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ABSTRACT

Driven by climate mitigation goals countries around the world are prioritising low-cost renewables for economic growth and recovery from the aftermath of the global pandemic. It is quite clear that sustainable technology choices result in broader socioeconomic benefits, as is shown by countries that have been early movers in transitioning their energy sectors towards higher shares of renewables. There is growing interest in better understanding the direct impact on employment by energy transitions with concerns over jobs lost in the conventional energy sectors, which will be crucial in informing decision making around the world. This research focuses on the net employment impacts of an accelerated uptake of renewable energy that envisages the world deriving 100 % of its energy from renewable sources by 2050, compatible with the ambitious goals of the Paris Agreement. Direct energy jobs associated with the power, heat, transport, and desalination sectors increase substantially from about 57 million in 2020 to nearly 134 million by 2050. Value chains in renewables and sustainable technologies are found to be more labour intensive than extractive fossil fuels. The results indicate that a global energy transition will have positive impacts on future stability and growth of economies around the world.

1. Introduction

The Paris Agreement, negotiated at the 21st Conference of the Parties (COP21) in 2015 [1], has set an important foundation for the global community to aspire and move towards building a sustainable future. A global energy transition is at the heart of realising sustainable development goals, as the energy sector accounts for over three-quarters of global greenhouse gas (GHG) emissions [2,3]. Despite a share of just around 2–6% in global gross domestic product (GDP) [4], the energy sector is a major economic contributor with significant prospects for investments and employment in countries around the world. As the energy sector is increasingly intertwined with economic welfare, social priorities and environmental needs, an integration of social processes along with technical and economic analyses of energy systems are emerging as a necessity. The techno-economic implications of a shift towards high shares of renewable energy such as additional generation capacities, investment needs and reduction in GHG emissions have been explored for a range of scenarios in many countries as well as globally [5–9], as enlisted and analysed by the Centre for Alternative Technology [10]. As in other economic and technological shifts, transitioning to a low carbon economy will result in additional jobs being created, jobs being substituted, jobs being eliminated and existing jobs being transformed [11]. Combining different methods as proposed by Fortes et al. [12], is a way to advance scenario building by assimilating different ideas and approaches along with key socioeconomic parameters.

Employment impacts form a crucial aspect of energy policy, as highlighted by Fischer et al. [13] in the case of Germany, where jobs are one of the five controversial issues in the debate on the "Energiewende". In recent years, employment impacts of renewable energy technologies in context to the energy transition has received attention from many stakeholders including academia, multilateral and intergovernmental agencies, private sector, and civil society. Employment trends can vary significantly for the different energy technologies across their value chains including production, generation, storage, transmission and distribution, and

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flexibility options. There have been a number of efforts to quantify employment impacts of the changing energy sector and have been well documented in literature review studies, such as Breitschopf et al. [14], Meyer and Sommer [15] and Cameron and Van Der Zwaan [16] and the net impacts on employment have been verified with actual data by the International Labour Organisation (ILO) [17] and Proença and Fortes [18].

In general, there are different types of jobs associated with the energy industry; the commonly adopted classification is 'direct', 'indirect' and 'induced' jobs. As the International Renewable Energy Agency (IRENA) [19] elaborates, direct energy jobs are the ones associated directly to an activity in the value chain of a particular energy technology, whereas, indirect and induced jobs include those jobs that are either created by auxiliary activities or activities that are an outcome of enabling energy availability. The various approaches to estimate employment impacts of deploying energy technologies can be categorised into bottom-up and top-down approaches, or more specifically as using the analytical or input–output (IO) models [20]. Lund and Hvelplund [21] have described and promoted Concrete Institutional Economics as a tool and methodology of designing strategies to utilise economic crises and investments in sustainable energy as a driver of job creation and have applied it to the case of Denmark [21,22]. Additionally, a value-chain approach [23] and a life-cycle approach [24] have been adopted for estimating job creation mainly from the adoption of renewable power generation technologies. Jacobson et al. [5,25] estimate the baseline jobs per unit energy in their main scenario, which are based on National Renewable Energy Laboratory's (NREL) Jobs and Economic Development Impacts (JEDI) models [26]. These are economic input-output (IO) models with several assumptions and uncertainties. In contrast, IRENA [27,28] and Greenpeace [29] adopt simpler analytical approaches to estimating job impacts that also have a high level of transparency. This entails utilising job intensities or employment factors (EF), defined as the number of jobs derived from the capacity addition or investment in a certain energy technology through the value chain and the technical lifetime. The EF approach utilised for estimates of job creation potential in Greenpeace's energy scenarios is provided by Rutovitz et al. [30], which results from a continuous refinement of the methods and updating of employment factors corresponding to developments in energy technologies. Ortega et al. [31] have further proposed a dynamic employment factor approach considering trade and technology learning effects, which were applied to the countries of the European Union (EU) and the results were validated successfully with historical data in the time frame 2008–2012. The EF approach is ideal to explore direct energy jobs linked to deployment of energy technologies and enables comprehensive analyses of the associated value chains to determine comprehensive direct job creation resulting from energy transitions, as documented in Ram et al. [32]. Ram et al. [32] have further refined the EF approach with the consideration of regional labour productivity, technology learning effects and decommissioning of power plants and estimated the net direct energy jobs created during an energy transition globally, but limited to the power sector only. However, this research is an effort to further advance and expand the methods from Ram et al. [32] from the power sector to other energy sectors and conduct a more comprehensive analysis of the net direct energy jobs created during an energy transition, which includes a broad range of energy technologies, as highlighted in Table S1 in the supplementary material. It is additionally the first research to estimate the job creation potential of complementary heat storage and power-to-X technologies (including the production of hydrogen and e-fuels) across the energy sector comprising power, heat, transport, and desalination demands. The research has also included estimates of decommissioning jobs across the various energy technologies and estimated jobs linked to transmission and distribution of electricity created during the energy transition in the next three decades (2020–2050), which is based on comprehensive data collation of actual jobs across different countries and regions of the world. It also estimates the jobs involved in the production and trade of fossil fuels across different major regions of the world.

