Sustainability Science (2024) 19:125–150
https://doi.org/10.1007/s11625-023-01440-y

SPECIAL FEATURE: REVIEW ARTICLE

Accelerating Actions for Leveraging a Climate-Neutral, Sustainable Society

Job creation in a low carbon transition to renewables and energy efficiency: a review of international evidence

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Received: 12 January 2023 / Accepted: 14 November 2023 / Published online: 11 January 2024

Abstract
In this paper, we present findings from a systematic review on job creation, quality, and skills, focusing on decarbonisation in the energy sector. We compare a range of gross job employment factors which indicate that overall, investment in renewable energy and energy efficiency can deliver more jobs than gas or coal power generation. In addition, we review a subset of recent studies which estimate the net employment effects of decarbonisation in the energy sector at a national scale, across various international contexts. These national studies largely agree that the most likely outcome over the next few decades is a modest net positive creation of jobs and moderate economic growth. In certain regions within these countries, jobs in fossil fuel industries may be lost faster than the pace at which low carbon energy sectors can offer new employment. There may be mismatches between regions where displaced workers live and where new opportunities become available, which may be a barrier to accepting alternative employment even if former workers have the requisite skills. In these cases national government transition plans are recommended, coordinated with local governments, to manage the impacts of displacement from carbon-intensive sectors and respond to the need to build a new low carbon workforce including through skills development and training. We highlight a lack of metrics and data in the literature on job quality, skills, and the geographic distribution of employment impacts in decarbonising energy systems, and these should be priority areas for further research.

Keywords Green jobs · Job creation · Renewable energy · Energy efficiency · Decarbonisation · Decent work

Introduction

There is a growing international momentum behind the setting of net zero emissions targets in law or policy (Climate Watch 2023) and the introduction of Green New Deals involving substantial investments in green jobs and infrastructure, for example in the USA and EU (Green 2022). Over the last decade, the costs of leading renewable energy technologies such as solar photovoltaics (PV) and wind power have fallen rapidly or substantially (IRENA 2020; Jansen et al. 2020). In 2021, there were at least 12.7 million people employed in renewable energy sectors worldwide, both directly and in wider supply chains, with the majority of these jobs concentrated in China, Brazil, the EU, the USA, and India (IRENA and ILO 2022). Given the economic implications of the COVID-19 pandemic and recent gas and electricity price spikes (Fernández Alvarez and Molnar 2021), a key question is whether investment in the low carbon transition can contribute to economic growth and resilience both in the short term and longer term (Figueres and Zycher 2020). There have been various calls for investment in green jobs, skills, and infrastructure to help consolidate economic recovery from COVID-19, in a way that is compatible with achieving net zero emissions and a societally just transition (Allan et al. 2020; EEIG 2020; IEA 2020; Jung and Murphy 2020; IRENA and ILO 2021). This paper reviews international evidence on the quantity and quality of jobs created through a low carbon energy transition, focusing in particular on renewable energy and energy efficiency.

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There are various definitions of green jobs, and while it is important to clarify the scope of the present paper in relation to these, we do not set out to contribute further to the existing definitional debate. In the UK for example, the Green Jobs Taskforce consider a green job as "*employment in an activity that directly contributes to—or indirectly supports—the achievement of the UK's net zero emissions target and other environmental goals, such as nature restoration and mitigation against climate risks*" (Green Jobs Taskforce 2021, p. 15). Green jobs may vary in 'greenness', for example, in terms of the proportion of tasks carried out on 'green' or 'non-green' activities (Bowen et al. 2018). Definitions of green jobs (e.g. International Labour Organization 2018) may also include a quality aspect, suggesting that green employment needs to be characterised by 'decent' work or good quality jobs, e.g. in terms of adequate salaries and safe working conditions (Office for National Statistics 2021).

A key definitional issue relevant to this paper is the distinction between 'gross' and 'net' jobs. Gross effects include only the positive impact on employment which may be associated with a particular investment. For any specific energy technology, gross jobs refer to those which are created from project spending on equipment manufacturing, installation, operation, and maintenance (Blyth 2014). Gross jobs can also include employment created in associated supply chains and the wider economy. Net employment is a more holistic metric that accounts for jobs that might be displaced in other parts of the economy as a result of the initial investment. For example, overall net employment could be the number of gross jobs created through additional renewable energy deployment, offset by the implied number of gross jobs that would be lost due to less power generation needed from gas and coal (Blyth 2014).

Various studies attempt to associate policies supporting green growth and a low carbon economy, including fiscal stimuli, financial incentives and regulations, with numbers of jobs created (e.g. Dsouza 2015; Dvořák et al. 2017; Mundaca and Luth Richter 2015; Lim et al. 2020; Lee 2017). Dvořák et al. (2017) find that job creation in renewable energy in the Czech Republic has depended upon the continuity of financial incentives. A US-focused study suggests that green stimulus programmes supporting wind power and solar PV helped to boost job creation, expand manufacturing capacity and supply chains, and increase revenue from sales of renewable energy technology (Mundaca and Luth Richter 2015).

Pre-existing reviews of the literature suggest that substituting fossil fuels with renewables and energy efficiency is most likely to result in small net employment gains (Blyth 2014; Stavropoulos and Burger 2020). Stavropoulos and Burger (2020) present a meta-analysis of 30 studies of the net employment effects of expanding renewable energy and energy efficiency measures. Of these, the authors found that 22 studies reported positive net job creation, 4 negative, and 4 a mixture of positive and negative net employment impacts (Stavropoulos and Burger 2020). Since this meta-analysis reviewed analyses published between 2002 and 2017 (most relating to Germany or USA), in the present paper we provide an updated review of national-scale studies of net job creation (or destruction) likely to result from a low carbon energy transition, and associated impacts with respect to where and when jobs might be created and displaced, across country regions and over the coming decades. A review of the impact of various climate change mitigation policies across 20 countries finds that they tend to lead to an overall increase (or otherwise no change) in employment net of jobs displaced (Godinho 2022). There is also a risk that some of the newly created jobs may be of poor quality and this may be compounded by insufficient labour market policies or regulations (Godinho 2022). We therefore further review studies which attempt to measure what decarbonising the energy sector might mean for quality of work, e.g. in terms of wages and job security, and the supply and availability of requisite skills for low carbon energy jobs, considering the impacts on displaced workers from fossil fuel industries. Rather than addressing the impact of individual policies, in this paper we review research on the job creation outcomes of energy system decarbonisation. We focus specifically on the energy sector rather than applying a wider definition of green employment. While the focus is on the electricity generation sector and energy efficiency in buildings, we also consider estimates of net job creation across the energy sector as a whole (including electricity, heat, transport, and industry). Our paper reviews recent evidence on three aspects of low carbon energy job creation, for countries where available information has been identified: (1) quantity: how many jobs can be created by a low carbon transition to renewable energy and energy efficiency compared to supporting fossil fuel incumbents? (2) geographic and temporal distribution: how are employment impacts of national decarbonisation strategies likely to be distributed across different regions within countries, and over time? (3) What are the national and regional implications of supporting a low carbon energy transition for quality of jobs, skills requirements, and training?

"Materials and methods" outlines our approach to addressing these research questions through the systematic review, and includes several observations on the measurement of energy sector job creation. The following two sections present the results of the review, which captures a wide range of internationally diverse evidence. In "Review findings on quantity of job creation", we analyse studies which estimate how much employment could be created through policy support or investment in different energy production technologies (fossil fuels, renewables, nuclear) and energy efficiency interventions. In "Review findings on quality

Table 1 Search terms applied in systematic review

Employment and job creation	Energy and environment	Fossil fuels/nuclear	Job creation metrics	Policy/techno-economics	Geography, quality, and skills
Job	Energy	Gas	Jobs/MW	Policy	Local
"Green job"	Green	"Natural gas"	Jobs/GW	"Net zero"	Regional
					National
"Low carbon job"	Renewable	"Shale gas"	Direct	Subsidy	Location
Employment	"Low carbon"	Coal	Indirect	Incentive	Geography
"Employment creation"	Decarbonisation	Fossil	Induced	Stimulus	Quality
"Job creation"	"Renewable energy"	"Fossil fuel"	Multiplier	Invest	Skill
"Job destruction"	"Energy efficiency"	Nuclear	"Employment factor"	Spend	Qualification
Net	"Climate change "		"Supply chain"	CAPEX	"Decent work"
				OPEX	"Just transition"

of job creation, occupations, and skills", we consider the extent of identified evidence on quality aspects, occupational characteristics, and skill levels of jobs created in fossil fuel, renewable and energy efficiency sectors. The final section "Conclusions" concludes the study, suggesting priority areas for policy and further research.

Materials and methods

This paper presents findings from a full systematic review, i.e. "a broad systematic review of existing research on a topic;" following the UKERC Technology and Policy Assessment (TPA) approach (UKERC 2023) and based on the practice of systematic review (Sorrell 2007). As part of this process, the research approach and outcomes were informed and critiqued by a small group of expert advisers and policy makers who have brought their experience and perspectives to bear on the research topic (see Supplementary Information).

Systematic review approach

The focus of the evidence review is on a low carbon transition in the energy sector, considering particularly (but not exclusively) renewable energy, energy efficiency, end use energy demand sectors, fossil fuels and nuclear power. The geographical coverage is international, but limited to evidence available in English. For the systematic review, we selected a range of key words or phrases related to: job creation; climate change and decarbonisation; energy technologies; fuel sources and energy efficiency; policies and financial incentives; quality and skill levels of jobs created and their geographic distribution (Table 1). The searches were restricted to the years 2014–2023 to provide an update to a previous UKERC review on low carbon job creation (Blyth 2014). The search terms were developed based on those used in the 2014 UKERC review on green jobs and our own preliminary, scoping review of the literature. Search terms were combined in search strings and applied to three databases, selected to obtain academic and grey literature across different publishers: Google Scholar, Science Direct, and Web of Science (See Supplementary Information, Table S1).

Returned results were filtered manually for relevance to the research questions based on their title and/or abstract, and each document was given a relevance rating from 1 to 4, according to the criteria set out in Fig. 1. If this was not sufficient to determine relevance, further inspection of the main text was performed. This paper presents findings from a review of 121 of the most relevant documents (all relevance rating 1 studies and eight documents snowballed from relevance rating 1 studies), drawn from a wider body of 1007 potentially relevant documents identified through the search strategy (Fig. 1). In particular, the review set out specifically to identify "relevance rating 1" publications which contain job creation metrics relating to quantity (e.g. gross or net job creation) or quality (e.g. occupational profiles, skills, or wages). With respect to their geographic coverage, around half of the 121 documents identified are national- and/or regional-scale studies focused on Europe, Asia and North America, with many others considering multiple countries or being international/global in scope (Table 2). Six documents focused on countries within Africa (mainly South Africa) and a further six on South American countries. Table S4 in the Supplementary Information includes a list of all publications included in the review by country/continent/international focus and broad sectoral/technology scope in relation to job creation.

