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Abstract

Aside from reducing the energy sector's negative impacts on the environment, renewable power generation technologies are creating new wealth and becoming important job creators for the 21st century. Employment creation over the duration of the global energy transition is an important aspect to explore, which could have policy ramifications around the world. This research focuses on the employment impact of an accelerated uptake of renewable electricity generation that sees the world derive 100% of its electricity from renewable sources by 2050, in order to meet the goals set by the Paris Agreement. An analytical job creation assessment for the global power sector from 2015 to 2050 is estimated and presented on a regional basis. It is found that the global direct jobs associated with the electricity sector increases from about 21 million in 2015 to nearly 35 million in 2050. Solar PV, batteries and wind power are the major job creating technologies during the energy transition from 2015 to 2050. This is the first global study presenting job creation projections for energy storage. The results indicate that a global energy transition will have an overall positive impact on the future stability and growth of economies around the world.

Keywords

Jobs, Employment, Renewable Energy, Energy Storage, Energy Transition

Abbreviations

A-CAES	Adiabatic Compressed Air Energy Storage
BNEF	Bloomberg New Energy Finance
BPS	Best Policies Scenario
CAPEX	Capital Expenditures
CCGT	Combined Cycle Gas Turbine
CPS	Current Policies Scenario
CSP	Concentrated Solar Thermal Power
EU	European Union
FLH	Full Load Hours
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GW	Gigawatt
IEA	International Energy Agency
IMF	International Monetary Fund
IPCC	International Panel on Climate Change
ILO	International Labour Organization
IRENA	International Renewable Energy Agency
LCOE	Levelised Cost of Electricity
MW	Megawatt

OCGT	Open Cycle Gas Turbine
OPEX	Operational Expenditures
PtG	Power-to-Gas
PtH	Power-to-Heat
PV	Photovoltaics
TW	Terawatt
USD	United States Dollar

1. Introduction

The risks and impacts posed by devastating socioeconomic consequences of climate inaction have been conspicuously stressed in the International Panel on Climate Change (IPCC) 4th and 5th assessment reports (IPCC, 2007, 2014a) as well as the Stern review (Stern, 2007). In this regard, the Paris Agreement, negotiated at the 21st Conference of the Parties (COP21) in 2015 (UNFCCC, 2015), has set an important foundation on which the global community can build a sustainable future. With electricity generation accounting for around 25% of global greenhouse gas (GHG) emissions, reducing emissions in this sector is a critical component in the transition towards a low carbon development pathway (IPCC, 2014b). A global energy transition is well underway with nearly 160 GW of renewables (without considering large hydropower) been added in 2017, of which 98 GW was solar and 53 GW wind power (Frankfurt School - UNEP & BNEF, 2018; GWEC, 2018). In addition, tumbling technology costs have propelled investments in renewable energy power generation and from a levelised cost of energy (LCOE) outlook, renewables have become a more attractive investment proposition than fossil fuels in many countries around the world (Ram et al., 2017a; Ram et al., 2018). The effects of the new energy system would not be restricted to energy production only, but would have consequences for the whole society (Breyer, etal., 2017a).

Energy use is either the cause or the facilitator of economic growth. Moreover, sufficient evidence over the years point to the positive correlation between energy use, economic growth and employment (CDC & ODI, 2016). As the global energy system is a major economic sector with a share of around 8% in global gross domestic product (GDP) (IER, 2010), the prospects for investment and employment in the sector are significant to economies around the world. The physical implications of a shift towards greater shares of renewable electricity 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, as enlisted and analysed in Child et al. (2018). However, employment associated with the electricity sector and the impact of an accelerated uptake of renewables on employment creation in the sector, has received relatively lesser attention. A review was performed by Sheikh et al. (2016) to determine the criteria that are elements of the social and political perspectives, which found that renewable energy has the potential to play a significant role in fulfilling the employment criterion. 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 (UNEP, 2008). Combining different methods, as proposed by Fortes et al. (2015), is a way to advance scenario building by integrating different collective thinking and other socioeconomic parameters.

As the energy sector increasingly moves hand in hand with economic development, social priorities and environmental needs, an integration of social processes with technical and economic analyses of energy systems is therefore a necessity. In purview, this research evaluates the hypothesis of sound economic impacts from transitioning to a sustainable economy by determining the employment effects of achieving 100% renewable power supply by 2050, across the world structured into 9 major regions. The world is categorised into Europe, Eurasia, Middle East and North Africa (MENA), Sub-Saharan Africa, South Asian Association for Regional Cooperation (SAARC), Northeast Asia, Southeast Asia, North America and South America. The transition of power sectors across these regions, as showcased in Breyer et al. (2017b) and Ram et al. (2017a), serves as the basis for estimating jobs created during the transition period from 2015 to 2050. Additionally, job creation potential is estimated on a technology-wise basis as well as on a category-wise basis during the energy transition to provide better insights on the types of jobs created. Moreover, this research is the first to estimate potential job creation by the various storage technologies during the energy transition on a global basis. This is primarily due to the innovative aspects of the LUT Energy System Transition modelling tool (Breyer et al., 2017b; Ram et al., 2017a), which analyses power systems across the world on an hourly basis enabling detailed analyses of storage requirements.

Further, this research presents an overview of existing literature in section 2. The detailed methods, various assumptions and other relevant material in estimating job creation during the energy transition are highlighted in section 3. The following section 4 presents the results on a regional basis and displays the jobs created on a technology basis as well as on a category basis. In addition, section 5 discusses the results from a global perspective and draws a few comparisons to other such studies. Finally, section 6 draws conclusions and possible implications of the results.

2. Literature Review

In recent years, the job creation potential of renewable energy technologies in the context of the energy transition has received attention from some of the stakeholders including academia, government agencies, private sector and the civil society (Child et al., 2018). The International Renewable Energy Agency (IRENA) has estimated jobs associated with renewable energy to rise to around 16.7 million by 2030 (IRENA, 2013) and their annual review of global employment related to renewable energy shows that 10.3 million people were employed in 2017 (IRENA, 2018). Jacobson et al. (2014) estimated jobs created and jobs lost for a long-term sustainable energy infrastructure that supplies 100% of energy in all sectors (electricity, transportation, heating/cooling, and industry) from wind, water, and solar power (without fossil fuels, biofuels, or nuclear power) for the state of California and found that it will create a net of 220,000 40-year construction plus operation jobs (442,200 new 40-yr construction jobs and 190,600 new 40-yr operation jobs, less 413,000 jobs lost in current California fossil- and nuclear-based industries). Further, Jacobson et al. (2017) estimate that their main scenario by 2050 (that is electricity generation with 100% wind, water, and solar power for all energy sectors) would create a net of 24.3 million permanent, full-time jobs across 139 countries of the world. This estimate includes creation of 52 million new ongoing jobs for 100% renewable electricity generation and transmission supplying for highly electrified energy sectors (including power, heat and transport) up to 2050, while 27.7 million jobs are lost in the current fossil fuel, biofuel, and nuclear industries (Jacobson et al., 2017). Various editions of the Energy [R]evolution, published since 2007, project probable employment outcomes across a broad range of scenarios (Greenpeace International, 2015). The latest edition offers a global estimate for energy sector employment to be 46.1 million by 2030 for the Advanced Energy [R]evolution scenario. Nevertheless, there are studies that have estimated the impact of renewable energy development on job creation to be negative, resulting in job losses. Almutairi et al. (2018) show a loss of 4.45 million jobs worldwide up to 2030 in the Renewable and Nuclear Energy (RNE) scenario (based on the predictions of the international energy outlook) compared to the business as usual (BAU) scenario. This study (Almutairi et al., 2018) has made an effort to estimate both the direct and indirect jobs associated with the different energy scenarios by assessing the overall impacts on the gross domestic product (GDP) of different countries. However, Markandya et al. (2016) found the net employment impacts from the transformation of the European Union energy sector in the period 1995–2009, when the European Union's energy structure went through a significant shift, away from the more carbon intensive sources, towards gas and renewables to be positive. Moreover, the research estimated the net employment generated from this structural change at 530,000 jobs in the European Union and further analysis showed that the change in the input structure of the European electricity and gas supply sector, motivated significantly by the desire to shift towards a green economy, had a net positive impact on employment (Markandya et al., 2016). Whereas, Böhringer et al. (2013) suggest with a computable general equilibrium analysis of subsidised electricity production from renewable energy sources (RES-E) in Germany that the prospects for employment and welfare gains are quite limited and hinge crucially on the level of the subsidy rate and the financing mechanism. To the contrary, by linking investments in energy sector and jobs created, Garrett-Peltier (2017) finds that on average, 2.65 full-time equivalent (FTE) jobs are created from 1 million USD spending in fossil fuels, while that same amount of spending would create 7.49 or 7.72 FTE jobs in renewables or energy efficiency. It is further concluded that each 1 million USD shifted from brown (includes fossil fuels and nuclear) to green energy will create a net increase of 5 jobs (Garrett-Peltier, 2017). The results of these studies are difficult, if not impossible to compare due to their differing assumptions and modelling approaches. However, one recurring theme seems to be the positive contribution of high shares of renewable energy uptake to the labour market thereby generating ample employment.

Employment trends vary significantly across the different energy generation technologies. There are a number of identifiable methods that have been used to quantify employment impacts of the changing energy sector and have been well documented in literature review studies, such as Breitschopf et al. (2011), Cameron and Zwaan (2015) and Meyer and Sommer (2014). However, in general, the various methods applied can be categorised into bottom-up and top-down approaches, or more specifically as using the analytical or input–output (IO) models (World Bank, 2011). Additionally, Llera et al. (2013) and Hondo and Moriizumi (2017), highlight a value-chain approach and a life-cycle approach respectively, for estimating job creation mainly from renewable energy deployment. Furthermore, the various studies consider different types of jobs associated with the energy industry; the common adopted classification is 'direct', 'indirect' and 'induced' jobs. IRENA (2011) elaborates a clear and operational definition of these terms, as well as their interpretation across studies. Lambert and Silva (2012) find that analytical studies using extensive surveys are found to be more appropriate for regional studies, while input–output methods are better suited to national and international studies.

In Jacobson et al. (2014; 2017), estimates of baseline jobs per unit energy in their main scenario are based on National Renewable Energy Laboratory's (NREL) Jobs and Economic Development Impacts (JEDI) models (NREL, 2013). These are economic IO models with several assumptions and uncertainties. In contrast, IRENA (2013) and Greenpeace International (2015) 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 a certain energy technology capacity addition or investment. The EF approach utilised for estimates of job creation potential in Greenpeace's energy scenarios is documented by Rutovitz and Atherton (2009), an improved version is presented in Rutovitz and Harris (2012) and the latest version in Rutovitz et al. (2015). This research is an effort to further refine the methods and conduct a more comprehensive analysis of the net jobs created during an energy transition, which includes a broad range of technologies and is the first to estimate job creation potential of the complementary storage technologies. The research has also included estimates of decommissioning jobs across the various power generation technologies created during the energy transition up to 2050.

3. Methods and Materials

For this research, an analytical approach towards estimating jobs in an energy transition scenario was adopted. Moreover, the methods were based on the approach highlighted in Rutovitz et al. (2015) and further modified and improved for better results as well as applied to a broader range of technologies.

3.1 The Employment Factor approach

Jobs generated during the global energy transition from 2015 to 2050 are estimated utilising the EF approach, adopted from Rutovitz et al. (2015). The EF method was utilised amongst the other methods (Breitschopf et al., 2011), due to its simplicity and effectiveness in estimating direct employment associated with energy generation, storage and transmission. 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. The Figure 1 gives an overview of the methods utilised to estimate jobs created during the energy transition from 2015 to 2050 across the different regions.

Figure 1: Method for estimation of job creation during the energy transition. Abbreviations: Employment Factor (EF), Capital Expenditure (CAPEX) and Operational Expenditure (OPEX).

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 generation, decommissioning of power plants at the end of their lifetimes and transmission. The category of jobs are as follows,

- Manufacturing Jobs – encompasses the number of jobs necessary to manufacture a unit of power generation capacity. Manufacturing of equipment and components for a power plant project may require several weeks, months or at most a few years' worth of work. As such, they represent relatively temporary employment in comparison to the entire plant lifetime. Hence, they are expressed as job-years, or the total number of full-time jobs needed for manufacturing over the plant's lifetime (IRENA, 2013). Additionally, the manufacturing of equipment and components for power plants may occur outside the country where the power generation capacity is being installed. Many countries rely on importing, especially renewable energy technologies, as the domestic production is insufficient or non-existent yet. On the other hand, countries that export renewable energy equipment and components can generate employment, which is additional to that relating to their domestic energy capacity addition by producing for export markets (IRENA, 2013). To account for the degree of import dependence, the local manufacturing factor is considered which is further highlighted below.

- Construction and Installation Jobs – includes all the jobs associated with constructing and installing a unit of power generation capacity. It is assumed that a local workforce will undertake the installation and construction of all energy projects, as is in most cases. Similar to manufacturing, these are expressed as job-years, or the total number of full-time jobs needed for construction and installation over the plant's lifetime. These jobs are predominantly in the beginning phase of a power plant (that is in the first few years) and last during the period in which the power plants are built until the first operation. In this case, the construction and installation jobs are annualised over the construction period of a power plant, which is the time required for construction and installation of unit power plant capacities (in terms of per MW). The construction times for all technologies in years can be found in the Supplementary Material.
- Operation and Maintenance Jobs – comprises all the jobs associated with operating and maintaining the operational condition of a power plant over its technical operational lifetime. As power plants are usually designed to run for decades, operation and maintenance jobs last for a relatively longer duration and therefore interpreted as jobs per capacity of power generation. These jobs are considered for the lifetime of the respective power plants and are further annualised to get total number of jobs during the transition period. As and when power plants are decommissioned and new power plants replace the capacity, the O&M jobs continue to exist. A learning factor, which is correlated to the productivity increase in operational expenditures (Opex), is adopted to reflect the decline in O&M jobs as technologies and operational processes further mature.
- Fuel Jobs – includes all the jobs associated with fuel supply to power plants (nuclear, fossil and bioenergy). These are expressed as jobs per unit of primary energy, factoring the different rates of fuel consumption for power plants corresponding to the fuel utilised based on conversion efficiencies during the transition period.
- Decommissioning Jobs – consists of all jobs associated with the decommissioning of installed power plants at the end of their operational lifetimes, especially if plants are repowered or if certain elements are recycled or reused. These jobs are comparable to construction and installation jobs and are expressed as job-years, or the total number of full-time jobs needed for decommissioning over the plant's lifetime. These jobs are further annualised during the transition period to derive the total number of jobs created.
- Transmission Jobs – includes all the jobs associated with power transmission activities. In context to this research, transmission jobs are expressed in terms of investments made in transmission infrastructure, i.e. jobs per unit investments (in billion euros). As the LUT Energy System Transition modelling tool considers only key transmission infrastructure required, the full extent of jobs associated with transmission infrastructure is not reflected in this research. The jobs from transmission infrastructure will be a lot higher when more accurate transmission data is considered.
- Jobs Loss: The jobs lost in fossil fuel and nuclear power plants are corresponding to the decommissioned capacities of conventional power plants during the transition period. As renewables are mostly installed beyond 2020, jobs do not arise in conventional power plants and these plants are decommissioned at the end of their technical lifetimes, which creates additional decommissioning jobs.

