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Electricity generation technologies: comparison of materials use, energy return on investment, jobs creation and CO_2 emissions reduction

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Highlights

- New life-cycle method implemented to compare 19 electricity generation technologies.
- Long distance fuel transport significantly reduces energetic-economic viability.
- Low load factors for solar and wind sharply reduces energetic-economic viability.
- Electricity sector jobs for generation will double in renewable-majority futures.
- Natural gas without carbon capture is not a suitable bridge for a low-carbon future.

Abstract

Shifting to a low-carbon electricity future requires up-to-date information on the energetic, environmental and socio-economic performance of technologies. Here, we present a novel comprehensive bottom-up process chain framework that is applied to 19 electricity generation technologies, consistently incorporating 12 life-cycle phases from extraction to decommissioning. For each life-cycle phase of each technology the following 4 key metrics were assessed: material consumption, energy return ratios, job requirements and greenhouse gas emissions. We also calculate a novel global electricity to grid average for these metrics and present a metric variability analysis by altering transport distance, load factors, efficiency, and fuel density per technology. This work quantitatively supports model-to-policy frameworks that drive technology selection and investment based on energetic-economic viability, job creation and carbon emission reduction of technologies. The results suggest energetic-economic infeasibility of electricity generation networks with substantial shares of: i) liquefied natural gas transport, ii) long distance transport based hard and brown coal and pipeline natural gas, and iii) low-load factor solar-photovoltaic, concentrated solar power, onshore and offshore wind. Direct sector jobs can be expected to double in renewable-majority scenarios. All combustion-powered technologies without natural (biomass) or artificial carbon capture (fossil fuels) are not compatible with a low carbon electricity generation future.

Keywords
Electricity technology comparison, net electricity, electricity generation supply chain, electricity generation jobs, electricity generation greenhouse gas emissions.

1. Introduction

Currently, our electricity supply chains are material, fuel, and carbon emission intensive, and thereby alter the greenhouse gas (GHG) balance of the planet [1]. Substantial world-wide effort is made to decarbonise our energy system, with the aim of a global GHG emission reduction of at least 80% by 2050 [2,3]. Emissions in the electricity sector need to be reduced to half of current levels by 2030, and with 85% by 2050 to meet a 2° global warming emission reduction target [4]. Several electricity sector technology pathways have been modelled individually to achieve a low-carbon electricity system, with varying outcome and accuracy for different technologies, including: hydro-power, thermal- and PV-solar, onshore and offshore wind, biomass, geothermal, nuclear plants, natural gas, and clean coal with carbon capture and storage [5,6].

Sound technology policy and investment decision making requires apple-to-apple comparisons of individual pathways on the performance of multiple key technology characteristics [7]. Model based scenario calculations of GHG emissions and financial cost outcomes at a grid level has become standard practice, yet the evaluation of jobs, material use, fuel use, and overall energy costs to deliver energy, defined as the Energy Return on Investment (EROI), is still missing, with only few studies published with insights at the electricity system level [8–10]. If jobs, material inputs and EROI are not taken into account, large gaps can result in our understanding of the feasibility of energy scenarios. This way, the following issues remain unresolved: (1) whether the mineral resources are available to build the new energy system [11]; (2) if the speed of required change will be constrained by skills shortages due to additional employment needs [12]; and (3) whether the energy cost of newly invested energy infrastructure will cannibalise upon discretionary energy available to other sectors [13].

A key reason why these aspects are not typically calculated is that the underlying datasets and the methodology to calculate them, are still evolving. There is not yet a scientific consensus on how metrics should be calculated, thus a wide variety of methods are used with different system boundaries, uncertainties and key parameters, which reduces the robustness and comparability of published values [14–17]. Another challenge is the rapid change of parameters in the life-cycle inventory data for particular technologies [18,19], such as the Energy Return Ratio of solar-PV [20–23], GHG emissions of liquefied natural gas (LNG) [24], job requirements in solar and wind energy supply chains [14], and energy inputs and emissions in biomass power generation [25–27].

Since electricity technology supply chains involve many processes, especially when accounting for downstream material extraction, concentrating and manufacturing, it is imperative to carry out analyses in a standardised, comprehensive, accurate and transparent manner. Poor research practices in the absence of a common standard include: i) incomplete reporting of key parameter assumptions [19], ii) lack of transparently employed technology boundaries [16], iii) comparisons of metrics based on power plant capacity as opposed to generated electricity [14,28], and iv) the absence of variability and uncertainty analysis stemming from variation in physical and technology conditions to explore study result differences [15].

Consequently, comparisons for single technologies across study results, let alone comparisons between technologies and on their performance, cannot be reliably carried out [23,29]. Despite these obvious shortcomings, a number of meta-analyses have been published without compensating for differences in system boundaries [30–32]. Yet since system boundaries and key parameters in underlying studies are often not accurately reported guesstimates need to be introduced, which introduces the risk of ‘apple-to-pear’ comparisons [33,34].

To address these shortcomings and related model-to-policy needs, we developed a detailed bottom-up methodology which is comprehensive in its life-cycle scope, and can be utilised to calculate key performance metrics. Our framework consists of 12 cradle-to-grave life-cycle phases, describing processes and resource flows from raw material extraction to decommissioning, using 4 metrics to assess material, energy, and labour inputs as well as GHG emissions per functional unit of a petajoule (PJ) of electricity output into the local grid at the power plant. These 4 metrics and the life-cycle framework have been uniformly applied on 19 electricity generation technologies, yielding a robust and reliable technology comparison. In addition, this enables us to calculate a novel global average benchmark for each metric. The value can be used for comparison of individual electricity generation technologies, and to compare global electricity sector transition scenarios. Such a comparison helps to understand if a technology or scenario would reduce or increase the value of a respective metric over time if implemented in the energy system. The added granularity allows decision makers, which are using a global scenario perspective, to better rank scenarios and technology options for the overall feasibility of the global energy transition.

Our analysis is based on standardised life-cycle material and energy process methodologies [7,32], and incorporate specific data reporting recommendations from previous studies for electricity generation technologies [16]. All calculations are carried out on a bottom-up engineering (physical) basis, also referred to as process chain analysis (PCA), as opposed to using financial values to estimate physical inputs, which can result in aggregation bias [35,36]. The impact of min-max parameter variability on results was also analysed for transport distances, load factors, power plant efficiency and fuel density. Geographic and supply chain differences are thereby captured by approximation to provide a more accurate understanding of how local technology factors between countries impact results. The presented results do not show values at individual country level but give an approximation. Specific country values are not the scope of this paper, as it would also require study and reporting on grid-level supply-demand analysis and scenario creation for each country [9], which demands an individual study in its own right, and for which the results presented here are a pre-requisite.

2. Methods

2.1. Technologies, Boundaries and Metrics

Nineteen electricity generation technologies were selected for the analysis, listed in Table 1, along the technology acronyms used in the article. To capture solar-PV irradiation differences three variants were calculated based on north-Chile, south-Spain, and the United Kingdom, using solar load factors 39.0%, 27.6%, and 13.6% based on 2-axis tracker geo-localized renewable energy data [37,38]. Pipeline and liquefied natural gas (LNG) tanker variants for natural gas power plants were also modelled. Composite technology estimates were made for the global electricity mix of 1995 and 2015 which can be interpreted as a global energy-economy average for power plant to grid electricity supply. In addition, to make the results comparable to the 2015 global values, all electricity inputs from the grid which were used in the life cycle supply chain, except power plant parasitic load, were converted into a 2015 global energy system equivalent input, to include fuel use for electricity generation (see section 2.4). The global average values, next to power generation technologies, also include inputs for pumped hydro storage plants given their widespread use.

Table 1. Technologies and key parameters used in the analysis.

Technology	Acronym	Load Factor (%) Min/Base/Max	Efficiency (%) Min/Base/Max	Fuel Density (GJ/tonne)	Lifetime (years)	(%) Annual Degradation	Parasitic load (%)
Pulverized hard coal	PH-coal	62%	30%/42%/45%	22.0	40	0.16%	5.3%
IGCC hard coal	IGCC-coal	62%	30%/42%/45%	22.0	40	0.16%	11.0%
Lignite coal plant	L-coal	62%	26%/38%/43%	9.0	40	0.16%	9.0%
CCGT baseload	CCGT-bl	62%	38%/50%/62%	48.0	34	0.20%	1.5%
CCGT load following	CCGT-lf	44%	35%/46%/58%	48.0	34	0.20%	1.5%
SCGT peaker plant	SC-peak	8%	22%/32%/50%	48.0	34	0.10%	1.5%
SC-Heavy Fuel Oil peaker	HFO-peak	24%	27%/29%/47%	42.8	34	0.10%	8.0%
Biomass Municipal Waste	Bio-MSW	53%	10%/20%/27%	9.3	25	0.20%	13.0%
Biomass wood pellets	Bio-WP	62%	14%/32%/39%	17.3	40	0.20%	5.0%
EPR gen. III nuclear	EPRIII-nuclear	40%/74%/95%	30%/33%/50%	5,014,000	40	0.20%	4.2%
Geothermal-hydrothermal	Geo-HT	41%/74%/95%	n.a.	n.a.	30	0.20%	7.9%
Enhanced Geothermal	Geo-EGS	41%/74%/95%	n.a.	n.a.	30	0.20%	46.0%
Onshore Wind	On-Wind	14%/22%/60%	n.a.	n.a.	25	0.40%	3.5%
Offshore Wind	Off-Wind	20%/39%/55%	n.a.	n.a.	25	0.40%	0.7%
Hydro-electric Dam	Hyd-Dam	11%/46.4%/95%	n.a.	n.a.	60	0.20%	6.0%
Hydro-electric ROR	Hyd-RoR	30%/46.4%/90%	n.a.	n.a.	60	0.20%	1.0%
Polysilicon Solar-PV	Sol-PV	13.6%/27.5%/39%	14%/17%/24%	n.a.	25	0.50%	1.0%
Solar-CSP trough	Sol-CSP	15%/27%/35%	n.a.	n.a.	30	0.20%	7.2%
CSP trough w 12h	Sol-CSP-Salt	30%/55%/70%	n.a.	n.a.	30	0.20%	15.0%

As the functional unit, the electricity output into the local grid from each power plant in petajoule (PJ) was used. The SI unit of PJ was chosen because this allows cross-comparability to other energy uses such as transport, energy storage, and heat. Based on this functional unit for each of the 19 power generation technologies and the global mix, five technology metrics were established:

(1) Material inputs per electricity output in tonnes/PJ, including cement, steel, copper, aluminium, glass, silicon, and "others" lumping together all additional materials.

(2) Life cycle Gross energy ratio (GER) of lifetime electricity output divided by fuel and electricity inputs, including embodied energy in materials and operational electricity use in PJ/PJ (see section 2.3). As stated above electricity inputs were converted to a 2015 global energy system fuel equivalent input.

(3) Life cycle Gross external energy ratio (GEER) which is similar to GER but excludes operational electricity use as an input in PJ/PJ (see section 2.3).

(4) Equivalent number of jobs per electricity output in jobs/PJ, based on the division of total life-cycle labour hours per PJ of lifetime electricity output by 255 days of 8 hours (or 2040 hours per year) to obtain the number of full-time job equivalents.

(5) GHG emissions per PJ electricity output, calculated from direct CO_2 emissions, methane (CH_4) and nitrous oxide (N_2O) emissions released from the combustion of fuels using IPCC emissions factors, and a global composite emission factor of electricity system inputs (see section 2.5).

