A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015-2030

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1. Introduction

The United Nations adopted two historically significant agreements in 2015: the Paris Agreement (UNFCCC, 2015) and the 2030 Agenda for Sustainable Development (United Nations, 2015). Governments agreed to a long-term target of limiting the increase in global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit temperature increase to 1.5°C (UNFCCC, 2015; Roehrkasten et al., 2016). The agreement calls for global greenhouse gas (GHG) emissions to peak as soon as possible, recognizing that this will take longer for developing countries, and for rapid emission reductions thereafter. Moreover, the United Nations has for the first time included energy in its new Sustainable Development Goals (SDG 7 - Ensure access to affordable, reliable, sustainable and modern energy for all), calling

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for an increased acceleration of renewable energy (RE) deployment. Two-thirds of global GHG emissions stem from energy production and consumption, which puts the energy sector at the core of efforts to combat climate change and the successful outcome of these international agreements will depend on a rapid transition of the global energy system (IPCC, 2014; Halsnæs and Garg, 2011).

Economies around the world face the complex challenge of tackling climate change whilst ensuring the social and economic progress of their populations. In this context, the Group of Twenty (G20), which is a critical forum for global economic governance, has the prerogative to set the agenda for a global energy transition. It includes twenty of the world’s largest economies: Argentina, Australia, Brazil, Canada, China, the European Union (EU), France, Germany, India, Indonesia, Italy, Japan, Mexico, Russia, Saudi Arabia, South Africa, Republic of Korea, Turkey, the United Kingdom (UK) and the United States of America (USA) (G20 Research Group, 2018). Member countries account for 86% of the global GDP, more than three quarters of global energy demand and 84% of global GHG emissions from the energy sector as indicated in Fig. 1. Given the sheer weight in the global energy system of the G20 countries with nearly 85% of the global power consumption, it is not surprising that 87% of global renewable power capacity addition happened in the G20 nations as indicated in Fig. 1. Hence, any collective move by the group will have substantial effects on global energy markets.

A rapid transition of power systems in the G20 countries is taking shape, and in this context, costs will play an important role in determining the required investment levels across the entire power system. The fall in costs of wind turbines, solar photovoltaics (PV) and batteries, mainly due to their increasing deployment, is well documented and demonstrated by overall investments in renewable sources remaining quite flat between 2011 and 2015 despite annual capacity additions rising by 40% (Ram et al., 2017; Frankfurt School-UNEP Centre/BNEF, 2017). An International Renewable Energy Agency (IRENA) analysis shows that between the end of 2009 and 2016, solar PV module costs have fallen by around 80% and those of wind turbines by 30–40% (IRENA, 2016).

In many regions of the world, biomass for power, hydropower, geothermal and onshore wind can all now provide electricity competitively compared to fossil fuel-fired electricity generation (Ram et al., 2017). The levelised cost of energy (LCOE) of solar PV has fallen by more than 60% between 2010 and 2016 based on preliminary data; moreover, solar PV achieved highly competitive levels at the utility-scale across the world (IEA-PVPS, 2017).

The G20’s energy agenda has been evolving in recent years. The task of the G20 through successive summits has been to seize the momentum of the Paris Agreement and the SDGs to foster collective action towards a sustainable, decarbonised and affordable global energy system (Roehrkasten et al., 2016). Investments in efficiency and renewable energy are expected to become the norm, as investments in fossil-based power generation will be an exception with clearly defined timelines for an exit. One of the main agendas for the global community is to move away from fossil fuel subsidies both in developed and in developing countries that are beginning to show adverse economic impacts (Mills, 2017). A shift in investments towards sustainable energy sources is already underway, as governments and financial institutions want to avoid lock-in effects. This will be a challenging undertaking, as the G20 members are highly diverse, often with very divergent interests in the energy spectrum. Fig. 2 highlights the diverse energy mix of the G20 countries and their corresponding shares of installed capacities. If the G20 members agree on joint action, this will have important international signalling effects and considerable influence on international policymaking. This could make the G20 an ideal forum to steer an energy transition by complementing existing institutions and bringing greater coherence to the global energy architecture.

Technology and finance are strong determinants of future societal paths. While society’s current systems of allocating and distributing resources while prioritising efforts towards investments and innovations are in many ways robust and dynamic, there are some fundamental tensions with the underlying objectives of global sustainable development. Technological innovations and financial systems are highly responsive to short-term motivations, and are sensitive to broader social and environmental costs and benefits only, to an often limited extent that these costs and benefits are internalised by regulation, taxation, laws and social norms (IPCC, 2014). In this context, as costs are a vital indicator for planning and decision making of government’s around the world, this research paper analyses the costs of power generation in the G20 countries in the present context and from a future perspective for 2030. It involves estimating the LCOE for different power generation and storage technologies for each of the G20 member countries in 2015 and for the possible situation in 2030. It also

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**Abbreviations**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>BECCS</td>
<td>Bioenergy Carbon Capture and Storage</td>
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<td>BEV</td>
<td>Battery Electric Vehicle</td>
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<td>BNEF</td>
<td>Bloomberg New Energy Finance</td>
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<td>CAES</td>
<td>Compressed Air Energy Storage</td>
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<td>CBM</td>
<td>Coal Bed Methane</td>
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<td>CCS</td>
<td>Carbon Capture and Storage</td>
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<td>CCGT</td>
<td>Combined Cycle Gas Turbine</td>
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<td>COP</td>
<td>Conference of the Parties</td>
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<td>CSP</td>
<td>Concentrated Solar Thermal Power</td>
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<td>DACCS</td>
<td>Direct Air Carbon Capture and Storage</td>
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<td>EU</td>
<td>European Union</td>
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<td>FLH</td>
<td>Full Load Hours</td>
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<td>GDP</td>
<td>Gross Domestic Product</td>
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<td>GHG</td>
<td>Greenhouse Gases</td>
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<td>GW</td>
<td>Gigawatts</td>
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<td>G20</td>
<td>Group of Twenty</td>
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<td>IEA</td>
<td>International Energy Agency</td>
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<td>IMF</td>
<td>International Monetary Fund</td>
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<td>IPCC</td>
<td>International Panel on Climate Change</td>
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<td>IRENA</td>
<td>International Renewable Energy Agency</td>
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<td>LCOE</td>
<td>Levelised Cost of Electricity</td>
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<td>MW</td>
<td>Megawatt</td>
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<td>OCCT</td>
<td>Open Cycle Gas Turbine</td>
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<tr>
<td>PHEV</td>
<td>Plug-in Hybrid Electric Vehicle</td>
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<tr>
<td>PHS</td>
<td>Pumped Hydroelectric Storage</td>
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<tr>
<td>PtL</td>
<td>Power-to-Liquids</td>
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<tr>
<td>PtX</td>
<td>Power-to-X</td>
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<tr>
<td>PV</td>
<td>Photovoltaics</td>
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<tr>
<td>RE</td>
<td>Renewable Energy, partly used in the sense of Renewable Electricity</td>
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<tr>
<td>SDGs</td>
<td>Sustainable Development Goals</td>
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<tr>
<td>SNG</td>
<td>Synthetic Natural Gas</td>
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<tr>
<td>TPE</td>
<td>Total Primary Energy Demand</td>
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<tr>
<td>TW</td>
<td>Terawatt</td>
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<td>USD</td>
<td>United States Dollar</td>
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<td>WEO</td>
<td>World Energy Outlook (flagship report of the IEA)</td>
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considers the effects of externalities such as, additional costs of GHG emissions, health related costs amongst other societal costs and subsidies on the levelised costs of power generation in the G20 countries. Additionally, this is a first of its kind study aimed at estimating LCOE (with and without external as well as GHG emission costs) of the most relevant power generation and storage technologies for each of the G20 member countries from a future perspective. Furthermore, providing a comparative analysis of the costs of renewable power generation combined with storage, and the costs of fossil fuels and nuclear. These results will assist policymakers across the G20 and other countries to make informed decisions in carving out their future energy pathways, and inform all the stakeholders as well as civil society in general. This paper includes a literature review of most relevant cost of energy estimations across the different parts of the world presented in section 2. The detailed methodology along with the relevant assumptions and parameters adopted for estimating LCOE are presented in section 3. Followed by section 4, which highlights the results for all G20 countries in 2015 and 2030, and section 5 presents the analyses of LCOE for renewables and storage in comparison to conventional fossil fuel and nuclear power generation. Finally, section 6 draws conclusions and raises a few policy implications of the results.

