Meeting well-below 2°C target would increase energy sector jobs globally

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Article

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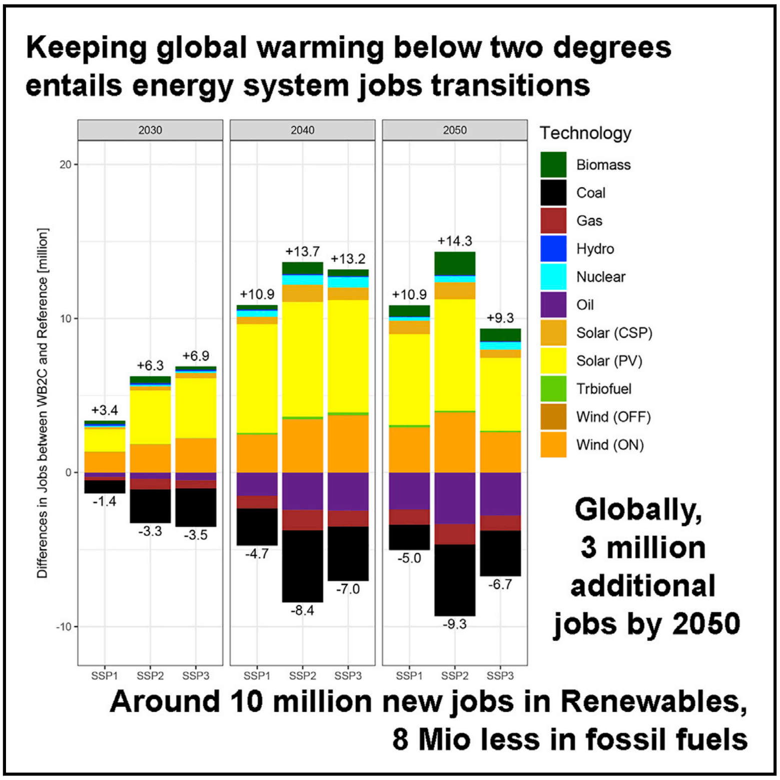
Graphical abstract



Highlights

- Implementing the Paris Agreement targets will entail shifts in energy jobs
- Globally, we find an increase in direct global energy jobs under well-below 2°C
- Over 80% of energy jobs by 2050 are expected to be in renewables
- Solar and wind manufacturing sectors will provide millions of jobs globally

Authors

Sandeep Pai, Johannes Emmerling, Laurent Drouet, Hisham Zerriffi, Jessica Jewell

Correspondence

johannes.emmerling@eiee.org

In brief

If the world meets the 2°C target, by 2050, there may be an increase in direct energy jobs from today's 18 million to 26 million. While fossil fuel extraction jobs will decline dramatically, renewable energy jobs will expand rapidly. By 2050, we estimate that around 84% of all energy jobs could be in solar and wind generation and manufacturing. While most countries will see net job increase, China and fossil-fuel-exporting countries could witness net job losses.

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Meeting well-below 2°C target would increase energy sector jobs globally

Sandeep Pai,[1] Johannes Emmerling,[2,8,*] Laurent Drouet,[2] Hisham Zerriffi,[3,4] and Jessica Jewell[5,6,7]
[1]Institute for Resources, Environment and Sustainability, The University of British Columbia, 2202 Main Mall, Vancouver, BC V6T 1Z4, Canada
[2]RFF-CMCC European Institute on Economics and the Environment (EIEE), Centro Euro-Mediterraneo sui Cambiamenti Climatici, Via Bergognone 34, 20144 Milan, Italy
[3]Faculty of Forestry, The University of British Columbia, 2424 Main Mall, Vancouver, BC V6T 1Z4, Canada
[4]Payne Institute, Colorado School of Mines, 1500 Illinois St, Golden, CO 80401, USA
[5]Department of Space, Earth and Environment, Division of Physical Resource Theory, Sweden Chalmers University, SE-412 96 Gothenburg, Sweden
[6]Centre for Climate and Energy Transformations & Department of Geography, Faculty of Social Sciences, Postbox 7802, University of Bergen, 5020 Bergen, Norway
[7]Advancing Systems Analysis Program, International Institute for Applied Systems Analysis, Schlossplatz 1, Laxeburg 2360, Austria
[8]Lead contact
*Correspondence: johannes.emmerling@eiee.org
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SCIENCE FOR SOCIETY To keep global warming well-below 2°C, fossil fuels need to dramatically decline and be replaced by low-carbon energy sources. While the technologies to replace fossil fuels are widely available, support for their expansion is often linked to the impact they have on fossil fuel jobs. Here, we analyze this question quantitatively by creating a novel dataset of job footprints in over 50 countries. These job intensities are applied to output from an integrated assessment model. We find that, by 2050, jobs in the energy sector would grow from today's 18 million to 21 million in the reference scenario and even more, to 26 million, under our well-below 2°C scenario. Overall, in 2050, under well-below 2°C scenario, of the total jobs, 84% would be renewable jobs, 11% fossil fuels, and 5% nuclear jobs. While fossil fuel extraction jobs rapidly decline, these losses are compensated by gains in solar and wind jobs, particularly in the solar and wind manufacturing sector.

SUMMARY

To limit global warming to well-below 2°C (WB2C), fossil fuels must be replaced by low-carbon energy sources. Support for this transition is often dampened by the impact on fossil fuel jobs. Previous work shows that pro-climate polices could increase employment by 20 million net energy jobs, but these studies rely on Organisation for Economic Co-operation and Development (OECD) jobs data, assumptions about jobs in non-OECD countries, and a single baseline assumption. Here we combine a global dataset of job intensities across 11 energy technologies and five job categories in 50 countries with an integrated assessment model under three shared socioeconomic pathways. We estimate direct energy jobs under a WB2C scenario and current policy scenarios. We find that, by 2050, energy sector jobs would grow from today's 18 million to 26 million under a WB2C scenario compared with 21 million under the current policy scenario. Fossil fuel extraction jobs would rapidly decline, but losses will be compensated by gains in solar and wind jobs, particularly in the manufacturing sector (totaling 7.7 million in 2050).

