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Decarbonizing the US power system presents diverse challenges and opportunities in the changing employment landscape

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Article

Keywords:

DOI: https://doi.org/

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Additional Declarations: There is **NO** Competing Interest.

Decarbonizing the US power system presents diverse challenges and opportunities in the changing employment landscape

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Abstract

The transition towards a low-carbon power system presents immense challenges and opportunities to the workforce. Studies of the energy transition's regional and distributional employment impacts are mainly qualitative or disconnected from prevailing energy modeling scenarios. Here, we couple a power sector optimization model, an employment impact model, and demographic databases to further understand the state-level job characteristics and societal implications in the US. Major fossil fuel producers risk job losses even without new emission reduction policies, requiring the reskilling of up to 30% of the current workforce. The results highlight the need for investments in human capital and a supply chain restructuring. Blue-collar workers are crucial to delivering the transition. Expanding renewable energy could improve job opportunities for women in states dependent on fossil fuels, but not enough to disrupt the national status quo. This work sets a new quantitative perspective to inform proactive local Just Transition policymaking.

Main text

Starting as a labor union movement[1], the concept of Just Transition rose to prominence in the climate change policy discourse since the 2015 Paris Agreement[2]. This has broadened the aim of the low carbon transition from boosting more "well paying, local jobs" to highlighting the importance of inclusivity and social dialogues[3,4]. The International Labour Organisation (ILO), an early supporter of the concept, argued that the transition would present both opportunities and challenges in the workforce[5]. While the fossil fuels workforce is expected to decline, a well below 2°C world would lead to more opportunities in the manufacturing and construction of renewable technologies[6–8]. However, the local impacts of such transition are highly dependent on political, industrial, and technological factors of a particular region[9].

The United States employs more people and has the highest sales revenue in the green economy of any OECD country[10]. As the country with the largest footprint in global fossil fuels assets, the US also has a high stake in the transition from future financial risks[11]. Expanding the low-carbon economy is crucial for the US to remain competitive internationally and to boost the economy during downturns, as evidenced by the clean energy provision of the 2022 Inflation Reduction Act[12]. The societal impacts of environmental policies, however, are not simple. For example, the 1990 Clean Air Act led to $5.9 billion in foregone earnings due to reduced employment[13]. This time around, policymakers need to manage the transition more proactively to minimize "collateral damage" in the workforce. States need to plan accordingly for the unemployment, retraining, and relocation costs of the declining fossil fuels workforce to avoid a persistent fall in living standards[14].

Utilizing the low carbon transition for job growth in the US[14,15] and around the world[6–8] is not a new concept, but it is important yet difficult to distribute these opportunities more equitably[16]. Given the impactful role of subnational climate actors[17] and the cost-effective potential for state-driven strategies[18], geographically granular analyses are needed to produce relevant insights for those actions. The Net Zero America report by Princeton University highlighted the growth in solar, wind, and grid jobs overall[19]. Retraining coal workers for solar jobs is both feasible and financially manageable[20]. Solar also exhibits more resource availability to provide local jobs in coal mining regions[21]. Expanding wind energy in states with large existing capacities could create significant economic impacts both locally and through spill-over impacts in other states[22]. These employment impacts are not distributed equally across states[19], and neither are the relevant local social policies. Uncertainties around the future energy system, especially in natural gas prices[23] and

geopolitical tensions[24], further complicate the problem. Existing studies on the employment impacts often show a disconnect from the wide range of potential energy system future scenarios. Further evaluations of the wider social implications are often qualitative and even more distant from these scenarios. A better systematic understanding of state-level challenges and opportunities in the uncertain future would help improve institutional readiness to leverage the transition.

We systematically evaluate the transition of the US power sector workforce by coupling the Regional Energy Deployment System (ReEDS) model[25], a state-level power sector optimization model, with a suite of Jobs and Economic Development Impact (JEDI) models[26] and demographic databases. The code developed for this analysis is publicly accessible via GitHub. Acknowledging the wide uncertainties in the future energy system[23], we estimate the required scale and pace of workforce transition under 48 individual scenarios based on three trajectories of decarbonization ambition and 16 energy system assumptions (Fig. 1). We contextualize their feasibility by comparing results with historical technology-led workforce mobilization events. The specific scales of needs are highlighted in states, economic sectors, and skill levels. We further discuss how the changing employment landscape may impact the demographics of local communities and lead to changing social dynamics. From these results, we derive the policy implications relevant to the Just Transition at local and federal levels and suggest future research directions.

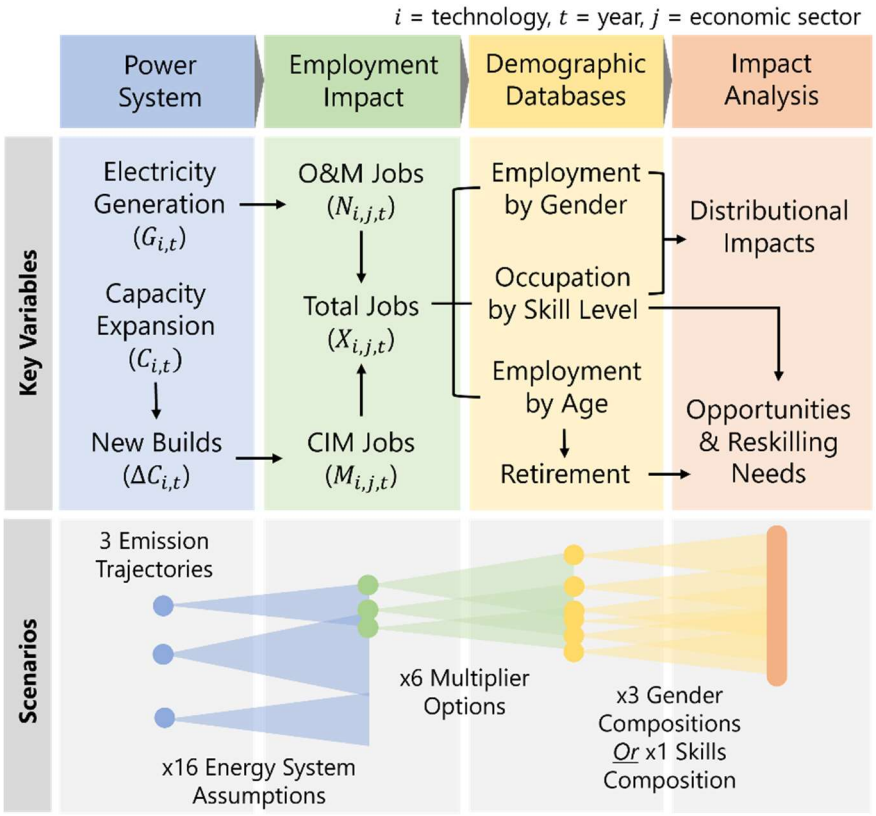


Fig. 1 | The schematics of the model and analysis workflow to evaluate the distributional employment impacts of power system transition scenarios. The key variables used to pass data between models are given in parentheses: installed capacity (C), annual electricity generation (G), and the number of jobs (M, N, X). This framework accounted for 3 emission trajectories, 16 energy system assumptions, 6 multiplier options, and 3 gender compositions.

Scale and pace of the workforce transition

We find that more ambitious emission reductions in the power sector will create substantial employment growth. Without an emission reduction target, the No New Policy (NNP) scenario with mid-case assumptions would require a workforce expansion by 80% (74% to 121% across all energy systems assumptions, min/max spread) of the current workforce nationally. The increasing cost-effectiveness of renewable technologies[27] contributes to their capacity expansion even without enforcing climate policies, hence reducing emissions by 95% by 2050 would give only a slight increase of 1.13±0.08 times to 91% (79% to 165%). Moving this emission target 15 years earlier and aiming to reach net zero by mid-century (95% by 2035), however, would require an additional expansion of 1.79±0.13 times to 157% (125% to 215%). This near doubling of opportunities from the NNP scenario is largely due to the fast expansion of Direct Air Capture (DAC). The energy system assumption of high

electrification results in much larger job growths under all emission reduction trajectories (Extended Data Fig. 1) Reducing residual emissions would however pose unprecedented challenges[28] in economic and human capital investments.

