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Green jobs and just transition: Employment implications of Europe's Net Zero pathway

Johannes Emmerling [a,b,*], Laurent Drouet [a,b], Jessica Jewell [c,d,h], Lola Nacke [c], Sandeep Pai [e], Hisham Zerriffi [f,g]

[a] CMCC Foundation - Euro-Mediterranean Center on Climate Change, Italy
[b] RFF-CMCC European Institute on Economics and the Environment, Via Bergognone 34, I-20144 Milan, Italy
[c] Department of Space, Earth and Environment, Division of Physical Resource Theory, Chalmers University, SE-412 96 Gothenburg, Sweden
[d] Centre for Climate and Energy Transformations & Department of Geography, Faculty of Social Sciences, Postbox 7802, University of Bergen, 5020 Bergen, Norway
[e] Swaniti Global, 1109A Marconi Street, Houston, TX 77019, USA
[f] Faculty of Forestry, The University of British Columbia, 2424 Main Mall, Vancouver, British Columbia V6T 1Z4, Canada
[g] Payne Institute, Colorado School of Mines, 1500 Illinois St, Golden, CO 80401, USA
[h] Advancing Systems Analysis, International Institute for Applied Systems Analysis, Schlossplatz 1, Laxenburg, Austria

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ABSTRACT

The European Green Deal promises a "just and inclusive transition" to net-zero emissions by 2050, but employment implications remain poorly quantified. We address how Europe's net-zero transition affects energy sector employment and whether current policies ensure a just transition for affected workers. While the net-zero transition creates substantial net employment gains, we argue that significant mismatches in skills, geography, and timing require more targeted policy interventions than currently provided. Using the WITCH integrated assessment model coupled with global employment factors, we estimate changes across five job categories and eleven energy technologies for EU member states under current policies and the Net Zero emission target by 2050. Results show Europe's energy jobs increase substantially by 2050: from 1.3 million today to over 2 million under current policies and 2.5–3 million under Net Zero. Renewable energy accounts for 80 % of total energy jobs by 2050 under Net Zero, with solar PV representing three-quarters of job growth due to high labor intensity, while wind contributes 15 %. However, 300,000 jobs are lost in the coal and oil sectors under Net Zero (versus 100,000 under current policies), concentrated in Poland, Germany, and the Czech Republic. We also analyze the EU Just Transition Fund allocations to assess policy alignment and find a policy emphasis on addressing fossil fuel phase-out impacts rather than facilitating workforce transition to renewable energy. While coal-dependent countries receive substantial funding, critical gaps exist in skills development programs necessary for renewable energy expansion.

1. Introduction

The European Green Deal promises a "just and inclusive transition" to net-zero emissions by 2050, a target it reaffirmed in the EU's recent Clean Industrial Deal [1–3]. A critical step to reaching net-zero emissions is phasing out coal power, increasing power generation from renewables, reducing energy demand, and shifting non-electric energy use to carbon-free alternatives. This transformation will impact the European labour market, including the overall level and types of jobs in the energy sector [4–8]. These impacts are unequally distributed across Europe, with some regions that are rich in energy jobs potentially facing employment and GDP losses [6,9], which raises concerns about the acceptability of the European Green Deal [10]. The job shifts required for the European Green Deal risk impacting its implementation due to resistance from regions that may face job losses. At the same time, labour shortages and a green skills gap have been identified as significant implementation challenges to the European Green Deal [11]. Therefore, there is a need for dedicated policies for supporting regions and workers economically impacted by job losses as well as scaling up green jobs for new industries. Disaggregated quantitative analysis on labour market changes, including the type of occupations and skills lost or gained, and where these changes will occur, is needed to support the design and

* Corresponding author at: CMCC Foundation - Euro-Mediterranean Center on Climate Change, Italy.
E-mail address: johannes.emmerling@cmcc.it (J. Emmerling).

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implementation of such policies [12]. Understanding these employment dynamics is crucial for three interconnected reasons. First, employment impacts significantly influence public and political support for climate policies, with job losses potentially undermining Green Deal implementation. Second, quantifying where and what types of jobs are created or lost is essential for designing effective just transition policies that support affected workers and communities. Third, anticipating skills mismatches between declining fossil fuel industries and emerging renewable energy sectors is critical for ensuring adequate workforce development programs can prevent labor shortages that could impede the transition itself.

Extensive literature has examined the impact of renewable energy on employment, revealing both opportunities and challenges for labour markets during energy transitions. Early studies established that renewable energy technologies are generally more labour-intensive than fossil fuel alternatives, with solar photovoltaics showing particularly high employment factors during installation phases [4,13]. Cross-country analyses consistently find that renewable energy deployment creates more jobs per unit of investment or energy generated compared to conventional energy sources, though with significant variation across technologies and regions [14,15]. Wind energy studies highlight substantial employment in manufacturing and maintenance, while biomass and biofuels are strongly tied to agricultural jobs. However, the literature also identifies critical challenges, including spatial mismatches between job losses in fossil fuel regions and renewable energy job creation, skills gaps requiring extensive retraining programs, and temporal misalignments between job destruction and creation [6,10]. Methodological approaches have evolved from simple employment factor calculations to sophisticated input-output and computable general equilibrium models that capture indirect and induced economic effects [16,17]. Regional studies consistently show heterogeneous impacts, with coal-dependent areas facing disproportionate adjustment challenges while regions with renewable energy potential experience employment gains [9]. Recent literature emphasizes the importance of policy design in determining net employment outcomes, particularly regarding just transition mechanisms, skills development programs, and industrial policies that influence where renewable energy manufacturing occurs [7,8,12]. Despite this extensive research, gaps remain in comprehensive, technology-disaggregated analyses that combine detailed energy system modeling with employment factors across multiple scenarios and timeframes, particularly for policy-relevant assessments of transition pathways. The literature on reskilling and workforce transitions in energy sectors reveals opportunities and constraints for worker mobility between fossil fuel and renewable energy industries. Skills mapping studies demonstrate significant overlap in core competencies, particularly for technical trades like electricians, welders, and heavy equipment operators, with transferability rates ranging from 30 to 70 % depending on specific occupations [18,19]. Research on coal miner transitions shows that workers with maintenance and electrical backgrounds adapt most readily to wind and solar technician roles, often requiring several months or more of supplementary training rather than complete career changes.

This paper addresses the following research questions: How will Europe's transition to net-zero emissions affect energy sector employment across different technologies and regions, and are current just transition policies adequate to address the challenges on the labour market? While the net-zero transition will generate substantial net employment gains, significant skills, geography, and timing mismatches between job losses and creation require more targeted policy interventions than currently provided, particularly regarding workforce development for renewable energy sectors. This paper proceeds in four steps. First, using integrated assessment modeling, we quantify direct energy employment changes under Reference and Net Zero scenarios. Second, we examine the geographic and sectoral distribution of employment impacts across European regions. Third, we analyze current Just Transition Fund allocations to assess policy alignment with employment needs. Finally, we identify policy gaps and recommend targeted interventions to ensure a more equitable and feasible energy transition.

2. Methodology and data

We use the World Induced Technical Change Hybrid (WITCH) integrated assessment model to assess employment implications of reaching net-zero emissions by 2050 for EU member states and neighbouring countries. We couple this model with a comprehensive global dataset of employment factors [20] to project the future energy jobs under a Reference (or current policies) scenario and Net Zero scenario. We then examine existing policy support for this transition, focusing on the EU's Just Transition Fund (JTF), which was set up as part of the European Green Deal to support "workers and regions to develop new skills and thrive in the green economy".[1] We compare existing policy support to our findings on employment effects to identify the most significant policy gaps within the European Green Deal.