INTRODUCTION

Meeting the global climate target of the Paris Agreement of staying well-below 2°C (WB2C) or even reaching 1.5°C requires rapid growth of low-carbon energy and phaseout of fossil fuels.[1] Such a shift in energy systems would have wide-ranging implications beyond meeting the climate target. One impact would be on jobs across the energy sector as older industries decline and new energy industries rise with corresponding shifts in the location and types of jobs that exist within the energy sector. Understanding these potential job shifts is important for a couple of reasons. First, in economies where fossil fuel production and exports are important, political support for low-carbon transitions increasingly centers on the debate of jobs versus the environment or climate,[2–6] and it is important to know the impact such climate action may have on what are often politically salient jobs. Many politicians support fossil fuel industries due to the importance of the associated jobs.[6] For example, in the 2016 US presidential election, candidate Trump referred to coal miners 294 times and campaigned on a platform of reviving the coal industry and coal jobs.[4,7] When announcing his intention to withdraw the US from the Paris Agreement in 2017, President Trump said, "… I happen to love the coal miners."[8] Australian Prime Minister Scott Morrison was re-elected after running on a campaign that vowed to protect the fossil fuel industry and related jobs in the face of stronger climate policies.[9]

Second, green politicians and environmental groups argue that taking bold climate action, including phasing out fossil fuels, can go hand in hand with a "just transition"[10] for fossil fuel workers[5,6] that includes retraining these workers to renewable energy jobs.[11,12] However, any just-transition program needs to understand the scale of shifts of jobs away from fossil fuels. Additionally, left and green politicians, along with environmentalists, are interested in understanding the scale and scope of potential renewable energy jobs under a "green economy."[3,7,13–19]

There are three main strands of literature that have examined potential job shifts. The first has investigated the short-term and economy-wide job impacts of climate-policy-driven energy transitions at the regional[20] and global levels.[21,22] These studies use computable general equilibrium models or macro-econometric models to quantify overall shifts in employment in the economy between broad sectors such as manufacturing and services in the short term under scenarios with and without climate policies. However, such analyses generally focus on specific countries rather than having a global scope. In addition, as these are top-down economic models, the energy systems are represented at a higher level of aggregation and so they tend not to cover a wide range of energy technologies and job categories. The second strand combines estimates of energy sector jobs from input-output models (the Jobs and Economic Development Impact [JEDI] model) with future scenarios of 100% renewable energy systems to estimate direct, indirect, and induced jobs in 2050.[23,24]

Finally, the third strand looks at the specific energy sector job impacts of climate policies[13,15–17,25–30] using energy systems models to analyze changes in energy jobs, between energy technologies such as coal and solar; job categories such as coal mining and solar manufacturing; and regions under various scenarios. This third type of analysis is important in climate policy debates because empirical and historical analyses have shown that some types of energy workers, such as coal miners or oil extraction workers, exert greater political influence because of their ability to physically control the flow of fuel, due to their higher unionization rates and their iconic status.[31,32]

Our work builds on the third body of literature. The past work on energy-sector-specific analyses has been conducted on a small set of Organisation for Economic Co-operation and Development (OECD) countries[15,17,25–30] or relied mainly on empirical data from OECD country employment factors (i.e., how many workers are employed per unit of electrical and refining capacity or fuel production) to estimate energy job impacts globally[13,33] or in other countries.[16] While these analyses have been useful in understanding future shifts, they have limitations. The OECD-only analyses do not capture the large number of jobs in non-OECD countries such as India, Brazil, and China where energy production and demand is expected to continue to grow. Applying modified OECD job numbers to non-OECD contexts[13,33] fails to capture the very different labor conditions that lead to differences in job numbers per unit of energy production. Overall, we find that employment factors vary greatly between different regions of the world; for example, we find that extracting one million tonnes of coal in India takes an order of magnitude more workers than in the US (725 versus 73).

To overcome this data gap, we built a new global dataset of employment factors (central to such estimates) in 50 countries by technology and job category and used an integrated assessment model (IAM) to investigate the impact of the global climate targets of WB2C on energy sector employment by energy technologies, job categories, and regions. Specifically, we focus on quantifying the impact of energy system changes on "direct jobs," or jobs that relate to core activities involved in energy supply chains[15,17] since these jobs are most closely correlated with the growth and decline of energy technologies[17] (see experimental procedures).

By doing so, we increase the spatial coverage of the dataset by including data from China, India, Russia, Mexico, Brazil, Nigeria, Saudi Arabia, and others, and create a full country, technology, and jobs category dataset based on the best available data for each country. Moreover, despite the wide use of IAMs in influential Intergovernmental Panel on Climate Change (IPCC) reports, no study has used an IAM for energy jobs analysis. Thus, our paper also represents a methodological contribution of applying job analysis in these influential tools, highlighting that, in the WB2C scenarios, the number of energy system jobs typically increases. Our results show that, today, approximately 18 million people are directly employed in the energy sector: 12.6 million people in fossil fuel industries, 4.6 million in renewable energy industries, and 0.8 million in the nuclear industry (Figure S6). Out of the 12.6 million people employed in fossil fuel industries, about 9.2 million are employed in fossil fuel extraction sectors (coal mining and oil and gas extraction). This is an important finding as it indicates that extraction sectors are where governments need to focus their efforts in order to create just-transition policies as the extraction sector is more vulnerable to decarbonization than other energy sectors.

RESULTS

Measuring and modeling energy jobs

We first compiled a comprehensive global dataset of employment factors for nearly 50 countries spanning 11 energy technologies and five job categories (construction and installation, operations and maintenance (O&M), manufacturing, fuel production, and refining) using scientific articles, publicly available government or consultancy reports, national databases, annual reports and official documents of leading energy companies, and correspondence with trade unions (see experimental procedures). All in all, our jobs dataset directly covers 80% of the total estimated global jobs from energy production and conversion processes and represents all major fossil-fuel-producing countries (note S1 and Figure S1). We then used the World Induced Technical Change Hybrid (WITCH) IAM to project the future energy jobs under both a reference scenario and WB2C scenario.

Table 1. Energy technologies and job categories included in the analysis

Job categories	Coal	Gas	Oil	Nuclear	Hydropower	Solar (PV)	Solar (CSP)	Traditional biofuels	Wind (onshore)	Wind (offshore)	Solid biomass
Construction and installation	X	X	X	X	X	X	X	–	X	X	X
Manufacturing	X	X	X	X	X	X	X	–	X	X	X
O&M	X	X	X	X	X	X	X	–	X	X	X
Fuel production	X	X	X	X	–	–	–	O	–	–	O
Refining	–	–	X	–	–	–	–	X	–	–	–

The table shows 11 energy technologies and five job categories included in our analysis. "X" indicates the technology/category combination is included in our analysis, "O" that the technology/category was excluded due to a lack of data availability, and "–" that the technology/category combination does not exist. In total, 36 combinations are considered.