Given the significant scale and pace required for workforce mobilization, the modeled state-level employment growth is on par with historical energy and technology transitions. Fig. 2 shows the state-level employment growth and percentage of the national and state workforce[29] to be mobilized, compared to the 1850 California Gold Rush[30], the 1960 Silicon Valley Tech Boom[31], and the 2007 North Dakota Oil Boom[32]. The pace of workforce mobilization required to reach net zero by mid-century (95% by 2035) is mostly comparable with manual historical transitions. Although Wyoming's power sector workforce takes up nearly 10% of the state's population, the composition is modeled to decline across all scenarios. North Dakota stands out as it requires a faster transition to fulfill DAC expansion compared to the high-tech Silicon Valley tech boom. The low-carbon transition would mobilize the national population one order of magnitude less than the Gold Rush. Similarly, the high electrification system assumption would require accelerated growth in more states, but all at manageable scales and paces (Extended Data Fig. 2).

The power systems model we use (and many other energy systems models[33]) meets this emission reduction target through the large-scale deployment of Carbon Dioxide Removal (CDR) technologies in the final decade. Relying on such drastic movements in the workforce could be risky without proactive social planning. Alternatively, energy modelers could incorporate more realistic workforce mobilization constraints in future modeling practices to improve feasibility. Nonetheless, the additional emission reduction of DAC in North Dakota contributes to 3.6% of the total, which could realistically be shared between other states or prevented through earlier intermediary targets. The limited economic information on DAC at present means there can be a limited understanding of its employment impacts, which may be overestimated with early-stage cost data[34]. Further work to scale up the technology and integrate it into the existing supply chains could help provide more realistic employment estimations.

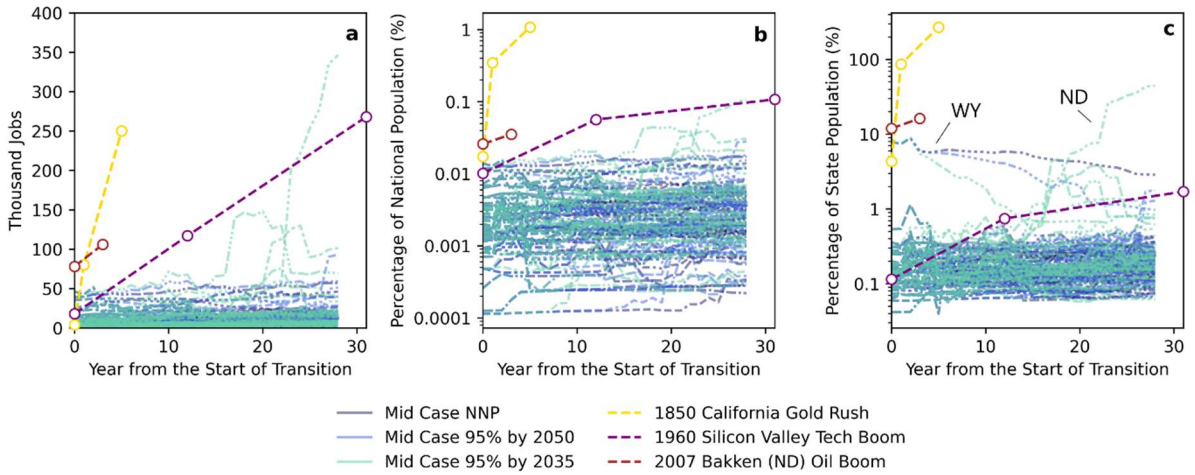


Fig. 2 | Modeled state-level employment growth under mid-case energy system assumptions compared to historical workforce mobilization events in energy and technology in the US. The modeled results are shown over the planning horizon of 2022-2050 for power system scenarios with No New Policy (NNP) and CO_2 emissions targets of a 95% reduction by 2050 and 2035. Panel (**a**) shows the absolute employment growth, (**b**) shows the percentage of the total US national population mobilized as workforce at the start of the transition, and (**c**) shows the percentage of the state population mobilized as workforce at the start of the transition

Despite the overall growth in jobs, rapid decarbonization would introduce a winner-loser dichotomy geographically. Fig. 3 shows the net employment impact of decarbonization scenarios compared to NNP. The disparity across states is intensified with more stringent emission reduction targets. Generally, more opportunities are generated along the coasts and the Midwest under the more stringent target. The Great Plains region along with Texas and California see sizable growth in DAC jobs, accompanied by the steady expansion of onshore wind and utility-scale PV. North Dakota, for example, sees up to an 80-fold increase of the state's electricity workforce in the 95% by 2035 scenario (Extended Data Fig. 3) compared to 2-fold in NNP (Supplementary Section 7). Florida sees major growth of utility-scale PV jobs, which supplies most of the state's future demand increases. Understandably, states with heavy fossil-fuel dependency experience less net employment growth in decarbonized futures. Wyoming could experience job losses from the declining coal supply chain in all scenarios. With tightening emission constraints, Pennsylvania shows contracted employment growth due to the combination of reduced generation and moving away from its stranded natural gas assets. Other states with lower job growth under decarbonization scenarios show low levels of consistency between scenarios, meaning the employment impact could be positive relative to NNP, depending on the energy system assumptions. For example, decarbonization reduces employment growth in Idaho under most energy system

futures. In the case of an electrified energy system, the 95% by 2035 scenario could introduce nearly 50% additional jobs. Alternatively, despite benefiting from decarbonization in the mid-case, Nebraska could experience negative employment impacts under various cases including electrification and low renewable costs. In absolute terms, however, the employment impacts are overwhelmingly positive except for Wyoming and Rhode Island (Extended Data Fig. 4). Despite its current misalignment with decarbonization, Pennsylvania's power sector workforce would expect some new entrants, as its natural retirement outweighs the jobs lost.

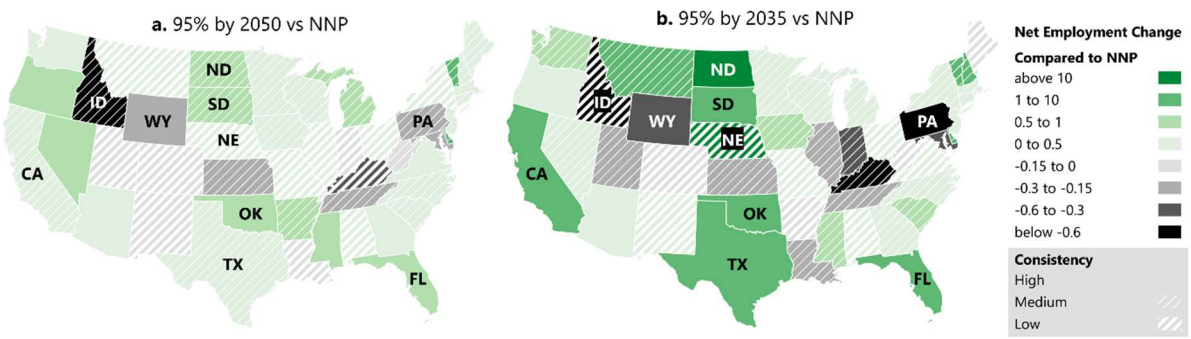


Fig. 3 | Modeled net employment change under the mid-case emission reduction scenarios compared to No New Policy in the 2040s. Employment change describes the normalized difference of the workforce in the decade before mid-century compared to today while accounting for natural retirement. Net employment change (Equation 5) indicates the employment change of an emission reduction trajectory compared to that of the No New Policy (NNP) trajectory. A net employment change of 0.5 suggests that the emission reduction scenario introduces more job opportunities in 50% of the current state electricity workforce. A value of -0.3 suggests less job creation in 30% of the current workforce. The maps show (**a**) the 95% reduction by 2050 and (**b**) the 95% reduction by 2035 then net zero in 2050. States colored green see greater employment under decarbonization than NNP while gray states see less. Hatching denotes the level of consistency across energy system assumptions within each group. High consistency means all scenarios have the same sign of change as the mid-case (i.e., always more or always less than NNP). Medium and low consistencies represent more than and less than 80% of the 16 energy system assumptions sharing the same sign as the mid-case, respectively.

Future sectoral and skill-level training needs

A granular understanding of the sectoral characteristics of the future workforce will help to capitalize on future opportunities and proactively manage potential risks. In line with the literature[6,7], we find that construction and electrical equipment exhibit the highest

employment growth nationally (2.6 and 1.9 times respectively) even without new policies (Extended Data Fig. 5). Some states lead in growth due to the expansion of onshore wind (Nebraska and Vermont), solar (Delaware and South Carolina), and natural gas (Idaho and South Carolina). Other states fall behind due to the saturation of offshore wind (New Jersey, Massachusetts, and Rhode Island), which leads to the losses of professional services jobs in engineering, management, and legal services in the construction stage. Additionally, the contraction of coal in West Virginia and Wyoming would lead to losses in mining jobs. Under costly future renewable energy assumptions, employment in states with existing renewable infrastructure (Vermont) would be negatively impacted. In the case of high natural gas prices, employment in states with existing natural gas assets (Idaho and Kentucky) would be reduced.