Some of the parameters considered in the estimation of job creation potential of various power generation and storage technologies,

- Employment Factors – are the number of jobs per unit of installed capacity, separated into manufacturing, construction and installation, operation and maintenance, and decommissioning. Further, it is also jobs per unit of primary energy for fuel supply and jobs per unit of investment for transmission of power. EFs for this research were mainly adopted from Rutovitz et al. (2015), along with some modifications and estimates from a few other sources. These are Solar Power Europe (2015) for rooftop PV, GTM Research and ESA (2016), Hart and Sarkissian (2016) and The Solar Foundation (2016) for battery storage, Arcadis (2018) and Government of U.K. (2015) for gas storage, RFF (2017), Evonik Industries (2010) and Oldham (2009) for decommissioning and The Brattle Group (2011) for transmission. The different EFs for the various power generation and storage technologies, along with transmission are shown in Table A1 in the Appendix.
- Decline Factors – job creation can be expected to reduce as technologies and production of these technologies mature. This maturing occurs as a result of the growing experience and volume in the energy industry (mainly renewables and storage); i.e. learning by doing and economies of scale (Cameron and Zwaan, 2015). In order to account for the maturity of technology and corresponding reduction in employment generation with increase in production capacities, EFs are correlated with the rate of reduction in capital expenditures (CAPEX) of the corresponding power generation and storage technologies during the transition period, in the case of manufacturing, construction and installation jobs. While, in the case of operation and maintenance jobs the EFs are correlated with the rate of decline in operational expenditures (OPEX) of the respective power generation and storage technologies through the transition period. CAPEX and OPEX values during the transition period from 2015 to 2050 can be referred to in the Supplementary Material.
- Regional Employment Multiplier – of the various regions are adopted to account for the differential labour intensive economic activity in the different regions across the world. Since the EFs considered are mainly from OECD countries, the regional employment multiplier accounts for the additional employment that will be generated in non-OECD countries, which needs adjustment for differing stages of economic development. In general, the lower the cost of labour in a country, the greater the number of workers that will be employed to produce a unit of any particular output be it manufacturing, construction or agriculture. Low average labour costs are closely associated with low GDP per capita, a key indicator of economic development (Rutovitz et al., 2015). Therefore, deriving a proxy factor correlated to average labour productivity, measured as GDP (or value added) per worker is the most reasonable indicator. The regional employment multipliers are expected to change over the transition period (2015-2050), as the differences in labour productivity evolve with regional economic growth. The projected change in GDP per capita derived from GDP growth and population growth is factored to adjust the regional employment multipliers for the 9 major regions over time. The method from Rutovitz et al. (2015) along with labour productivity data from International Labour Organization (ILO) (ILO, 2016) was used to determine the regional employment multipliers for the corresponding regions. Table A2 in the Appendix indicates these values.
- Local Manufacturing Factor – represents the percentage of local manufacturing across the various regions of the world. As manufacturing of mainly renewable energy and storage technologies is quite unevenly distributed across the world, many regions still rely heavily on imports. Import and

export proportions as well as current export and corresponding import regions are set according to current practices, which are derived from trade flows in the energy sector (predominantly renewables) and industrial activity in corresponding major regions adjusted to indicators from UNIDO (2013). Currently, the more industrialised regions of China, Europe and North America dominate the global export of renewable energy technologies. However, with economic growth in other regions, this research considers in an optimistic scenario that all major regions across the world will develop towards regional self-sustenance up to 2050. This entails all major regions having domestic manufacturing capabilities by 2050. In addition, the research has considered a conservative scenario in which global export-import conditions remain in present conditions (according to 2015 assumptions), to examine the deviation in jobs created. The values were mostly adopted from Rutovitz et al. (2015), UNIDO (2013) and PwC (2017); Table A3 in the Appendix indicates these values.

As indicated in Figure 1, 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 capacity for every 5-year interval between 2015 and 2050. The fuel EFs are applied to annual electricity generation form the various power generation technologies that utilise fuel sources. The decommissioning EFs are applied to the annual decommissioned capacities of power generation and storage technologies during the entire transition period. The transmission EF is applied to the total annual investments in transmission for different regions during the transition period. The installed capacities, electricity generation, fuel consumption, decommissioned capacities and investments in transmission for the various power generation and storage technologies are adopted from the results of the LUT Energy System Transition model, as comprehensively documented in Bogdanov et al. (2019), Ram et al. (2017a) and Breyer et al. (2017b).

3.2 The LUT Energy Transition Model

The LUT Energy System Transition modelling tool (Bogdanov et al., 2019; Bogdanov and Breyer, 2016; Kilickaplan et al., 2017; Ram et al., 2017a) simulates an energy system under given conditions, which is applied for 5-year time periods from 2015 to 2050. For each period, the model defines a cost optimal energy system structure and operation mode for the given set of constraints that are power demand, available generation and storage technologies, financial and technical assumptions, and limits on installed capacity for all applied technologies. The model is based on linear optimisation and performed on an hourly resolution for entire years of the transition period. The model ensures high precision computation and reliable results. The costs of the entire power system are calculated as a sum of the annualised capital expenditures including the costs of capital, operational expenditures (including ramping costs), fuel costs and the costs of GHG emissions for all available technologies under mitigation assumptions.

The energy system transition analyses also consists of distributed self-generation and consumption of residential, commercial and industrial PV prosumers, which are simulated with a different model describing the PV prosumer and battery capacity development. PV prosumers have the option to install their own rooftop PV systems with or without lithium-ion batteries, and draw power from the grid in order to fulfil their demand (Keiner et al., 2019; Ram et al., 2017b), while also having the option to feed-in to the grid their surplus electricity (Ford et al., 2017). The target function for PV prosumers is the minimisation of the cost of consumed electricity, calculated as a sum of self-generation, annual costs and the cost of electricity consumed from the grid, minus the cost of electricity sold to the grid. The share of consumers opting to install their own generation and storage is projected to gradually increase from 3% in 2015 (IEA-PVPS, 2016; SolarPower Europe, 2016) to 20% by 2050 (UBS, 2013). The share of PV prosumers increases in accordance with the logistic function, in steps of 3, 9, 15, 18 and 20%. For a given year, if self-consumption of electricity becomes economically feasible, then the share of prosumers for the following year increases, otherwise the share of potential prosumers remains the same. Bogdanov et al. (2019), Ram et al. (2017a) and Breyer et al. (2017b) provide the full set of technical as well as financial assumptions utilised in the modelling of the energy transition.

The model has integrated all crucial aspects of power systems: power generation, storage and transmission. The technologies introduced in the model are classified into the following categories:

- Technologies for electricity generation: renewable, fossil fuel and nuclear technologies
- Energy storage technologies
- Electricity transmission technologies

Figure 2 displays the schematic representation of the LUT Energy System Transition model and all the power sector technologies considered for simulating the global energy transition (Bogdanov et al., 2019). Renewable energy technologies in the model comprise solar PV (optimally fixed-tilted, single-axis north-south tracking and rooftop), concentrating solar thermal power (CSP), wind turbines (onshore and offshore), hydropower (run-of-river and reservoir/ dam), geothermal and bioenergy (solid biomass, biogas and waste-to-energy power plants). Fossil fuel based power generation technologies considered are coal-fired power plants, oil-based internal combustion engines (ICE), open cycle gas turbines (OCGT) and combined cycle gas turbines (CCGT).

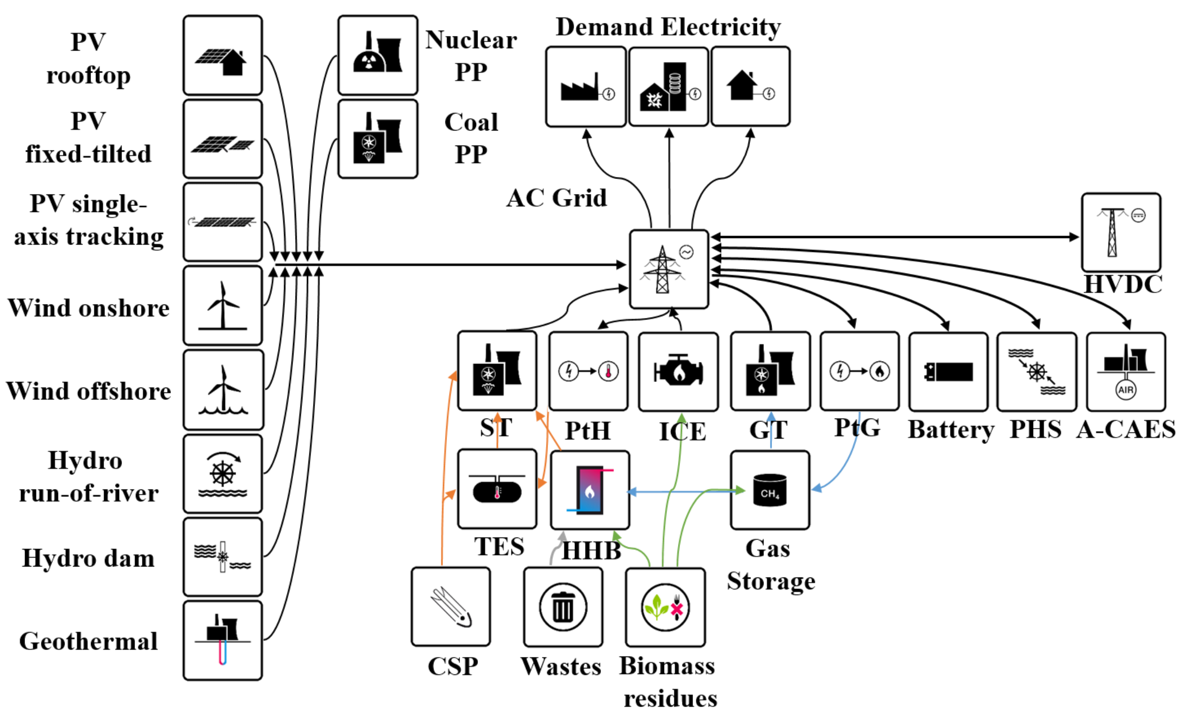

Figure 2: The schematic representation of the LUT Energy System Transition model for the power sector with the various sources of power generation, transmission options, storage technologies and power demand sectors (Ram et al., 2017a).

Storage technologies are further classified into the following categories:

- Short-term: Li-ion batteries and pumped hydro storage (PHS)
- Medium-term: adiabatic compressed air energy storage (A-CAES) according to Aghahosseini and Breyer (2018) and thermal energy storage (TES)
- Long-term: gas storage including power-to-gas technology, which allows production of synthetic methane for the energy system.

The transition to a fully renewable powered energy system has been carried out for the whole world, which is categorised into 9 major regions that are Europe, Eurasia, Middle East and North Africa (MENA), Sub-Saharan Africa, South Asian Association for Regional Cooperation (SAARC), Northeast Asia, Southeast Asia, North America and South America (Ram et al., 2017a). The energy transition simulation takes into account the existing power grid, its development and impact on overall electricity transmission and distribution losses (Sadovskaia et al., 2018). All regions within a country are interconnected with either high voltage direct current (HVDC) or high voltage alternating current (HVAC) power lines, therefore increasing local flexibility while reducing overall national system costs.

All the financial and technical assumptions with the corresponding references to data sources for all energy system components are highlighted in Ram et al. (2017a). Electricity demand of the global power sector is estimated to increase from 23,141 TWh in 2015 to about 48,800 TWh in the year 2050, which represents a global average compound annual growth rate of 2.2% in the energy transition period, and is comparable to the assumption of 1.9% by the IEA (2016). The global power plant capacity is structured according to the major power generation and storage technologies and their corresponding country and region of location along with the year of commissioning, in an annual resolution (Farfan and Breyer, 2017).

3.3 Best Policy Scenario

A Best Policy Scenario (BPS) entails 100% electricity generation from renewable energy resources and various storage options across the different regions of the world, in line with the goals of the Paris Agreement. The development of the power sector is characterised by a dynamically growing electricity demand driven by developing and emerging countries and an increasing share of renewable electricity in the overall supply mix. The results show a growing renewable energy trend that will compensate for the phasing out of nuclear power production as well as for the continually reducing number of fossil fuel based power plants. As per the results, the installed capacity of renewables will reach about 14,000 GW in 2030 and more than 28,000 GW by 2050. A 100% electricity supply from renewable energy resources leads to around 23,600 GW of installed generation capacities of solar PV, wind energy, hydropower, bioenergy and geothermal power by 2050 as highlighted in Bogdanov et al. (2019) and Ram et al. (2017a). The share of renewable electricity in the overall mix will reach 99.65% of the electricity generated worldwide in 2050. Renewable power generation technologies, mainly solar PV and wind energy, are expected to contribute nearly 87% to the total electricity generation by 2050. Storage technologies play a vital role in enabling the transition towards a fully renewables powered energy system. The overall storage output covers 31% of the total electricity demand in 2050, of which batteries deliver 95%. The installed capacities are dominated by gas storage, whereas the overall output is dominated by battery storage. The levelised cost of electricity for the global power system declines from around 70 €/MWh in 2015 to about 52 €/MWh by 2050. Additionally, regional results of the energy transition worldwide can be found in Bogdanov et al. (2019) and Ram et al. (2017a).

4. Results

The resulting least cost energy mix comprising various power generation and storage technologies in each of the 9 major regions during the energy transition period from 2015 to 2050 from the Best Policy Scenario, serves as the basis for estimating the corresponding employment creation.

The results are presented according to the major regions followed by the global estimates.

4.1 Europe

Europe is one of the major economic centres of the world with an 18% share of global GDP (IMF, 2017), and amongst the biggest energy consumers across the world, with total electricity consumption of around 4000 TWh in 2015, which is estimated to rise to around 5400 TWh by 2050 (IEA, 2016). Europe has been at the forefront of the global energy transition with about 37% of installed power capacity and nearly 30% of electricity generation from renewables (REN21, 2017).

There were just over 2 million direct jobs in the energy sector across Europe in 2015, with more than 50% of these in the renewable energy sector. With the rapid increase in renewable energy installations up to 2025, jobs in the energy sector are seen to rise to around 3.7 million, and stabilise between 3.3 million by 2035 and 3.4 million by 2050 as shown in Figure 3. Solar PV emerges as the major job creating sector with 1.73 million jobs by 2050, while bioenergy (675 thousand jobs by 2050) and hydropower (212 thousand jobs by 2050) create stable number jobs through the transition period. Whereas, the wind power sector is expected to create around 400 thousand jobs in 2025 (bulk of the share in onshore and a few thousand in offshore) and further as capacities installed are lesser with more cost effective solar PV, jobs created in wind are around 264 thousand by 2050. Storage technologies led by batteries are observed to start creating jobs from 2025 onwards, with a stable share until 2050 (277 thousand jobs in the battery sector). Whereas, jobs in the fossil fuel and nuclear sectors decline through the transition period and by 2050 are almost non-existent apart from a few thousand jobs associated with decommissioning of conventional power plants. This trend can already be observed across Europe with many countries opting to phase out coal and nuclear power generation, with some of the countries also divesting from conventional power generation projects (Agora Energiewende & Sandbag, 2018).

