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LETTER

Solar has greater techno-economic resource suitability than wind for replacing coal mining jobs

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Abstract

Coal mining directly employs over 7 million workers and benefits millions more through indirect jobs. However, to meet the 1.5 °C global climate target, coal's share in global energy supply should decline between 73% and 97% by 2050. But what will happen to coal miners as coal jobs disappear ? Answering this question is necessary to ensure a just transition and to ensure that politically powerful coal mining interests do not impede energy transitions. Some suggest that coal miners can transition to renewable jobs. However, prior research has not investigated the potential for renewable jobs to replace 'local' coal mining jobs. Historic analyses of coal industry declines show that coal miners do not migrate when they lose their jobs. By focusing on China, India, the US, and Australia, which represent 70% of global coal production, we investigate: (1) the local solar and wind capacity required in each coal mining area to enable all coal miners to transition to solar/wind jobs; (2) whether there are suitable solar and wind power resources in coal mining areas in order to install solar/wind plants and create those jobs; and (3) the scale of renewables deployment required to transition coal miners in areas suitable for solar/wind power. We find that with the exception of the US, several GWs of solar or wind capacity would be required in each coal mining area to transition all coal miners to solar/wind jobs. Moreover, while solar has more resource suitability than wind in coal mining areas, these resources are not available everywhere. In China, the country with the largest coal mining workforce, only 29% of coal mining areas are suitable for solar power. In all four countries, less than 7% of coal mining areas have suitable wind resources. Further, countries would have to scale-up their current solar capacity significantly to transition coal miners who work in areas suitable for solar development.

1. Introduction

The Intergovernmental Panel on Climate Change's 1.5 °C report states that keeping global warming below 1.5 °C requires the share of coal in total primary energy supply to decrease by 73%–97% by 2050 (IPCC 2018). Meeting these targets would lead to a near elimination of coal mining jobs related to production of coal for both electricity (hard coal and lignite) and non-electricity sectors (metallurgical coal). A rich literature is now emerging on the need for a 'just transition' for coal miners whose livelihoods depend on coal production, in order to minimize the impact on those workers (Newell and Mulvaney 2013, Baker *et al* 2014, Abraham 2017). Just transition plans are also seen as tools to overcome possible political resistance against

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the policies needed to phase out coal (Thurber 2019, Healy and Barry 2017). Coal miners, who are typically a formidable voting bloc, might support candidates who favor the coal industry in the absence of just transition plans (Healy and Barry 2017, Bennhold 2018, Buncombe 2018). In the United States (US), coal miners helped support the rise of President Donald Trump, who, once elected, pulled the US out of the Paris climate agreement. Even autocratic states like China have faced resistance from powerful coal mining interests when attempting to close down coal mines (Wright 2007).

Some scholars argue that just transition plans should include retraining fossil fuel workers such as coal miners for alternate jobs (Kammen *et al* 2004, Miller *et al* 2013, Louie and Pearce 2016, Abraham 2017, Johnstone and Hielscher 2017). These alternate job options for coal miners may vary across a wide range of economic sectors, such as manufacturing or services, and are not limited to only renewable energy (RE) jobs. However, in the last few years, the policy debate and academic research regarding alternate jobs for coal miners has increasingly focused on RE jobs for coal miners. This paper specifically focuses on RE jobs for coal miners, in order to further our understanding of this possibility.

Recently, scholarly articles on just transitions, reports by inter-governmental organizations, and numerous media reports highlight that coal miners could be retrained in order to specifically switch to jobs in the growing RE industries (Hancock 2016, Louie and Pearce 2016, Collins 2018, European Commission 2018, Pollin and Callaci 2018). For example, Louie and Pearce's (2016, p 301) paper, focusing on US coal workers (mine and power plant), concludes that, '…a relatively minor investment in retraining would allow the vast majority of coal workers to switch to PV-related positions even in the event of the elimination of the coal industry.' A recent European Commission (2018, p 112) report also identifies the wind and solar PV industries 'as particularly suitable for reemploying coal workers after adjustment of skills,' and recommends that countries should explore converting current coal mining sites into solar/wind projects (which will result in the creation of corresponding jobs).

Apart from retraining aspects, past studies have also claimed that RE jobs will offset fossil fuel job losses (including coal mining job losses) in terms of absolute numbers (ILO 2018, IRENA 2018a, 2018b). For example, the International Labour Organization (ILO) estimates that around 24 million 'green-jobs,' including RE jobs, could be created worldwide by 2030 if governments take action to limit warming to 2 °C, enough to offset fossil fuel industry job losses (ILO 2018).

The idea that coal miners can make an employment transition to RE jobs is a current topic extending beyond academic and policy discourse. Some RE companies such as China-based Goldwind Americas have officially declared plans to retrain coal miners in wind jobs (Cardwell 2017a). Moreover, recent media reports indicate that coal miners in certain local coal mining areas in China, the US, and Australia have already transitioned to deployment jobs in the solar and wind industries (Cardwell 2017b, Manson 2018, Gribbin 2019).

Overall, the policy debate and academic research regarding alternate jobs for coal miners has focused either on retraining issues or on comparing the current number of coal jobs with projections for future RE jobs. No study has assessed the potential for RE jobs to replace 'local' coal mining jobs. In this paper, we contribute to filling this knowledge gap by conducting the first spatial analysis on this topic, focusing on the world's top coal-producing countries: China, India, the US, and Australia.

We focus on local jobs because creating local jobs for coal mine industry workers is considered crucial. Past academic work on the decline of coal mining in the academic fields of labor economics and geography has shown that, unlike other professional workers who migrate to find new jobs when they are laid off, most coal miners become 'inactive' when they lose their jobs. This is due to a strong connection to their local community, and the fact that most are older and less skilled (Hollywood 2002, Danson 2005, Beatty *et al* 2007, Gore and Hollywood 2009). At the same time, research has found that some younger coal miners migrate within the region when they lose their jobs (Hollywood 2002, Danson 2005, Gore and Hollywood 2009).