A comprehensive literature review is conducted to determine the most ideal EFs for all technologies in the energy system that are presented in Table S1. The components of the energy system are classified into power generation technologies, heat generation technologies, combined heat and power technologies, storage technologies (electricity and heat) and fuel production technologies (fossil and synthetic). The EFs are categorised as manufacturing, construction and installation, operation and maintenance, fuel supply and decommissioning to capture the entire value chain in energy conversion and supply (refer to Section 1.1 and Table S1 in the supplementary material). In addition, transmission and distribution grid jobs are linked to electricity generation (refer to section 1.1 and Table S8 in the supplementary material), which are linearly extrapolated to determine jobs with the corresponding electricity generation in the future across the different regions of the world. These are comprised of Europe, Eurasia, Middle East and North Africa (MENA), sub-Saharan Africa (SSA), South Asian Association for Regional Cooperation (SAARC), Northeast Asia, Southeast Asia, North America and South America (for the full composition of these regions refer to Bogdanov et al. [33]). The divergence in labour productivity and intensity is captured with regional productivity factors across nine major regions of the world. The effects of scaling and automation are captured through declining labour intensity factors linked to the declining costs of energy technologies (both capital expenditure and operational expenditure). The global job creation through the transition is an aggregate of the job creation computed across the nine major regions of the world, which also considers exports and imports of fossil fuels and manufactured technologies exchanged across the nine major regions. The methods, EFs and assumptions (Table S1 to Table S8) are presented briefly in the methods and materials section and further in detail in Section 1 of the supplementary material.

This research evaluates the hypothesis of sound economic impacts from transitioning to a sustainable energy future by determining the employment effects of achieving 100 % renewable energy supply to the power, heat, transport and desalination sectors by 2050 in a high electrification scenario, across the world structured in nine major regions based on 145 detailed regions. The transition of power, heat, transport and desalination sectors across these regions, as showcased in Ram et al. [34] and Bogdanov et al. [33], serves as the basis for estimating jobs created during the transition period from 2020 to 2050. Additionally, the job creation potential is estimated on a technology-wise basis as well as on a category-wise basis through the energy value chain during the energy transition to provide better insights on the types of jobs created. This is primarily enabled by the innovative aspects of the LUT Energy System Transition modelling tool [33], which analyses cost optimal energy systems across the world on high levels of geospatial (145 regions) and temporal (hourly) resolutions, and which has been identified as one of the most sophisticated tools for long-term energy system transition modelling [35].

2. Methods and materials

For this research, an analytical approach towards estimating direct energy jobs corresponding to the value chain during an energy transition across the different regions of the world was adopted. Further, a dynamic approach with learning effects of technologies through the transition years and change in labour intensities across the different regions of the world are considered. The methods are based on the approach highlighted in Ram et al. [32] and Rutovitz et al. [30] and further modified and improved for better results as well as applied to a broader range of energy technologies across the power, heat, transport and desalination sectors (see Table S1). The Employment Factor (EF) method was adopted amongst the other methods [14], due to its simplicity and effectiveness in estimating direct employment associated with energy generation, storage, flexibility options and transmission and distribution of electricity. One of the main advantages of the EF approach is that it can be modified for specific contexts, as well as applied over a range of energy scenarios [31]. In the context of this research, the total direct jobs are a sum of jobs in manufacturing, construction and installation, operations and maintenance, fuel supply associated with electricity and heat generation, decommissioning of energy plants at the end of their lifetimes and transmission and distribution of electricity. This is further highlighted in Fig. S1 and the approach is explained in detail in section 1.1 in the supplementary material.

Some of the parameters considered in the estimation of the job creation potential of various energy technologies include employment factors, which are the number of jobs per unit of installed capacity, separated into manufacturing, construction and installation, operation and maintenance, and decommissioning. It is also jobs per unit of primary energy for fuel supply and jobs per unit of transmitted and distributed electricity, decline factors are linked to the decline in capital expenditure (Capex) and operational expenditure (Opex) of the different energy technologies, job creation can be expected to reduce as technologies and production of these technologies mature (refer to section 1 in the supplementary material). This maturing occurs because of the growing experience and volume in the energy industry (mainly renewables, storage, and e-fuels production), which are captured by Capex and Opex. Regional employment multipliers for the various regions are adopted to account for the differential labour intensive economic activity in the different regions across the world, which are normalised with OECD (represented by North America in this research) for the other regions in the world having relatively higher labour intensities compared to North America (refer to Table S2 and section 1.1 for more details). The import-export shares for manufacturing and fossil fuels production, which represents the percentage of local manufacturing/local fossil fuel production (according to the fuel coal, oil and gas) across the various regions of the world, linking the importing and exporting regions are taken into account. These are presented in Table S4 to Table S7. Jobs associated with transmission and distribution of electricity were linked to the generated electricity of the different regions rather than the investments in transmission networks as in Ram et al. [32]. This allows for a more comprehensive coverage of jobs in transmission and distribution of electricity, as these are based on actual jobs in countries and regions as listed in Table S8 in the supplementary material.

Further on, the manufacturing EFs and construction and installation EFs are applied to the newly installed capacities for each year during the transition period from 2015 to 2050. While operation and maintenance EFs are applied to the cumulative installed capacities for every 5-year interval between 2015 and 2050. The fuel EFs are applied to annual electricity and heat generation form the various power and heat generation technologies that utilise fuel sources along with the fuel demand for the various transport modes. The decommissioning EFs are applied to the annual decommissioned capacities of energy technologies during the entire transition period. The transmission and distribution of electricity EF is applied to the total annual electricity generated across the different regions during the transition period. The new and cumulative installed capacities, electricity generation, fuel consumption and decommissioned capacities for the various energy technologies are adopted from the results of the LUT Energy System Transition model, which is comprehensively documented in Bogdanov et al. [33]. The detailed methods, assumptions and EFs are presented in the supplementary material in section 1, Figure S1 highlights the EF approach and Table S1 lists the various EFs for all energy technologies. Section 1.1 details the EF approach with all assumptions listed in Table S1 and Table S2, while section 1.2 gives a brief overview of the LUT Energy Transition Modelling tool. Section 2 of the supplementary material presents the results of jobs created in each of the major regions highlighted in Figure S2 to Figure S37. Additionally, the jobs estimated globally and for each major region is presented in Table S10 to Table S18, along with estimations for 92 countries and regions around the world in Table S19. The 92 countries/regions structuring is defined in Ram et al. [34] and Bogdanov et al. [33]. This is a first of its kind research attempt at a comprehensive assessment of the job creation impacts during an energy transition towards 100 % renewable energy across power, heat and transport sectors with energy demand for desalination in a high electrification scenario, with an exhaustive list of technologies that cover both electricity and heat storage along with production of hydrogen and e-fuels. Moreover, results are presented from global, regional and country perspectives on sectoral, technological and value chain basis over the transition period.