2.1. Assessing the employment implications of Europe's net-zero pathway

We used a supply chain approach [20] to identify and quantify the core activities within each energy sector. We collected data on the most significant direct job categories for each energy technology and calculated "employment factors" that represent full-time jobs per unit of energy or capacity (jobs/GW or jobs/PJ). We converted data from job-years/GW (the original units) to jobs/GW based on typical construction duration to account for the temporary nature of construction jobs. For construction and manufacturing jobs, we converted job-years per GW to jobs per GW by dividing by technology-specific construction durations (ranging from 1 to 10 years), since these represent temporary employment concentrated during project development phases [21]. We consider the five job categories related to manufacturing (manufacturing equipment related to energy technologies), Construction & Installation, O&M jobs (jobs involved in running and maintaining power plants), fuel production jobs in extracting fossil fuels and uranium, and crude oil refining jobs.

The employment factors are then taken as given for 2020 across countries and sectors. Two assumptions are key to derive the dynamic trajectory until mid-century. First, autonomous technical progress has been found to decrease job intensity over time. Some studies use a learning rate for labour-saving based on limited empirical data or modeling assumptions and the cost reductions of renewables [4,13] Whether overall cost savings are capital or labour-saving, Grossmann et al. [14] argue that "…in empirical macroeconomic studies most technological progress is found to be Hicks neutral", therefore the labour-capital input ratio is assumed to be constant over time, while technological progress raises the productivity of both factors. One study [15] provides learning rates for labour-saving technical progress for solar and wind technologies, of about 0.75 % per year, which we use in this study up until 2050. While we apply uniform annual learning rates across scenarios for simplicity, we acknowledge that learning-by-doing effects tied to cumulative production could yield scenario-specific trajectories, with accelerated deployment under Net Zero potentially driving faster labor productivity improvements [22]. The second important assumption is how regional job intensities vary or converge over time due to spill-overs and cross-regional learning. Here, we assume that regional jobs intensities converge to the regional minimum values entirely by 2050 linearly, capturing the strong international learning [23].

Our employment factor methodology captures the full employment potential of different renewable energy value chain configurations. For

[1] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/story-von-der-leyen-commission/european-green-deal_en.

solar PV, manufacturing employment represents approximately 60 % of total jobs per GW installed, compared to 25 % for installation and 15 % for operations and maintenance. This distribution has profound implications for regional development strategies, as manufacturing jobs are less geographically constrained than installation jobs and offer greater potential for clustering effects that support broader industrial ecosystems. The current geographic distribution of these manufacturing jobs means Europe captures only a fraction of the potential employment benefits from its renewable energy deployment, highlighting the strategic importance of industrial policies that could reshape this distribution.

Then we implement several scenarios in the WITCH model: First, a Reference or "Current Policies" set of scenarios that includes both current policies and their continuation as well as policies to be implemented between now and 2030; Second, a Net Zero pathways (Net Zero) scenario, which ensures reaching Net Zero Emissions in Europe in 2050. For creating the Reference scenario, the model starts with the current implemented policies officially ratified (until 2020). After the cut-off date of 2020, there is no new climate policy, although trends may continue through technology improvements and GDP-driven changes. The reference scenario represents a world where no further mitigation action beyond mid-2020 is taken, serving as the Reference against which the policy scenarios are compared. The current policy list is detailed in van Soest et al. [24]. For creating the Net Zero pathways, we used the globally estimated peak carbon budget (1150 GtCO2 for the period 2020–2100) [25] for developing scenarios that globally meet the Paris Agreement target of staying well-below 2 degrees, and in the EU we meet the Net Zero greenhouse has emission target [26–28]. To ensure the robustness of our results, we implemented both the Reference and the Net Zero scenario using all five of the Shared Socio-economic Pathways (SSP) [29], which are designed to explore a wide range of socio-economic and technological assumptions relevant for climate change policy and have been widely used for similar What-if analyses [30]. Here, we focus on the key challenge of climate change mitigation and thus present our main results for a "middle-of-the-road" (SSP2), where socio-economic trends and technological change follow historical trends. We also test whether our key findings change under the different SSPs. While WITCH's optimization framework may not fully capture real-world energy decision-making driven by energy security, political, and local factors [31], our use of multiple SSP scenarios and comparison between Reference and Net Zero pathways helps assess robustness to different technological and socio-economic trajectories.

While our analysis focuses on direct energy sector employment, the net-zero transition will generate substantial indirect and induced employment effects throughout the broader economy that merit consideration. Indirect effects arise from supply chain linkages, where renewable energy deployment creates demand for steel, concrete, electronics, and specialized services, while fossil fuel phase-out reduces demand in related industries. Induced effects emerge from spending patterns of newly employed workers and regional economic multipliers. Studies using input-output and computable general equilibrium models suggest these multiplier effects typically range from 1.5 to 3.0 for renewable energy investments, meaning each direct job creates 0.5 to 2.0 additional indirect and induced jobs [16,17]. For Europe's energy transition, research indicates that while coal regions may experience adverse multiplier effects from mine closures, renewable energy investments—particularly in manufacturing and installation—generate positive spillovers in construction, transport, and business services sectors. However, the net employment impact depends critically on policy design, including revenue recycling mechanisms and regional development strategies. Our focus on direct energy jobs provides the granular technological and regional detail necessary for targeted transition policies, while acknowledging that broader economic modeling would be required to capture the full employment implications of Europe's net-zero pathway.

To calculate current jobs and future jobs, we converted the employment factors dataset denoted by $e = 1..E$ for energy technologies and $j = 1..J$ for job categories to jobs per standard unit of energy or power capacity $\left(\frac{jobs}{PJ}\, or \frac{jobs}{GW}\right)$ denoted $jobint_e^j$. Then, we used energy-related output quantities from the WITCH model to compute the total current jobs.

Here, the WITCH model's energy-related outputs are denoted as: yearly installations I_EN_e in GW; total installed capacity K_EN_e, in GW; fuel extraction Q_OUT_e, in PJ; and total primary energy supply Q_PES_e, in PJ.

The total number of direct energy jobs is then computed for the base year as:

$$\begin{aligned} \boldsymbol{TotalJobs} = & \sum_e \boldsymbol{jobint_e^{Installation}} \bullet \boldsymbol{I\_EN_e} + \sum_e \boldsymbol{jobint_e^{Manufacturing}} \\ & \bullet \boldsymbol{I\_EN_e} + \sum_e \boldsymbol{jobint_e^{O\&M}} \bullet \boldsymbol{K\_EN_e} + \sum_e \boldsymbol{jobint_e^{Fuel\ production}} \\ & \bullet \boldsymbol{Q\_OUT_e} + \sum_e \boldsymbol{jobint_e^{Refinery}} \bullet \boldsymbol{Q\_PES_e}. \end{aligned}$$

To compute Future *TotalJobs*, the above was applied to the scenario pathways generated by the WITCH model in all 34 countries and regions (see below) according to energy quantities produced by the model in each of these regions.[2] To represent labour productivity improvements, the employment factors in non-OECD countries are assumed to converge linearly towards the mean in the OECD regions by 2050. Only for future manufacturing jobs related to solar and wind, the yearly capacity instalments beyond the latest historical manufacturing capacity data were assumed to be produced as a "Global Pool" instead of individual regions. We assign future manufacturing jobs to this "global pool" because these industries have historically relocated rapidly based on policy and cost factors. Our employment factor dataset contains only one value per technology and job category for each country. Therefore, we conducted an uncertainty analysis. For each macro region in the WITCH model (see below), we used the minimum and maximum values for each country, technology, and job category. By combining these ranges with the ranges across SSP scenarios, we account for the uncertainty of our results.

Prior studies on this topic that used computable general equilibrium (CGE) models or macro econometric models were able to show changes in economy-wide job numbers. They were useful in exploring the economy-related job implications [16,17,32]. By using an IAM we can conduct complementary work to that. We can zoom in on the energy sector and understand the job gains and losses by 11 energy technologies (coal, gas, oil, nuclear, hydropower, solar pv, solar csp, biofuels, wind onshore, wind offshore, solid biomass) and five job categories (construction and installation, operation and maintenance, manufacturing, fuel production, and refining). For example, our work would be useful in understanding the extent of job losses under the Net Zero scenario in, say, Indian or Chinese coal mining industries. Moreover, our analysis also shows that the largest *direct* job gains under stringent climate policies would be in manufacturing, which could lead to interesting dynamics where countries compete for these new jobs.