Among various RE jobs, we focus on solar and wind jobs because they represent over half of today's RE jobs (IRENA 2018a). While we focus on solar and wind jobs, we fully recognize that coal miners can transition to other RE production jobs or jobs in completely different industries. In fact, one of the contributions of this paper is that it describes and applies a novel spatial methodology that can be used to conduct similar assessments regarding coal miner transition to other RE jobs such as geothermal or bioenergy, or jobs in completely different sectors.

Specifically, we first estimate the local solar and wind capacity required to be built in coal mining areas to enable all coal miners in these areas to transition to solar or wind jobs. Next, we conduct a techno-economic resource suitability analysis to assess whether there are suitable solar and wind power resources in local areas around coal mines. Then, by using the results from the techno-economic resource suitability analysis and specifically focusing on coal mining areas suitable for solar/wind power, we calculate the total national solar/wind capacity required to transition all coal miners living in suitable areas to solar or wind jobs.

In addition, we conduct a regional techno-economic resource suitability analysis to assess whether there are suitable solar and wind power resources in the major coal-producing states/provinces within our case study countries. This is in line with the past research discussed above, which suggests that some younger coal miners migrate for work within their region.

In the next section (2) we explain our methods. In section (3) we summarize our results. In the final section (4) we discuss our results in the context of existing literature, and discuss the policy implications and limitations of our study.

2. Methods and data

In this paper, we focus on China, India, the US, and Australia. These are the top coal-producing countries and account for over 70% of global coal production (Enerdata 2018) (table 1).

Specifically, we focus on utility-scale solar and/or wind power projects and related jobs. The jobs in these projects can be divided into manufacturing jobs, which can be located anywhere, and deployment jobs such as operations and maintenance (O&M) jobs that are located in specific areas (e.g. coal mining areas). Deployment jobs are directly influenced by the distribution of solar or wind resources. There are also some similarities worth noting between the nature and skill requirements of solar and wind jobs on the one hand and coal mining jobs on the other. Solar and wind power includes permanent (O&M) jobs (IRENA 2018a), similar to the permanent nature of coal mining jobs (Pai and Carr-Wilson 2018). Additionally, although more country specific evidence is required, at least for the US, scholars Louie and Pearce (2016) state that all coal miners can transition to PV jobs either directly or with some retraining.

We focus on the techno-economic resource potential for creating utility-scale solar and/or wind power projects in coal mining areas and in top coal mining provinces/states in our focus countries. We do this by assessing a key parameter for setting up solar and/or wind projects—availability of suitable solar and wind power resources in the area (Mahtta *et al* 2014, Clifton *et al* 2018), which is a key requirement identified for developers/companies or governments to start a solar or wind power project (Mahtta *et al* 2014, Clifton *et al* 2018).

2.1. Possibility of creating solar and wind power plants in coal mining regions

In this paper, we used GIS tools to create four composite maps (one for each country) that include coal mine/field locations and long-term averages of solar and wind power resources (see supplementary information for detailed explanations, available online at stacks.iop.org/ERL/15/034065/mmedia). We use these maps to show (1) the percentage of total local coal mining areas in each country that are suitable for solar and/or wind power generation; and, (2) the percentage of areas in key coal-producing provinces/states suitable for solar or wind power generation.

To calculate (1), we first defined areas where coal mining is concentrated today and the surrounding areas where coal miners live. We operationalized this parameter as the radius within 50 km of a specific coal mine. For sensitivity analysis of this parameter, apart from the 50 km radius, we also conducted a similar analysis using a 20 km radius, and a similar analysis using the mine point itself. There was negligible change in results (less than 5.21% for any country) (see supplementary section 'Local Coal Mining Level Analysis' available online at stacks.iop.org/ERL/15/034065/mmedia).

Next, we calculated the average solar and/or wind power potential of this 50 km coal mining area based on measures of technical feasibility (see section 2.2) for solar and wind power generation. We then used resource suitability limits for solar and wind power resources to calculate the percentage of local coal mining areas within a country and province/state suitable for utility-scale solar and/or wind power generation. For calculating (2), we focused on the top coal-producing provinces/states (table 1) and used the same resource suitability cut-offs for the percentage calculation.

2.2. Defining techno-economic resource suitability

To measure the techno-economic resource suitability, we used the average long-term Global Horizontal Irradiance (GHI) data for solar power generation (Clifton *et al*, Mahtta *et al* 2014, He and Kammen 2016) and the average wind speed at a hub height of 80 m for wind power generation (Archer and Jacobson 2003, Archer and Jacobson 2005, McElroy *et al* 2009, Holt and Wang 2012, Hallgren *et al* 2014, Wang *et al* 2018) in line with previous studies. For utility-scale solar and wind power plants to be feasible, the long-term average GHI must be $\geqslant 4\ \mathrm{kWh\ m^{-2}\ d^{-1}}$ (Mahtta *et al* 2014) and the long-term average wind speed must be $\geqslant 6.9\ \mathrm{m\ s^{-1}}$ respectively (Archer and Jacobson 2003, Archer and Jacobson 2005, Archer and Jacobson 2007, Yu *et al* 2016). We used these as lower limits in our analysis. To verify our approach we calculated what percentage of current utility-scale solar installations in our focus countries are located in areas with average GHI values $\geqslant 4\ \mathrm{kWh\ m^{-2}\ d^{-1}}$ and found that between 82% and 100% are located in such areas (supplementary information table 1 available online at stacks.iop.org/ERL/15/034065/mmedia). For wind, we do not have comparable data so we could not conduct such analyses, but many previous studies have utilized standard wind speed classes (1–7) (supplementary information table 2) and used the limit of $6.9\ \mathrm{m\ s^{-1}}$ (Class 3 wind speed) to calculate feasible wind power potential (Archer and Jacobson 2005, Archer and Jacobson 2003, 2007, Yu *et al* 2016).