3. Results

The results of Ram et al. [34] and Bogdanov et al. [33], which form the basis for estimating the jobs creation, highlight a few trends during the energy transition until 2050. First, the energy transition across the power, heat, transport, and desalination sectors is driven by massive electrification, with 89 % of primary energy demand comprised of electricity in 2050. Second, the global energy system undergoes a complete defossilisation and reaches zero GHG emissions in 2050. Third, storage and power-to-X technologies along with green hydrogen and e-fuels emerge as critical components of the new carbon neutral energy system. These trends lead to a rapid ramp-up in installed capacities of renewable electricity generation technologies, compensating for the phasing out of fossil fuels and nuclear based energy capacities around the world. In this context, the overall direct energy sector jobs increase significantly from about 57 million in 2020 to around 134 million by 2050, as highlighted in Fig. 1. Driven by strong growth in the renewable energy sector, coupled with direct and indirect electrification the direct power generation jobs are more than tripled in 2050 with 69 million, as compared to 20 million jobs in 2020. As compared to Ram et al. [32] that analysed exclusively the global power sector transition and found direct jobs to increase from about 20 million in 2015 to 35 million in 2050. While, in this research, which is based on high electrification across the other energy sectors of heat and transport, the jobs for electricity generation are nearly twice as much in 2050 owing to the high electricity generation covering demand from the entire energy system during the transition. While in the heat sector, jobs created decline in the initial periods due to high levels of electrification and increase later in the transition to about 28 million jobs with the complete defossilisation in 2050. Similarly, jobs associated with fuels mainly for the transport sector decline initially with the decline in utilisation of fossil fuels as a consequence of phasing in electric road vehicles and increase later in the transition with the production of e-fuels, reaching 5 million jobs in 2050. Storage jobs take off in the 2030s reaching about 10 million jobs by 2050. The high levels of electrification also drive the transmission and

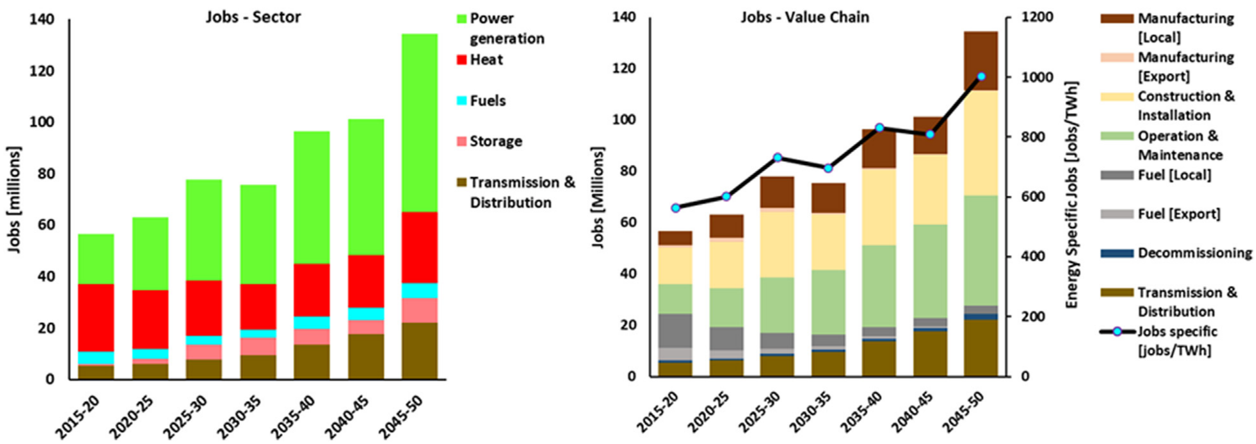

Fig. 1. Jobs across the different energy sectors (left) and jobs across the energy value chain with the development of final energy demand specific jobs (right) during the energy transition from 2015 to 2050 globally.

distribution grid jobs through the transition reaching about 22 million jobs in 2050, see Fig. 1.

Direct energy jobs through the value chain in manufacturing, construction and installation, operation and maintenance, fuel supply, decommissioning and transmission created during the energy transition from 2020 to 2050 are shown in Fig. 1. Manufacturing of energy technologies leads to a significant increase in manufacturing jobs from around 6 million in 2020 to over 23 million in 2050, which includes some shares of export quantities, however, in this research the major regions are expected to domestically manufacture energy technologies by 2050. Thereby, ensuring more domestic job creation. Jobs associated with the operation and maintenance of energy technologies create the greatest number of jobs by 2050, with around 42 million jobs around the world. Similarly, construction and installation of energy technologies leads to over 40 million jobs by 2050. Jobs associated with the production and supply of fossil fuels, both domestic and exports are set to decline from around 32 % of the total energy jobs in 2020 to just around 3 % of the jobs by 2050, with mainly decommissioning of fossil fuels and nuclear power capacities. Global export volumes of fossil fuels account for around 8 % of total energy jobs in 2020 and are eliminated by 2050 with no exports of fossil fuels, as countries transition to adopting locally produced e-fuels and some bioenergy. However, countries with excellent renewable resources, thriving ecosystems with favourable costs of production for e-fuels could emerge as exporters, creating more direct energy jobs.

The trends in job creation indicate that the transition towards a global 100 % renewable energy system across the power, heat, transport and desalination sectors enables the creation of more stable and local jobs, which can contribute to stable economic growth of countries, mainly in the developing regions of the world as a means of tackling high unemployment rates, especially amongst the youth [36]. In many parts of the world, this could be a catalyst to raise social welfare and create conducive environments for political stability [37]. Furthermore, Fig. 1 also illustrates the development of the final energy demand specific jobs, which increases through the transition period, from 563 jobs/TWh in 2020 to 1000 jobs/TWh in 2050. This indicates that an energy system based on renewables creates nearly twice as many jobs for every unit of energy demand covered, as compared to the current fossil fuels based energy system. The energy system transition can be realised in a cost neutral pathway [33,34], as energetically inefficient and less labour intensive combustion processes are largely substituted by highly efficient and more labour intensive renewable electricity-based solutions. This implies that more jobs could be created with a transition towards more sustainable energy technologies resulting in lower levelised cost of energy.