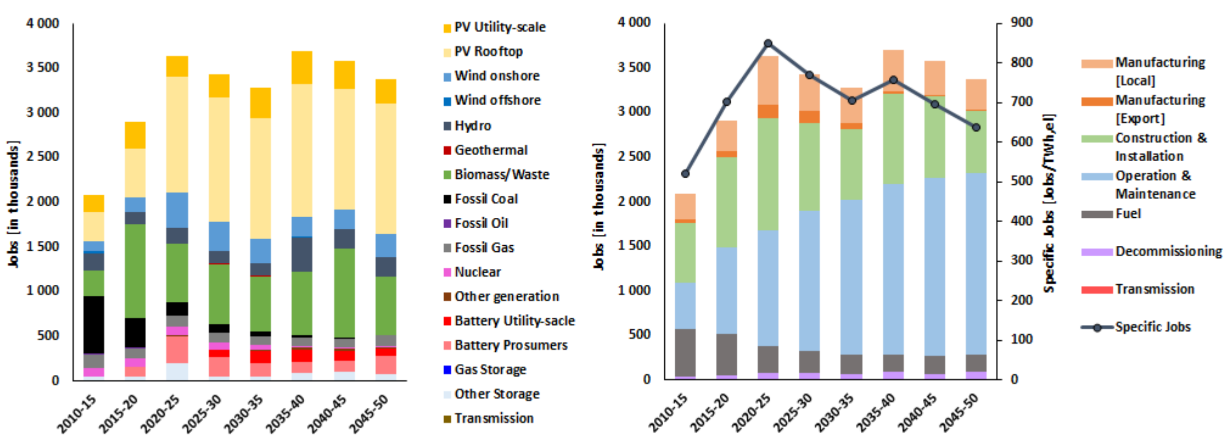

Figure 3: Jobs created by the various power generation and storage technologies (left) and jobs created

based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in Europe.

The category-wise distribution of jobs for Europe during the transition period is shown in Figure 3. Manufacturing, construction and installation of renewable energy technologies create a significant share of jobs enabling the rapid ramp up of capacity until 2025, beyond this period there are stable number of jobs created in these sectors up to 2050 with over a million jobs. Furthermore, manufacturing includes both for local use as well as for exports to other regions as indicated by Table A3 in the Appendix. The share of exports initially rise up to 2030 with over 4% of total jobs, beyond which it declines and manufacturing is predominantly to cater to the local power market across Europe. Fuel jobs continue to decline through the transition period reaching just 6% of total jobs by 2050, as capacities of conventional power plants continue to decline. To the contrary, operation and maintenance jobs continue to grow through the transition period and become the major job segment by 2050 with 61% of total jobs. As operation and maintenance jobs last through the lifetime of power plants, they offer relatively stable long-term job prospects. This has the potential to create a positive effect in many countries across Europe that suffer from high levels of unemployment, especially amongst the youth. In January 2018, 3.65 million young people (under 25) were unemployed across the European Union (EU) (Eurostat, 2017). The electricity demand specific jobs, which indicates total number of jobs created annually for every TWh_{el} of annual electricity generation during the energy transition. As indicated in Figure 3, the specific jobs were at 516 jobs/TWh_{el} in 2015, increasing to 859 jobs/TWh_{el} in 2025 with the rapid ramp up in renewable energy installations. Beyond 2025, it declines steadily to 638 jobs/TWh_{el} by 2050.

4.2 Eurasia

Eurasia comprises countries that are amongst the emerging economies of the world, with around a 6% share of global GDP (IMF, 2017). This implies a rapidly growing appetite for energy, with total electricity consumption of around 1080 TWh in 2015 that is estimated to grow to 1630 TWh by 2050 (IEA, 2016). Hydropower has been the prominent resource in the region with around 50 GW of installed capacity in Russia. In recent years, renewables have been making inroads into power systems across the region and are expected to develop rapidly with the widespread presence of excellent resources (UNECE & REN21, 2017).

The total direct energy jobs in this region are set to increase with the initial ramp up of installations from about 566 thousand in 2015 to around 871 thousand by 2025, after a decline in 2030, it is observed to steadily rise to around 925 thousand by 2050. With great potential for wind power, bulk of the jobs from 2020 to 2030 are observed to be associated with wind power development creating around 353 thousand jobs in 2025. As solar PV delivers the least cost energy from 2030 onwards (Breyer et al., 2017; Ram et al., 2017a), along with driving up installed capacities, it emerges as the prime job creator in the region up to 2050 with about 411 thousand jobs, as shown in Figure 4. The hydropower sector with 130 thousand jobs by 2050 is seen to provide stable number of jobs through the transition period, along with some jobs from geothermal and bioenergy sectors (combined 75 thousand jobs by 2050). Jobs associated with the storage sector begin to develop from 2040 onwards, but remain relatively lower than other regions with just about 58 thousand jobs by 2050, as hydropower in combination with robust transmission networks play a prominent role in reducing the need for storage.

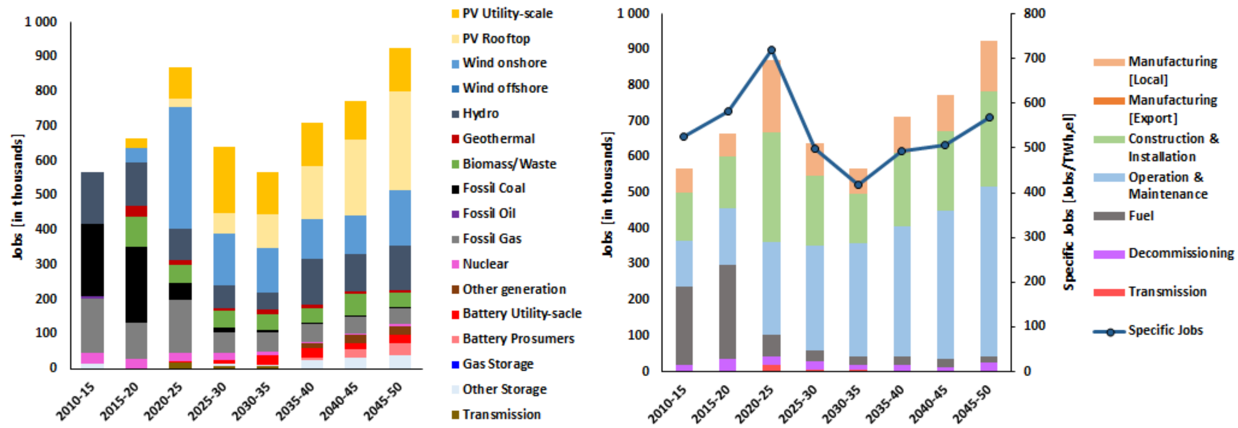

Figure 4: Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in Eurasia.

The category-wise distribution of jobs for Eurasia during the transition period is as depicted in Figure 4. Local manufacturing, construction and installation of renewable energy technologies create a significant share of jobs enabling the rapid build-up of capacities in the period 2020-2025 (508 thousand jobs), this is also due to the fact that most conventional power plants in this region are quite old and nearing their end of lifetimes that have to be replaced (Farfan and Breyer, 2017). This could serve as a co-benefit of the energy transition for countries across Eurasia. Beyond 2030, there are stable number of jobs created in these sectors up to 2050 with around 407 thousand jobs. Fuel jobs after an initial increase in 2020 (40% of total jobs),decline through the transition period as capacities of conventional power plants are replaced by renewables until 2030 and further decline up to 2050 reaching just about 2% of total jobs. On the contrary, operation and maintenance jobs continue to grow through the transition period and become the major job creating segment by 2050, with 51% of total jobs. As operation and maintenance jobs last through the lifetime of power plants, they offer relatively stable long-term job prospects. As indicated in Figure 4, the electricity demand specific jobs was at 516 jobs/TWh$_{el}$ in 2015 and increases to 859 jobs/TWh$_{el}$ in 2025 with the rapid ramp up in renewable energy installations. Beyond 2025, it declines steadily to 638 jobs/TWh$_{el}$ by 2050.

4.3 MENA

MENA is comprised of countries that are emerging economies as well as developed, with around 7% share in global GDP (IMF, 2017). This region is amongst the largest energy producers in the world, with an increasingly high share of demand (Aghahosseini et al., 2016). The total electricity consumption was around 1360 TWh in 2015, which is estimated to rise to 3320 TWh by 2050 (IEA, 2016). This region has immense solar resources, which can be harnessed to meet this growing demand.

With record low auctions for solar power across the MENA region, solar PV has emerged as the most attractive source of electricity generation (Dipaola, 2017). Both utility-scale and rooftop PV are seen to develop through the transition period to be the dominant source for power generation by 2050 (MEED, 2017; Ram et al., 2017a). Similarly, solar PV is the prime job creator through the transition period with almost a million jobs by 2050, as indicated in Figure 5. Wind power generation creates a fair share of jobs during the period of 2020 to 2030 (260 thousand jobs in 2030), beyond which the shares are reduced, as PV becomes more cost competitive. Storage technologies in the form of batteries take off from 2030 onwards and lead to a decent share of jobs created up to 2050 (193 thousand jobs in the battery sector). The total number of direct energy jobs across the MENA region are observed to increase from just around 590 thousand in 2015 to nearly 1.7 million by 2050.

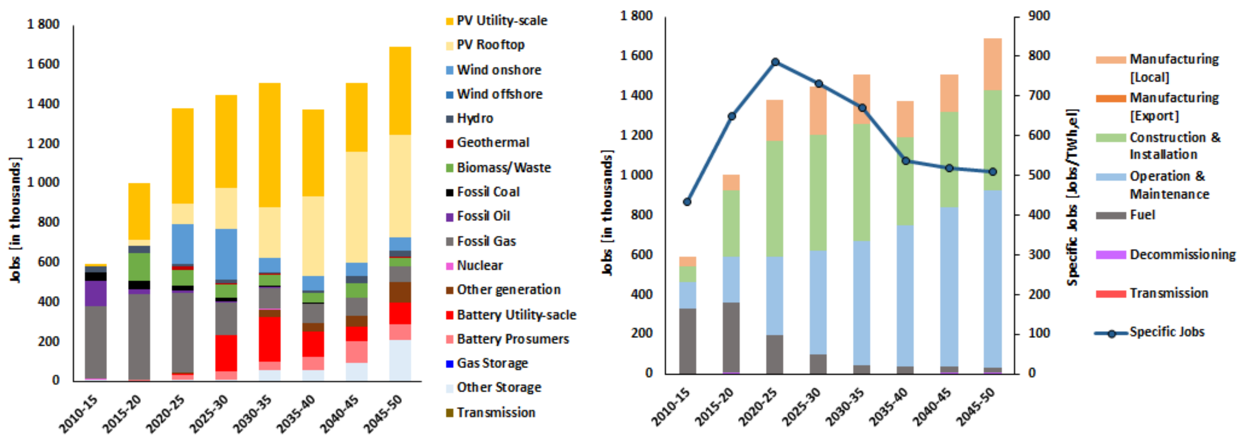

Figure 5: Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in the MENA region.

Figure 5, also indicates the distribution of jobs across the different categories during the transition period in the MENA region. With rapid installation of capacities up to 2035, bulk of the jobs are created in the construction and installation of power generation technologies. Manufacturing jobs have a relatively lower share in the initial periods up to 2020 as the share of imports is high. From 2025onwards, as domestic production capabilities build up, a higher share of manufacturing jobs are observed until 2050 with 15% of total jobs. The share of fuel related jobs continues to diminish from 2020 onwards through the transition period reaching just 1% of total jobs by 2050, as conventional power plants are replaced by renewable and storage technologies. Whereas, the share of operation and maintenance jobs grows through the transition period up to 53% of total jobs by 2050. This means more stable jobs for a region suffering from high unemployment amongst the youth and a growing number of economic migrants. A higher share of investments in developing sustainable power infrastructure could be the right catalyst to create long-term jobs in this region (Ianchovichina et al., 2013). The electricity demand specific jobs increases from 435 jobs/TWh_{el} in 2015 to 788 jobs/TWh_{el} in 2025 with the rapid ramp up in renewable energy installations. Beyond 2025, it declines steadily to around 509 jobs/TWh_{el} by 2050, as shown in Figure 5.

4.4 Sub-Saharan Africa

Sub-Saharan Africa is a region with a large number of emerging economies, with just around a 3% share in global GDP (IMF, 2017), but is poised to be one of the fastest growing regions in the world. With rapidly growing population, unprecedented economic progress and need for reliable, modern energy access, the total electricity consumption that is around 484 TWh in 2015, is estimated to rise to 2747 TWh by 2050 (IEA, 2016). The renewable energy sector is growing in Sub-Saharan Africa, with 14 countries having set themselves targets and doubling investments to above 5 billion USD, between 2014 and 2015 (BNEF, 2017).

Countries such as South Africa, Kenya, Ethiopia and Rwanda have accelerated their renewable energy adoption and are leading the energy transition across Sub-Saharan Africa (BonelliErede, 2017). As this trend is observed to pick up across the region during the transition period with solar PV emerging as the dominant source of power generation by 2050 (Barasa et al., 2018; Ram et al., 2017a). Likewise, solar PV is observed to be the prime job creator through the transition period, with 65% of the total jobs created by

2050, as depicted in Figure 6. A fair share of jobs are created by wind power (283 thousand jobs in 2025) and bioenergy (377 thousand jobs in 2025) initially, which tend to stabilise later on, as solar PV is far more cost competitive beyond 2030. Jobs created by storage technologies mainly driven by batteries, increase in share beyond 2030 and continue to grow up to 2050 (862 thousand jobs in the battery sector). While, jobs associated with fossil fuels, mainly coal and gas power generation, rapidly diminish across the region. Overall, the number of direct energy jobs are seen to grow massively from just under 1.2 million in 2015 to nearly 5.5 million by 2050.

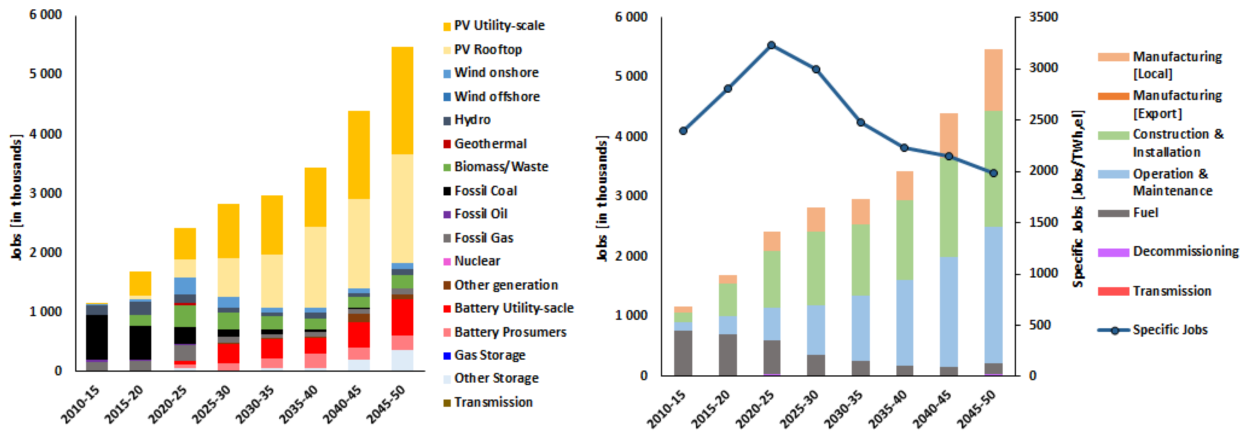

Figure 6: Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in Sub-Saharan Africa.