System boundaries to calculate these metrics per technology were selected to encompass all process chain life-cycle stages on a cradle-to-grave basis as shown in Figure 1, including [39]:

1) Raw material extraction and beneficiation to concentrates
2) Concentrate material transport
3) Processing of concentrates into power plant components
4) Transport of power plant components from factory to installation site
5) Power plant facility construction
6) Fuel extraction and processing
7) Fuel transport
8) Facility operation to generate electricity
9) Facility maintenance
10) Maintenance material transport
11) Facility decommissioning
12) Decommissioned materials transport

Fuel extraction and processing includes natural gas extraction, crude oil extraction and refining, uranium extraction and fuel fabrication, lignite strip mining, hard coal mining, and biomass harvesting and pelleting, with details available in the Supplementary Information (SI). Inputs of material, energy, and labour, as well as CO_2 emissions were calculated for each of the twelve life-cycle phases separately and aggregated to obtain a life-cycle based metric. These process-chain life-cycle phases, system boundaries and metrics were uniformly applied to all 19 technologies.

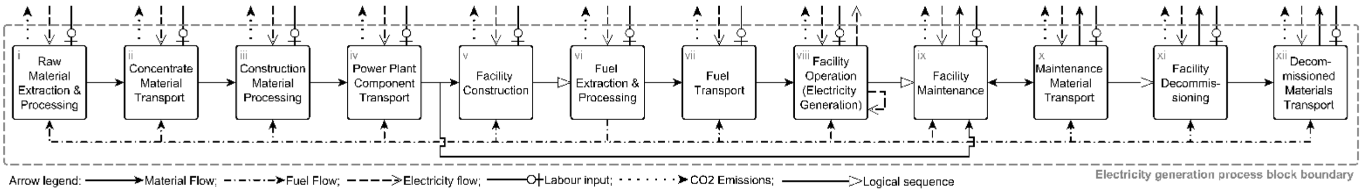

Figure 1. The 12 life cycle phases used in the study. Factory-level processing phases are illustrated in rounded rectangular boxes and flow phases (transports) to and from factory-level processing steps are indicated by arrows. Material flows, energy flows, labour, and GHG emissions as applied to each life-cycle phase are indicated by different arrow types.

2.2. Material, Electricity, GHG Input and Output Flow Calculations

The functional unit was calculated per technology ($t = 1,2, \dots n$) for gross (EO^{gross}) and net electricity output (EO^{net}) levels using nameplate capacity (CA), facility lifetime ($r = 1,2, \dots l$), load factor (LF), parasitic load factor (PL), and annual load factor degradation (DE). The gross-net difference enables the calculation of GER and GEER indicators. Calculations were carried out for a standardised 1 GW of capacity operating for one year for each technology. Specific to solar-PV, also an adjustment to electricity output was made based on a performance ratio (PR) of 80% [40]**.** Electricity outputs of onshore-wind and offshore-wind were further adjusted with a lost production factor (MF), that identifies the percentage of time that a turbine is offline even though wind is available. The MF was evaluated at 2% per year for onshore-wind and offshore-wind based on operational practice since 2015 globally and in the UK, respectively [41,42]**.** Calculations in GJ were thus carried out as:

$$EO_t^{net} = \sum_r^l (CA_t \cdot (LF_t - DE_{t,r}) \cdot 8760\ ) \text{ -> General} \tag{1}$$

$$EO_t^{net} = \sum_r^l (CA_t \cdot (LF_t - DE_{t,r}) \cdot 8760 \cdot MF_t) \text{ -> Wind-Power variant} \tag{2}$$

$$EO_t^{net} = \sum_r^l (CA_t \cdot (LF_t - DE_{t,r}) \cdot 8760 \cdot PR_t \cdot) \text{ -> Solar-PV variant} \tag{3}$$

$$EO_t^{gross} = EO_t^{net} \cdot (1 + PL_t) \tag{4}$$

Calculation of materials associated with life cycle stages $(s = 1,2, \dots 12)$ started with establishing material inputs (M) from datasets in tonnes per 1 GW capacity for each material $(m = 1,2, \dots n)$. Total inputs flows (I) with index $(i = 1,2, \dots n)$ for energy $(e \subseteq I)$ and labour $(l \subseteq I)$ were established by summation across life cycle stages (s):

$$I_i = \sum_i^n \sum_s^{12} I_{t,i,s} \tag{5}$$

Calculation of input flows for life cycle stages $(s = 1,3,5,11)$ for mining to the establishment of power plants, as well as decommissioning, were based on an intensity factor (A) for electricity input in GJ/tonne $(e \subseteq A)$, fuel inputs in GJ/tonne $(f \subseteq A)$, or labour input in hours/tonne $(l \subseteq A)$. To obtain societal energy system value for electricity inputs, a current global energy system fuel equivalent conversion factor (s) was applied based on the global electricity mix, to incorporate the additional fuel inputs needed to provide electricity inputs to the grid (specified in section 2.3). This results in the used equation:

$$I_{t,i,s} = M_{s,t} \cdot A_{s,t,i} \cdot s_{i=e} \tag{6}$$

To establish fuel inputs (FU) for fossil fuel, nuclear and biomass plants in life cycle stages $(s = 6,7,8)$ net electricity output (EO) was divided by the energy density of the fuel (ED) in GJ/tonne and power plant lower heating value efficiency (ef) in % as:

$$FU_{t,} = EO_t^{net} / (ED_t \cdot ef_t) \tag{7}$$

Calculations for input flows (I) for energy and labour in transport life cycle stages $(s = 2,4,7,10,12)$ were calculated based on truck, train, gas pipeline, oil pipeline, and shipping intensity factors (B) in GJ per tonne-kilometre for energy $(e \subseteq B)$, and in hours per tonne-kilometre for labour $(f \subseteq B)$. Distance factors (D) in kilometre determined the number of tonne-kilometres transported resulting in the formulas:

$$I_{s,t,i} = M_{s,t} \cdot B_{s,t,i} \cdot D_{s,t,i} \cdot s_{i=e} \tag{8}$$

$$I_{s,t,i} = FU_{s,t} \cdot B_{s,t,i} \cdot D_{s,t,i} \quad (9)$$

Calculations for fuel extraction and processing energy and labour cost $(s = 6)$ were based on processing energy intensity factors (L) resulting in formula:

$$I_{s=6,t,i} = FU_{s,t} \cdot L_{s,t,i} \cdot s_{i=e} \quad (10)$$

Calculations for operation and maintenance $(s = 8,9)$ were based on parasitic load factor (PL) for operational electricity use, a maintenance energy factor (C) in GJ/GW/year. To compute labour requirements an operational labour factor (E) in hours per GJ and annual maintenance labour (F) in hours per GW per year was used. Resulting in the formulas:

$$I_{s,t,i} = (EO_t^{net} \cdot PL_{s,t} + C_{s,t,i}) \cdot s_{i=e} \quad (11)$$

$$I_{s,t,i} = EO_t^{net} \cdot E_{s,t} + F_{s,t,i} \quad (12)$$

GHG emissions were calculated based on direct CO_2 emissions, methane (CH_4) and nitrous oxide (N_2O) emissions. Calculations for GHG flows (CO) were derived from fuel equivalent input values for all life-cycle stages $(s = 1,2, \ldots 12)$ by multiplication with IPCC default CO_2, CH_4 and N_2O emissions factors (G) in tonne/GJ. In case of electricity inputs, a global composite CO_2 emission factor of 0.14 tonnes per GJ (also expressed as 140,681 tonnes/PJ and 506 gCO_2/kWh) was used, which was calculated in this study from the global 2015 energy mix based on the same IPCC default CO_2 emissions factors. The formula is expressed as:

$$CO_t = \sum_s^n \sum_{i=e}^n I_{s,t,i} \cdot G_i \quad (13)$$

Similarly, for calculating CH_4 and N_2O emissions associated with electricity use in the electricity generation supply chain, composite CH_4 and N_2O emission factor were calculated, and CH_4 and N_2O emissions were converted into CO_2 equivalent (CO_2 eq.) emission values (see online SI section 1.1.4).

2.3. Energy Return Metrics

Many energy flow calculations in the literature utilise the Energy Return on Investment (EROI), qualitatively defined as the ratio between the energy output for a process to the energy input required to establish and operate it. EROI considers as inputs energy that needs to be invested by society to retrieve energy supplied to that society. It is thereby different from inputs summed as Cumulative Energy Demand (CED) used in Life Cycle Assessment (LCA), as this includes all primary energy harvested from nature/the geo-biosphere. For example, the kinetic and photonic energy inputs for wind and solar electricity, and the energy content of fossil fuels [43,44]. Both are not considered in EROI calculations as inputs. Thus, the energy content of fuels combusted in power plants was not included as an energy input, in contrast to CED estimates [44].

Historically, the absence of an explicit quantitative formulation of the energy systems flow in many EROI studies has led to substantial boundary problems, in what to count as energy inputs and outputs, as well as the cut-off of included cradle-to-grave processes [30,45]. Several efforts have been made to standardise and extend EROI calculations [45–49]. Brandt et al. (2011) developed a mathematical bottom-up framework which explicates two novel elements, resulting in four Energy Return Ratios (ERR) that form variants of the EROI. First, a distinction between Gross and Net Energy Ratios (GER and NER) (see table 2). In the NER energy output the numerator excludes the portion of output consumed (embodied) to provide indirect materials and energy sources for the energy system of study, which is not subtracted in the GER from the energy output. Second, two variants which excludes any internally self-consumed energy, such as parasitic load of power plants, or oil consumed to fuel an oil refinery. These Gross and Net External Ratios (GEER and NEER) provide insights in the ability of an energy generating process to increase the energy supply to society. The majority of EROI calculations for power plants in the literature are composed of a GEER, because they exclude self-consumption of electricity as an input. However, the boundaries taken in terms of life cycle stages vary substantially from study to study, as identified in meta-analyses [19]. In the scope of this study both the life cycle GER and GEER from mine-mouth to disposal are calculated as variants of the EROI. Comparisons of results of this study with EROI studies that do not take a full life cycle perspective into account, thus fall short.

Table 2. Life Cycle Energy Return Ratio’s (ERR’s) as adapted from [7]

ERR Type	**Formulation**	**Description**

Gross Energy Return	$GER_n = \frac{EO_n}{\sum_s I_{s=8,9} + \sum_s I_{s=4,5,6,7,10,11,12} + \sum_s I_{s=1,2,3}}$	Energy output EO from electricity generation pathway n divided by inputs of externally generated energy ($s = 4,5,6,7,10,11,12$), and indirect embodied energy ($s = 1,2,3$) for Gross and Net External Energy Return ratios. Includes self-produced energy ($s = 8,9$) for Gross and Net Energy Return Ratios. To establish Net and Net External Energy Return the fraction r_s of indirect energy consumption that comes from the pathway to supply indirect embodied energy inputs ($s = 1,2,3$) is subtracted
Net Energy Return	$NER_n = \frac{EO_n - r_s \sum_s I_{s=1,2,3}}{\sum_s I_{s=8,9} + \sum_s I_{s=4,5,6,7,10,11,12} + \sum_s I_{s=1,2,3}}$	
Gross External Energy Return	$GEER_n = \frac{EO_n}{\sum_s I_{s=4,5,6,7,10,11,12} + \sum_s I_{s=1,2,3}}$	
Net External Energy Return	$NEER_n = \frac{EO_n - r_s \sum_s I_{s=1,2,3}}{\sum_s I_{s=4,5,6,7,10,11,12} + \sum_s I_{s=1,2,3}}$	
Additional parameters		
Self-use fraction of indirect energy consumption	r_s	Fraction of indirect energy consumption *I* which was generated by the pathway of study n to supply the energy needed to establish material inputs into various energy supply stages.

