



Climate policy accelerates structural changes in energy employment

Aman Malik^{a,*}, Christoph Bertram^a, Elmar Kriegler^{a,c}, Gunnar Luderer^{a,b}

^a Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany

^b Global Energy Systems Analysis, Technische Universität Berlin, Berlin, Germany

^c Faculty of Economics and Social Sciences, University of Potsdam, Potsdam, Germany

ARTICLE INFO

Keywords:

Energy supply
Employment
Just transition
Political feasibility
Mitigation pathways
Integrated assessment models

ABSTRACT

The employment implications of decarbonizing the energy sector have received far less attention than the technology dimension of the transition, although being of critical importance to policymakers. In this work, we adapt a methodology based on employment factors to project future changes in quantity and composition of direct energy supply jobs for two scenarios - (1) relatively weak emissions reductions as pledged in the nationally determined contributions (NDC) and (2) stringent reductions compatible with the 1.5 °C target. We find that in the near-term the 1.5°C-compatible scenario results in a net increase in jobs through gains in solar and wind jobs in construction, installation, and manufacturing, despite significant losses in coal fuel supply; eventually leading to a peak in total direct energy jobs in 2025. In the long run, improvements in labour productivity lead to a decrease of total direct energy employment compared to today, however, total jobs are still higher in a 1.5 °C than in an NDC scenario. Operation and maintenance jobs dominate future jobs, replacing fuel supply jobs. The results point to the need for active policies aimed at retraining, both inside and outside the renewable energy sector, to complement climate policies within the concept of a “just transition”.

1. Introduction

Reduction of emissions to reach the goals of the Paris Agreement will require a drastic energy transition— not only replacing fossil fuels by renewables for power generation, but higher end-use electrification, adoption of other low-carbon fuels, greater energy efficiency, and behavioural change (Dubois et al., 2019; Luderer et al., 2018; Weber, 2015).

The employment implications of decarbonizing the global energy sector system are of critical importance for the political salience of global mitigation pathways towards the goals of the Paris Agreement. Employment in the energy sector represents a tiny fraction (~1.2%) of total global employment. In 2019, against a total world employment of around 3.3 billion (15+ age) (ILO, 2020) there were only 40 million total world energy jobs (including production, distribution, and transportation) (IEA, 2020). Despite the insignificant overall share, energy sector jobs, especially on the supply side are directly and visibly linked to energy policy, are a source of indirect job creation, and important revenue for states and sub-regions. Thus, their consideration is critical to the speed and direction of energy transition.

An energy transition will lead to a change in the number, structure,

and required skill of jobs in the energy sector. To be sure, such a ‘conscious’, policy-induced transition will be superimposed to an autonomous long-term trend towards more service-based economies and increasing endogenous labour productivity (often accompanied by shift in factors of production from labour to capital). Whatever the type of transition, two things are clear – i) job creation and employment will continue to be a major political force affecting political decisions at all administrative levels, and ii) unlike a “natural transition”, there will be higher resistance to a “conscious transition”, especially because the long-history of incumbent technologies has resulted in strong political affiliations and lobbying power of relevant stakeholders, both regionally and nationally (Caldecott et al., 2016; Spencer et al., 2018). In some cases, such as coal, a which have a long history in certain regions, the loss would not only be that of employment but whole cultures – festivals, language etc.

The emerging field of “just transition”, defined as “a process by which economies that progress towards a green economy also strengthen each of the four pillars of decent work for all (i.e. social dialogue, social protection, rights at work and employment)” (ILO, 2018) has partly arisen to ease the opposition from people/groups, whose jobs which will be lost or at risk of being lost due to an energy

* Corresponding author.

E-mail address: amalik@pik-potsdam.de (A. Malik).

<https://doi.org/10.1016/j.enpol.2021.112642>

Received 15 January 2021; Received in revised form 23 September 2021; Accepted 30 September 2021

Available online 8 October 2021

0301-4215/© 2021 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

transition and to dilute the climate-specific focus of energy policies to include broader societal goals as put down in the Sustainable Development Goals SDGs, thereby increasing political support (McCauley and Heffron, 2018).

To contribute to both the ongoing effort on societal implications of energy transitions and political feasibility of scenarios (in the context of employment) requires first and foremost, a technology-specific quantification of energy sector jobs under alternative policy pathways. Thus, the first objective of the paper is to bring forth a transparent and in-depth methodology of estimating employment, including identifying its most important drivers. The second objective is to find differences in near-term and long-term structure of (global) jobs in the energy supply sector. Lastly, using this information, we seek to identify if employment transitions in the near-term could hinder decarbonisation.

The current study provides a method to account for employment effects of global climate policy scenarios, which although widely used in international scientific and policy communities (e.g., IPCC), hardly provide employment impacts. Previous studies using this method, include energy models (Dominish et al., 2019; Ram et al., 2019, 2022) and global integrated assessment models (IAM) (Pai et al., 2021). We go beyond these studies by discussing in detail the uncertain but crucial determinants for energy employment.

2. Methods

2.1. Overview of methodologies for estimating energy employment

Approaches to measure employment effects from renewable deployment or energy policies can broadly be broken down into two types – i) those using input–output (IO) or computable general equilibrium models (CGE) of the economy, and ii) those relying on analytical approaches (Kammen et al., 2004). The former includes flow of goods and services between different sectors of the economy, i.e., everything produced either serves as an input to the next level of production or an end-use purpose (IRENA, 2014). This allows finding the macro-economic impacts, including employment, of various energy and climate policies (Lambert and Silva, 2012). However, their coarse sectoral coverage prevents detailed breakdown of jobs by technology and/or fuel (for studies using the GEM-E3 CGE see, for e.g., Vandyck et al., 2016; Vrontisi et al., 2020).

The second approach and more relevant for this paper involves calculation of job intensities or employment factors (EF), defined as the number of jobs resulting from a unit investment or unit production of a physical commodity. When combined with energy transformation pathways they yield gross employment (only direct jobs) in that sector, although multipliers have been used to extend the scope of the approach to include indirect jobs (IRENA, 2014). A schematic of the employment factor approach is shown in Fig. 1. Direct jobs in the energy supply sector are broken down into stages or activities commonly associated with the supply chain or life cycle of a fuel/technology – manufacturing, construction and installation (C & I), operation and maintenance (O & M), fuel supply or production. Each activity and technology require a separate employment factor and when estimating jobs globally, also country-specific factors. Since manufacturing and C & I jobs are only created during the capacity addition, they are multiplied to the added capacity, O & M to the existing capacity, and fuel supply factors to the fuel production. The distinction of jobs in the value chain also helps to distinguish between the temporal (short-term manufacturing and C & I jobs), spatial (export-oriented manufacturing jobs vs. regional C & I and O & M jobs), and to some extent worker-skills characteristic of each technology.