### 2. Literature review

In general terms, LCOE is the estimated amount of money that is incurred for a particular electricity generation plant to produce a standard amount of electricity (either kWh or MWh) over its expected lifetime. Despite some critiques of LCOE as a tool for comparing costs across power generation technologies such as Hirh et al. (2015), Schmalensee (2016) and Synapse Energy Economics (2016) amongst others, LCOE remains a robust tool, as it offers several advantages as a cost metric, such as its ability to normalise costs into a consistent format across decades and technology types. Additionally, it provides ample flexibility to incorporate many factors and parameters to provide comprehensive cost perspectives. Consequently, it has become the de-facto standard for cost comparisons amongst the many stakeholders such as policymakers, analysts, and advocacy groups (Rhodes et al., 2017). There are many organisations that estimate LCOE values on an annual basis, a few of them are BNEF (Frankfurt School-UNEP Centre/BNEF, 2018, 2017) that analyse LCOE for the different power generation technologies and Lazard (2016; 2017) that determine the LCOE of all technologies in the power sector of the USA. Whereas, IRENA estimates the renewable power generation costs across the world on a periodic basis (IRENA, 2018, 2015). Similarly, the IEA with it’s annual flagship report world energy outlook (WEO) (IEA, 2017, 2016) have long term projections of LCOE upto 2050 for the different power generation technologies. Furthermore, various government organisations have developed LCOE models customised for their respective countries, such as US LCOE model by the Department of Energy (DOE) (USDOE and NREL, 2018), UK Government’s electricity costs model developed by Department of Energy and Climate Change (DECC) (DECC, 2013) and Australia Energy Technology Assessment (AETA) model by Bureau of Resources and Energy Economics (BREE) (Arif Syed (BREE), 2013), amongst many others. But, there is a huge variance in the consideration of externalities and other parameters, as shown in the comparative analysis amongst these along with a few other LCOE models in Foster et al. (2014).

Although LCOE is a well developed and standard technique in evaluating energy sector economics, authors approach model formulation in various ways, so as to ensure the model matches research objectives and data availability (Foster et al., 2014). There
have been previous efforts to comprehensively integrate social and environmental costs of power generation as part of LCOE estimations, some of the interesting approaches are (Rhodes et al., 2017), which applied a geographically-resolved method to calculate the LCOE of new power plants on a county-by-county basis while including estimates of some environmental externalities across the USA. Küchler and Meyer (2012) estimate the full cost of power generation and systematically compare state subsidies for nuclear, hard coal, and lignite with those for renewables across Germany. Also, Siemens Wind Power (2014) showcases LCOE including societal and economic benefits for the different power generation technologies across UK and Germany.

While these studies have comprehensively addressed the aspects of externalities of power generation costs from national perspectives, there is still a need to expand this to a broader global context to inform public policy discourse. In this regard, the research paper is an effort to highlight LCOE of key power generation technologies across the G20 countries with and without consideration of external and GHG emission costs. Moreover, most LCOE estimations lack in providing a long term purview of cost developments that can aid in developing future plans and agendas. Therefore, this research estimates LCOE in 2015 to represent the current trends and LCOE in 2030 to represent the likely development prospects of the various technologies across the G20 countries. Besides, almost none of the studies include storage (mainly batteries) as part of power source options. In recent years, apart from the increasing share of battery storage adoption among prosumers (REN21, 2017), there have been a growing number of utility-scale battery storage installations across countries such as USA, UK, Germany and Australia (Clover, 2018; Cook, 2017; Mcconnell, 2018; Walton, 2018). The trend for solar PV with large-scale battery storage installations is becoming more widespread as costs of batteries are declining rapidly (Kenning, 2018). Considering these developments, this research paper is the first of its kind to estimate levelised costs of batteries along with solar PV (both utility-scale and rooftop) across the G20 countries for 2015 and 2030. Unlike most LCOE estimates, this research juxtaposes the estimated levelised costs of renewable power and storage with those of fossil fuel and nuclear power, considering external as well as GHG emission costs, in 2015 and 2030, across all the G20 countries. With the growing relevance and significance of the G20 forum, the purpose of this research is to inform global energy policy discourse with comprehensive, rigorous and impartial cost analysis of the existing as well as emerging power technologies.

Fig. 2. Shares of different power generation capacities across the G20, with Brazil at the top having the highest share of renewables and Saudi Arabia at the bottom with the lowest share (IRENA, 2017b; Coal Tracker, 2017; Knoema, 2016; Schneider and Froggatt, 2016).
3. Materials and methods

In order to represent the comparative annualised costs of electricity generation for different technologies on an equal footing, a LCOE calculation is often employed (Short et al., 1995). In general, LCOE calculations include all the costs of building and operating a power plant in relation to the energy generation over its lifetime. Costs of transmitting and distributing this energy are not usually included in such plant level LCOE calculations. Importantly, socio-ecological externalities are also often excluded from LCOE calculations beyond the market cost of CO2 emissions. However, this analysis will attempt to include the full costs of energy generation by internalising them as fairly as possible. To this end, a wider range of costs both upstream and downstream from power plants are included in order to give a more accurate representation of the full costs of energy generation. Such costs will include those related to effects on human health, the environment, global warming, long-term waste management, plant decommissioning, financing and budget overruns.

Too often, LCOE calculations merely represent so-called overnight costs of power plants, which do not fully represent the fact that the true costs may differ significantly from originally budgeted costs. As financing of construction may be done over many years and there may be significant time and budget overruns. For some technologies, these are exceptional. However, for others, they appear to be rather normal due to inherent complexity and changing public expectations (Sovacool et al., 2014a,b). For example, a solar PV rooftop system on an individual home can be ordered from a service provider who can deliver a turnkey product within weeks. In addition, as such projects can be paid for by homeowners, financing costs are rather minimal. In contrast, a nuclear power plant will take many years to go through the long process of availing permissions and construction. Moreover, a recent trend has been observed in time and cost overruns that significantly from originally budgeted costs. A case in point is the Olkiluoto 3 reactor in Finland. The first application for this project was made in 2000 to the Finnish cabinet, and construction began in 2005. The project was originally estimated to be completed by 2010 for a cost of approximately 2.8 b €. However, the reactor has not yet been commissioned by end of 2017, and recent cost estimates exceed 8.5 b € (Koistinen, 2012; World Nuclear Association, 2017b).

