Vergleich der Stromgestehungskosten von Erneuerbaren Energien mit denen fossiler und nuklearer Kraftwerke in den G20-Ländern

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Vergleich der Stromgestehungskosten von Erneuerbaren Energien mit denen fossiler und nuklearer Kraftwerke in den G20-Ländern

Comparing electricity production costs of renewables to fossil and nuclear power plants in G20 countries

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Lappeenranta University of Technology (LUT), 2017

➡ Kein Geld von Industrie und Staat

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Vorwort

Die G20-Staaten stehen für mehr als 80 Prozent der weltweiten Treibhausgasemissionen. Als mit Abstand größte CO2-Quelle ist die Energieerzeugung dabei von besonderer Bedeutung. Das bedeutet: Globaler Klimaschutz ist weder ohne die G20 möglich, noch ohne eine Erneuerung der Stromerzeugung.

Die gute Nachricht: Der anstehende Umbau der Energieerzeugung geht mit wirtschaftlichen Vorteilen einher. Wind- und Solaranlagen gewinnen immer häufiger den Wettkampf um die günstigsten Preise. Staats- und Regierungschefs, die weiter mit Kohle und Atom planen statt die Erneuerbaren Energien weiter auszubauen, schaden nicht nur dem Klima, sie richten auch volkswirtschaftliche Schäden an.

Die vorliegende Studie zeigt: Erneuerbare Energien sind die günstigste Art der Stromerzeugung – bereits heute in knapp der Hälfte der G20-Staaten, spätestens im Jahr 2030 aber in all diesen Ländern. Der kontinuierliche Preisverfall für Solarpanele und Windräder macht deutlich, dass diese Entwicklung schon weit vor dem hier untersuchten Stichtag erreicht sein wird.

So eindeutig die Sache ökonomisch ist, so unentschieden ist sie bislang auf politischer Ebene. Noch immer werden schmutzige und gefährliche Energien wie Kohle und Atom mit massiven Subventionen begünstigt. Zwar haben die G20-Staaten ihren Abbau schon vor Jahren beschlossen und die G7 dafür das Enddatum 2025 beschlossen, doch mit der konsequenten Umsetzung hat noch kein Land begonnen. Zudem ist die Förderung Erneuerbarer Energien oft unzureichend – auch in Deutschland. Die Bundesregierung hat den Ausbau Erneuerbarer Energien mit einem Deckel gebremst, obwohl die sauberen Energien heute günstig sind wie nie. Ein noch absurderes Bild zeigt sich in den USA: Während Präsident Trump verspricht, Kohle und Atomkraft wiederzubeleben, ist die Windkraft bereits heute die günstigste Energieform.

Die chinesische Regierung hat die wirtschaftlichen und ökologischen Vorteile der Erneuerbaren erkannt. Auch hier ist die Windkraft inzwischen die günstige Form, Strom zu erzeugen. Kein anderes Land baut heute mehr Windräder und Solaranlagen wie China.

Die vorliegende Studie betrachtet zudem die Folgekosten schmutziger Stromerzeugung. Nimmt man diese auch in den Blick, zeigt sich bereits jetzt der finanzielle Vorteil einer Energiewende. Dass ein beschleunigter Umstieg auch für Staaten mit heute noch wenig Erneuerbaren Energien sinnvoll ist, zeigt gerade das Beispiel Südkorea. Die Regierung des Lands hat unlängst einen Atom- und Kohleausstieg verkündet.

Während heute Windräder an Land den häufig günstigsten Strom liefern, werden Solarpanele in naher Zukunft in vielen Ländern noch einmal billiger werden. Begleitet von rapide sinkenden Preisen für Batteriespeicher, zeichnet sich eine grundlegende Veränderung der weltweiten Stromsysteme ab. Darauf müssen sich Staaten vorbereitet. Sie müssen ihre Stromnetz fit für die Erneuerbaren machen, Know-How für diese Veränderungen entwickeln und Fachkräfte anlocken und ausbilden.

Zahllose Reports haben gezeigt, dass Klimaschutz ökologisch dringend nötig ist. Diese Studie zeigt, dass er auch wirtschaftlich sinnvoll ist.

Tobias Austrup, Hamburg, Juli 2017

Zusammenfassung

Antworten auf die Herausforderungen des Klimawandels gehören zu den Hauptthemen des anstehenden Treffens der G20 Staats- und Regierungschefs. Die Folgen der zunehmenden Erderhitzung stellt eine Bedrohung für Millionen von Menschen dar und gleichzeitig ein wirtschaftliches Risiko. Um diese Gefahren zu minimieren muss der weltweite Verbrauch von Kohle, Öl und Gas, die bisher den Großteil des weltweiten Gesamtenergiebedarfs stellen, rasch gesenkt und schließlich auf null gebracht werden.

Die Erneuerbaren Energien sind weltweit inzwischen hinreichend ausgereift. Diese sauberen Energieformen stellt damit in vielen Teilen der Welt nicht nur eine wirtschaftliche Alternative zu klimaschädlichen, konventionellen Kraftwerken dar, zugleich sind sie auch der bevorzugte Weg, um den Herausforderungen des Klimawandels zu begegnen.