2.1.1. Estimation of employment factors

An important pre-requisite for the calculation of jobs in this study is the employment factor (EF). EFs have been reported in literature either through I/O models, industry surveys, or back-calculation based on employment and capacity figures in a particular year (Cameron and van der Zwaan, 2015). Several studies have aggregated and analysed these EFs, providing important insights – i) Renewables EFs are reported more often than conventional technologies (Cameron and van der Zwaan, 2015; IRENA, 2014; Lambert and Silva, 2012), ii) Most studies are for/from OECD countries (Cameron and van der Zwaan, 2015; Rutovitz et al., 2015), iii) EFs for RE technologies are much higher than conventional technologies (measured in MW or MWh) (del Río and Burguillo, 2008), and solar PV C & I + manufacturing EFs are higher than corresponding wind EFs (Cameron and van der Zwaan, 2015), iv) Large variation exists in EFs for similar technologies (Breitschopf et al., 2012; Cameron and van der Zwaan, 2015). The large variation in turn exists because of unclear boundaries between-direct and indirect jobs and the various activities in the supply chain; local and export/import

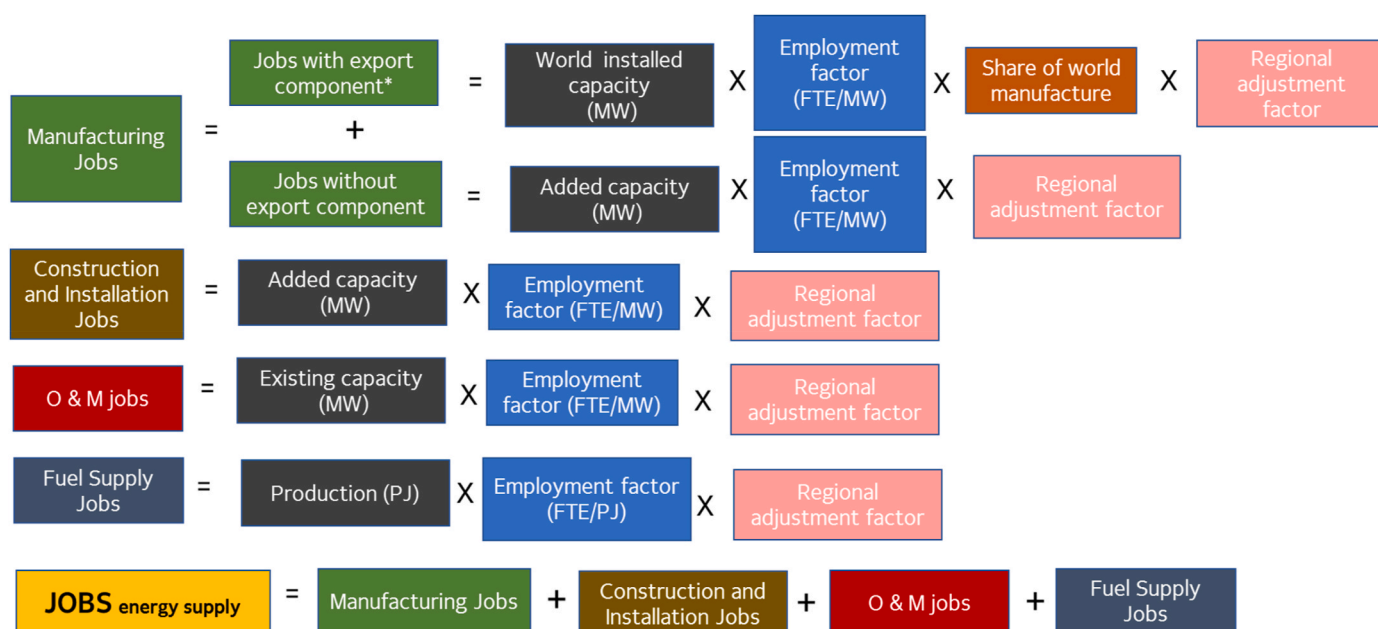


Fig. 1. Schematic explaining how direct energy supply jobs are calculated (Based on (Rutovitz et al., 2015, 2020).

component of jobs; specific country-contexts; and methodology (for e.g., not considering or reporting effects of economies of scale) (Cameron and van der Zwaan, 2015; IRENA, 2014). (Llera et al., 2013) further note that even with a consistent methodology for data collection, differences could still arise from maturity of the industry or availability of skilled workers.

2.1.2. Estimation of jobs using the EF approach

The EF approach has been used by many studies to calculate existing or future jobs in the energy sector, although most of them have been limited to regional or sub-regional scales and included only renewable technologies (Kammen et al., 2004; Stavropoulos and Burger, 2020). On the other hand, Rutovitz et al. have used the EF approach to calculate regionally differentiated global energy supply job estimates, divided by technology and type (Rutovitz et al., 2015; Rutovitz and Atherton, 2009; Rutovitz and Harris, 2012). Their methodological updates, published every three years, have updated the employment factors (as more data is discovered and/or made published) and expanded sectoral scope of jobs, e.g., from heat supply. Additions have also been made by (Ram et al., 2019, 2022) notably the inclusion of decommissioning, storage-battery, and power-to-X jobs, although these have not been used in this study due to very few (empirical) data points.

2.2. Approach and employment factors used in the study

The following sub-sections provide an in-depth review of methodology of Rutovitz et al. (2015) (the first paragraph) and is accompanied by changes and additions undertaken in the current work (second paragraph). These sub-sections cover – the source of employment factors (*Calculation of employment factors*), assumptions on how EFs evolve into the future (*Evolution of employment factors*), inclusion of trade of fuels to differentiate import and export components of jobs (*Trade*), differentiating manufacturing to account for uneven distribution of manufactured components (*Manufacturing jobs*), the accounting for technologies not included but important in energy employment (*Share of sub-technologies*), and the comparison of the resulting employment numbers with other literature (*Comparison with other sources*). Additional information, wherever required, is provided in the Supplementary Information (SI) and indicated in the paragraphs. The limitations of the study for e.g., the limited sectors where employment is estimated is provided in section 3.4.