A number of steps were taken to maximise the validity of the review and minimise bias in the identification of relevant studies (Avellar et al. 2017). The review has followed a standard procedure adopted as part of conducting UKERC

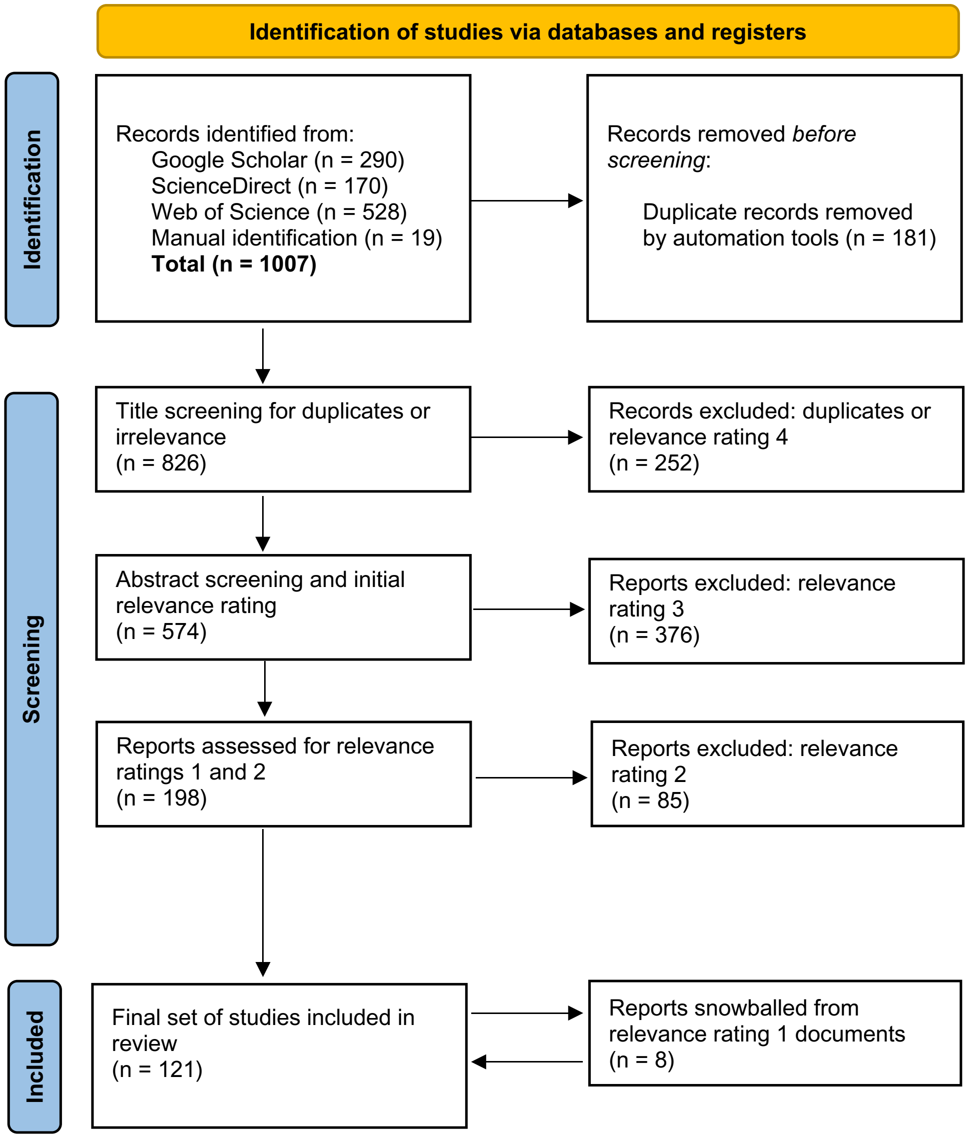


Fig. 1 Summary of systematic review process based on PRISMA. *Notes*: a. Each document was assigned a relevance rating from 1 to 4 according to the following criteria: (1) article shows clear discussion and/or data that is directly focused on the research questions: it contains job creation metrics relating to quantity (e.g. gross jobs/installed capacity or generation, gross jobs/investment, net job creation) or quality (e.g. occupational profiles, skills, or wages). (2) Article shows clear discussion and/or data that is related to, but is not directly focused on, the main research question, but may be relevant to sub-questions (e.g. discussion of job creation—including local/regional and related to skills/quality—but no directly relevant job creation metrics as set out in criterion 1 are presented). (3) Article mentions at least one of the search terms, but is of only limited relevance to the research questions (e.g. is about green jobs in general but does not include substantive material on job creation pertaining to renewable energy, energy efficiency or a low carbon energy transition). (4) Article is found to be irrelevant or duplicate on closer inspection, or is not accessible (e.g. page not found, incomplete access to book chapter, main text not in English language). b. Figure 1 adapts a PRISMA template for systematic review reporting available in Page et al. (2021)

TPA systematic reviews (Hanna et al. 2020). Initially, the planned search strategy was published in the form of a scoping note (Hanna et al. 2020). Prior to commencing the review, a meeting of the above-mentioned expert group was arranged to quality assure the proposed review approach. The systematic review has used clear inclusion and exclusion criteria by applying pre-determined relevance ratings to each document extracted from the initial searches. This process is presented in Fig. 1 based on the PRISMA template for systematic review reporting (Page et al. 2021).

Search terms were balanced to reduce bias. Part of the analysis in this study involves comparing low carbon job estimates with estimates of jobs in traditional (fossil-fired) power generation, to gauge the net job impacts of renewables

Table 2 Publications included in the systematic review by geographic focus

Country of study continent or international coverage	Number of relevance rating 1 documents identified
Asia	19
Africa	6
Europe	27
Europe/Asia	3
Oceania	0
North America	17
South America	6
International—Africa	2
International—Europe	12
International—OECD	2
International—Global South	1
International—various	15
Global	11
Total number of publications included in review	121

and energy efficiency compared to fossil fuels. To reduce any bias that may arise in the 'green jobs' literature with respect to job estimates for fossil-fired technology, several search strings combined search terms related to fossil fuel energy with job and employment creation and job creation metric key words. Search terms seeking information on net jobs effects included both "job creation" and "job destruction" to capture studies which might show positive and/or negative employment creation outcomes of shifting to low carbon energy technologies or infrastructure.

Job quantity, quality, and skills metrics presented in this paper reflect those identified in the relevance rating 1 studies for which sufficient information was available on their methodology in the source documents, therefore allowing meaningful comparisons and consideration in the sections which follow. In "How job creation in the energy sector is measured", we comment further on the nature of job creation metrics in the energy sector. To provide an assessment of the quality of studies compared in our review, we have categorised source documents in terms of publication type (the majority are academic peer-reviewed journal articles with some grey literature). See for example Tables S2 and S3 in the Supplementary Information, which also present information on methods used in each study to generate the estimates included in our comparative analysis.

How job creation in the energy sector is measured

Methods for estimating the quantity of job creation in the energy sector vary from literature reviews to calculating employment factors,[1] collation of data and statistical analysis, to several different types of modelling including statistical (e.g. regression) models, input–output models, or computable general equilibrium (CGE) models and macroeconomic or macroeconometric models. Box 1 summarises several of the most common methods identified in the literature and outlines key advantages and disadvantages. Studies vary in terms of whether they represent direct employment impacts or wider "multiplier" employment created in supply chains or due to increased spending in the economy. Direct employment refers to those jobs that arise directly as a result of an investment; indirect employment commonly refers to the jobs created within the supply chain supporting a specific project. Induced employment can refer to jobs created as a result of the increased household expenditure of direct and indirect employees, but induced effects may also be linked to electricity price and salary changes (Blyth 2014; Stavropoulos and Burger 2020).

In our review, we compare an international evidence base of identified studies which estimate employment factors for gross job creation relating to different types of renewable energy, energy efficiency, and fossil fuel generation. We collate employment factors from the literature which normalise the quantity of job creation according to the scale of activity, e.g. Gigawatts (GW) of electricity installed or level of investment. The studies reviewed vary in terms of the types of jobs or employment impacts represented (e.g. direct, indirect, and induced) and how boundaries between

[1] Defined by Cameron and Van Der Zwaan (2015, p. 161) as "the number of jobs derived from a certain renewable technology investment or capacity".

these categories are defined, i.e. which jobs are included as direct or indirect, which induced effects are modelled, etc. Another challenge is that there is a high degree of repeat referencing or replication of employment factors across literature focused on the energy sector (Cameron and Van Der Zwaan 2015; García-García et al. 2020). Our comparative analysis on gross employment factors, presented in "Review findings on quantity of job creation", is therefore indicative. We also review estimates of whether or not low carbon energy transitions might result in net employment gains or losses at country or regional scales. A more limited body of literature identified considers quality and relative skill levels of low carbon energy jobs (e.g. in relation to fossil fuel industries). Such studies may be based upon analyses of employment surveys or occupational profiles derived from input–output tables, and we discuss examples in "Review findings on quality of job creation, occupations, and skills".

Box 1 Typical methods used to estimate low carbon energy job creation[a]

Employment factors and analytical models

Employment factors divide the number of jobs created by a measure of the scale of activity. This allows projects/programmes of different sizes to be compared, giving an indication of their relative effectiveness in terms of job creation. A common indicator used with respect to green stimulus project/programmes is the number of jobs created per US dollar (USD) (or other currency) invested. Alternative units used for renewable energy specifically are 'jobs per MW capacity installed' or 'jobs per GWh electricity generated'. Employment factors may be derived from industry surveys or interviews, or collated from literature, and then used in a simple, spreadsheet-based analytical model to estimate direct employment impacts.

Economy-wide modelling

Another approach is to take an economy-wide perspective and aim not to count low carbon jobs as such, but to account for wider labour market impacts of green policies. These modelling approaches, which include *input–output analysis* and *computable general equilibrium (CGE) models*, evaluate whether overall jobs or other indicators of the labour market or the economy as a whole are impacted positively or negatively by renewable energy and energy efficiency policies.