In der Vergangenheit wurden Erneuerbare Energien (EE) oft mit den Risiken von Zukunftstechnologien assoziiert, wodurch sie für konventionelle Investoren oft ausschieden. Der rasant wachsende Anteil an den weltweiten Stromkapazitäten, senkt die Stromgestehungskosten Erneuerbarer Energien jedoch inzwischen auf ein Niveau, dass sie wettbewerbsfähig zu konventionellen Stromquellen macht. Laut eines vom UNEP und BNEF beauftragten Berichts[1] sanken die durchschnittlichen Stromgestehungskosten aus der Photovoltaik im vergangenen Jahr um 17 Prozent, die Kosten der Onshore-Windkraft fielen um 18 Prozent und die der Offshore-Windkraft um 28 Prozent. In vielen Ländern beginnen die Kosten für Erneuerbare Energien, die Kosten aller anderen neuen Erzeugungskapazitäten zu unterschreiten. So sanken die Kosten für ein Windkraftprojekt in Marokko auf etwa 26 Euro pro MWh. In Abu Dhabi wurden im vergangenen Jahr 24 Euro pro MWh für ein Solarkraftwerk geboten[2]. Beide Beispiele zählen zu den niedrigsten Strompreisen weltweit bei neuen Kraftwerksprojekten.

Trotz deutlich sinkender Kosten bevorzugen viele G20-Länder nach wie vor fossile Brennstoffe und Stromerzeugung aus Atomkraft. Der vorliegende Report belegt, dass solche Entscheidungen wirtschaftlich nicht mehr zu rechtfertigen sind. Der Bericht beinhaltet Abschätzung zu den aktuellen und künftigen Gesamtkosten verschiedener Stromerzeugungsoptionen in jedem G20-Land. Überdies liefert er einen umfassenden Überblick über die erforderliche Flexibilität und nötige Speicherkapazitäten, untersucht das Subventionsproblem des konventionellen Energiesystems und analysiert die günstigsten 100-Prozent-Erneuerbare–Energien-Systeme, die mit dem Pariser Abkommen vereinbar wären.

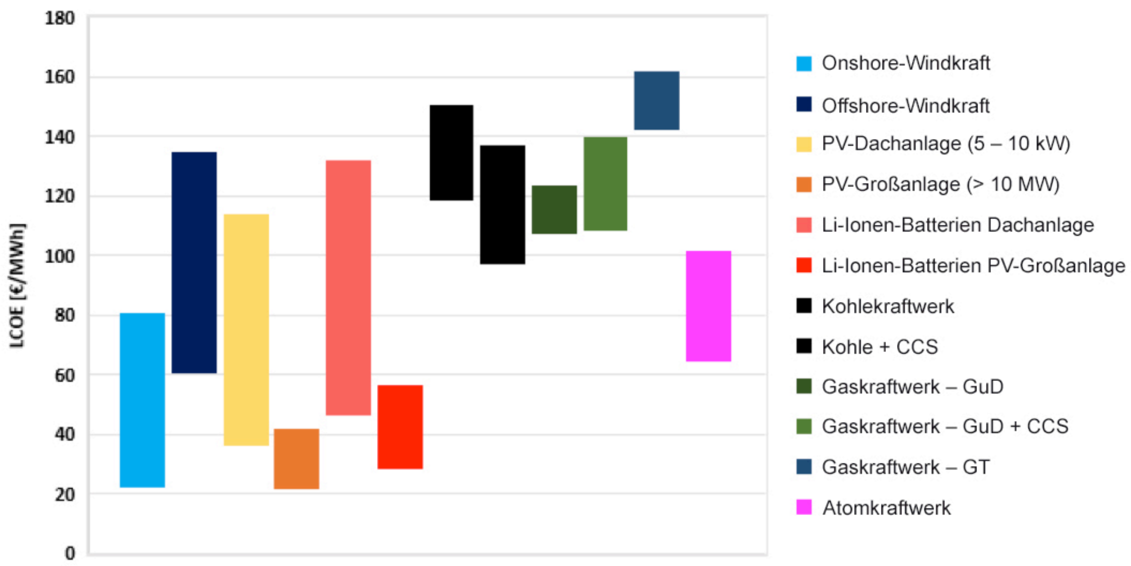


Abbildung ES-1: Bandbreite durchschnittlicher Stromgestehungskosten (Levelised cost of electricity = LCOE) einschließlich externer Kosten sowie Kosten der Treibhausgasemissionen (THG) aus verschiedenen Stromerzeugungstechnologien für die G20-Länder im Jahr 2030. Die externen Kosten für Atomkraft beinhalten nicht das hohe Risiko einer begrenzten Schadensabdeckung durch Versicherungen im Fall einer Nuklearkatastrophe.

Zudem können die Kosten für regenerativen Strom inzwischen in vielen G20-Ländern mit den Preisen der lokalen Versorgungsnetze konkurrieren. Laut Schätzungen dieses Reports und wie in Abbildung ES-1 dargestellt, liegen die Kosten Erneuerbarer Energien in allen G20-Ländern bis spätestens 2030 deutlich unter denen konventioneller Energieträger. Wie die Schätzungen dieses Reports zeigen, werden die Kosten für regenerative Technologien noch weiter fallen, was zu extrem niedrigen Kosten für erneuerbaren Strom und zu großen Veränderungen des weltweiten Energiesektors führen wird. Auch die Batteriekosten sind in den vergangenen Jahren dramatisch gesunken, was die Entwicklung im Bereich erneuerbaren Stroms weiter ergänzen wird. Wie Abbildung ES-1 zeigt, werden die Preise für Batterien durch die vermehrte Nutzung in Kombination mit groß- und kleinskaligen Solaranlagen, die breite Nutzung von Elektrofahrzeugen und die erhöhte Batterieproduktion weiter fallen.