2.4. Electricity inputs

Today the electricity mix is largely supplied from fuel based sources. Therefore, to establish the energy input based on the currently energy system equivalent, so as to enable comparisons with the 2015 energy system wide GER and GEER, electricity inputs were converted using a conversion factor (s), as included in equations 6,8,10, and 11. Note that the base case results therefore can only be interpreted to compare energy technologies in the context of the current fossil fuel energy system, and are not valid for scenarios of fully non-fuel based energy systems. To include results for a non-fuel based system a sensitivity analysis was carried out with a conversion multiplier of 1.0 (see section 2.6). Typically, as a conversion multipliers, also referred to as a primary energy equivalent or a primary energy factor, values of 2.6 or 3.0 are used as defined by BP and the IEA, respectively [50,51]. In this study an electricity-to-primary conversion multiplier of 2.24 was used, calculated from the 2015 global electricity grid mix based on IEA data and average generation efficiency per technology as per table 1 [52],[52].

2.5. GHG emissions metric

CO_2 emitted per PJ of electricity, as well as CO_2 emission equivalents for methane (CH_4) and nitrous oxide (N_2O) per PJ of electricity, was calculated by multiplying fuel combusted in each life-cycle phase with fuel-specific IPCC emission factors, such as 74.1 tonne CO_2 per TJ for diesel fuel, as listed in Table S5. To obtain emissions associated with electricity consumption, a composite emission factors of 0.14 tonne CO_2 per GJ (506 gCO_2/kWh) of electricity, 1.54×10^{-6} tonne CH_4 per GJ of electricity, and 9.04×10^{-7} tonne N_2O per GJ of electricity was calculated in this study, based on the global 2015 electricity generation mix (see SI section 1.14). For this, the share of energy input for electricity generation globally for a specific technology was calculated by dividing the global energy input required by a specific technology with the total energy input required by all the technologies based on IEA data [52]. Next, technology specific emission values were calculated based on IPCC CO_2 emission values of the fuel type used for powering specific technologies. Finally, the composite emission factor was calculated as the sum of the products of technology specific emission values and the share of technology specific energy input values. Other incorporated CO_2 emission include: (1) limestone during cement production; (2) the carbon electrode during aluminium production; (3) calcium-, magnesium- and sodium-carbonate during glass production; (3) calcium-, magnesium- and sodium-carbonate during silicon metal production, (4) limestone during sulphur dioxide removal from flue gas; and (5) limestone during hydrogen chloride and hydrogen fluoride removal from flue gas and sodium bicarbonate ($NaHCO_3$) drying to sodium carbonate (Na_2CO_3).

2.6. Technology variability ranges

The sensitivity of results to changes in five parameters was independently assessed to gain insights in geographic and technological differences. First, the sensitivity of GEER to changes in the conversion factor from electricity to energy system equivalents was calculated. In the minimum case a conversion of 1.0 was assumed, representing a fully flow source based system with no fuel inputs (e.g. a 100% renewable system). In the maximum case it was assumed that all electricity inputs are from fuel based power plants with an efficiency of 30%, based on a 3.3 electricity-to-primary equivalence factor [53]. Second, the sensitivity of GHG emissions due to differences in the minimum and maximum IPCC CO_2 emission intensity values was computed [54–56]. For example, the IPCC lists 90.9 and 115 tonnes of CO_2 perTJ for lignite as the minimum to maximum emission values, respectively. In addition, the composite emission factor of 0.14 tonne CO_2 per GJ was also set to a minimum and maximum value. The maximum was based on the 2015/16 Chinese electricity grid mix which has a 65% coal share, resulting in a 0.19 tonne CO_2 per GJ value for electricity inputs [57]. The minimum value of 0.016 tonne CO_2 per GJ was based on the 2050 IEA/IRENA energy transition perspective study grid mix, indicative of a future low-carbon electricity mix [4].

Third, effect of variations in power plant efficiency for fuel plants and in load factors for flow based plants were calculated for the GEER, jobs, and GHG emissions. A literature analysis of efficiencies and load factors was carried out with minimum and maximum values as per Table 1 (see column efficiency and load factor). Fourth, the impact of variation in fuel transport distance on the GEER and job numbers was determined based on a minimum and maximum value (see Table 3) using actual cases, such as biomass pellets imports for Drax in the UK from Louisiana on the US east coast, lignite transport for the Opatovice power plant in Czech Republic by electric train from the German Profen lignite mine. Fifth, variation in GEER and jobs due to changes in fuel specific energy in GJ/tonne based on minimum and maximum calorific value ranges (see Table 4) were computed.

Table 2. Transport variation minima and maxima

Fuel		Transport
Hard coal	Min	Plant at mine: 30 km diesel-electric train
	Max	S-Africa to Japan: 15.000 km ship+250 km truck
Lignite	Min	Germany: 30 km conveyor belt
	Max	Greece: 500 km diesel-electric train
Fuel Oil	Min	At refinery: 30 km pipeline
	Max	US-China: 19.000 km ship+250 km truck
Nat.gas pipeline	Min	Plant at field: 30 km pipeline
	Max	Russia-UK: 5000 km pipeline
Nat.gas LNG	Min	Algeria to Spain: 1000 km
	Max	Algeria to Japan: 18000 km
Biomass Pellets	Min	Plant at forest: 30 km diesel-electric train
	Max	US-UK: 15.000 km ship+250 km truck
Nuclear fuel	Min	Local enrichment: 30 km truck
	Max	Imports: 15.000 km ship + 250 km truck

Table 3. Fuel energy content LHV minimum to maximum range

Fuel	Minimum (GJ/tonne)	Base case (GJ/tonne)	Maximum (GJ/tonne)
Hard Coal	16.1	22.0	28.8
Lignite	5.2	9.0	14.5
Fuel Oil	40.0	41.0	42.6
Natural Gas	38.0	52.0	54.0
Biomass Pellets	14.4	17.3	17.9
Biomass MSW	3.1	9.3	20.2

2.7. Data Specifics and Sources

To obtain values for the metrics above for materials, jobs, and energy inputs were calculated for all life-cycle phases of the selected electricity technologies, either per GW capacity or per GJ of electricity output. Data was collected from peer-review, industry, mine-site and factory-site analyses, and life-cycle assessment (LCA) literature, and compiled using a bottom-up approach and converted into metric units. Details on data inputs and sources for all technologies, including direct data values and all parameters, are available in the Supplementary Information (SI) document for manuscript brevity.

3. Results

3.1. Base case results

The results for the four metrics of material consumption, energy return ratio, number of jobs and GHG emission are shown in Figure 2 for each life-cycle phase per technology.

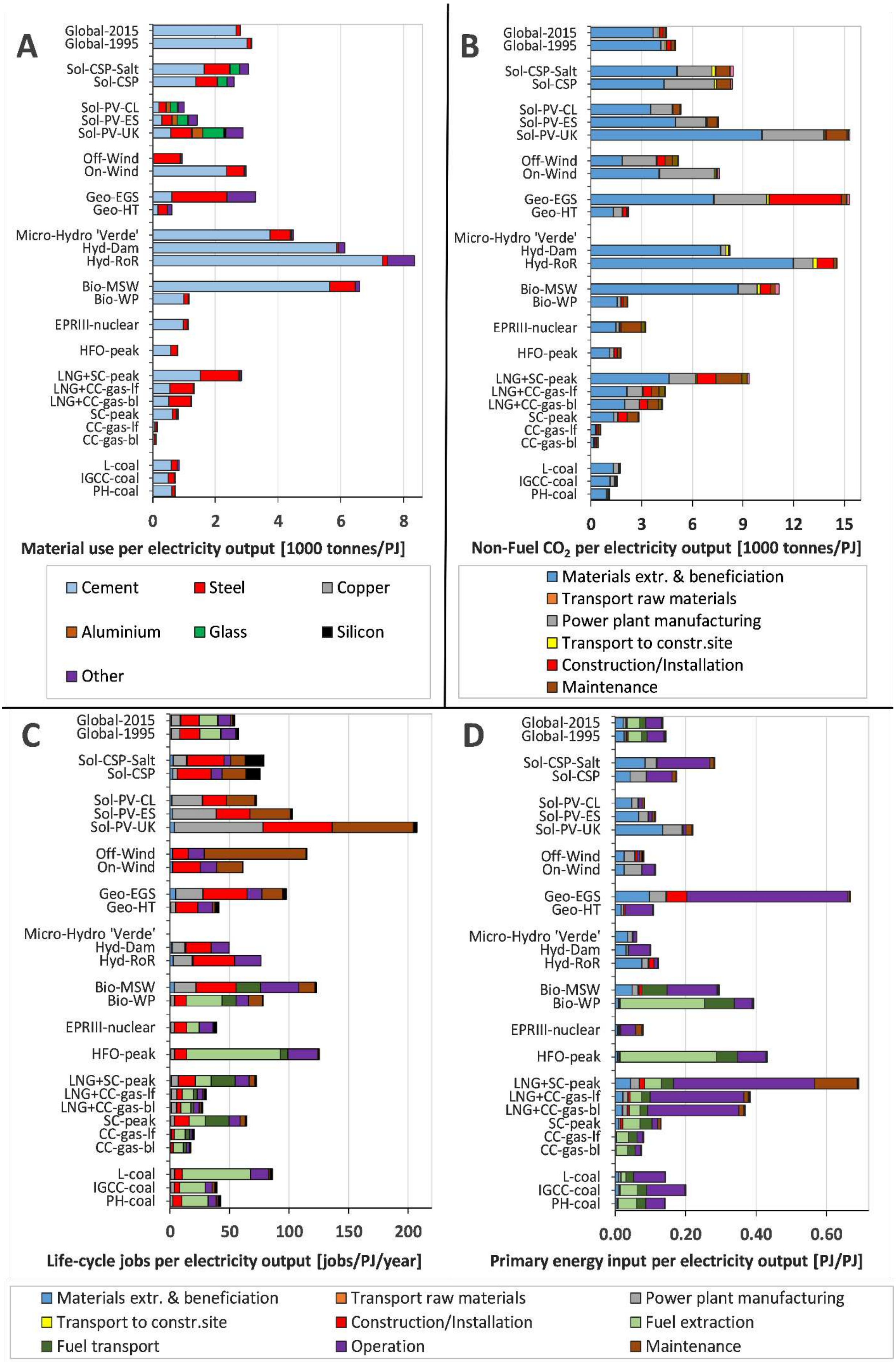
A
Global-2015
Global-1995
Sol-CSP-Salt
Sol-CSP
Sol-PV-CL
Sol-PV-ES
Sol-PV-UK
Off-Wind
On-Wind
Geo-EGS
Geo-HT
Micro-Hydro 'Verde'
Hyd-Dam
Hyd-RoR
Bio-MSW
Bio-WP
EPRIII-nuclear
HFO-peak
LNG+SC-peak
LNG+CC-gas-lf
LNG+CC-gas-bl
SC-peak
CC-gas-lf
CC-gas-bl
L-coal
IGCC-coal
PH-coal
0
2
4
6
8
Material use per electricity output [1000 tonnes/PJ]
Cement
Steel
Copper
Aluminium
Glass
Silicon
Other
B
Non-Fuel CO$_2$ per electricity output [1000 tonnes/PJ]
0
3
6
9
12
15
Materials extr. & beneficiation
Transport raw materials
Power plant manufacturing
Transport to constr.site
Construction/Installation
Maintenance
C
Life-cycle jobs per electricity output [jobs/PJ/year]
0
50
100
150
200
D
Primary energy input per electricity output [PJ/PJ]
0.00
0.20
0.40
0.60
Materials extr. & beneficiation
Transport raw materials
Power plant manufacturing
Transport to constr.site
Construction/Installation
Fuel extraction
Fuel transport
Operation
Maintenance

Figure 2. Life cycle material use, primary energy input, job generation GHG emissions comparison across technologies. **A.** Material use excluding fuels in 1000 tonnes per PJ electricity output. **B.** GHG emissions related to material flows, excluding fuel extraction, fuel transport and operation. Expressed in tonnes of CO_2 equivalent (CO_2 eq.) per PJ of electricity output. **C.** Life cycle job equivalents to provide one PJ per year. **B.** GJ primary energy input per GJ of electricity output.