We used a supply-chain approach to determine the equivalent core activities for each of the energy sectors (note S2). For each energy technology, we focused on the most significant direct jobs and collected data to be able to calculate employment factors for each energy technology and job category. We accounted for the fact that construction jobs are temporary by converting from job years/gigawatt (GW; the original units) to jobs/GW based on the number of years for construction (see experimental procedures, Table S1). As a result, the number of jobs we report is full-time jobs/GW.

Table 1 shows the energy technologies and the job categories included in our analysis. In this paper, we are missing only two entries, namely fuel production for biofuels and biomass and the equipment manufacturing of these sectors. We excluded these categories due to the lack of data. We define the job categories as follows:

- Manufacturing jobs: these are jobs involved in manufacturing equipment related to energy technologies.
- Construction and installation jobs: these are jobs involved in actual construction of power plants and installation of equipment in those power plants.
- O&M jobs: these are jobs involved in running and maintaining power plants.
- Fuel production jobs: these are jobs involved in the extraction of fossil fuels and uranium.
- Refining jobs: these are jobs involved in refining of crude oil.

We run six scenarios: three reference scenarios, which assume a continuation of current policies, and three WB2C scenarios, which ensure global warming stays well-below 2°C. For creating the reference scenario, the model starts with the currently implemented policies (until 2020) and we extrapolate the implied emission intensity improvement afterward (see experimental procedures). For creating the WB2C pathways, we used the globally estimated peak carbon budget (742 gigatonnes of CO_2 [$GtCO_2$] for the period 2011–2100),[34] for creating scenarios to meet the WB2C target. To ensure the robustness of our results, we explored both reference and WB2C scenarios using the standard shared socioeconomic pathways (SSP) storylines,[35] which are designed to explore a wide range of socioeconomic and technological assumptions relevant for climate change policy and have been widely used for similar what-if analyses.[36] Here, we focus on the key challenge of climate change mitigation and thus present our main results for a middle-of-the road scenario (SSP2), where socioeconomic trends and technological change follow historical trends. We also test if any of our key findings change under a fossil-rich world (SSP3), where climate change mitigation becomes a larger challenge, and, under a sustainable world (SSP1), rich in green technologies. Finally, in all six pathways, we incorporated labor productivity improvements by assuming that the employment factors in non-OECD countries converge linearly toward the mean in the OECD regions by 2050 (see experimental procedures). We did this because previous work has shown that non-OECD countries currently have more jobs per unit of electricity because these countries have more labor-intensive practices, but, in the future, there may be improvements in labor productivity.[13]

Figure S2 shows baseline gross domestic product (GDP) and population drivers across scenarios, Figures 6 and S3 show the primary energy mix, and Figure S4 shows the electricity mix for each of the scenarios; Figure S5 shows the global CO_2 emissions and GDP across all scenarios and policies.

Our results are discussed for the central estimate and SSP2, and we report uncertainty ranges in brackets for the other SSPs as well as when our conclusions are not robust under a given SSP.

Future renewable energy manufacturing jobs differ from other job categories as there is nothing physically tying these jobs to a particular geography in the same way that coal mining has to happen where coal deposits are located. There is some argument to be made that countries with current manufacturing capacity would be at an advantage for having future manufacturing (and jobs) occur there. However, we cannot make any strong assumptions about what proportion of future manufacturing jobs would happen in the same countries of today. Historical evidence shows that, for manufacturing sectors, first-mover advantage is not supreme, particularly in the face of large industry expansion. Data on solar photovoltaics (PV) shows that, although Chinese firms only entered the market in 2000, which was 20 years after the first movers, Chinese firms now account for over half of all manufacturing.[37] This shift happened in only 10 years. Thus, in the face of a massive expansion of renewables, the further development of manufacturing capacity where it is currently located is not a foregone conclusion, and new entrants have the potential to compete with today's manufacturers with smart industrial policies. One factor that might influence future renewable manufacturing expansion in different countries