Seit einigen Jahren beziehen zudem mehr und mehr Unternehmen und Konzerne ihren Strom von Erneuerbaren Anbietern. Ein Großteil der Fortune-100-Unternehmen, die zu den weltweit einflussreichsten zählen, haben sich Ziele für Erneuerbare Energien und Nachhaltigkeit gesetzt, während sich ein guter Teil der Fortune-500-Unternehmen dazu verpflichtet haben, ihre Stromversorgung zu 100 Prozent auf Erneuerbare Energien umzustellen. Zeitgleich trennen sich viele Unternehmen und Investoren bewusst von Vermögenswerten aus konventionellen Energiesystemen, insbesondere aus Kohle und Atomenergie[3].

Trotz der positiven Impulse, die vom Erneuerbare-Energien-Sektor ausgehen, gibt es riesige Herausforderungen, die die Aufmerksamkeit der globalen Gemeinschaft verlangen. Eines der größeren Probleme sind die Subventionen für fossile Brennstoffe. Die Internationale Energieagentur (IEA) schätzt, dass die Länder im Jahr 2014 fast 500 Milliarden an Subventionen für fossile Brennstoffe ausgegeben haben, 90 Prozent der Ausgaben entfallen auf die Regierungen der G20-Länder. Ein weiteres Problem liegt in den externen Kosten der Energieerzeugung, jenen Kosten also, die nicht von den Anlagenbetreibern, sondern von der Gesellschaft getragen werden müssen. Dies schließt die negativen gesundheitlichen Folgen der verschiedenen Emissionen, die Verschmutzung durch den Abbau der Energieträger sowie die Klimafolgekosten mit ein. Selbst wenn man diese externen Kosten der fossilen Energien und des Atomstroms bis 2030 nicht berücksichtigt, erweisen sich die erneuerbaren Energien als deutlich kostengünstiger, so die Schätzungen dieser Studie.

Der Mythos, die Erneuerbaren seien „zu teuer", konnte bereits mehrfach widerlegt werden, und der Kostenrückgang bei Wind- und Solartechnologien übersteigt bei Weitem das Gros der Branchenerwartungen. Dieser Report untermauert den Trend nicht nur, er zeigt auch anhand von Statistiken, dass alle G20-Länder das Potential haben, ihren Anteil an Erneuerbaren Energien einschließlich ergänzender Speichertechnologien bis 2030 signifikant zu erhöhen. Somit können die G20-Länder bei ihrer Wirtschaftsentwicklung weiterhin auf Nachhaltigkeit setzen, mit erheblichen positiven Nebeneffekten für angrenzende Politikbereiche wie einen steigenden Lebensstandard, besserer Gesundheitsschutz, entsprechend niedrigeren Gesundheitskosten, verbesserter Energiesicherheit und vielem mehr. Die Abbildungen ES-2 und ES-3 zeigen die Stromerzeugungskosten von Onshore-Windkraft, Photovoltaik (Dachanlagen sowie großskalige Anlagen), Lithiumbatterien sowie Kohle-, Gas- und Atomkraftwerke in allen G20-Staaten für die Jahre 2015 und 2030. In den rot unterlegten G20-Ländern ist die Stromerzeugung auf Basis fossiler oder nuklearer Brennstoffe zum angegebenen Zeitpunkt die günstigste. In den gelb unterlegten Ländern liegen die Kosten für erneuerbare Energien auf dem gleichen Niveau wie die fossiler und nuklearer Energieträger. In den grün unterlegten Staaten sind erneuerbare Stromquellen die günstigste Form der Stromerzeugung.

Die Ergebnisse der Studie geben den Regierungen der G20-Staaten eine eindeutige energiepolitische Empfehlung: Erneuerbare Energien sind für einige G20-Länder bereits im Jahr 2015 die kostengünstigste Stromquelle. Deutlich vor dem Jahr 2030 werden die Erneuerbaren in allen G20-Staaten die günstigste Form der Stromversorgung sein.

Die wichtigsten Ergebnisse dieses Reports:

- Mit dem Pariser Abkommen haben die Staaten einen grundlegenden Umbau des globalen Energiesystems in Richtung Nachhaltigkeit beschlossen.
- Es ist dringend erforderlich, die Energiesysteme zu dekarbonisieren, schädliche Emissionen jenseits von CO_2 zu eliminieren und die globale Widerstandsfähigkeit gegen die Folgen des Klimawandels zu erhöhen.
- Erneuerbaren Energien, allen voran Solar- und Windkraft, sind in den vergangenen Jahren massiv gewachsen. Ihre kontinuierliche Weiterentwicklung sorgt dafür, dass sie mittelfristig alle anderen Energietechnologien ökonomisch abhängen werden.
- Legt man die Gesamtkosten der Erzeugung zu Grunde, so kann die dezeit noch dominierende konventionelle Stromerzeugung aus fossilen Brennstoffen und Atomenergie immer weniger mit den Erneuerbaren Energien mithalten, weder in ökologischer noch in sozialer noch in ökonomischer Hinsicht.
- Die niedrigen Stromgestehungskosten (LCOE), die sich mit Solar- und Windressourcen erreichen lassen, zeigen: Erneuerbare Energien sind in vielen G20-Ländern bereits wettbewerbsfähig. Bis 2030 werden Erneuerbare Energien in sämtlichen G20-Staaten die kostengünstigsten Lösungen darstellen, wobei die Kosten von Windkraft und Photovoltaik alle anderen Formen der Stromerzeugung weit vor 2030, möglicherweise bereits 2020, aus dem Rennen schlagen wird.
- Bioenergie mit CO_2-Abscheidung und -speicherung (BECCS), Direkte CO2-Abscheidung und -speicherung aus der Umgebungsluft (DACCS) sowie CO_2-Abscheidung und -verwendung (CCU) bieten ein gewisses Potenzial, um die THG-Emissionen zu senken, doch fossile CO_2-Abscheidung und -speicherung (CCS) stellen ein - auch wirtschaftlich gesehen - nicht abzubildendes Risiko dar.
- Die geringe wirtschaftliche Realisierbarkeit von CCS wird durch den hohen Grad der sozialisierten Risiken und die Bedrohung der menschlichen Gesundheit weiter verstärkt.

- Speichertechnologien können eine entscheidende Rolle beim Umstieg auf Nachhaltigkeit spielen, indem sie komplementäre Flexibilität für Solar- und Windressourcen liefern.
- Besonders bemerkenswert für die globalen Energiesysteme ist der rasante Rückgang der Kosten für Batteriespeicher sowie das signifikante Potenzial der Elektromobilität.
- Die enormen Subventionen für fossile Brennstoffe und Kernkraft führen zu ungleichen Wettbewerbsbedingungen, verzerren die Ökonomie des Strommarktes, begünstigen schmutzige Stromproduktion und untergraben die Bemühungen, dem Klimawandel entgegenzuwirken.
- Es sind weitaus größere Anstrengungen erforderlich, um die hohen sozialen, ökologischen und ökonomischen Lasten der fossilen Brennstoffe und der Kernkraft, die bislang häufig außer Acht gelassen wurden, zu internalisieren.
- Eine Reihe internationaler Berichte und akademischer Studien weist darauf hin, dass innerhalb der globalen Energiesysteme ein hoher Anteil an erneuerbaren Energien, insbesondere Solar- und Windkraft, erreicht werden kann.
- Den G20-Ländern kommt eine wichtige Rolle zu: Sie müssen die Energiewende, die für die Umsetzung der Ziele des Pariser Abkommens erforderlich ist, anführen.
- Steuerliche Anreize und Regulierungsmaßnahmen in den G20-Ländern können eine Umgebung schaffen, die zu höherer Nutzung von erneuerbaren Energien und stärkeren Klimaschutzmaßnahmen führt.
- Zudem müssen die vergangenen, gegenwärtigen und künftigen Risiken weltweiter Energiesysteme und ihrer Entwicklung voll und ganz anerkannt werden.

In vielen Regionen der Welt sind die Betriebskosten der Kohlekraftwerkskapazitäten höher als die Gesamtkosten neuer Windenergieanlagen. Dies wird in Abbildung ES-2 deutlich: Sie zeigt, dass die aktuellen Windenergiekosten in einigen G20-Ländern, die grün dargestellt sind, unter denen für fossile und nukleare Energie liegen. Diese Länder, zu denen die USA, China, Brasilien, Argentinien, Australien und ein Großteil Europas zählen, verfügen über exzellente Windkraftressourcen, die zum rapiden Kostenrückgang beigetragen haben. Dieser Trend setzt sich fort: Bei den jüngsten Stromauktionen lag das volumengewichtete Durchschnittsgebot für Onshore-Windkraft in Deutschland bei 57 Euro pro MWh (bei einer Preisspanne von 42 bis 58 Euro pro MWh). In Spanien lagen die Kosten bei 43 Euro pro MWh[4].

Die Photovoltaik holt rasant auf und hat in vielen Teilen der Welt bereits die gesamte Konkurrenz überholt. Dies zeigt sich bei aktuellen Auktionen und weltweit abgeschlossenen Kaufverträgen für Solarstrom. So lagen die Kosten in Indien bei etwa 33,5 Euro pro MWh, in Dubai fielen sie auf 26,5 Euro pro MWh, und Chile verzeichnete Stromkosten von 25,8 Euro pro MWh [4]. Überdies belegt ein aktuelles Gebot in Abu Dhabi, dass ein Preis von 24,2 Euro pro MWh durchaus im Bereich des Möglichen liegt[2]. Die zunehmende Nutzung erneuerbarer Energien profitiert dabei auch von steigenden Kosten für Importe von flüssigem Erdgas (LNG) und fossilen Brennstoffen in vielen Ländern. Insbesondere im asiatischen Raum, beispielsweise in Indonesien und Indien, wo die Stromnetze noch in der Entwicklung sind und bislang noch nicht die gesamte Bevölkerung erreichen, erweisen sich dezentrale Solaranlagen auf Hausdächern als günstige Option zur Stromerzeugung. Der größte Veränderungsdruck geht von den Verbrauchern aus, denn diese prüfen und bevorzugen Produkte und Dienstleistungen von Unternehmen, die sich verpflichten, die Abhängigkeit von fossilen Brennstoffen zu reduzieren und/oder zu eliminieren. In nahezu in allen Ländern, die jetzt von kostengünstigem Strom aus Photovoltaik und Windkraft profitieren, gab es anfangs Fördermaßnahmen. Auch mit dem Ziel, neue Branchen zu unterstützen, von denen inzwischen etliche eine führende Position auf dem Weltmarkt erreicht haben. Ergänzt wird dies durch die Initiativen des Bildungssektors, der mit entsprechenden Ausbildungen auf die Nachfrage nach entsprechenden Arbeitskräften reagiert.