Figure 6, also indicates the distribution of jobs across the different categories during the transition period across Sub-Saharan Africa. With ramp up of installations up to 2035, bulk of the jobs are created in the construction and installation of power generation technologies. Manufacturing jobs have a relatively lower share in the initial periods up to 2020, as the share of imports is high. From 2025 onwards, as domestic production capabilities build up, a higher share of manufacturing jobs are observed until 2050 with 19% of total jobs. The share of fuel related jobs continues to diminish through the transition period from 63% of total jobs in 2015 to just 3% of total jobs by 2050, as conventional power plants are replaced by renewable and storage technologies. Whereas, the share of operation and maintenance jobs grow through the transition period reaching 42% of total jobs by 2050. This could be the boost required for employment prospects in Sub-Saharan Africa, which are presently stagnating due to low productivity attributed to the region's lack of economic diversification (Brookings, 2017). The electricity demand specific jobs increase from 2399 $jobs/TWh_{el}$ in 2015 to 3235 $jobs/TWh_{el}$ in 2025 with the rapid ramp up in renewable energy installations. Beyond 2025, it declines steadily to around 1990 $jobs/TWh_{el}$ by 2050, as shown in Figure 6. The electricity demand specific jobs are the highest in comparison to all other regions across the world as Sub-Saharan Africa continues to have a high labour intensity through the transition period (the labour intensity factors can be referred to in the Supplementary Material).

4.5 SAARC

SAARC consists of some of the most fast-paced growing economies, with around 9% share of global GDP and 21% of the global population (IMF, 2017). With rapidly growing population, unprecedented economic progress and need for reliable modern energy services, the total electricity consumption that is around 1694 TWh in 2015, is estimated to rise to 6979 TWh by 2050 (IEA, 2016; Gulagi et al., 2018). The region lead by India with around 50 GW of solar and wind power capacity has recently witnessed an increasing shift towards renewable energy (Buckley and Shah, 2018). Driven by policy initiatives and the tremendous drop in costs have made wind and solar PV the most attractive propositions for power generation.

In the last 2 quarters of 2017, only renewable energy capacities were added in the Indian power sector (Saurabh, 2018) and Sri Lanka has already made plans to generate 100% of their power from renewable energy sources (ADB & UNDP, 2017). This trend is set to continue with solar PV complemented by batteries to dominate the power share by 2050. Similarly, solar PV (4.18 million jobs) and battery storage (894 thousand jobs) sectors emerge as the major job creators across the region by 2050 as shown in Figure 7. Wind power (504 thousand in 2030), hydropower (297 thousand jobs in 2020) and bioenergy (523 thousand jobs in 2025) create a fair share of the jobs in the initial periods of the transition. Beyond 2030, the shares decrease and stabilise until 2050. The storage sector led by batteries create a fair share of the jobs in 2030 with 23% of total jobs and continue to contribute until 2050 with a steady share. Whereas, the jobs associated primarily with coal and gas power generation diminish rapidly. The total number of direct energy jobs increase rapidly from over 4.2 million in 2015 to just over 7 million by 2030, thereafter stabilising around 5.8 million by 2050. This drop is primarily due to the rapid ramping up of power capacity installations to ensure energy access for the vast number of un-electrified people in this region up to 2030. Beyond that, capacity addition would be at a slower rate to fulfil economic development.

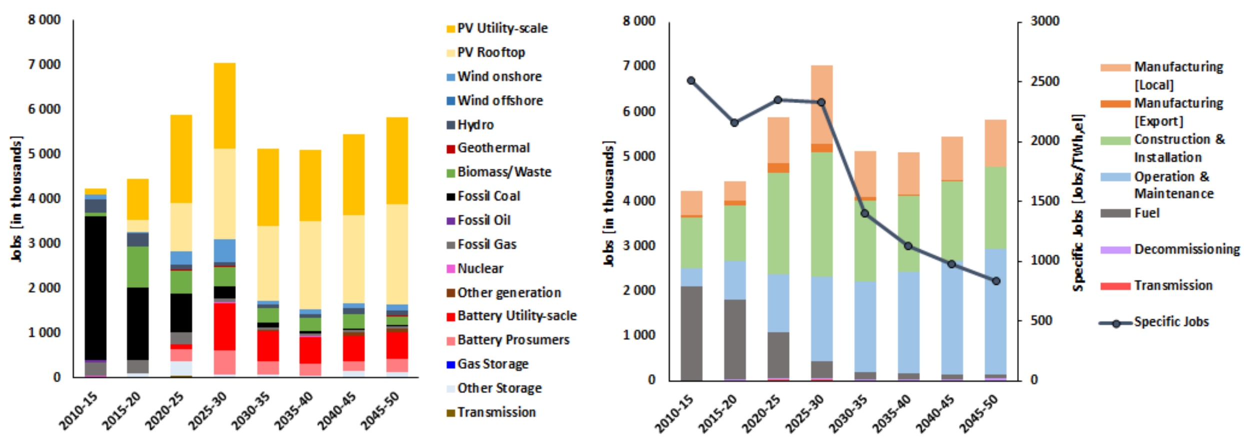

Figure 7: Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in the SAARC region.

The category-wise distribution of jobs created in the SAARC region through the transition period is shown in Figure 7. With a rapid ramp up of installations up to 2030, bulk of the jobs are created in the construction and installation of power generation technologies with 40% of total jobs in 2030. While, manufacturing jobs increase in share during 2020 to 2030, with some shares of exports (domestic manufacturing creates 25% and exports creates 2% of total jobs in 2030). The SAARC region is an importer as well as an exporter of power generation technologies (the shares of import and export can be referred to Table A3 in the Appendix). Beyond 2030, as production capabilities in other importing regions build up, a relatively lower share of manufacturing jobs are observed until 2050 (around 18% of total jobs). The share of fuel related jobs continues to diminish through the transition period, as conventional power plants are replaced by renewable and storage technologies (from 49% of total jobs in 2015 to just 1% of total jobs by 2050). Whereas, the share of operation and maintenance jobs continues to grow through the transition period with 48% of total jobs by 2050. The electricity demand specific jobs decrease steadily from 2508 jobs/TWh$_{el}$ in 2015 to 2335 jobs/TWh$_{el}$ in 2030 with the rapid ramp up in renewable energy installations. Beyond 2030, it declines rapidly to around 834 jobs/TWh$_{el}$ by 2050, as shown in Figure 7. The electricity demand specific jobs have a rapid decline as most countries of SAARC have rapidly growing economies, which are expected to witness better economic conditions beyond 2030. Further improving up to 2050, resulting in a declining labour intensity through the transition period (the labour intensity factors can be referred to in the Supplementary Material).

4.6 Northeast Asia

The Northeast Asian region is comprised of the fastest growing economies, with around a 25% share of the global GDP and 22% of the global population (Haysom et al., 2015). With rapid industrialisation, unprecedented economic progress and a soaring appetite for energy, the total electricity consumption that is around 6847 TWh in 2015, is estimated to soar up to 15,078 TWh by 2050 (IEA, 2016; Bogdanov and Breyer, 2016). Renewable energy is high on the agenda for countries across Northeast Asia, with excellent wind and solar resources particularly in Mongolia (Breyer et al., 2015).

China has been leading not only in the region, but also globally with a cumulative solar PV capacity of around 130 GW and 163 GW of wind by the end of 2017 (Frankfurt School - UNEP & BNEF, 2018). Additionally, Japan and South Korea have developed plans to increase the share of renewables in their respective power mixes (BNEF, 2017). Renewable energy capacities are observed to increase rapidly in the next couple of decades across the region (Ram et al., 2017a). Likewise, jobs are created from mainly wind (2 million jobs in 2025) and solar PV (3.5 million jobs in 2025) in the early stages of the transition. From 2030 onwards, solar PV is observed to be the main source of power generation and correspondingly creating the most number of jobs (6.7 million jobs by 2050) as indicated in Figure 8. Storage technologies led by batteries are observed to create a fair share of jobs from 2030 onwards and continue unto 2050 with 1.3 million jobs in the battery sector. Whereas, jobs associated with the coal sector are seen to decrease rapidly. The total direct jobs are seen to increase from around 8 million in 2015 to 9.5 million by 2030 and after a decline, number of jobs rises back to around 10 million by 2050. Primarily with the replacements of power plants beginning to increase in the period from 2045 to 2050.

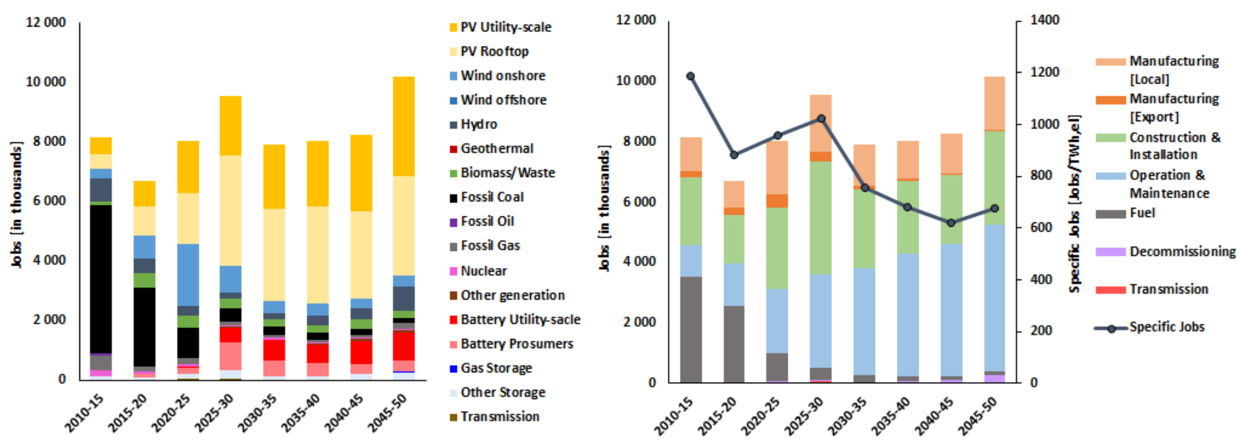

Figure 8: Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in Northeast Asia.

The distribution of jobs according to the different categories during the transition period across Northeast Asia is shown in Figure 8. With a ramp up of installations until 2030, bulk of the jobs are created in the construction and installation of power generation technologies (39% of total jobs in 2030). Manufacturing jobs have a higher share in the initial periods up to 2030, beyond which the shares stabilise up to 2050. The Northeast Asian region contributes a major share of the global exports to all other regions (refer to Table

A3 in the Appendix). However, the share of jobs created by exports reduce beyond 2030, as other regions are expected to increase their domestic production capabilities (exports creating just 36 thousand jobs by 2050). The share of fuel related jobs continue to diminish through the transition period from 43% of total jobs in 2015 to just 1% of total jobs by 2050, as conventional power plants are replaced by renewable and storage technologies. Whereas, the share of operation and maintenance jobs grows through the transition period from 13% of total jobs in 2015 to 48% of total jobs in 2050. Additionally, decommissioning jobs that include replacement of end of life power plants begin to create some jobs by 2050 (293 thousand jobs). The electricity demand specific jobs is reduced from 1187 jobs/TWh_{el} in 2015 to 675 jobs/TWh_{el} by 2050, as shown in Figure 8. This is primarily due to the rising economic growth of the region forecasted for the future, resulting in much lower labour intensity by 2050.

4.7 Southeast Asia

The Southeast Asian region including Australia, New Zealand and the Pacific Islands is comprised of rapidly growing economies, with around 7% share of global GDP (IMF, 2017). With rapid economic growth in most of these countries, the need for energy is ever increasing and some of the more developed countries have a high rate of consumption to sustain. In this context, the total electricity consumption that is around 1208 TWh in 2015, is estimated to soar up to 4222 TWh by 2050 (IEA, 2016; Gulagi et al., 2017). Renewables have grown rapidly as a power source across Southeast Asia, with their installed capacity at around 15 GW in 2016 (IRENA, 2018).

By the end of 2017, cumulative installed capacity for solar PV in Australia was around 6.4 GW with close to 1.8 million rooftop installations (AEC, 2018).Whereas, New Zealand aims to produce 90% of their electricity from renewable sources by 2025 (Electricity Authority, 2016; Ford et al., 2017). With the trend across the region indicating a shift towards renewable energy, it can be observed that solar PV along with battery storage emerge as the primary power source by 2050 (Gulagi et al., 2017; Ram et al., 2017a). Likewise, solar PV and battery storage sectors create the major share of jobs through the transition period as shown in Figure 9. Biomass and hydropower create a higher share in the initial periods up to 2025, but continue to create some jobs through the transition period. Wind power sector creates some jobs during 2020 to 2030 (96 thousand jobs in 2025), beyond which fewer jobs are created as solar PV becomes more cost effective and installations increase in share with 2.1 million jobs by 2050. The storage sector led by batteries create a fair share of the jobs from 2030 onwards and continues through to 2050 with 414 thousand jobs in the battery sector by 2050. This could happen lot earlier as countries such as Australia are already witnessing both utility-scale as well as prosumer scale battery installations (AEC, 2018). Jobs associated with coal and gas power generation are seen to decline rapidly. The total number of direct energy jobs increases significantly from around 1.2 million in 2015 to over 3.3 million in 2030, beyond which there is a decline to under 2.5 million by 2040, after which there is a steady increase up to around 3.2 million by 2050.

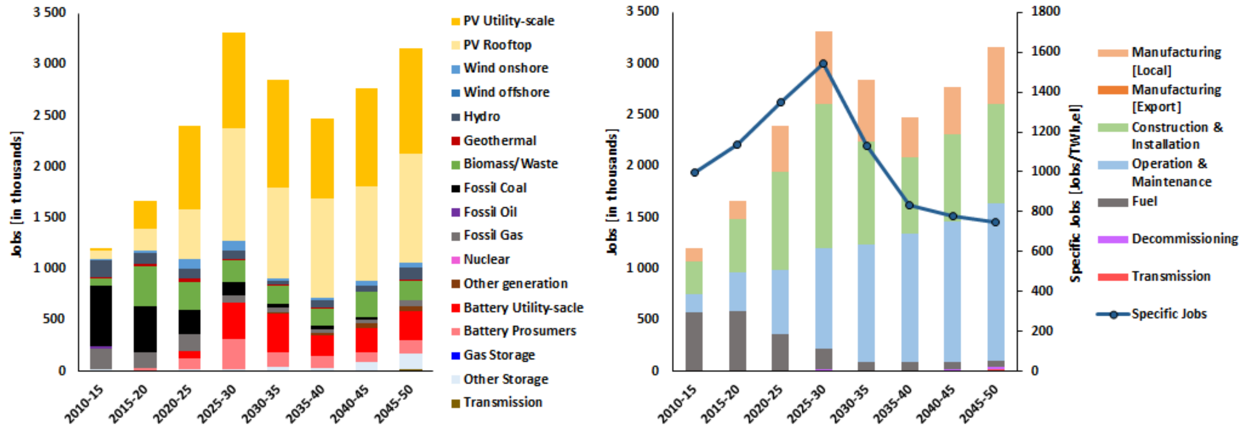

Figure 9: Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in Southeast Asia.