Input–output (IO) analysis requires the use of a set of national IO accounts for an economy. The IO table gives a 'snapshot' of the nature of production and consumption flows in an economy during a specific period of time, usually a year. IO models support evaluation of interdependencies between (i) inputs used and outputs produced by different industries, and (ii) industry outputs and final demand from consumers of goods and services. IO models can be used to estimate the employment impacts of deploying a technology across multiple sectors of the economy. They can quantify the net job impacts of employment gains in one sector (e.g. renewable energy deployment) versus employment losses in another sector (e.g. phasing out fossil fuel generation). IO models can produce separate forecasts of direct, indirect, and induced employment 'multipliers' arising from low carbon energy deployment. In this way, IO analysis can estimate the size of Type 1 (direct + indirect jobs) and Type 2 multipliers (direct + indirect + induced jobs).

A *computable general equilibrium* (CGE) model is an analytically consistent mathematical representation of an economy, which captures the interdependencies across all sectors in the economy at a particular point in time. The models are solved computationally, with an equilibrium being characterised by a set of prices and level of production across all sectors, such that demand equals supply for all commodities simultaneously. CGE models are used to estimate how an economy might react to changes in policy or other exogenous influences, and can capture direct and indirect employment effects, and most types of economy-wide induced effects.

[a]The Box 1 text is based on a range of sources (Blyth 2014; Cameron and Van Der Zwaan 2015; Yi and Liu 2015; Mikulić et al. 2016; Garrett-Peltier 2017; Park and Lee 2017; Mu et al. 2018; Nasirov et al. 2021).

Review findings on quantity of job creation

In this section, we review findings and quantitative metrics from the literature as they relate to how many jobs can be created by deploying renewable energy and energy efficiency compared to supporting investment in fossil fuel energy production. We also consider net employment and economic effects of transitioning to a low carbon energy system at a national and regional scale, and how these may vary over time. This section therefore addresses the first two research questions set out in the introduction on quantity of job creation and the geographic and temporal distribution of its impacts within countries.

In our review, most of the identified studies quantifying job creation by technology estimated gross employment. Therefore, following an approach taken by Blyth (2014), we provide an approximate assessment of net jobs impacts by comparing gross employment factors for renewable energy and energy efficiency with those for fossil fuels. The first two sub-sections below review gross employment factors according to different metrics identified in the reviewed literature, relating to the scale of technological activity and level of investment.

Evidence identified in our review on net job creation applies predominantly to international, national and regional scales, and tends to focus more on net effects as a result of low carbon transition across the power sector or wider energy system rather than exclusively as a result of deploying single technologies. In "Does a shift to low carbon energy create jobs? Estimates of net job creation or destruction at a national or regional scale", we consider studies which estimate how many jobs are created as a result of decarbonising the energy sector, net of jobs lost in more carbon-intensive, fossil fuel activities. These studies attempt to characterise how net job creation, destruction, and linked economic impacts might be manifested at a national or regional level, e.g. as a result of climate change mitigation targets or nationally determined contributions (NDCs). "Economic impacts of net job creation or destruction at a country or regional scale" discusses findings from the literature on the economic impact of low carbon energy job creation.

Comparing gross job creation of energy technologies and interventions by scale of activity

In Fig. 2a, b, we have collated data from our review on job creation per installed capacity for different life stages of electricity generation technologies: manufacturing (in job-years/GW); construction and installation (in job-years/GW); and operation and maintenance (in jobs/GW). This data is presented in additional detail in Table S2 in the Supplementary Information. One job-year is one full-time job for one person lasting for a year (Dufo-López et al. 2016). These units show the number of jobs created annually and are used to characterise manufacturing and construction/installation jobs, which are required in the first few years of projects and at a project level tend to be shorter term in nature compared to ongoing employment in operation/maintenance. Operation and maintenance jobs are typically expressed in jobs/MW, as it is assumed that these jobs are more permanent in nature and should last over the lifetime of energy technologies (Ram et al. 2022). These more granular estimates broken down by technology life stage are only available in a limited range of studies in the literature. In Fig. 2a, b, we have converted jobs and job-years from the original datasets, so they are normalised by GW rather than MW. This helps to aid comparison of the potential volume of jobs created by technology.

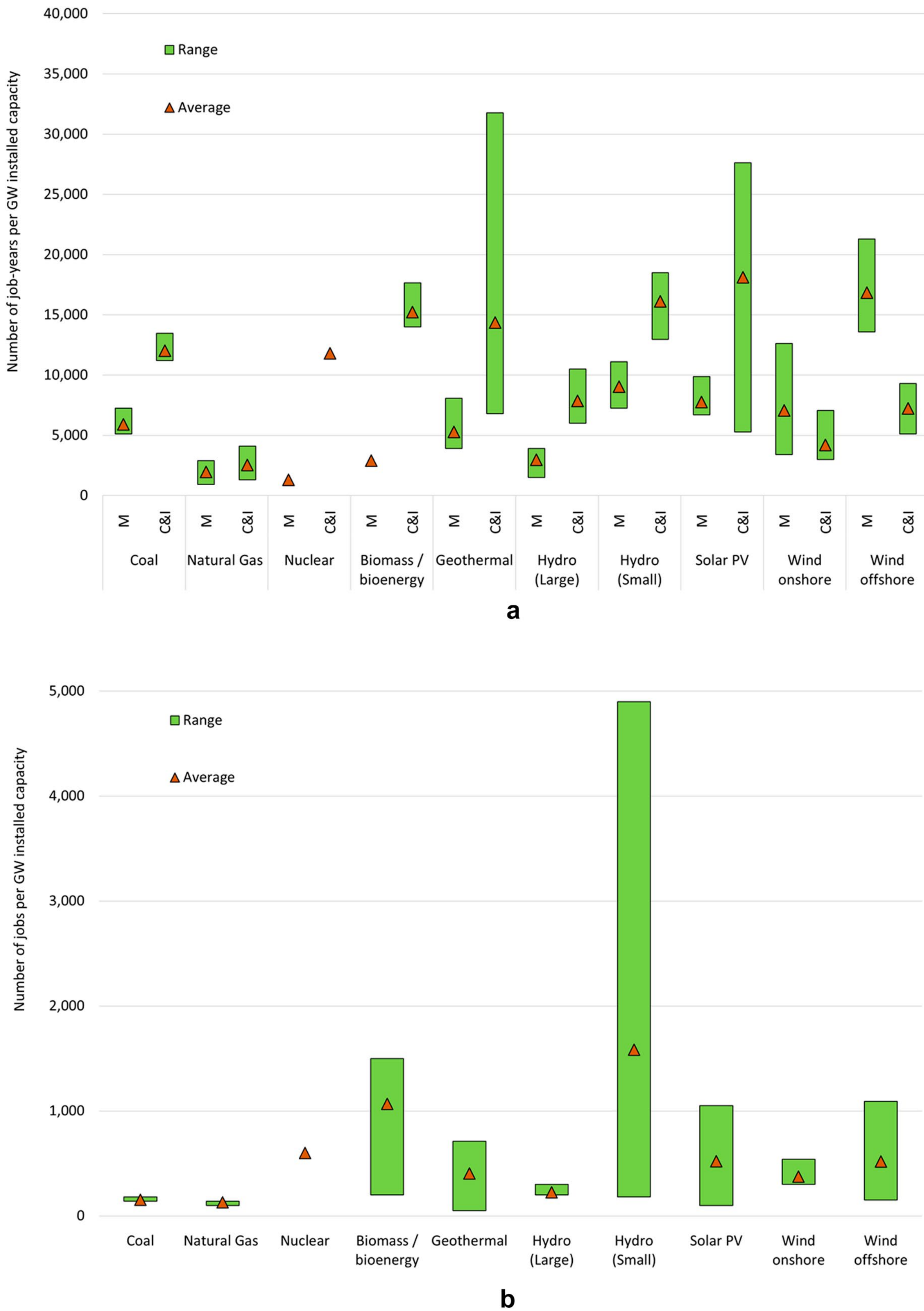
Most of the documents from which this dataset has been derived estimate direct and/or indirect employment impacts using an analytical approach (see notes to Fig. 2a, b). Two studies apply an input–output model, but only estimates from the global analysis of Jacobson et al.'s (2017) account for direct, indirect, and induced jobs. Therefore, the data shown in these figures relates mainly to employment created directly in the activities shown, or in associated supply chains.

A number of key observations can be made with respect to this dataset. Firstly, there is a higher level of manufacturing job creation per GW for several types of renewables (including offshore wind, small hydro, and solar PV) compared to gas or coal-fired electricity generation (Fig. 2a). The average estimate of job-years created per unit of installed capacity is particularly high for offshore wind (16,800 job-years per GW). The potential to make use of high employment factors for manufacturing depends on the presence of a renewables manufacturing base in any given country. Moreover, many construction/installation and operation/maintenance jobs may effectively be exported overseas depending on the development and size of an export market for manufactured renewables. Simas and Pacca (2014) observe that the standard metric of manufacturing job-years/unit of installed capacity in a particular year may be misleading, since it does not account for the proportion of imports or exports. It would therefore be possible for a country to have a very high index if installed capacity is low due to most manufactured technologies being exported.

The evidence on construction and installation (Fig. 2a) indicates that this activity creates most jobs for solar PV, biomass, and small hydro, around between 15,000 and 18,000 job-years per GW. Construction of natural gas power plants is associated with the lowest level of employment (2,500 job-years per GW). Wind farm installation performs relatively modestly (averaging 4,200 and 7,200 job-years per GW for onshore wind and offshore wind, respectively). Ram et al. (2022) observe that demand for construction, installation, and operation and maintenance jobs tends to be created locally, and these activities are therefore a fairly good indication of the potential to generate jobs within a country or region. However, a key uncertainty is the extent to which labour and supply chain services may be imported from other countries.

Figure 2b suggests that operation and maintenance is associated with the highest number of jobs over technology lifetimes for small hydro (1,600 jobs/GW) and biomass (1,100 jobs/GW). Natural gas and coal have the lowest employment factors for operation and maintenance (130 and 155 jobs/GW, respectively).