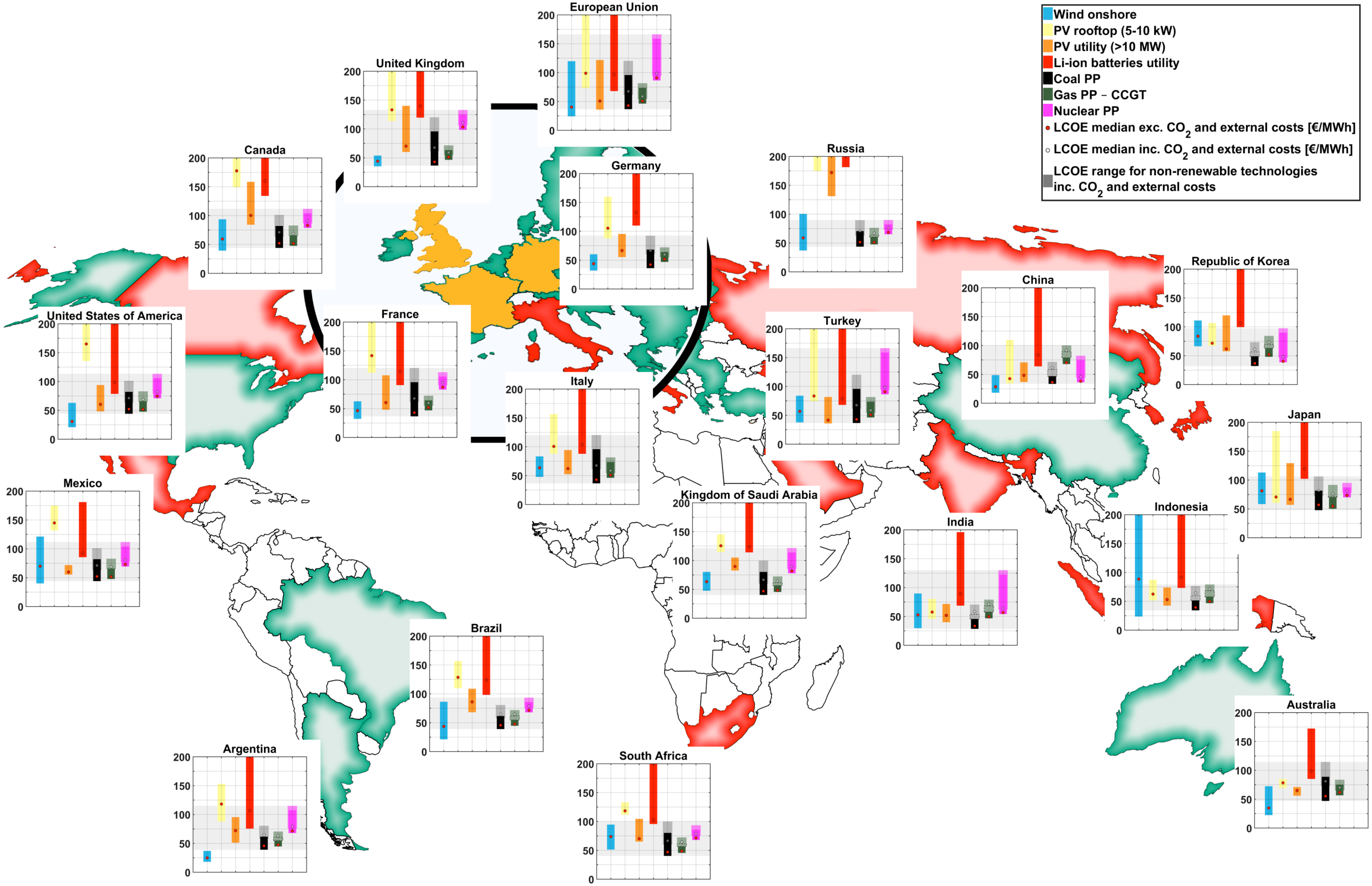


Figure ES-2: LCOE of various power generation technologies across the G20 in 2015