A category-wise distribution of jobs in the region through the transition period is shown in Figure 9. With rapid installation of capacities up to 2030, bulk of the jobs are created in the construction and installation of power generation technologies with 42% of total jobs by 2030. Manufacturing jobs have a relatively lower share in the initial periods up to 2020 as the share of imports is relatively high. Beyond 2025 as domestic production capabilities build up, a high share of manufacturing jobs are observed until 2050 (from 21% of total jobs in 2035 to 17% of total jobs by 2050). The share of fuel related jobs continues to diminish from 2020 onwards through the transition period reaching just 2% of total jobs by 2050, as conventional power plants are replaced by renewable and storage technologies. Whereas, the share of operation and maintenance jobs continues to grow through the transition period with 49% of total jobs by 2050. The electricity demand specific jobs increases from 997 jobs/TWh$_{el}$ in 2015 to 1541 jobs/TWh$_{el}$ in 2030 with the rapid ramp up in renewable energy installations. Beyond 2030, it declines steadily to around 748 jobs/TWh$_{el}$ by 2050, as highlighted in Figure 9.

4.8 North America

North America is comprised of the major economic centres of the world, the USA, Canada and a rapidly emerging economy in Mexico, with a 19% share of global GDP (IMF, 2017), and is one of the largest energy consumption centres across the world, with total electricity consumption of around 5284 TWh in 2015. This is estimated to rise to 7069 TWh by 2050, mainly driven by the rapid growth of Mexico as well as stable electricity demands from the USA and Canada (IEA, 2016; Aghahosseini et al., 2017). Renewable energy has been on the rise in the recent years across all the 3 countries. By the end of 2017, the USA had installed capacities of 91 GW of wind and 52 GW of solar in its power mix. There has been a steady rise in the share of renewable power generation in Canada and the latest power generation auctions in Mexico yielded some of the lowest bids, with an average in the range of 17 – 18 €/MWh (Bellini, 2017; Rabson, 2017).

Mexico has set a target of at least 35% of total electricity generation by 2024 to be from renewable energy sources (REN21, 2017). The trend is set to continue in the USA and Canada too, and a combination of wind, solar PV, hydropower and battery storage are seen as the most economical power generation sources by 2050 (Ram et al., 2017a). Similarly, solar PV (1.62 million jobs in 2025) along with wind (762 thousand jobs in 2025) emerge to be the dominant job creating sectors during the transition period as shown in Figure 10. Additionally, hydropower (180 thousand jobs by 2050) and bioenergy (180 thousand jobs by 2050) create a stable share of jobs through the transition period. Storage led by batteries begin to create jobs from 2025 onwards with a stable share until 2050 with 330 thousand jobs in the battery sector. Whereas, coal and gas power generation associated jobs are seen to decline rapidly. Overall, jobs are set to increase from around 1.8 million in 2015 to nearly 3.8 million, with the rapid ramp up in installations up to 2025 and then a steady decline towards nearly 2.7 million by 2050.

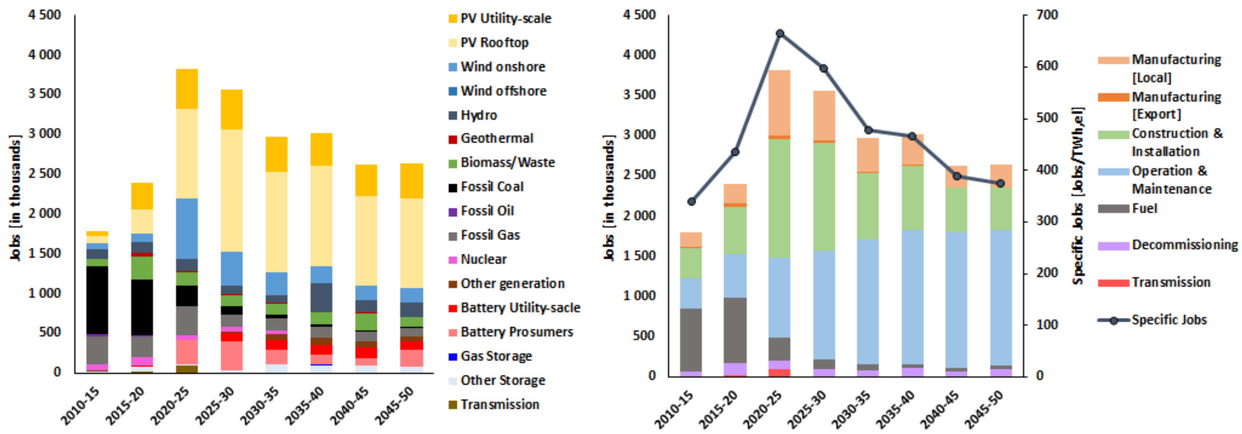

Figure 10: Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in North America.

The category-wise distribution of jobs in North America during the transition period is shown in Figure 10. Manufacturing, construction and installation of renewable energy technologies create a significant share of jobs enabling the rapid ramp up of capacity until 2030, beyond this period there are stable number of jobs created in these sectors up to 2050. Furthermore, manufacturing includes both for local use as well as for exports to the other regions as indicated by Table A3 in the Appendix. The share of manufacturing jobs along with a marginal share of exports initially rise up to 2025 (21% and 1% of total jobs respectively), beyond which they decline. As manufacturing is predominantly to cater to the local power markets across North America with domestic manufacturing having a share of 11% of total jobs by 2050 and only 4 thousand jobs for exports. Fuel jobs continue to decline through the transition period reaching just 2% of total jobs by 2050, as capacities of conventional power plants continue to decline. On the contrary, operation and maintenance jobs continue to grow through the transition period and become the major job creating segment by 2050 with 64% of total jobs. As operation and maintenance jobs last through the lifetime of power plants, they offer relatively stable long-term job prospects. This has the potential to create a positive effect in many parts of the USA that suffer from persistent unemployment (U.S. Bureau of Labor Statistics, 2018). The electricity demand specific jobs initially increase from 339 jobs/TWh$_{el}$ in 2015 to 666 jobs/TWh$_{el}$ in 2025 with the rapid ramp up in renewable energy installations. Beyond 2025, it declines steadily to 374 jobs/TWh$_{el}$ by 2050 as highlighted in Figure 10.

4.9 South America

The South American region including Central American countries is comprised of growing economies, with around a 6% share of global GDP (IMF, 2017). With steadily increasing economic growth in most of the countries, the need for energy is rising. The total electricity consumption that is around 1180 TWh in 2015, is estimated to rise up to 2420 TWh by 2050 (IEA, 2016; Barbosa et al., 2017). A distinctive feature of South America's power generation mix is the predominance of hydropower and bioenergy, due largely to the high shares in Brazil, which generates about 40% of the total regional electricity (IRENA, 2016).

In recent years, South America has witnessed an impressive growth in renewable power generation, whose installed capacities have more than tripled between 2006 and 2015, from 10 GW to 36 GW (IRENA, 2016; REN21, 2017). While in absolute terms most of that growth has been in bioenergy and onshore wind primarily in Brazil, solar PV has also grown significantly in Chile, Peru and Uruguay (BNEF, 2017). This trend is seen to rapidly increase in the near future and continue through the transition period, with solar PV complemented by hydropower, wind and biomass emerging as the main sources of power generation by 2050 (Barbosa et al., 2017; Ram et al., 2017a). Likewise, jobs are predominantly created in the bioenergy (827 thousand jobs by 2020) and hydropower (357 thousand jobs by 2025) sectors during the initial periods of the transition up to 2030 as shown in Figure 11. Beyond which, solar PV (930 thousand jobs by 2050) along with battery storage (202 thousand jobs by 2050) emerge as the major job creators. Storage led by batteries create jobs from 2025 onwards and maintain a stable share (9% of total jobs in 2025) through the transition period until 2050 (12% of total jobs). Whereas, coal, gas and oil power generation associated jobs decline rapidly, almost disappearing by 2025. With the brisk build up in installations, the total number of direct energy jobs rise from just under 1 million to nearly 2.2 million by 2025 and a steady decline thereafter towards 1.6 million by 2050.

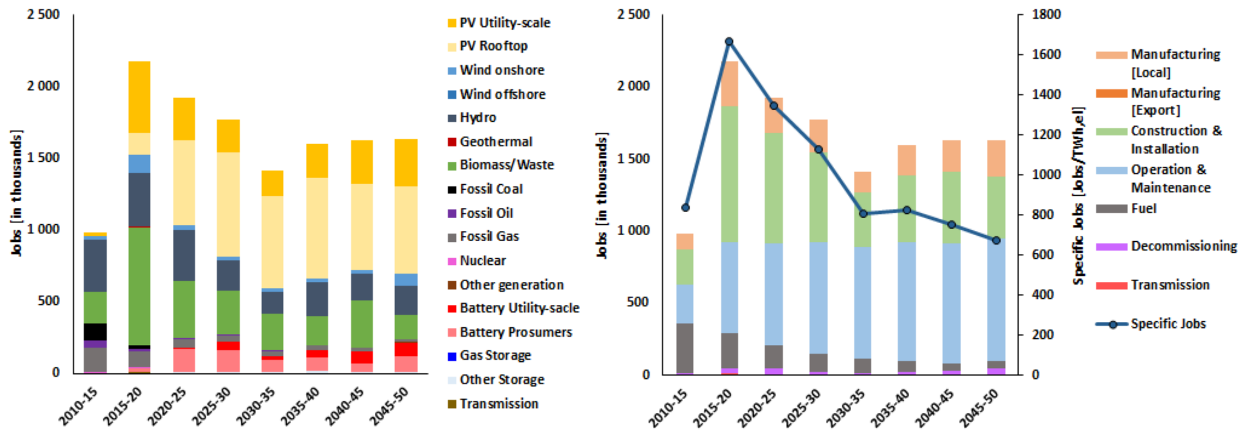

Figure 11: Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in South America.

A category-wise distribution of jobs in South America through the transition period is shown in Figure 11. With rapid installation of power generation capacities in the initial period of 2020 to 2030, bulk of the jobs are created in the construction and installation of power generation technologies with 40% of total jobs by 2025. Manufacturing jobs have a relatively lower share in the initial periods with a high share of imports. Beyond 2030, the share of manufacturing jobs are observed to stabilise until 2050 (16% of total jobs), with increase in domestic production capabilities. The share of fuel related jobs continues to diminish through the transition period reaching just 3% of total jobs by 2050, as conventional power plants are replaced by renewable and storage technologies. Whereas, the share of operation and maintenance jobs grows through the transition period with 52% of total jobs by 2050. A small share of decommissioning jobs with around 3% of total jobs by 2050, are created through the transition period with the continuous replacement of power plants at the end of their lifetimes. The electricity demand specific jobs rapidly increases from 835 jobs/TWh_{el} in 2015 to 1669 jobs/TWh_{el} in 2020 with the rapid ramp up in renewable energy installations. Beyond 2020, it declines steadily to around 674 jobs/TWh_{el} by 2050, as highlighted in Figure 11.

4.10 Global

With the rapid ramp up of installed capacities, a growing share of renewable power generation technologies are observed to compensate for the phasing out of nuclear power production as well as for the continually reducing number of fossil fuel power plants globally (Breyer et al., 2017b; Ram et al., 2017a). This strong growth in the renewable energy sector leads to an increase of around 70% more direct power sector jobs by 2030, and the overall jobs created are 1.5 times as high in 2050, compared to 2015. Jobs created continue to rise to reach around 34 million direct energy jobs by 2030. Beyond this point, they decline to around the 30 million range and then steadily increase to nearly 35 million by 2050 as shown in Figure 12. This is mainly due to large capacities being replaced and reinvested in, as they would reach end of their lifetimes with decommissioning contributing around 2% of total jobs by 2050. Solar PV (22.2 million jobs by 2050), batteries (4.5 million jobs by 2050) and wind energy (1.4 million jobs by 2050) are the major job creating technologies during the entire transition period from 2015 to 2050. In the case of wind energy, around 7.3 million jobs are created in the period from 2020 to 2030, beyond that, as solar PV becomes more cost effective they drive majority of the installations until 2050 and jobs in the wind sector are stabilised. While, hydropower (1.9 million jobs by 2050) and bioenergy (2.3 million jobs by 2050) create a stable share of jobs through the transition period. Solar PV is observed to replace coal as the major job creating energy resource, with around 64% of total jobs by 2050, as compared to just 10% of total jobs in 2015. Additionally, it is well complemented by battery storage creating around 13% of total jobs by 2050. Whereas, jobs in the coal, gas and nuclear power sectors are observed to decline rapidly as shown in Figure 12.

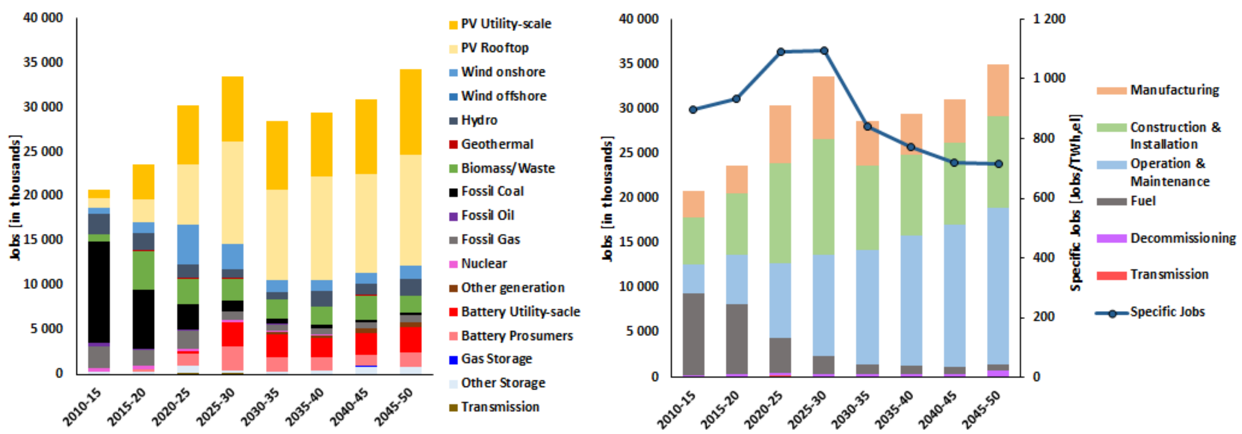

Figure 12: Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 globally.

A category-wise classification of jobs in manufacturing, construction and installation, operation and maintenance, fuel supply, decommissioning and transmission created during the energy transition from 2015 to 2050 is shown in Figure 12. Fuel sector jobs are set to decline from 44% of the total jobs in 2015 to just around 2% of the total jobs by 2050, as fossil fuels and nuclear power capacities decline. On the other hand, it can be observed that operation and maintenance jobs have the most significant increase in the share of the total jobs created from 15% in 2015 to 50% by 2050. This indicates that the transition towards a 100% renewable power system enables creation of more stable jobs, which can contribute to stable economic growth of countries mainly in the developing regions of the world and provide a means of tackling youth unemployment (Ali, 2014). In many parts of the world, this could be a catalyst to improve social wellbeing as well as political stability (Kollewe, 2010). Furthermore, Figure 12 also illustrates the development of the electricity demand specific jobs, which remain quite stable through the transition period.

With 897 jobs/TWh_{el} in 2015 and rising up to 1091 jobs/TWh_{el} in 2030 due to a large share of investments during this period, beyond 2030 it declines steadily to around 715 jobs/TWh_{el} in 2050.