It is generally agreed that many values representing these components vary greatly on a global level. Hence, low, median and high values of LCOE for each technology have been calculated for each of the G20 countries in 2015 and 2030. Accurate background data were available for all technologies and collected using respected international and local sources. These include the following:

- International Energy Agency (IEA, 2016)
- European Commission Joint Research Centre, 2014 (EC, 2014)
- Danish Energy Agency, 2016 (Danish Energy Agency, 2016)
- Bongers, 2015 (Bongers, 2015)
- Lazard, 2016 (Lazard, 2016)
- Grausz, 2011 (Grausz, 2011)
- Ahmad and Ramana, 2014 (Ahmad and Ramana, 2014)
- World Nuclear Association, 2017 (World Nuclear Association, 2017c)
- Rafaj and Kypreos, 2007 (Rafaj and Kypreos, 2007)
- Mann et al., 2014 (Mann et al., 2014)
- Schlissel, 2016 (Schlissel, 2016)
- Central Electricity Regulatory Commission of India, 2015 (CERC, 2015)
- UBS, 2017 (UBS, 2017)
- Pöller et al., 2015 (Pöller et al., 2015)
- World Nuclear Association, 2017 (World Nuclear Association, 2017a)
- Schneider and Froggatt, 2016 (Schneider and Froggatt, 2016)

The current situation is represented by values from 2015, which are at this time the latest available on a global scale. LCOE is also estimated for 2030 using recognised projections of cost components. In many cases, when reliable data was unavailable for a particular G20 country, a value was substituted from a source found from a regionally neighbouring country. Primarily, these assumptions were made based on the similar economic and geographic conditions prevailing in some of the G20 countries. Such regional groupings were most often related to geographic closeness, but could also represent political closeness in the case of EU member states. Regional groupings were most often made for Argentina and Brazil; Australia, Indonesia, India, Japan and the Republic of Korea; Canada, the USA and Mexico; the Kingdom of Saudi Arabia and South Africa; the United Kingdom and the countries of the EU. These can be further examined in the supplementary material.

The components of the LCOE calculations employed in this analysis includes real capital expenditures (capex) instead of overnight costs. In addition, this analysis includes plant decommissioning costs, fixed operational and maintenance expenditures (opex fixed), variable operational and maintenance expenditures (opex variable), storage costs, fuel costs, GHG emission costs, waste disposal costs, and a full range of additional socio-economic costs. Other important components of the LCOE calculations are plant lifetimes and full load hours (FLH) of annual operation.

The calculation of LCOE (expressed as €/MWhel), representing a discounted cash flow approach for the case of constant annual cash flows (Short et al., 1995), is this report is characterised by the following equation (1):

\[
\text{LCOE} = \frac{(\text{Capex}_{\text{Real}} \times \text{crf}) + \text{Opex}_{\text{Fixed}} + \text{Decommissioning costs}}{\text{FLH}} + \text{Opex}_{\text{Variable}} + \text{LCOE} + \text{Fuel costs} + \text{Waste disposal costs} + \text{External costs} + \text{GHG costs}
\]

where,
- \text{Capex}_{\text{Real}} is annual capital expenditures (€/MW}_{\text{el}}, which include a low and high estimate for investments and budget overruns; \text{Opex}_{\text{Fixed}} are fixed operation and maintenance costs (percentage of capex/year); Decommissioning costs are expressed as a percentage of capex for all technologies except nuclear power plants, for which they are expressed as a value in €/MW}_{\text{el}}; N is the operational lifetime of the technology (years); \text{Opex}_{\text{Variable}} is the annual variable operation and maintenance costs (€/MW}_{\text{el}}; \text{LCOE} is the levelised cost of storage in €/MW}_{\text{el}} (see below); Fuel costs are expressed in €/MW}_{\text{el}}; \text{Waste disposal costs are expressed in €/MW}_{\text{el}}; \text{External costs (annual)} include a range of socio-economic costs related to energy generation (€/MW}_{\text{el}}); \text{GHG costs (annual)} include the full socio-economic costs of GHG emissions (€/MW}_{\text{el}}). Importantly, there has been no discounting of decommissioning
costs, i.e. a social discounting rate of 0% has been applied for supporting real societal costs. Instead, they are applied to the time of energy generation.

The capital recovery factor (crf) is calculated according to the following equation (2):

$$crf = \frac{WACC \times (1 + WACC)^N}{(1 + WACC)^N - 1} \quad (2)$$

where,

- WACC is the weighted average cost of capital; N is the operational lifetime of the technology (years).
- WACC is set at 7% per year for all technologies with the exception of coal and nuclear power, which are set at 10%. In general, the WACC represents the weighted cost of both debt and equity based capital. WACC is also a representation of the relative risk that various investors perceive in the development of a project. For this reason, a higher WACC was used for coal and nuclear power. This is due to the fact that we are currently seeing divestment from such assets and a higher risk of stranded investments (Baron and Fischer, 2015). This risk is a result of accelerated phasing out of coal plants in many parts of the world due to climate change mitigation, and shut downs of nuclear plants in a post-Fukushima world. In addition, budget overruns in recent years of nuclear power projects have left investors sceptical (Koplow, 2011; Moody’s Investors Service, 2008; Pearce, 2017; Schneider and Froggatt, 2016), making it more difficult to raise capital.

The levelised cost of storage (LCOS) is calculated for the case of both rooftop and utility solar PV according to the following equation (3):

$$LCOS = \frac{\text{Storage capacity} \times (\text{CapexReal}_{\text{Storage}} \times crf + \text{Opex}_{\text{fixed}})}{\text{System output}} + \frac{\text{Costs of battery losses}}{\text{System output}} \quad (3)$$

Major components of LCOE are further described in turn below. Afterwards, a brief explanation of how low, median and high values of LCOE were calculated.

3.1. Capex

Overnight capital expenditures were derived from a range of internationally recognised sources for each of the G20 countries. In most cases, these sources supplied low and high ranges for many technologies. When data was not available for a particular country, values from a neighbouring country were substituted in the manner described above. For utility-scale solar PV, the most economical option is sometimes a fixed, optimally tilted system. Such is the case for countries such as Canada, France, Germany, Japan, Russia and the UK. However, at other times it is more advantageous to operate a single-axis tracking system, since the higher yield of the system outweighs the additional capex. Therefore, for all other countries an additional cost of 10% was added to capex values (Bolinger et al., 2017) to reflect the additional costs of the tracking systems.

In all cases but three, a value for this overnight capex was the starting point of all calculations. The exceptions will be discussed below in the section on CapexReal.