We used the WITCH model with two climate policy scenarios and three different socio-economic assumptions to create six pathways of energy-economy development. WITCH (World Induced Technical Change Hybrid) is an integrated assessment model developed and maintained at the RFF-CMCC European Institute on Economics and the Environment and is designed to assess climate change mitigation and adaptation policies [33,34]. It is a global dynamic model that integrates the most important drivers of climate change into a unified framework, and an inter-temporal optimal growth model captures the long-term economic growth dynamics. In the model, a compact representation of

[2] We processed our dataset in R—the corresponding code and dataset can be found at https://github.com/witch-team/energy-jobs-dataset-iiasadb.

the energy sector is fully integrated (hard-linked) with the rest of the economy so that energy investments and resources are chosen optimally, together with the other macroeconomic variables.

WITCH [34] represents the world in a set of a varying number of macro regions – for the present study, a new version with 34 world regions, and we split its "Europe" region into 12 EU member states (all countries with more than 10 million inhabitants), plus Switzerland and the United Kingdom, and four country groupings (the BeNeLux countries (BNL), the Balkan countries, Northern Europe and Eastern Europe). For each region, it generates the optimal mitigation strategy for the long term (from 2005 to 2100) as a response to a carbon price compatible with external constraints on emissions. A modeling mechanism aggregates the national policies on emission reduction or the energy mix into the WITCH regions. Finally, a distinguishing feature of the WITCH model is the endogenous representation of R&D diffusion and innovation processes that allows a description of how R&D investments in energy efficiency and carbon-free technologies integrate the mitigation options currently available. Non-CO2 emissions in energy and industry are endogenously modelled with potentials derived from the literature (marginal abatement cost curves). Projections for agriculture, land use, land-use change, and forestry emissions and food indicators are derived from the Global Biosphere Management Model (dynamic look-up of emissions depending on climate policy and biomass-energy use), calibrated on historical emissions and food demand.

2.2. Assessing policy support for Europe's net-zero pathway in the EU's Just Transition Fund

We focus on financial transfers under the EU's Just Transition Fund (JTF), a landmark policy mechanism for addressing employment and equity challenges to implementing the European Green Deal specifically [8,35]. We retrieve individual financial funding flows for each country from the Cohesion Open Data Platform [current ref. 38]. We do this by retrieving the dataset on "2021-2027 Planned finances detailed categorisation multi funds", where flows are coded by fund, programme, priority, policy objective, specific objective, category of region, dimension types in the categorisation system, categories of funding purposes, and in the case of the JTF by "jtf_themes".

First, we extract only JTF-flows under the "fund" variable. To avoid double counting of flows under "dimension types", we extract the coding by "intervention field". We then apply the official coding scheme from the Directorate-General for Regional and Urban Policy that classifies individual flows by ten "main thematic priorities", or "jtf_themes" in the dataset.[3] This coding scheme includes a specific category for flows dedicated to "skills, job search and education". It allows us to analyze the thematic investment priorities that the EU aims to address with the JTF, and compare these to the employment implications of the European Green Deal. In addition to the overarching JTF-themes, we also conduct an exploratory analysis of the underlying funding "categories", which describe the allocation of specific flows in more detail. This helps to understand what type of funding purposes are encompassed within the overarching funding themes.

To explicitly compare JTF funding themes and employment implications, we first differentiate flows by countries and by investment themes. We then map employment implications in the net-zero scenario by 2050. We map JTF funding to two measures: total job losses and job turnover. Job turnover is calculated as the absolute amount of job losses and job gains. While job losses indicates the extent to which the European Green Deal may lead to unemployment, total job turnover indicates to what extent the European Green Deal may cause overall change in the relevant economies, with job gains likely also requiring policy support to reskill workers, or attract new workers to the relevant regions.

We also conduct an exploratory review of additional policy measures to support employment implications of the European Green Deal, and the net zero transition more generally. To this end, we examine funding options on the European Commission website, and retrieve those that explicitly relate to employment effects of decarbonisation.

3. Results

The total employment numbers for Europe under all scenarios are shown in Fig. 1 for Net Zero and Reference and all five SSPs. Compared to the Reference scenario, the Net Zero scenario will mean more jobs in the energy sector in Europe. This near doubling of employment is due to the large-scale shift to more granular renewables technologies. Solar PV in particular will witness the most significant increase due to the highest job intensity in terms of construction and Operation and Maintenance.

Looking at losers and winners, the job gains in Wind, Solar, and Biomass, including Biofuels far outweigh any losses in Coal and Oil, while Natural Gas shows small gains or losses. We also find substantial differences across the fundamental socio-economic drivers, notably with SSP5 having the highest overall energy system expansion driven by its assumptions about economic growth (see Fig. 2).

This increase is notable in Europe, which has an ambitious net-zero target and widespread adoption of renewables. The Net Zero target leads to a significant reduction in Final Energy Intensity of GDP from today's value of about 3.2 to about 2–2.5 MJ per US-$, and the carbon intensity of energy is falling fast under Net Zero. However, regarding jobs required to provide the primary energy, this "jobs intensity" increases from around 30 full-time jobs per PJ to up to 60 full-time jobs per PJ of Final Energy, but with a wide range between Scenarios and SSPs, see Fig. 3.

While our analysis shows an enormous potential for renewable energy job creation in many regions, spatially explicit work is required to assess whether renewable energy jobs can be created for fossil fuel workers locally in areas where they live and work. Our prior research, conducted at the global level highlighted some key differences across world regions. Globally, under all our scenarios, China would lose jobs compared to today. Still, others, such as Middle East & North Africa and the US, gain jobs due to renewable energy expansion [20]. In Europe, and at the country level, we see already quite a heterogeneity in jobs by technology, comparing the Reference (current policies) and Net Zero scenario by 2050, see Fig. 4.

But how important are these energy jobs related to the whole economy? Here, cross-country variation is quite large given different energy-intensive sectors and extraction. We use data on the total workforce per country, and Fig. 5 shows the share of energy jobs lost as a share of 1 % of the national workforce. This threshold is similar to the lower end of the share of energy jobs in the 15 most vulnerable EU regions identified by Vrontisi et al. [9], which ranges from 0.7 % to 6.5 %.

One important category of employment in the decarbonization transition involves the manufacturing of equipment for Solar PV and Wind energy. Notably, the production of Solar Panels and Wind Turbines already accounts for approximately 1.5 million jobs globally. However, around 80 % of these jobs are located overseas, with China in Solar PV covering over 75 % of the market. In our modeling exercise, we assume that the current manufacturing capacity for solar PV is kept at today's locations and that the equipment can be provided up to today's maximum capacity annually. For the required expansion of production capacities, we do not assign the manufacturing jobs due to new and increased installations to any region, but rather to a "global pool" [20], since in the past these sectors have moved over the pace of only a few years from Germany to Canada, the US, and China. All new manufacturing capacity is assigned to the global pool for Wind turbines, as the distribution is much more diverse across countries. Ultimately, these jobs can in principle be placed anywhere in the world, mainly depending on skilled labour availability, capital availability, but notably industrial policies, tariffs, and trade policies. Globally, these jobs can amount to about 5 million by 2050, up to almost 20 million in SSP5

[3] https://cohesiondata.ec.europa.eu/stories/s/28yb-762c.