The estimates of job creation presented so far pertain to electricity generation technologies. Ram et al. (2022) include employment factors for a range of heating technologies in a recent global scenario analysis based on an energy transition to 100% renewables, with a high level of electrification, from 2015 to 2050. The authors present job intensities by manufacturing, construction and installation, and operation and


40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
Range
Average
Number of job-years per GW installed capacity
M
C&I
Coal
Natural Gas
Nuclear
Biomass / bioenergy
Geothermal
Hydro (Large)
Hydro (Small)
Solar PV
Wind onshore
Wind offshore
a
5,000
4,000
3,000
2,000
1,000
0
Range
Average
Number of jobs per GW installed capacity
Coal
Natural Gas
Nuclear
Biomass / bioenergy
Geothermal
Hydro (Large)
Hydro (Small)
Solar PV
Wind onshore
Wind offshore
b

◂**Fig. 2** **a** Gross job-years created in manufacturing (M) and construction and installation (C&I) per GW of installed capacity. **b** Gross jobs created in operation and maintenance per GW of installed capacity. *Notes*: a. Data reflects average and minimum/maximum values extracted from a range of studies (Ortega et al. 2015; Ortega et al. 2020; Atilgan and Azapagic 2016; Henriques et al. 2016; Jacobson et al. 2017; Dominish et al. 2019; Ram et al. 2020; Ram et al. 2022). b. The job creation data relates to the global scale, Europe, Portugal, and Turkey. c. Methods: six studies derive employment factors from literature, of which five studies utilise analytical methods; two studies use input–output analysis. d. Multipliers: four studies include direct jobs only; three include direct and indirect jobs; one study includes direct, indirect, and induced jobs

maintenance activities, expressed in units of jobs (or job-years) created per megawatts of thermal (MW_{th}) installed capacity. In general, these particular estimates suggest that Construction, Installation and Manufacturing (CIM) activities are associated with a higher number of job-years per megawatts thermal (MWth) for low carbon heating technologies and fuels sources (e.g. individual heat pumps, district heating sourced from heat pumps or biomass, or waste-to-energy combined heat and power) compared to gas or oil heating. Estimates for employment creation in operation and maintenance (jobs per MWth) are similar for individual oil, gas, electric, and heat pump technologies, but highest for solar thermal and individual biomass heating systems.

Comparing gross job creation of energy technologies and interventions by level of investment

Figure 3 summarises the evidence identified across 14 studies which estimate the number of gross jobs created per USD million invested for different energy technologies. This represents total investment, across public and private sectors, and is largely based on studies which model estimates of job creation potential using input–output analysis (see notes to Fig. 3 and Table S3 in the Supplementary Information). Half of the studies account for direct and indirect employment effects only, with the other half representing indirect and induced employment multipliers as well as direct job impacts. Employment factors extracted from five documents reviewed capture investment only or mainly in the CIM phase, with a further four studies quantifying jobs per investment in CIM and O&M phases. However, the remaining six studies are unclear on which phase/s are represented.

The comparison presented in Fig. 3 suggests that renewables or energy efficiency can generate more jobs per US dollars invested than fossil fuel generation or nuclear power. Fossil fuel generation creates five jobs per USD million invested on average across the various studies, compared to eight jobs/USD million for nuclear power and 15 jobs/USD million for the renewable energy technologies shown in the chart. Building energy efficiency demonstrates the highest job creation potential per level of investment, creating an average of 22 jobs/USD million.

The relative employment outcomes of investing in higher carbon or low carbon technologies or energy efficiency may reflect a number of factors, including the ratio of spending on local content versus imports, the ratio of spending on labour as opposed to capital, and average wage levels for jobs in particular technology sectors and their supply chains (Pollin and Garrett-Peltier 2009). The extent to which high employment factors are desirable as a policy objective is a point to which we return later. Lower employment factors for fossil fuel power generation may also be associated with greater market maturity of well-established, conventional technologies compared to renewables or energy efficiency.

Does a shift to low carbon energy create jobs? Estimates of net job creation or destruction at a national or regional scale

Investment in renewables and energy efficiency can be justified with reference to the ‘gross’ numbers of jobs that such investment might create in a particular sector. However, a fuller understanding of the employment impacts should be based on ‘net jobs’, which also account for jobs displaced in fossil fuel production and supply as a result of supporting a low carbon energy transition. Global analyses are in broad agreement that the net employment effects of climate change mitigation policy and a low carbon energy transition will be positive, estimating that by 2030 and 2050, more jobs will be created by a shift to low carbon, renewable energy than the number of jobs displaced from decommissioning fossil fuel power plants (e.g. ILO 2019; Jacobson et al. 2019; IRENA 2021; Pai et al. 2021). Nevertheless, key questions for policy makers are how job creation and job destruction will be geographically distributed, and how the impacts of this transition will fall in particular countries and regions at different points in time.

In Table 3, we summarise the scope, methods, and findings from 18 studies identified in our review which estimate how decarbonisation in the energy sector affects the overall number of jobs created and displaced at a national and/or regional scale. Taken together, these studies represent evidence from Argentina, Brazil, China, India, Turkey, Japan, and eight European countries (including the UK). Ten of the studies in Table 3 focus on the impacts of decarbonisation in the power sector alone, but several studies consider other energy sectors such as heat, transport, and industry (Sievers et al. 2019; Füllemann et al. 2020; Lee et al. 2022), or energy efficiency and energy intensity (Chen et al. 2023). An important variation between the studies relates to how they use counterfactuals to calculate net employment impacts. Across the 18 documents, overall job creation or destruction is typically estimated as being the net of avoided investment

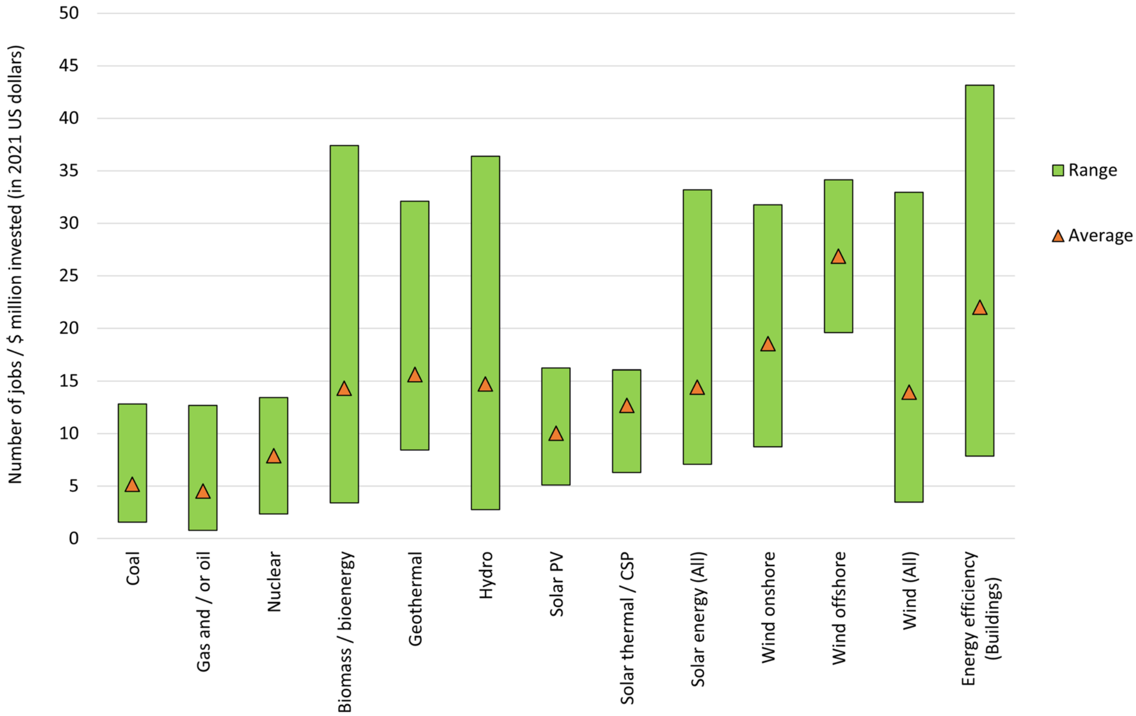


Fig. 3 Gross jobs created per USD million invested. *Notes*: a. This chart shows identified evidence from 14 studies on the number of gross jobs created per USD million (US dollars) invested for different energy technologies or interventions. b. The 14 studies were published from 2009 to 2020, pertaining to Europe, Croatia, Germany, Greece, Spain, UK, US, and India (Pollin and Garrett-Peltier 2009; Lambert and Silva 2012; Zabin and Scott 2013; Markaki et al. 2013; Pollin et al. 2014; Rosenow et al. 2014; Calzadilla et al. 2014; Mirasgedis et al. 2014; Cambridge Econometrics 2015; Mundaca and Luth Richter 2015; Reddy 2016; Mikulić et al. 2016; Garrett-Peltier 2017; Brown et al. 2020). c. Methods: nine studies use input–output analysis, including two which also use an analytical method and one which also employs a global CGE model. Two studies employ alternative model types. Three studies collate data from different literature sources. d. Multipliers: seven studies include direct, indirect and induced jobs; seven studies account for direct and indirect jobs only. e. Phase: five studies include only or predominantly the CIM phase; four studies include both CIM and O&M phases, and six documents are not clear on their inclusion. f. Where the investment currency in the original datasets was not US dollars (USD), it has been converted from EUR or pound sterling to USD, based on Eurostat (2023) and OECD (2023), and then adjusted for inflation to 2021 USD using an inflation calculator (U.S. Bureau of Labor Statistics 2023)

in fossil fuels (either domestic industries or imports), or net of reference (e.g. continuation of current policy) scenarios. In terms of methods, input–output analysis is most commonly used (six studies) followed by CGE models (four studies), including Perrier and Quirion (2018) who combine both model types. Sievers et al. (2019) and Lee et al. (2022) apply a macro-economic and macro-econometric model, respectively; Chen et al. (2023) combine an econometric model with panel data. Seven of the identified documents account for direct, indirect, and induced employment; six studies consider direct and indirect but not induced jobs; and two studies estimate direct jobs' effects alone.[2]

The documents reviewed in Table 3 address the net employment impact of climate change mitigation or decarbonisation scenarios over the next one to three decades, achieving higher shares or capacities of renewable energy and/or substituting fossil fuels with renewables and energy efficiency. 13 of the 18 studies conclude that, at a national scale, there is likely to be positive net job creation overall from replacing fossil fuels with renewables/improving energy efficiency or as a result of energy sector decarbonisation. Whilst some of these additional jobs are relatively short term since they relate to the construction and installation phase, Arvanitopoulos and Agnolucci (2020) find that in the UK, there is still likely to be an increase in overall jobs in the long term. Perrier and Quirion (2018) observe that both an input–output and CGE model generate positive net employment outcomes in France for a €1 billion investment in solar PV installation or building weatherisation.

Three studies find that a mixture of job creation and displacement effects could result in China, India and Italy, respectively (Cai et al. 2017; Mu et al. 2018; Sharma and Banerjee 2021). Mu et al. (2018) model alternative ways of financing a feed-in tariff in China to attain a 1 Terawatt-hour

[2] Three documents do not provide information on the representation of direct, indirect and/or induced jobs.