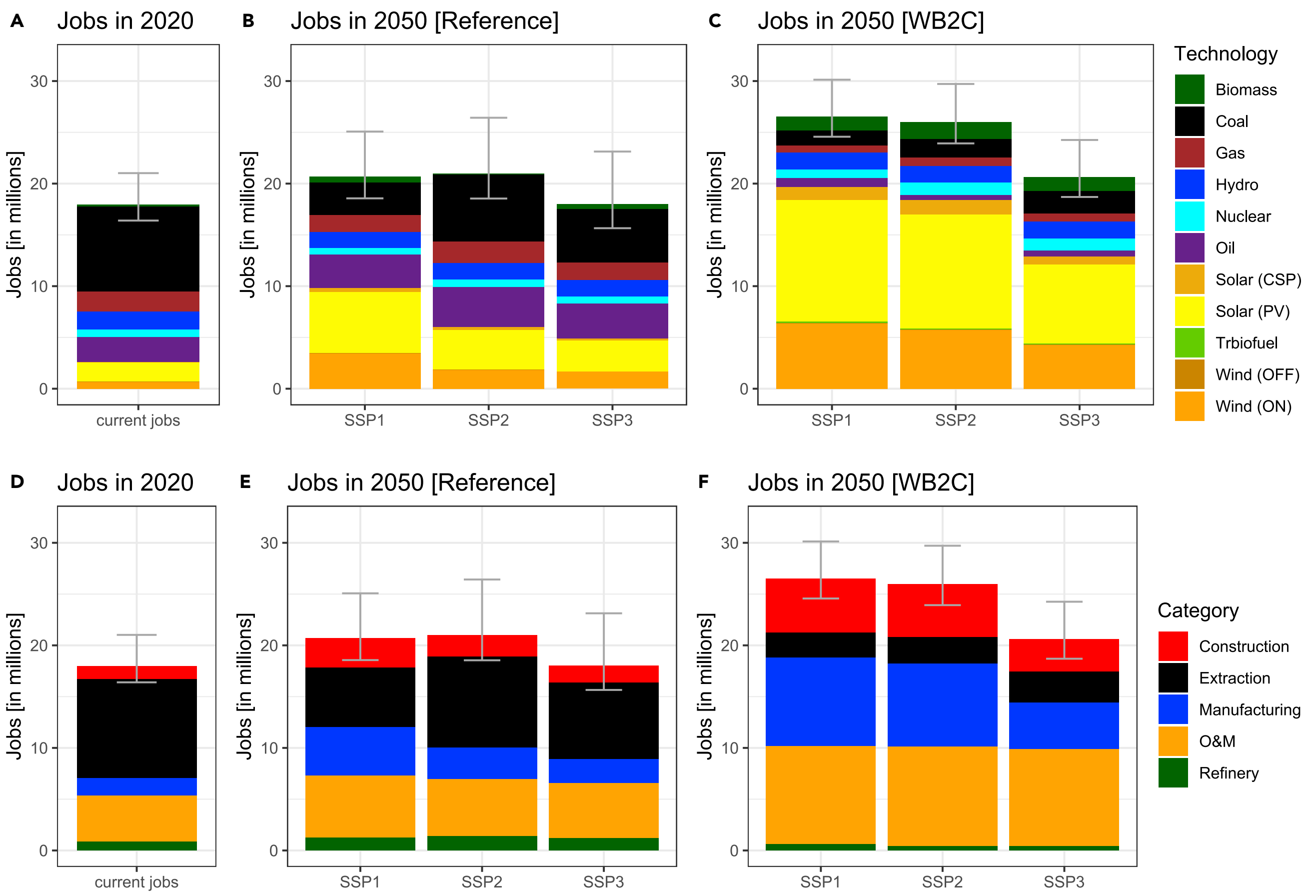

Figure 1. Current jobs and jobs in 2050 by energy technology and category under different scenarios

The figure shows the changes in energy sector jobs by energy technology and category between 2020 and 2050 under both reference and WB2C scenarios. Below, SSP1 represents sustainability, SSP2 represents middle of the road, and SSP3 represents regional rivalry. Whiskers indicate the uncertainty range based on the minimum and maximum of jobs intensities across countries in each region.

is the geopolitics of metals and metalloids required for renewable energy technology manufacturing.[38] In light of these considerations, we assigned these jobs to a global pool of jobs that all countries could potentially compete for instead of individual countries or regions. However, we conducted sensitivity analysis by computing manufacturing jobs based on current production shares for PV in different countries.

Results under the different scenarios

Under our projected reference scenario, we find that, by 2050, energy sector jobs grow to 21 million (16 million to 26 million) and under a WB2C target to 26 million (19 million to 30 million) jobs (Figure 1 and S6–S8). In our WB2C scenarios, fossil fuel jobs might decline considerably from 12.6 million today to 3.1 million (2.6 million to 5.3 million). This decline is concentrated in the extraction of fossil fuels (coal mining, oil, and gas production and exploration), which account for around 80% of the job losses. However, these job losses can be compensated by large gains in renewable energy jobs, growing from 4.6 million jobs today to 22 million (15 million to 25 million) in 2050, with over 85% of these gains in the solar and wind industry. These jobs would span manufacturing, O&M, and construction jobs. The gains and losses in jobs across technologies are reported in Figure 2.

With regard to the different SSPs, we find similar results in a middle-of-the-road scenario (SSP2) or a green-growth scenario (SSP1). In contrast, the fossil-fuel-rich scenario (SSP3) results in about 2 million fewer jobs by 2050. The change in the total number of energy jobs is a function of the carbon intensity, energy intensity, and job intensity (which we define in the number of energy jobs per petajoule of total primary energy supply) (Figures S9 and S10). In WB2C scenarios, the energy intensity declines faster than in reference scenarios. This decline in energy intensity combined with the shift to low-carbon technologies that are more job intensive leads to an increase and spike in jobs, particularly during the expansion of renewable energy capacity (mainly in construction and manufacturing jobs). At some point, however, due to technological progress and reduction in the transition speed, jobs slowly start to decline (Figure 3).

There are some studies that assess global energy sector jobs. Comparing these studies with ours is not always possible due to different sectoral coverage, scenarios, and job definitions (Table S2). For example, Jacobson et al.[24] combined JEDI models' job direct, indirect, and induced estimates (primarily using the US data from JEDI model and applying adjustment factors for other countries) to estimate global and regional jobs in a 100%

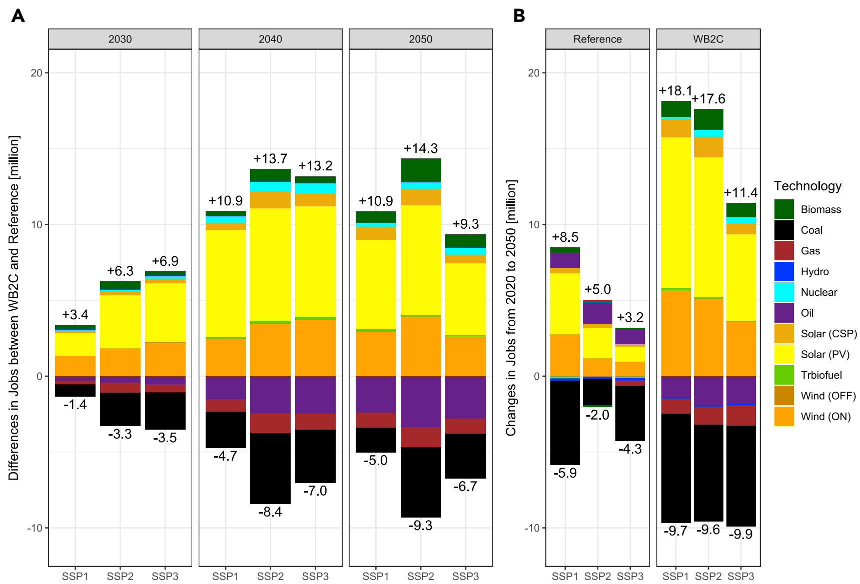

Figure 2. Gains and losses of jobs per energy technology

The figure shows the changes in energy sector jobs by energy technology comparing different scenarios (see axis description) and across the different SSPs.

renewable energy world. Hence it cannot be compared with ours as we focus only on direct jobs and use a global dataset.