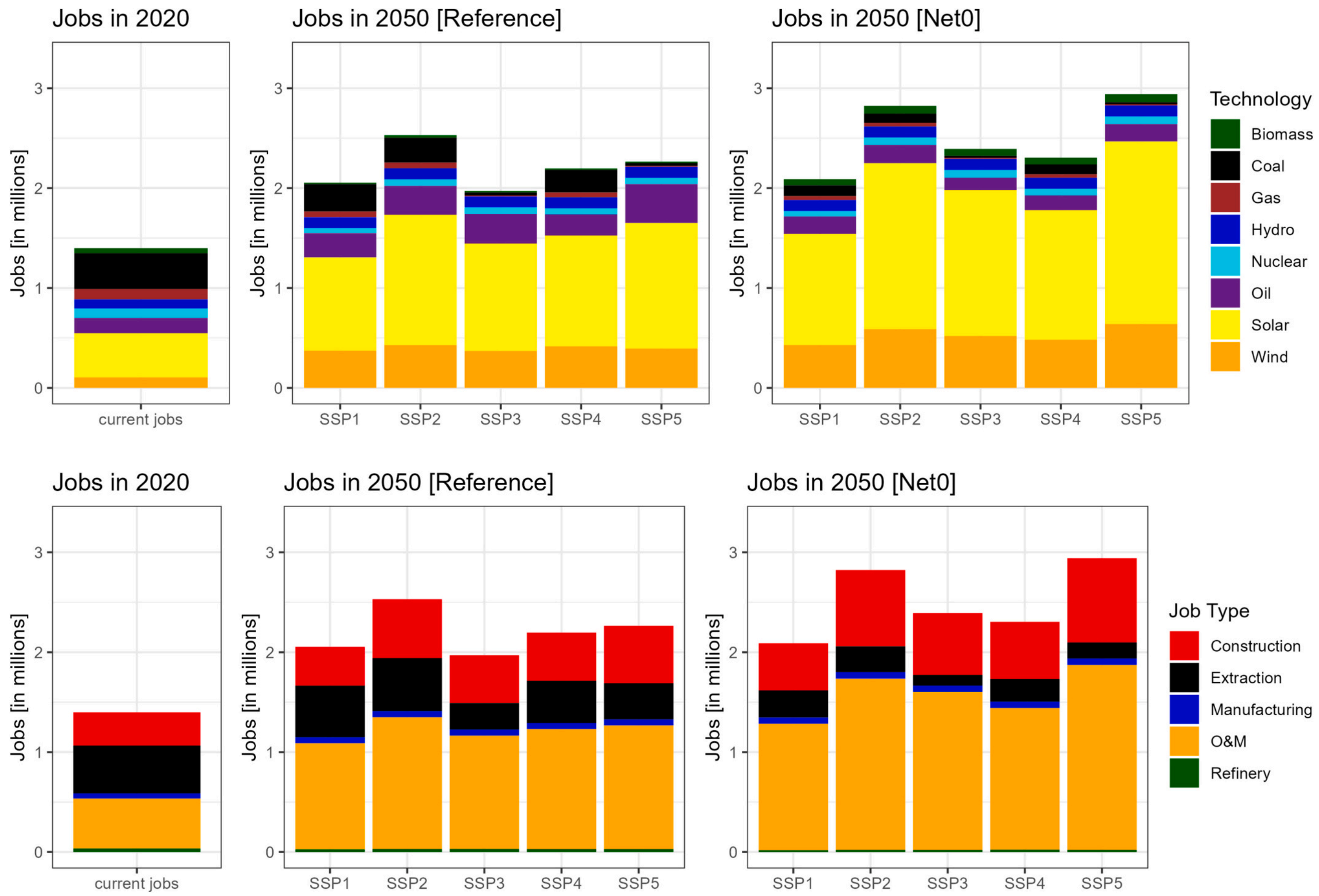

Fig. 1. Total employment in the energy sector in Europe. Total jobs are shown as of 2020 and 2050, in the Reference and Net Zero scenario for all five SSPs. The top bar shows the break down by technology while the second row shows the job types.

under Net Zero, and increasingly for Solar electricity generation. Consequently, establishing significant manufacturing industries in renewables manufacturing could increase direct energy system jobs in Europe substantially. This result highlights the importance of Industrial Policies and other measures, which could bring significant gains for some actors due to the allocation of the industries of renewable equipment across the globe (Fig. 6).

4. Policies to address employment impacts

Policy support for re-employment and upskilling of the workforce is essential for increasing the acceptability and feasibility of the European Green Deal [7,12]. The European Green Deal itself includes supporting measures, such as its Just Transition Fund (JTF) to support the "territories expected to be the most negatively impacted by the transition towards climate-neutrality" [1]. Since the introduction of the European Green Deal, the EU has implemented several additional policy measures to address concerns around the acceptability of its targeted low-carbon transition (Fig. 7). The recent "Clean Industrial Deal", for example, aims to reinforce financial support, streamline processes for skills recognition, and increase the attractiveness of jobs required for the low-carbon transition [2]. Both the Green and the Industrial Deal are embedded within a broader climate change, territorial cohesion, industrial, and labour policy landscape. For example, the EU Recovery Instrument, established to support EU member states in the wake of the 2020 COVID pandemic, increased the original JTF by 10 billion EUR. The recovery instrument also included the establishment of the Recovery and Resilience Facility (RRF), supporting the resilience of EU countries in the wake of both the green and digital transitions. However, only a minor share (roughly 1 %) of this fund is allocated to green skills and jobs.[4] The EU has also established a Modernisation Fund financed by revenues obtained under the EU Emissions Trading System. This funding is earmarked to support renewables deployment, energy efficiency, and just transitions in carbon-dependent regions. However, the amount paid to each theme depends on the project proposals submitted annually by eligible member states and approved by the European Investment Bank (EIB).[5] In addition to these EU-wide policies, national governments implement just transition policies domestically, adding to the resources deployed for re- and upskilling [37]. While a comprehensive analysis of this complex policy landscape is beyond the scope of this paper, our findings may inform priorities for future assessments of these policies. For example, our findings suggest that policy efforts for the renewables sector may be especially well-placed with a focus on solar power, which is likely to play a large role in jobs in 2050 across many European countries. Support for wind power may also be relevant, especially in Northern and Western European countries, see Fig. 8. In addition to EU policies, support on the national level is likely also required in neighbouring countries included in our analysis (e.g., Norway and the UK) that are also likely to face job losses and shifts in required skills profiles.

Here, we focus on comparing funding under the EU JTF against the employment implications of the EU's targeted net-zero transition. The EU JTF is a key policy instrument under both the European Green Deal

[4] https://ec.europa.eu/economy_finance/recovery-and-resilience-scoreboard/green.html.

[5] https://modernisationfund.eu/how-it-works/.