3.2. Investment and overruns

For solar PV and wind energy generation technologies, a low value of 1.5% of capex and high value of 3.5% of capex were added (IEA & NEA, 2015). These values reflect the fact that solar and wind installations typically have very short construction times (1–2 years), but that some delays may occur due to complex procedures related to permitting. Battery technologies did not have an investment and overrun addition. It was assumed that coal and gas-based thermal power plants have low and high investment and overrun additions of 5% and 15%, respectively. These capex additions are consistent with estimates made by the IEA (IEA & NEA, 2015; IEA, 2016). For nuclear power, a low investment and overrun addition of 20% was assumed due to the longer construction times of nuclear power plants. This was also consistent with high IEA estimates. However, another source was used to estimate the high investment and overrun addition of 40% (Kooomy and Hultman, 2007). This source was deemed to better account the reality of the international trend towards longer construction times and budget overruns. It also showed that such overruns have gotten progressively larger over time. Currently, nuclear power plants in Finland and France are seven years beyond their scheduled construction time of 5 years, and cost overruns are approximately 300% (Koistinen, 2012; Le Monde, 2012). The applied range of 20%–40% of cost overruns is rather conservative, given the scientific analysis for 180 nuclear reactors which had a cost overrun of 117% on average and no single reactor within the planned budget had been found (Sovacool et al., 2014a, b).

3.3. CapexReal

A high and low value for CapexReal was calculated by adding the high and low investment and overrun additions to the high and low values of capex. In some cases, only a single value for capex was available, and so the variance in CapexReal represents only the variance in the investment and overruns addition.

In three cases, values for CapexReal were not the result of calculations, but were taken straight from the literature. Thereby, the value of overnight capex could be derived in reverse for the high values of Argentinian, Chinese and South Korean nuclear power plants. The high CapexReal value for nuclear power in Argentina was based on a known cost of 5.8 bUSD for the 800 MW Atucha 3 reactor (Schneider and Froggatt, 2016; World Nuclear Association, 2017a). Interestingly, the technology provider for the Atucha 3 reactor is China (CANDU), and the cost of similar projects in China are generally reported at much lower costs. This indicates a high level of domestic subsidy possibly incorporated in the reported overnight costs that are commonly used in international publications. The same phenomenon is suspected for Korean technology providers. Therefore, high CapexReal Values for China and the Republic of Korea are derived from known costs for the same technologies in other countries. The high CapexReal value for nuclear power in China was based on a known cost of 9.6 bUSD for the 2028 MW Karachi 1&2 reactors in Pakistan built by the Chinese National Nuclear Corporation (Schneider and Froggatt, 2016; World Nuclear Association, 2017a). Likewise, the high CapexReal value for nuclear power in South Korea is based on an estimated cost of 32 bUSD for the 5380 MW Barakah 1–4 reactors in the United Arab Emirates, which are built by the Korean Electric Power Corp. (Schneider and Froggatt, 2016).

3.4. Decommissioning

A decommissioning cost of 5% of capex was applied to solar PV, wind, coal and gas technologies. No decommissioning costs were applied to batteries. For nuclear power plants, a decommissioning cost of 1100 €/kW was applied. However, the difficulty in accounting decommissioning costs accurately merits further discussion. Globally, there is very little actual experience and information
related to fully decommissioned nuclear power plants. For this reason, estimates of future costs range from values as low as 200 €/kW for reactors in Finland (219 mUSD for 2*440 MW VVER) to 1500 €/kW for reactors in Slovakia (1.3 b€ for 2*440 MW VVER) (EC, 2016; IAEA, 2002). In this research, it is assumed that decommissioning costs globally will be 1100 €/kW in 2015 and 2030. The effect of varying this value by ±50% has an effect on LCOE of ±1 €/MWhel.

3.5. Opex

This category is divided into fixed and variable operational and maintenance expenditures. Opex\textsubscript{fixed} is commonly expressed as a percentage of capex per year, and represents costs unrelated to how many hours per year the plant operates. Such costs include material, personnel, administration and insurance costs, but do not include fuel or emissions costs. Opex\textsubscript{variable} represents costs that are directly related to the frequency and duration of plant operations. Some operations and maintenance costs, such as those related to pumps, fans and lubricating fluids, are incurred only when the plant operates. In the case of batteries, a similar value to Opex\textsubscript{variable} is calculated based on the costs related to storage losses. These losses are a function of the energy throughput and battery efficiency.

3.6. Lifetime

Assumptions made related to plant lifetimes are consistent with those made by the International Energy Agency and other international agencies. Wind energy plants are assumed to have a lifetime of 25 years. Solar PV rooftop units and power plants are assumed to have a lifetime of 30 years (ETIP-PV, 2017). This value was chosen even though some facilities may have physical lifetimes of up to 35 years. Increasing PV lifetime by 10 years would mean that LCOE could be reduced by about 5 €/MWhel. The real lifetime of solar PV modules and wind turbines installed today are, obviously, unknown. More relevant to LCOE calculations, however, is the perceived economic lifetime by the international community, including investors. Another unknown is the lifetime of batteries, which has been set at 10 years for 2015 and 15 years for 2030. The extended lifetime for 2030 is based on projected lifetimes of electric vehicle Li-ion batteries (UBS, 2017). Complicating this matter is that batteries have both calendric and cycle lifetimes, meaning batteries that are charged and discharged more frequently and deeply will have reduced lifetimes. The lifetimes of coal and gas power plants is assumed to be 40 years. Nuclear power plant economic lifetime is set at 50 years. It should be noted, however, that nuclear power plants are typically given operating permits for 30–40 year periods, after which refurbishment or renovation is needed to extend the physical lifetime to 60 years or beyond. And again, perceived economic lifetimes for investors are typically shorter, making a 40 year economic lifetime perhaps more relevant for the purposes of LCOE calculations. The same was done by Lazard (Lazard (2016). The competition of low cost solar PV and wind plants already led to earlier than possible shut down decisions (Nikolewski, 2016). However, the high risk profile of nuclear power plants may lead to much shorter lifetimes, due to detracted societal willingness to accept the risk, which seems to be also well covered by liberal western constituencies, as confirmed by the Federal Constitutional Court of Germany in 2016 (The Federal Constitutional Court of Germany (Bundesverfassungsgericht), 2016).

3.7. Full load hours

For nuclear plants, baseload operation is assumed. Therefore, FLH values reflect capacity factors of 80% at a low end to 90% at the high end. For coal power plants, some of which have not witnessed such high FLH in recent years due to competition with renewable energy and decarbonisation targets, capacity factors range between 50% and 90%. Median values for coal and nuclear power plants are the average between the lower and upper estimates. For open cycle gas turbines, low, median and high capacity factors are assumed to be 10%, 45% and 80%, respectively, due to the more peak following profile of generation. Similarly, these values are set at 40%, 60% and 80%, respectively, for combined cycle gas turbines. These values are consistent with international agencies.