Table 1. Coal production, reserves, miners, and major coal-producing regions for China, India, The US, and Australia. Together, these countries account for 70% of global annual coal production. Within each country we also focused on the top coal-producing provinces/states, responsible for over 85% of each country's coal production.

Country	Coal production (million tonnes)[a] (Enerdata 2018)	Coal reserves (million tonnes)[b]	Coal miners (thousands)[c]	Provinces/states covered in this paper	% of national production covered[d]
China	3349	138 819	6110	Shanxi, Inner Mongolia, Shaanxi, Anhui, Heilongjiang, Xinjiang, Shandong, Henan, Guizhou	90%
India	717	97 728	485	Chhattisgarh, Jharkhand, Orissa, Madhya Pradesh, Telangana	85%
US	701	250 916	52	Wyoming, West Virginia, Pennsylvania, Illinois, Kentucky, Texas, Montana, Indiana, North Dakota	90%
Australia	478	144 818	50	New South Wales, Queensland, Victoria	99%

[a] Enerdata (2018).

[b] British Petroleum (2018).

[c] Ministry of Coal (2017), Song *et al* (2017), Bureau of Labor Statistics (2018), Minerals Council of Australia (2018).

[d] Maslyuk and Dharmaratna (2013), Ministry of Coal (2016), Energy Information Administration (2017), Bai *et al* (2018).

Table 2. Employment factors for solar and wind technologies (O&M jobs) in different countries.

Countries	Solar employment factors (Jobs/GWe)[a]	Wind employment factors (Jobs/GWe)[b]
China	497	378
India	500	500
US	225	400
Australia	130	100

[a] Roam Consulting (2014), IRENA (2018a), Solar foundation (2018), Kuldeep *et al* (2019).
[b] Wei *et al* (2010), Cai *et al* (2011), Roam Consulting (2014), Kuldeep *et al* (2019).

2.3. Assessing solar or wind capacity required to transition coal miners to solar or wind jobs

To estimate the local solar or wind capacity required to transition all coal miners to solar and wind jobs, we first calculated the average number of coal miners working in each coal mining area by country. Next, using this average, and the data on country-specific 'employment factors,' or how many workers are employed per GW of installed capacity (Jobs/GW) for O&M jobs for solar and wind power projects, we calculated the local solar and wind capacity (in GW) required to transition all coal miners living in these areas to solar or wind jobs. Here, we focused on O&M jobs as they are typically long-term permanent jobs similar to coal mining jobs.

Further, using the results from our local techno-economic resource suitability analysis and focusing only on coal mining areas suitable for solar or wind power, we calculated the national aggregate renewable energy capacity required to transition all coal miners just in those suitable areas to local solar or wind jobs. We then compared this required national capacity to current deployment of solar and wind in all four countries (IRENA 2019).

2.4. Data collection

For solar power potential, we utilized the latest GHI data from the Global Solar Atlas, owned by the World Bank Group (2016) and provided by Solargis, to create the maps that provide average GHI value for the period from '1994, 1999, or 2007 (depending on the geographical region) to 2015'. For wind potential, we used Vaisala's Global Wind datasets for 5 km onshore wind speed at 80 m hub height that provide average wind speed calculated over a 10 year period (IRENA 2018c).

We used shapefiles for coal mine locations from nationally-specific sources: for China, we used the US Geological Survey (USGS) dataset (Trippi *et al* 2014); for the US, we used the US Energy Information Administration (2018) dataset; for Australia, we used the Geoscience (2015) dataset. For India, since coal mine datasets are not available, we used the USGS's coalfields dataset (Trippi and Tewalt 2011) and highlighted the key coalfields where large-scale coal mining is currently happening. We conducted our analysis using the coalfields dataset and operationalized the 50 km radius concept for India. This did not affect our results (See supplementary information data analysis).

We also collected the latest country-specific employment factors (Jobs/GW) data (for O&M jobs) to calculate the required solar or wind capacity locally and nationally (table 2). We collected this employment factors data from academic literature, consultancy reports, and reports by international organisations. However, the solar power employment factors for China and the US were not available. We calculated the employment factors for these countries by collecting the actual O&M jobs data from IRENA (2018) and the US Solar foundation (2018) respectively, and then dividing it by total capacity for the same year (IRENA 2019).

3. Results

3.1. Majority of China's coal mining areas have limited suitability for solar power but even less for wind

China, the world's biggest coal-producer, accounts for 45% of global coal production (Enerdata 2018) employing 6 million coal miners (Song *et al* 2017). Coal production in China is concentrated in nine key coal-producing provinces (table 1).

In China 5.73 GWe of solar capacity would need to be installed in each coal mining area to transition all coal miners in these areas to solar jobs. However, our GIS analysis shows that only 29% of the coal mining areas in China are suitable for solar power generation, with heterogeneity between provinces ranging from 88% in Inner Mongolia to no suitable areas in some provinces (table 3). For about 1.8 million coal miners working in the coal mining areas that are suitable for solar power, an additional 3565 GWe of capacity would need to be deployed, roughly twenty times the current 175 GWe capacity (table 4).