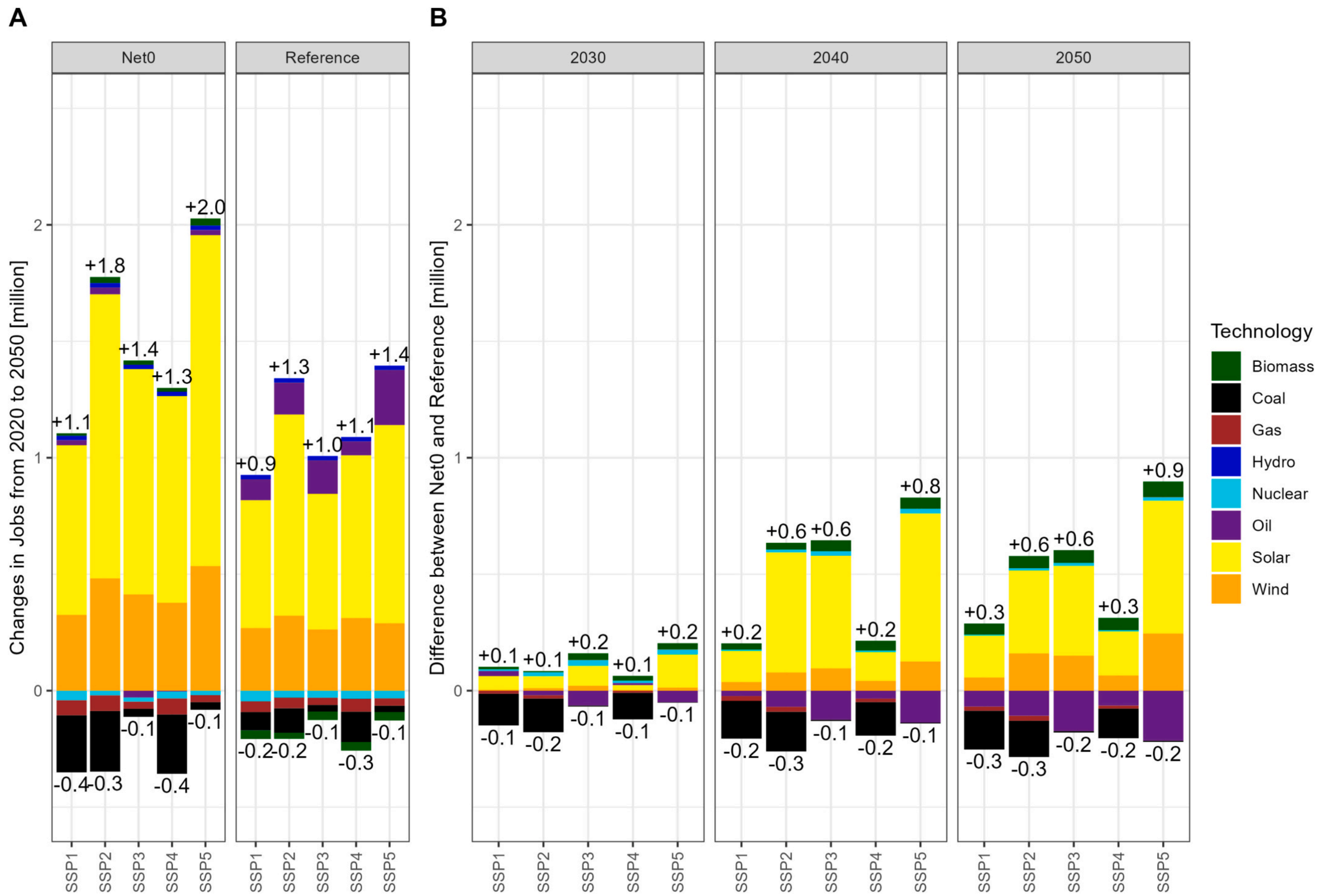

Fig. 2. Losses and gains across technologies, with respect to today (Panel A) and between Net Zero and the Reference scenario (Panel B).

and Clean Industrial Deal, specifically related to the European Green Deal, and with two major priorities: diversify regional economies, and reskilling workers.[6] Our analysis shows that the EU JTF is targeted at remedying the negative effects of fossil fuel phase-out rather than supporting up- and re-skilling required for the growth of renewables. While funding to increase renewables capacity is relatively prominent, flows allocated to "skills, job search, and education" typically do not surpass roughly 25 % of the financing per country. Instead, funding tends to be concentrated on economic diversification for enterprises (for example supporting innovation processes in small and medium-sized enterprises, or supporting funders of start-ups), which in some cases accounts for more than half of all funding in a country. Funding for diversifying the regional economy may also have more indirect effects on additional employment. For example, some funds are allocated for "Research and innovation activities"; or for "digitising, including e-Commerce, e-Business and networked business processes, digital innovation hubs, living labs, web entrepreneurs" of companies. While these activities may potentially include hiring of additional personnel, it is highly unclear whether this would benefit workers from former carbon-intensive industries; and whether workers with the required skills would be available locally.

Among the more specific funding allocations for "skills, job-search and education" are for example measures to improve "digital skills and digital inclusion", "measures to improve access to employment", "infrastructure for vocational education[,] training and adult learning", "support for labour market matching" and "labour mobility". Some flows are also specifically earmarked to unemployed youth, or early childhood education and care. The variance of specific funding types encompassed by the "skills, job-search and education" category indicates the size of the challenge related to green skills.

In addition to assessing the allocation of funding to various investment priorities, we compare the amount of EU JTF funding to estimated job gains and losses in EU countries by 2050. Poland, where most job losses, especially from coal decline, are estimated, receives the bulk of funding. Germany and Czechia will also face high losses due to the decline of coal and receive high amounts of funding, independent of the fact that much higher job gains are estimated in Germany than in Czechia. Benelux, France, Italy and Spain - all with relatively large job gains but low amounts of job losses - receive lower amounts of funding. Two outliers are Romania and Greece. Romania receives relatively little funding compared to its job losses, mainly from oil - indicating that the JTF focuses on the coal rather than the oil sector. Greece receives a relatively large amount of funding compared to its job losses and turnover - one reason may be the exceptionally high socio-economic vulnerability of Greek regions [9]. The focus of funding on the negative effects, especially of coal phase-out, is not surprising since allocation of JTF funding is based on local greenhouse gas emissions, employment in coal mining and carbon-intensive industries, and production of peat and oil shale. Allocation measures have also been put in place to avoid any single country receiving an extensive share of funding, which may explain why the amount for Poland is relatively low compared to its coal job losses [39].

[6] https://cohesiondata.ec.europa.eu/stories/s/28yb-762c.

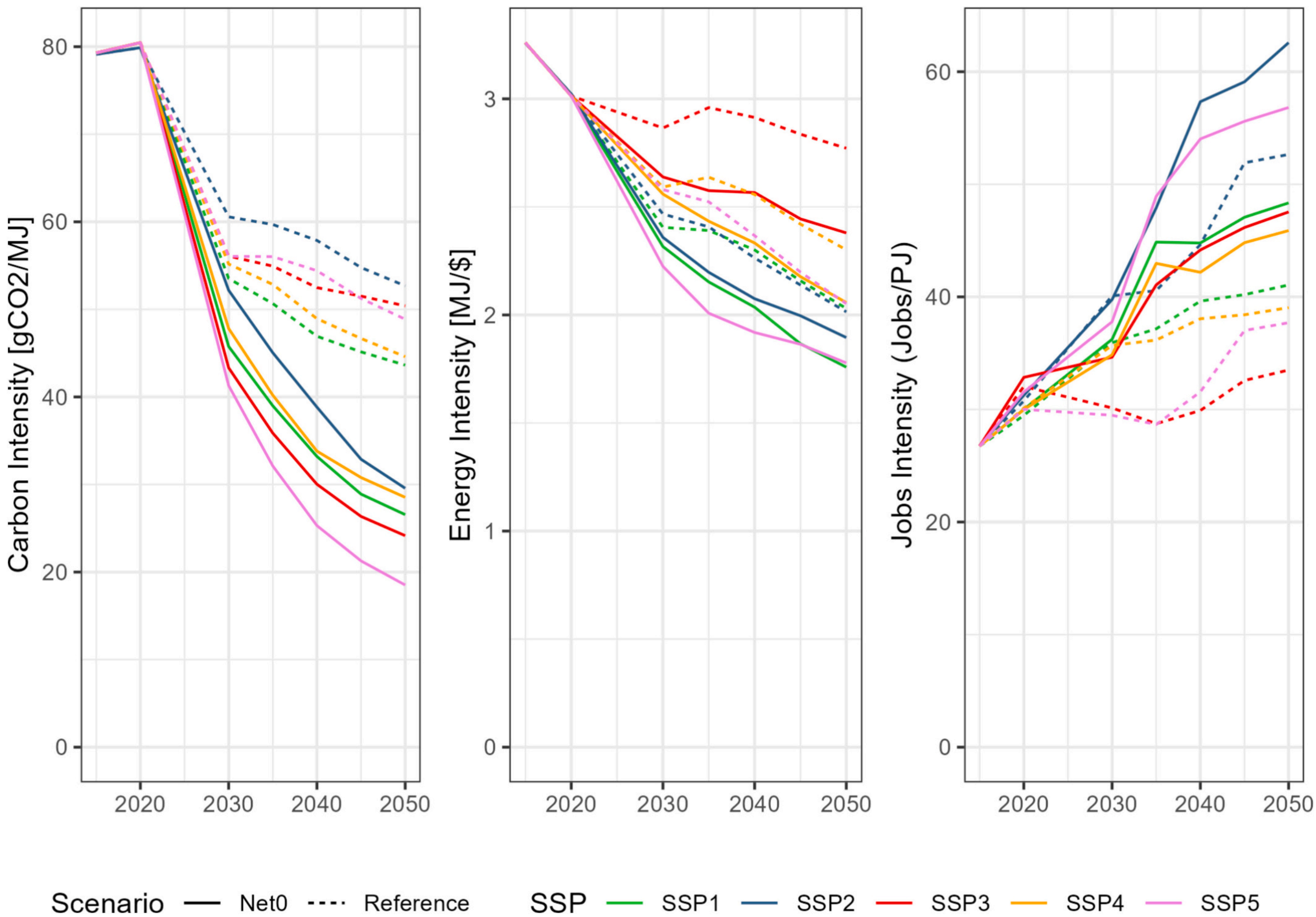

Fig. 3. Carbon intensity of final energy, final energy intensity of GDP, and jobs intensity of final energy within EU27 countries, all scenarios.