5. Discussion

With respect to labour markets across the world, many regions are facing stagnating economies accompanied by high and rising unemployment rates, particularly amongst the youth. Unemployment rates of youngsters in Europe reached 23.5% in the first quarter of 2013, more than twice the rate for the overall population and in some countries, more than half of young people under the age of 25 are unemployed (EC, 2013). Likewise, global unemployment levels and rates have been high in the last few years and are expected to remain high in the range of 5.8% bringing total unemployment to over 200 million in 2017 (ILO, 2017). Moreover, vulnerable forms of employment (those that lack access to contributory social protection schemes) are expected to remain above 42% of the total employment in 2017, accounting for around 1.4 billion people worldwide (ILO, 2017). At the same time, the risk of social unrest or discontent has heightened across many regions of the world. 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 between 2015 and 2016 (ILO, 2017; Kollewe, 2010). Therefore, the creation of employment opportunities is a major policy priority, especially for countries with high levels of unemployment and underemployment, be it a long-term issue or the immediate consequence of an economic recession. In this context, the renewable energy sector has weathered the latest financial and economic crisis successfully, as compared to many other industries (IRENA, 2013). 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 (Behrens et al., 2014; Greenpeace International, 2015; Jacobson et al., 2017).

The global employment creation in the power sector with increased shares of renewable power generation capacity will have a net positive effect, which is the number of jobs created by installing new capacities of renewable energy are significantly higher than the number of jobs associated with fossil and nuclear power generation. As shown by results from the previous section as well as other studies IRENA (2013), Behrens et al. (2014), Greenpeace International (2015), EPFL (2018) and Jacobson et al. (2017). This research estimates the total direct energy jobs to reach 34 million by 2050 for the global power sector only. In comparison to 52 million new ongoing jobs (net of 24.3 million after considering job losses) form wind energy, hydropower and solar energy (WWS) generators with transmission for the entire energy sector (power, heat and transportation), as estimated by Jacobson et al. (2017). In comparison to Greenpeace International (2015), which estimates energy jobs to reach 46.1 million by 2030, the results of this reserch show total direct energy jobs at around 34 million by 2030. Additionally, Greenpeace International (2015) estimate solar PV to contribute around 9.7 million jobs by 2030, while this research estimates total solar PV jobs at around 18.7 million by 2030, mainly due to higher installed solar PV capacity in this research resulting from a cost optimised energy mix. The methods of this research were adopted for the case of South Africa, which is further highlighted in Oyewo et al. (2019) and the results were compared with Wright et al. (2017) that adopt a different model for job estimation. Wherein, the decarbonised scenario and the least cost scenario with ‘expected costs’ are estimated to create 331 thousand jobs and around 380-392 thousand jobs by 2050, respectively (Wright et al., 2017). The results of Oyewo et al. (2019) indicate a comparable share during the transition ranging from 408 thousand jobs in 2035 to 278 thousand jobs by 2050. Nevertheless, both the results from Wright et al. (2017), as well as Oyewo et al. (2019) indicate a difference of 100 thousand jobs or more between the conservative Current Policy Scenario (CPS) and the more progressive Best Policy Scenario.

Most renewable energy and storage technologies are still in their initial phases of development and are expected to grow rapidly, in proportion to their current lower levels of installations. From the point of view of regional and national labour markets, the pattern varies across different renewable power generation and storage technologies. As there is limited activity in some of the countries, rapid growth in others, steady growth in some of the others, and a relatively mature industry elsewhere (IRENA, 2013). In this research, as part of the BPS with an optimistic outlook all major regions worldwide are expected to reach 100% local manufacturing capabilities by 2050. However, a conservation approach in which manufacturing shares and export-import shares are expected to remain as in 2015 through the transition period until 2050 were estimated. The major beneficial regions were China (with additional 523 thousand jobs) and Europe (204 thousand additional jobs) and to a lesser extent North America (46 thousand additional jobs). Whereas, rest of the regions lose jobs and Sub-Saharan Africa is impacted the most with a loss of 603 thousand jobs by 2050. Globally, 334 thousand jobs are reduced by 2050 as compared to the optimistic scenario with self-sustaining local manufacturing across the major regions. In general, it can be noticed that despite having higher shares of imports for some regions, the total number of jobs created will still be higher as renewables will create more localised O&M jobs as indicated earlier. Indeed, employment benefits of renewable energy could go to countries that start early and build strong export markets. 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 (PwC, 2017; UNIDO, 2013). This regional and technological variation in global job creation through the energy transition period is captured in Figure 13.

The regional distribution of jobs created in the 9 major regions through the transition period is shown in Figure 13. The share of jobs in Europe remains quite stable in the range of 10% to 13% through the transition period. Similarly, the share of jobs in Eurasia remains stable ranging from 2% to 3% of the global jobs created through the transition. In case of the MENA region, the share of jobs increases from 3% in 2015 to 5% in 2035 and thereafter remain stable until 2050. A steady increase in the share of jobs from 6% in 2015 to 16% by 2050 is observed in the region of Sub-Saharan Africa, through the transition period. On the contrary, the share of jobs in the SAARC region decreases slightly from about 20% in 2015 to 17% in 2050. Whereas, a significant decrease in the share of jobs, from 39% in 2015 to 29% by 2050 is observed in Northeast Asia. Both the SAARC and Northeast Asian regions have high economic growth rates currently, which are expected to drop to lower levels and flatten out over the long-term as higher levels of development are accomplished. In Southeast Asia and the Pacific Rim, the share of jobs created are observed to increase initially from 6% in 2015 to 10% in 2030, and thereafter a marginal decline to 9% in 2050. An initial increase in the share of jobs from 9% in 2015 to 13% in 2025 is observed for North America, beyond which the share decreases to 8% by 2050. Likewise, an initial increase from 5% in 2015 to 9% in 2020 is seen for South America, further declining to 5% by 2050 thereafter. The primary reason for the initial rise in the share of jobs during the initial periods of the transition across these regions is the massive capacity additions that are expected in this period.

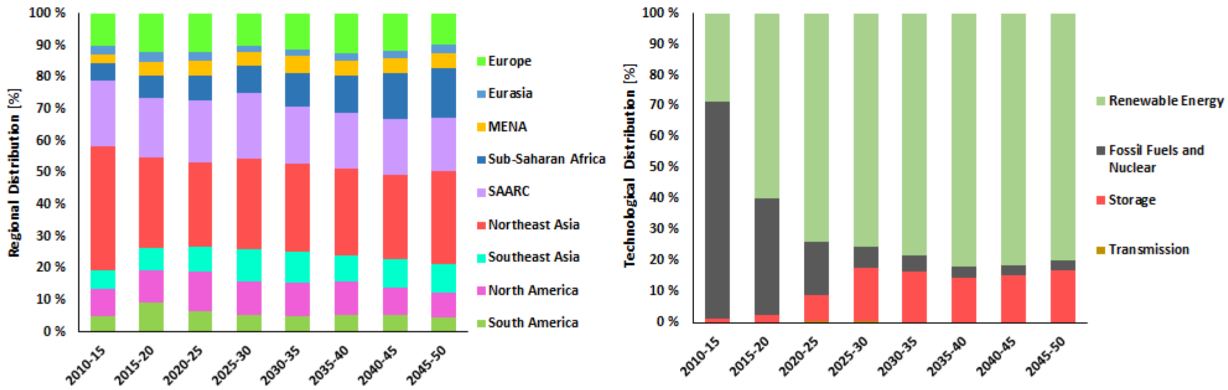

Figure 13: Regional distribution of jobs created (left) and technological distribution of jobs created (right) during the energy transition from 2015 to 2050 globally.

The share of fossil fuels and nuclear power based jobs are observed to decline through the transition period, from about 70% in 2015 to a mere 3% in 2050, as indicated in Figure 13. 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 80% of total direct energy jobs by 2050, in contrast to just about 28% in 2015, as they emerge to be the least costing sources for power generation (Breyer et al., 2017b; Ram et al., 2017a; Ram et al., 2018). The storage sector creates around 17% of the jobs in 2030, with the steady ramp up in installations and cost competitiveness. Beyond 2030, they continue to maintain a stable share of 17% of the jobs created until 2050, as shown in Figure 13. Renewable energy and storage generate up to 92% of the total jobs by 2030, which is comparable to the results of Greenpeace International (2015), in which renewable energy accounts for 86% of energy jobs by 2030. Transmission contributes just a marginal share of jobs in the range of 0 to 1%, through the transition period. As the LUT Energy System Transition model does not account for the additional distribution networks, these estimates are limited to inter-regional transmission within countries of the different major regions. A significantly higher number of jobs are currently associated with the transmission and distribution of power, e.g. an analysis of jobs in the USA, showed around 500 thousand people were directly employed in the electricity transmission and distribution sector in 2013 (U.S. Department of Energy, 2017). Hence, the potential transmission and distribution jobs created during the energy transition period will be a lot higher with additional power infrastructure needed.

A number of 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 plants. That is for every megawatt of installed capacity, it is estimated that renewable energy sources create between 1.7 to 14.7 times more jobs than natural gas based power generation plants and up to 4 times more jobs than those supplied with coal fired power plants (Cameron and Zwaan, 2015). Renewable energy is already contributing more towards job creation in many markets across the world. 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 (The Solar Foundation, 2017; U.S. Department of Energy, 2017). 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 generation and storage technologies.

As the employment level increases 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 manage renewable power generation and storage technologies (UNEP, 2008). 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. With an increasing requirement for individuals with diverse skill-sets and talents foreseen in the near future, significant efforts in training and education will be needed to provide the labour market with the necessary skills.

IRENA estimates that achieving the objective of universal access to modern energy services by 2030 could create 4.5 million jobs in the off-grid renewables-based electricity sector (IRENA, 2013). There is growing evidence that decentralised renewable energy solutions can create value locally in terms of both employment and fostering economic growth (WRI, 2017). The benefits of transitioning to renewable energy and electrifying rural communities extend far beyond better employment opportunities (Winkler et al., 2011). For the world's poorest people, increased energy access means more time for children to study after school, greater productivity and income for families, and improved health outcomes (WRI, 2017). Although rural electrification is not directly part of this research, creating good quality renewable energy jobs that will enable poverty reduction in rural, underdeveloped regions is a crucial added benefit, which is often overseen.

6. Conclusions

This research has affirmed the proposition that renewable energy technologies create more jobs than conventional energy technologies and hence generate greater socioeconomic benefits. Additionally, this is the first research estimating potential jobs created by storage technologies, enabled by the unique hourly simulation capabilities of the LUT Energy System Transition model. As showcased in the previous sections, developing renewable power generation and storage capacities can make a significant contribution to job creation in the long run. The results indicate that job losses in fossil fuels and nuclear power sectors are more than outweighed by the job creation in renewable power generation and storage sectors. This if further emphasised in the Figure 13, with renewable energy contributing to around 80% of the jobs created by 2050.

The employment patterns in manufacturing and distribution of renewable energy and storage technologies are similar to those in other capital investment goods industries. Manufacturing represents 16% of the total jobs created globally and vary from 10% in Europe to 19% in Sub-Saran Africa for 2050. Quite different are the patterns in construction and installation, as the work is mainly project based. Construction and installation jobs have a share of 29% globally and vary from 20% in North America to 35% in Sub-Saharan Africa in 2050. The patterns of employment in the operation and maintenance segment are indeed more stable. As, operation and maintenance jobs have a 50% share globally and vary from 42% in Sub-Saharan Africa to 64% in North America for 2050. Evidently, the total employment created tends to grow rapidly when a significant number of new installations are implemented as shown by the regional as well as global results, particularly in the period of 2020 to 2030. The electricity generation specific jobs at 897 jobs/TWh_{el} in 2015 rise up to 1091 jobs/TWh_{el} in 2030 and then decline steadily to around 715 jobs/TWh_{el} in 2050. The decline in specific jobs is predominantly due to improving learning rates of technologies, which account for higher level of efficiency in industrial processes. Higher productivity due to economic growth further reduce the specific jobs, an effect which affects all technologies, not only renewable ones. Despite the decline, the total jobs created compensate for the jobs lost in the conventional energy sector. This indicates that even with increasing industrial efficiencies and continued learning for renewable energy and storage technologies, a high volume of jobs can be expected in the long term. While for the case of South Africa in a separate study (Oyewo et al., 2019), jobs were estimated using the methods of this research, which showed that the specific jobs further decline with higher shares of conventional technologies in a

Current Policy Scenario (CPS) as compared to a Best Policy Scenario (BPS) with higher shares of renewable energy.

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) and a global approach towards climate protection (e.g. carbon tax or cap and trade systems) in order to leverage existing opportunities from renewables (Ram et al., 2017a). Additionally, a reform in energy prices and exorbitant subsidies for the fossil fuel and nuclear sectors is much required (Coady et al., 2017). Although this study has suggested a favourable increase in employment, a reorganisation of a country's power system could have far more significant benefits to its entire economy. This indicates that more integrated assessments of job impacts are necessary as the penetration of renewable energy increases in future energy systems.

Supplementary Material

The supplementary data associated with this article can be found in the online version at (link to be added)

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References

[ADB] Asian Development Bank and [UNDP] United Nations Development Programme. (2017). *100% Electricity generation through renewable energy by 2050: Assessment of Sri Lanka's power sector*. Manila, New York. Retrieved from https://www.adb.org/publications/electricity-generation-renewable-energy-2050-sri-lanka

[AEC] - Australian Energy Council. (2018). *Solar Report - January 2018.* Melbourne. Retrieved from https://www.energycouncil.com.au/media/11188/australian-energy-council-solar-report_-january-2018.pdf

[BNEF] - Bloomberg New Energy Finance. (2017). *Climatescope 2017 - The Clean Energy Country Competitiveness Index*. London. Retrieved from http://global-climatescope.org/en/download/reports/climatescope-2017-report-en.pdf

[EC] - European Commission. (2013). *Labour Market Developments in Europe 2013*. Brussels. https://doi.org/10.2765/40221

[IEA-PVPS] - Internation Energy Agency Photovoltaics Power Systems. (2016). *Trends 2016 in Photovoltaic Applications. Survey Report of Selected IEA Countries between 1992 and 2015*. *Survey Report of Selected IEA Countries between 1992 and 2015*. Ursen, Switzerland. Retrieved from http://www.iea-pvps.org/?id=256

[IEA] - International Energy Agency. (2016). *World Energy Outlook 2016*. Paris. https://doi.org/http://www.iea.org/publications/freepublications/publication/WEB_WorldEnergyOutlook2015ExecutiveSummaryEnglishFinal.pdf

[IER] - Institute for Energy Research. (2010). *A Primer on Energy and the Economy: Energy's Large Share of the Economy Requires Caution in Determining Policies That Affect It - IER*. Washington

D.C. Retrieved from http://instituteforenergyresearch.org/analysis/a-primer-on-energy-and-the-economy-energys-large-share-of-the-economy-requires-caution-in-determining-policies-that-affect-it/

[ILO] - International Labor Organization. (2017). *World Employment Social Outlook Trends 2017*. Geneva. Retrieved from http://www.ilo.org/wcmsp5/groups/public/---dgreports/---dcomm/---publ/documents/publication/wcms_541211.pdf

[ILO] - International Labour Organization. (2016). *Summary Report: Labour productivity - ILO modelled estimates*. Geneva. Retrieved from http://www.ilo.org/global/statistics-and-databases/research-and-databases/kilm/lang--en/index.htm

[IMF] - International Monetary Fund. (2017). *World Economic Outlook (April 2017) - Real GDP growth*. Washington D.C. Retrieved from https://www.imf.org/external/pubs/ft/weo/2017/02/weodata/index.aspx