Emission reduction targets would intensify the disparities across sectors. In the 95% by 2050 scenario (Extended Data Fig. 6), Delaware leads employment growth with a massive expansion of solar, creating jobs in utilities and electrical equipment. These sectors are dominated by lower skill levels. States with lower employment growth are further impacted by the contraction of coal and natural gas. Net zero by mid-century would lead to slightly more losses in mining and fabricated metals up to 30% of the current sectoral workforce (Fig. 4). In Rhode Island and Wyoming, the growth in finance and real estate may not be able to compensate for the bulk of job losses. Wyoming could benefit from nearby growth in North Dakota by migrating some of the displaced mining and utility workforces. For Rhode Island, the displaced professional services workers may not be able to fulfill roles in New England and Mid-Atlantic, so they may be required to retrain or migrate.

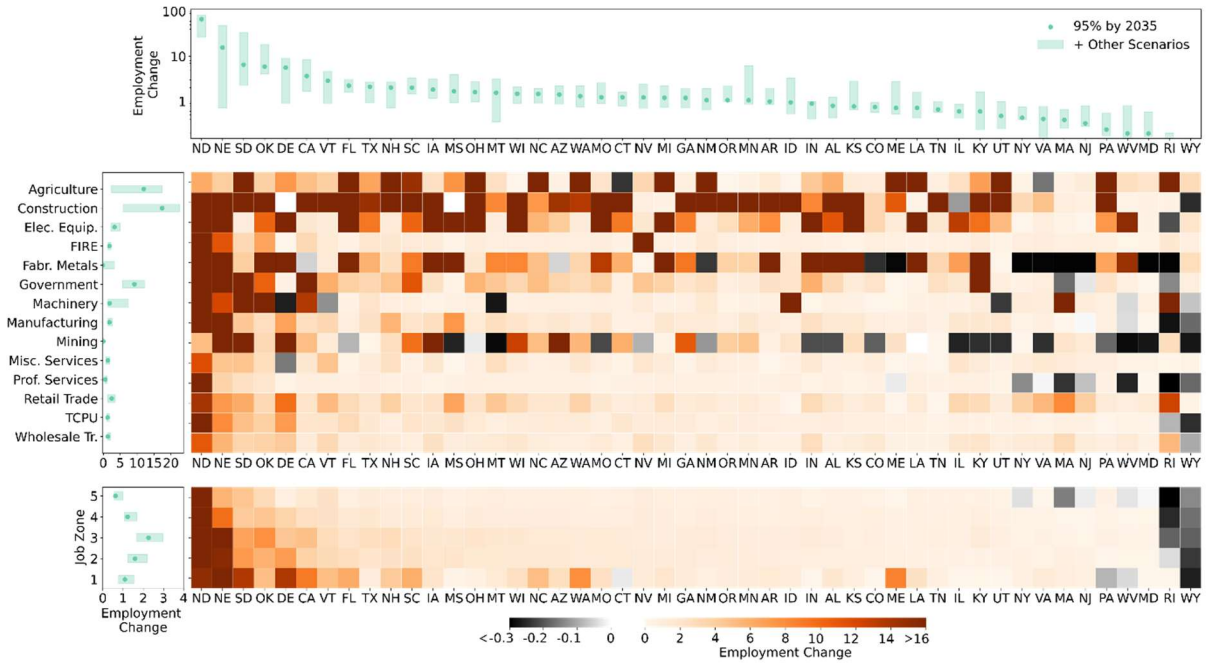


Fig. 4 | Distribution of employment change in the 95% by 2035 scenario between the 2020s and 2040s. The bar graphs show the impact aggregated by state (top), economic sector (middle left), and job zone (bottom left) across all power sector transition scenarios. In the top panel, the scatters represent the mid-case energy system assumption, and the transparent bars represent the full suite of scenarios. The y-axis is logarithmically scaled. States are sorted in descending order of their state-level employment growth. Heatmaps represent the disaggregated impact in the mid-case scenario. They show the magnitudes of employment growth (orange color scheme) and reskilling needs (gray color scheme) in the last decade of the planning horizon (2041–2050) compared to each subset of the workforce at the start of the planning horizon (2022–2030). These state-level subsets are disaggregated by the economic sector (middle) and job zone (bottom). TCPU stands for Transportation, Communications, and Public Utilities. FIRE stands for Finance, Insurance, and Real Estate. Miscellaneous services include sectors such as education, healthcare, and the arts.

Blue-collar workers play an essential role in the power sector workforce, especially so with more stringent emission reduction targets. Fig. 5 shows the employment changes across Job Zones[35] 1 (little or no preparation, e.g., conveyor belt operator), 3 (medium preparation, e.g., geothermal production manager), and 5 (extensive preparation, e.g., chief sustainability officer). Jobs with minimal preparation requirements will be in high demand in most states. Given the large composition of lower-skilled mining workers in Wyoming, the lower-skilled workforce there is the most negatively affected. Lower skilled jobs in North Dakota and Nebraska, otherwise, are highly benefited from the scale of expansion in construction work brought by DAC and onshore wind. Jobs in middle-skill levels, including those with educations in high school (Job Zone 2), vocational school (Job Zone 3), and 4-year

bachelor's degrees (Job Zone 4), take up a majority of the workforce historically (Supplementary Section 6.3). Job needs in these areas are more evenly distributed and mostly positive across scenarios, although growth in Job Zone 4 is slightly smaller (Extended Data Fig. 7). Higher-skilled jobs would experience the slowest growth compared to others. Rhode Island and Massachusetts will be most affected by the declining need for high-skilled professional services jobs, due to the saturation of lower-cost offshore wind projects in the 2020s. Since these states have not yet exhausted the natural potential, recent progress in offshore wind cost reduction[36] could help leverage the existing local human capital and deliver further emission reduction. Although high-skilled jobs in West Virginia would experience losses in the mid-case, those jobs would experience employment gains under a future of low nuclear and CCS costs.