3.2. Material use metric

Materials used in the largest quantities were steel and cement, at about 10 to 1000 times greater than that of other materials by mass, as shown in Figure 2A. Average global material use in 2015 was established at 1498 and 465 tonnes/PJ for cement and steel, respectively. Hyd-RoR is the most material intensive technology, requiting 8338 tonnes of total materials per PJ electricity output. The second highest total material amounts, at 6605 tonnes/PJ, are used in Bio-MSW plants. The technology with the highest cement consumption was hydro-power with 5864 and 7328 tonnes/PJ for Hyd-Dam and Hyd-ROR, respectively. Geo-EGS required the highest overall steel inputs at 1746 tonnes/PJ. Nuclear and coal power plants have medium steel requirements. Natural gas power has a low material footprint, however, when an LNG supply chain is utilised, material use increases ~3-fold for cement and ~12-fold for steel. It can be anticipated that steel inputs in the electricity sector will expand rapidly as the renewable energy share increases, due to solar-CSP, On-Wind, and Off-wind. Glass is required mainly for solar energy, especially in low solar radiation regions per PJ of electricity output.

3.3. Labour input metric

As shown in Figure 2C, the most labour-intensive life-cycle phase per PJ of electricity for thermal power plants is fuel extraction, and installation, operation and maintenance for renewable power plants. The results confirm the perspective that employment will grow substantially as the electricity system shifts from fuel to renewable energy sources, and that this shift will result in up to a tripling of present employment levels in the electricity sector.

3.4. Energy Return Ratio metric

Primary energy inputs per unit of electricity output for the 12 life-cycle stages of each technology are shown in Figure 2B. For thermal power plants the highest consumption occurs during operation due to high parasitic load and fuel extraction. For renewable technologies, the construction material extraction and beneficiation and plant component manufacturing tend to be the most energy intensive. The gross energy ratio (GER) and gross external energy ratio (GEER) are shown in Figure 3 for each technology, alongside an estimated 2015 global GER average of 7.4 and global GEER average of 11.3 PJ/PJ. Technologies with a GEER substantially below the global average are: HFO-peak plants, due to the high energy consumption during fuel extraction and refining; LNG based electricity generation, explained by transport and (re)-gasification electricity inputs requirements and boiling losses; Solar-CSP-Salt, because of high embodied energy; Bio-MSW and Bio-WP, due to low fuel energy content; Geo-EGS, because of high steel inputs for geothermal at large depths; and Sol-PV-UK, due to low solar irradiation at high latitudes. The inclusion of parasitic load for the GER ratio results in a much lower outcome relative to the GEER for PH-Coal, IGCC-Coal, L-Coal, EPRIII-nuclear, Biomass-MSW, Hyd-Dam, Geo-HT, Sol-CSP, Sol-CSP-Salt, and Geo-EGS. Other technologies have a low parasitic load and thus their GEER value is quite close to the GER.

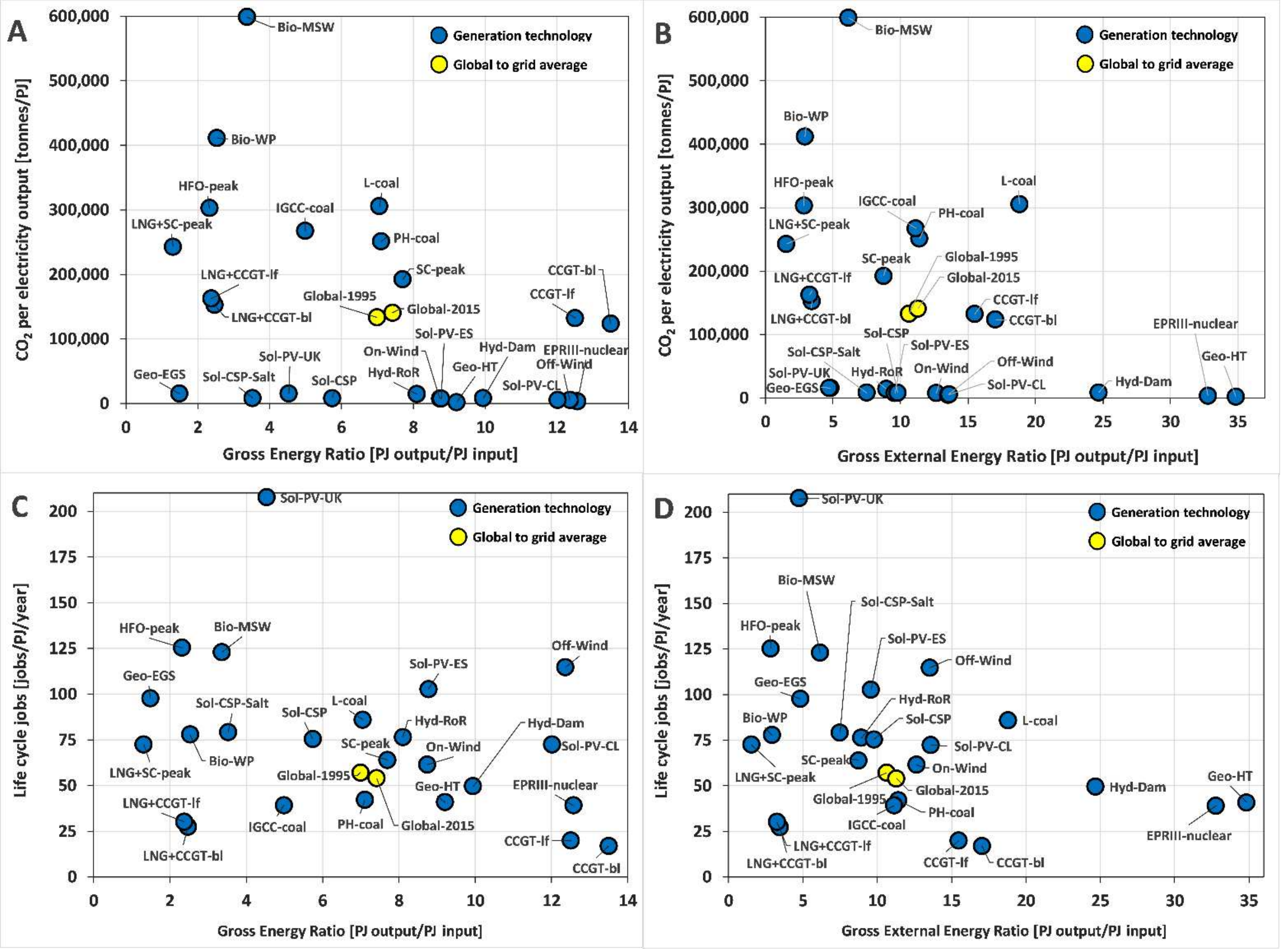

Figure 3. Technology cross-comparison in terms of GHG emission, gross energy ratio (GER), gross external energy ratio (GEER) and jobs across the entire technology life-cycle. Metrics for electricity generation (blue), and the global electricity mix (yellow) in scatter plots. **A.** Comparison of life-cycle GHG emissions

versus GER. x-axis: GER in PJ/PJ, y-axis: GHG emissions per electricity output in metric tonnes of CO_2 equivalent (CO_2 eq.) per PJ. **B.** Comparison of life-cycle GHG emissions versus GEER. X-axis: GEER in PJ/PJ, y-axis: GHG emissions per electricity output in metric tonnes of CO_2 equivalent per PJ. **C.** Comparison of life-cycle job generation versus GER. x-axis: GER in PJ/PJ, y-axis: life-cycle job requirements per electricity output per year in jobs/PJ/year. **D.** Comparison of life-cycle job generation versus GEER. X-axis: GEER in PJ/PJ, y-axis: life-cycle job requirements per electricity output per year in jobs/PJ/year.

3.5. GHG emission metric

The largest source of CO_2 equivalent emissions for thermal power plants are fuel related with only a minor share (below 3%) from other life-cycle phases, as illustrated in Figure 2D. For non-fuel technologies, the largest proportion of CO_2 equivalent is emitted during raw material extraction and beneficiation, with a share ranging from 40% for Offshore-Wind to 95% for Hydro-Dam, cf. Figure 2B.

A global average 1995 CO_2 equivalent emissions level of 133,8090 tonnes/PJ (482 gCO2 eq./kWh), was calculated. Based on the 2° Paris Climate Agreement target, at least an 85% GHG emission reduction is needed by 2050 for the electricity sector [4], which thereby implies a technology maximum of 20,071 tonnes CO_2 eq./PJ, or 72 g CO_2 eq./kWh. All fossil fuel-based technologies are substantially above this limit. Biomass technologies do not meet the requirement, unless fuel combustion is discounted on the principle of biomass growth carbon sequestration. All flow based renewable electricity generation technologies yield emissions below a 20,071 tonnes CO_2 eq./PJ, or 72 g CO_2 eq./kWh, threshold value.

3.6. GEER Variability ranges

The sensitivity of GEER to variations in the electricity-to-primary multiplier, fuel transport distances and modalities, fuel energy content, operation efficiency, and load factors is shown in Figure 4. The results for lowering the electricity-to-primary conversion multiplier from 2.24 to 1, and increasing it to 3.3, is shown in Figure 5A. Variation of the electricity-to-primary multiplier has the largest effect on the GEER for L-Coal, EPRIII-Nuclear, Hyd-Dam, Geo-HT, and Sol-PV. The GEER range for L-Coal is caused by strip-mining energy costs which is solely powered by electricity. Nuclear-EPRIII GEER variation is due to high electricity requirements in several life-cycle phases. Hyd-Dam, Geo-HT and Sol-PV GEER ranges are caused by the energy consumption in mining, processing, and manufacturing. This multiplier causes limited changes in the GEER of other technologies.

The impact of fuel transport distances as per Table 3 on GEER is substantial for coal technologies and natural gas pipeline transport, as shown in Figure 4B. A distance of 15.000 km coal shipping and 250 km truck from South Africa to Japan results in a far lower 6.4 PH-Coal GEER, compared to a 36.3 GEER for only 30 km local train transport. The change of lignite transport of 30-km by conveyor belt or transport by diesel-electric train across 500 km results in an L-Coal GEER range of 23.7 to 8.3. A natural gas pipeline distance of 30 km versus 5000 km yields a GEER range for CCGT-bl from 26.9 to 6.8. The impact on LNG transport to natural gas power plants is limited since the GEER is already quite low which dampens the effect.