3.1. Technological and sectoral distribution

Driven by direct and indirect electrification, power generation grows substantially through the transition to meet the rapidly increasing electricity demand. As the other energy sectors of heat and transport increasingly rely on electricity for heat generation, charging batteries and producing e-fuels. Generating the least cost energy, solar PV emerges as the prime electricity generation source and in the process creating 60 million jobs by 2050. Almost a tenfold increase from just around 7 million in 2020, as can be seen in Fig. 2. Most of the jobs are from utility-scale solar PV with 44 million jobs in 2050, while solar PV prosumers covering residential, commercial, and industrial segments provides about 16 million jobs around the world in 2050. In the case of wind energy, around 8 million jobs are created in the period from 2020 to 2025, beyond which solar PV becomes more cost effective in many part of the world leading to jobs in the wind energy sector to be stabilised at around 5 to 6 million from 2025 to 2050. While, hydropower, geothermal and bioenergy create a stable share of jobs through the transition period as highlighted in Fig. 2. On the contrary, coal and gas power jobs decline drastically from nearly 50 % of the power generation jobs in 2020, to just a few thousand in 2050, which are predominantly decommissioning jobs. Similarly, nuclear power jobs are almost non-existent by 2050, which is mainly a consequence of unviable economics of nuclear energy [38,39], as shown in Fig. 2. Solar PV replaces coal as the major job creating energy resource, with around 87 % of total power generation jobs by 2050, which indicates that renewable energy technologies can more than compensate for the jobs lost in the conventional power industry. However, there will be challenges of reskilling and training of personnel to enable switching jobs, which can be well managed with innovative social engineering and policy making.

The heating demand consisting of domestic hot water demand, space heating, biomass for cooking and industrial process heat is predominantly covered by the range of heating technologies indicated in Fig. 2 and Table S1 in the supplementary material. In contrast to the power generation, heat sector jobs decline initially and then increase later in the transition with complete defossilisation of the sector, eventually with around 28 million jobs by 2050 as highlighted in Fig. 2. Fossil fuels and bioenergy jobs comprise most of the heat sector jobs in 2020, coal is the highest contributor

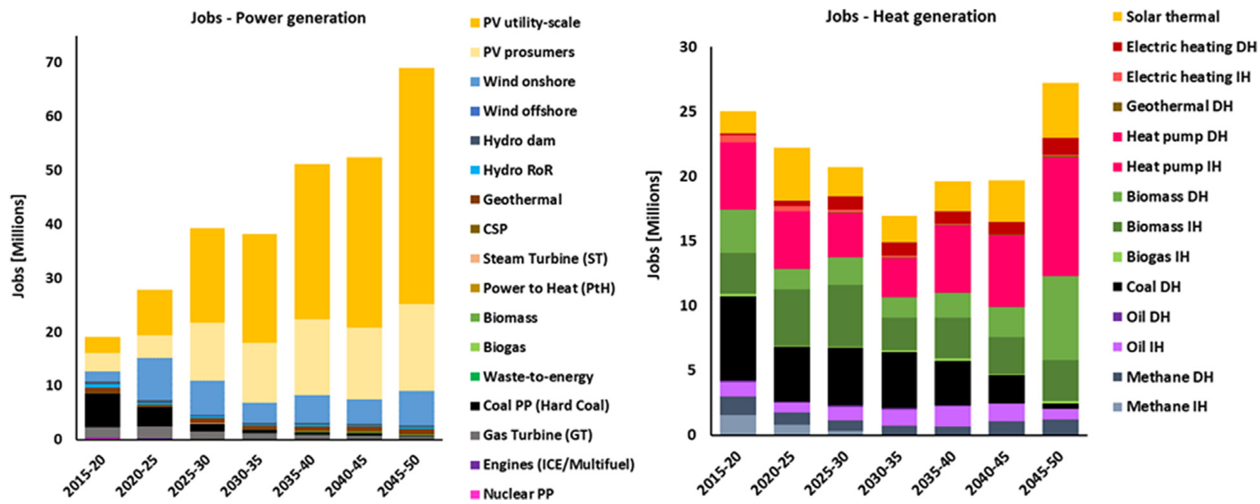

Fig. 2. Jobs across power generation technologies (left) and jobs across heat generation technologies (right) during the energy transition from 2015 to 2050 globally.

with nearly 6 million jobs. However, fossil-based jobs in the heat sector decline through the transition, which are replaced with jobs related to heat pumps, electric heating, and solar thermal leading to an additional 3 million jobs in 2050, compared to 25 million jobs in 2020.

Combined heat and power (CHP) plants contribute around 1.5 million jobs in 2020, which are predominantly from coal and gas plants as shown in Fig. 3. Bioenergy jobs comprising biomass, biogas and waste-to-energy technologies contribute a major share of the jobs as the fossil fuels based CHP jobs decline through the transition. However, with increasing integration of the power and heat sectors coupled with the adoption of more efficient heat pumps and electric heating results in fewer operational CHP plants by 2050. This results in the overall reduction in jobs to around 700 thousand, mainly bioenergy CHP jobs in 2050 as highlighted in Fig. 3.

Jobs in the storage sector encounter massive growth with nearly 6 million jobs in the period 2025 to 2030, with predominantly battery jobs both at the utility scale and prosumer scale as shown in Fig. 3. Some shares of jobs in pumped hydro and compressed air energy storage grow up to 2030. This is mainly driven by massive capacity additions of battery storage required by 2030 to complement the growth in renewable electricity generation. Furthermore, by 2050 there are close to 10 million jobs in the storage sector, which are mainly associated with battery technology as it emerges as the most cost effective storage technology as highlighted in Fig. 3. Additionally, there could be a significantly higher number of jobs in the battery industry driven by the demand for batteries from electric vehicles in the transport sector. This research is limited to batteries in the energy system, including the energy demand for transport (with high shares of electrification) and does not account for the batteries required for battery electric vehicles (BEV), which could be very significant and mainly corresponds to the jobs in the automotive industry.

Jobs associated with the production of fuels, which are predominantly fossil fuels decline through the transition from about 18 million in 2020 to around 4 million in 2050, as highlighted in Fig. 4. The demand for coal, oil and gas is expected to decline with increasing electrification driven by low cost renewable electricity resulting in the decline of corresponding jobs through the transition.

Contrary to the diminishing role of fossil fuels, e-fuels are expected to play a critical role in the future energy system across the power, heat, and transport sectors. As indicated by Fig. 4, the