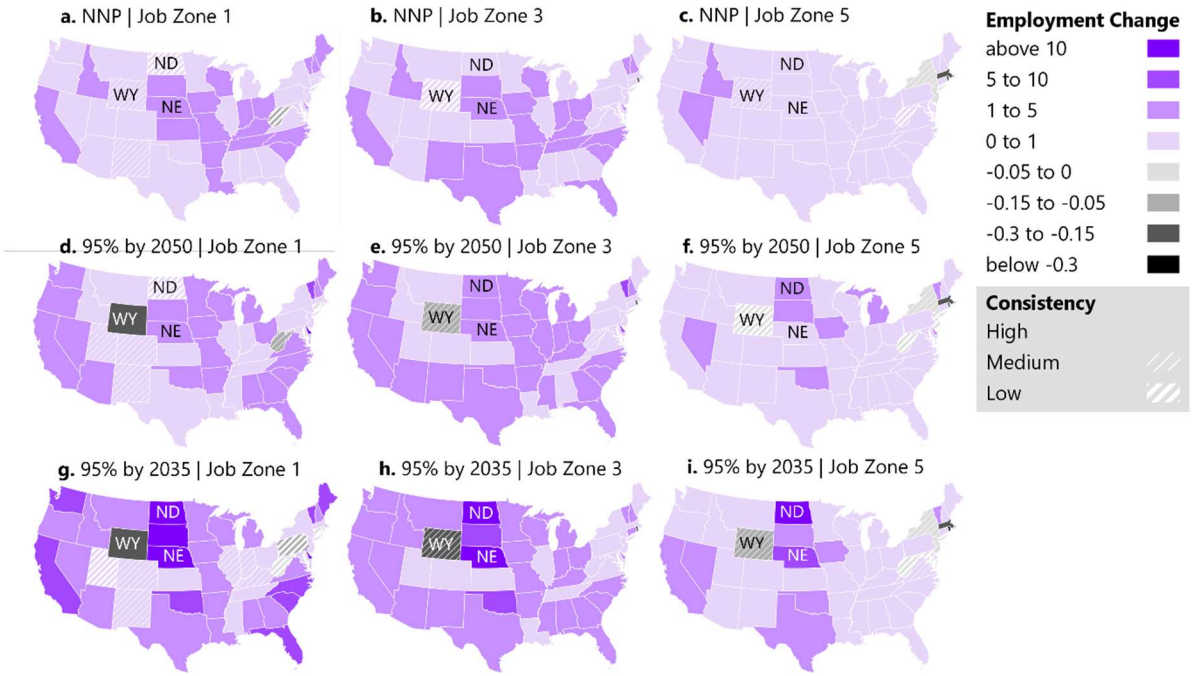


Fig. 5 | Modeled employment change in Job Zones 1, 3, and 5 of the 2040s compared to 2020s. Employment change refers to the job requirement of the future workforce in the state and Job Zone compared to the current workforce under the same category in the final decade of the planning horizon (excluding those in natural retirement) normalized to the size of the current workforce now. An employment change value of 0.5 indicates that 50% more opportunities in the Job Zone and state are needed. A value of -0.3 indicates that 30% of the current workforce in the Job Zone and state needs to be reskilled. The top panel (**a-c**) shows the No New Policy (NNP) emission trajectory, the middle panel (**d-f**) shows the 95% reduction by 2050 constraint, and the bottom panel (**g-i**) shows the 95% reduction by 2035 constraint. The purple color scheme represents the employment gains, and the gray color scheme represents reskilling needs. Hatching denotes the level of consistency across energy system assumptions within each group. High consistency means all scenarios have the same sign of change as the mid-case (i.e., always positive, or always negative). Medium and low consistencies represent more than and less than 80% of the 16 energy system assumptions sharing the same sign as the mid-case, respectively.

Social dynamics in the communities

Low gender and racial diversity persist across the US energy sector[37]. The renewable energy sector globally employs a greater share of women (32%) than the fossil fuels workforce (22%), but mostly in administrative roles[38]. The construction and manufacturing jobs created through the low-carbon transition are likely to be male-dominated[6]. The changing employment landscape would also lead to changes in the local communities. For example,

although the North Dakota oil boom brought considerable economic activities, these came with social service challenges and shifting cultures[39]. In a Just Energy Transition, the benefits and ills 'must be more equitably distributed[40] while accounting for the intersectionality of these social outcomes[41].

The three sectors that employ the lowest share of women are mining, construction, and agriculture[42] (Supplementary Fig. S15). Fig. 6 shows the modeled composition of women in each state's power sector workforce (Equation 2). The NNP and 95% by 2050 scenarios do not change the future gender composition substantially, as the structural changes required are not as disruptive. The 95% by 2035 scenario, on the other hand, may disproportionally bring more benefits to men in some states due to significant human capital needs in construction. These states are especially impacted by capacity expansion needs in the onshore wind (Montana) and DAC (South Dakota, Nebraska, Oklahoma, California, North Dakota, and Texas). South Carolina expands in solar and natural gas to meet increasing demand. Especially for states starting with fewer than average women employed in the power sector, the same transition pathways may present more positive opportunities to improve workplace gender diversity. Illinois and Pennsylvania benefit from the shift from natural gas to onshore wind. Indiana, Kentucky, and Wyoming benefit from the transition from coal to onshore wind. The transition from fossil fuels to renewable energy leads to jobs from mining to utilities, which employs more women historically. The improvements, however, do not raise women's employment opportunities much above the national status quo. The lower employment opportunities for women that we find in US decarbonization resemble similar analyses in China[43] and the EU[44], highlighting the need for policy interventions.

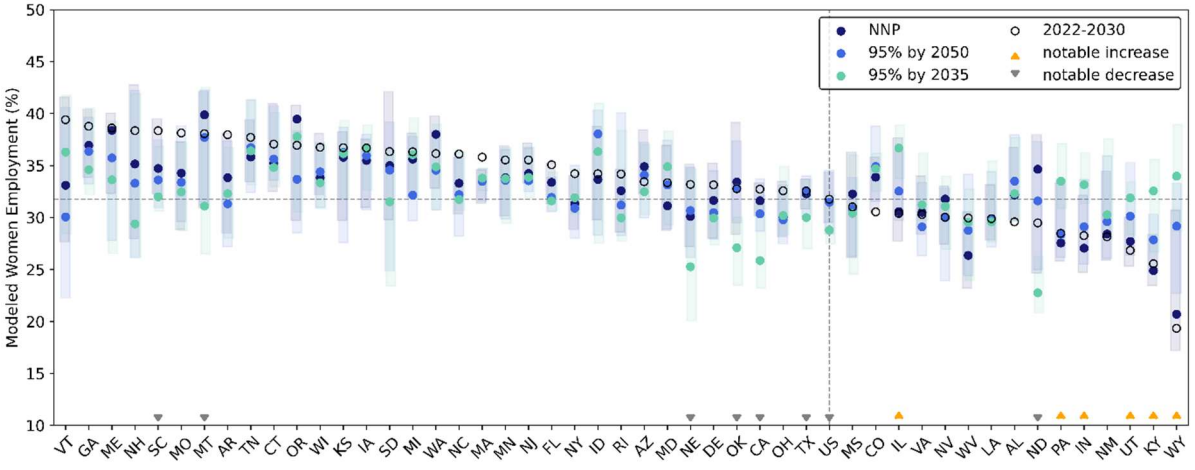


Fig. 6 | Modeled percentage of women in the power sector workforce. The bars represent the range of outcomes in the 2040s from the full suite of energy system assumptions. The filled circles represent the values from the mid-case scenarios. The empty circles represent the starting value (the 2020s) of No New Policy (NNP), by which the states are sorted in descending order. States are labeled with orange up- or gray down-arrows if the most ambitious outcome (mid-case 95% by 2035) lies above or below the range of all scenario variants in less ambitious cases, respectively.

People of color bear more health burdens through socioeconomic and environmental disadvantages[45]. Without intentionally designed infrastructure, marginalized communities will be even more vulnerable to climate and environmental degradation[46]. Supplementary Fig. S22 shows that in 2021, Asian Americans and Black or African Americans make up 2.1% and 6.3% of the construction sector while their national population compositions are 5.9% and 13.4%. Hispanic Americans (18.5% of the national population) benefit from the growth in constructions as they make up 32.6% of the sector. The electrical equipment sector, another growth sector in the transition, consists of 12.5% Hispanic Americans and 6.4% Black Americans, leaving these under-represented communities behind (Supplementary Fig. S22). Starting from the pipeline, Black students and especially Black women are significantly underrepresented in STEM subjects[47]. Without intentional policy planning to engage these underrepresented populations, existing social inequalities may further deteriorate. The current lack of workforce demographic data on indigenous people demonstrates that they would likely miss out on the bulk of the employment benefits through centralized low-carbon transitions. The Tribal Energy Development Organization (TEDO) created by the Red Lake Nation[48] sets an example for the much-needed indigenous ownership of energy initiatives.

Discussion of policy implications and paths forward

The labor demands for decarbonizing the US power systems will be substantial, especially reaching net zero by mid-century, but no more so than historical technology and energy-based workforce mobilization. The blue-collar workforce would need to expand faster than higher-skilled jobs. However, the pace at which automation and other productivity increases unfold is unknown, and likely to vary between sectors and skill levels, which may counter some of this job creation potential. While most states benefit from the low-carbon transition, some states with energy supply chains that do not align with this national transition may lose out through reduced employment growth. Policymakers in these states could deviate from least-cost electricity system transition pathways and invest in more low-carbon technologies that would introduce more social benefits. The states could also leverage support from the Inflation Reduction Act[12] to expand their manufacturing sectors and create disruptive changes in the supply chain of new and renewable technologies. Additional investments should be made to support existing programs aimed to reskill ex-coal workers and provide federal-level Trade Adjustment Assistance for jobs displaced through the low-carbon transition[49]. Learning from the decline of coal in the UK in the 1990s, intentional engagement with the affected industries, and developing attractive future scenarios with them in mind would be key to preventing social conflicts[50].

This study found that the low carbon transition could improve gender diversity for some currently fossil-fuel-dependent states. It may reduce gender diversity in other states because the infrastructure expansion requires (currently) male-dominated construction. The transition itself will not provide disruptive change away from the status quo, unless policymakers, private sector actors, and the education system intervene. Cross-national studies have found that the per capita emission is lower in countries where women have higher political status[51–53]. Leveraging this diversity of thought[54] in leadership could boost the movement. Especially for state workforces at risk of becoming more homogenous, fostering enabling environments for gender and racial diversity across the board would be crucial[55]. The US government's commitment to dedicate 40% of federal investments towards disadvantaged communities[56] is a good start. In the private sector, limited perception of gender roles and lack of flexibility in the workplace are key barriers for women to enter the energy sector and advance in their careers[38]. Educational practices can be adapted to improve the experience of Black students, including the introduction of culturally relevant pedagogy in the curriculum and the accommodation of students' psychological needs[57].