2.2.1. Employment factors

As mentioned in the section before, the majority of EFs are only available for OECD countries and where available, often show a spread of values. To tackle these two issues Rutovitz and Atherton (2009) i) calculated EF per technology for OECD countries by a weighted average or average spanning the country-specific studies ii) calculated the EF for non-OECD countries by assuming a regional adjustment factor. For the base year (2015) this factor is the labour productivity (measured as GDP (or value added) per worker, of the whole economy excluding agriculture) for different nations relative to OECD. The adjustment factors are assumed to be the same across the different activities and technologies. iii) For a few studies that report EFs for non-OECD countries (for specific technologies), values from step ii) are replaced.

All EFs from Rutovitz et al. (2015) for OECD countries, are taken as values for the year 2020 in the current study but updated according to recent literature (Fragkos and Paroussos, 2018; IRENA, 2017a, 2017b). Following the methodology of Rutovitz et al. (2015), for countries without empirical data (mostly non-OECD), the EF is calculated by multiplying the OECD EF from Rutovitz et al. (2015) to a regional adjustment factor. Next, wherever possible, the resulting EFs have been replaced by country-specific values using studies mentioned in Rutovitz et al. (2015), recent studies (CEEW, 2019; Rutovitz et al., 2020; The Solar Foundation, 2020), or own calculations, e.g., coal EF. Lastly, some EFs are modified for specific countries/technologies by comparing the

resulting jobs from the EF approach with bottom-up regional and global studies providing job estimates. See SI section 1.1 for all these details.

2.2.2. Evolution of employment factors

To estimate jobs into the future, the employment factors need to be projected into the future. They calculate this by considering two developments – improvements in LP and decline factors.

- Improvement in labour productivity – EF for all countries into the future evolve with the improvements in labour productivity and are assumed to be equal to (inverse of) future GDP per capita (relative to OECD). For OECD countries, the factor is 1. The data on GDP per capita comes from the energy model used in the study.
- Decline factors – account for the reduction in EF as technologies mature. They are assumed to evolve with the changing capital costs of technologies, which is an input to the energy model. Decline factors are undifferentiated across activities, except for coal fuel supply. No decline factors are assumed for oil, gas, and nuclear fuel supply (Rutovitz et al., 2015, sec. 6).

To better understand the dynamics of the system in the future, the method is slightly simplified. The employment factors calculated IEA, 2020 are subjected to - i) (inverse of) future GDP per capita for all countries (relative to 2020), which is used as a proxy for improvements in labour productivity (SI section 2.3) and ii) capital costs of technologies relative to 2020 (SI section 2.2). Data for both comes from REMIND, except the improvements in labour productivity for coal fuel supply which are exogenous (see SI Section 1.1.4).

2.2.3. Trade

Since the import of fuels (coal, gas, and biomass) does not lead to creation of fuel supply jobs in the consuming country, it is important to differentiate between the amounts of fuel produced in the country vs. amount of fuel exported/imported.

Rutovitz et al. (2015) therefore make these assumptions for each region and time step.

Trade of coal, gas, oil, biomass, and nuclear¹ is endogenous to REMIND. This means that production/import/export of a fuel are readily available as outputs of the model. The fuel supply jobs (per region, fuel, and time step) are calculated by multiplying the employment factor with the amount of fuel produced in the country.

2.2.4. Manufacturing jobs

As for fuels, the manufacturing of components required for each technology are unevenly distributed in the world and need to be differentiated. For each region and time step, the proportion of local manufacturing and share of import from all other regions is assumed. It is also assumed that countries become self-sufficient over time. The same shares are applied for wind, solar PV, solar thermal power, geothermal power, and ocean (wave and tidal) technologies. All manufacturing for fossil fuel, biomass, hydro and nuclear technologies occurs within the region.

Instead of appropriating local vs. import shares for each region and time step, the current study assigns the share of total world production/manufacture to each region, although only for solar PV and wind. All other technologies are assumed to be manufactured domestically/regionally. These shares evolve such that those regions manufacture their own share of technology deployment locally by 2050. This assumption reflects that countries will promote domestic manufacturing to create jobs locally and for reasons of energy security; at the same time

¹ Employment factor for nuclear fuel supply is based on the secondary energy of nuclear-based electricity. Furthermore, no trade in uranium is assumed, i.e., all extraction and processing jobs are created place within the consuming regions.

income convergence assumed in the SSP2 socio-economic scenario underlying our results, and spill-over effects and diffusion of technological know-how will make manufacturing available widely. The methodology is also flexible to consider fixed manufacturing shares at current levels or other assumptions for the exploration of alternative socio-economic futures.

2.2.5. Share of sub-technologies

The energy model used by Rutovitz et al. (2015) includes sub-technologies or variants of traditional RE technologies –wind onshore and offshore; small and large hydro. Solar PV is however not differentiated into rooftop and utility.

REMIND currently includes a generic technology representation each for solar PV, solar CSP, wind, and hydro as power-generating technologies, i.e., it does not differentiate between solar PV utility and Solar PV rooftop, wind offshore and onshore, and small and big hydro. For the parametrization of costs and potentials, mostly the cheaper variants (utility scale PV, onshore wind and large hydro) have been considered, but some adjustments are done to account for additional potentials (e.g., of rooftop solar in densely populated countries like Japan and India). When the only consideration is cost, only larger and cheaper variants of the technology would be installed. In reality, different constraints, e.g., land, political feasibility, energy security etc. make it impractical to exclusively deploy the dominant variants (for e.g., Germany has 60% of its installed solar capacity as rooftop). Nevertheless, the share (in terms of installed capacity) of the alternative more expensive variants for most countries remains small. When estimating energy-related jobs, these sub-technology differentiations can play an important role because the more expensive variants tend to have higher employment factors (depending on the technology and activity) (CEEW, 2019; Rutovitz et al., 2015; The Solar Foundation, 2020).

To capture this effect to some extent, an external share controls how much of the additional and existing installation from REMIND (for solar PV, wind, and hydro), is supposed to be of the different sub-technology variants. A detailed explanation of this assumption is provided in SI Section 4.1.