Dominish et al.,[13] which is the only study comparable with ours in terms of study design, has a higher job estimate compared with our study. However, even this study differs from ours in terms of employment factors used and the system boundaries chosen. While we cover 11 energy technologies and five job categories, Dominish et al.[13] cover 16 energy technologies and four job categories. More importantly, the Dominish et al.[13] study used OECD employment factors data (the key data input) and then generalized these employment factors for non-OECD countries using regional multipliers.[13] By contrast, we used country level data for our analysis. This makes a significant difference in our results. For example, in our dataset, which was collected from in-country data sources, the US employment factor for solar PV for O&M jobs is 225 jobs/GW, while for India it is 500 jobs/GW for the year 2020. Based on this, to match the empirical data of the two countries would require a regional multiplier of 2.22 for India, which means that, for every one job/GW in solar PV O&M in the US, there are 2.2 jobs/GW in solar PV O&M in India. However, in the previous study, the regional multiplier was 5.6 for India compared with an OECD country. This means that India's employment factor for solar PV was 5.6 times the OECD average, which overestimates India's solar PV jobs.[13]

Growth of manufacturing jobs in solar and wind

A large portion (7.7 million [4.1 million to 8.8 million] in 2050) or 36% of the expansion of renewable energy jobs in 2050 to meet the WB2C climate targets would be in the manufacturing of solar and wind. This trend captures the shift in the landscape of energy sector jobs between old energy technologies (coal, oil, and gas), where jobs are linked to extraction, versus new energy technologies (solar and wind), where the bulk of the jobs are likely to occur in manufacturing jobs. Currently, China dominates solar and wind manufacturing jobs, but this might change in the future. Many countries are now vocal about self-sufficiency and are promoting domestic renewable energy manufacturing.[39]

Therefore, we define these potential future manufacturing jobs as a global pool and do not allocate them to any specific country (Figure 4). We find that the growth of manufacturing jobs in the global pool is observed in the reference scenario; however, after 2030, there are consistently at least 2 million more global pool jobs in the WB2C scenario than in the reference scenario.

Regional employment gains and losses

The development of energy jobs varies greatly between regions. This can be seen in Figure 5, which shows the percentage change in jobs between 2020 and 2050 for the reference (Figure 5A) and WB2C scenarios (Figure 5B). For each of the regions, the specific changes over time in job numbers are the result of a complex inter-play between changing energy supply due to policy, differences in job intensities between energy supply sectors, shifts in energy demand, and the role of economic drivers (which differ between the three SSPs included in the analysis). Most regions show job increases in the reference scenario compared with today, except for moderate job losses in India (under some SSPs), and the notable exception of China with job losses of up to 39%. However, comparing both panels shows the effect within regions of the climate policy (Figure 5).

Some fossil-fuel-exporting regions such as Mexico, Australia, Canada, South Africa (except for SSP2), and sub-Saharan Africa (constituting oil exporters such as Nigeria and Angola), would see those job gains disappear with a strong climate policy (i.e., in WB2C scenario). Most of the current energy sector jobs in these exporting countries are in the extraction sector either in coal mining or oil and gas exploration and production. As the demand for fossil fuels falls in the WB2C scenario, these exporting countries would lose employment in their extraction sectors, which is not compensated by an increase in renewables energy jobs. However, it should be noted that regions such as sub-Saharan Africa have a relatively small number of energy sector jobs, such that even small differences between the reference and WB2C scenarios (around 15,000 jobs difference in 2050) can result in high-percentage differences in jobs.

Many other regions (South East Asia, Middle East and North Africa, Indonesia, the US, Brazil, South Asia, India, and Japan and Korea), show an even higher percentage increase in jobs in the energy sector under a stringent climate policy (i.e., the WB2C scenario). In absolute terms, the Middle East and North Africa, and the US might gain over a million jobs in 2050 in WB2C scenario compared with today, while other regions show more modest gains (Table S3). In the case of these regions,

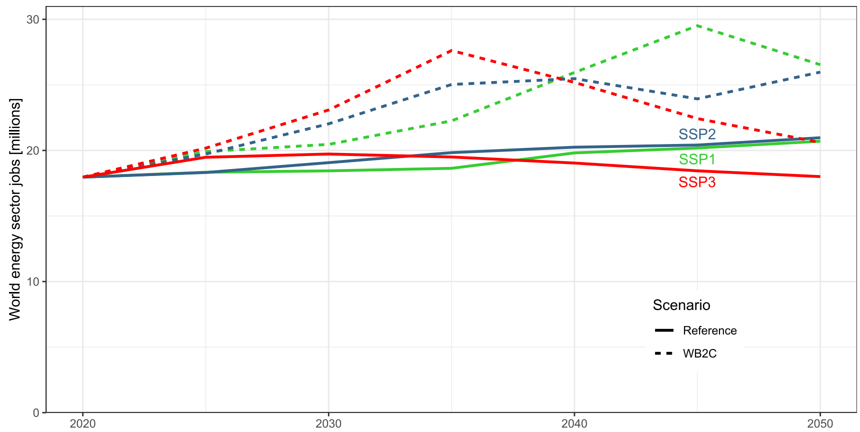

Figure 3. Evolution of the energy jobs at world level in the reference and WB2C scenarios until 2050

The figure shows the changes in energy sector jobs over time from 2020 and 2050 under both reference (solid) and WB2C (dashed) scenarios. The SSPs are depicted with different colors.

future job losses are in their relatively low-job-intensity fossil fuel sector (meaning fewer people are employed). However, these regions also have high renewable energy potential (with higher job intensities in the renewable energy sector) resulting in higher job numbers in the future overall.

The emerging economies of Indonesia, South East Asia, Brazil, India, and South Asia currently have a large number of jobs in the fossil fuel sector with higher job intensities than the Middle East and North Africa and the US. In our WB2C scenarios, while their fossil fuel jobs decrease, the increase in energy demand and massive deployment of renewables leads to an overall rise in jobs. Japan and Korea, which currently rely on imports of all fossil fuels, would transition to low-carbon sources under WB2C scenarios, creating a slight increase in overall jobs compared with today.

In regions such as the European Union, Russia and TE, and Latin America, there would be overall job increases in both WB2C and reference scenarios compared with today, but the percentage increase depends on the SSPs-led pathways these regions follow. The precise outcomes for any of these regions over time and as their energy sectors shift with policy are a complex mix of changes in job intensity, energy demand, and differing impacts of economic drivers associated with the three SSPs.

One key finding is that, under both current reference and WB2C scenarios, China would have lower energy sector jobs in 2050 compared with today, due to the loss of jobs in the coal mining sector. Generally, those regions facing job losses or only modest job gains over time may compete for the between 2.4 million and 7.3 million expected manufacturing jobs in future up-scaled installation of solar and wind, which are allocated in the global pool (Figure 4). The growth of new manufacturing jobs is highest under a green-growth world (SSP1) and lowest under a fossil-fueled (SSP3) world. In Figures S11–S13, we show the results without the global pool. It shows large potential job increases in China, but also India and Europe. China and other major renewable energy equipment manufacturing countries have a head start over other countries, which puts them at an advantage to attract these jobs.