5. Discussion

Our analysis demonstrates that Europe's Net Zero transition offers significant employment opportunities while creating critical challenges in job displacement and skills development. The nearly doubling of energy employment, driven primarily by solar PV and wind deployment, indicates that decarbonization can be a net positive for European labour markets. However, the heterogeneous distribution of benefits raises equity concerns, as coal and oil-dependent regions will disproportionately bear transition costs.

The "global pool" of renewable energy manufacturing jobs presents a critical policy opportunity. With 80 % of solar PV and wind manufacturing jobs currently overseas and China dominating production, establishing European manufacturing capacity could multiply direct energy jobs by up to fivefold. This result aligns with recent policies like the Net Zero Industry Act but requires coordinated industrial policies, R&D investment, workforce training, and potentially protective trade measures. The industrial policy dimension extends beyond simple job creation to encompass broader economic development and strategic autonomy considerations. Manufacturing jobs typically offer higher wages, more stable employment, and stronger regional economic multipliers than installation and maintenance positions. Moreover, control over manufacturing capabilities provides strategic leverage in global clean energy supply chains and reduces vulnerability to geopolitical disruptions, as evidenced by recent supply chain challenges. European industrial policy initiatives recognize these dynamics, with the Net Zero Industry Act setting targets for 40 % of annual EU deployment needs to be manufactured domestically by 2030. However, achieving these targets requires coordinated interventions across multiple policy domains: research and development support for next-generation technologies, investment incentives and de-risking mechanisms for manufacturing facilities, workforce development programs aligned with manufacturing skill requirements, and potentially trade measures to level competitive playing fields with state-subsidized international competitors.

Our analysis also reveals significant skills, geography, and timing mismatches that could impede implementation. Solar PV installation and maintenance require specific technical skills that existing fossil fuel workers may lack without retraining. While approximately 43 % of coal industry jobs could transfer to solar PV without extensive retraining [40], substantial skills development remains necessary. Geographic mismatches between job losses and creation locations present additional labour market challenges. While substantial skills overlap exists between fossil fuel and renewable energy sectors, realizing this potential requires moving beyond the current emphasis on general economic diversification towards targeted workforce development programs informed by detailed skills mapping and employer engagement. Current Just Transition Fund allocations appear insufficient to support the required comprehensive re-skilling infrastructure, particularly given the scale of workforce transition implied by our employment projections. Priority areas for policy development include establishing renewable energy training centers in coal-dependent regions, creating apprenticeship programs that combine classroom learning with hands-on experience in growing renewable energy installations, and developing portable certification systems that recognize transferable skills across energy sectors.

Our Just Transition Fund (JTF) analysis reveals policy misalignments with labour market needs. The focus on economic diversification for enterprises rather than skills development (typically <25 % of country

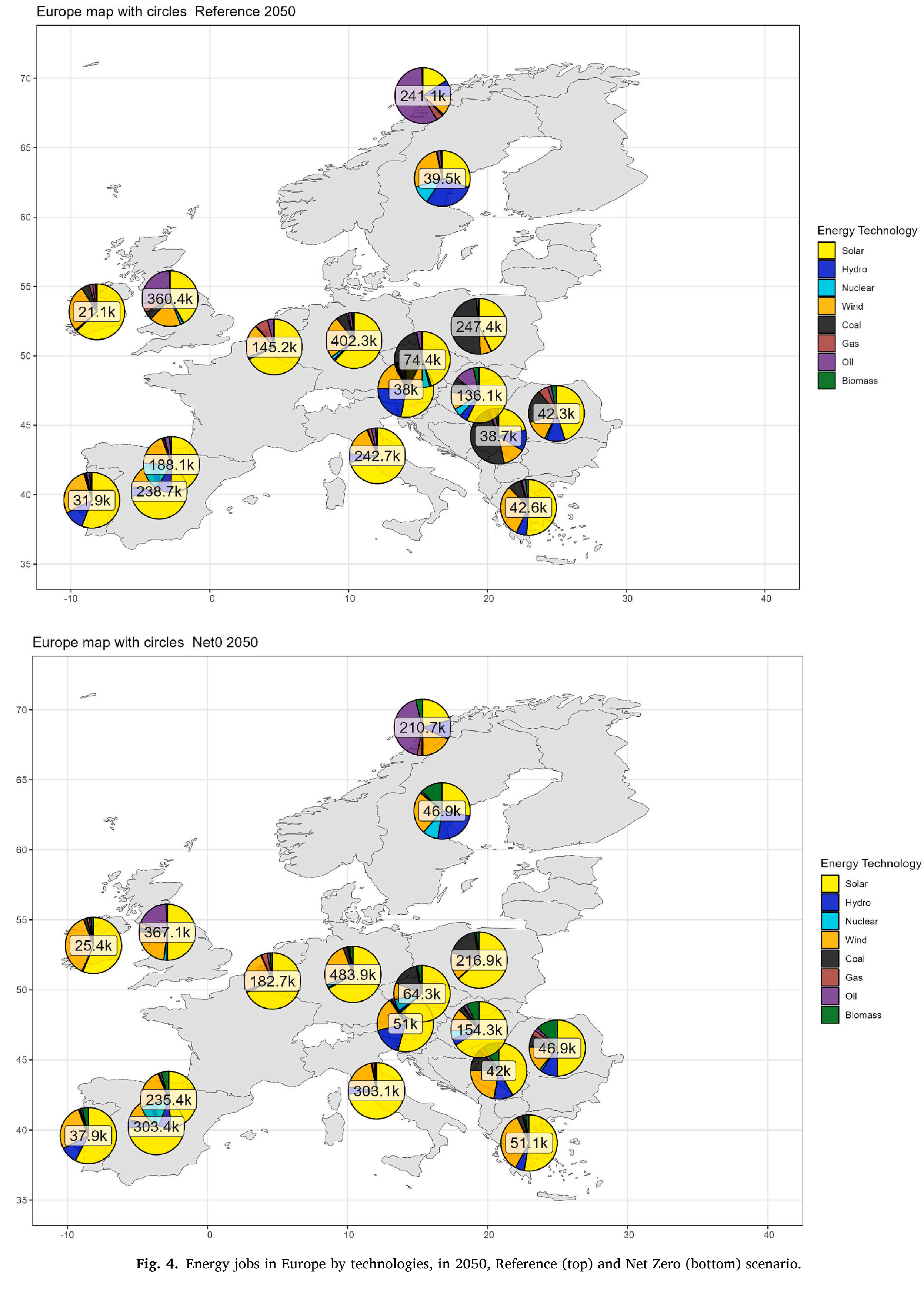

Fig. 4. Energy jobs in Europe by technologies, in 2050, Reference (top) and Net Zero (bottom) scenario.

