act." Congressional Research Service, January 22nd, 2020. https://crsreports.congress.gov/product/pdf/IF/IF11411
78. Walton, Robert. "Utilities sound alarm over distribution transformer shortage as procurement times surpass 1 year and costs triple." Utility Dive. December 19th, 2022 https://www.utilitydive.com/news/distribution-transformer-shortage-appa-casten/639059/?utm_source=pocket_reader
79. Wang, Eva Ruoyun; Yang, Jarome Leslie; Duan, Jinglin; Lan, Tianying. "How does electric transmission benefit you? Identifying and measuring the life-cycle benefits of infrastructure investment," London Economics Institute, 2018. https://wiresgroup.com/wp-content/uploads/2020/06/2018-01-08-London-Economics-Intl-How-Does-Electric-Transmission-Benefit-You.pdf
80. Watson, Christopher, "Report to Congress on U.S Aluminum Industry." Congressional Research Service, October 26, 2022. https://news.usni.org/2022/11/03/report-to-congress-on-u-s-aluminum-industry
81. Wayner, Claire; Siegner, Katie; Einberger, Mathias; Mendell, Russell; Toth, Sarah. "Going the Distance on Interconnection Queue Reform." Rocky Mountain Institute, August 2023. https://rmi.org/going-the-distance-on-interconnection-queue-reform/
82. Wilson, John, and Zimmerman, Zach. "The Era of Flat Power Demand is Over." Clean Grid Strategies, 12/2023. https://gridstrategiesllc.com/wp-content/uploads/2023/12/National-Load-Growth-Report-2023.pdf
83. White Kristopher, "Mississippi's Largest Economic Project Holds Hiring Event," WJTV News, October 2023. https://www.wjtv.com/news/state/mississippis-largest-economic-project-holds-hiring-event/
84. Willson, Miranda. "How a $6B transmission project made it in New York." E&E News ENERGYWIRE, March 1st, 2023. https://www.eenews.net/articles/how-a-6b-transmission-project-made-it-in-new-york/

85. Wilson, Adam, "Data Center Companies Continue Renewable Buying Spree." S&P Global Market Intelligence, March 2023. https://www.spglobal.com/marketintelligence/en/news-insights/research/datacenter-companies-continue-renewable-buying-spree-surpassing-40-gw-in-us
86. Winn, Rosalie. “Landowner Compensation in Transmission Siting for Renewable Energy Facilities.” The Electricity Journal 27, June 2014, A. https://doi.org/10.1016/j.tej.2014.05.010.
87. Yoder, Kate and Grist. "The American Climate Corps Wants You." Scientific American, September 28th, 2023. https://www.scientificamerican.com/article/the-american-climate-corps-wants-you/
88. Zaifman, Hagai; Schaff, John T.; Mitchell, Aaron S. "Inflation Reduction Act: Overview of Energy-Related Tax Provisions – An Energy Transition 'Game Changer'." Sidley Austin, August 18th, 2022. https://www.sidley.com/en/insights/newsupdates/2022/08/inflation-reduction-act-an-energy-transition-game-changer
89. Zhang, Allan. "Explainer: How Does the Inflation Reduction Act Relieve Doubts About Clean Energy Tax Credits?" Clean Energy Finance Forum, Yale University Center for Business and the Environment, January 12th, 2023. https://www.cleanenergyfinanceforum.com/2023/01/12/explainer-how-does-the-inflation-reduction-act-relieve-doubts-about-clean-energy-tax