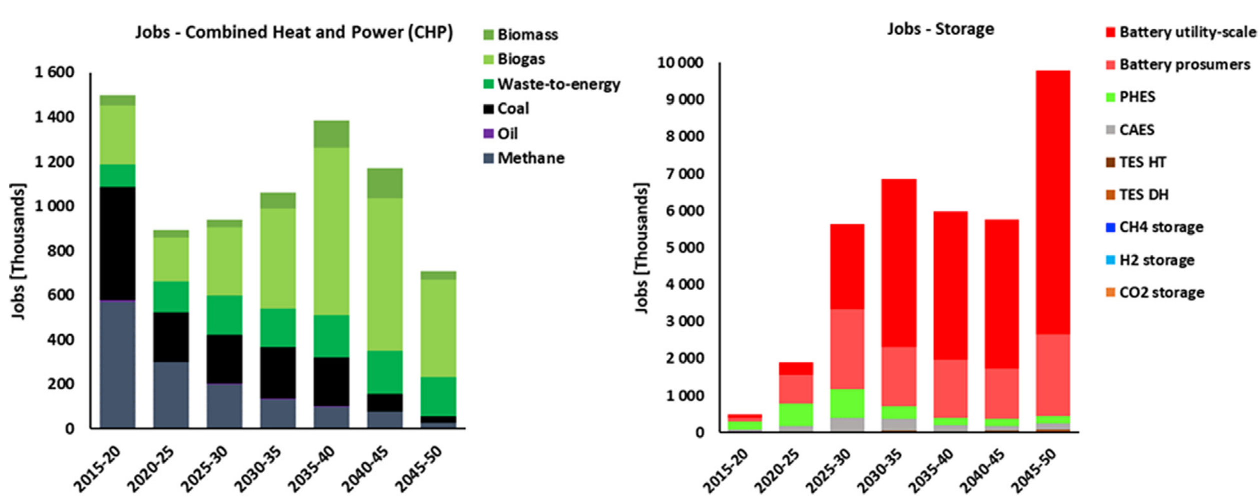

Fig. 3. Jobs across the different combined heat and power technologies (left) and jobs across the different storage technologies (right) during the energy transition from 2015 to 2050 globally.

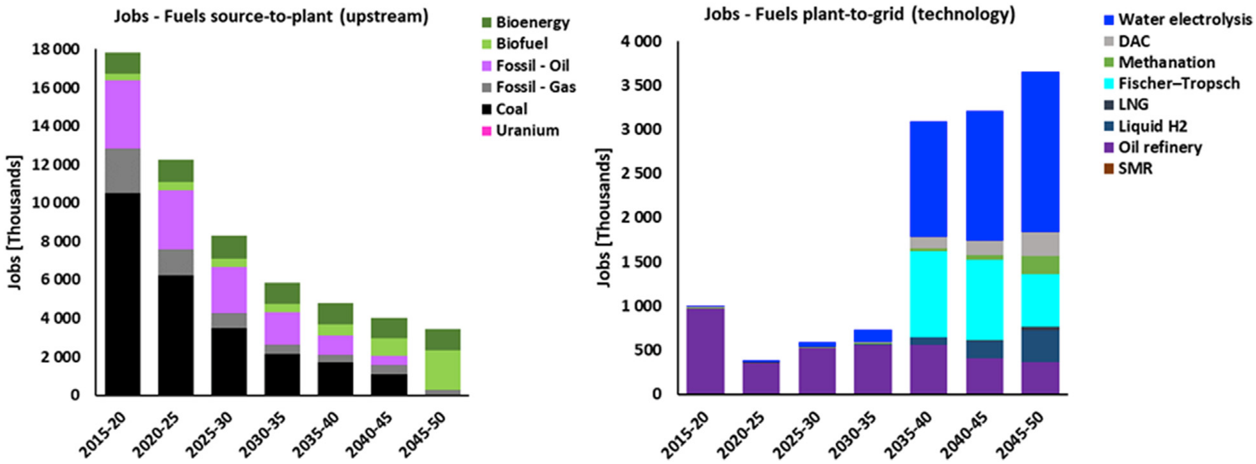

Fig. 4. Jobs across the different fuel sources (left) and jobs across the different fuel technologies (right) during the energy transition from 2015 to 2050 globally.

production of hydrogen, synthetic natural gas (SNG) and Fischer-Tropsch fuels contribute to a substantial number of jobs in the later part of the transition with over 3.6 million jobs in 2050. A bulk of the jobs are from water electrolysers, mainly to produce hydrogen. The strong rise in jobs around 2040 is a consequence of the underlying scenario [33,34], but may be triggered even earlier with an advanced industry ramp-up.

The sectoral analyses of job creation indicate that power generation will create the bulk of energy jobs in the future, driven by the massive electrification of the heat and transport sectors. This research shows that the power generation along with the transmission and distribution of electricity has the potential to create over 70 million direct jobs by 2050. This is primarily driven by structural changes in the energy system with most energy demand covered by electricity in future highly electrified energy systems. Job creation in the heat sector is rather stable with the sustenance of over 20 million jobs through the transition. Whereas storage and e-fuel production have great potential to create over 13 million direct jobs by 2050. Overall, the energy transition towards 100 % renewable energy across the power, heat, transport, and desalination sectors has a net positive impact on jobs created. The power generation alone has the potential to create a significantly greater number of jobs, than jobs lost in the conventional energy sector, mainly fossil fuels and nuclear. However, the impacts of employment creation during the energy transition can vary according to the region of the world and the corresponding energy system.

3.2. Regional distribution

Global direct energy job creation through the transition period from 2015 to 2050 is an aggregate of the job creation estimated across nine major regions, where the transition to 100 % renewable energy in the power, heat, transport, and desalination sectors is projected. The regional distribution of jobs across the major regions through the transition period is shown in Fig. 5. The share of jobs in Europe grows substantially from about 7 % in 2020 to 12 % by 2050 of total energy jobs in the world. This is mainly driven by high shares of electrification across the energy sectors and production of domestic e-fuels, creating around 16 million direct energy jobs in 2050. While the share of jobs in Eurasia initially decline from about 8 % of global energy jobs in 2020 to around 6 % in 2030, and thereafter stabilise at around 7 % by 2050. As most Eurasian countries are exporters of fossil fuels, a decline in these jobs contributes to declining shares in global energy jobs, however, in the later part of the transition more jobs are created as a result of massive uptake of renewables and e-fuels leading to 9 million jobs across Eurasia in 2050. Similarly, in the MENA region, the share of jobs decreases from 7 % in 2020 to 5 % in 2050 of global energy jobs. As the region is amongst the highest exporters of fossil fuels, jobs associated with the production of fossil fuels declines through the transition (the shares of local production, import shares and import regions of fossil fuels are presented in Table S5 to Table S7 in the supplementary material). However, in terms of total jobs created there are 6 million jobs in 2050, compared to about 4 million jobs in 2020 across MENA. This indicates that despite the loss of jobs in fossil fuel exports, a transition to high shares of renewables creates ample the number of domestic jobs in these regions. On the contrary, sub-Saharan Africa experiences the highest growth in total energy jobs created across the world, increasing from just around 2 million in 2020 to 12 million by 2050. As most of the energy infrastructure is yet to be built in this region, there is massive potential for developing renewable energy and creating jobs for the local populations. The SAARC region comprising south Asian countries and Northeast Asia together account for over 50 % of the global energy jobs in 2020, and this share is sustained through the transition with just below 50 % in 2050. Whereas the total energy jobs more than double by 2050 with 26 million across SAARC and 39 million across Northeast Asia. Both SAARC and Northeast Asia are currently driven by high economic growth rates, which are expected to drop to lower levels and flatten out over the long-term as they reach higher levels of development resulting in lower levels of labour intensity. In Southeast Asia and the Pacific countries, the share of jobs created are observed to decline from 8 % in 2020 to 6 % in 2050 of global energy jobs. Coal exporting countries such as Indonesia and Australia, contribute to the decline in the share of jobs. Whereas the transition to renewables results in increasing jobs from 4 million in 2020 to 8 million in 2050 across the region. In the case of North America, the share of global energy jobs remains stable through the transition at around 10 %. With a more diversified energy sector the total energy jobs across North America more than double from 5 million in 2020 to 12 million by 2050. The total energy jobs across South America nearly double from 3 million in 2020 to 6 million by 2050. While the share in global energy jobs from the regions declines from 6 % in 2020 to 4 % in 2050, mainly driven by the loss of fossil fuel exports in some of the countries of the region. The region has excellent renewable resources and has the potential to tap into these to create stable and long-term employment. The detailed job creation analyses through the