Conclusion

A detailed appraisal of global energy system jobs and the impact of different climate and energy policy pathways is still missing in the literature. Here, we contribute to bridging this gap, and we find that, by 2050, jobs in the energy sector would grow from today's 18 million to 21 million (16 million to 26 million) in the reference scenario and even more, to 26 million (19 million to 30 million), under our WB2C scenario. Climate policies are often pitted against job losses in national politics; however, our results show that, while the majority of fossil fuel jobs could be lost as those sectors decline in WB2C scenarios, in many parts of the world (although not all), these jobs could be offset by gains in renewable energy jobs. In particular, there would be a large expansion of renewable manufacturing jobs, which could lead to competition to attract and expand solar and wind industries. This is an important finding as current fossil fuel dependent countries with substantial fossil fuel extraction jobs who face job losses in sectors like coal mining or others could promote the domestic renewable energy equipment manufacturing sector to create a large number of domestic jobs. Countries like India are already rolling out policies in this direction.[39]

Our research also highlights some key regional differences. Under all our scenarios, China would lose jobs with respect to today, but others, such as Middle East and North Africa and the US, gain jobs due to renewable energy expansion. While our analysis shows a large potential for renewable energy job creation in many regions, future work should assess whether renewable energy jobs can be created for fossil fuel workers locally in areas where they live and work. Our employment factors dataset can be used to estimate local job numbers for more detailed spatial analyses.[3,7] Moreover, our employment factors dataset can be used across a large set of IAMs and energy system models to perform a model comparison project in order for a robust assessment based on different models. Finally, country-specific studies can be conducted to understand the retraining needs, among others, of fossil fuel workers in renewable energy jobs.

Overall, the results from our analysis will further scholarly understanding of the trade-offs, challenges, and opportunities of low-carbon transition by focusing on the employment transition. We also find that certain global developments would lead to more jobs than others. In particular, a green-growth (SSP1) or middle-of-the-road development (SSP2) leads to the highest net increase in jobs compared with both today and a reference case, whereas a fossil-fueled development (SSP3) leads to fewer jobs. By doing so, it contributes to the growing body of literature that focuses on social and political aspects of low-carbon transitions. The trends and results of this work will also be useful for policy makers, advocacy groups, trade unions, and nongovernmental organizations as it sheds light on specific energy

Figure 4. Manufacturing jobs over time in solar and wind industries represented as a global pool

Solar and wind manufacturing jobs are nearly always higher in WB2C scenarios compared with reference scenario. Shaded areas indicate the uncertainty range.

technology and job categories that they can focus their efforts on for creation of just-transition plans.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Please contact the lead contact Dr. Johannes Emmerling (johannes.emmerling@eiee.org) for information related to the data and code described in the following experimental procedures section.

Materials availability

No materials were used in this study.

Data and code availability

The dataset and code generated during this study are available at Github: https://github.com/witch-team/energy-jobs-dataset.

Methodology

In this paper, we created an original dataset of energy sector jobs covering 11 energy technologies (coal, gas, oil, nuclear, hydropower, solar PV, concentrated solar power [CSP], biofuels, wind onshore, wind offshore, solid biomass) and five job categories (construction and installation, O&M, manufacturing, fuel production, and refining) and used the IAM WITCH to create two scenarios representing six pathways (Figure 6 shows primary energy for each pathway).

Energy jobs data collection

Our dataset includes detailed country level employment factors for over 50 countries, including key fossil-fuel-based economies previously missing in the literature,[13] such as China, India, Canada, Russia, South Africa, Australia, Brazil, and the Middle East (Figure S1). We collected data on direct jobs in the energy sector; that is, jobs that relate to core activities involved in energy supply chains.[15,17] We focus on direct jobs as these jobs unequivocally correlate to the rate of growth of energy technologies.[17] This excludes indirect jobs related to government oversight in the energy sector and research organisations,[15,17] which cannot be allocated to a specific energy technology or job category. Moreover, fuel transport is also considered an indirect job and is also difficult to estimate as it is often a service provided by non-energy firms or can be largely informal (e.g., coal transport in India).[15] However, we acknowledge that including indirect jobs assessment is important, and future scholarly work can focus on this.

We used a supply-chain approach to determine the equivalent core activities for each of the energy sectors (note S2). Focusing on the most significant direct jobs for every energy technology, we collected employment factors data, or how many workers are employed per unit of energy for each energy sector and job category.

In order to collate data on employment factors, we first collected country-specific employment factors data published in the academic literature, government reports, and reports by well-known international organizations or consultancies. If the data were not already available in the form of employment factors, our second approach was to collect the most up-to-date number of jobs for different energy technologies disaggregated into job categories in different countries and then divide these job numbers by the respective energy capacity and/or amount of fuel produced associated with that country, energy technology, or job category (Figure S14). For this approach, in addition to collating current job numbers published in the literature and reports, we drew from annual reports, sustainability reports, prospectus documents, and