In terms of wind power, 7.54 GWe wind capacity would need to be installed in each coal mining area to transition coal miners to wind jobs. However, our analysis shows that only 5% of coal mining areas in the country are suitable for wind power generation with Inner Mongolia having 32% of its coal mining areas suitable for wind and all other key coal provinces less than 5% (figure 1). For the 0.3 million coal miners who work in coal mines in areas that are suitable for wind power, the national capacity required is

Table 3. Percentage of coal mining areas, and percentage of areas within provinces/states suitable for solar or wind power generation. Coal mining areas here means an area with a 50 km radius around the point location of a coal mine. For suitable solar and wind power, average GHI value should be greater than or equal to 4 kWh m^{-2} d^{-1} (Mahtta *et al* 2014) and wind speed at 80 m should be greater than or equal to 6.9 m s^{-1} (Archer and Jacobson 2003, 2007, Yu *et al* 2016) respectively. The first three columns show the percentage of total coal mining areas suitable for solar and/or wind. The last two columns show the percentage of total areas within the province/state suitable for solar or wind power.

	Percentage of coal mining areas suitable for …			Percentage of major coal-producing province/state areas suitable for …	
	Solar power	Wind power	Solar and wind power	Solar power	Wind power
China	29%	5%	5%	N/A	N/A
Shanxi	87%	1%	1%	81%	17%
Inner Mongolia	88%	32%	31%	78%	28%
Shaanxi	18%	0%	0%	38%	4%
Anhui	0%	0%	0%	0%	0%
Heilongjiang	0%	5%	0%	2%	5%
Xinjiang	58%	5%	5%	70%	18%
Shandong	0%	0%	0%	9%	0%
Henan	0%	0%	0%	0%	1%
Guizhou	0%	0%	0%	1%	3%
India	99%	1%	1%	N/A	N/A
Chhattisgarh	100%	0%	0%	100%	0%
Jharkhand	100%	0%	0%	100%	0%
Orissa	100%	0%	0%	100%	0%
Madhya Pradesh	100%	0%	0%	100%	0%
Telangana	100%	0%	0%	100%	0%
US	62%	7%	2%	N/A	N/A
Wyoming	100%	69%	69%	98%	47%
West Virginia	60%	2%	0%	41%	13%
Pennsylvania	0%	14%	0%	15%	8%
Illinois	100%	0%	0%	87%	1%
Kentucky	100%	0%	0%	100%	0%
Texas	100%	0%	0%	100%	34%
Montana	83%	0%	0%	66%	24%
Indiana	100%	0%	0%	80%	1%
North Dakota	0%	100%	0%	12%	86%
Australia	96%	4%	2%	N/A	N/A
New South Wales	100%	0%	0%	100%	4%
Queensland	100%	0%	0%	100%	2%
Victoria	40%	40%	40%	89%	17%

808 GWe (table 5). This is roughly four times the current national wind capacity of 180 GWe.

We find that only 5% of the coal mining areas are suitable for both solar and wind power, mainly in Inner Mongolia.

At the provincial level, we find that suitability for solar power generation ranges from 70% of provincial areas to less than 10%. Our analysis for wind power shows that less than 30% of the land area in all provinces is suitable for wind power (table 3).

3.2. Nearly all coal mining areas in India are suitable for solar power but not for wind power

In India, 485 000 coal miners (Ministry of Coal 2017) produce over 700 million tonnes (MT) of coal annually (Enerdata 2018). Coal production in India is concentrated in five key states (table 1).

In India, 1.96 GWe of solar power capacity would need to be installed in each local coal mining area to transition all coal miners to local solar jobs. Our analysis shows that in India, nearly all the local coal mining areas are suitable for solar power generation including in the key coal-producing states (table 3). For about 0.5 million coal miners working in these coal mining areas suitable for solar power, India would require an additional 960 GWe of capacity (table 4). This would mean increasing the current capacity by nearly 37 times (from today's capacity of 27 GWe).

To replace local coal mining jobs with wind jobs, India would need to install 1.96 GWe of wind power capacity in each coal mining area. However, we find

Table 4. Solar capacity required to transition all coal miners working in coal mining areas suitable for solar power to solar jobs.

	Average coal coal mining areas jobs per mine	Number of coal mining areas suitable for solar power	Number of workers in coal mining areas suitable for solar power	Local solar capacity required in each coal mining area to replace coal mining jobs (GWe)	National solar capacity required to replace coal mining jobs in suitable solar areas (GWe)	Current solar installed capacity (2018) (GWe)[a]
China	2852	621	1771387	5.73	3565	175
India	984	488	480081	1.96	960	27
US	73	440	32225	0.32	143	50
Australia	435	110	47826	3.34	369	10

[a] IRENA (2019).

Table 5. Wind capacity required to transition all coal miners working in coal mining areas suitable for wind power to wind jobs.

	Average coal mining jobs per mine	Number of coal mining areas suitable for wind power	Number of workers in coal mining areas suitable for wind power	Local wind capacity required in each coal mining area to replace coal mining jobs (GWe)	National wind capacity required to replace coal mining jobs in suitable wind areas (GWe)	Current wind installed capacity (2018) (GWe)[a]
China	2852	107	305500	7.54	808	180
India	984	5	4850	1.96	10	35
US	73	50	3640	0.18	9	94
Australia	435	5	2000	4.35	20	6

[a] IRENA (2019).

that almost no coal mining areas in India and its key coal-producing states are suitable for wind power generation. For the small number of coal miners working in these coal mining areas suitable for wind power (4850) to transition to local wind jobs, the cumulative national capacity required is 10 GWe (table 5). Figure 2 shows solar and/or wind power potential in India along with locations of coalfields, particularly highlighting the coalfields in the key coal-producing Indian states.

Furthermore, there are negligible (less than 1%) coal mining areas that are suitable for both solar and wind.

At the regional level, all key coal-producing states are suitable for solar power generation, however, no areas in the key coal-producing states are suitable for wind power generation.

3.3. Majority of coal mining areas in the US are suitable for solar power but not for wind power

The US boasts similar coal production to India and employs 52 000 coal miners (Bureau of Labor Statistics 2018). Coal production is concentrated in nine states (table 1).