Comparison with other sources.

Due to the different methods and boundaries (for e.g., between direct and indirect jobs) of measuring jobs, there is no 1:1 comparison between jobs estimates from this study with the previous literature. However, comparisons can still be useful to get an indication if the numbers from this study make sense and assess the relative confidence of estimates for different technologies/regions.

Such a preliminary comparison reveals that REMIND job estimates are well consistent to other national and global estimates (see SI section 1.2 for more a detailed comparison).

2.3. Scenario setup

The global integrated assessment model REMIND in its version 2.1 (Baumstark et al., 2021) was used to run two policy scenarios “NDC” and “1.5C” (described in Table 1). The evolution of employment factors into the future was explored by building EF-scenarios (ex-post). The eventual EF scenario selected included both capital costs and improvements in labour productivity driving the results. See SI section 2.1 on the process and explanation.

3. Results and discussion

3.1. Future energy sector jobs

IEA, 2020, the total direct energy supply jobs in the world are around 20.4 million, with a roughly equal proportion between fossil and non-fossil jobs (Fig. 2a). These jobs are dominated by coal (4.3 million) followed by Hydro, solar PV, and Gas (~3 million each) (Fig. 2b and c). Fig. 2c shows that most of the current coal jobs are in fuel supply

Table 1

Scenario name and description used in the study.

Scenario name	Scenario description
NDC	Reaching NDC targets (as submitted to UNFCCC until 2019, a rather conservative policy scenario as new neutrality pledges and 2030 targets announced by EU, China, Japan, and others are not considered) in 2030 via regionally differentiated, iteratively adjusted carbon prices, and assuming gradual convergence to average carbon prices thereafter.
1.5C	Immediate introduction of regionally differentiated carbon prices which converge in 2050, iteratively adjusted to fulfil a constraint in carbon budget (900 GtCO ₂) from 2011 to time of net-zero global CO ₂ emissions. Carbon prices after reaching net-zero increase moderately, leading to moderate net-negative emissions thereafter, and a 66% chance of limiting temperature increase below 1.5 °C at the end of century (2100).

(purple) whereas solar PV jobs are almost equally split between construction and installation (C & I) (green), and manufacturing (rust yellow). Furthermore, fuel supply constitutes the largest share (~50%) of the current energy supply jobs (see also Fig. S19, which is directly expressed as shares).

In 2050, the total energy supply jobs decrease to 16 million under the NDC scenario and to 18.2 million with 1.5 °C policies (Fig. 2d). Independent of the policy scenario, the share of fuel supply jobs (purple) strongly decreases – from 50% IEA, 2020 (mainly in coal, biomass, oil, and gas) to 27% in NDC and 24% (mainly in biomass and oil) in the 1.5 °C scenario. Also, in absolute terms, the fossil fuel supply jobs decrease strongly in both scenarios, although the absolute fossil fuel supply differs by a factor of 2 in 2050 (see Fig. S17b). On the other hand, the share of fossil jobs decreases to 12–25% of total jobs, depending upon the scenario. In both NDC and 1.5 °C policy case, wind jobs dominate in 2050, and operation and maintenance (O & M) becomes the activity employing the most people (Fig. 2b and Fig. S19). In both scenarios, there is a steep increase in power generation and shift from fossils to non-fossils (mainly wind and solar), which accompanied by wide-scale end-use electrification reduces the need for conventional fuels (Fig. S17). Although renewable technologies require more jobs per MW,² their exponential uptake is also accompanied by steeply decreasing employment factors (due to decreasing capital costs and improvements in labour productivity) (Fig. S16). This eventually leads to lesser people employed directly in the energy supply sector than now.³

A good contrast on how employment factors eventually influence the shape of the curve is between wind and solar PV. Although installations for both these technologies increase steeply in the future (with solar growths higher than wind) (see Fig. S17), EFs for solar also have a sharper decline (Fig. S16). The net effect is that while jobs in wind increase almost linearly over time and become the largest employer in 2050 (Fig. 2b), solar PV jobs might be prone to periods of boom, bust, and eventual stagnation (Fig. 2b).

3.2. Near-term jobs

In the near term, there is a net increase in jobs for a 1.5 scenario (+838,500), compared to a net decrease in the NDC scenario

² Comparison across per technology per MW fails to capture fuel supply jobs for fossil technologies. The correct unit of measurement to compare employment across technologies should be per GWh. However, the point here is the rapid decrease in employment factors of VRE technologies in comparison to traditional technologies.

³ A big caveat here is that jobs which might become significant in the future – storage, transmission and distribution, decommissioning, hydrogen production, and all jobs on the demand side, including energy efficiency have not been included due to data limitations. See Section 3.4.