For solar PV and wind energy generation, FLH for each country in the G20 were calculated individually, based on real weather data over the period of 1994–2005. The procedure for estimating FLH was complex, but took into account both geographic and temporal variation of the resources. Data was derived from (Stackhouse, 2016; Stetter, 2012), which gave irradiation and wind speed data on an hourly resolution for the years indicated. The geographic resolution of the data is a 0.45° latitude by 0.45° longitude node (approximately 50 km by 50 km at the equator). These nodes were ranked in terms of the quality of the resource as percentiles, with the 100th percentile being the node with the highest average annual irradiation or wind speed. Maximum FLH for solar PV and wind energy were determined as the highest value for the 100th percentile node over the time period (1994-2005). Minimum FLH were determined as the lowest value for the 51st percentile node over the same time period. To determine the median FLH value, a weighted average of nodes was used. It was assumed that all capacity of solar PV and wind could be located in only the best sites, and that most of the worst sites could be rejected as being infeasible. So, 10% of capacity would be located in the areas ranked from the 51st to 60th percentile, 10% of capacity would be located in the areas ranked 61st to 70th, 20% of capacity would be located in areas ranked 71st to 80th, 30% of capacity would be located in areas ranked 81st to 90th, and the remaining 30% of capacity would be located in areas ranked 91st to 100th. The weighted average value for FLH was calculated for each country and each year, and the median was calculated as the average over the time period.

Exceptions to the above were made for several countries that have less than ideal wind conditions: Brazil, Indonesia, India, Mexico, Kingdom of Saudi Arabia, and Turkey. It was assumed that there would be limited locations of sufficient wind quality in some onshore and offshore locations, so the range of acceptable nodes were limited between the 81st and 100th percentiles. For Italy, Mexico, Kingdom of Saudi Arabia and Turkey, this limitation was applied only to offshore wind energy generation.

For single-axis tracking PV systems, FLH data was only available for a single year (2005). However, this data was compared to the values for fixed optimally tilted systems for the same year, and values for other years were extrapolated based on this comparison. For LCOE calculations for solar PV + Batteries, FLH were assumed to be the same for solar PV rooftop. However, the ratio of storage capacity to generation capacity was varied, with a ratio of 1 assigned for low and median LCOE calculations, and a ratio of 2 assigned for high LCOE calculations. This takes into account that larger battery capacity that would lead to higher LCOE. At the same time, this raises an important point. The LCOE for the solar PV + Battery systems may not, therefore, be immediately comparable to the LCOE of the other generation technologies, but should be compared to consumer’s costs of electricity in order to determine if it is low or high.
3.8. Fuel

Fuel costs were taken from projections found in Bloomberg New Energy Finance’s New Energy Outlook 2015 (BNEF, 2015) and are summarised in Table 1. A cost of 5.26 €/MWhth for nuclear fuel (IEA, 2016) was assumed for all countries for both 2015 and 2030 due to large stockpiles of nuclear fuel. This corresponds to an approximate cost of 7 USD/MWhth, and may vary by ±1 €/MWhth globally.

3.9. Waste disposal

Waste disposal costs were considered only for nuclear power plants and were derived directly from the IEA (IEA & NEA, 2015). This source reported values for each country in 2015 which included both fuel and waste disposal costs. The waste disposal costs were determined after subtracting the above fuel costs. Values reflect the economic difficulty that some countries have in safely disposing off nuclear waste (Japan, the USA and the UK).

3.10. External costs

A comprehensive review by Climate Advisers (Grausz, 2011) of the total social cost of different forms of electricity generation determined that the work of Rafaj and Kypreos (2007) provided the most comprehensive estimates of the external costs of electricity generation. Similarly, these same costs have been used as the basis for LCOE calculations in this present study, and are summarised in Table 2 below. Note that values do not include external costs related to CO2 emissions, which will be explained in the next section.

3.11. GHG emission costs

For CO2 emissions, a range of costs exist that represent the cost of a metric ton of emissions. Some of these are market based, while others are politically determined. Carbon markets are perceived to be imperfect mechanisms that often transfer and consolidate power and wealth, as concluded in (Sovacool, 2011) in which the author reviewed more than 300 articles discussing the merits and drawbacks of global and regional carbon markets over the past decade. In this research, a value of 7 €/ton of CO2eq was assumed based on the market value of carbon in the EU for the year 2015. For 2030, a value of 74 €/ton of CO2eq was assumed based on estimates of the social cost of carbon by the Stern Review (Stern, 2007). The recent report of the High-Level Commission on carbon price reforms CO2eq emission costs of up to 74 €/ton of CO2eq for the year 2030 (Carbon Pricing Leadership Coalition, 2017). However, it should be noted that there are a range of estimates related to the actual costs of carbon from 30 to 165 €/ton of CO2eq (Moore and Diaz, 2015). Some others (Jakob et al., 2016) argue that emissions pricing could be utilised to promote sustainable socio-economic development by providing public goods that are essential for human well-being through public financing.

Determining a single, universally acceptable value for GHG emissions is an impossible task, which often leads to confusion or objection. In truth, measuring the full socio-economic impacts of GHG emissions is inherently inaccurate and thus open to debate. The range of impacts included or excluded play a major role. The Stern Review (Stern, 2007) was amongst the first influential publications to place a social cost on GHG emissions. This was set at 85 USD2007 per ton (74 €2015/ton of CO2eq) for the case of a business as usual scenario with global concentration exceeding 550 ppm in the atmosphere. However, the Stern Review acknowledged that this cost could be up to a third lower if global concentration was around 450 ppm. This shows that the cost of GHG emissions, even the social cost, is not static. Instead, we must accept that the costs will be higher as global atmospheric concentrations increase. What is more, a recent study (Moore and Diaz, 2015) suggests that higher concentrations of GHG emissions in the atmosphere will have a so far inadequately accounted, negative effect on economic growth, which may lead to much higher impact on a full socio-economic level. The article argues that to this point the focus has been on the environmental impacts of GHG emissions on people. The authors remind that there will also be significant economic impacts on people. If effects on global economic growth are also taken into account, the full cost of GHG emissions could be much higher, up to 220 USD/ton (165 €/ton of CO2eq) (Moore and Diaz, 2015).