Future research on the distributive employment impact of the net zero transition could build on this work. The method demonstrated in this study and the open code provided here could enable others to replicate and expand the analyses especially for countries experiencing the brunt of the climate crisis. The development and maintenance of more granular demographic data would improve quantitative capabilities to evaluate these social implications. In energy modeling, work such as this could provide additional constraints on the realistic pace of workforce mobilization to help evaluate the necessary social policies to achieve decarbonization. While the input-output method used in this work was validated with ex-post analysis[58], further efforts in this area should continue. As this work only evaluated direct and indirect jobs from the power sector transitions, future work could adopt more dynamic models that capture the induced employment impact through state-level economic activities and cross-state trades. More detailed task- and skill-based occupation analyses on the workforce could highlight energy jobs more susceptible to automation[59] and identify viable pathways for reskilling. In a changing employment landscape, the continuation of this work will provide decision-makers the insights to proactively manage future challenges and take full advantage of new opportunities.

Methods

The analytical framework in this study couples three sets of models and datasets (Fig. 1) to convert US state-level energy system transition pathways to distributional employment impacts. The analysis begins with using a power sector model to provide new build capacities (MW) and the annual electricity generation (MWh) across different power technologies i. These values are used as inputs to an employment impact model, where Construction, Installation, and Manufacturing (CIM) jobs are attributed to the capacity, and Operation & Maintenance (O&M) jobs are attributed to the power generated across different industry sectors j. These jobs are then summarized and mapped onto existing demographic databases giving the labor composition across gender and skill level. This step estimates how these distributional factors change as a function of the future power systems' configuration. Analyses of new opportunities and employment displacements account for the natural retirement of the workforce and the mismatch between the current and the future power sector workforces in specific industries and skill levels. Additional assumptions can be found in the Supplementary Information.

Power system transition scenarios. The Regional Energy Development System (ReEDS) model is an open-source power sector capacity planning model developed and maintained by the National Renewable Energy Laboratory (NREL)[25]. The power sector transition scenarios analyzed here are the 2021 Standard Scenarios[60]. The outputs include installed capacity, annual electricity generation, and CO_2 emissions at the state level for the 48 continental states. They are reported in two-year steps from 2022 to 2050. The years in-between reported data points are linearly interpolated. These Standard Scenarios (Fig. 1 and Supplementary Section 1) include 16 energy system future assumptions based on a wide range of input assumptions, including future fuel prices, technology costs, and scale of electrification, to represent various energy futures[25]. The list of energy system assumptions used in this analysis includes Reduced Renewable Energy Resource, Production Tax Credit (PTC) and Investment Tax Credit Extension, Mid Case, Mid Case with Base Flexibility, Low Transmission, Low Renewable Energy Cost, Low Nuclear CCS Cost, Low Natural Gas Price, Low Everything, Low Demand Growth, High Transmission, High Renewable Energy Cost, High Natural Gas Price, High Demand Growth, Electrification, and Electrification with Enhanced Flexibility. Three emission reduction trajectories introduced by the Standard Scenarios include No New Policy (NNP), 95% power sector emission reduction by 2050

compared to 2005 (95% by 2050), and 95% reduction by 2035 and 100% reduction by 2050 (95% by 2035)[60].

The ReEDS Standard Scenario Viewer does not explicitly state the amount of new-build capacity in each time step, so this is derived from the change in total installed capacity and our calculation for the capacity that would retire. The capacity of new-build facilities is used to calculate the associated CIM jobs in the next step. The existing fleet of generators and their retirement schedules are from the U.S. Energy Information (EIA) National Energy Modeling System (NEMS) Generator Database and is part of the inputs into the ReEDS model. Assuming no early retirement, we assigned the generators to either retire in their scheduled retirement year or at the end of their lifetime (Supplementary Table S1), whichever came first. For states with existing fleets of certain technologies, three options of nameplate capacities are used in the next steps of the analysis to incorporate the employment uncertainty new builds may bring (Supplementary Fig. S4-7).

Spatial and sectoral employment analysis. The Jobs and Economic Development Impact (JEDI) model is an open-source model developed and maintained by NREL to evaluate the employment and economic impact of constructing and operating power generation technologies[26]. The model operates on an input-output basis using the IMPLAN database[61]. The model is selected due to its spatial granularity at the state level and data accessibility. The JEDI framework uses detailed capital and operational cost breakdown of each technology to calculate the local and state-level job creation impact in 14 main economic sectors. Direct jobs associated with power generation and indirect jobs associated with the supply chain are extracted. Although the JEDI models provide information on induced jobs, they are not included in the analysis due to their uncertainties in addressing microeconomic interactions, especially inter-state trading.

The existing suite of models for specific technologies includes biopower, coal, concentrated solar power, geothermal, conventional hydro, land-based wind, offshore wind, natural gas combined cycle, photovoltaics (both rooftop and utility-scale), and transmission. Additional technologies not provided by the JEDI website include batteries (2h to 10h), biopower with CCS, direct air capture, hydrogen combustion turbine, natural gas combined cycle with CCS, nuclear, oil gas steam, and photovoltaics with batteries. We created proxy JEDI models for these technologies by modifying the cost components in existing models of similar technologies. Further details on assumptions made in these modifications can be found in Supplementary Section 3.

The local shares of technology components are primarily based on the JEDI default values. For fuel-consuming technologies, the local shares of the fuel are based on state-level historical fuel production and consumption data from the EIA[62,63], which can be found in Supplementary Section 5.1. Local shares of uranium are assumed to be zero since historically purchased imports have supplied the majority of the fuel[64]. The local shares of biomass feedstocks are assumed to be 100% because the states themselves could generally produce more than is required for power generation, and the details of future inter-state biomass trade are too uncertain to quantify in the scope of this work (Supplementary Section 5.2).

While the O&M jobs of fuel-consuming technologies can vary based on the consumption of fuels, those of renewable technologies are more fixed. O&M jobs are assumed to be long-term and calculated annually. The summation of O&M jobs and the shorter-term CIM jobs assume that the latter (in job-years) span equally over the construction period (Supplementary Table S1). The final job impacts are calculated annually in 14 economic sectors and 48 states.

Distributional impact analysis on skill levels. The Occupation Information Network (O*NET) introduced the Job Zone[35] framework to describe the education, related experience, and on-the-job training required for occupations. The Job Zones range from "little to no preparation needed" (Zone 1) to "extensive preparations needed" (Zone 5). The Job Zone designations for occupations are updated by expert analysts from 2004 (e.g., telemarketers) to 2021 (e.g., chief sustainability officers). We utilize the full set of occupations in the database assuming they remain in the same Job Zones as when they were designated. This framework was used as a proxy for the skill levels and training requirements. The occupations' assignments to industries [65] and Job Zones [66] and their compositions in states[67] were used to calculate the Job Zone compositions of the workforce across industries and states (Supplementary Section 6.3).

Assuming the current skills composition to remain in the future workforce, the power sector employment associated with industry sector j and Job Zone z in state s in year t can be calculated as,

$$X_{s,j,z,t} = \sum_{i} P_{z,s,j} X_{s,j,t} \quad (1)$$

where $P_{z,s,j}$ is the percentage of jobs in Job Zone z in the workforce of industry sector j in state s and $X_{s,j,t}$ is the employment associated with the industry sector j in year t and state s.

Distributional impact analysis on gender. The US Census American Community Survey (ACS) table[42] provides the gender distribution of the workforce by state and industry. Given the continuing need to expand nuancedly gendered demographic data[54], this work has to interpret "sex" as "gender" (*i.e.*, males interpreted as men and females interpreted as women). The historical trends in the gender distributions (Supplementary Fig. S15) across industry sectors remained relatively steady from 2010 to 2020. Thus, we assume the gender distributions to remain at 2020 levels (Supplementary Fig. S17) for the planning horizon. The modeled composition of women in the power sector workforce (Modeled Women Employment) in year t in state s, $W_{s,t}$, were calculated as follows,

$$W_{s,t}[\%] = \frac{\sum_j W_{s,j} X_{s,j,t}}{\sum_j X_{s,j,t}} \quad (2)$$

where $W_{s,j}$ is the percentage of women employed in the industry sector j in state s and $X_{s,j,t}$ is the total number of jobs associated with the power sector workforce disaggregated to state s and industry sector j in year t. This modeled composition does not project the absolute future of women's employment in the power sector. Instead, it can be used to compare the potential impacts in different transition scenarios and highlight the need for gender-related policy support in certain states, especially if the gender dynamics in the workplace remain static.