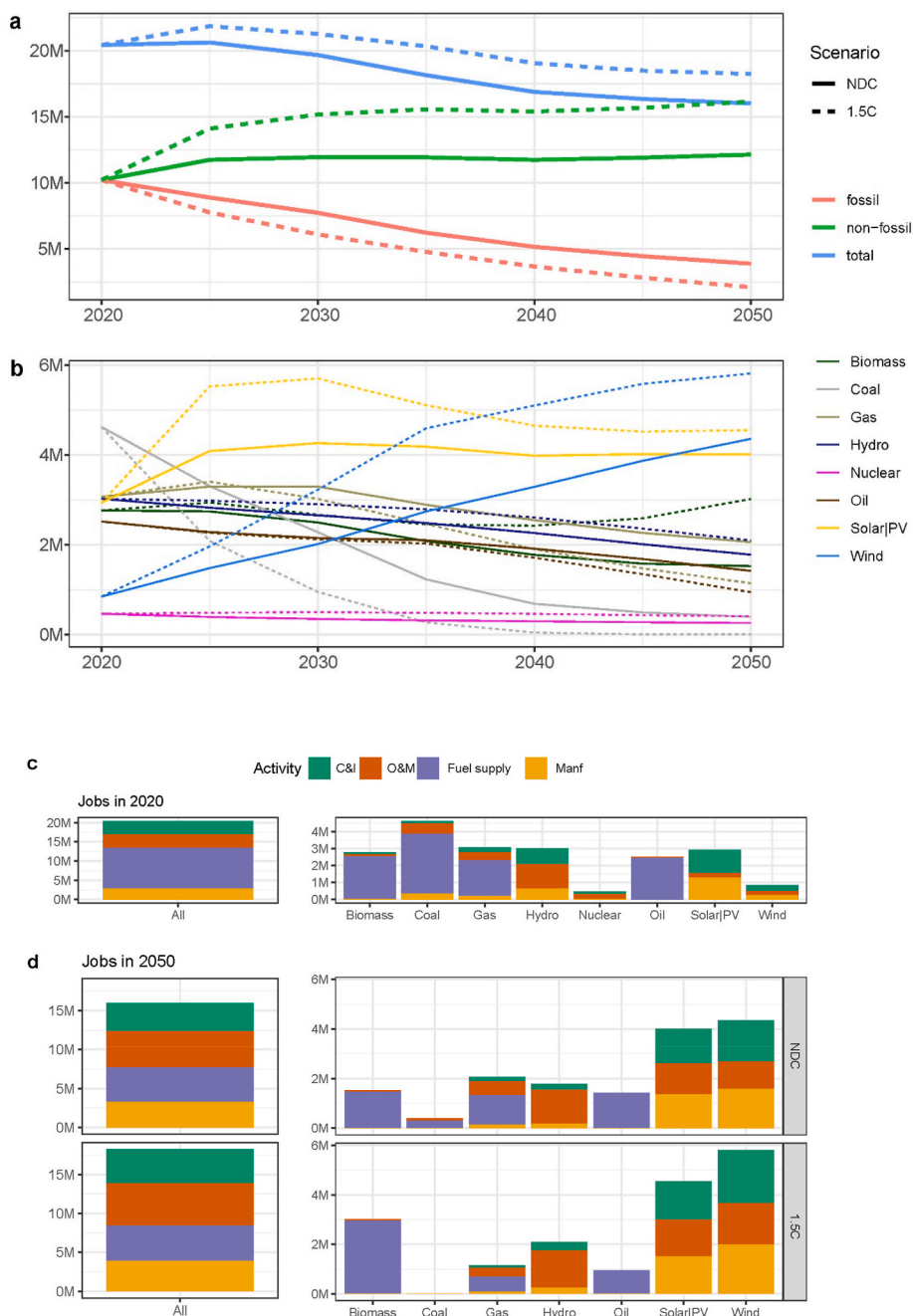


Fig. 2. Total world jobs by (a) scenario and type (Solar CSP and Geothermal not shown for clarity) (b) by scenario and technology, (c) bar plots for jobs by activity per technology IEA, 2020 and (d) in 2050 for NDC and 1.5 policy cases.

(−760,000) (in 2030 compared IEA, 2020) (Fig. 3a). Losses in the fossil sector are mainly from coal fuel supply (85–90%) and amount to 2.2–3.7 million (depending on the scenario), while gains are mainly from C & I and Manufacturing activities in solar and wind (~90%) and amount to 2.5–4.3 million (Fig. 3b).

The competing effect of capacity/production and employment factor on jobs for different technologies and scenarios can be seen in Fig. 3c. The black diagonal line represents the case where change in jobs is entirely due to change in capacity/production. The further the dot is from the linear line, the stronger the effect of the employment factor on total jobs. For e.g., while capacity increases almost 700% for solar PV in the 1.5C case, jobs increase only 94%. For coal mining in NDC while production decreases 12%, jobs decrease 51%. Comparing this with other fossil fuels (still for the NDC), we see that an increase of 9% of oil

production, leads to 15% decrease in jobs, while for gas a 17% increase in production, leads to a 7% increase in jobs implying a lower effect of labour productivity improvements.⁴

3.3. Implications of the results

In Fig. 2a we showed that even with a significant expansion in

⁴ This is by design. Employment factors in coal change depending upon historical trends while oil and gas employment factors change with (inverse of) GDP/capita.