3.12. Other technical assumptions

The technology-wise assumptions are as listed below,

1. Wind onshore: Full Load Hours (FLH) are based on the power curve of a 3 MW onshore wind turbine (Enercon E101 with a hub height of 150 m).
2. Wind offshore: Full Load Hours (FLH) are based on the power curve of a 3.6 MW offshore wind turbine (Siemens SWT-3.6-120 with a hub height of 100 m).
3. PV rooftop: Performance characteristics are based on the scale of a 5 kWp system.
4. PV utility: Performance characteristics are based on the scale of a 50 MWp system.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Fuel cost assumptions for coal (upper) and gas (lower) in €/MWhth.</th>
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<tbody>
<tr>
<td></td>
<td>2015</td>
</tr>
<tr>
<td></td>
<td>€/t</td>
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<tr>
<td>Coal Europe</td>
<td>45.86</td>
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<tr>
<td>Coal China</td>
<td>71.43</td>
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<tr>
<td>Coal India</td>
<td>30.08</td>
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<tr>
<td>average</td>
<td>6.03</td>
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</tbody>
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| Table 2 | External costs of electricity generation excluding CO2 costs used for LCOE calculations. From (Rafaj and Kypreos, 2007). All values are in €2015/MWh of electricity produced and based on long-term conversion of 1.33 EUR/USD and 57% inflation of the USD between June 1995 and June 2015. ASIA includes all Asian countries. OECD includes Australia and all other countries not specified. NAME includes all North American countries. EEFUS includes all Eastern European and Former Soviet Union countries. LAFM includes countries of Latin America, Africa and the Middle East. In the Table, PP is Power Plants, CCS is Carbon Capture and Storage and CCGT is Combined Cycle Gas Turbine. |
|---------|-----------------|-----------------|-----------------|-----------------|-----------------|
|         | ASIA            | OECD            | NAME            | EEFUS           | LAFM            |
|         | €/MWhth          | €/MWhth          | €/MWhth          | €/MWhth          | €/MWhth          |
| Coal PP | 18.9            | 18.9            | 13.3            | 13.3            | 13.3            |
| Coal PP + CCS | 22.7          | 22.7            | 15.9            | 15.9            | 15.9            |
| Gas PP - CCGT | 19.0          | 5.7             | 14.8            | 13.5            | 13.5            |
| Gas PP - CCGT + CCS | 22.7         | 6.5             | 7.4             | 15.2            | 15.2            |
| Nuclear PP | 7.7           | 7.7             | 7.7             | 7.7             | 7.7             |
| Solar PV | 1.5             | 1.5             | 1.5             | 1.5             | 1.5             |
| Wind turbine | 1.5          | 1.5             | 1.5             | 1.5             | 1.5             |
5. Li-ion batteries: Characteristics based on power capacity of 1–3 MW and storage capacity of 0.5–1.2 MWh for utility-scale.
6. Coal PP: Characteristics based on supercritical, pulverised coal condensing power plant burning black coal; plant efficiency based on lower heating value.
7. CCGT PP: Characteristics based on combined cycle gas turbine of up to 580 MW (net); plant efficiency based on lower heating value of fuel.
8. OCGT PP: Characteristics based on advanced open cycle gas turbine of up to 250 MW (net); plant efficiency based on lower heating value of fuel.
9. CCS: Characteristics based on post-combustion carbon capture; plant efficiency based on lower heating value of fuel.
10. Nuclear PP: Characteristics based on advanced light water reactor technologies in the range of 1000–3300 MW; plant efficiency based on lower heating value of fuel.

3.13. Summary of calculations

Calculations for low, median and high LCOE were made to account for national differences in LCOE components and variance in energy generation from different technologies, and these are available along with all the Supplementary Material. The variance may be due to geographic factors in the case of solar PV and wind energy generation, but also due to how technologies are used in the energy system (peaking vs. baseload plants). The main factors for the variance in LCOE are capex, investment and overruns, and FLH. At the same time, fuel costs and assumptions about technology lifetimes could slightly increase the variance as discussed above. Low LCOE values are calculated from a combination of low capex estimates, low values for investment and overruns, and high FLH. Median LCOE values are calculated from a combination of low capex estimates, low values for investment and overruns, and median FLH. High LCOE values are derived from a combination of high capex estimates, high values for investment and overruns, and low FLH. Importantly, high values for gas turbines should not immediately be seen as entirely negative. Such high values are primarily the result of low FLH of peak-following gas turbines, which have an important regulatory function in many energy systems.

While a full range of values were calculated for LCOE, only values below 250 €/MWh are shown in figures in the results section. Above this level, investments are highly unlikely to be profitable in all but the most extreme, off-grid situations, or when technologies play an important regulatory function, such as frequency control of grids.

4. Results

Results of LCOE calculations for all the G20 countries are presented in Figs. 3–6, and all the applied assumptions and data are shown in detail in the supplementary material. The range of LCOE values for the years 2015 and 2030 are represented by bars that are coloured corresponding to the different technologies as shown in the legend. The range of LCOE values for conventional technologies (coal, gas and nuclear) also include CO2eq and external costs. The median values for LCOE across the different technologies are represented by the red dots (which do not include the CO2eq and external costs) and the white dots (which include the CO2eq and external costs).

In general, onshore wind energy currently shows the lowest overall LCOE, especially in regions of high latitudes (either north or south). Notable exceptions exist for some regions in Asia where wind resources are less favourable as compared to the solar resource, which is more favourable. In 2030, solar PV utility power plants represent the lowest LCOE of all technologies across all the G20 countries with the exception of Northern European countries that are part of the European Union, where onshore wind continues to have the lowest LCOE. On a global level represented by all the G20 countries, rooftop solar PV becomes more competitive than conventional energy production (fossil fuels and nuclear) in 2030, especially when a more complete range of costs are internalised for all technologies. Cost reductions projected for battery storage in 2030 also increase the competitiveness of PV + Battery systems (rooftop and utility) across all the G20 countries. Conventional fuels become significantly less competitive in 2030 when the costs of CO2eq and other externalities are fully considered. Gas-based technologies, important providers of flexibility to global energy systems, have the potential to reduce overall LCOE through switching from natural gas to more sustainable bio-based or synthet methan. Carbon capture and storage offers an opportunity to reduce costs associated with fossil fuel combustion, but remains significantly higher in costs than renewable energy generation, even with the anticipated cost reductions due to development of CCS technology. It needs to be noted that net zero emissions are almost, if not impossible, with fossil based CO2 capture, whereas costs than renewable energy based systems. Nuclear power has already lost its competitiveness to wind and solar PV in 2015 in most of the G20 countries and further worsens its relative competitiveness with renewable energy in 2030 when high levels of social, environmental and economic risks are internalised in the LCOE calculations.

As shown in Fig. 3, the results for Argentina indicate that LCOE of wind onshore power (25 €/MWh) is already lower than fossil fuel based power generation (with coal having LCOE of 46 €/MWh) in 2015, and by 2030 LCOE of wind (22 €/MWh) along with utility-scale PV (22 €/MWh) will be much lower. In the case of Australia, wind onshore power has lower LCOE (35 €/MWh) as compared to fossil based power (with coal having LCOE of 55 €/MWh) in the present context, and by 2030 rooftop (36 €/MWh) and utility-scale PV (22 €/MWh) along with wind onshore (30 €/MWh) will be the cheapest sources of electricity. In Brazil, LCOE of wind onshore power (44 €/MWh) is competitive with respect to fossil fuel based power generation (with coal having LCOE of 46 €/MWh) in 2015 and remains competitive in 2030, whereas utility-scale PV (24 €/MWh) along with utility battery storage (32 €/MWh) will have the lowest LCOE in 2030. In Canada, fossil fuel based power generation (with coal and CCGT having LCOE of 52 €/MWh) has lower LCOE in the present context, whereas wind onshore (40 €/MWh) and utility-scale PV (35 €/MWh) will have lower LCOE by 2030. In China, wind onshore power has the lowest LCOE (29 €/MWh) in 2015, and by 2030 wind onshore (27 €/MWh) and utility-scale PV (23 €/MWh) will have lower LCOE than fossil and nuclear power (with coal having LCOE of 36 €/MWh).