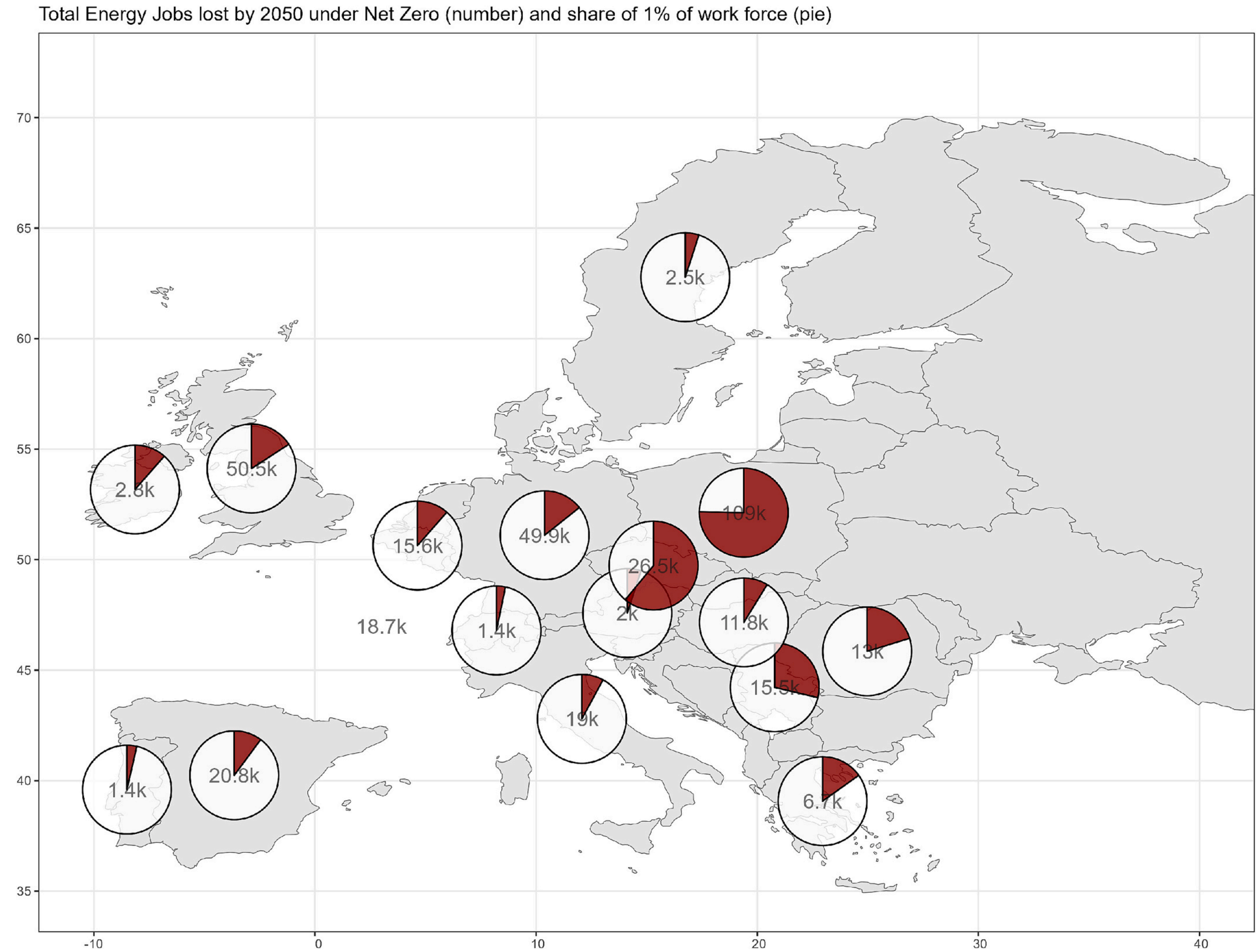

Fig. 5. Jobs lost (without newly created jobs) in 2050, under Net Zero as of 2050 of the national total workforce today. The numbers indicate the total number of jobs lost (without new jobs created). The circle indicates how much of 1 % of the workforce this represents, e.g., for Poland, these total jobs lost represent about 0.75 % of the total workforce.

funding) may reflect acknowledgment of economy-wide transition difficulties but represents a missed opportunity for addressing renewable energy skills gaps. While funding concentration in coal-dependent regions like Poland, Germany, and Czechia aligns with our job loss findings, limited renewable energy skills focus and relative underfunding of oil-dependent regions like Romania suggest incomplete alignment with fossil fuel phase-out impacts.

While our analysis focuses on direct energy sector jobs, broader economic implications merit consideration. The energy transition affects indirect and induced employment throughout supply chains and the wider economy. Research using computable general equilibrium models suggests positive economic impacts when revenue recycling and dynamic innovation effects are considered.

6. Conclusions

Europe's Net Zero energy transition presents substantial employment opportunities and implementation challenges. While total energy jobs will increase significantly, targeted policies are essential to address sectoral and regional disparities and ensure adequate skills for emerging clean energy industries. Our key findings thus include that renewable energy jobs will dominate future employment with solar PV representing the most significant growth; manufacturing opportunities could multiply European energy jobs if captured through industrial policy; and current Just Transition mechanisms, while necessary, require careful implementation to address employment dimensions fully. While the EU should establish funding frameworks and minimum standards for skills development, implementation requires coordinated action between national governments (for policy design and financing) and regional authorities (for local workforce development programs tailored to specific labor market conditions).

Our policy recommendations focus on enhanced skills development programs, particularly for solar and wind technologies, improved geographic targeting of transition support, and stronger integration of workforce development with industrial strategy. Compared to enterprise diversification, the relative underfunding of skills development suggests rebalancing JTF priorities could better serve transition needs. With appropriate policy support targeting skills gaps and regional vulnerabilities, Europe's energy transition can deliver inclusive economic development alongside environmental benefits across European regions.

CRediT authorship contribution statement

Johannes Emmerling: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Laurent Drouet:** Writing – review & editing, Formal analysis,