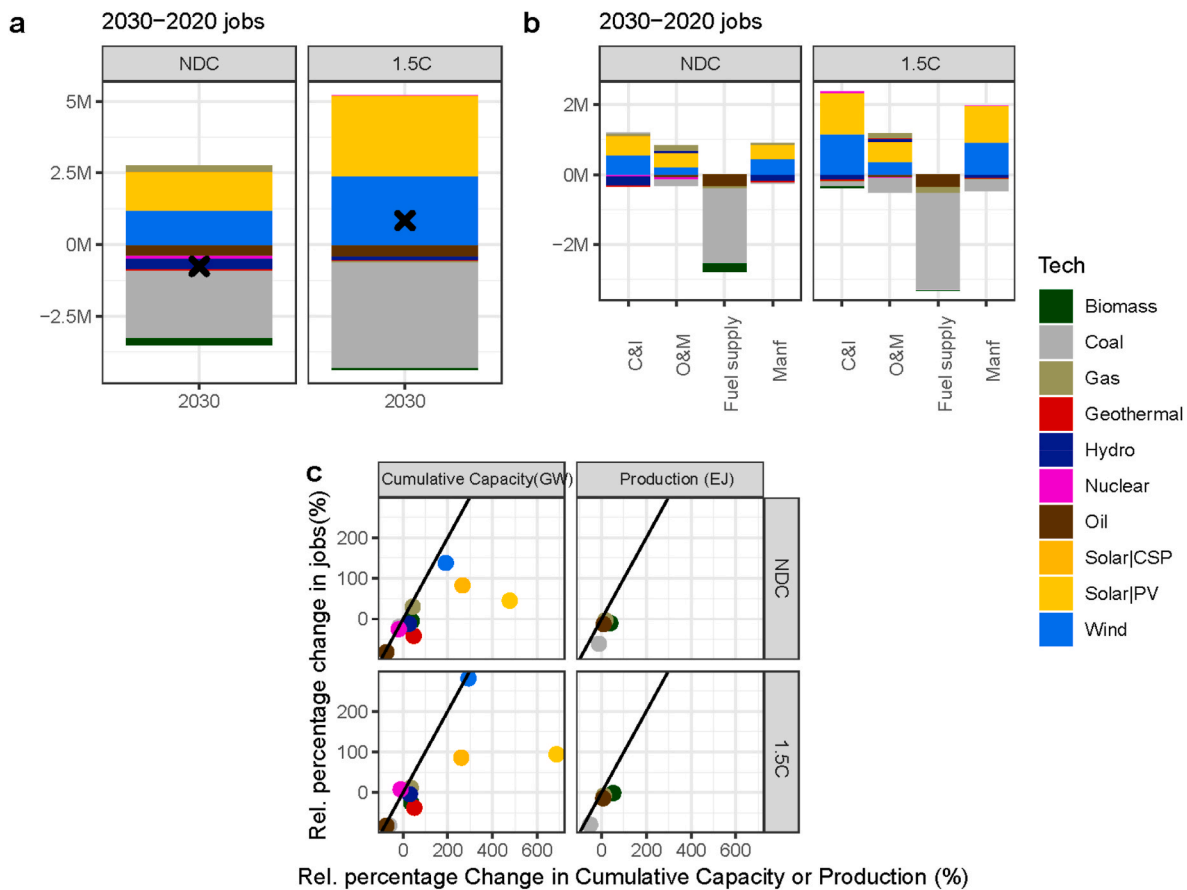


Fig. 3. Difference in Global jobs (2030-2020) for (a) different technologies (with cross denoting the net gain/loss) and (b) technologies and activities, and (c) relative percentage change in jobs vs. relative percentage change in capacity (GW)/production (EJ) (in 2030 relative to 2020) for the two policy scenarios.

renewables, energy supply jobs, after peaking around 2025, decrease because of the strong effect of increasing labour productivity and decrease in capital costs.⁵ This result is not surprising. Under the assumption of decreasing capital costs, increasing wages and constant share of labour in total capital costs, employment factors must fall faster than the capital costs.

The employment-related challenges in the oncoming energy transition for both the NDC and policy cases, can be understood from Fig. 3b. In NDC, almost 2.7 million jobs are lost in fuel supply, compared to 2.5 million gained through solar PV and wind. Thus, even under an ideal assumption that all coal workers manage could be retrained to be employed in these new jobs, these will not be enough. How many of the new jobs go eventually to people who lost them depends on many factors – skill requirements and location of created and lost jobs, options for retraining and relocating, incentives and compensation. Additionally, in the case of manufacturing, not all jobs might be created locally (at least in the near term), particularly for late entrant countries that fall back in technology development. On the other side, countries currently mostly relying on fuel imports and therefore sustaining fuel supply jobs abroad can potentially increase their domestic energy-related jobs by transitioning to local renewable energy forms.

For a 1.5 scenario, the challenges already present in the NDC scenario are somewhat exacerbated. Although there is a net increase in jobs, an extra 1.3 million jobs in fuel supply will be lost over the same period. Since most of these lost jobs would be regionally concentrated,

this can result in additional challenges for policy. To alleviate the related political economy concerns will require faster and more intensive engagement between firms, employees, state government and local administration. This might not be easy considering that – i) areas of and around coal mines might not be prime areas for renewable energy development (Pai et al., 2020) and thus might not immediately gain from increasing RE deployment, ii) unlike C & I and O & M jobs, manufacturing jobs are often not local, and thus wouldn't necessarily contribute to job growth, iii) Subsequent increases in the same amount of RE capacity will employ lesser people and could lead to conditions of boom and bust.

In either case, the first step in the direction of reducing challenges and increasing support of the energy transition would be constituting regional and sub-regional studies on what, how, and how much of new RE technologies could (either theoretically or economically) substitute job losses in the fuel supply (mainly coal) at a sub-regional level (see for example Alves Dias et al., 2018; Pai et al., 2020), and then progressively move to options directly outside the energy sector. These should pay attention to the fact that, i) C & I jobs could be considered as long-term jobs (and thus on par with O & M and fuel supply jobs), under increasing RE capacity, ii) sub-technologies like solar-rooftop, small-hydro often employ much more people than large-scale solar-utility and hydropower projects.

Over decades, the results show various promising aspects of large-scale RE deployment. Firstly, fuel supply jobs in fossil are progressively replaced by O & M jobs, both of which offer job stability (see Fig. S19 and Fig. S20 for share of activity until 2050). Secondly, unlike the present day where majority of supply jobs are concentrated in coal, oil, and gas-producing countries; in a RE-based energy system jobs would be more evenly spread across the whole world, with the possible

⁵ Both these factors are essentially improvements in labour productivity, with the former mostly occurring outside the energy sector (e.g., artificial intelligence, drones etc.), while the latter occur mostly within the sector.

exception for manufacturing of components, though increasing transport costs in decarbonized futures and a focus to create jobs locally might incentivize stronger local production. Thirdly, within a country, energy supply will be distributed both across remote parts containing utility-scale solar and wind farms but also in cities as solar rooftop, though the relative importance of these options has implications for costs, grid requirements and broader sustainability considerations, and largely depends on policy settings.

3.4. Limitations and future research

Our result must be read with the important caveat that we only include direct energy jobs from the currently existing supply technologies. We thus do not include many other energy-related jobs on both the supply and demand sides, which could become significant into the future. These include Transmission and Distribution (T & D), Battery storage, Decentralised PV, Heating (solar thermal, heat pumps etc.), hydrogen production, and energy efficiency. Previous studies have shown that significant investment would need to go to these sectors/technologies/fuels (Bertram et al., 2021; McCollum et al., 2018), thus also highlighting their importance. Employment factors for some of these have been provided by Ram et al. (2019, 2022), however given that they are based on a few empirical studies and/or are immature technologies, their values are highly uncertain and have not been used here. Furthermore, given the specific scope of our methodology, we are unable to comment and quantify how mitigation policies would influence job numbers and structure outside (direct) energy supply, for e.g., in the automotive or chemical industry sector.

The employment factor approach relies on accurate estimation of employment factors for a technology. Moreover, an estimation of global energy supply jobs requires such values for major countries around the world. As mentioned previously, although most of the energy supply jobs exist in non-OECD countries, employment factor studies are mostly available for OECD countries. Thus, besides the need of studies calculating employment factors for both conventional and new technologies, the spatial scope needs to cover more non-OECD countries.