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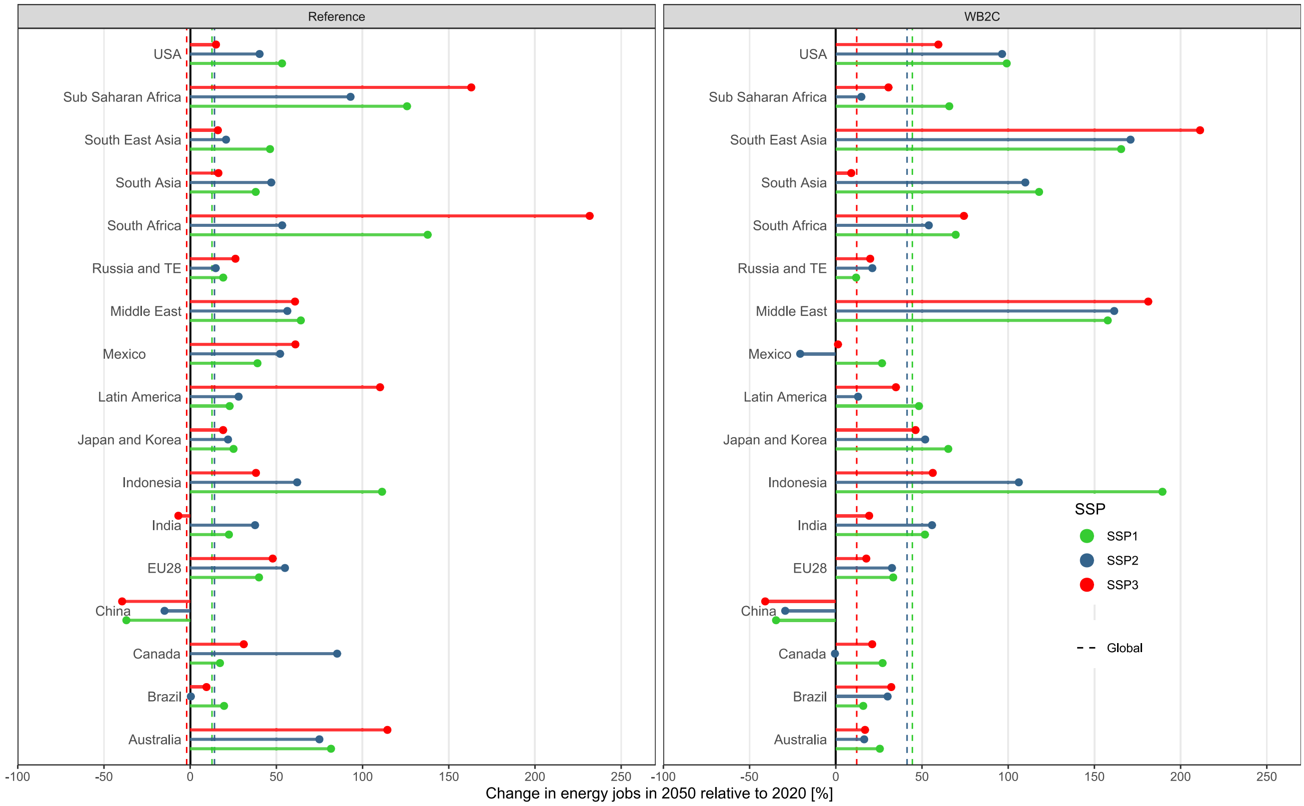

Figure 5. Regional changes in energy jobs from 2020 to 2050 for the reference and the WB2C scenarios

Values are expressed in percentage change. Socioeconomic projections (i.e., SSPs) are depicted with different colors. The global change in energy jobs is denoted by the dashed lines. Regions are ordered by the mean changes across SSPs in the reference scenario.

official Websites of leading oil and gas companies like Saudi Aramco (Saudi Arabia), Gazprom (Russia), Sinopec (China), Kuwait National Petroleum Company (Kuwait), PetroVietnam (Vietnam), and Pemex (Mexico), or from leading coal companies such as Coal India (India), Eskom (South Africa), and SUEK Ltd (Russia); written communications with trade associations like the World Nuclear Association and trade unions like the Federation of Oil Unions (Iraq) and Central de los Trabajadores y Trabajadoras (Brazil); and from official national statistics, such as Statistics Norway (Norway) and Ministry of Petroleum and Natural Gas (India). For example, for coal mining in India, we collected data on the current number of jobs in Coal India Limited (India's monopoly coal mining company), and then collected coal production data for that year. Finally, we divided the jobs data with production data to generate employment factors for coal mining in India in the form of jobs/million tonnes of coal produced. We used this second approach to collect the majority of employment factors data in fossil fuel industries, nuclear, and a large portion of data for renewables, especially for non-OECD countries.

In our dataset, we complied employment factors data on coal production in jobs/million tonnes produced; uranium production in jobs/petajoule; oil and gas exploration and production in jobs/thousand barrels of oil equivalent produced; biofuel production in jobs/million liters produced; oil refining in jobs/thousand barrels per day capacity; and power plant O&M jobs in jobs/GW capacity. In line with past studies, for construction and installation and manufacturing jobs, we collected employment factors data in "job years"/GW instead of jobs/GW, as these are temporary jobs typically occurring at the beginning of the project development.[15,17,40] Here, job years represent the number of workers multiplied by the number of years they work. Then, we converted job years/GW data into jobs/GW by dividing by the number of years required for construction, which vary between 1 and 10 years for different energy technologies[40] (Table S1). For example, a typical onshore wind power plant requires 2 years for construction; thus, we divided job years/(GW × 2) to get jobs/GW data for a particular year. Our dataset for fuels is further divided into hard coal and lignite, while oil and gas is divided into conventional and unconventional (Table S4).

Data processing

In order 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 common unit of energy or power capacity ($\frac{jobs}{PJ}$ or $\frac{jobs}{GW}$) denoted $jobint_{ej}$. Then, we used energy-related output quantities from the WITCH model to compute the total current jobs numbers.

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

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

$$\textbf{\textit{TotalJobs}} = \sum_e \textbf{\textit{jobint}}_{ej} \cdot \textbf{\textit{I\_EN}}_e + \sum_e \textbf{\textit{jobint}}_{ej} \cdot \textbf{\textit{I\_EN}}_e + \sum_e \textbf{\textit{jobint}}_{ej} \cdot \textbf{\textit{K\_EN}}_e + \sum_e \textbf{\textit{jobint}}_{ej} \cdot \textbf{\textit{Q\_OUT}}_e + \sum_e \textbf{\textit{jobint}}_{ej} \cdot \textbf{\textit{Q\_PES}}_e.$$

(Equation 1)

To compute future *TotalJobs*, the above was applied to the scenario pathways generated by the WITCH model in all 17 regions (see below) according to energy quantities produced by the model in each of these regions (Figure S15). We processed our dataset in R (the corresponding code and dataset can be found at: https://github.com/witch-team/energy-jobs-dataset). To represent labor productivity improvements, the employment factors in non-OECD countries are assumed to converge linearly toward the mean in the OECD regions by 2050. Only for future manufacturing jobs related to solar and wind, the yearly capacity installments beyond the latest historical manufacturing capacity data were assumed to be produced as a global pool