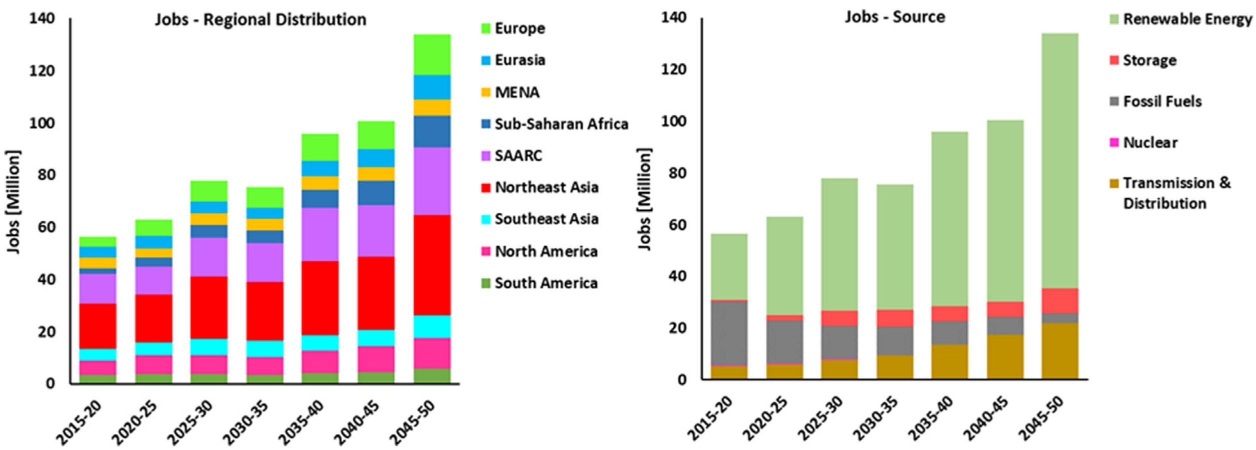

Fig. 5. Regional distribution of jobs (left) and distribution of jobs according to the source of energy (right) during the energy transition from 2015 to 2050 globally.

transition in each of the major region is further highlighted in Section 2 of the supplementary material with Figure S2 to Figure S37. Additionally, total direct energy jobs have been estimated for 92 countries and regions around the world, applying energy specific jobs of major regions to the corresponding final energy demands of respective countries and regions, which is highlighted in Figure S38. The estimated jobs during the energy transition from 2015 to 2050 are presented in the supplementary material with Table S9 for global estimates, Table S10 to Table S18 for each of the nine major regions and Table S19 presents the job estimates across the 92 countries and regions.

The source based distribution of global energy jobs through the transition is highlighted in Fig. 5. It is evident that renewable energy technologies will create the most energy jobs, with nearly 100 million jobs in a high electrification pathway to a carbon neutral global energy system by 2050. Contrarily, the share of fossil fuels and nuclear based jobs are observed to decline through the transition period, from about 50 % in 2020 to a mere 3 % in 2050, as indicated in Fig. 5. These jobs are primarily associated with decommissioning of the remaining fossil and nuclear power plants that are approaching the end of their lifetimes. Renewable energy accounts for around 75 % of total direct energy jobs by 2050, in contrast to about 45 % in 2020, as they emerge to be the least costing sources for power generation [33,34]. The storage sector creates around 10 million jobs in 2050, with the steady ramp-up in installations and cost competitiveness beyond 2030, as shown in Fig. 5. High shares of electrification across the different energy sectors and widespread installations of renewable energy generation capacities along with large scale battery storage capacities will entail the need for increase in electricity transmission and distribution infrastructure, which creates steady and long-term jobs. Jobs associated with transmission and distribution of electricity is expected to grow form about 5 million in 2020 to nearly 22 million by 2050, as highlighted in Fig. 5.

Most renewable energy and storage technologies are still in their initial phases of development and are expected to grow rapidly, relative to their current levels of installations around the world. However, the pattern varies across different renewable power generation and storage technologies as there is limited activity in some countries, rapid growth in others, steady growth in a few, and relatively mature markets in the rest [27]. In this research, as part of the underlying Best Policy Scenario (BPS) with an optimistic outlook, the nine major regions are expected to reach 100 % local manufacturing capabilities by 2050 (local manufacturing shares and import shares with corresponding import regions are presented in Table S4 in the supplementary material). However, presuming a conservation approach in which manufacturing shares and export-import shares are expected to peak in 2025, and domestic manufacturing grows through the transition period until 2050. The major beneficial regions would be Northeast Asia with additional 600 thousand jobs, SAARC with 400 thousand jobs, Europe with 270 thousand jobs, Southeast Asia with 210 thousand jobs and to a lesser extent North America with 73 thousand additional jobs. Whereas, the rest of the regions would have fewer local manufacturing jobs with sub-Saharan Africa impacted the most. On the other hand, fossil fuel export jobs continue to decline through the transition and are comparatively less labour intensive as compared to renewable energy generation technologies. In general, it can be noticed that despite having higher shares of imports or higher shares of fossil fuel exports in some regions, the total number of jobs created will still be higher as renewables will create more localised construction and installation as well as operation and maintenance jobs as indicated in Fig. 1. Indeed, employment benefits from renewable energy could go to early mover countries, which start early and create strong export markets with better cost competitiveness. This aspect has been observed in the results of some of the exporting regions presented in the earlier section. Nevertheless, from a long-term perspective, the export-import shares across the different regions of the world are expected to stabilise and self-sustaining economies are foreseen by 2050 [40,41]. This regional and technological variation in global job creation through the energy transition period is captured in Fig. 5.