Overall, in the US, 0.32 GWe of solar capacity would need to be installed in each coal mining area to transition all coal miners in those areas to solar jobs. Our analysis shows that around 62% of the local coal mining areas in the US are suitable for solar power generation—in some states over 80% of coal mining areas are suitable for solar power and in others no coal mining areas are suitable for solar power generation (table 3). For the 32 000 mine workers who work in coal mining areas suitable for solar power to get local solar jobs, the US would require 143 GWe of cumulative capacity, roughly three times the current national solar capacity (table 4).

In terms of wind power, 0.18 GWe of wind capacity would need to be installed in each coal mining area to transition all coal miners to wind jobs. However, only 7% of coal mining areas in the US are suitable for wind power generation. The suitable areas for wind power generation are concentrated in North Dakota, where all the coal mining areas are suitable for wind power, and in Wyoming where 70% of coal mining areas have wind power suitability (table 3). Transitioning the small number of coal miners (3600) who work in areas suitable for wind power to local wind jobs would require increasing the national wind power capacity by 9 GWe (table 5).

Moreover, we found that less than 2% of coal mining areas in the US are suitable for both solar and wind power, mostly concentrated in Wyoming (figure 3).

At the state level, there is heterogeneity between states in terms of solar power suitability—ranging from over 80% in Wyoming, Texas, Illinois, Indiana, and Kentucky to less than 15% in Pennsylvania and North Dakota. In terms of state-wide wind suitability, North Dakota has large areas (86%) suitable for wind power generation and the rest of the states are under 50%.

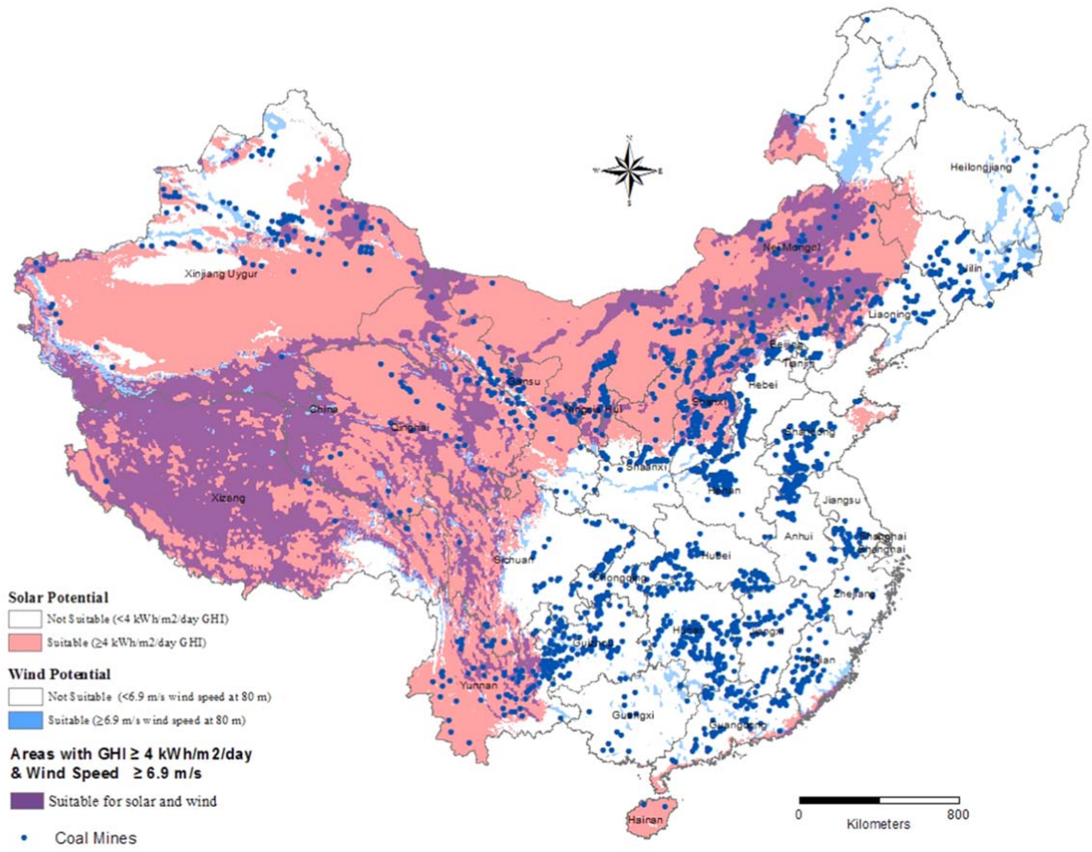

Figure 1. Solar and/or wind potential, and coal mines in China. The coal mining areas with average GHI value greater than or equal to 4 kWh m^{-2} d^{-1} (Mahtta *et al* 2014) and wind speed at 80 m greater than or equal to 6.9 m s^{-1} (Archer and Jacobson 2003 2007, Yu *et al* 2016) are considered suitable for solar and wind power generation respectively. The blue points represent locations of coal mines. The map shows areas suitable for only solar power, only wind power, and for both solar and wind power. A large number of coal mines in Eastern and South-Central China are located in places not suitable for either solar and/or wind power.

3.4. Nearly all coal mining areas in Australia are suitable for solar power but not for wind power

Australia produces close to 500 MT of coal annually and employs 50 000 miners (Enerdata 2018, Minerals Council of Australia 2018). Coal production is concentrated in three states (table 1).

In Australia, 3.34 GWe of solar capacity would need to be installed in each coal mining area to transition its coal miners to solar jobs. Here, we find that close to 96% of the coal mining areas are suitable for solar power generation. All coal mining areas in NSW and Queensland, and 40% in Victoria are suitable for solar power generation (table 3). For transitioning coal miners working in these suitable coal mining areas, Australia would require 369 GWe of national capacity, roughly 37 times the current 10 GWe capacity (table 4).