Table 3 Net job creation/destruction and economic impact from supporting renewables and energy efficiency: national and regional scale estimates

Author (year)	Document type (publisher)	Geography (timescale)	Energy sectors included	Method (direct/indirect/induced jobs included?)	Findings on net job creation/destruction and economic impact
Le Treut et al. (2021)	Academic peer-reviewed journal article (Elsevier)	Argentina (2015–2050)	Power sector decarbonisation	Deep decarbonisation pathways developed using the LEAP model and loaded into IMACLIM-Country—a multi-sector CGE model (direct, indirect, and induced jobs)	Net job creation is slightly negative across the whole economy (− 0.5 to − 0.7%) reflecting sectoral net job creation in energy, construction, and manufacturing, but net job destruction in agriculture, transport, and services
Heideier et al. (2020)	Academic peer-reviewed journal article (Elsevier)	Brazil (2017–2040)	Solar PV distributed generation (PVDG) and energy efficiency— impacts of wider diffusion on markets of three power distribution utilities	Accounting simulation model scenarios (direct jobs)	Net job creation (gross jobs created less a counterfactual of jobs created by investment in thermal power plants with equivalent electricity output) was positive for PVDG and energy efficiency measures for all three distribution utilities
Chen et al.(2023)	Academic peer-reviewed journal article (Elsevier)	China: focus on cities (2006 to 2019)	Energy efficiency and reducing energy intensity (energy consumed per unit of GDP)	Econometric model and panel data for around 280 Chinese cities (N/A)	A 1% increase in the energy intensity reduction rate resulted in a 2% rise in the employment growth rate. It is found that improving energy efficiency promoted employment creation overall, accounting for job creation and job destruction
Mu et al. (2018)	Academic peer-reviewed journal article (Elsevier)	China (based on 2012 Input–output table)	Effect of expanding solar PV and wind power by 1TWh under scenarios with alternative renewable energy financing mechanisms, compared to 2012 reference scenario	CGE modelling: China Hybrid Energy and Economic Research model (Direct, indirect and induced jobs)	Direct and indirect effects lead to job creation and induced effects cause job losses. Overall, 3 of 4 scenarios for solar PV and wind power reveal net job creation of 13,600 to 34,100 jobs/TWh, and 1 scenario net job losses of 800 jobs/TWh

Table 3 (continued)

Author (year)	Document type (publisher)	Geography (timescale)	Energy sectors included	Method (direct/indirect/induced jobs included?)	Findings on net job creation/destruction and economic impact
Zhang et al. (2022)	Academic peer-reviewed journal article (Elsevier)	China and provinces (2020–2050)	Power sector decarbonisation: coal phaseout, renewables, and energy storage. “Orderly” and “disorderly” net zero by 2050 scenarios compared, which vary according to the timing of restrictions on building new coal plants and retiring existing ones	Plant-level job accounting model combined with a power sector optimization model (direct and indirect jobs)	Nationally, it is estimated that by 2050 there could be a net job creation of 6.5 million workers in both the orderly and disorderly transition pathways compared to a reference scenario. Early phaseout of coal in China would help to ensure a geographically and socially equitable transition to low carbon energy can take place over an achievable time frame, reducing risk of sudden, mass unemployment
Perrier and Quirion (2018)	Academic peer-reviewed journal article (Elsevier)	France (2013)	€1 billion investment in solar PV installation or building weatherisation compared with €1 billion avoided investment in power, gas, and heat sectors	Input–output and CGE modelling (N/A)	Solar PV installation and building weatherisation have positive net employment impacts across both IO and CGE models applied, but positive impacts are higher in the IO model
Sievers et al. (2019)	Academic peer-reviewed journal article (Elsevier)	Germany and federal states (2010–2030)	Power sector, buildings heating and transport, industry, renewable energy and energy efficiency, and fossil fuels	Low carbon energy transition scenario and macroeconomic/economic impact assessment models of national economy, regional and sectoral distribution of economic and employment impacts (direct, indirect, and induced jobs)	By 2030, energy transition scenario results in: 1.1% higher total employment nationally and 1.6% higher GDP compared to reference scenario (no new policies). Northern and eastern German states may benefit the most economically as they have attractive locations for renewable energy and are less impacted by declining fossil fuel power generation

Table 3 (continued)

Author (year)	Document type (publisher)	Geography (timescale)	Energy sectors included	Method (direct/indirect/induced jobs included?)	Findings on net job creation/destruction and economic impact
Stamopoulos et al. (2021)	Academic peer-reviewed journal article (MDPI)	Greece (2020–2030)	Transition from fossil fuels to renewable energy for electricity production including phaseout of lignite power generation by 2028	Input–output modelling to assess impact of increased investment in a higher share of renewables under the Greek National Energy and Climate Plan (direct, indirect, and induced jobs)	Estimated that implementing Greek National Energy and Climate Plan would create 154,000 jobs from 2020–2030 and contribute EUR 6.83 billion to Greek GDP. This overall positive economic impact is attributed mainly to investments in solar PV and wind generation
Sharma and Banerjee (2021)	Academic peer-reviewed journal article (Elsevier)	India and regional states (2017–2022)	Power sector, specifically: solar PV; land use change resulting from siting new solar power plants; coal power stations and coal mining	Analytical model using employment factors to assess geographic distribution of job creation/destruction impacts (direct and indirect jobs)	Achieving national target of installing 100GW of solar PV by 2022 and retirement of coal power stations would lead to net job creation in six southern and western states but net job destruction in six other states with significant coal mining activity, particularly in four states in eastern India
Kamidelivand et al. (2018)	Academic peer-reviewed journal article (Elsevier)	Ireland (based on 2010 input–output table)	Energy and non-energy sectors; substituting electricity from imported gas and coal with renewables	Input–output substitution model (direct and indirect jobs)	Substituting gas with renewables creates 26.2 net jobs for each 1 per cent GHG reduced
Cai et al. (2017)	Academic peer-reviewed journal article (Elsevier)	Italy (2006–2014)	Solar PV, onshore wind, hydropower and bioenergy contribution to value added and employment	Input–output analysis combined with analytical model accounting for imports (direct and indirect jobs)	Renewable energy CIM job creation and value added lower than three counterfactual scenarios—attributed to significant import shares of renewable energy components. Renewable O&M phase used mainly local goods and services and had generally higher labour intensities and value added than counterfactual activities

Table 3 (continued)

Author (year)	Document type (publisher)	Geography (timescale)	Energy sectors included	Method (direct/indirect/induced jobs included?)	Findings on net job creation/destruction and economic impact
Ju et al.(2022)	Academic peer-reviewed journal article (Elsevier)	Japan (2010–2050)	Power sector decarbonisation, including: renewable energy manufacturing, construction and electricity supply sectors, and all other power generation activities	Partial equilibrium integrated assessment models (IAMs) and input–output modelling (direct and indirect, and induced jobs)	Net job creation may be positive in 2030 with job creation in renewable energy manufacturing and construction exceeding job losses in thermal power generation and associated mining and construction activities. This positive net job creation will increase “dramatically” by 2050 (a 90% CO_2 emissions reduction scenario could result in up to 3.5 million jobs across all activities related to electricity supply)
Kuriyama and Abe (2021)	Academic peer-reviewed journal article (Elsevier)	Japan and regions (2016–2050)	Power sector decarbonisation using renewable energy	Employment factors based on input–output tables, and just transition scenarios for power sector decarbonisation (direct and indirect jobs)	Shift to low carbon electricity generation via renewables leads to net job creation domestically, particularly in O&M and stable, long duration employment in rural areas. Reduced fossil fuel imports from abroad implies a significant decline in overseas labour
Lee et al. (2022)	Academic peer-reviewed journal article (Taylor & Francis)	Japan (2018–2050)	Power generation, transport, building heating, steel, and other industrial sectors	E3ME macro-econometric model and two policy scenarios (including carbon tax) to reach Net Zero by 2050 (direct, indirect and induced jobs)	Net Zero policy scenarios lead to increased GDP (4–4.5%) and employment (2%) by 2050 compared to reference scenario (based on continuation of current policies and 32% CO_2 emissions reduction by 2050)
Baran et al. (2020)	Academic peer-reviewed journal article (Elsevier)	Poland (2020–2030)	Substituting coal with renewables, energy efficiency or natural gas imports	Dynamic stochastic general equilibrium model (N/A)	Net loss of labour and GDP reductions would result unless former coal miners can move to jobs in green or "neutral" sectors

Table 3 (continued)

Author (year)	Document type (publisher)	Geography (timescale)	Energy sectors included	Method (direct/indirect/induced jobs included?)	Findings on net job creation/destruction and economic impact
Füllemann et al. (2020)	Academic peer-reviewed journal article (Taylor & Francis)	Switzerland (2011/2050)	Switching from fossil fuels to renewable electricity generation, greater energy efficiency in buildings, industry, transport and services	National energy transition scenarios and input–output tables (direct and indirect jobs)	Net 20% increase in FTE jobs (particularly in heating and building retrofit)
Acar et al. (2023)	Academic peer-reviewed journal article (Elsevier)	Turkey (2018–2030)	Transformation scenario for power system decarbonisation with renewable energy, energy efficiency and end use electrification	Power system model soft-linked with a CGE model using input–output data. Employment factors and decomposition analysis used to estimate total employment impacts (direct, indirect and induced jobs)	Compared to a Business As Usual scenario, by 2030 the Transformation scenario leads to: net creation of around 43,000 jobs, including more highly skilled jobs in services sectors; net 1% increase in GDP due to higher real wage incomes and energy efficiency gains
Arvanitopoulos and Agnolucci (2020)	Academic peer-reviewed journal article (Elsevier)	UK (2030)	Power generation sector: conventional thermal, CCGT, nuclear, renewables	Econometric: Vector error correction model and UK Times model decarbonisation scenarios (direct jobs)	Five alternative decarbonisation scenarios result in net employment creation ranging from 12,000 to 152,500 jobs by 2030

(TWh) expansion target for solar PV and wind power. These lead to direct and indirect job creation, but induced job losses, with net job creation arising overall in three scenarios and modest net job destruction in one scenario for wind power compared to a reference scenario.