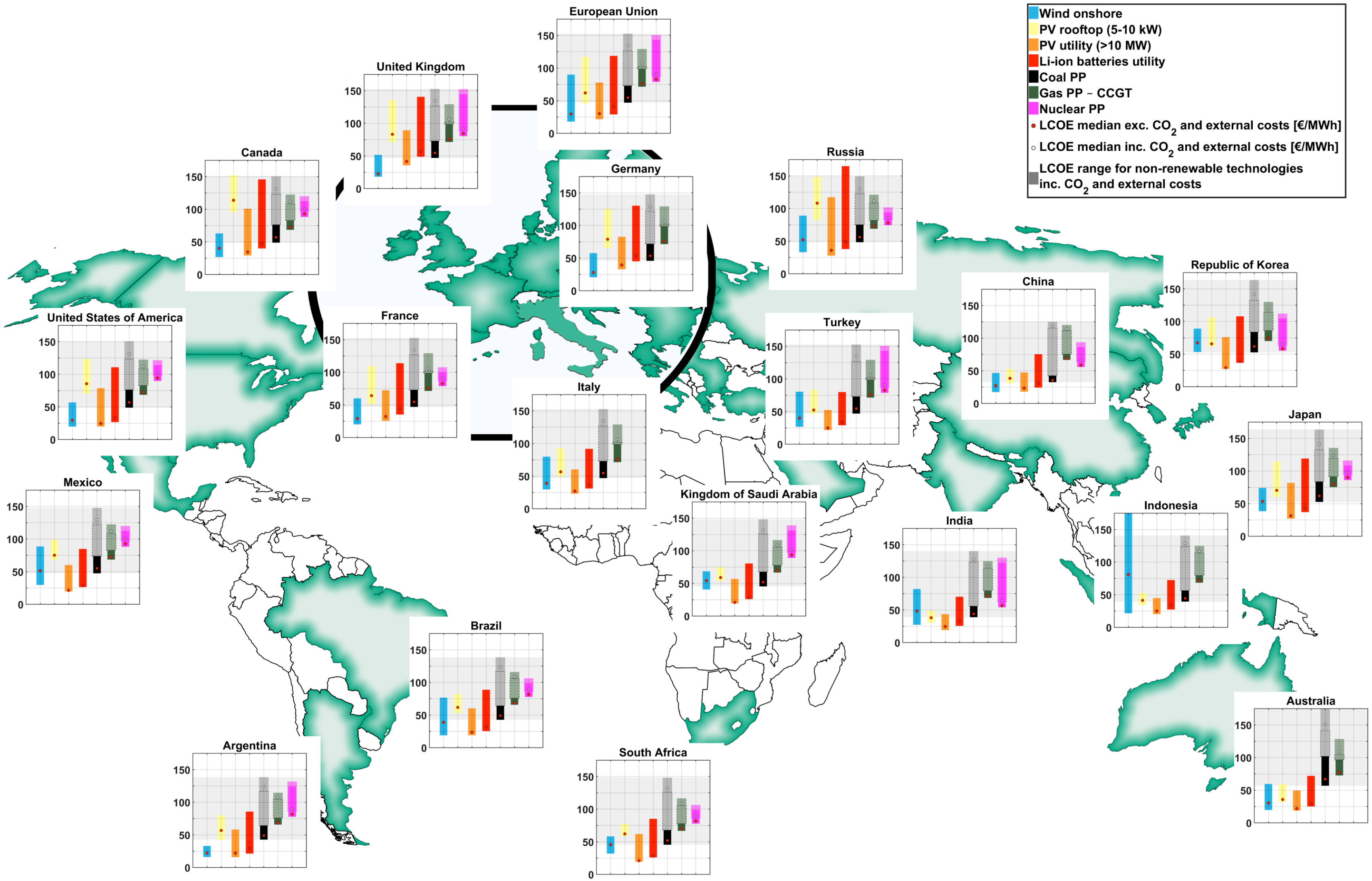


Figure ES-3: LCOE of various power generation technologies across the G20 in 2030

Argentina
Excellent solar and wind resources means there is very high potential for the lowest cost RE generation in the world, both currently and in the future. The country is highly vulnerable to climate change and variability.

Current status:

- 34% share of renewable installed capacity, mostly hydropower [5]
- Excellent potential for solar and wind power generation and recent auctions have been initiated
- Most recently commissioned nuclear reactor (Atucha-2) took 33 years to reach rated power

Key results of analysis:

- Potential to achieve lowest LCOE for electricity in G20 for solar PV and wind (16 €/MWh)
- Very predictable wind power generation with little interannual variation
- International financing needed to reach full potential of sustainable energy development

Australia
Excellent solar and wind resources result in very high potential for low cost RE generation currently and in the future.

Current status:

- Power sector currently dominated by coal at 41% of installed capacity [6]
- Only 10% of electricity generated from renewables [7]
- Goal of 23% renewable electricity by 2020 [7]

Key results of analysis:

- Very low cost wind energy potential currently and in 2030
- Utility scale and rooftop solar PV also promising; low interannual variation of resource
- Cost of coal based energy amongst highest in the world when full costs are internalised

Brazil
Already a world leader in renewable energy capacity, with excellent hydropower, bioenergy and wind resources. Reductions in GHG emissions to date amongst largest in the world despite serious social and environmental challenges.

Current status:

- 85% of installed capacity is based on renewables, mostly hydropower [5]
- Growing share of onshore wind installed capacity
- Plans to expand already successful biofuel production

Key results of analysis:

- Low cost wind energy can continue to help diversify renewable energy mix
- Utility-scale solar PV can emerge as least cost technology by 2030
- Opportunities also for solar PV prosumers in near future

Canada

Excellent wind conditions result in high potential of RE generation in addition to strong base of hydropower and bioenergy. Province of Ontario was among the vanguard of regions to end electricity production from coal in 2014.

Current status:

- Solar PV more attractive in southern parts of the country where most people live
- Wind conditions in eastern Canada amongst best in the world
- Future role of pipelines carrying fossil fuels is divisive social and environmental issue

Key results of analysis:

- Fossil fuels and nuclear power less competitive in LCOE terms when all costs considered
- Wind energy set to become least cost technology by 2030
- Utility-scale solar PV offers attractive investment opportunity

China

High levels of airborne pollution from fossil fuels result in high external costs of electricity generation. These impacts can be greatly reduced by utilising low cost RE, almost all of which can be produced from domestic technology.