4. Discussion

The global employment creation in the energy sector with increased shares of renewable energy generation will have a net positive effect, which indicates that the number of jobs created by installing new capacities of renewable energy and complementary technologies are significantly higher than the number of jobs associated with the production and supply of fossil fuels and nuclear energy generation across the world. These results are validated by other studies such as Jacobson et al. [5,25,42], IEA [43], IRENA [27,28], Behrens et al. [44], Greenpeace [29], Dominish et al. [45], EPFL [46] among many others, which all tend to indicate that higher shares of renewables do have net positive impacts on employment. This research estimates the net employment generation from a global energy transition across the power, heat, transport, and desalination sectors to be 134 million direct energy jobs by 2050. There are four recent studies that estimate employment impacts in the context of global energy transitions, which are Jacobson et al. [25], Dominish et al. [45], IRENA [28] and IEA [43]. Jacobson et al. [25] estimate nearly 55 million total energy jobs in 2050 (net of 29 million after considering jobs lost) form wind energy, water and solar energy (WWS) generators with transmission for the entire energy sector (power, heat and transportation). Dominish et al. [45], quantitatively estimate that in 2050, there will be 29.6 million energy sector jobs in the 5.0 °C scenario, 50.4 million energy jobs in the 2.0 °C scenario, and 47.8 million energy jobs in the 1.5 °C scenario. In IEA's net zero emissions 2050 (NZE2050) scenario, clean energy employment increases by 14 million to 2030, while employment in oil, gas and coal fuel supply and power plants declines by around 5 million, leading to a net increase of nearly 9 million jobs resulting in a total of 49 million energy jobs in 2030 [43]. IRENA [28] estimates 100 million jobs in the energy sector by 2050, however, the energy transition pathway results in just 65 % renewable energy in the total primary energy supply in 2050. Moreover, storage technologies and the production of e-fuels have not been considered. Comparatively, IEA [43], Jacobson et al. [25] and Dominish et al. [45] have lower estimates of jobs created in 100 % renewable energy systems, as they have considered only renewable energy generation, with limited technology options, in addition to a lower final energy demand. It is increasingly evident that 100 % renewable energy systems will require complementary storage and flexible technology options, along with renewable electricity based e-fuels mainly in hard to abate sectors such as marine, aviation and others. Therefore, these sectors and jobs created by the adoption of these technologies must be factored for more comprehensive analyses on the employment impacts of 100 % renewable energy systems. IRENA [28] estimates job creation in energy efficiency, energy flexibility and grid, but still relies on fossil fuels for much of the primary energy demand, which is not compatible with climate change mitigation goals and does not result in a carbon neutral energy system. However, the findings of IRENA [28] indicate a net positive impact with higher shares of renewables than the current plans of countries around the world. In comparison to this research, a 100 % renewable energy system around the world can provide an additional 34 million energy jobs in context to IRENA's energy transition pathway and around 48 million additional energy jobs in context to the current plans of countries by 2050.

Several studies have demonstrated that the exploitation of renewable energy sources for electricity production creates a greater number of jobs than that supplied by conventional power sources and is analysed by Cameron and Van Der Zwaan [16]. It is found that for every megawatt of installed power capacity, renewable energy sources create between 1.7 and 14.7 times more jobs than natural gas based power generation and up to 4 times more jobs than those supplied with coal fired power generation [16]. A similar conclusion was drawn by Cai et al. [47] that for every one percent increase in the share of solar PV generation there could be a 0.68 % increase in total employment in China, larger than any other power generation technology. Renewable energy is already contributing more towards job creation in many markets across the world and studies for Chile [48] and Japan [49] show the potential for a lot more, particularly in the power sector. Renewables in the heat sector too have the potential to create substantially more number of jobs as highlighted by Connolly et al. [50] for the transition of the European heat sector until 2050. In the specific case of the USA, solar power generating capacity represents only slightly more than 1 % of the total power capacity, whereas coal contributes around 26 % to the power mix. However, solar workers are already twice as numerous, compared to those in the highly automated coal industry [51,52]. Likewise, the number of direct jobs estimated in this study can fall short of the actual number of total jobs including indirect and induced jobs created by the installation of renewable power and heat generation, storage technologies, production of e-fuels and transmission and distribution of electricity.

The direct energy jobs estimated in this research were validated with some approximations and estimates from other research. This research estimates around 57 million jobs in the period 2015 to 2020, which is in the range of the IRENA [28] estimate of 58 million jobs in 2017. While, Dominish et al. [45] estimate around 30 million direct jobs in 2015, which seems to be rather conservative. The IEA energy employment database shows that in 2019, the energy industry − including electricity, oil, gas, coal and biofuels − directly employed around 40 million people globally [58]. ILO [17] estimates jobs in the electricity sector to be about 25 million in 2014, in comparison this research finds 20 million direct energy jobs in the power sector and 5 million jobs in the transmission and distribution of electricity for the period 2015 to 2020. This is also validated by the results of Ram et al. [32] that estimate about 20 million direct jobs in 2015 and over 24 million jobs in 2020 across the global power sector. IRENA [59] estimates around 30 million jobs in the fossil fuels industry, in comparison this research estimates nearly 19 million jobs in the coal, oil and gas industries (jobs are estimated from source to plant, mainly upstream jobs). However, estimating fossil fuel jobs varies significantly with the consideration of value chains and the informal nature of the industry mainly in developing and undeveloped regions of the world adds to uncertainties. ILO [60] estimates around 6 million jobs in the global petroleum industry and Pai et al. [61] estimate over 7 million jobs in the coal industry around the world. In comparison, this research estimates 7 million jobs in the oil and gas industry and 12 million jobs in the coal industry. Pai et al. [61] also note that China accounts for over 6 million coal jobs, thus it is reasonable to assume that there are a lot more jobs in the coal industry around the world with majority in countries such as India, Indonesia and South Africa where the coal industry is still very labour intensive.