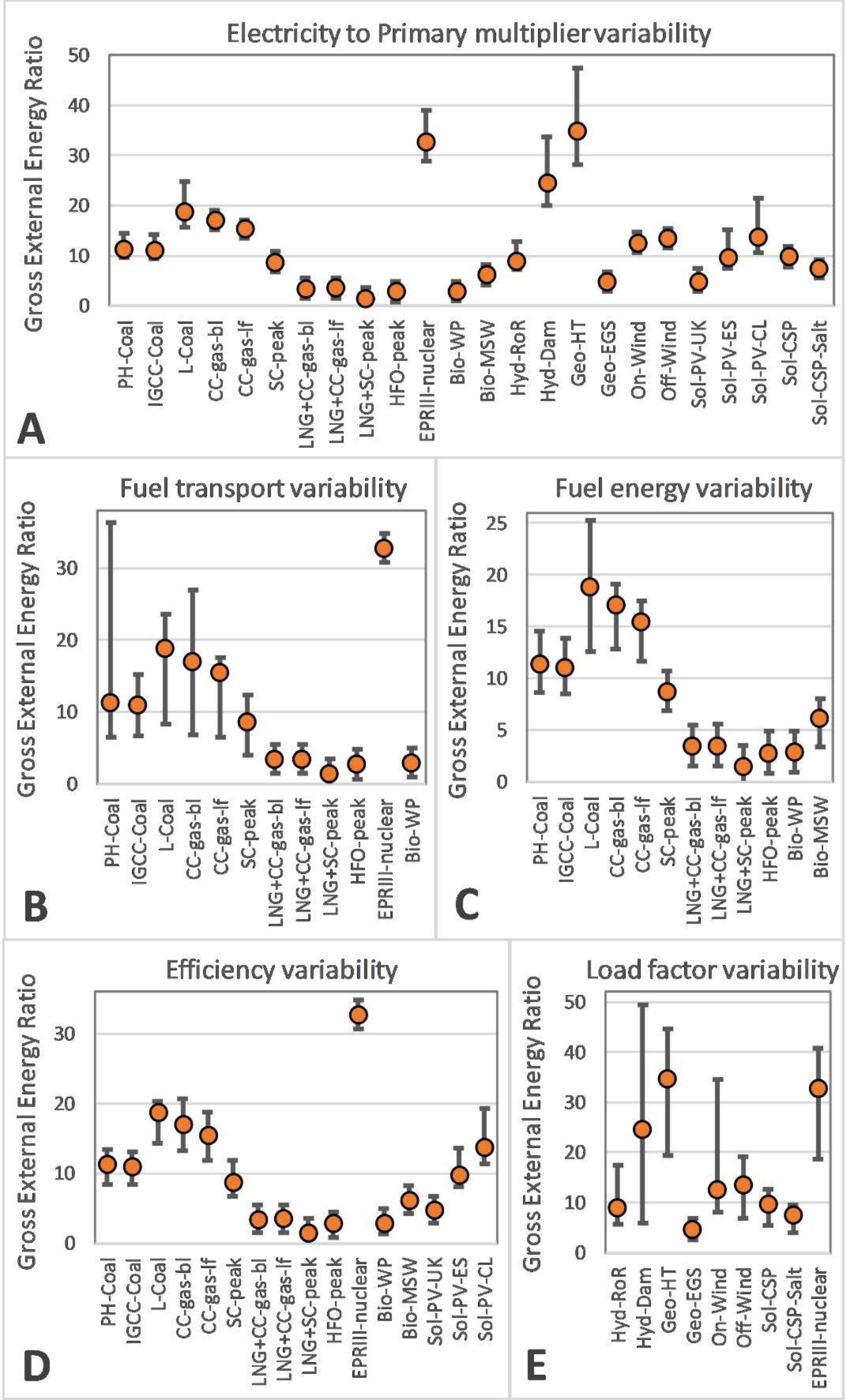

Figure 4. Variability of GEER in function of changes in the electricity-to-primary conversion factor, fuel transport, fuel energy density, plant efficiency and load factor. Technologies are shown on the x-axis and GEER on the y-axis. **A.** The effect of varying the electricity-to-primary conversion factor, from 1 to 3.3, on

GEER. **B.** The impact of transporting fuel to various distances using different modalities, as indicated by min-max values in Table 3, on GEER. **C.** Impact of variations in fuel energy densities, as per min-max values in Table 4, on GEER. **D.** Impact of differences in power plant operational efficiencies, range shown in Table 1, on GEER. **E.** Impact of variations in load factors, as per min-max values in Table 1, on GEER.

Results for variability in fuel specific energy content mainly affect coal GEER values as displayed in Figure 4C. Variations in plant operation efficiency substantially impact Bio-WP, Sol-PV GEER values, cf. Figure 4D, as per Table 1. Nuclear EPRIII, HFO-Peak and LNG based natural gas power is marginally affected by efficiency change. Coal-based power sees similar sized GEER variations due to efficiency as caused by changes in fuel energy content.

Load factor variation has a substantial impact on all the flow technologies, cf. Figure 4E. For load factor values see Table 1. Differences between Sol-PV-UK and Sol-PV-CL with load factors ranging from 13.6% to 39% yields a GEER difference between 4.7 and 13.6. The analysis for onshore wind load factors from the worst 14% to best 60% yields a GEER range of 8.1 to 34.5, and for offshore wind a variation between 20% and 55% yields a GEER range from 6.9 to 19.1. The GEER triples from 5.8 to 17.4 for Hyd-ROR with load factor shifts from 30% to 90%, and grows for Hyd-Dam from 5.9 to 49.6 as the load factor is shifted from 11% to 95%. Sol-CSP improves from 5.4 to 12.7 with a load factor increase from 15% to 35%, and with molten salt storage improves from 4.1 to 9.5 under a load factor shift from 30% to 70%. The GEER variability for geothermal plants is due to load factor variation from 41% to 95%, reported world-wide [58].

3.7. Job Creation Sensitivity

The sensitivity of the number of jobs is shown in Figure 5. The impacts of fuel transport distances (see Figure 5A) on job numbers are mainly visible for HFO-peak, with a growth from 119 to 245 life-cycle jobs due to a shift from 30 km by pipeline to 19.000 km by oil tanker plus 250 km by truck. Specific energy content variation of fuels (see Figure 6B) impacts primarily lignite coal life-cycle jobs due to the increase in mining labour with an energy content drop. Also, a substantial shift is found for Bio-MSW with a jobs/PJ/year increase from 112 to 163 when 20.2 instead of 3.1 GJ/tonne specific energy in municipal solid waste is considered.

Power plant conversion efficiency effects (see Figure 6C) on job numbers are highest for Bio-WP, Bio-MSW, and Sol-PV. Solar-PV efficiency affects the number of needed solar panels, which results in reduced numbers of manufacturing and installation jobs. Job requirements range from 150 to 246 for Sol-PV-UK, from 74 to 121 for Sol-PV-ES, and from 52 to 86 for Sol-PV-CL, relative to an improvement in solar panel efficiency of 14% to 24%. The impacts of load factors (see Figure 6D) on jobs is substantial for flow based electricity generation technologies. Life-cycle jobs per PJ per year decline from 134 to 59 and from 209 to 38 for Hyd-ROR and Hyd-Dam, respectively, if load factors grow from 30% to 90% and from 11% to 95%. The values for On-Wind and Off-Wind change from 87 to 31 and from 207 to 84 jobs when load factors change from 14% to 60% and from 20% to 55%, respectively. Similarly, Sol-CSP and Sol-CSP-Salt lifecycle job needs per PJ per year drop from 128 to 75 and 140 to 79 when the load factor increases from 15% to 35% and from 30% to 70%, respectively. The impacts of load factors show that jobs growth for renewable energy is highly dependent on the location and thus the intensity of the associated wind or solar resource.

3.8. GHG emissions variability ranges

The impact of IPCC CO_2 intensity values and power plant efficiency variations on GHG emissions is shown in Figure 6A and Figure 6B, respectively. The largest change due to IPCC emissions range is visible for biomass. Therein, Bio-WP resulted in 358,571 to 487,2846 tonnes of CO_2 equivalent per PJ, which corresponds to 1291 to 1754 g of CO_2 eq. per kWh electricity. Bio-MSW in a range from 518,469 to 709,635 tonnes of CO_2 eq. per PJ of electricity, which is 1866 to 2555 g of CO_2 eq. per kWh, excluding the subtraction from initial absorption of CO_2 by plants. The impact on other technologies is minor given the low spread in their IPCC emissions range.

The impact of power plant efficiency on GHG emissions is substantial, with variations for PH-Coal from 238,172 to 355,608 tonne/PJ (857 to 1280 gCO_2eq./kWh), for IGCC-coal from 250,786 to 374,310 tonne/PJ (903 to 1348 gCO_2eq./kWh) and for L-coal from 271,495 to 446,383 tonne/PJ (977 to 1607 gCO_2eq./kWh), relative to efficiencies ranging from 26% to 45%. Impacts on natural gas and oil-fired power are close to a doubling in emissions. The impact is also substantial for Bio-WP which sees its emissions drop from 949,575 to 343,848 tonnes of CO_2 eq. per PJ of electricity (3418 to 1238 gCO_2eq./kWh) excluding carbon neutrality, and from 57,213 to 21,941tonnes of CO_2 eq. per PJ (206 to 79 gCO_2eq./kWh) when including carbon neutrality. Carbon neutrality here meaning that since all carbon emitted by burning biomass was once absorbed from the atmosphere, and is thus not counted in the emission values. Similarly, Bio-MSW emissions drop from 1,205 to 0.445 million tonnes of CO_2 eq. per PJ (4341 to 1639 gCO_2eq./kWh) within a 10% to 27% efficiency range excluding carbon neutrality, and from 21,487to 14,982tonnes of CO_2 eq. per PJ (77 to 54 gCO_2eq./kWh) when including carbon neutrality. Efforts to increase the efficiency of power plants by introducing ultra-supercritical technologies are critical from a carbon dioxide reduction perspective. However, all renewable and nuclear energy sources deliver at least a factor 10 and up to 100 times lower life-cycle emissions than fossil fuel based power sources, and should receive the highest priority from a GHG emissions reduction perspective.

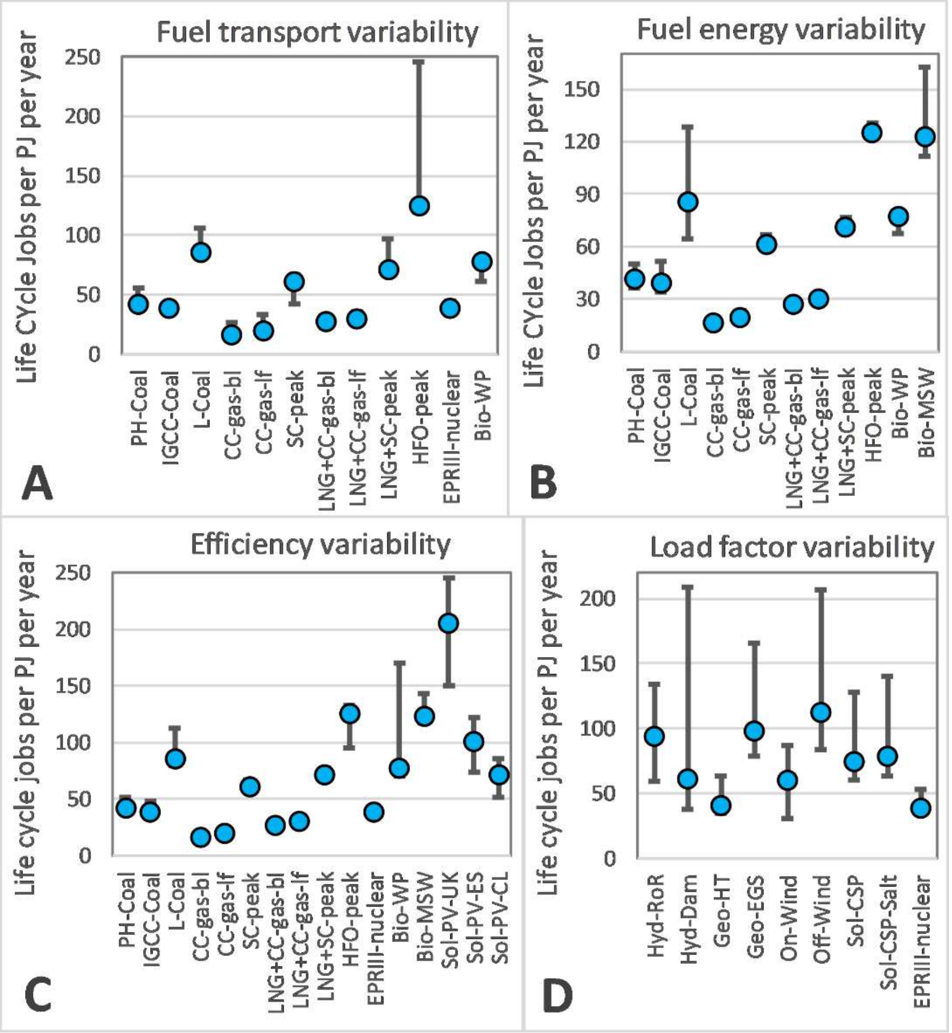

Figure 5. The variability of life-cycle job numbers due to changes in fuel transport, fuel energy density, plant efficiency and load factor. Technologies are shown on the x-axis and the y-axis displays total life-cycle jobs, in jobs per PJ electricity output per year. **A.** The impact of transporting fuel to various distances by different modalities, as indicated by min-max values in Table 3, on the number of jobs. **B.** Impact of variations in fuel energy densities, as per min-max values in Table 4, on the number of jobs. **C.** Impact of differences in power plant efficiencies, range shown in Table 1, on the number of jobs. **D.** Impact of variations in load factors, as per min-max values in Table 1, on the number of jobs.