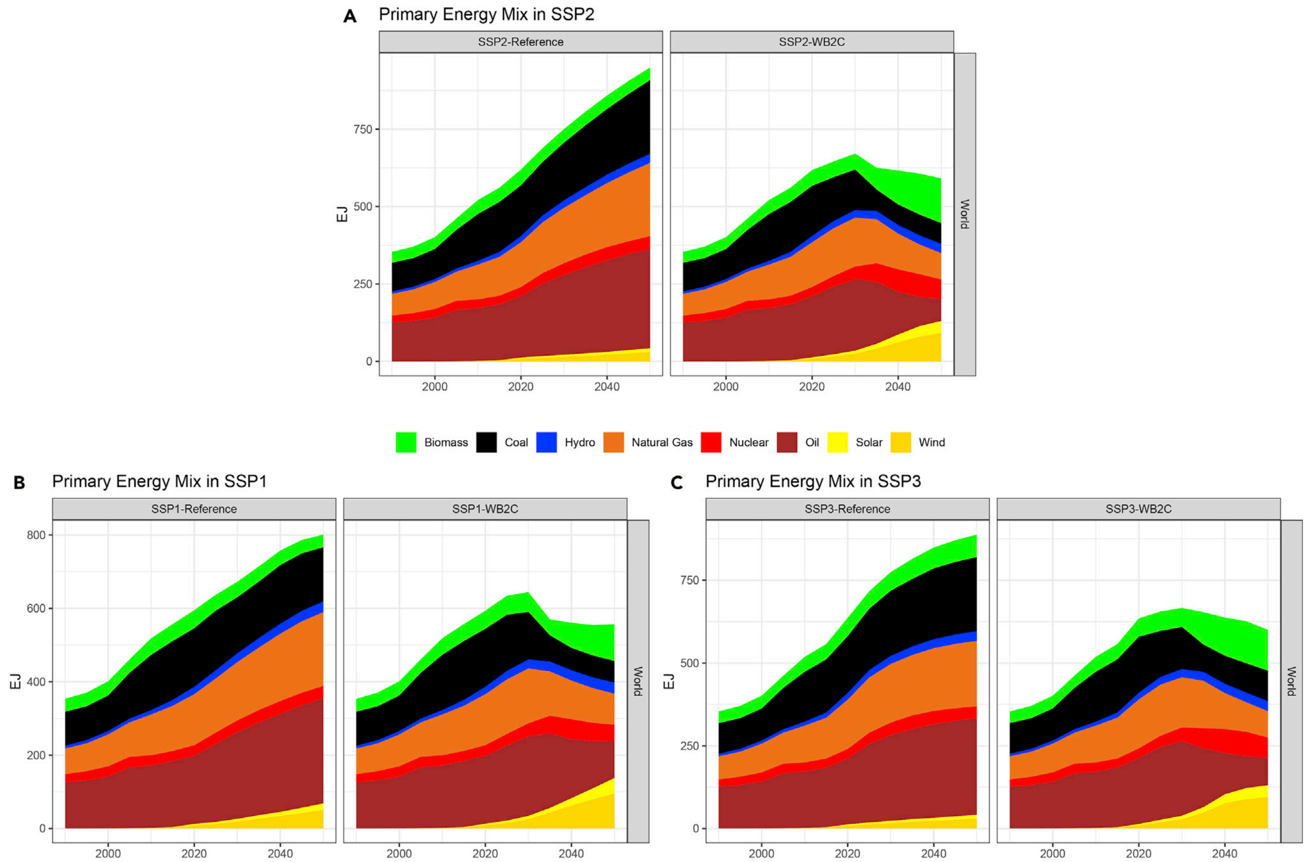

Figure 6. Primary energy mix for two scenarios WB2C and reference and its associated pathways

The figure shows primary energy mix from 2020 and 2100 under both WB2C and reference scenarios and their pathways under SSPs.

instead of individual regions. This was done as we cannot assume the future manufacturing jobs would happen in the same countries as today.

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.

Using IAMs for jobs assessment

Prior studies on this topic that used computable general equilibrium models or macro-econometric models were able to show changes in economy-wide job numbers, and were useful to explore the full economy-related job implications.[20–22] By using an IAM, we are able to conduct work that is complimentary to that. We are able to 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, O&M, manufacturing, fuel production, and refining). For example, our work would be useful to understand the extent of job losses under the WB2C scenario in, say, Indian or Chinese coal mining industries. Moreover, our analysis also allows us to show that the largest *direct* jobs gains under stringent climate policies would be in manufacturing and could lead to interesting dynamics where countries compete for these new jobs.

The WITCH model

We used the WITCH model with two climate policy scenarios and three different socioeconomic assumptions to create six pathways of energy-economy development. WITCH is an IAM 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.[41,42] It is a global dynamic model that integrates into a unified framework the most important drivers of climate change and an inter-temporal optimal growth model captures the long-term economic growth dynamics. In the model, a compact representation of 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 represents the world in a set of a varying number of macro-regions; for the present study, the version with 17 representative regions has been used (Figure S15). For each, 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 on the energy mix into the WITCH regions. Finally, a distinguishing feature of the WITCH model is the endogenous representation of research and development (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-CO_2 emissions in energy and industry are endogenously modeled 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 (from United Nations Framework Convention on Climate Change, Food and Agriculture Organization, Emission Database for Global Atmospheric Research)

Scenario design

Our paper is based on six scenario pathways along two dimensions: with and without climate policy and varying socioeconomic parameters. With respect to the former, our reference scenario is based on the currently implemented policies, which are assumed to continue in the future, keeping constant the relative regional emission abatement from the SSP-related baseline scenario, while the climate policy scenario ramps up the currently implemented policies (until 2020) to restrict the global temperature increase to WB2C. For the WB2C scenario, we used the globally estimated peak carbon budget (742 $GtCO_2$ for the period 2011–2100)[34] left to meet the WB2C target.

The socioeconomic parameters for the second dimension are based on the SSPs, which were developed by climate scientists, energy modelers, and economists. The SSPs are qualitative storylines that describe pathways for demographics and economics change until the end of the century.[43–45] Over time, several studies have quantified these qualitative SSP storylines making projections for population growth[44] and long-term economic growth.[45] The WITCH model uses these quantitative estimates for different SSPs[42] to create cost-optimal projections of energy sector changes (as these are hard linked) for different regions to meet climate targets. To ensure the robustness of our results, we created the reference and WB2C scenarios under three SSPs, namely SSP1 (sustainability), SSP2 (middle of the road), and SSP3 (regional rivalry: a rocky road ahead), thereby incorporating their different assumptions about population and economic growth among other factors.[35] Our reported job estimates are always for the middle-of-the-road" scenario SSP2, with lower and upper bounds referring to the results using SSP3 and SSP1.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2021.06.005.

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AUTHOR CONTRIBUTIONS

S.P. and J.E. contributed equally as lead authors. All authors collectively designed the study, conceptualized the manuscript, edited drafts of the manuscript, and were responsible for the final manuscript. S.P. led the data collection process along with J.J., H.Z., and J.E., while J.E., L.D., and S.P. were responsible for data processing. L.D. created and ran the scenarios used in the study. S.P. and J.E. wrote the first draft of the manuscript, and J.E., L.D., and S.P. created the graphs for this study.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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