Two studies report overall net job destruction or indicate a significant risk of such an outcome (Baran et al. 2020; Le Treut et al. 2021). Le Treut et al. (2021)'s CGE model analysis concludes that power sector decarbonisation in Argentina could cause a small proportion of job losses across the economy (−0.5 to −0.7%), and that net job creation in energy, construction, and manufacturing would be offset by job destruction in other economic sectors. Additionally, significant structural change would be implied within the energy sector due to the fast decline of fossil fuels and rapid growth of low carbon power generation (Le Treut et al. 2021). Baran et al. (2020) caution that a transition away from coal production and use in Poland could lead to net job destruction, without a well-managed plan to help displaced coal miners transition to new roles in renewable energy and energy efficiency sectors.

The aggregate balance of job creation and destruction across a national economy also depends on the extent to which new and displaced energy sectors utilise labour within or outside a given country. Cai et al. (2017) combine input–output and analytical models to evaluate employment impacts of solar PV, onshore wind, hydropower, and bioenergy in Italy from 2006 to 2014. The authors contend that lower job creation for renewable energy CIM activities compared to three potential alternative investments in other economic sectors is due to many renewable energy components being imported. Conversely, O&M in Italy's renewables sector used mostly local goods and services and generated higher employment factors than the counterfactual investments. Similarly, in an input–output analysis of a transition to low carbon electricity generation in Japan by 2050, Kuriyama and Abe (2021) find that a shift to renewable energy could lead to net job creation within the country by reducing the need for fossil fuel imports and reliance on overseas labour. In an alternative IAM and input–output analysis, Ju et al. (2022) caution that very high positive net job creation from power sector decarbonisation by 2050 may lead to possible workforce shortages and a need to source 30% of non-electricity and manufacturing jobs from outside Japan by 2050. Making the most of domestic job-generating opportunities depends on effective national and local government support providing training, recruiting workers, and developing a labour force with requisite skills in renewable energy sectors (Kuriyama and Abe 2021).

Five of the studies in Table 3 attempt to quantify the regional distribution of low carbon energy employment. Sharma and Banerjee (2021) find that retiring coal power plants in India and attaining a national 100GW solar PV capacity target would have mixed net jobs impacts across different regions. While the authors' analytical model suggests an outcome of positive net job creation in six Indian states, net job destruction is projected in six other states, particularly those which have considerable coal mining activity. In Zhang et al. (2022), the balance of projected job creation and displacement is modelled for ten Chinese states, which together represent 65% of installed coal power generation nationally. An "orderly" net zero transition scenario with an early coal phaseout leads to net job creation across all ten of these states. However, in a "disorderly" net zero pathway with late coal phaseout, four states experience net job losses from 2030 to 2040 due to sudden closure of coal power stations (Zhang et al. 2022). Chen et al. (2023) conduct an econometric analysis of employment impacts of energy intensity reductions and energy efficiency improvements in Chinese cities from 2006 to 2019, finding that net employment gains were highest in cities which had lower, pre-existing levels of employment and energy efficiency.

Kuriyama and Abe (2021) conclude that transitioning to renewable electricity generation in Japan could be particularly favourable for creating stable, long-term jobs in O&M in rural areas. The study illustrates that early planning is required for conventional power plant phaseout to avoid a surplus of workers, accounting for regional differences in the impact of this phaseout and new opportunities available for renewables, energy efficiency, or other low carbon energy sectors. Elsewhere, Sievers et al. (2019) investigate a low carbon transition scenario across the energy system in Germany using a macroeconomic model and an economic impact assessment model; their approach includes a regional breakdown of employment impacts. The study finds that a low carbon energy transition could create around 1% more jobs in total, nationally, from 2010 to 2030. Northern and eastern German states would likely gain the most economically given their high suitability of locations for siting renewable energy, and would be less affected by the phaseout of fossil fuel power plants (Sievers et al. 2019).

Economic impacts of net job creation or destruction at a country or regional scale

Evidence reviewed above and shown in Fig. 3 indicates that renewables and energy efficiency can generate more jobs than fossil fuels for the same level of investment. It does not automatically follow, however, that prioritising investment in these technologies will result in higher employment for any given national economy in the long term. Investing in options with higher job multipliers such as certain renewable energy CIM activities or installing building energy efficiency interventions makes sense in a depressed economy in which aggregate demand is low compared to potential supply of goods and services (creating a so-called "Keynesian output gap"). In such a context, stimulating additional employment in labour-intensive sectors is very likely to lead to higher overall employment (Blyth 2014).

While the circumstances around the COVID-19 economic recession and the 2009 financial crisis are very different, evidence from the 2009 crisis indicates that the green measures (e.g. in renewable energy infrastructure) forming part of the recovery stimulus created more jobs than conventional stimulus measures (Allan et al. 2020). The UK's Climate Change Committee (CCC) recommend that in the short term, "*green stimulus policies can be economically advantageous compared to traditional fiscal stimuli. They tend to have higher short run multipliers and higher numbers of jobs created*" (CCC 2020, p. 141). Domestic construction projects such as insulation retrofits or building wind turbines may be particularly favourable and less prone to offshoring services overseas. In comparison to the renewable energy CIM phase, employment in the operation and maintenance of renewable power generation technologies is typically more permanent, with potential to last over technology lifetimes (Ram et al. 2022).

There is a debate in the literature identified in our review around the extent to which policies supporting renewable energy may contribute to longer term economic growth, notwithstanding short-term employment and growth benefits (e.g. Jaraite et al. 2017; Safwat Kabel and Bassim 2019). While we have not found extensive evidence to definitively answer this question, identified studies suggest that subject to geographic and contextual variations, low carbon energy shifts may promote modest economic growth effects and are unlikely to be detrimental to economies at a national level. Several of the studies presented in Table 3 suggest that supporting a low carbon energy transition is compatible with longer-term economic growth over the next 10–30 years. For example, Stamopoulos et al. (2021) note that increased investments in solar PV and wind power are key to their modelled outcome that the Greek National Energy and Climate Plan could contribute EUR 6.8 billion to Greek GDP by 2030. Similarly, Sievers et al. (2019) project a 1.6% increase in GDP versus a reference scenario in Germany from 2010 to 2030 as a result of energy sector decarbonisation. Elsewhere, Lee et al. (2022) analyse two net zero policy scenarios for Japan (with and without nuclear power phaseout), finding that by 2050 decarbonisation across the energy system could add 4–4.5% to GDP compared to a reference scenario.

On the other hand, and linked to the challenge of allocating displaced coal miners to new low carbon energy jobs, there is a significant risk that replacing coal power with renewables and energy efficiency in Poland could lead to reductions in GDP as well as net labour losses (Baran et al. 2020). The contribution of different renewable energy phases to net employment and value added in a given country may also depend upon the extent to which goods, services and labour are sourced locally. Cai et al. (2017) find that due to significant component imports, renewable energy CIM in Italy contributed less to value added historically than counterfactual scenarios. By contrast, the predominantly local content and higher labour intensities of renewables O&M led to higher value added than the counterfactuals. Pegels and Lütkenhorst (2014, p. 529) found that renewables component manufacturing in Germany was "*often located in the traditional industrial centres",* some with the "*highest unemployment ratios nationwide*".

While well established, high carbon technologies and sectors may be close to their limits in terms of additional innovation and economic productivity gains, investment in less mature, faster growing low carbon technologies such as renewables could contribute more to productivity through greater scope for innovation and learning by doing (CCC 2019). Careful planning is required to optimise the design of subsidy schemes for renewable energy technologies to lower risks of increasing income inequality or regressive distributional impacts on low-income households, such as those which have been modelled in studies of Ireland and Germany respectively (Többen 2017; Farrell et al. 2020). When designing stimulus programmes, it makes sense from a Keynesian perspective to support technologies and projects that have a positive, long-term impact on economic productivity beyond the time frame of the direct stimulus effects. In a longer-term context, labour intensity is not in and of itself economically advantageous. If it implies lower levels of labour productivity (economic output per worker), then it could adversely affect prospects for long-term economic growth. On the other hand, critiques of Green New Deal approaches argue that they perpetuate a narrative around the need for full employment, high production, high consumption economies which are incompatible with conserving finite resources and minimising ecological footprint (Green 2022). Developing on from Blyth (2014), we therefore contend that policy should not be focused on maximising jobs per unit of investment in the long run. Rather, policy decisions should be based on whether investments can contribute to an economically efficient transition towards effective climate change mitigation, taking account of the need for a just transition, wider ecological impacts, and energy security considerations.

Review findings on quality of job creation, occupations, and skills

In addition to assessing the quantity and distribution of job creation or destruction through low carbon energy transformation, the third and final objective of our review is to consider implications for quality of jobs, skills and training, at national and regional scales. In this section, we discuss key highlights from relevant literature related to these topics and examples of relevant metrics identified in the review.

Quality of job creation

Mattos (2018) suggests that "*evidence on green policy impacts on job quality is minimal*." In our review of international literature, we have identified a subset of studies which discuss the quality of green or low carbon energy jobs in qualitative terms. Lambert and Silva (2012) have previously noted that developing job ratios to characterise job type or quality is more challenging than counting the number of jobs created. We have found a limited number of studies which use quantitative metrics to assess employment quality, occupation types or relative skill levels in low carbon energy compared to high carbon energy sectors.

The Paris Agreement (UNFCCC 2015) sets out that national priorities for low carbon development should ensure a just transition through the creation of decent work and quality jobs. Several studies extracted from our review highlight the importance of ensuring the quality of green jobs, and some documents refer to the concept of 'decent work'. For example, Mattos (2018) writes that "*green jobs are, by definition, decent jobs, i.e. a subset of jobs in environmental sectors which provide adequate wages, safe working conditions, safeguard workers' rights and social dialogue, and which provide social protection*." In other documents identified in our review, higher job quality is described for example in terms of high wages and full-time employment (Jung 2015), and permanent rather than temporary jobs (MacCallum 2016; Mattos 2018).

Wages can to some extent be represented through certain modelling approaches used to analyse quantity of job creation. Computable general equilibrium (CGE) models can account for a wider set of induced effects than input–output models, such as changes in workers' salaries (Mu et al. 2018). One example is Acar et al. (2023), who soft-link a power system model with a CGE model and account for wage income. The authors reveal that in a power sector decarbonisation scenario for Turkey, higher real wage incomes and energy efficiency gains contribute to a net 1% GDP increase by 2030 compared to a business as usual scenario (Acar et al. 2023).