In terms of wind, 4.35 GWe wind capacity would need to be installed in each coal mining area to transition its coal miners to wind jobs. However, only 4% of coal mining areas in Australia are suitable for wind power generation—none in Queensland and NSW and just 40% in Victoria. For the 2000 coal miners who work in coal mining areas suitable for wind power to transition to wind jobs locally, the cumulative capacity required is 20 GWe (table 5).

Overall, our analysis shows that only 2% of coal mining areas in Australia are suitable for both solar and wind power (figure 4).

At the state level, all of NSW and Queensland and the majority of Victoria (89%) is suitable for solar power generation. In terms of wind power, less than 4% of the area in all three states is suitable for wind power generation (table 3).

4. Discussion and conclusion

Prior studies on job options for coal miners have either focused on issues like retraining (Louie and Pearce's 2016, Pollin and Callaci 2018) or comparing the current number of coal jobs with projections for future RE jobs (ILO 2018, IRENA 2018a, 2018b). While these studies make important contributions to the literature, they do not explore whether RE jobs can be created locally for coal miners. This is an important question since past studies have shown that out-of-work coal miners typically do not migrate for work.

Based on this historical understanding, we focused on evaluating the local solar and wind capacity required in each coal mining area to enable all coal miners to transition to solar or wind jobs, and assessed

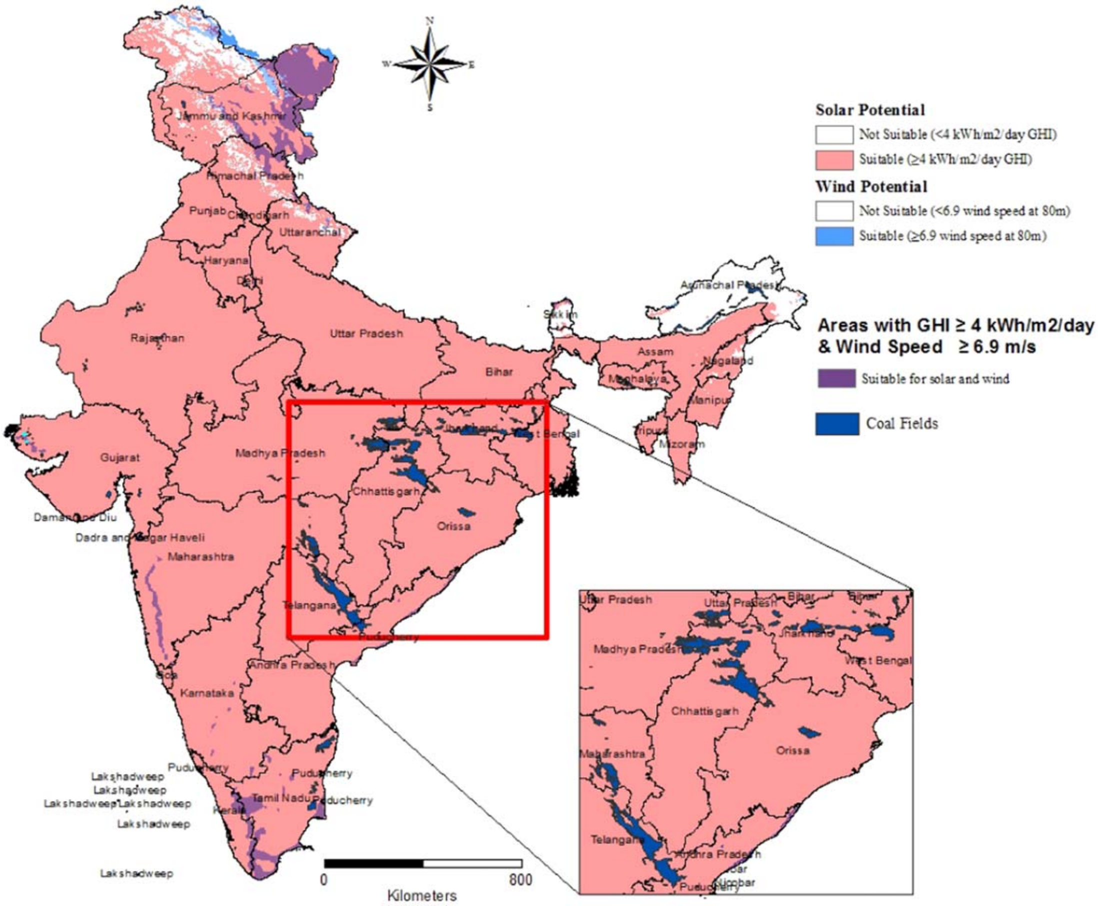

Figure 2. Solar and/or wind potential, and coalfields in India. The coal mining areas with average GHI value greater than or equal to 4 kWh m^{-2} d^{-1} (Mahtta *et al* 2014) and wind speed at 80 m greater than or equal to 6.9 m s^{-1} are considered suitable for solar and wind power generation (Archer and Jacobson 2003, 2007, Yu *et al* 2016) respectively. The blue points represent locations of coalfields in India. The map shows areas suitable for only solar power, only wind power, and both solar and wind power. The map shows nearly all coalfields (including all key coalfields in Eastern and Central India) are located in areas suitable for solar power generation. On the other hand, all major coalfields in Eastern and Central India are located in areas not suitable for wind power generation.

the techno-economic resource suitability of creating local solar and/or wind power projects (and their related jobs) in key coal-producing countries. We also assessed the scale of renewable energy deployment required to help coal miners transition to local solar or wind jobs. By doing so, this paper makes a significant conceptual contribution to the emerging just transitions literature focusing on fossil fuel workers' livelihood issues. Since spatial analysis is considered a 'blind-spot' in energy transitions studies (Coenen *et al* 2012, Bridge *et al* 2013), this paper also contributes methodologically by explicitly considering the spatial distribution of coal production versus solar/wind potential.