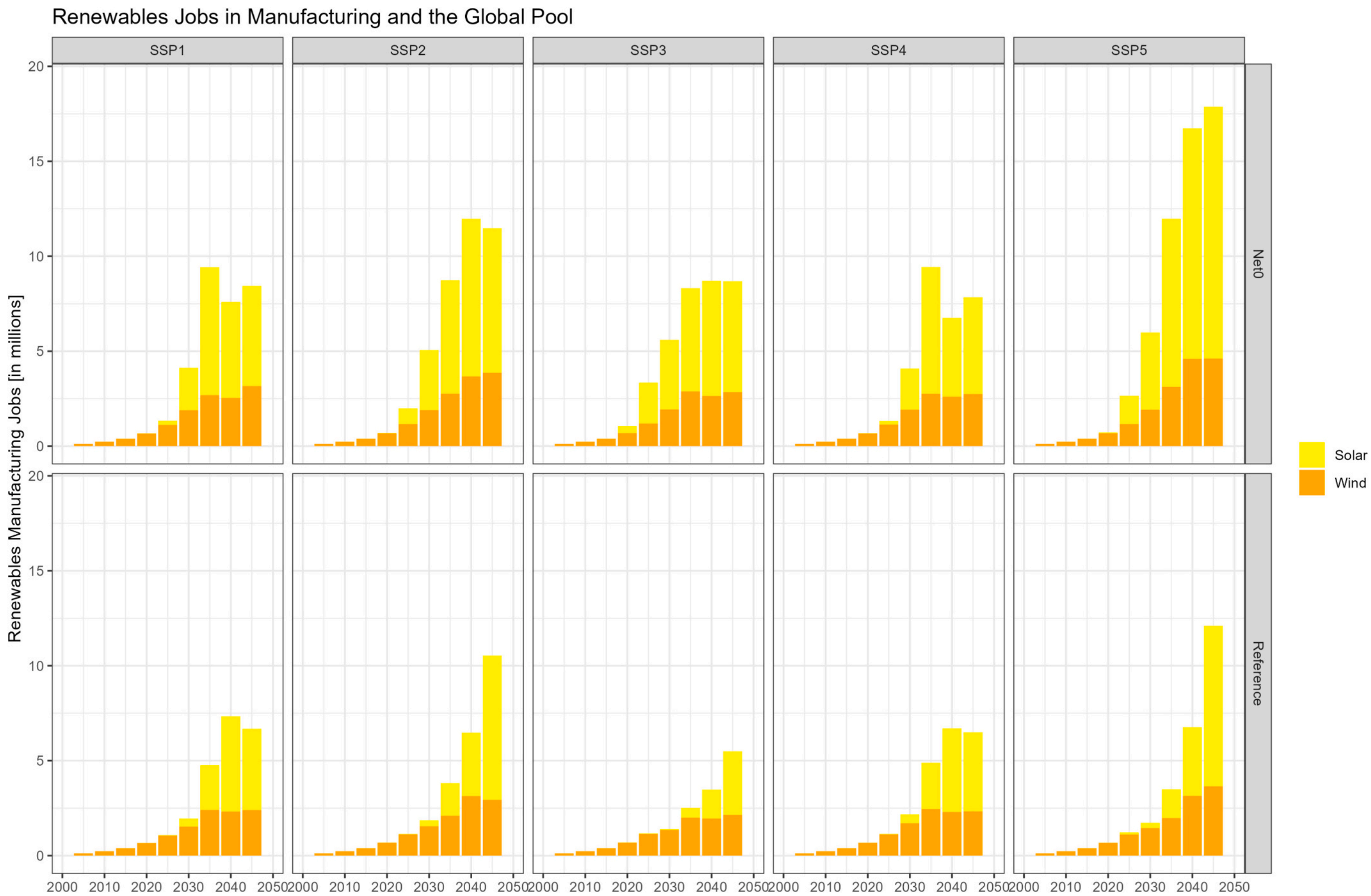

Fig. 6. The global pool of renewables manufacturing jobs. The global pool represents all new capacity for manufacturing renewables equipment beyond the 2020 levels in place (by region). It is not assigned to any region, as the location of this new production capacity largely depends on energy and industrial as well as trade policies, which are highly uncertain and region-specific today.

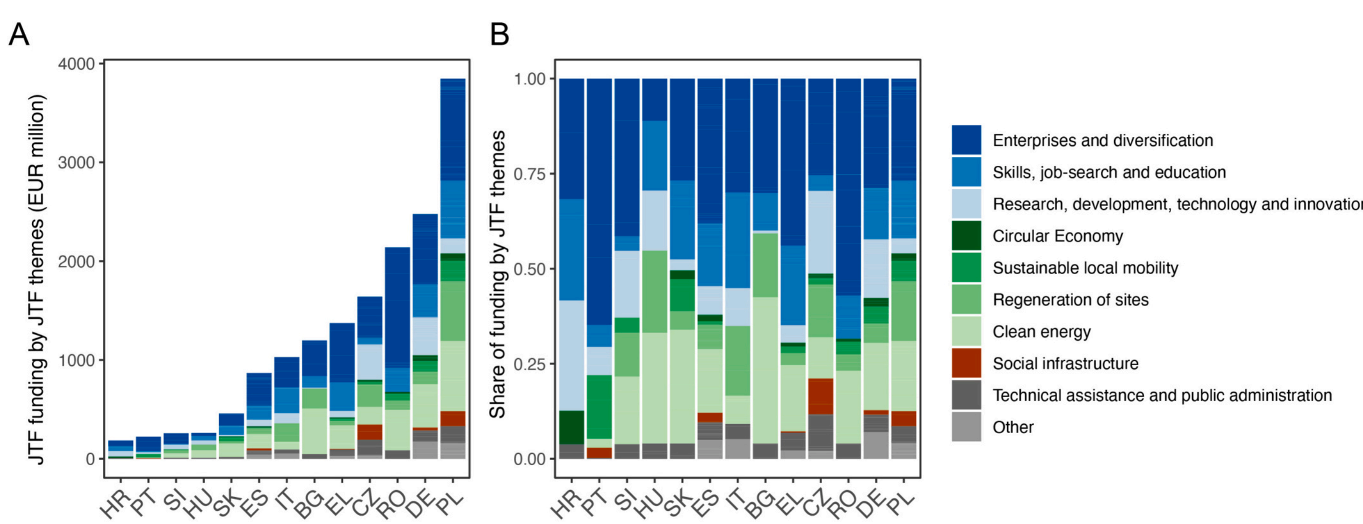

Fig. 7. Total (panel A) and share (panel B) of Just Transition Fund funding by themes. Funding data and allocation to themes are retrieved from the Cohesion Open Data Platform.

Conceptualization. **Jessica Jewell:** Writing – review & editing, Visualization, Formal analysis, Conceptualization. **Lola Nacke:** Writing – review & editing, Visualization, Formal analysis, Data curation. **Sandeep Pai:** Writing – review & editing, Data curation, Conceptualization. **Hisham Zerriffi:** Writing – review & editing, Visualization, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Johannes Emmerling reports financial support was provided by European Commission. The other authors declare that they have no known

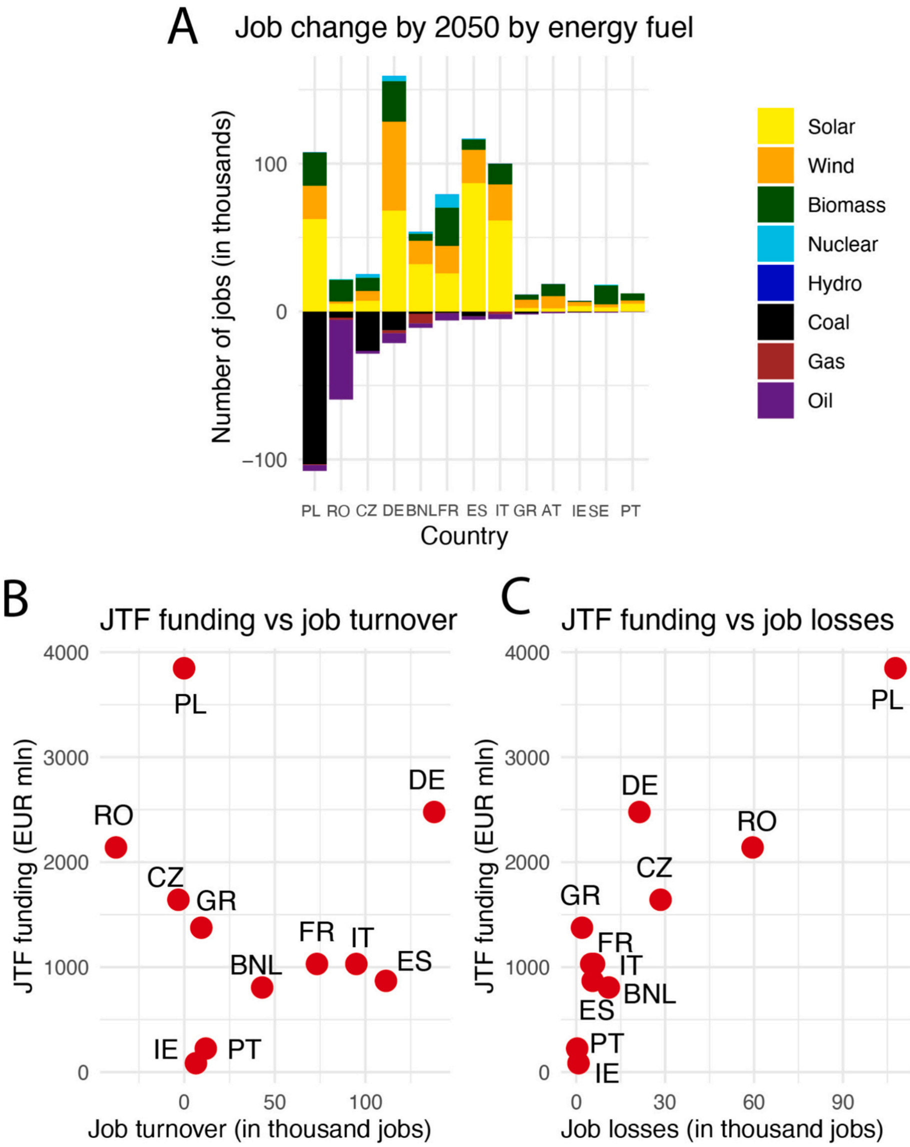

Fig. 8. Job impacts and JTF funding. Panel A shows job losses and gains (in thousand jobs) by using energy fuel under net zero by 2050. Panel B shows total job turnover (in thousand jobs) as the absolute amount of job losses, gains, and JTF funding. Panel C shows total job losses (in thousand jobs), and JTF funding.

competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The full primary dataset and scripts are available at https://github.com/witch-team/energy-jobs-dataset-iiasadb. The detailed results and scripts to generate all figures are available from the authors upon request.

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