Green or low carbon energy jobs may not always or necessarily be 'higher'-quality jobs. It has been suggested variously in the literature that direct employment in renewable energy construction or installation may be linked to temporary work which expires on completion of specific projects or might no longer be needed once renewable energy capacity targets have been met (MacCallum 2016; Sofroniou and Anderson 2021; Godinho 2022). MacCallum (2016) develop metrics to capture the longevity of renewable energy employment in Kingston, Canada, according to the following categories: "Temporary jobs"; "New direct jobs"; "New indirect jobs"; "Ongoing direct jobs"; and "Ongoing indirect jobs". In the UK, the Smart Metering Implementation Programme may create the need for smart meter installers as a new occupation—but the longer-term job security or career prospects of these jobs requires further exploration (Sofroniou and Anderson 2021).

With reference to data on Scotland, Connolly et al. (2016) suggest that labour intensity may fall as renewables mature and employment needs shift from construction to maintenance and servicing. The authors observed that "*between 2007 and 2012 the number of LCEGS [Low Carbon Environmental Goods and Services] jobs declined whereas the installed capacity of renewable generation in Scotland more than doubled*" (Connolly et al. 2016). Nevertheless, it is likely that achieving national net zero or decarbonisation targets will require a prolonged period of construction and installation of new renewables capacity over the next several decades.

Skills and occupational profiles

A cluster of studies was identified around the issue of skills and typical education levels associated with green jobs. Based on an analysis of US employment and occupational data, Consoli et al. (2016) suggest that "*Green jobs exhibit higher levels of education, work experience and job training*" and "*use more intensively high-level cognitive and interpersonal skills compared to non-green jobs*". This is supported by the findings of a study (Elliott and Lindley 2017) that analysed data from the US Bureau of Labour Statistics, and found that green industries "*increased the quantity of workers demanded from the middle of the skill distribution at the same time as they reduced the quantity demanded for lower skilled workers*". The same study went on to conclude that it was "*College graduates who gain the most from the expansion of green jobs*". A German study (Pegels and Lütkenhorst 2014) used data from the Federal Ministry for the Environment to assess the costs and benefits of Germany's Energiewende, focusing on wind and solar PV. The study found that "*the share of university-degree*

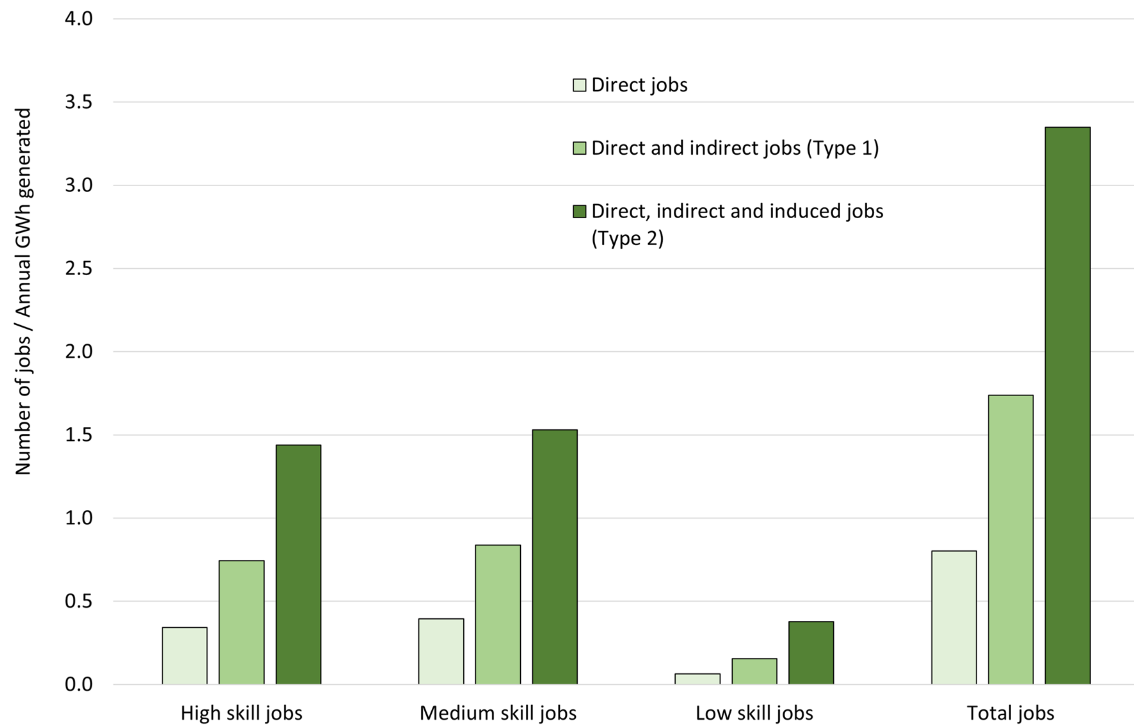


Fig. 4 Offshore wind in the UK: gross jobs per GWh by skill level, direct, indirect, and induced jobs. Data derived from Allan et al. (2021). *Notes*: a. High-skill jobs—managers, directors and senior officials; professional; associate professional and technical occupations. b. Medium-skill jobs—administrative and secretarial; skilled trades occupations; caring, leisure and other services. c. Low-skill jobs—sales and customer services; process, plant and machine operatives; elementary occupations. d. The factor by which indirect or induced jobs increase for a given increase in direct jobs is the multiplier, indirect job multipliers are often referred to as 'type 1', while induced job multipliers (including direct, indirect, and induced jobs) are referred to as 'type 2'

staff is around three times as high as the national industry average".

Allan et al. (2021) classify jobs in the UK offshore wind sector according to skill level, through a method involving extraction of data from a UK input–output (IO) table. The data is from 2010, the latest available to allow a detailed breakdown by occupational skills. The authors aggregate nine occupational SIC (Standard Industrial Classification of economic activities) categories to form three groups representing high, medium, and low skill levels. Figure 4 indicates that almost 90% of offshore wind jobs in 2010 were in the high to medium skill categories, and that most jobs are created indirectly in the supply chain or through the induced effect of additional household expenditure.

Vona et al. (2018) also report high skill levels and salaries for green occupations compared to non-green employment in the USA. Despite some identified differences in skill levels between green and non-green jobs, Reddy (2016) suggests that the skills required are not new, and Bowen et al. (2018) propose that much retraining in the green economy can occur 'on the job'. Others contend that the greening of the economy will require new skills, competencies and qualifications, linked to the creation of new markets and activities (Aceleanu et al. 2015; Shanghi and Sharma 2014). Several studies note the potential to train and employ young people in these new areas, while helping to address youth unemployment (Aceleanu et al. 2015; Rutkowska-Podołowska et al. 2016; Sulich, Rutkowska and Popławski 2020). Kapetaniou and McIvor (2020) highlight that in the UK, younger and male workers are concentrated in brown sectors, where most jobs require low- or medium-level skills. This implies challenges for younger males working in routine or manual brown occupations if they need to switch to green jobs; they may have to learn new skills to avoid job displacement difficulties (Kapetaniou and McIvor 2020).

The identified evidence does not support a straightforward claim that renewable energy or energy efficiency jobs are more skilled than higher carbon energy sectors, and this depends on the extent to which direct, indirect, and induced job creation are considered. Several analyses (e.g. Allan and Ross 2019; Dominish et al. 2019) observe that significant shares of employment in fossil fuel generation and extraction are in higher-skilled occupational categories. There is also demand for lower-skilled, manual occupations which may for example comprise much of solar PV installation and offshore wind construction activities.

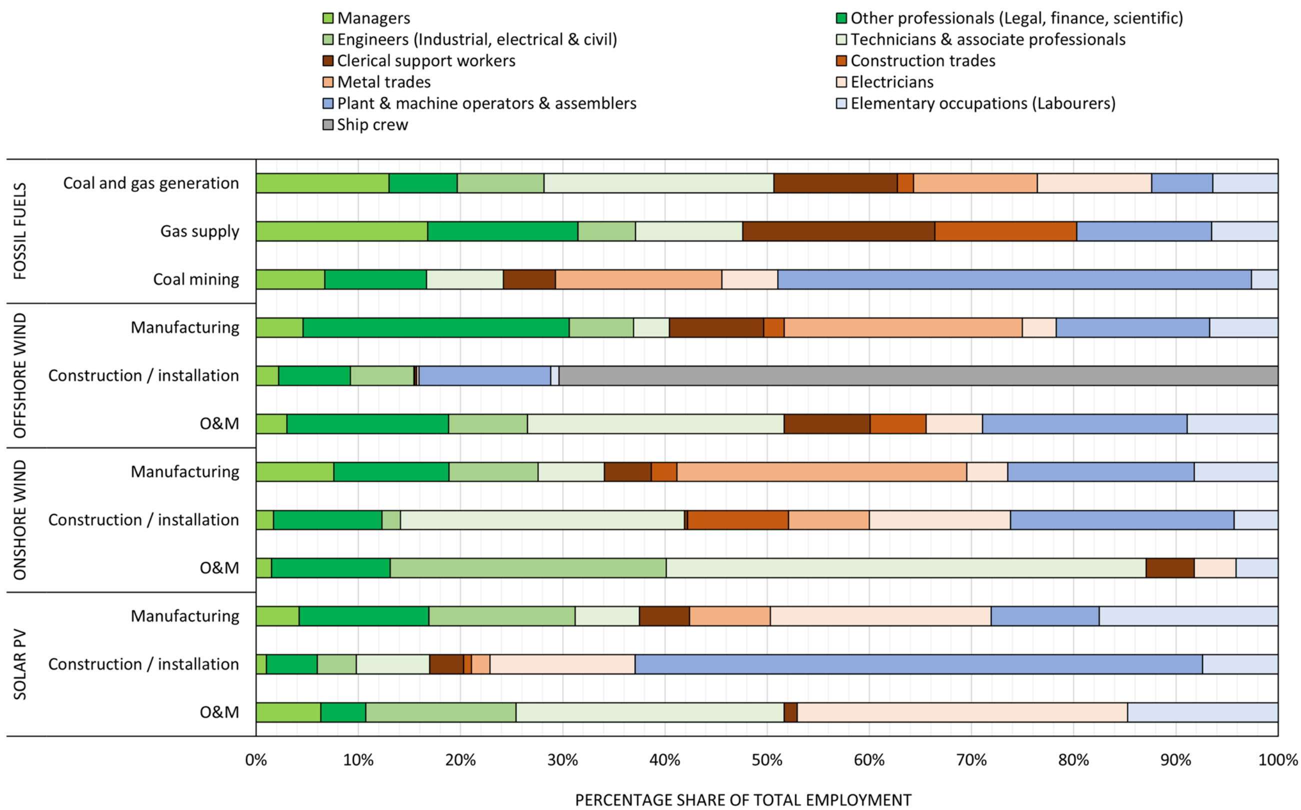


Fig. 5 Share of occupational categories by electricity generation technology/fuel source and activity. *Notes*: a. Data sourced from Dominish et al. (2019). b. The occupational data is based on surveys of wind and solar PV industries in various developed and developing countries carried out by the International Renewable Energy Agency (IRENA 2017a, b, 2018). c. Occupational data for fossil fuels has been derived from labour statistics in the Australian 2016 national census, and adjusted using regional job multipliers to account for different labour intensities in different parts of the world (Dominish et al. 2019)

Figure 5 presents a chart of data sourced from Dominish et al. (2019), which compares the share of occupation types and categories for several renewable electricity generation technologies with fossil fuel power generation (and associated activities). The data for solar PV and onshore and offshore wind has been drawn from international surveys carried out by IRENA (2017a, b, 2018). This has then been compared to equivalent occupational data derived from the Australian 2016 national census, which has been scaled using regional employment multipliers to represent different world regions (Dominish et al. 2019).