Jobs have always been a contentious topic, with most opinions swayed by political commentary about the adverse impacts of an energy transition on employment in a particular state, region, or country [62]. Over the recent past, several studies have examined and analysed the net employment effects of energy transitions. Although the majority of them conclude that the net employment effects will be positive, as concluded by Lund and Hvelplund [63] in a study conducted as early as 1998. While, some studies are less optimistic about net employment creation, and the outcomes seem to depend very much on the methodology [64]. Stavropoulos and Burgerv [64] found that estimations with induced effects are generally less optimistic about net employment creation in the wake of the energy transition. A comparative analysis of direct employment of renewable and non-renewable power plants found renewables to be generally higher, but under some circumstances non-renewables to be comparable [65]. However, this research is focused on estimating only direct energy jobs and the net jobs resulting from a global energy transition towards 100 % renewable energy. The net positive impacts have also been verified with actual data, the ILO [17] have found evidence by linking decades-long trends in employment in the electricity generation sector to the sources of electricity generation itself and by analysing the indirect linkages. Results from the analyses showed that increases in generation from non-hydropower renewables favour employment in the electricity sector, with important differences observed in developed and developing countries [17]. Moreover, the study also found that renewables offered higher indirect employment effects as well. Even assessments on a power plant level have indicated better prospects for local economic growth and job creation, as highlighted by a feasibility study for a coal power plant in Thailand [66].

It must be noted and acknowledged that as is with most research methods there are limitation with this research as well. The method relies on extensive and comprehensive literature review for EFs, which in the case of most energy technologies are quite robust with verified employment effects. Whereas some energy technologies are still in the nascent stages of development and still require scaling to a great extent for the employment effects to be analysed and verified. In addition, there are prevailing uncertainties about the development of certain regions and countries around the world, given the geopolitical challenges and economic ambiguities for the future. Moreover, the effects of changes in electricity prices, labour policies and wages and household incomes are mostly uncertain from a long-term perspective. Further limitations of this research extend from perceived limitations of 100 % renewable energy systems, which are mostly related to stability of power systems in handling variable renewable energy and availability of materials to enable the transition to 100 % renewables in a sustainable manner. Stability of the power system in handling variable renewable energy has been discussed in detail by Brown et al. [53] concluding that from the time scale of seconds up to seasons, stable power systems are regularly enabled in well-designed 100 % renewable power systems. Recent research by Denholm et al. [54] clearly confirmed for the case of the US that no fundamental technical reason has been identified as to why a 100 % renewable power system could not be achieved. While issues of materials limitations are increasingly studied for 100 % renewable energy systems and investigated in high detail for the most exclusive materials in Junne et al. [55], concluding that substantially more comprehensive research has to be conducted and mitigation strategies to be explored. Most critical materials seem to be manageable, such as Cobalt and Lithium [56], whereas, Neodymium and Dysprosium can be substituted with new technical solutions [57]. However, continuous research efforts in improving the data availability and upgrading current information will help in addressing many of the uncertainties and a few others can be overcome with reasonable assumptions. Similarly, Proenca and Fortes [18] analysed empirically the relationship between renewable energy deployment and job creation, by employing econometric methods from panel data analysis. The research was focused on the EU and analysed the relationship between historical values of renewable power generation installed capacities and corresponding employment over the period 2000 to 2016. The results suggested a positive relationship between the two variables, showing an increase of 0.48 % in employment for each 1 % increase in renewable power generation capacity [18]. This can be substantiated with the findings of this research indicating that the final energy demand specific jobs nearly double from 563 jobs/TWh in 2020 to about 1000 jobs/TWh in 2050.

5. Conclusions

Jobs are critical in enabling well-functioning economies and, more importantly, in ensuring political and societal stability around the world. The disruptive impact of the COVID-19 crisis on workers, labour markets, and livelihoods has further underlined the importance of employment generation along with the global green economic recovery across countries. With respect to labour markets across the world, many regions are facing stagnating economies accompanied by high and rising unemployment rates, which is further exacerbated by the COVID-19 pandemic. Global unemployment levels and rates have been high in the last few years and are expected to remain high with more than 470 million people worldwide lack adequate access to paid work as such or are being denied the opportunity to work the desired number of hours [67]. Moreover, the risk of social unrest or discontent has heightened across many regions of the world with high unemployment rates. The ILO's social unrest index, which seeks to proxy the expressed discontent with the socioeconomic situation in countries, indicates that average global social unrest increased in the last few years [67]. Therefore, employment generation is a major policy priority, particularly for countries with high levels of unemployment and underemployment. This could either be a long-term issue or the immediate consequence of an economic recession as induced by the current COVID-19 pandemic. In this context, the renewable energy sector has weathered previous financial and economic crises successfully, as compared to many other industries and is also resilient in the current situation [27,68]. Moreover, it has become a relatively mature economic sector with steady technological progress, falling production costs and rising labour productivity. As the global transition towards sustainable energy continues, renewable energy labour force requirements are set to increase [5,29,44]. This is the first research estimating potential jobs created by heat storage technologies and the production of hydrogen and e-fuels in the context of a global energy transition until 2050, enabled by the hourly simulation capabilities of the LUT Energy System Transition model. The results emphasised in Fig. 5, affirm that renewable energy technologies have the potential to create a significant number of jobs in a global climate compliant energy transition scenario, contributing to around 74 % of the jobs created by 2050.

As the employment levels increase during the global energy transition, the employment structure of the energy sector may shift towards more highly qualified workers, particularly due to the relatively higher level of qualifications required to operate and manage renewable power generation and storage technologies [45]. This means that the energy transition will provide not only more jobs, but also better-qualified ones. Many job opportunities will be created along the different categories of the value chain, as the results presented in the earlier sections indicate. This poses a challenge with the increasing demand for personnel with diverse skill-sets and talents in the near future. Therefore, significant efforts in training and education will be needed to provide the labour market with necessary skills and reskilling of labour in certain cases. Finally, it appears that there is considerable growth potential for renewables and renewable employment creation in a variety of markets across the world, as shown in earlier sections. However, these markets have to be triggered by stable and sensibly designed policy instruments and investment strategies, such as long-term supporting schemes (e.g. feed-in tariffs or portfolio standards) and a global approach towards climate protection (e.g. carbon tax or cap and trade systems) in order to leverage existing opportunities from renewables [33,34]. Although this research has highlighted the net increase in employment, a reorganisation of a country's energy system could have far more significant benefits to the entire economy. This indicates that more integrated assessments of employment impacts are necessary as the penetration of renewable energy increases in future energy systems. But more importantly, this can be compatible with the ambitious goals of the Paris Agreement and the global community can benefit from declining GHG emissions and reduced local air pollution levels, while boosting economic growth with lower energy costs and higher job creation.

Authors contribution statement

Manish Ram: Conceptualization, Methodology, Software, Investigation, Data curation, Writing – original draft. Juan Carlos Osorio-Aravena: Methodology, Investigation, Data curation. Arman Aghahosseini: Investigation, Data curation. Dmitrii Bogdanov: Investigation, Software. Christian Breyer: Conceptualization,

Methodology, Investigation, Writing − review & editing, Funding acquisition.

Declaration of competing interest

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

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Appendix A. Supplementary data

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