As shown in Fig. 4, the results for France and Germany show that LCOE of wind onshore power (with 47 and 44 €/MWh) is presently competitive with fossil fuel based power (with coal having LCOE of 43 and 42 €/MWh), and by 2030 wind onshore (29 and 28 €/MWh) and utility-scale PV (32 and 40 €/MWh) have much lower LCOE. In India, fossil fuel sources (with coal having LCOE of 34 €/MWh) have lower LCOE in 2015, whereas utility-scale PV (25 €/MWh) has much lower LCOE in 2030. Similarly in Indonesia, fossil fuel sources (with coal having LCOE of 39 €/MWh) have lower LCOE in 2015, whereas utility-scale PV (25 €/MWh) has much lower LCOE in 2030. In Italy, fossil fuel produces power (with coal having LCOE of 43 €/MWh) at a lower LCOE in 2015, whereas by 2030 wind onshore (29 €/MWh) and utility-scale PV (27 €/MWh) shows lower LCOE than fossil fuel sources (with coal having LCOE of 39 €/MWh) in 2015.
As shown in Fig. 5, the results for Japan indicate that fossil fuel based power (with coal and CCGT having LCOE of 57 and 55 €/MWhel) have lower LCOE in 2015, whereas by 2030 utility-scale PV (31 €/MWhel) and wind onshore (54 €/MWhel) will have lower LCOE. In the case of Republic of Korea, fossil fuel and nuclear power (with coal and nuclear having LCOE of 37 and 40 €/MWhel) have lower LCOE in 2015, whereas utility-scale PV (29 €/MWhel) has much lower LCOE in 2030. In Mexico, utility-scale PV (60 €/MWhel) is competitive with fossil fuel based power (with coal and CCGT having LCOE of 52 and 51 €/MWhel) in 2015, and by 2030 utility-scale PV (21 €/MWhel) and wind onshore (51 €/MWhel) have much lower LCOE. Whereas, in Russia, wind onshore power (59 €/MWhel) is competitive with fossil fuel based power (with coal and CCGT having LCOE of 52 and 51 €/MWhel) in 2015, and by 2030 utility-scale solar PV (36 €/MWhel) and wind onshore (52 €/MWhel) have lower LCOE. In Saudi Arabia, fossil fuel sources (with coal and CCGT having LCOE of 47 and 49 €/MWhel) have lower LCOE in 2015, whereas utility-scale PV (21 €/MWhel) has much lower LCOE in 2030.
As shown in Fig. 6, the results for South Africa indicate that fossil fuel produces power (with coal having LCOE of 47 €/MWhₑ) at a lower LCOE in 2015, whereas by 2030 wind onshore (46 €/MWhₑ) and utility-scale PV (21 €/MWhₑ) will have lower LCOE. Similarly, in Turkey, fossil fuel sources (with coal having LCOE of 43 €/MWhₑ) have lower LCOE in 2015, whereas utility-scale PV (25 €/MWhₑ) and wind onshore (40 €/MWhₑ) have much lower LCOE in 2030. In the UK, wind onshore power (44 €/MWhₑ) is competitive with fossil fuel based power (with coal having LCOE of 43 €/MWhₑ) in 2015, and by 2030 wind onshore power has the lowest LCOE (23 €/MWhₑ). In the USA, wind onshore power (31 €/MWhₑ) has the lowest LCOE in 2015, and by 2030 wind onshore (30 €/MWhₑ) and utility-scale PV (25 €/MWhₑ) have much lower LCOE than fossil fuel based power (with coal having LCOE of 55 €/MWhₑ). Lastly, in the EU, wind onshore power (40 €/MWhₑ) has lower LCOE in comparison to fossil fuel based power (with coal and CCGT having

![Fig. 4. Results of LCOE calculations for the G20 countries France, Germany, India, Indonesia and Italy in 2015 and 2030 (€/MWhₑ).](image-url)
LCOE of 43 and 51 €/MWhel) and by 2030, wind onshore (30 €/MWhel) and utility-scale PV (30 €/MWhel) have lower LCOE.

5. Discussion

The LCOE of all technologies across the G20 countries are compiled into renewables and storage that includes wind onshore, wind offshore, PV rooftop, PV utility, Li-ion batteries rooftop and Li-ion batteries utility, and fossil fuels and nuclear that includes Coal PP, Coal with CCS, CCGT, CCGT with CCS, OCGT and Nuclear PP. Further, the LCOE of renewables and storage are evaluated against the LCOE of fossil fuels and nuclear, with and without the consideration of external and CO2eq costs for 2015 as well as 2030. Fig. 7 presents the comparative results for LCOE of renewables and storage with LCOE of fossil fuels and nuclear in 2015, with and without external and CO2eq costs. Countries are shaded in green when the LCOE of renewables and storage is lesser than the LCOE of fossil fuels and nuclear, shaded orange when the LCOE of renewables and storage is greater than the LCOE of fossil fuels and nuclear, and shaded grey when the LCOE of renewables and storage is equal to the LCOE of fossil fuels and nuclear.

Fig. 5. Results of LCOE calculations for the G20 countries Japan, Republic of Korea, Mexico, Russia and Kingdom of Saudi Arabia in 2015 and 2030 (€/MWhel).
storage are the same as the LCOE of fossil fuels and nuclear, and shaded red when the LCOE of fossil fuels and nuclear are lesser than the LCOE of renewables and storage.

On comparing the LCOE of all power generation technologies across the G20 countries in 2015, it can be concluded that the LCOE of renewable energy sources are already on par with fossil and nuclear sources in many of the G20 countries even without the inclusion of external and CO2eq costs. Whereas, when external and CO2eq costs are included in the LCOE estimations, the LCOE of renewables and storage are lesser than the LCOE of fossil fuels and nuclear in almost all the G20 countries. Apart from Republic of Korea, where the LCOE of fossil fuels and nuclear is still lesser than the LCOE of renewables and storage, and in Italy and South Africa, where the LCOE of renewables and storage are the same as the LCOE of fossil fuels and nuclear.

Onshore wind is currently the least cost source of electricity in many of the G20 countries, ranging from 18 to 121 €/MWhel (excluding Indonesia), and utility-scale PV, which is quite...
competitive in many of these countries ranges from 36 to 140 €/MWhel (excluding Russia). These values are comparable to present auction prices as shown in (Agora Energiewende, 2017). As indicated in Fig. 7, if external and CO2eq costs are taken into account, wind and solar PV along with batteries will be cheaper in almost all the G20 countries in terms of LCOE.

Fossil fuel based energy generation currently appears relatively low in cost due to low costs of GHG emissions imposed by many global markets, which does not represent the real impacts of those emissions. Coal-based generation appears to be the lowest cost of the fossil fuels due to the baseload nature of plant operation when compared to gas based technologies. It should be noted, however, that gas based technologies play important roles in grid stabilisation and balancing. Therefore, lower full load hours of gas turbine plants are a major contributor to higher LCOE. CCS technologies appear very high in costs at the moment and do not represent an economically competitive option in the near term. Nuclear power appears relatively lower in costs in China and the Republic of Korea (likely due to high domestic subsidies), but has significantly higher costs in other parts of the world, when the costs of financing, budget overruns, waste management, decommissioning and associated risks are included.