Our results also show that except for the US, each coal mining area would require several GWs of solar or wind power capacity locally to enable all coal miners in these areas to transition to solar or wind jobs. Furthermore, our GIS analysis shows that deploying solar and wind power may not be techno-economically feasible in all coal mining areas due to low suitability of the resource. From our analysis it is clear that while solar has greater techno-economic resource suitability than wind for replacing local coal mining jobs, this suitability does not exist in all coal mining areas. In China, only 29% of the coal mining areas have suitable solar power resources. However, in India and Australia nearly all coal mining areas are suitable for solar power, while around 62% of the coal mining areas in the US are suitable for solar power. Moreover, the wind power suitability in coal mining areas is low in all four countries, with less than 7% of coal mining areas having suitable resources. Additionally, less than 5% of coal mining areas are suitable for both solar and wind power generation. Even at the provincial/state level, our analysis shows that solar has more resource potential than wind to replace coal mining jobs.

Yet, even for solar, countries would need to substantially increase their current installed solar capacity (from 3 times in the US to 37 times in India), to transition only those coal miners who live in suitable solar areas to solar jobs. The scale of deployment of renewable energy required raises serious questions about the viability of a transition path that depends solely on local renewable energy jobs for coal miners. This is true at both the local level where several GWe of

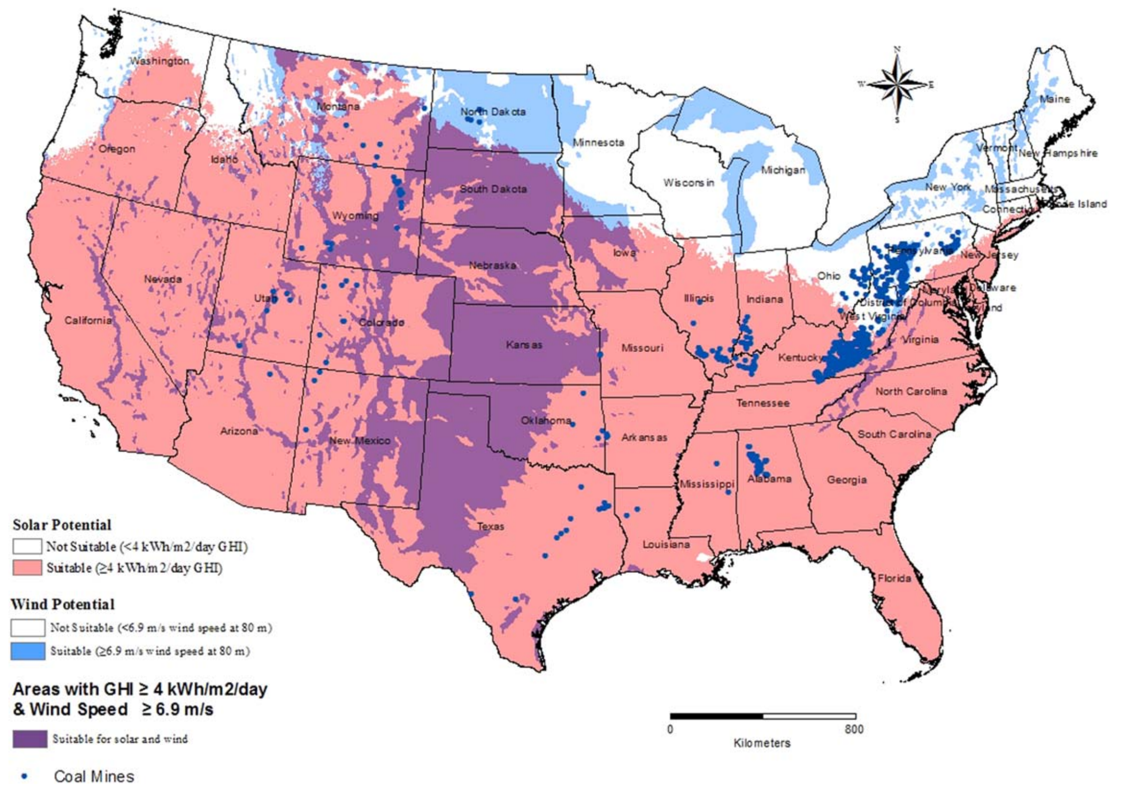

Figure 3. Solar and/or wind potential, and coal mines in the US. The coal mining areas with average GHI value greater than or equal to 4 kWh m^{-2} d^{-1} (Mahtta *et al* 2014) and wind speed at 80 m greater than or equal to 6.9 m s^{-1} are considered suitable for solar and wind power generation (Archer and Jacobson 2003, 2007, Yu *et al* 2016) respectively. The blue points represent locations of coal mines. The map shows areas suitable for only solar power, only wind power, and for both solar and wind power. Except coal mines in parts of the Eastern US and North Dakota, most other coal mines are located in suitable solar power generation areas. The majority of coal mines in the US are located in places not suitable for wind power generation. Wyoming is the only state with several coal mines located in areas suitable for both solar and wind power generation.

installed capacity would be required per coal mining area and in aggregate where several times national capacity would be required just for absorbing mining jobs in areas suitable for RE deployment. This means, in practical terms, not all coal miners may be able to transition to solar or wind jobs locally even in areas with suitable resources. Policy makers, other stakeholders, and analysts concerned about transitioning coal mining workers should, therefore, consider expanding the scope of their options beyond renewable energy jobs. Policy interventions considering employment in other sectors could build on the methodology developed in this paper to assess the suitability of other industries such as tourism.