Employment opportunities and challenges. The employment transition indices were calculated on the basis that a portion of the current workforce would naturally retire throughout the nearly 30-year planning horizon. Assuming the current workforce would retire at age 65, the snapshot of the retired workforce can be calculated from the age distribution of the current workforce across industries[68] in Supplementary Fig. S18. Due to the lack of state-level data and the small variations (roughly 5%) in age group compositions aggregated over states (Supplementary Fig. S19), we assumed that the same sectoral age distributions apply to all states. The remaining historical workforce can be calculated as,

$$\Delta X_{s,j,t_n} = X_{s,j,t_0} \times (1 - P_{retire,j}) \quad (3)$$

where X_{s,j,t_0} is the workforce attributed to state s and industry j at the start of the planning horizon (2022) and $P_{retire,j}$ is the percentage of industry j estimated to retire by the end of the period.

The number of future jobs by states, sectors, and Job Zones are compared against the remaining historical workforce. The Employment Change ($EC_{s,j}$) is normalized to the size of the workforce section at the start of the planning horizon (2022). It can be calculated as,

$$EC_{s,j} = \frac{X_{s,j,t_n} - \Delta X_{s,j,t_n}}{X_{s,j,t_0}} \quad (4)$$

where X_{s,j,t_n} is the workforce attributed to state s and industry j at the end of the planning horizon. Here we assume the end of the planning horizon to be the average value in the final decade (2041–2050) to minimize the effect of drastic changes in certain years. When this value is positive, it indicates the scale of expansion of the current workforce. For example, a value of 1 means an additional group of new entrants the size of the current workforce would be needed to deliver the transition. When this value is negative, it indicates the scale of unemployment risks for the current workforce. For example, a value of -0.3 implies that 30% of the current workforce would lose their jobs (over and above natural retirement) and thus need to prepare for retraining or migration in the next three decades.

When comparing the Employment Change across emission reduction scenarios A and B, the Net Employment Change is defined as,

$$NEC_{s,AB} = \frac{X_{s,t_n,A} - \Delta X_{s,t_n}}{X_{s,t_0}} - \frac{X_{s,t_n,B} - \Delta X_{s,t_n}}{X_{s,t_0}} = \frac{X_{s,t_n,A} - X_{s,t_n,B}}{X_{s,t_0}} \quad (5)$$

Where $X_{s,t_n,A}$ and $X_{s,t_n,B}$ are the total number of jobs in each state in the final decade (2041–2050) for scenarios A and B. X_{s,t_0} is the total number of jobs in each state at the start of the transition.

Data availability

Information contained herein was obtained using the Regional Energy Deployment System model (ReEDS), developed by and licensed from Alliance for Sustainable Energy, LLC, manager and operating contractor of the National Renewable Energy Laboratory on behalf of the U.S. Department of Energy. The ReEDS model is open access on GitHub upon request through the NREL website (https://www.nrel.gov/analysis/reeds/request-access.html). The JEDI models are open-access Excel sheets on the NREL website (https://www.nrel.gov/analysis/jedi/models.html) as well. The 2021 ReEDS Standard Scenarios can be accessed from the Scenario Viewer (https://scenarioviewer.nrel.gov/) along with standard scenarios from previous years. The databases produced by the U.S. Energy Information Administration, Census Bureau, and Bureau of Labor Statistics can be found in their relevant sections as they are mentioned throughout the manuscript.

Code availability

The code used in this work can be accessed from its GitHub repository under the Apache-2.0 License (https://github.com/judyjwxie/LoCaTED). The framework is named the Low Carbon Transition Employment Distribution (LoCaTED) model and is set up to run by inputting additional open-access files from ReEDS and JEDI. Refer to the README file for more instructions.

Acknowledgments

J.X. would like to thank the Imperial College London President's PhD Scholarship for funding this work. I.S. was funded by the Engineering and Physical Sciences Research Council [EP/R045518/1] through the IDLES programme.

Author contributions

J.X. and M.M. contributed to the integration of ReEDS and JEDI models. J.X. is responsible for coding the framework, data analysis, visualization, and the initial draft of the manuscript. I.S. and J.R. supervised this study. All authors contributed to the project design and manuscript revisions.

Competing interests

The authors declare no competing interests.

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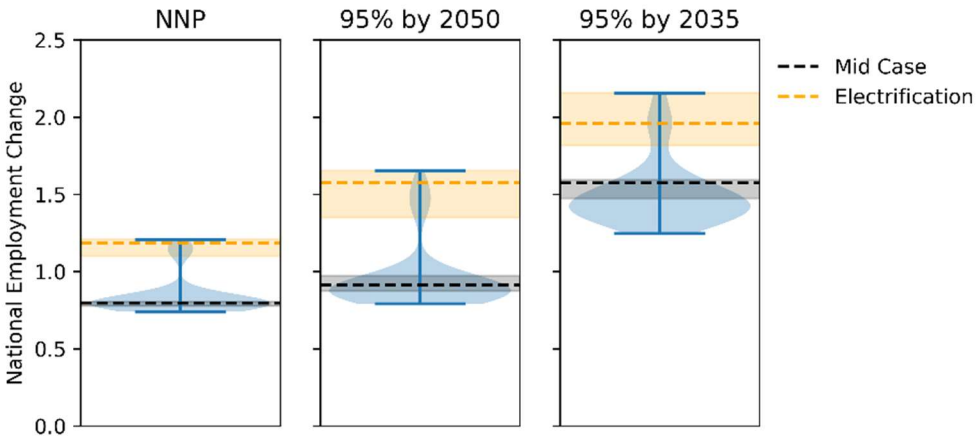
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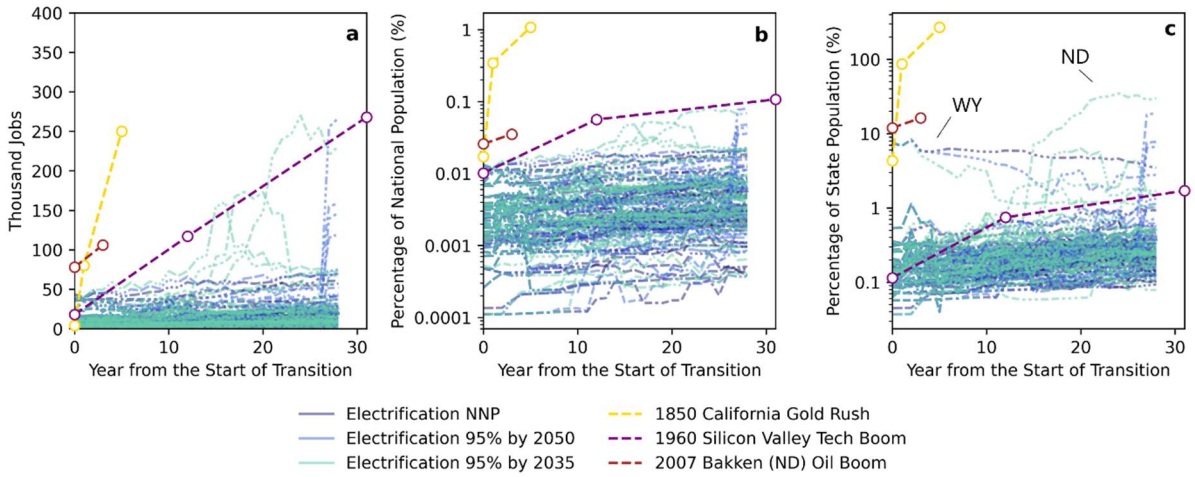
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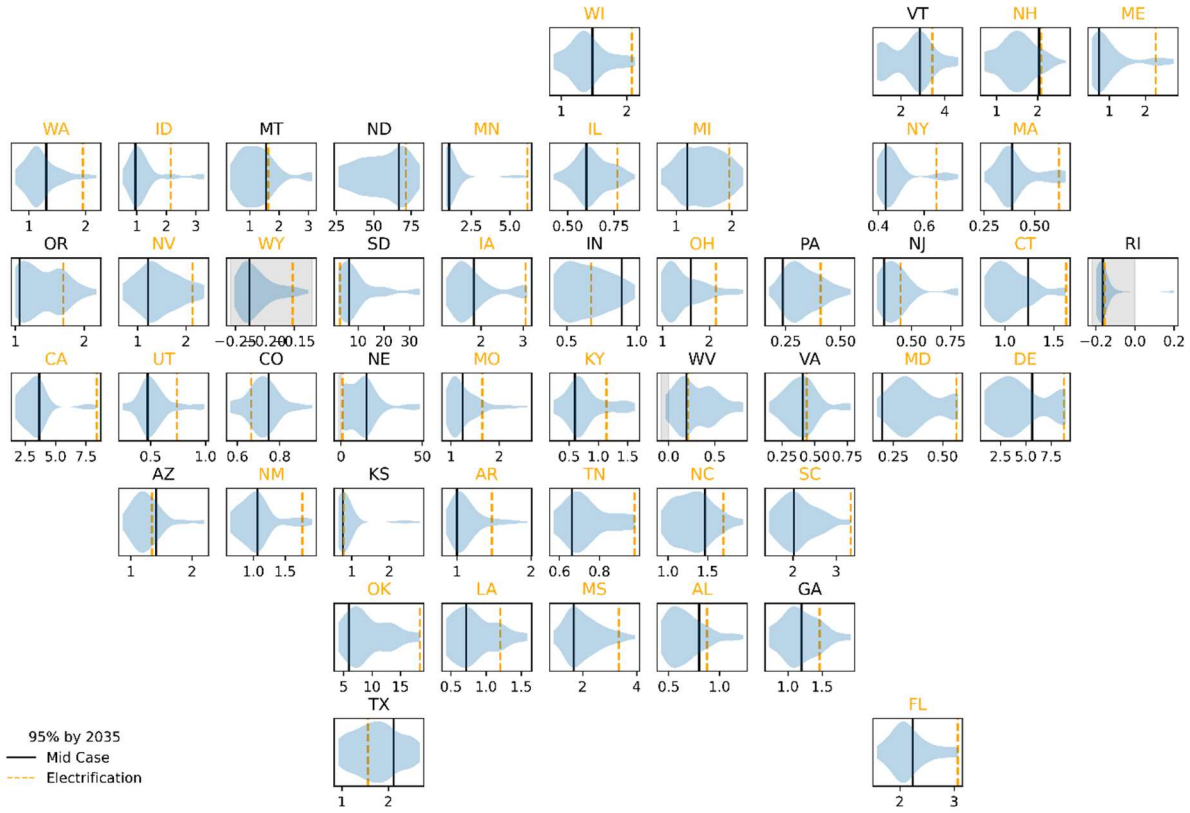
Extended Data Figures