4. Conclusions and policy implications

Our estimation of employment in the energy supply sector was based on the employment factor approach, whose different assumptions were explored before. Using this approach, we quantified direct jobs in the energy supply sector for two scenarios – NDC (weak climate mitigation) and 1.5C (strong climate mitigation). We showed that for both policy and NDC scenarios the direct energy supply jobs decrease in the future compared to 2020, however ambitious policy jobs are higher than the latter. Secondly, the increase in cumulative solar and wind capacity, against the decrease in total fuel production means that the O & M jobs overtake fuel supply as the major share of total jobs. Lastly, in the near-term, net gains are seen only in the 1.5C policy case, however, lead to considerable losses in the coal mining sector. This exposes the trade-off of ambitious climate policy – both of increasing job losses and gains, and eventually the dichotomy of political support – in the form of winners and losers. To align both towards a strong climate ambition will require that (people/regions/firms) currently working on the fossil side are made available the opportunities in the new RE energy world or compensated through other means.

5. Data availability

The input data, including the code to produce the figures, both in the main text and SI, is available here - <https://gitlab.pik-potsdam.de/amalik/energy-employment>. The scenarios were prepared using the open-source integrated assessment model REMIND (<https://github.com/remindmodel/remind> and <https://zenodo.org/record/4091409>).

CRedit authorship contribution statement

Aman Malik: designed the study, designed and produced the figures, and wrote the manuscript. **Christoph Bertram:** designed the study and provided inputs to the manuscript. **Elmar Kriegler:** provided inputs to the manuscript. **Gunnar Luderer:** provided inputs to the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank the two anonymous reviewers for their comments and feedback.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.enpol.2021.112642>.

Funding sources

The study has been produced as part of the NAVIGATE (Next generation of AdVanced InteGrated Assessment modelling to support climate policy making - European Union's Horizon 2020 grant agreement No 821124), ENGAGE (European Union's Horizon 2020 - grant agreement No 821471) projects, and University of Tokyo's "Global Commons Stewardship Framework" project.

References

- Alves Dias, P., Kanellopoulos, K., Medarac, H., Kapetaki, Z., Miranda-Barbosa, E., Shortall, R., Czako, V., Telsnig, T., Vazquez-Hernandez, C., Lacial Arántegui, R., Nijs, W., Gonzalez Aparicio, I., Trombetti, M., Mandras, G., Peteves, E., Tzimas, E., European Commission, Joint Research Centre, 2018. EU Coal Regions Opportunities and Challenges Ahead. <https://doi.org/10.2760/064809>.
- Baumstark, L., Bauer, N., Benke, F., Bertram, C., Bi, S., Gong, C.C., Dietrich, J.P., Dirmaichner, A., Giannousakis, A., Hilaire, J., Klein, D., Koch, J., Leimbach, M., Levesque, A., Madeddu, S., Malik, A., Merfort, A., Merfort, L., Odenweller, A., et al., 2021. REMIND2.1: transformation and innovation dynamics of the energy-economic system within climate and sustainability limits. *Geosci. Model Dev. Discuss. (GMDD)* 1–50. <https://doi.org/10.5194/gmd-2021-85>, 2021.
- Bertram, C., Riahi, K., Hilaire, J., Bosetti, V., Drouet, L., Fricko, O., Malik, A., Nogueira, L., Zwaan, B. van der, Ruijven Vuuren, D. P. van, B. van, Weitzel, M., Longa, F.D., Boer, H.-S. de, Emmerling, J., Fosse, F., Fragkiadakis, K., Harmsen, M., Keramidis, K., Luderer, G., 2021. Energy system developments and investments in the decisive decade for the Paris Agreement goals. *Environmental Research Letters* 16 (7). <https://doi.org/10.1088/1748-9326/ac09ac>.
- Breitschopf, B., Nathani, C., Resch, G., 2012. Methodological Guidelines for Estimating the Employment Impacts of Using Renewable Energies for Electricity Generation.
- Caldecott, B., Kruitwagen, L., Dericks, G., Tulloch, D.J., Kok, I., Mitchell, J., 2016. Stranded assets and thermal coal: an analysis of environment-related risk exposure. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.2724550>.
- Cameron, L., van der Zwaan, B., 2015. Employment factors for wind and solar energy technologies: a literature review. *Renew. Sustain. Energy Rev.* 45, 160–172. <https://doi.org/10.1016/j.rser.2015.01.001>.
- CEEW, 2019. Powering Jobs Growth with Clean Energy. CEEW. <https://www.ceew.in/sites/default/files/CEEW-Jobs-Issue-Brief-2019-2-web-24Jul19.pdf>.
- del Río, P., Burguillo, M., 2008. Assessing the impact of renewable energy deployment on local sustainability: towards a theoretical framework. *Renew. Sustain. Energy Rev.* 12 (5), 1325–1344. <https://doi.org/10.1016/j.rser.2007.03.004>.
- Dominish, E., Briggs, C., Teske, S., Mey, F., 2019. Just transition: employment projections for the 2.0 °C and 1.5 °C scenarios. In: Teske, S. (Ed.), *Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5°C and +2°C*. Springer International Publishing, pp. 413–435. https://doi.org/10.1007/978-3-030-05843-2_10.
- Dubois, G., Sovacool, B., Aall, C., Nilsson, M., Barbier, C., Herrmann, A., Bruyère, S., Andersson, C., Skold, B., Nadaud, F., Dorner, F., Moberg, K.R., Ceron, J.P., Fischer, H., Amelung, D., Baltruszewicz, M., Fischer, J., Benevise, F., Louis, V.R., Sauerborn, R., 2019. It starts at home? Climate policies targeting household consumption and behavioral decisions are key to low-carbon futures. *Energy*