[IRENA] - International Renewable Energy Agency. (2011). *IRENA Working Paper: Renewable Energy Jobs: Status, prospects & policies*. Abu Dhabi. https://doi.org/24/03/2015

[IRENA] - International Renewable Energy Agency. (2013). *Renewable Energy and Jobs*. Abu Dhabi. Retrieved from http://www.irena.org/documentdownloads/publications/renewableenergyjobs.pdf

[IRENA] - International Renewable Energy Agency. (2016). *Renewable Energy Market Analysis: Latin America*. Abu Dhabi. https://doi.org/http://www.irena.org/DocumentDownloads/Publications/IRENA_Market_GCC_2016.pdf

[IRENA] - International Renewable Energy Agency. (2018). *Renewable Energy and Jobs: Annual Review 2018*. Abu Dhabi. Retrieved from https://www.irena.org/DocumentDownloads/Publications/IRENA_RE_Jobs_Annual_Review_2018.pdf

[IRENA] - International Renewable Energy Agency. (2018). *Renewable Energy Market Analysis: Southeast Asia*. Abu Dhabi. Retrieved from http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_Market_Southeast_Asia_2018.pdf

[NREL] - National Renewable Energy Laboratory. (2013). *Assessment of the Value , Impact , and Validity of the Jobs and Economic Development Impacts (JEDI) Suite of Models*. Golden. Retrieved from www.nrel.gov/publications

[PwC] - Price Waterhouse Coopers. (2017). *The Long View: How will the global economic order change by 2050 ?* London. Retrieved from www.pwc.com

[RFF] - Resources for the Future. (2017). *Decommissioning US Power Plants: Decisions, Costs, and Key Issues*. Washington D.C. Retrieved from http://www.rff.org/research/publications/decommissioning-us-power-plants-decisions-costs-and-key-issues KY

[UNFCCC] - United Nations Framework Covention on Climate Change. Conference of the Parties (COP). (2015). *Paris Climate Change Conference-November 2015, COP 21. Adoption of the Paris Agreement. Proposal by the President.* Bonn. https://doi.org/FCCC/CP/2015/L.9/Rev.1

[UNIDO] - United Nations Industrial Development Organization. (2013). *Emerging trends in global manufacturing industries*. Vienna. Retrieved from http://www.unido.org/fileadmin/user_media/Services/PSD/Emerging_Trends_UNIDO_2013.PDF

[WRI] - World Resources Institute. (2017). *Can Renewable Energy Jobs Help Reduce Poverty in India?*

Washington D.C. Retrieved from http://www.wri.org/sites/default/files/can-renewable-energy-jobs-reduce-poverty-india.pdf

Aghahosseini, A., Bogdanov, D., & Breyer, C. (2016). The MENA Super Grid towards 100 % Renewable Energy Power Supply by 2030 The MENA Super Grid towards 100 % Renewable Energy Power Supply by 2030. In *11th International Energy Conference*. Tehran.

Aghahosseini, A., Bogdanov, D., & Breyer, C. (2017). A Techno-Economic Study of an Entirely Renewable Energy-Based Power Supply for North America for 2030 Conditions. *Energies, 10*(1171). https://doi.org/10.3390/en10081171

Aghahosseini, A., & Breyer, C. (2018). Assessment of geological resource potential for compressed air energy storage in global electricity supply. *Energy Conversion and Management*, *169*, 161–173. https://doi.org/10.1016/j.enconman.2018.05.058

Agora Energiewende, & Sandbag. (2018). *The European Power Sector in 2017. State of Affairs and Review of Current Developments. Agora Energiewende and Sandbag*. Berlin. Retrieved from www.sandbag.org.uk%0Awww.agora-energiewende.de

Ali, M. (2014). Youth Unemployment: A Global Security Challenge. Retrieved April 8, 2018, from http://hir.harvard.edu/article/?a=7296

Almutairi, K., Thoma, G., Durand-Morat, A. (2018). Ex-Ante Analysis of Economic, Social and Environmental Impacts of Large-Scale Renewable and Nuclear Energy Targets for Global Electricity Generation by 2030. *Sustainability*, 10, 2884. doi:10.3390/su10082884

Arcadis. (2018). Preesall Underground Gas Storage. Retrieved from https://www.arcadis.com/en/united-kingdom/what-we-do/our-projects/uk/preesall-underground-gas-storage-facility/

Barasa, M., Bogdanov, D., Oyewo, A. S., & Breyer, C. (2018). A Cost Optimal Resolution for Sub-Saharan Africa powered by 100% Renewables for Year 2030 Assumptions. *Renewable and Sustainable Energy Reviews*, *92*, 440–457. https://doi.org/10.1016/j.rser.2018.04.110

Barbosa, L., Bogdanov, D., Vainikka, P., & Breyer, C. (2017). Hydro, wind and solar power as a base for a 100% Renewable Energy supply for South and Central America. *PLoS ONE*, *12*(3). https://doi.org/10.1371/journal.pone.0173820

Behrens, A., Coulie, C., Genoese, F., Alessi, M., Wieczorkiewicz, J., & Egenhofer, C. (2014). *Impact of the Decarbonisation of the Energy System on Employment in Europe, Centre for European Policy Studies (CEPS)*. Brussels. Retrieved from www.ceps.eu

Bellini, E. (2017). *Mexico's power auction pre-selects 16 bids with average price of $20.57/MWh and 2.56 GW of combined capacity*. *PV Magzine International*. Berlin. Retrieved from https://www.pv-magazine.com/2017/11/16/mexicos-power-auction-pre-selects-16-bids-with-average-price-of-20-57mwh-and-2-56-gw-of-combined-capacity/

Bogdanov, D., & Breyer, C. (2016). North-East Asian Super Grid for 100% renewable energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options. *Energy Conversion and Management*, *112*(October 2017), 176–190. https://doi.org/10.1016/j.enconman.2016.01.019Bogdanov D, Farfan J, Sadovskaia K, Aghahosseini A, Child M, Gulagi A, Oyewo AS, Barbosa LSNS, Breyer C. (2019). Pathway towards sustainable electricity - Radical transformation via evolutionary steps. *Nature Communications* 10(1):1077. DOI: 10.1038/s41467-019-08855-1

BonelliErede. (2017). *Sub-Saharan Africa's hunger for renewable energy* |. Retrieved from https://www.belex.com/en/news/sub-saharan-africas-hunger-for-renewable-energy/

Böhringer, C., Keller, A., van der Werf, E. (2013). Are green hopes too rosy? Employment and welfare impacts of renewable energy promotion. *Energy Economics*, 36, 277-285. https://doi.org/10.1016/j.eneco.2012.08.029

Breitschopf, B., Nathani, C., & Resch, G. (2011). *Review of approaches for employment impact assessment of renewable energy deployment*. *Prepared by Fraunhofer Institute for Systems and Innovation Research (ISI) for IEA-RETD*. Karlsruhe. Retrieved from http://iea-retd.org/wp-content/uploads/2012/12/Assessment-approaches.pdf

Breyer, C., Bogdanov, D., Gulagi, A., Aghahosseini, A., Barbosa, L. S. N. S., Koskinen, O., … Vainikka, P. (2017b). On the role of solar photovoltaics in global energy transition scenarios. *Progress in Photovoltaics: Research and Applications*, *25*(8), 727–745. https://doi.org/10.1002/pip.2885

Breyer, C., Bogdanov, D., Komoto, K., Ehara, T., Song, J., & Enebish, N. (2015). North-East Asian Super Grid: Renewable energy mix and economics. *Japanese Journal of Applied Physics*, *54*(8S1), 08KJ01. https://doi.org/10.7567/JJAP.54.08KJ01

Breyer, C., Heinonen, S., & Ruotsalainen, J. (2017a). New consciousness: A societal and energetic vision for rebalancing humankind within the limits of planet Earth. *Technological Forecasting and Social Change*, *114*, 7–15. https://doi.org/10.1016/j.techfore.2016.06.029

Brookings. (2017). *Foresight Africa: Top Priorities for the Continent in 2017*. Washington D.C. Retrieved from https://www.brookings.edu/wp-content/uploads/2017/01/global_20170109_foresight_africa.pdf

Buckley, T., & Shah, K. (2018). *Electricity Sector Transformation in India: A Case Study of Tamil Nadu*. Cleveland. Retrieved from http://ieefa.org/wp-content/uploads/2018/02/Electricity-Sector-Transformation-in-India-A-Case-Study-of-Tamil-Nadu_7-Feb-2018.pdf

Cameron, L., & Zwaan, B. Van Der. (2015). Employment factors for wind and solar energy technologies: A literature review. *Renewable and Sustainable Energy Reviews*, *45*, 160–172. https://doi.org/10.1016/j.rser.2015.01.001

CDC and (ODI) Overseas Development Institute. (2016). *Development Impact Evaluation: What are the links between power, economic growth and job creation?* London. Retrieved from http://www.cdcgroup.com/Documents/Evaluations/Power economic growth and jobs.pdf

Child, M., Koskinen, O., Linnanen, L., & Breyer, C. (2018). Sustainability guardrails for energy scenarios of the global energy transition. *Renewable and Sustainable Energy Reviews*, *91*, 321–334. https://doi.org/10.1016/j.rser.2018.03.079

Coady, D., Parry, I., Sears, L., & Shang, B. (2017). How Large Are Global Fossil Fuel Subsidies? *World Development*, *91*, 11–27. https://doi.org/10.1016/j.worlddev.2016.10.004

Dipaola, A. (2017). *Saudi Arabia Gets Cheapest Bids for Solar Power in Auction*. *Bloomberg Markets*. New York. Retrieved from https://www.bloomberg.com/news/articles/2017-10-03/saudi-arabia-gets-cheapest-ever-bids-for-solar-power-in-auction

Ecole Polytechnique Federale de Lausanne (EPFL). (2018). *EPFL analyzes the economic impact of three energy-transition scenario*. *EPFL Energy Center*. Lausanne. https://doi.org/https://actu.epfl.ch/news/epfl-analyzes-the-economic-impact-of-three-energy-/

Electricity Authority. (2016). *Electricity in New Zealand*. Wellington. Retrieved from https://www.ea.govt.nz/dmsdocument/20410

Eurostat. (2017). *Euro area unemployment at 8.6%*. Luxemborg. Retrieved from http://ec.europa.eu/eurostat/documents/2995521/8266821/3-02102017-AP-EN.pdf/be6fb31a-cc00-44fa-9944-39b4616ebe81

Evonik. (2010). *Study for Decommissioning of Kosovo-A Power Plant. Prepared for European Commission Liaison Office*. Essen. Retrieved from https://eeas.europa.eu/delegations/kosovo/documents/press_corner/decommissioning_study_kosovo_a_power_plant_en.pdf

Farfan, J., & Breyer, C. (2017). Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator. *Journal of Cleaner Production*, *141*, 370–384. https://doi.org/10.1016/j.jclepro.2016.09.068

Ford, R., Walton, S., Stephenson, J., Rees, D., Scott, M., King, G., … Wooliscroft, B. (2017). Emerging energy transitions: PV uptake beyond subsidies. *Technological Forecasting and Social Change*, *117*, 138–150. https://doi.org/10.1016/j.techfore.2016.12.007

Fortes, P., Alvarenga, A., Seixas, J., & Rodrigues, S. (2015). Long-term energy scenarios: Bridging the gap between socio-economic storylines and energy modeling. *Technological Forecasting and Social Change*, *91*, 161–178. https://doi.org/10.1016/j.techfore.2014.02.006

Frankfurt School-UNEP Centre/BNEF. (2017). *Global Trends in Renewable Energy Investment*. Frankfurt. Retrieved from http://fs-unep-centre.org/sites/default/files/publications

Garrett-Peltier, H. (2017). Green versus brown: Comparing the employment impacts of energy efficiency, renewable energy, and fossil fuels using an input-output model. *Economic Modelling*, 61, 439-447. https://doi.org/10.1016/j.econmod.2016.11.012

Government of U.K. (2015). *Preesall underground gas storage facility receives planning consent - GOV.UK*. London. Retrieved from https://www.gov.uk/government/news/preesall-underground-gas-storage-facility-receives-planning-consent

Greenpeace International. (2015). *Energy [R]evolution*. Amsterdam. Retrieved from https://www.greenpeace.org/archive-international/en/publications/Campaign-reports/Climate-Reports/Energy-Revolution-2015/

GTM Research and Energy Storage Association (ESA). (2016). *U.S. Energy Storage Monitor: 2015 Year in Review Executive Summary*. Boston. Retrieved from www.energystoragemonitor.com. GTMResearch/ESA U.S. Energy Storage Monitor: 2015 Year in Review 1

Gulagi, A., Bogdanov, D., & Breyer, C. (2017). A cost optimized fully sustainable power system for Southeast Asia and the Pacific Rim. *Energies*, *10*(5), 583. https://doi.org/10.3390/en10050583

Gulagi, A., Bogdanov, D., & Breyer, C. (2018). The role of storage technologies in energy transition pathways towards achieving a fully sustainable energy system for India. *Journal of Energy Storage*, *17*, 525–539. https://doi.org/10.1016/j.est.2017.11.012

GWEC. (2018). *Global Wind Statistics 2017. Global Wind Energy Council*. Brussels. Retrieved from http://gwec.net/wp-content/uploads/vip/GWEC_PRstats2017_EN-003_FINAL.pdf

Hart, D., & Sarkissian, A. (2016). *Deployment of Grid-Scale Batteries in the United States. Schar School of Policy and Government George Mason University Prepared for Office of Energy Policy and Systems Analysis U.S. Department of Energy*. Fairfax. Retrieved from http://davidhart.gmu.edu/wp-content/uploads/2016/11/Grid-Scale-Batteries-GMU-case-study-final-9-19-16.pdf

Haysom, J. E., Jafarieh, O., Anis, H., Hinzer, K., & Wright, D. (2015). Learning curve analysis of concentrated photovoltaic systems. *Progress in Photovoltaics: Research and Applications*, *23*(11), 1678–1686. https://doi.org/10.1002/pip.2567

Hondo, H., & Moriizumi, Y. (2017). Employment creation potential of renewable power generation technologies: A life cycle approach. *Renewable and Sustainable Energy Reviews*, *79*, 128–136. https://doi.org/10.1016/j.rser.2017.05.039

Ianchovichina, E., Estache, A., Foucart, R., Garsous, G., & Yepes, T. (2013). Job Creation through Infrastructure Investment in the Middle East and North Africa. *World Development*, *45*, 209–222. https://doi.org/10.1016/j.worlddev.2012.11.014

IPCC. (2007). *Climate Change 2007 Synthesis Report. Contribution of the Working Groups I, II and II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]*. Geneva. https://doi.org/10.1256/004316502320517344

IPCC. (2014a). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. *Core Writing Team, R.K. Pachauri and L.A. Meyer*. Geneva. https://doi.org/10.1017/CBO9781107415324.004

IPCC. (2014b). *Summary for Policymakers. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S.* Cambridge University Press, Cambridge and New York, NY, USA. https://doi.org/10.1017/CBO9781107415324

Jacobson, M.Z., Delucchi, M. A., Ingraffea, A. R., Howarth, R.W., Bazouin, G., Bridgeland, B., … Yeskoo, T. (2014). A roadmap for repowering California for all purposes with wind, water, and sunlight. *Energy, 73,* 875-889, doi:10.1016/j.energy.2014.06.099.