The relative distribution of occupations shown in Fig. 5 highlights areas where low-skilled jobs are particularly concentrated: for example, assemblers comprise the majority of jobs in solar PV installation, and approximately half of all jobs in coal mining are in elementary occupations. Around 70% of offshore wind construction jobs are comprised of ship crew. Plant and machine operators, assemblers and elementary occupations contribute a small but significant share of wind manufacturing and construction activities. Whilst it is clear that higher-skilled professional occupations comprise substantial shares of operation and maintenance jobs in wind and solar PV, Fig. 5 does not indicate clear differences between renewables and fossil fuels in terms of relative skill levels.

Other studies identified in our review also set out to quantify the relative distribution of skill levels in fossil fuel and low carbon energy sectors. For example, Zhang et al. (2022) conducted a survey of coal power stations and renewable power plants located in 11 cities within five provinces in China, to obtain information on skills requirements based on professional qualification levels. According to this survey and classification, 15% of coal power workers were high-skilled workers (senior engineers or engineers), versus 4% of solar and wind power employees, while the proportions for low-skilled workers (junior technicians) were 9 and 17% respectively. Most workers in coal and solar/wind electricity were medium skilled (senior or mid-ranking technicians): 76 and 79%, respectively (Zhang et al. 2022). For India, Reddy (2016) categorise renewable and fossil fuel electricity generation and energy efficiency employment according to share of high, middle and low skill level workers, and the proportion who are executives, graduates, and labourers.

The evidence reviewed suggests that green skills supply and demand should be carefully managed through policies supporting green job creation, and coordination of training activities. According to OECD/Cedefop (2014, p. 12) this "*will prevent the situation of green skills demand being stimulated by government policy, but not being matched by equivalent action to meet this demand, leading to skills bottlenecks and/or programme failure due to unskilled operators*." In the context of India, Reddy (2016, p. 300) suggests a need for "*collaboration between government authorities and business houses to develop industry-endorsed training programs that give graduates nationally recognised technological skills and provides skilled employees with a diploma certificate. Secondly, there is need to create a nationwide, online skill database that would link students, colleges and employers*."

To facilitate a just transition to a low carbon energy system, IRENA and ILO (2021) emphasise the need for proactive policy which sets out to anticipate and plan for a series of misalignments that are likely to occur. Each type of misalignment is reflected in a number of studies identified in our review and discussed in this paper. These include: temporal misalignments between the pace and scale of job losses and the rate and capacity of job gains required to compensate them; geographic misalignments between the location of new jobs and the regions in which displaced workers live; skills and job role misalignments between outgoing and incoming energy industries; and value chain misalignments as transitions away from fossil fuels create a shift from conventional mining and fuel extraction to sourcing of renewable energy components and materials (IRENA and ILO 2021).

Godinho (2022) point to OECD research which indicates that lower-skilled employees in the energy supply sector are more likely to be affected by job displacement as a result of low carbon energy transitions, and this may be compounded by workers losing benefits from previous work in carbon-intensive sectors (Chateau et al. 2018; Botta 2019). In China, the "disorderly" net zero transition pathway of Zhang et al. (2022) featuring late coal phaseout, suggests that almost 75,000 low-skilled workers may need to be made redundant as coal plants close from 2030 to 2040, and it would be challenging to retrain and relocate them. During the same decade, there would be a corresponding need to recruit between approximately 190,000 and 3,700,000 new workers in wind and solar power, creating high pressure on the supply of skilled labour (Zhang et al. 2022) Overall, managing unemployment in decommissioned industries will require stronger labour market policies and regulations, skills and training strategies, and increasing the availability of alternative, decent work in affected regions (IRENA and ILO 2021; Godinho 2022).

Conclusions

In this paper, we present findings from a systematic literature review of 121 publications on job creation, quality, and skills in the energy sector, focusing on a shift to renewable energy and energy efficiency. The international literature has revealed that various methods and units are used to estimate the quantity of low carbon energy job creation. In general, much greater standardisation of methods would be desirable in order to compare how many jobs could be created by transitioning to low carbon energy and deploying energy efficiency at national and regional scales within countries. A key insight from our review is that there is a relative lack of metrics and data in the identified literature on job quality, skills, and the geographic distribution of employment impacts in decarbonising energy systems. Therefore, these should be priority areas for further research.

We compare a range of recent gross job creation estimates which indicate that overall, investment in renewable energy and energy efficiency can deliver more jobs than gas or coal power generation. This finding is consistently supported across a range of different job creation metrics and when focusing on different technology life stages, i.e. manufacturing, construction and installation, and operation and maintenance. This suggests that policies supporting renewables and energy efficiency may lead to net job creation compared to the counterfactual of jobs which may otherwise have been created by investing in fossil fuels. Gross jobs per USD million invested are found to be highest on average for wind power and building energy efficiency interventions, across 14 studies in which this metric was identified. Caution should be applied to interpreting data on gross employment per level of investment for any given technology, which may be indicative of various factors including relative technological maturity, share of spending on local content or imports, share of spending on labour (versus capital), and average salary levels.

We identify 18 recent additional studies which estimate the net employment effects of decarbonising part or all of the energy sector at a national scale. These national studies largely agree that the most likely outcome over the next few decades is a modest net positive creation of jobs. This implies that the number of jobs created in renewables and energy efficiency sectors will outweigh the number lost as conventional fossil fuel power plants are retired.

Several studies illustrate how overall net job creation in a given country may reflect a balance of net jobs gains and losses in different regions, economic sectors and parts of the value chain. This balance also depends on the nature of the value chain in outgoing and incoming energy industries and how much a country may rely on imports for fossil fuels, manufacturing of renewables components or labour based in other countries (or indeed, the extent to which there is an export market for domestically manufactured components). In certain regions, jobs in fossil fuel industries may be lost faster than the pace at which low carbon energy sectors can offer new employment. There may be mismatches between regions where displaced workers live and where new opportunities become available, which may be a barrier to accepting alternative employment even if former workers have the requisite skills. In these cases national government transition plans are recommended, coordinated with local governments, to manage the impacts of displacement from carbon-intensive sectors and to respond to the need to build a new low carbon workforce including through skills development and training. Overall, there is limited evidence in the literature reviewed on the geographic and sectoral implications of low carbon energy job creation, and more research is required to improve understanding of issues around local or regional displacement and substitution of employment in high carbon sectors.

Given the current context of high energy prices and consolidating economic recovery from COVID-19, we identify literature on the extent to which renewable energy and energy efficiency support policies may contribute to short-term and longer-term economic growth. This literature is not extensive but indicates that implementing a low carbon energy transition at a country scale could lead to moderate economic growth as well as positive net job creation overall. However, as with employment effects, this could mask regional and sectoral disparities and possible negative economic impacts in regions with a substantial presence of high carbon industries. Policies supporting domestically based manufacturing and installation of renewable energy, and building energy efficiency retrofitting, may be particularly effective at creating short-term jobs and economic stimulus. In comparison, operation and maintenance jobs can potentially last over energy technology lifetimes.

Jobs created per unit of investment represent only one aspect of a low carbon transition; what matters in the longer term is whether the investment contributes to an economically efficient transition towards a country's strategic goals, considering environmental impacts, the need for a just transition and energy security. Meeting decarbonisation and net zero targets internationally implies a continuous need for jobs over several decades, e.g. to build the new renewables capacity needed for likely greater demands for electrification from transport, heating and cooling, and to carry out widespread low carbon and energy efficiency retrofits across national building stocks. Wider impacts of such activities go well beyond job creation to include co-benefits such as improved air quality, more comfortable homes, more resilient energy supplies and reduced dependence on fossil fuels, whether they are sourced domestically or via imports.

There is a substantial literature on the quantity of job creation that may arise from decarbonisation in the energy sector. By comparison, we found a more limited subset of studies which investigate implications of such a transition for employment quality or relative skill levels. It is desirable that a low carbon energy transition should create quality jobs, for example in terms of adequate wages and employee rights, full-time employment, safe working conditions, and permanent rather than temporary jobs. Direct employment in renewable energy manufacturing, construction or installation has been linked to temporary or short-term work in several documents reviewed. It has been suggested that such employment is likely to expire on completion of specific projects. Sequential planning will be required to train and coordinate local workforces required for renewables expansion and building retrofits, minimising time gaps between projects and the need for workers to relocate.

There is agreement in the identified literature that green jobs in general tend to be more highly skilled compared to higher carbon occupations. However, it would be overly simplistic to suggest that renewable energy or energy efficiency jobs are necessarily more skilled than employment in fossil fuel sectors. The majority of jobs in the operation and maintenance of wind power and solar PV are in highly skilled, professional occupations. There is also demand for lower-skilled, manual occupations which for example comprise significant shares of solar PV installation and offshore wind construction activities. Nevertheless, several studies suggest that lower-skilled workers are most likely to be affected from job losses as a result of low carbon energy transitions. Stronger labour market policies and regulations are required to ensure displaced employees have access to alternative, decent work in low carbon sectors. There is a need for national policy makers to coordinate the development and supply of training so that it takes full account of the wide range of occupational functions required for manufacturing, installing, and servicing renewable energy and energy efficiency technologies.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11625-023-01440-y.

Author contributions RH, PH, and RG contributed to the study conception and design. The review and analysis were performed by RH and PH. The first draft of the manuscript was written by RH and all authors contributed to subsequent versions of the manuscript. All authors read and approved the final manuscript.

Funding This study was funded by the UK Energy Research Centre (UKERC) Phase 4 (Grant number LFEPR P77922).

Data availability All data underlying the results are available as part of the article or supplementary information.

Declarations

Conflict of interest The authors have no competing financial or non-financial interests to declare that are relevant to the content of this article.

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