Current status:

- Coal power dominates current electricity landscape
- Strong roles for hydropower and wind energy
- Promising outlook for solar PV and wind energy

Key results of analysis:

- Wind energy and solar PV emerge as lowest cost sources of electricity
- Coal power not economically competitive when external costs are included in LCOE
- Low cost battery storage offers opportunities for prosumers

France

High dependence on domestic nuclear power exposes the nation to environmental, financial and social risk. Very good solar and wind potential are found throughout the country that can result in lower cost and risk.

Current status:

- High cost nuclear industry plagued by high subsidies due to chronic safety and financial problems leading to an increase in cost of the electricity system.
- Strong role of hydropower with 21% of installed capacity [5]
- Role of solar PV and wind power is growing too slowly in comparison to other progressive G20 countries, partly due to energy law blocking renewables due to fixed nuclear capacity

Key results of analysis:

- Excellent opportunities for low cost wind energy production
- Utility-scale and prosumer solar PV will be competitive to traditional electricity production around 2020 in some parts of France.
- Nuclear energy is high cost, uncompetitive technology in LCOE terms now and in 2030
- Expensive refurbishment investments for nuclear lifetime prolongations may not pay off

Germany
Germany currently leads Europe in RE installed capacity, and is expected to continue to play a leading role in the global energy transition. Very good wind resources in the north complement good solar resources in the south.

Current status:

- Plans to accelerate phase out of nuclear and coal power
- Forerunner in development of electricity from solar PV and wind power
- Goal of 80% renewable electricity by 2050 [7]

Key results of analysis:

- Wind energy offers least cost technology in 2030 due to excellent resource conditions
- Prosumer and utility-scale solar PV will continue to demonstrate strong business cases
- Offshore wind in north will also offer attractive investment opportunities

India
High dependence on coal has resulted in high levels of pollution and unexpected financial burden. Currently, there are strong efforts to increase shares of more sustainable, renewable energy with ambitious targets.

Current status:

- Already amongst world's lowest cost of solar PV electricity production as a result of extremely competitive auctions in the last couple of years
- Wind energy also competitive depending on region
- Overall low quality of domestic coal contributes to greater health problems

Key results of analysis:

- Fossil fuel and nuclear power set to remain high when full costs are included
- Excellent solar resource promises solar PV will remain least cost solution
- Very good investment opportunities for battery storage to support renewable energy

Indonesia
High reliance on imported fossil fuels in the energy system. Opportunities exist to utilise high potential of sustainable biomass, especially agricultural residues. Highly vulnerable to natural disasters that may worsen in severity due to climate change.

Current status:

- Low wind speeds lead to relatively high wind energy costs
- Geothermal energy potential high
- Very little installed capacity of wind or solar PV

Key results of analysis:

- Wind energy development may be limited to specific regions of the country
- Solar PV offers least cost technology by 2030
- Solar resource quality is excellent; prosumers can be supported by battery storage

Italy
Strong efforts have been made to reduce GHG emissions, and the nation is amongst the leaders of Europe in solar PV and wind power development.

Current status:
- 34% of electricity already generated from renewable energy [7]
- Growing shares of installed capacities of solar PV and wind power
- Very good solar and wind resources result in positive business cases already in 2015

Key results of analysis:
- Utility-scale solar PV will offer least cost technology by 2030
- Also opportunities for solar PV prosumers supported by battery storage
- Wind energy generation will continue to be competitive

Japan
Ongoing Fukushima nuclear disaster has led to societal reconsideration of energy strategy. In LCOE terms, Japanese nuclear power was amongst the lowest cost technologies in the world. In reality, it continues to be devastatingly expensive and dangerous.

Current status:
- Installed capacity of renewables at 29%, mainly PV and hydro power. In 2016 renewables generated 14.9% of the nation's electricity.[5]
- High dependence on imported fossil fuels
- Electricity from wind and solar PV beginning to be increasingly competitive [8]

Key results of analysis:
- Utility-scale solar PV will offer least cost technology by 2030
- Also opportunities for solar PV prosumers supported by battery storage
- Very good investment opportunities for wind energy generation now and in 2030

Republic of Korea
Power sector dominated by fossil and nuclear power. However, the full extent to which nuclear power is supported by subsidies is unknown but suspected to be high. Development of renewable energy has been minimal.

Current status:
- Costs of fossil fuels and nuclear power reported to be amongst lowest in the world
- Share of renewables in electricity generation is amongst lowest in the world
- Recent announcement to gradually phase out all coal and nuclear power stations

Key results of analysis:
- Utilityscale solar PV set to become least cost technology by 2030
- Also opportunities for solar PV prosumers supported by battery storage
- Very good investment opportunities for wind energy generation now and in 2030

Mexico
Power sector is dominated by fossil fuels, with 68% of installed capacity [6,9]. Amongst leaders in geothermal electricity production. Relatively high rate of electrification and low GHG emissions per capita.