Jacobson, M. Z., Delucchi, M. A., Bauer, Z. A. F., Goodman, S. C., Chapman, W. E., Cameron, M. A., … Yachanin, A. S. (2017). 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. *Joule*, *1*(1), 108–121. https://doi.org/10.1016/j.joule.2017.07.005

Keiner, D., Ram, M., Barbosa, L. S. N. S., Bogdanov, D., Breyer, C. (2019). Cost optimal self-consumption of PV prosumers with stationary batteries, heat pumps, thermal energy storage and electric vehicles across the world up to 2050. *Solar Energy*, 185, 406-423. https://doi.org/10.1016/j.solener.2019.04.081

Kilickaplan, A., Bogdanov, D., Peker, O., Caldera, U., Aghahosseini, A., & Breyer, C. (2017). An energy transition pathway for Turkey to achieve 100% renewable energy powered electricity, desalination and non-energetic industrial gas demand sectors by 2050. *Solar Energy*, *158*, 218–235. https://doi.org/10.1016/j.solener.2017.09.030

Kollewe, J. (2010). *Global unemployment to trigger further social unrest, UN agency forecasts*. *The Guardian*. London. Retrieved from https://www.theguardian.com/business/2010/oct/01/job-market-recession-social-unrest-ilo

Lambert, R. J. and Silva, P. P. (2012). The challenges of determining the employment effects of renewable energy. *Renewable and Sustainable Energy Reviews.* 16(7), 4667-4674. https://doi.org/10.1016/j.rser.2012.03.072

Llera, E., Scarpellini, S., Aranda, A., & Zabalza, I. (2013). Forecasting job creation from renewable energy deployment through a value-chain approach. *Renewable and Sustainable Energy Reviews*, *21*, 262–271. https://doi.org/10.1016/j.rser.2012.12.053

Oyewo, A. S., Aghahosseini, A., Ram, M., Lohrmann, A., Breyer, C. (2019). Pathways towards achieving a 100% renewable energy powered electricity and desalination sector by 2050 for South Africa. submitted.

Markandya, A., Arto, I., Gonzalez-Eguino, M., Roman, M. V. (2016). Towards a green energy economy? Tracking the employment effects of low-carbon technologies in the European Union. Applied Energy. 179, 1342-1350. http://dx.doi.org/10.1016/j.apenergy.2016.02.122

MEED. (2017). *Region emerging as one of the worlds largest renewable energy markets*. Dubai. Retrieved from https://www.meed.com/region-emerging-as-one-of-the-worlds-largest-renewable-energy-markets/

Meyer, I., & Wolfgang Sommer, M. (2014). *Employment Effects of Renewable Energy Supply A Meta Analysis. Preapred by Austrian Institute of Economic Research (WIFO) for European Union* (No. 12–Policy Paper). Vienna. Retrieved from www.foreurope.eu

Oldham, K. (2009). *Decommissioning dams - costs and trends*. *International Water Power & Dam Construction*. London. Retrieved from http://www.waterpowermagazine.com/features/featuredecommissioning-dams-costs-and-trends/

Rabson, M. (2017). *Renewable energy growing in Canada but solar installations lagging behind | CBC News*. *The Canadian Press*. Toronto. Retrieved from http://www.cbc.ca/news/politics/neb-solar-renewable-energy-1.4457835

Ram, M., Bogdanov, D., Aghahosseini, A., Oyewo, A. S., Gulagi, A., Child, M., … Breyer, C. (2017a). *Global Energy System based on 100% Renewable Energy – Power Sector. Study by Lappeenranta University of Technology and Energy Watch Group*. Lappeenranta, Berlin. Retrieved from https://goo.gl/exkGdm

Ram, M., Keiner, D., Gulagi, A., & Breyer, C. (2017b). Role of Solar PV Prosumers in Enabling the Energy Transition Towards a Fully Renewables Based Power System for India. In *1st International Conference on Large-Scale Grid Integration of Renewable Energy in India. September 6-8*. New Delhi. Retrieved from https://goo.gl/CQmYwB

Ram, M., Child, M., Aghahosseini, A., Bogdanov, D., Poleva, A., & Breyer, C. (2018). A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015-2030. *Journal of Cleaner Production*. 199, 687-704. https://doi.org/10.1016/j.jclepro.2018.07.159 .

REN21. (2017). *Renewables: Global Status Report 2017*. Paris. Retrieved from http://www.ren21.net/status-of-renewables/global-status-report/

Rutovitz, J., & Atherton, A. (2009). *Energy sector jobs to 2030: A global analysis. Prepared for Greenpeace International by the Institute for Sustainable Futures, University of Technology, Sydney.* Retrieved from https://opus.lib.uts.edu.au/handle/10453/20458

Rutovitz, J., Dominish, E., & Downes, J. (2015). *Calculating global energy sector jobs 2015 methodology update 2015. Prepared for Greenpeace International by the Institute for Sustainable Futures, University of Technology Sydney.* Sydney. Retrieved from https://opus.lib.uts.edu.au/handle/10453/43718

Rutovitz, J., & Harris, S. (2012). *Calculating global energy sector jobs: 2012 methodology. Prepared for Greenpeace International by the Institute for Sustainable Futures, University of Technology, Sydney.* Retrieved from https://opus.lib.uts.edu.au/handle/10453/35045

Sadovskaia, K., Bogdanov, D., Honkapuro, S., & Breyer, C. (2018). Power Transmission and

Distributions Losses – A Model Based on Available Empirical Data and Future Trends for All Countries Globally. *International Journal of Electrical Power & Energy Systems*. 107, 98-109. DOI: 10.1016/j.ijepes.2018.11.012

Saurabh M. (2018). *Almost All Power Capacity Added In India In Q4 2017 Was Renewable*. *Clean Technica*. Retrieved from https://cleantechnica.com/2018/03/29/almost-all-power-capacity-added-in-india-in-q4-2017-was-renewable/

Sheikh, N. J., Kocaoglu, D. F., & Lutzenhiser, L. (2016). Social and political impacts of renewable energy: Literature review. *Technological Forecasting and Social Change*. North-Holland. https://doi.org/10.1016/j.techfore.2016.04.022

Solar Power Europe. (2015). *Solar Photovoltaics Jobs & Value Added in Europe*. Brussels. Retrieved from http://www.solarpowereurope.org/fileadmin/user_upload/documents/Media/Jobs___Growth.pdf

SolarPower Europe. (2016). *Global Market Outlook for Solar Power: 2016-2020*. Brussels. Retrieved from www.solarpowereurope.org/.../SolarPower_Webinar_Global_Market_Outlook.pdf

Stern, N. (2007). *The Economics of Climate Change*. *Stern Review*. Cambridge. https://doi.org/10.1257/aer.98.2.1

The Brattle Group for WIRES (Working group for Investment in Reliable and Economic electric Systems). (2011). *Employment and Economic Benefits of Transmission Infrastructure Investment in the U.S. and Canada*. Cambridge, Massachusetts. Retrieved from http://www.brattle.com/_documents/UploadLibrary/Upload947.pdf

The Solar Foundation. (2016). *Solar + Storage Jobs*. Washington D.C. Retrieved from www.TheSolarFoundation.org

The Solar Foundation. (2017). *National Solar Jobs Census 2017*. Washington D.C. Retrieved from SolarJobsCensus.org

U.S. Bureau of Labor Statistics. (2018). *United States Unemployment Rate: 1948-2018*. *Trading Economics*. Washington D.C. Retrieved from https://tradingeconomics.com/united-states/unemployment-rate

U.S. Department of Energy. (2017). *U.S. Energy and Employment Report*. Washington D.C. Retrieved from https://energy.gov/sites/prod/files/2017/01/f34/2017 US Energy and Jobs Report_0.pdf

UBS. (2013). *The unsubsidised solar revolution*. Basel. https://doi.org/http://www.qualenergia.it/sites/default/files/articolo-doc/UBS.pdf

UNECE and REN21. (2017). *Reneawable Energy Status Report*. Geneva, Paris. Retrieved from https://www.unece.org/fileadmin/DAM/energy/se/pp/renew/Renewable_energy_report_2017_web.pdf

Winkler, H., Simões, A. F., Rovere, E. L. la, Alam, M., Rahman, A., & Mwakasonda, S. (2011). Access and Affordability of Electricity in Developing Countries. *World Development*, *39*(6), 1037–1050. https://doi.org/10.1016/j.worlddev.2010.02.021

World Bank. (2011). *Issues in estimating the employment generated by energy sector activities, Sustainable Energy Department*. Washington D.C. Retrieved from http://siteresources.worldbank.org/INTOGMC/Resources/Measuring_the_employment_impact_of_energy_sector1.pdf

Worldwatch Institute and Cornell University Global Labor Institute for (UNEP) United Nations Environment Programme. (2008). *Green Jobs: Towards decent work in a sustainable, low-carbon world*. Nairobi, New York, Washington D.C. Retrieved from http://www.bls.gov/green/

Wright, J. G., Bischof-Niemz, T., Calitz, J., Mushwana, C., Van Heerden, R., Senatla M., 2017. Formal comments on the Integrated Resource Plan (IRP) Update Assumptions, Base Case and Observations 2016, Pretoria. https://www.csir.co.za/sites/default/files/Documents/20170331CSIR_EC_DOE.pdf

Appendix

Table A1: Employment factors used in the estimation of jobs created during the energy transition from 2015 to 2050. (Abbreviations: Mfc. – Manufacturing, C&I – Construction and Installation, O&M – Operation and Maintenance, Dcm. – Decommissioning)

Technologies	Mfc. [Job-yrs /MW]	C&I [Job-yrs /MW]	O&M [Jobs/ MW]	Fuel [Jobs/ PJ]	Dcm. [Job-yrs /MW]	Source
Wind onshore	4.70	3.20	0.30		0.72	Rutovitz et al., 2015
Wind offshore	15.60	8.00	0.20		2.99	Rutovitz et al., 2015
PV Utility-scale	6.70	13.00	0.70		0.80	Rutovitz et al., 2015
PV Rooftop	6.70	26.00	1.40		1.21	Solar Power Europe, 2015
Biomass	2.90	14.00	1.50	29.90	0.32	Rutovitz et al., 2015
Hydro Dam	3.50	7.40	0.20		2.22	Rutovitz et al., 2015
Hydro RoR	8.75	18.50	0.50		5.55	Assuming 2.5 times the value as Hydro Dam
Geothermal	3.90	6.80	0.40		0.21	Rutovitz et al., 2015
CSP	4.00	8.00	0.60		1.33	Rutovitz et al., 2015
Biogas PP	2.90	14.00	2.25	29.90	0.32	Rutovitz et al., 2015, 1.5 times more O&M jobs as Biomass PP
Waste-to-energy	2.90	14.00	2.25	29.90	0.32	Rutovitz et al., 2015, 1.5 times more O&M jobs as Biomass PP
Methanation	2.90	14.00	2.25		0.32	Rutovitz et al., 2015, 1.5 times more O&M jobs as Biomass PP
Coal PP (Hard Coal)	5.40	11.20	0.14	39.70	1.65	Rutovitz et al., 2015
Nuclear PP	1.30	11.80	0.60	0.001 (Jobs/ GWh)	0.95 (Jobs/ MW)	Rutovitz et al., 2015
OCGT	0.93	1.30	0.14	15.10	0.21	Rutovitz et al., 2015
CCGT	0.93	1.30	0.14	15.10	0.21	Rutovitz et al., 2015
Steam Turbine	0.93	1.30	0.14		0.21	Assuming same as Gas Turbine
PtH	1.86	2.60	0.28		0.21	Assuming 2 times the value as GT
ICE	0.93	1.30	0.21	15.10	0.44	Rutovitz et al., 2015,

					1.5 times more O&M jobs as GT
Gas Storage	0.00	0.12	0.01	0.11	Gov. of UK, 2015
PtG	1.86	2.60	0.28	0.21	Assuming 2 times the value as GT
Battery large-scale	16.90	10.80	0.40	0.80	0.5 times of prosumer storage
Battery prosumer	16.90	21.60	0.80	1.21	Derived from USDOE, 2017
Pumped Hydro Storage	7.00	14.80	0.40	4.44	Assuming 2 times the values for Hydro Dam
A-CAES	8.45	10.80	0.40	0.40	Assuming 1/2 the values for Batteries (large-scale)
Transmission	Employment factor with regard to investments – 5045 jobs/b€				The Brattle Group, 2011

The decommissioning employment factors are derived from (RFF, 2017), (Evonik, 2010) and (Oldham, 2009). Further details can be found in the Supplementary Material.

Table A2: Regional employment multipliers, based on labour productivity across the different regions used in the estimation of jobs created during the energy transition from 2015 to 2050. (Abbreviations: EUR – Europe, MENA – Middle East and North Africa, SSA – Sub-Saharan Africa, SAARC – South Asian Association for Regional Cooperation, NEA – Northeast Asia, SEA – Southeast Asia, NA – North America, SA – South America)

Regions	**Regional Employment Multipliers**							
	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
EUR	1.05	1.08	1.10	1.13	1.17	1.19	1.20	1.22
Eurasia	1.86	1.80	1.75	1.70	1.65	1.65	1.65	1.65
MENA	2.26	1.94	1.66	1.51	1.37	1.32	1.28	1.23
SSA	7.49	6.42	5.51	5.00	4.54	4.38	4.24	4.09
SAARC	5.18	3.99	3.07	2.56	2.13	2.00	1.88	1.76
NEA	2.22	1.89	1.60	1.50	1.41	1.42	1.42	1.43
SEA	2.52	2.20	1.93	1.77	1.63	1.58	1.52	1.47
NA	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SA	3.14	2.69	2.31	2.10	1.90	1.84	1.78	1.72

The regional employment multipliers, which are based on labour productivity factors are derived from (ILO, 2016) and (IMF, 2017). Further details can be found in the Supplementary Material and a description is provided in the methods section.

Table A3: Share of local manufacturing and corresponding share of imports across the different regions used in the estimation of jobs created during the energy transition from 2015 to 2050. (Abbreviations: EUR – Europe, MENA – Middle East and North Africa, SSA – Sub-Saharan Africa, SAARC – South Asian Association for Regional Cooperation, NEA – Northeast Asia, SEA – Southeast Asia, NA – North America, SA – South America)

Regions	**Share of Local Manufacturing [%]**	**Region of Import/ Import Shares [%]**

	2015	2020	2025	2030	2035	2040	2045	2050	EUR	NA	SAARC	NEA
EUR	90	90	90	90	100	100	100	100	-	25	-	75
Eurasia	40	50	60	70	80	90	100	100	25	-	25	50
MENA	30	30	40	50	60	70	80	90	25	-	25	50
SSA	30	30	40	50	60	70	80	90	25	15	10	50
SAARC	70	80	90	100	100	100	100	100	25	15	-	60
NEA	100	100	100	100	100	100	100	100	-	-	-	-
SEA	90	90	90	90	100	100	100	100	30	-	30	40
NA	80	90	90	90	100	100	100	100	50	-	-	50
SA	50	60	70	80	90	100	100	100	25	50	-	25

The development of the shares of local manufacturing in the different regions during the energy transition period from 2015 to 2050 and the corresponding regions of import, along with the shares of import are based on data gathered from (Rutovitz et al., 2015), (UNIDO, 2013) and (PwC, 2017).

Vitae

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