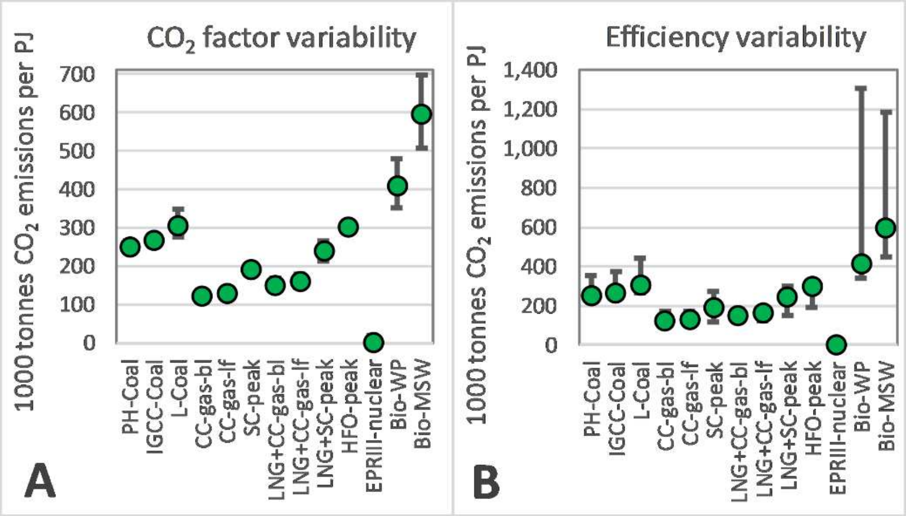

Figure 6. The variability of life-cycle GHG emission in function of IPCC CO$_2$ emission factor ranges combined with electricity generation technology mix caused CO$_2$ emission ranges and power plant efficiency ranges. Technologies are shown on the x-axis and CO$_2$ emission equivalent, in 1000 tonnes per PJ electricity output, on the y-axis. **A.** Impact of fuel-specific IPCC CO$_2$ emission factor ranges, as listed in Table S5, and the variations caused by the mix of renewable and non-renewable generation technologies on life-cycle GHG emission. **B.** Impact of power plant operational efficiency ranges, as per min-max values in Table 1, on life-cycle GHG emission.

4. Discussion

4.1. Methodological boundaries

The methodology developed and implemented here evaluates nineteen technologies using a metric comparison including an average comparative benchmark for the global electricity system. We focus on discussing the gross external energy ratio (GEER) as a variant of the energy return on investment (EROI) defined by Brandt et al. 2011 [47] (see section 2.3), the GHG emissions profile, and life-cycle number of jobs required per PJ output per year. Although, the material use metric served as a basis for calculating the other metrics, it did not offer insights to wide-ranging policy implications on its own, therefore it is not discussed in detail in this paper. In this study, GHG emissions were calculated based on direct CO$_2$ emissions, CH$_4$ and N$_2$O emissions resulting from fuel combustion. In general, according to previous studies, CO$_2$ accounts for approximately 95% of all GHG emissions in the energy sector and the remaining 5% GHG emission consists mostly of methane and nitrous oxide [54,56,59]. CO_2 emissions yielded by methane flaring were included in the LNG supply chain analyses, but unintended fugitive emissions were excluded. In case of the natural gas supply chain, the total supply chain GHG emissions, including CO_2, represent between 5% and 43% of total emissions, with a median estimate of 16% [24]. The natural gas supply chain is the largest emitter of methane per electricity produced [61,62].

The equivalent job requirement metric incorporates labour inputs in the entire supply-chain per electricity output across the power plant lifetime. The disadvantage of this metric is that a temporal profile is lost, but the advantage is that a macro comparison across energy technologies can be made. In contrast an alternative metric, estimates of jobs per technology capacity unit, is not comparable across technologies due to differences in technology capacity factors resulting in substantial variation in electricity output per year per GW capacity.

4.2. Study Relevance

To our knowledge, the methodology and results presented compare electricity generation technologies for the first time taking into account a complete process-chain life-cycle, with uniformly applied system boundaries and metrics for energy return ratio, material consumption, GHG emission and labour input requirements. The present bottom-up analysis validates previous electricity generation life cycle assessments. Our study demonstrates that local context is important in life-cycle energy-economic analysis of technologies as previously indicated [38,63]. In addition, this study presents new findings on the effect of future electricity generations technology implementations on job creating potential throughout the supply chain, as well as on the effect of LNG transport distances on the techno-economic feasibility of LNG based technologies. For a detailed comparison to previous studies the "Comparisons to previous studies" section as well as Table S6, S7 and S8 in the online SI document can be consulted.

We also present novel global averages for the EROI calculations of the GER and GEER, life-cycle number of jobs required per PJ output per year and GHG emissions. These are helpful to understand how feasible proposed global energy transition scenarios are, by enabling better ranking of scenarios and technology options in relative terms to the current 2015 electricity generation system. Such a global approximation yields additional insights especially for labour and EROI values such as the GER and GEER.

4.3. Energy Return on Investment

Globally, an average GEER benchmark of 11.3 was established, measured as electricity output to the grid per primary energy equivalent spent, excluding power plant operational electricity self-consumption (e.g. parasitic load). GEER is a useful indicator for the size of the electricity sector size required to supply electricity output [13]. For example, a GEER reduction from 11 to 9 indicates that a 1.25 times larger electricity sector is needed to supply the same end electricity output, and a drop from 11 to 5 implies a 2.5 times larger sector for the same end electricity output. A drop in GEER during a technology transition thus implies that far more power plants, factories, investments, and jobs are required to obtain the same level of electricity output as before the transition. As such, far more resources would need to be allocated from other sectors to the electricity sector, resulting in lower overall wealth. Consequently, this rapid shift can cause economic stresses and disruptions in the form of recessions and cost inflation [64]. Energy return ratio's such as the GEER can thus be used by energy modellers to provide policy advice on: (1) how the size of the electricity sector will evolve over time during transitioning to various electricity generation technology scenarios, and (2) what the consequence will be for sector inputs.

Few economic analyses have been carried out to determine the value of a heuristic “minimum” GEER, such as the study by Fizaine and Victor (2016) yielding a minimum GEER of 11 for energy in the US [65]. It is plausible that growth of electricity generation technologies in the grid mix that have a GEER close to the 2015 global 11.3 average will not result in substantial economic impacts. If we take a relatively arbitrary minimum cut-off GEER of 9, this implies a 25% larger electricity sector, relative to the global benchmark of 11.3. Many technologies provided GEER values above this threshold, including PH-coal, L-coal, Sol-CSP, Sol-PV-Chile and Sol-PV-Spain, CCGT-gas using pipeline transport, Hyd-ROR, Hyd-Dam, Nuclear-EPRIII, On-Wind, Off-Wind, and Geo-HT.

In contrast, nine technologies do not currently meet such a 9.0 GEER threshold, including pipeline based SC-peak natural gas, LNG supply chain based CCGT and SC-peak natural gas plants, Sol-CSP-Salt, HFO-peak, Bio-WP, Bio-MSW, and Geo-EGS. Polysilicon Sol-PV in low solar irradiance regions, such as the UK. If the role of these technologies without further innovation grows beyond a small contribution to the grid mix, the economic size of the electricity sector will need to grow significantly, with potentially substantial economic effects. This is especially critical in considering mature technologies with limited innovation potential, including LNG supplied natural gas power plants, Heavy Fuel Oil Peaker plants, and Biomass pellet and Municipal Solid Waste based power generation.

The variability analysis showed that GEER results can change substantially due to changes in the electricity-to-primary multiplier, fuel transport, fuel energy content, efficiency variability and load factors. It is therefore critical in analyses, both at a generic theoretical and applied country specific level, to adequately report on what parameter settings are included, and to take into account variability. Otherwise it is misleading to directly compare GEER or EROI evaluations for technologies with entirely different local supply chain contexts. For example, the value for a hard coal power plant in Japan with imports from South Africa was shown to yield a GEER of 6.4 versus 36.3 for a hard-coal power plant situated on-site at a coal mine.

4.4. GHG emissions

The global CO_2 emissions benchmark was established by setting a 85% reduction requirement [4] from the calculated CO_2 emission levels for 1995 of 133,809 tonnes per PJ of electricity output (482 $gCO_2eq./kWh$), yielding 20,071 tonnes of CO_2 equivalent per PJ of electricity (72 $gCO_2eq./kWh$) to meet 2050 climate change targets. None of the fossil fuel technologies meet this cut-off value. Coal and oil based power plants yield 2 to 2.5 fold higher CO_2 emission equivalent values per PJ of electricity output than the global 2015 average of 140,681 tonnes/PJ (506 gCO_2/kWh). The rise of emission intensity from 1995 to 2015 is mainly due to the higher share of coal use in the global electricity mix. CCGT baseload power plants emit 7% below the average global 2015 emissions at 123,581 tonnes CO_2 equivalent per PJ (445 $gCO_2eq./kWh$), (see Figure 4a and 4c), and when including LNG transport, the life-cycle emissions value increases to 152,704 tonnes CO_2 equivalent per PJ (550 $gCO_2eq./kWh$), which is 14% over the 2015 global average. Expansion of natural gas power plants thus only can to a limited extent be used for intermittency management to enable rapid expansion of low-carbon solar and wind technologies. To meet an 85% emissions reduction target, only a 10% or lower electricity mix share of 50% efficient peaker natural gas power plants can be allowed, for intermittency management, as part of a grid mix with renewable flow sources, when excluding carbon capture and storage technology. This is based on a calculated emissions level of 193,136 tonnes GHG emissions per PJ (695 gCO_2eq./kWh) of electricity for natural gas peaker plants, which is a factor nearly 10 fold higher than minimum requirements associated with a 85% CO_2 emissions reduction. For CO_2 emission reductions of up to 95%, fossil natural gas needs to be phased out altogether, unless carbon capture and storage utilisation becomes viable.

The finding confirms results that natural gas is not suitable as a standalone 'bridge' technology to a low-carbon future, and should be used only for enabling rapid scaling of renewable energy, and not as a replacement for coal [66–68].

The emissions cut-off threshold is met by all non-fossil fuel technologies except for Bio-WP and Bio-MSW which yielded 418,050 and 609,726 tonnes of CO_2 emission equivalent per PJ (1505 and 2195 gCO_2eq./kWh), respectively, when combustion emissions are included, without considering carbon neutrality. If carbon neutrality is assumed these technologies emissions drop to 40,417and 9,238 tonnes/PJ (145 and 33 gCO_2eq./kWh), respectively. Since carbon neutrality can only be partially assumed for Bio-MSW due to plastics and other non-biomass content, this technology requires further scrutiny from a CO_2 emissions perspective as to whether it fits within a low-carbon electricity mix.