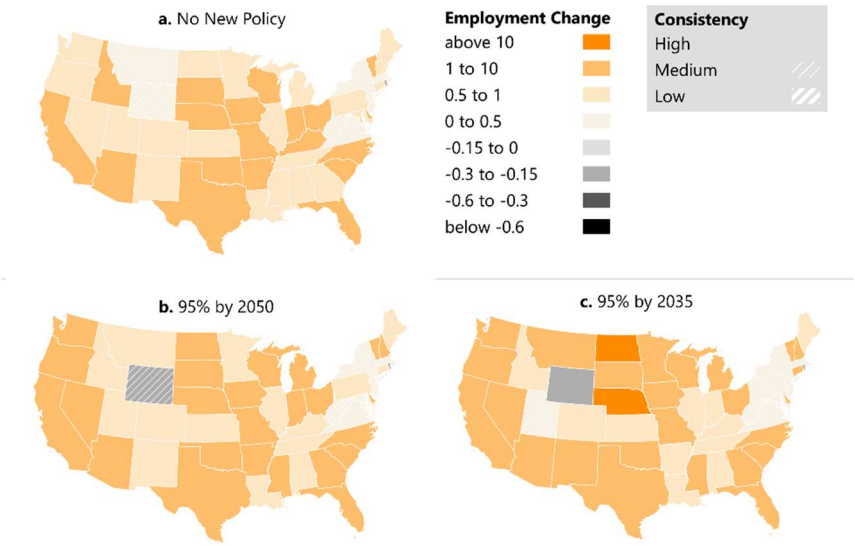
Extended Data Fig. 1 | Modeled national employment change across all emission reduction trajectories and energy system assumptions in the 2040s compared to the 2020s. Employment change values indicate the size of new opportunities created in the 2040s compared to the 2020s state-level electricity workforce. The violin plots illustrate the distribution of employment change outcomes across all modeled scenarios, which appears to be bimodal. The shaded areas indicate scenarios under the mid-case (black) and high electrification (orange) energy system assumptions; the dashed lines indicate the scenario under the medium multiplier option. The mid-case scenarios occur in the main peaks and the electrification scenarios take up the upper peaks.



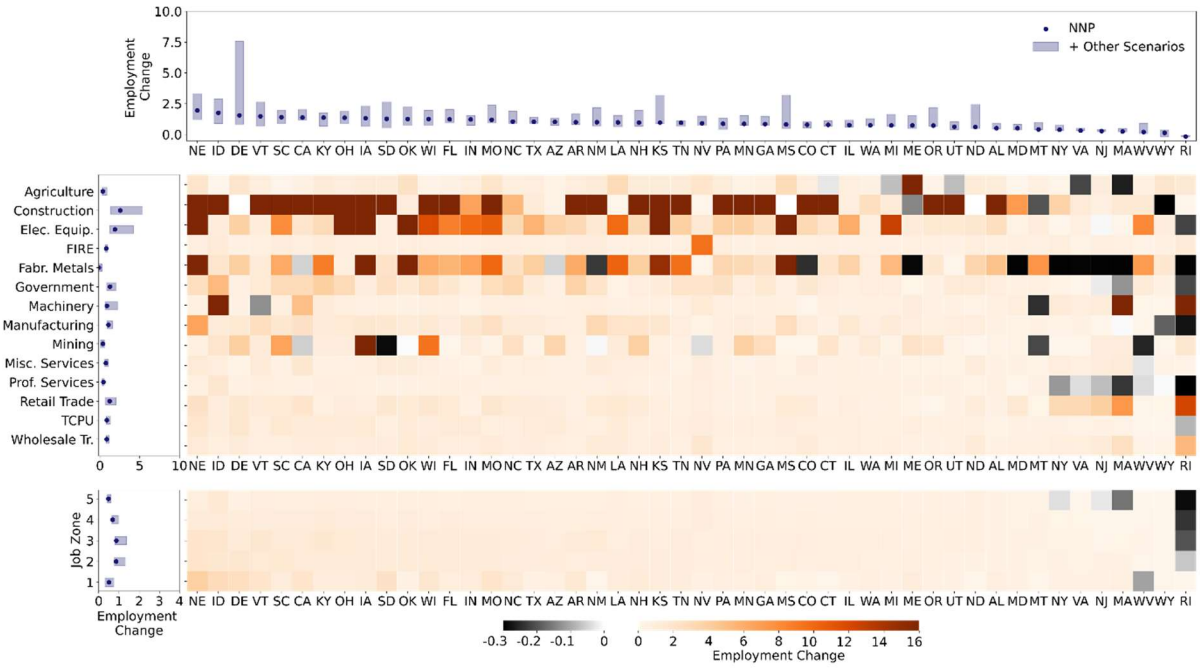
Extended Data Fig. 2 | Modeled state-level employment growth under the high electrification energy system assumption compared to historical workforce mobilization events in energy and technology in the US. The modeled results are shown over the planning horizon of 2022–2050 for power system scenarios with No New Policy (NNP) and CO_2 emissions targets of a 95% reduction by 2050 and 2035 under Mid Case energy system assumptions. Panel (**a**) shows the absolute employment growth, (**b**) shows the percentage of workforce mobilized over the US national population at the start of the transition, and (**c**) shows the percentage of the state population mobilized as workforce at the start of the transition.