While this paper contributes conceptually and methodologically to thinking about employment transitions in a spatial sense, it has a few limitations that are avenues for future work on this topic. We did not conduct a skills transferability analysis between coal mining jobs and RE jobs, which is an opportunity for further research. Further, the O&M job employment factors used in this study were collected from secondary data, and this data may include different work types in different countries. In the future, more disaggregated data with detailed work types could be collected at the country level using surveys or other primary data collection methods. We also did not account for detailed local land-use planning and policy assessments, which would influence the distribution of solar or wind power projects in each of these coal mining areas. We also did not calculate the number of declining coal mining jobs versus number of potential solar/wind jobs in different coal mining areas, given that job intensity in each coal mining area will vary due to factors such as labor and capital productivity, therefore, such analysis is most suitable initially for a few select coal mining areas. Future research can use our results to select specific coal mining areas suitable for solar or wind power to conduct more detailed local analyses.

If the world is serious about meeting the 1.5 °C climate target, it is indispensable that politically-powerful coal mining interests do not block coal phase-outs. One innovative way would be to provide coal miners with alternate jobs. Overall, our findings provide policymakers, industry, and non-profit organizations who are already invested in retraining coal miners for solar and wind jobs insight on where to target their efforts. However, we also show that while solar jobs could be the answer in some coal mining areas,

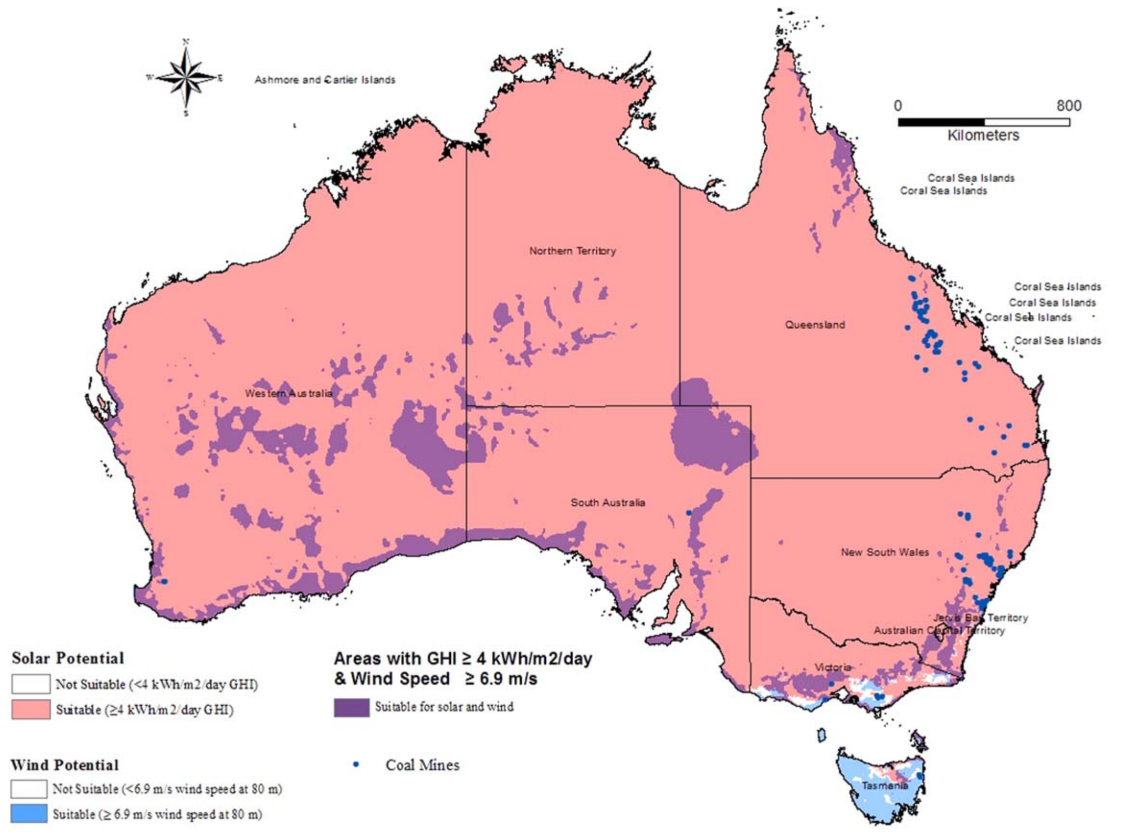

Figure 4. Solar and/or wind potential, and coal mines in Australia. The coal mining areas with average GHI value greater than or equal to 4 kWh m^{-2} d^{-1} (Mahtta *et al* 2014) and wind speed at 80 m greater than or equal to 6.9 m s^{-1} are considered suitable for solar and wind power generation (Archer and Jacobson 2003, 2007, Yu *et al* 2016) respectively. The blue points represent locations of coal mines. The map shows areas suitable for only solar power, only wind power, and for both solar and wind power. Except for some mines in Tasmania and in Victoria, all other coal mines are located in suitable solar resource potential areas. On the other hand, coal mines in Queensland and NSW are located in places not suitable for wind power generation. In the whole country, only two coal mines in Victoria are located in areas suitable for both solar and wind power.

policymakers would need to focus on a variety of industries including both renewables and non-renewables to help coal miners make an employment transition locally.

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Declaration

It must be noted that the boundaries, colors, legends, denominations, and any other information shown on the maps created for this paper do not imply, on the part of the authors, any judgement on the legal status of any territory, or any endorsements or acceptance of such boundaries.

Data availability statement

Any data that support the findings of this study are included within the article.

Below are the same links to the data.

Solar GHI shapefiles data:
http://globalsolaratlas.info/downloads

Wind speed shapefiles data:
https://irena.masdar.ac.a.e./gallery/#map/543

China coal mine data:
https://pubs.er.usgs.gov/publication/ofr20141219

India coalfields data:
https://pubs.usgs.gov/of/2011/1296

Australia coal mine data:
http://australianminesatlas.gov.au/mapping/downloads.html

United States coal mine data:
https://eia.gov/maps/layer_info-m.php

Conflict of interest

The authors declare no conflict of interest.

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