4.5. Labour inputs

The global benchmark for labour was established as a life-cycle equivalent of 54 jobs to provide a PJ of electrical energy per year, excluding any induced employment jobs not directly related to any of the 12 life-cycle phases. The underlying technologies which primarily influence this value are PH-coal, L-coal, Nuclear-EPRIII, Hyd-ROR, Hyd-Dam, and CCGT-bl, with 42, 86, 39, 94, 61, and 17 lifecycle jobs per PJ of electricity output per year. The analysis shows that a shift towards low carbon renewable electricity sources does result in an increase in job requirements in general, but the order of magnitude varies substantially between the types of technologies. The number of jobs to supply the same electricity output on a cradle-to-grave basis will need to grow for a low-carbon future by 15%-45% for grid systems with a majority share On-Wind, Hyd-Dam, Sol-CSP, high irradiance Sol-PV-CL, and Bio-WP technologies. In regions where fossil fuels are largely replaced by Hyd-ROR, Off-Wind and medium solar irradiance Sol-PV such as Spain, the number of jobs grow by 75%-110% under a majority shares of these technologies. Finally, if Sol-PV in low irradiance solar regions like the UK is utilised as a major source of power, job numbers would need to increase by 380%. The higher life-cycle job values for Sol-PV drop substantially with high (24%) efficiency solar panels, to 52, 74 and 149 for Chile, Spain and the UK, respectively, as less panels are needed to generate the same output. The number of lifecycle jobs for areas with high load factors, due to excellent wind and solar resources, is also substantially lower and quite close to the current lifecycle global average. The commonly found expectation that a transition to renewable electricity sources will lead to a 50% to 100% direct and indirect job increase over a fossil fuel based system is confirmed to be a reasonable approximation [69]. Therefore, investment in and implementation of renewable technologies will boost job generation, especially in geographical location where renewable technologies would operate at lower load factors.

5. Conclusions and Policy Implications

We developed a novel policy aiding framework based on physical flows, which promotes comprehensive and uniform quantitative evaluation and cross-comparison of electricity generation technologies from an energetic-economic, environmental, and labour perspective. It has been applied to evaluate and cross-compare the material, energy inputs requirements, job generation potential and GHG emissions of 19 electricity generation technologies. Based on the results five conclusions with associated implications for policy making are drawn.

First, the analysis confirmed that parameter variability based on local context is essential in life-cycle energy-economic analysis of technologies. Adequate reporting and variability assessments should be insisted upon to provide useful insights for policy purposes, both at a general theoretical and applied country perspective. This includes variability due to fuel transport distance and mode, fuel density, load factors and power plant efficiency. Especially when considering the utilisation of coal and pipeline based natural gas, transport distances matter significantly and supply chains with several thousand km transport distance should be avoided. Similarly, load factors matter for solar-PV, given that for the UK a GEER of 4.8 was established, versus 13.8 in sunny regions in Chile, implying that sensitivity to local conditions is substantial for solar-PV.

Second, the analysis found that the life-cycle EROI or Gross External Energy Ratio (GEER) analysis for an increasing number of renewable electricity technologies is higher or close to the global 11.3 average, as well as the 11.4 GEER estimated for pulverized hard coal based electricity with 1000 km coal transport, demonstrating that these technologies are viable to include in policy frameworks for large scale up from an energetic-economic perspective. This includes Solar-PV located in Chile and Spain, solar-CSP, onshore-wind, offshore-wind, geothermal-hydrothermal, hydro-Run-of-River and hydro-dams, with GEER ratios of 13.6, 9.6, 12.6, 13.5, 34.8, 8.9, and 24.7, respectively.

Third, several technologies were shown to provide a low to very low GEER value. Unless significant further innovation is possible that reduces energy input costs, these should not be scaled in a low-carbon future from an energy-economy perspective, otherwise the economic size of the electricity sector will need to grow significantly, requiring a lot more material and labour resources to be allocated to it. These technologies include liquified natural gas (LNG) based CCGT and LNG SC-peaker natural gas plants, heavy fuel oil, biomass pellet plants, municipal solid waste, solar-PV-UK, solar-CSP-salt, and enhanced geothermal, with GEER ratios of 3.5, 1.6, 2.9, 2.9, 6.2, 4.7, 7.5, and 5.9, respectively.

Fourth, to achieve an 85% CO_2 emission reduction by 2050 relative to the 1995 average, only 20,071 tonnes of CO_2 equivalent can be emitted per PJ (72 $gCO_2eq./kWh$) of electricity output. Only renewable and nuclear electricity generation technologies emit CO_2 per PJ below this threshold. This implies that far reaching decarbonisation policies can only rely on a 10% or lower share of natural gas in the electricity mix using 50%+ efficient power plants, for purposes of compensating for variable wind and solar power generation. If further GHG emission reductions up to 95% are needed, natural gas needs to be phased out altogether, unless carbon capture and storage or utilisation techniques can be applied.

Fifth, an estimated 54 work-floor jobs were needed in 2015 to supply a PJ electricity per year considering direct labour across the process chain life-cycle. The number of electricity sector jobs across the life-cycle will grow by 15%-45% in a future with a majority share of onshore wind, hydro-dams, solar-CSP, and biomass, and by 75%-110% if hydro-Run-of-River, offshore wind, and solar-PV supply the electricity majority. These job generation figures exclude grid-related, indirect services, and induced jobs. The results thereby confirm that a renewable energy future will result in significant employment gains in the energy sector.

Finally, further research is recommended on several fronts. The viability of Municipal Solid Waste (MSW) incineration in a low carbon future needs to be further investigated, given that 'carbon neutrality' assumption can only be applied to a fraction of the MSW by weight. These results should be coupled to country level grid models to provide an integrated grid systems perspective, which is especially relevant for intermittent solar and wind technologies to evaluate the impacts of, auxiliary supply-demand balancing mechanisms, such as demand flexibility, smoothing via technology complementarity, grid interconnection, and increased energy storage capacity [70].

Conflicts of interest

There are no conflicts of interest to declare.

References

1. Stocker TF, Dahe Q, Plattner G-K, Alexander L V., Allen SK, Bindoff NL, et al. Climate Change 2013: The Physical Science Basis. Technical Summary. 2013.
2. United Nations. Aggregate effect of the intended nationally determined contributions: an update. FCCC/CP/2016/2. 2016.
3. Rogelj J, den Elzen M, Höhne N, Fransen T, Fekete H, Winkler H, et al. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature [Internet]. Nature Publishing Group, a division of Macmillan Publishers Limited. All Rights Reserved.; 2016 Jun 30;534(7609):631–9. Available from: http://dx.doi.org/10.1038/nature18307
4. OECD/IEA, IRENA. Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System. Int Energy Agency [Internet]. 2017;204. Available from: http://www.irena.org/DocumentDownloads/Publications/Perspectives_for_the_Energy_Transition_2017.pdf
5. Eom J, Edmonds J, Krey V, Johnson N, Longden T, Luderer G, et al. The impact of near-term climate policy choices on technology and emission transition pathways. Technol Forecast Soc Change [Internet]. Elsevier Inc.; 2015;90(PA):73–88. Available from: http://dx.doi.org/10.1016/j.techfore.2013.09.017
6. Heard BP, Brook BW, Wigley TML, Bradshaw CJA. Burden of proof: A comprehensive review of the

feasibility of 100% renewable-electricity systems. Renew Sustain Energy Rev [Internet]. Elsevier Ltd; 2017;76(March):1122–33. Available from: http://dx.doi.org/10.1016/j.rser.2017.03.114

7. Brandt AR, Dale M. A general mathematical framework for calculating systems-scale efficiency of energy extraction and conversion: Energy return on investment (EROI) and other energy return ratios. Energies. 2011;4(8):1211–45.
8. Kucukvar M, Haider MA, Onat NC. Exploring the material footprints of national electricity production scenarios until 2050: The case for Turkey and UK. Resour Conserv Recycl [Internet]. Elsevier; 2017;125(March):251–63. Available from: http://dx.doi.org/10.1016/j.resconrec.2017.06.024
9. Raugei M, Leccisi E. A comprehensive assessment of the energy performance of the full range of electricity generation technologies deployed in the United Kingdom. Energy Policy [Internet]. Elsevier; 2016;90:46–59. Available from: http://dx.doi.org/10.1016/j.enpol.2015.12.011
10. Jacobson MZ, Delucchi MA, Bazouin G, Bauer ZAF, Heavey CC, Fisher E, et al. 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States. Energy Environ Sci [Internet]. Royal Society of Chemistry; 2015;8:2093–117. Available from: http://dx.doi.org/10.1039/C5EE01283J
11. Graedel TE. On the Future Availability of the Energy Metals. Annu Rev Mater Res [Internet]. 2011;41(1):323–35. Available from: http://www.annualreviews.org/doi/10.1146/annurev-matsci-062910-095759
12. Gabriel CA, Kirkwood J, Walton S, Rose EL. How do developing country constraints affect renewable energy entrepreneurs? Energy Sustain Dev [Internet]. International Energy Initiative; 2016;35:52–66. Available from: http://dx.doi.org/10.1016/j.esd.2016.09.006
13. Brandt AR. How Does Energy Resource Depletion Affect Prosperity? Mathematics of a Minimum Energy Return on Investment (EROI). Biophys Econ Resour Qual [Internet]. Springer International Publishing; 2017;2(1):2. Available from: http://link.springer.com/10.1007/s41247-017-0019-y
14. Cameron L, Van Der Zwaan B. Employment factors for wind and solar energy technologies: A literature review. Renew Sustain Energy Rev [Internet]. Elsevier; 2015;45:160–72. Available from: http://dx.doi.org/10.1016/j.rser.2015.01.001
15. Jones C, Gilbert P, Raugei M, Mander S, Leccisi E. An approach to prospective consequential life cycle assessment and net energy analysis of distributed electricity generation. Energy Policy [Internet]. Elsevier; 2017;100:350–8. Available from: http://dx.doi.org/10.1016/j.enpol.2016.08.030
16. Turconi R, Boldrin A, Astrup T. Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. Renew Sustain Energy Rev [Internet]. 2013 Dec;28:555–65. Available from: http://www.sciencedirect.com/science/article/pii/S1364032113005534
17. Hellweg S, Mila i Canals L. Emerging approaches, challenges and opportunities in life cycle assessment. Science (80-). 2014;344(6188):1109–13.
18. Su X, Zhang X. Temporal validation of life cycle greenhouse gas emissions of energy systems in China. J Clean Prod [Internet]. Elsevier Ltd; 2016;139(December):250–7. Available from: http://dx.doi.org/10.1016/j.jclepro.2016.08.043
19. Koppelaar RHEM. Solar-PV energy payback and net energy: Meta-assessment of study quality, reproducibility, and results harmonization. Renew Sustain Energy Rev [Internet]. Elsevier; 2016;1–15. Available from: http://dx.doi.org/10.1016/j.rser.2016.10.077
20. Louwen A, van Sark WGJHM, Faaij APC, Schropp REI. Re-assessment of net energy production and greenhouse gas emissions avoidance after 40 years of photovoltaics development. Nat Commun [Internet]. 2016 Dec 6;7:1–9. Available from: http://www.nature.com/doifinder/10.1038/ncomms13728
21. Ferroni F, Hopkirk RJ. Energy Return on Energy Invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation. Energy Policy [Internet]. Elsevier; 2016;94:336–44. Available from: http://dx.doi.org/10.1016/j.enpol.2016.03.034
22. Ferroni F, Guekos A, Hopkirk RJ. Further considerations to: Energy Return on Energy Invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation. Energy Policy [Internet]. Elsevier Ltd; 2017;107(March):498–505. Available from: http://dx.doi.org/10.1016/j.enpol.2017.05.007
23. Raugei M, Sgouridis S, Murphy D, Fthenakis V, Frischknecht R, Breyer C, et al. Energy Return on Energy Invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation: A comprehensive response. Energy Policy [Internet]. Elsevier Ltd; 2017;102(January):377–84. Available from: http://dx.doi.org/10.1016/j.enpol.2016.12.042
24. Balcombe P, Anderson K, Speirs J, Brandon N, Hawkes A. The Natural Gas Supply Chain: The Importance of Methane and Carbon Dioxide Emissions. ACS Sustain Chem Eng [Internet]. 2016;5(1):3–20. Available from: http://pubs.acs.org/doi/abs/10.1021/acssuschemeng.6b00144