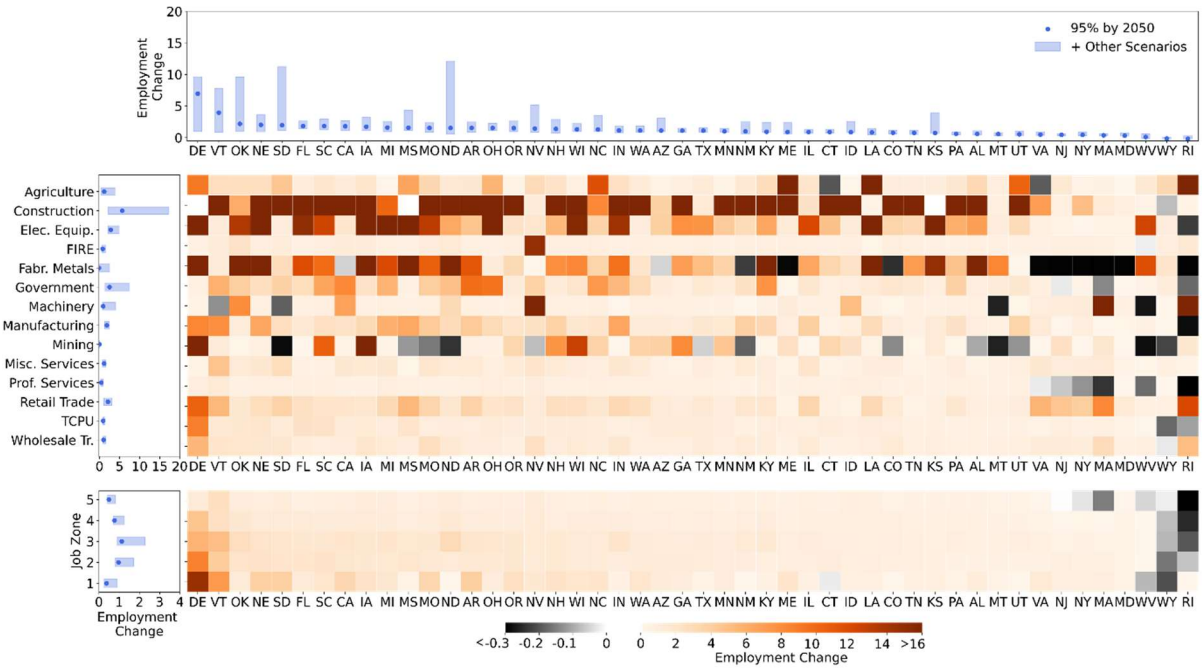
Extended Data Fig. 3 | Distribution of state-level employment change under the 95% by 2035 emission trajectory. The black lines represent the mid-case system assumption and the orange dashed lines represent the high electrification assumption, both with the medium multiplier option. The state labels are marked orange if the electrification case is one standard deviation more than the mid-case line. The negative areas are shaded gray.



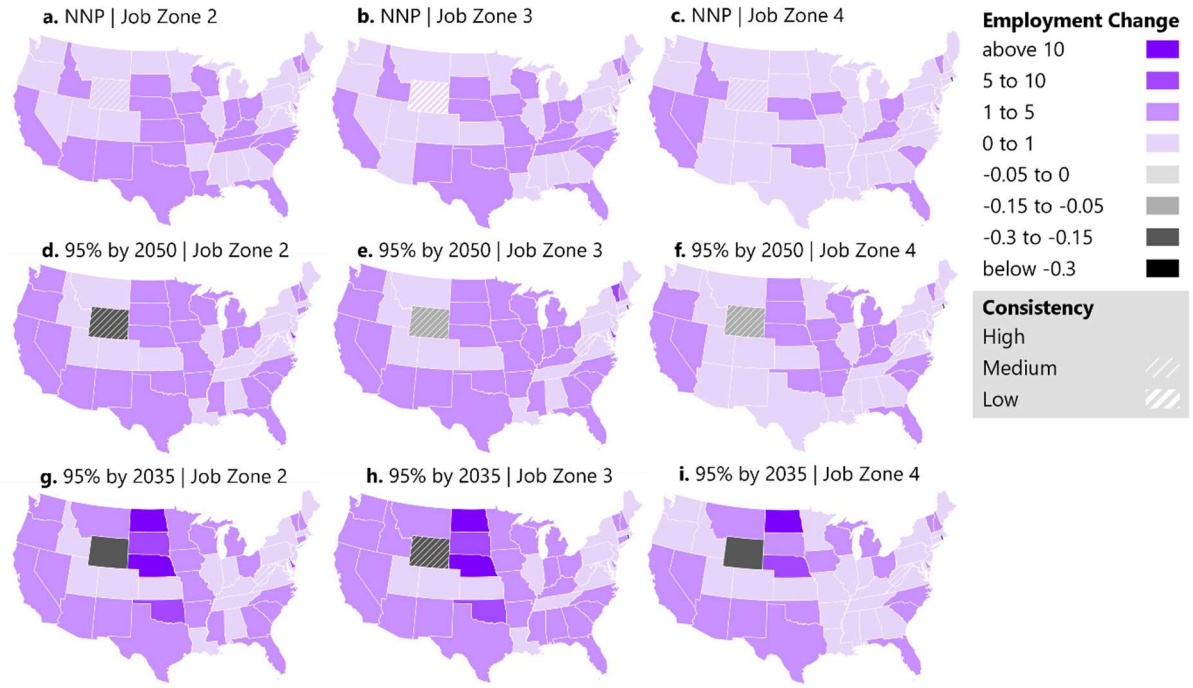
Extended Data Fig. 4 | Modeled absolute employment change under the mid-case. Employment change refers to the job requirement of the future workforce in the state compared to the current workforce in the final decade of the planning horizon (excluding those in natural retirement) normalized to the size of the current workforce now. The maps show (**a**) No New Policy, (**b**) the 95% reduction by 2050, and (**c**) the 95% reduction by 2035 then net zero in 2050. The orange color scheme represents the net employment gains, and the gray color scheme represents losses. The data consistencies are derived from the percentages of scenarios that result in the same sign as the mid-case. Low and medium uncertainties represent more than and less than 80% of the scenarios sharing the same sign as the mid-case, respectively. High consistency represents all scenarios with the same sign.



Extended Data Fig. 5 | Distribution of employment change in the No New Policy scenario between the 2020s and 2040s. The bar graphs show the impact aggregated by state (top), economic sector (middle left), and job zone (bottom left) across all power sector transition scenarios. In the top panel, the scatters represent the mid-case energy system assumption, and the transparent bars represent the full suite of scenarios. The y-axis is linearly scaled. States are sorted in descending order of their state-level employment growth. Heatmaps represent the disaggregated impact in the mid-case scenario. They show the magnitudes of employment growth (orange color scheme) and reskilling needs (gray color scheme) in the last decade of the planning horizon (2041–2050) compared to each subset of the workforce at the start of the planning horizon (2022–2030). These state-level subsets are disaggregated by the economic sector (middle) and job zone (bottom). TCPU stands for Transportation, Communications, and Public Utilities. FIRE stands for Finance, Insurance, and Real Estate. Miscellaneous services include sectors such as education, healthcare, and the arts.



Extended Data Fig. 6 | Distribution of employment change in the 95% by 2050 scenario. The bar graphs show the impact aggregated by state (top), economic sector (middle left), and job zone (bottom left) across all power sector transition scenarios. In the top panel, the scatters represent the mid-case energy system assumption, and the transparent bars represent the full suite of scenarios. The y-axis is linearly scaled. States are sorted in descending order of their state-level employment growth. Heatmaps represent the disaggregated impact in the mid-case scenario. They show the magnitudes of employment growth (orange color scheme) and reskilling needs (gray color scheme) in the last decade of the planning horizon (2041-2050) compared to each subset of the workforce at the start of the planning horizon (2022-2030). These state-level subsets are disaggregated by the economic sector (middle) and job zone (bottom). TCPU stands for Transportation, Communications, and Public Utilities. FIRE stands for Finance, Insurance, and Real Estate. Miscellaneous services include sectors such as education, healthcare, and the arts.



Extended Data Fig. 7 | Modeled employment change in Job Zones 2, 3, and 4. Employment change refers to the job requirement of the future workforce in the state and Job Zone compared to the current workforce under the same category in the final decade of the planning horizon (excluding those in natural retirement) normalized to the size of the current workforce now. The top panel (**a-c**) shows the No New Policy (NNP) emission trajectory, the middle panel (**d-f**) shows the 95% reduction by 2050 constraint, and the bottom panel (**g-i**) shows the 95% reduction by 2035 constraint. The purple color scheme represents the employment gains, and the gray color scheme represents losses. Hatching denotes the level of consistency across energy system assumptions within each group. High consistency means all scenarios have the same sign of change as the mid-case (i.e., always positive, or always negative). Medium and low consistencies represent more than and less than 80% of the 16 energy system assumptions sharing the same sign as the mid-case, respectively.

Supplementary Files

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