Fig. 8 presents the comparative results for LCOE of renewables and storage with LCOE of fossil fuels and nuclear in 2030 for all G20 countries without including external and CO2eq costs. It is quite evident that renewables and storage prove to be much cheaper even without considering external and CO2eq costs on a LCOE basis. This is primarily due to the rapid decline in costs expected for solar PV and battery systems, along with a steady decline in the costs of wind turbines up to 2030 (Breyer et al., 2017a,b).

Renewable energy technologies offer the lowest LCOE ranges across G20 countries in 2030. Utility-scale solar PV generally shows
the lowest values ranging from 16 to 117 €/MWhel, although there are notable exceptions for regions where the solar resource is more variable or the onshore wind resource is particularly good. The onshore wind LCOE range is from 16 to 90 €/MWhel (excluding Indonesia). This is the case for several countries at higher northern latitudes. Rooftop solar PV generally offers the next lowest LCOE ranging from 64 to 135 €/MWhel. However, similar exceptions exist for higher northern latitudes and in areas that typically have higher quality offshore wind resources (e.g., Canada, USA, UK). Solar PV and battery systems are highly competitive on an LCOE basis at utility-scale (21–165 €/MWhel) with overall market costs of electricity depending on local costs, and at residential scale (40–204 €/MWhel) depending on consumer costs of electricity including taxes, transmission costs, and distribution costs. As shown by Lazard (Lazard, 2017) and IRENA (IRENA, 2018), these costs are attainable even before 2030 with the current market trends indicating substantial drops in the costs of renewable technologies. This is further substantiated with the recent bids for solar PV in Chile and Mexico reaching 21.48 USD/MWh and 20.57 USD/MWh, respectively. Also, bids in Saudi Arabia for solar PV were below 20 USD/MWh (Bellini, 2017a, 2017b; Kenning, 2017). Interestingly, the lowest LCOE values seen for renewable energy technologies in the G20 are in Argentina, where both solar and wind resources are exceptional.

On the contrary, fossil fuel and nuclear power generation represents higher LCOE ranges across the G20 countries in 2030. Firstly, gas based energy generation represents the highest LCOE values with 107–124 €/MWhel for CCGT and 142 to 162 €/MWhel for OCGT. However, it must be reiterated that many of the higher range values are the result of operational conditions for gas turbines, especially OCGT. These operational conditions include the provision of essential control and stability for electricity grids, which may significantly limit the FLH of operation. In addition, gas-based technologies have the great potential to reduce costs associated with GHG emissions and external costs by switching to more sustainable fuels, such as biomethane and synthetic methane. Secondly, coal based power represents amongst the highest LCOE values ranging from 115 to 186 €/MWhel when CO2eq and external costs are accounted. This trend is seen across the G20 countries. Thirdly, nuclear power shows a wide range of LCOE values from 62 to 152 €/MWhel. Low values for 2030 are observed in China and the Republic of Korea as it is unclear if the reported overnight costs represent subsidised values. The technologies provided in these countries domestically differs significantly in cost to the same technologies installed internationally by the same technology providers. Conservative cost assumptions were used to specify the upper limit in relation to financing and overruns (40% of overnight capex). However, several projects worldwide have shown that such costs can exceed 300% of capex (Koistinen, 2012; Le Monde, 2012; Schneider and Froggatt, 2016) and the averaged cost overrun for 180 reactors has been found to be 117% (Sovacool et al., 2014a,b).

Lastly, CCS offers little hope for positive business cases in the Americas through to at least 2030. The range of LCOE for coal CCS is 89–205 €/MWhel, and the range for CCGT CCS is 102–179 €/MWhel.

In comparison to other LCOE estimates, such as Lazard (Lazard, 2017), IRENA (IRENA, 2017a, 2018) and Agora Energiewende (Agora Energiewende, 2017), these estimates seem rather on the conservative side with respect to LCOE values of renewable technologies, specifically utility-scale PV and onshore wind. Also, recent bids for large scale solar PV projects across Saudi Arabia, Chile and Mexico (around 20–22 USD/MWh) have demonstrated the rapid cost decline potential of solar PV power (Bellini, 2017a, 2017b; Kenning, 2017). Lazard’s LCOE estimates show utility-scale solar PV ranging from 43 to 48 USD/MWh and wind onshore ranging from 30 to 60 USD/MWh, whereas coal ranges from 60 to 143 USD/MWh and nuclear ranges from 112 to 183 USD/MWh. Agora Energiewende estimates the average LCOE for onshore wind in the context of Germany to be in the range of 5–9.5 cents/kWh. As the global energy transition increasingly shifts towards renewables and away from fossil and nuclear sources, the costs of energy are expected to decline further (Breyer et al., 2017a,b). These estimates further substantiate the results of this research in the context of 2030, as LCOE of renewables and storage are continuing to decline.

Fig. 8. Results of LCOE calculations for the G20 countries in 2030 without external and CO2eq costs.
6. Conclusions

From the LCOE results presented in Figs. 7 and 8, it is clear that renewable electricity generation in several of the G20 countries is already lower in cost than conventional alternatives. These include the USA, Argentina, Brazil, the EU, Turkey, China and Australia. This is the case when external and CO2eq costs are not considered, but with clear socio-economic and environmental impacts of power generation along with increasing adverse direct health impacts of fossil fuel and nuclear power generation being evident (Health Care Without Harm, 2015; Markandya and Wilkinson, 2007), the need to represent the real costs of power generation is incontrovertible. When the external and CO2eq costs of the various power generation technologies are considered, LCOE of renewables and storage are seen to be much less than the LCOE of fossil fuels and nuclear across most of the G20 countries. This suggests that there are clear socio-economic benefits in making the right energy choices for governments of the G20 countries as well as rest of the world. At the same time, as indicated earlier it is expected that all G20 countries will demonstrate full cost competitiveness of renewable sources by 2030 on a LCOE basis. Even without the consideration of external and CO2eq costs, renewables and storage make a fully viable economic case for all the G20 countries by 2030.

However, it should be stressed that all countries should begin to invest in renewable energy sources well ahead of 2030 in order to take full advantage of this opportunity and minimise adverse impacts. Firstly, waiting too long will mean that expanding intermittent renewable capacities may be unnecessarily disruptive to power systems if growth is too rapid. More gradual increases in capacities over the coming decade or so can mitigate such technical disruptions. Furthermore, existing industries and companies may need to adapt to the energy transition, and a steadier transition towards 2030 may help prepare them for the task ahead. Secondly, eliminating external costs as soon as possible will result in improved health and well-being, particularly in countries such as India and China (Jakob et al., 2016). As stated previously, these external costs are often felt disproportionately by the most vulnerable members of society. Therefore, each country must find its own unique transition towards greater sustainability based on their levels of population, affluence and technology (Shuai et al., 2017), and it would be unwise for any to lack an appropriate sense of urgency. Finally, renewable based power generation seems to be the reasonable option, as not only is it lower in costs and more efficient, but it also generates jobs and sustains economic growth as indicated in (Ram et al., 2017). Governments and institutions that most aggressively adopt the energy transition and create an enabling environment to facilitate faster flow of capital investments into their regions for renewable energy development will witness far more economic growth and benefit from it (Binz et al., 2017). It appears to be logical from an economic perspective, an environmental perspective, a health perspective and a moral perspective.

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2018.07.159.

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