25. Thornley P, Gilbert P, Shackley S, Hammond J. Maximizing the greenhouse gas reductions from biomass: The role of life cycle assessment. Biomass and Bioenergy [Internet]. Elsevier Ltd; 2015;81(0):35–43. Available from: http://dx.doi.org/10.1016/j.biombioe.2015.05.002

26. Thakur A, Canter CE, Kumar A. Life-cycle energy and emission analysis of power generation from forest biomass. Appl Energy [Internet]. Elsevier Ltd; 2014;128:246–53. Available from: http://dx.doi.org/10.1016/j.apenergy.2014.04.085

27. Muench S, Guenther E. A systematic review of bioenergy life cycle assessments. Appl Energy [Internet]. Elsevier Ltd; 2013;112:257–73. Available from: http://dx.doi.org/10.1016/j.apenergy.2013.06.001

28. Lambert RJ, Silva PP. The challenges of determining the employment effects of renewable energy. Renew Sustain Energy Rev [Internet]. 2012 Sep;16(7):4667–74. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1364032112002572

29. Raugei M, Carbajales-Dale M, Barnhart CJ, Fthenakis V. Rebuttal: "Comments on 'Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants' - Making clear of quite some confusion." Energy [Internet]. Elsevier Ltd; 2015;82(January):1088–91. Available from: http://dx.doi.org/10.1016/j.energy.2014.12.060

30. Murphy DJ, Hall CAS. Year in review-EROI or energy return on (energy) invested. Ann N Y Acad Sci. 2010;1185:102–18.

31. Hall CAS, Lambert JG, Balogh SB. EROI of different fuels and the implications for society. Energy Policy [Internet]. Elsevier; 2014;64:141–52. Available from: http://dx.doi.org/10.1016/j.enpol.2013.05.049

32. Murphy DJ, Carbajales-Dale M, Moeller D. Comparing Apples to Apples: Why the Net Energy Analysis Community Needs to Adopt the Life-Cycle Analysis Framework. Energies. 2016;9(11):917.

33. Bauer C, Treyer K, Heck T, Hirschberg S. Greenhouse Gas Emissions from Energy Systems, Comparison, and Overview. Earth Systems and Environmental Sciences [Internet]. Amsterdam: Elsevier; 2015. p. 1–13. Available from: http://dx.doi.org/10.1016/B978-0-12-409548-9.09276-9

34. Turconi R, Boldrin A, Astrup T. Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. Renew Sustain Energy Rev [Internet]. Elsevier; 2013;28:555–65. Available from: http://dx.doi.org/10.1016/j.rser.2013.08.013

35. Majeau-Bettez G, Pauliuk S, Wood R, Bouman EA, Strømman AH. Balance issues in input-output analysis: A comment on physical inhomogeneity, aggregation bias, and coproduction. Ecol Econ [Internet]. Elsevier B.V.; 2016;126:188–97. Available from: http://dx.doi.org/10.1016/j.ecolecon.2016.02.017

36. Weisz H, Duchin F. Physical and monetary input-output analysis: What makes the difference? Ecol Econ. 2006;57(3):534–41.

37. Pfenninger S, Staffell I. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy [Internet]. Elsevier Ltd; 2016;114:1251–65. Available from: http://dx.doi.org/10.1016/j.energy.2016.08.060

38. Pfenninger, S., Staffell I. Renewables.ninja [Internet]. 2017 [cited 2017 Jan 28]. Available from: https://www.renewables.ninja/

39. Jacquemin L, Pontalier PY, Sablayrolles C. Life cycle assessment (LCA) applied to the process industry: A review. Int J Life Cycle Assess. 2012;17(8):1028–41.

40. Leloux J, Taylor J, Moretón R, Narvarte L, Trebosc D, Desportes A, et al. Monitoring 30,000 PV systems in Europe : Performance , Faults, and State of the Art. 31st Eur Photovolt Sol Energy Conf Exhib. 2015;(September):1574–82.

41. The Crown Estate. Offshore Wind - Operational report 2015 [Internet]. The Crown Estate. Edinburgh; 2015. Available from: http://www.gwec.net

42. Belton D. Technology evolution and new market developments. New Zealand Wind Energy Conference, 13th April 2016, Wellington. Wellington: NZWEA; 2016. p. 22.

43. Arvesen A, Hertwich EG. More caution is needed when using life cycle assessment to determine energy return on investment (EROI). Energy Policy [Internet]. Elsevier; 2015;76:1–6. Available from: http://dx.doi.org/10.1016/j.enpol.2014.11.025

44. Frischknecht R, Wyss F, Knöpfel SB, Lützkendorf T, Balouktsi M. Cumulative energy demand in LCA: the energy harvested approach. Int J Life Cycle Assess [Internet]. 2015;20(7):957–69. Available from: http://link.springer.com/article/10.1007/s11367-015-0897-4%5Cnhttp://link.springer.com/content/pdf/10.1007%2Fs11367-015-0897-4.pdf

45. Hu Y, Hall CAS, Wang J, Feng L, Poisson A. Energy Return on Investment (EROI) of China's conventional fossil fuels: Historical and future trends. Energy [Internet]. Elsevier Ltd; 2013;54:352–64. Available from: http://dx.doi.org/10.1016/j.energy.2013.01.067

46. Murphy DJ, Hall C a S, Dale M, Cleveland C. Order from chaos: A preliminary protocol for determining the

EROI of fuels. Sustainability. 2011;3(10):1888–907.

47. Brandt AR, Dale M. A general mathematical framework for calculating systems-scale efficiency of energy extraction and conversion: Energy return on investment (EROI) and other energy return ratios. Energies. 2011;4(8):1211–45.

48. Brandt AR, Dale M, Barnhart CJ. Calculating systems-scale energy efficiency and net energy returns: A bottom-up matrix-based approach. Energy [Internet]. Elsevier Ltd; 2013;62:235–47. Available from: http://dx.doi.org/10.1016/j.energy.2013.09.054

49. Mulder K, Hagens NJ. Energy Return on Investment: Toward a Consistent Framework. AMBIO A J Hum Environ [Internet]. 2008;37(2):74–9. Available from: http://www.bioone.org/doi/abs/10.1579/0044-7447%282008%2937%5B74%3AEROITA%5D2.0.CO%3B2

50. BP. BP Statistical Review of World Energy. BP Statistical Review of World Energy. London, UK; 2016.

51. IEA. What are the methods of calculation of primary energy equivalent? [Internet]. International Energy Agency; 2017 [cited 2017 Mar 28]. Available from: https://www.iea.org/statistics/resources/questionnaires/faq/

52. IEA. IEA Online Data Service Energy Balance Flows [Internet]. Database. 2017 [cited 2017 Jan 17]. Available from: http://www.iea.org/statistics/onlinedataservice/

53. Giampietro M, Mayumi K, Sorman AH. Energy Analysis for a Sustainable Future: Multiscale integrated analysis of societal and ecosystem metabolism [Internet]. 1st ed. Oxford: Routledge; 2013. 360 p. Available from: http://www.tandfebooks.com/isbn/9780203107997

54. Gómez DR, Watterson JD, Americanohia BB, Ha C, Marland G, Matsika E, et al. Chapter 2: Stationary Combustion. In: Eggleston H.S., Buendia L., Miwa K. NT and TK, editor. IPCC Guidelines for National Greenhouse Gas Inventories [Internet]. Volume 2. Hayama, Kanagawa Prefecture, Japan: Intergovernmental Panel on Climate Change; Institute for Global Environmental Strategies; 2006. p. 47. Available from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf

55. Waldron CD, Maurice LQ, Kapshe M, Allyn DM, Harnisch J. Chapter 3: Mobile Combustion. In: Eggleston H.S., Buendia L., Miwa K. NT and TK, editor. 2006 IPCC Guidelines for National Greenhouse Gas Inventories [Internet]. Volume 2. Hayama, Kanagawa Prefecture, Japan: Intergovernmental Panel on Climate Change; Institute for Global Environmental Strategies; 2006. p. 1–78. Available from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_3_Ch3_Mobile_Combustion.pdf

56. Garg A, Pulles T. Volume 2: Energy. In: Carruthers I, Jaques A, Tejada F, editors. 2006 IPCC Guidelines for National Greenhouse Gas Inventories [Internet]. Volume 2. Hayama, Kanagawa Prefecture, Japan: Intergovernmental Panel on Climate Change; Institute for Global Environmental Strategies; 2006. Available from: https://www.ipcc.ch/meetings/session25/doc4a4b/vol2.pdf

57. Agora Energiewende, CNREC, Brainpool E, GIZ. Energy Transition in the Power Sector in China: State of Affairs in 2016 [Internet]. 2017. Available from: https://www.agora-energiewende.de/fileadmin/Projekte/2017/JAW_China_2016/Agora_Energy-Transition-China-2016-EN_WEB.pdf

58. Seyboth K, Sverrisson F, Sawin JL, Zervos A. Renewables 2016 global status report [Internet]. Paris, France: REN21 Secretariat; 2016. Available from: http://www.ren21.net/wp-content/uploads/2016/06/GSR_2016_Full_Report.pdf

59. Brandt AR, Heath GA, Cooley D. Methane Leaks from Natural Gas Systems Follow Extreme Distributions. Environ Sci Technol. American Chemical Society; 2016 Nov;50(22):12512–20.

60. Brandt AR, Heath GA, Kort EA, O'Sullivan F, Pétron G, Jordaan SM, et al. Methane Leaks from North American Natural Gas Systems. Science (80-). 2014 Feb;343(6172):733 LP-735.

61. Hall DS. By the numbers: greenhouse gas emissions and the fossil-fuel supply chain in the United States. Washington, DC, USA; 2007.

62. Center for climate and energy solutions C2ES. Leveraging Natural Gas to Reduce Greenhouse Gas Emissions. Arlington, VA, USA; 2013.

63. de Vries BJM, van Vuuren DP, Hoogwijk MM. Renewable energy sources: Their global potential for the first-half of the 21st century at a global level: An integrated approach. Energy Policy [Internet]. 2007;35(4):2590–610. Available from: http://www.sciencedirect.com/science/article/pii/S0301421506003326

64. Carbajales-Dale M, Barnhart CJ, Brandt AR, Benson SM. A better currency for investing in a sustainable future. Nat Clim Chang [Internet]. Nature Publishing Group; 2014;4(7):524–7. Available from: http://dx.doi.org/10.1038/nclimate2285%5Cn10.1038/nclimate2285

65. Fizaine F, Court V. Energy expenditure, economic growth, and the minimum EROI of society. Energy Policy

[Internet]. Elsevier; 2016;95(August):172–86. Available from: http://dx.doi.org/10.1016/j.enpol.2016.04.039

66. Howarth RW. A bridge to nowhere: Methane emissions and the greenhouse gas footprint of natural gas. Energy Sci Eng. 2014;2(2):47–60.
67. Hausfather Z. Bounding the climate viability of natural gas as a bridge fuel to displace coal. Energy Policy [Internet]. Elsevier; 2015;86:286–94. Available from: http://dx.doi.org/10.1016/j.enpol.2015.07.012
68. Zhang X, Myhrvold NP, Hausfather Z, Caldeira K. Climate benefits of natural gas as a bridge fuel and potential delay of near-zero energy systems. Appl Energy [Internet]. Elsevier Ltd; 2016;167:317–22. Available from: http://dx.doi.org/10.1016/j.apenergy.2015.10.016
69. Rutovitz J, Dominish E, Downes J. Calculating global energy sector jobs 2015 methodology update. Sydney, Australia; 2015.
70. International Energy Agency. Getting wind and sun onto the grid: a manual for policy makers [Internet]. Paris, France; 2017. Available from: https://www.iea.org/publications/insights/insightpublications/Getting_Wind_and_Sun.pdf