- Research & Social Science 52, 144–158. <https://doi.org/10.1016/j.erss.2019.02.001>.
- Fragkos, P., Paroussos, L., 2018. Employment creation in EU related to renewables expansion. *Appl. Energy* 230, 935–945. <https://doi.org/10.1016/j.apenergy.2018.09.032>.
- IEA, 2020. Sustainable Recovery—World Energy Outlook Special Report. IEA, p. 174.
- ILO, 2018. World Employment and Social Outlook 2018 – Greening with Jobs, p. 189.
- ILO, 2020. *ILO Data Explorer*. ILOSTAT Explorer. https://www.ilo.org/shinyapps/bulkeexplorer40/?lang=en&segment=&id=SDG_0111_SEX_AGE_RT_A.
- IRENA, 2014. Renewable Energy and Jobs, p. 144. 2013.
- IRENA, 2017a. Renewable Energy Benefits: Leveraging Local Capacity for Onshore Wind. International Renewable Energy Agency, p. 64.
- IRENA, 2017b. Renewable Energy Benefits-Leveraging Local Capacity for Solar PV. International Renewable Energy Agency. https://cms.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Jun/IRENA_Leveraging_for_Solar_PV_2017.ashx.
- Kammen, D.M., Kapadia, K., Fripp, M., 2004. Putting Renewables to Work: How Many Jobs Can the Clean Energy Industry Generate? Goldman School of Public Policy, University of California Berkeley, p. 28. <http://socrates.berkeley.edu/~rael/papers.html>.
- Lambert, R.J., Silva, P.P., 2012. The challenges of determining the employment effects of renewable energy. *Renew. Sustain. Energy Rev.* 16 (7), 4667–4674. <https://doi.org/10.1016/j.rser.2012.03.072>.
- Llera, E., Scarpellini, S., Aranda, A., Zabalza, I., 2013. Forecasting job creation from renewable energy deployment through a value-chain approach. *Renew. Sustain. Energy Rev.* 21, 262–271. <https://doi.org/10.1016/j.rser.2012.12.053>.
- Luderer, G., Vrontisi, Z., Bertram, C., Edelenbosch, O.Y., Pietzcker, R.C., Rogelj, J., Boer, H.S.D., Drouet, L., Emmerling, J., Fricko, O., Fujimori, S., Havlík, P., Iyer, G., Keramidas, K., Kitous, A., Pehl, M., Krey, V., Riahi, K., Saveyn, B., Kriegler, E., 2018. Residual fossil CO₂ emissions in 1.5–2 °C pathways. *Nat. Clim. Change* 1. <https://doi.org/10.1038/s41558-018-0198-6>.
- McCauley, D., Heffron, R., 2018. Just transition: integrating climate, energy and environmental justice. *Energy Pol.* 119, 1–7. <https://doi.org/10.1016/j.enpol.2018.04.014>.
- McCollum, D.L., Zhou, W., Bertram, C., de Boer, H.-S., Bosetti, V., Busch, S., Després, J., Drouet, L., Emmerling, J., Fay, M., Fricko, O., Fujimori, S., Gidden, M., Harmsen, M., Huppmann, D., Iyer, G., Krey, V., Kriegler, E., Nicolas, C., et al., 2018. Energy investment needs for fulfilling the Paris agreement and achieving the sustainable development goals. *Nature Energy* 3 (7), 589–599. <https://doi.org/10.1038/s41560-018-0179-z>.
- Pai, S., Emmerling, J., Drouet, L., Zerriffi, H., Jewell, J., 2021. Meeting well-below 2 °C target would increase energy sector jobs globally. *One Earth* 4 (7), 1026–1036. <https://doi.org/10.1016/j.oneear.2021.06.005>.
- Pai, S., Zerriffi, H., Jewell, J., Pathak, J., 2020. Solar has greater techno-economic resource suitability than wind for replacing coal mining jobs. *Environmental Research Letters* 15 (3). <https://doi.org/10.1088/1748-9326/ab6c6d>.
- Ram, M., Aghahosseini, A., Breyer, C., 2019. Job Creation during the Global Energy Transition towards 100% Renewable Power System by 2050. *Technological Forecasting and Social Change*, 119682. <https://doi.org/10.1016/j.techfore.2019.06.008>.
- Ram, M., Osorio-Aravena, J.C., Aghahosseini, A., Bogdanov, D., Breyer, C., 2022. Job creation during a climate compliant global energy transition across the power, heat, transport, and desalination sectors by 2050. *Energy* 238, 121690. <https://doi.org/10.1016/j.energy.2021.121690>.
- Rutovitz, J., Atherton, A., 2009. ENERGY SECTOR JOBS to 2030: A GLOBAL ANALYSIS Final Report Version 2. Institute for Sustainable Futures, University of Technology, Sydney. <https://opus.lib.uts.edu.au/bitstream/10453/35047/1/rutovitzatherton2009greenjobs.pdf>.
- Rutovitz, J., Briggs, C., Dominish, E., Nagrath, K., 2020. Renewable Energy Employment in Australia: Methodology. UTS Institute for Sustainable Futures.
- Rutovitz, J., Dominish, E., Downes, J., 2015. Calculating Global Energy Sector Jobs—2015 Methodology Update. Institute for Sustainable Futures, University of Technology, Sydney. <https://opus.lib.uts.edu.au/bitstream/10453/43718/1/Rutovitzetal2015Calculatingglobalenergysectorjobsmethodology.pdf>.
- Rutovitz, J., Harris, S., 2012. Calculating Global Energy Sector Jobs—2012 Methodology. Institute for Sustainable Futures, University of Technology, Sydney. <https://opus.lib.uts.edu.au/bitstream/10453/35045/1/rutovitzharris2012globalenergyjobsmethycalc.pdf>.
- Spencer, T., Colombier, M., Sartor, O., Garg, A., Tiwari, V., Burton, J., Caetano, T., Green, F., Teng, F., Wiseman, J., 2018. The 1.5 °C target and coal sector transition: at the limits of societal feasibility. *Clim. Pol.* 18 (3), 335–351. <https://doi.org/10.1080/14693062.2017.1386540>.
- Stavropoulos, S., Burger, M.J., 2020. Modelling strategy and net employment effects of renewable energy and energy efficiency: a meta-regression. *Energy Pol.* 136, 111047. <https://doi.org/10.1016/j.enpol.2019.111047>.
- The Solar Foundation, 2020. National Solar Job Census 2019. <https://www.thesolarfoundation.org/wp-content/uploads/2020/03/SolarJobsCensus2019.pdf>.
- Vandyck, T., Keramidas, K., Saveyn, B., Kitous, A., Vrontisi, Z., 2016. A global stocktake of the Paris pledges: implications for energy systems and economy. *Global Environ. Change* 41, 46–63. <https://doi.org/10.1016/j.gloenvcha.2016.08.006>.
- Vrontisi, Z., Fragkiadakis, K., Kannavou, M., Capros, P., 2020. Energy system transition and macroeconomic impacts of a European decarbonization action towards a below 2 °C climate stabilization. *Climatic Change* 162 (4), 1857–1875. <https://doi.org/10.1007/s10584-019-02440-7>.
- Weber, E.U., 2015. Climate change demands behavioral change: what are the challenges? *Soc. Res.: Int. Q.* 82 (3), 561–580. <https://muse.jhu.edu/article/603150>.