Current status:

- Share of renewable electricity production only 8.9%, mostly from hydropower [7]
- Goal of 35% renewable energy by 2024 [7]
- Excellent resource potential of solar PV and wind power

Key results of analysis:

- Utility-scale solar PV set to become least cost technology by 2030
- Battery storage and national net metering will support PV prosumers
- Southern Mexico offers excellent wind resource potential and investment opportunity

Russia
Domination of fossil fuels in the power sector. Notable installed capacity of hydropower throughout the country producing the comparable electricity from nuclear plants.

Current status:

- Extremely high costs reported for solar PV and wind power that are contrary to global trends; very high cost of capital; unknown role of corruption and currency instability
- Installed capacities of solar PV and wind power amongst lowest in the world in spite of significant potential, amongst the largest in the world

Key results of analysis:

- Solar PV and wind power offer lower cost solutions when full costs are included, in centralised and remote decentralised markets
- Selection of locations for renewable energy development will be key to success
- Very good investment opportunities for wind energy generation now and in 2030

Kingdom of Saudi Arabia
Energy system dominated by oil and gas, with plans to construct nuclear power plants in the future. The nation shows significant vulnerability to the impacts of climate change

Current status:

- Wind power is currently competitive with other forms of power generation
- Installed capacities of renewable energy amongst lowest in the world
- Ambitious plans to expand renewable energy generation and diversify energy mix

Key results of analysis:

- Nuclear power represents the highest cost technology in LCOE terms
- Utility-scale solar PV will emerge as the lest cost technology by 2030
- There are excellent opportunities for solar PV prosumers supported by battery storage

South Africa

The energy system is currently dominated by coal power production. However, the nation aims to diversify the energy mix through increasing shares of renewable energy. There is great need to extend electricity services to more of the population.

Current status:

- Installed capacity of renewable energy only 13% [5]
- Wind power is currently competitive with other forms of power generation
- Excellent potential for solar and wind power generation

Key results of analysis:

- Utility-scale solar PV set to become least cost technology by 2030
- Also opportunities for solar PV prosumers supported by battery storage
- Very good investment opportunities for wind energy generation now and in 2030

Turkey

Turkey has become one of the fastest growing energy markets in the world with a booming economy mainly powered by gas and coal power. Recent tenders for solar and wind are highly competitive and beginning to reshape the energy vision.

Current status:

- Gas and coal make up two-thirds of the power generation capacity in the country
- Plans to add nuclear power to the energy mix despite objections by neighbouring countries
- In the present context wind and solar are cost competitive with gas and coal power

Key results of analysis:

- Solar will be the least cost of energy by 2030, as the solar resource is excellent
- Wind and even with storage will show lower costs than conventional sources by 2030
- Nuclear, gas and coal will be far more expensive by 2030

United Kingdom

In recent years UK has become a hub for the wind power industry with significant capacity additions of both onshore and offshore. Still continue to rely heavily on gas coal and plans for new nuclear have been criticised for high costs and risks.

Current status:

- Gas, coal and nuclear constitute high share of power generation in the UK
- Hinkley Point C nuclear power station shows the high costs associated with nuclear power
- Renewables contributed 22% of total power generation in the country in 2016 [7]

Key results of analysis:

- With enormous onshore and offshore wind potential, wind energy will by far be the least cost source for power generation followed by utility-scale solar in 2030
- Coal, gas and nuclear will be far more expensive by 2030

United States of America
Despite the current government having a strong disinclination towards the Paris climate agreement, many states have set ambitious targets for renewable energy. Solar PV and wind are competitive with coal and gas in many states.

Current status:

- Solar and wind power account for around 8.4% of total electricity generation [7]
- Still high shares of coal and gas in the overall power system
- Solar PV and storage technologies become increasingly viable by 2030

Key results of analysis:

- Wind, solar and storage will be least cost energy systems across the US
- Both solar and wind potentials are well distributed across the country which will have a positive complementary effect for the grid

European Union
High renewable energy adoption with innovative policy and leadership in addressing the climate issue. The EU continues to be a hub for innovation and research in sustainable and renewable energy technologies.

Current status:

- Growing shares of renewable installations, mainly wind and solar PV
- Close to 20% installed capacity of wind and solar [5]
- In many countries renewables are already the least cost technologies

Key results of analysis:

- In northern regions wind power in the EU will be the least cost energy source in 2030
- Solar will also have low costs as there is high potential in the southern regions of the EU
- Coal, gas and nuclear will be highly expensive and economically unviable by 2030

All renewable energy shares mentioned in the above country analysis are based on IRENA, Renewable Energy Statistics 2017 [5] and REN21, Global Status Report 2017 [7].

A continued downward trend in the LCOE of renewable power will see increased deployment well before 2030, as industrialised and developing economies alike increasingly aspire to develop on a sustainable basis, whilst seeking cost efficient and rapidly deployable power generation solutions. In contrast, momentum is gaining to reject risks of stranded investments related to fossil fuel and nuclear power, as well as towards divestment from coal and nuclear assets especially [3].

The question now turns from whether renewables can compete and whether they makes sense, to how to redesign the world's power systems in order to accommodate the inevitable, significant levels of renewable deployment. According to estimates from IRENA, the G20 countries hold 75% of total global deployment potential and around 70% of total global investment potential for renewable energy between now and 2030. Hence, the G20 countries have the opportunity to shape the future [10].

Figure ES-3 clearly indicates that by 2030 developers in G20 countries who intend to build fossil fuel power plants are going to have difficulties justifying such decisions to investors and financiers, not on environmental grounds, but based purely on economic viability. As LCOE of mainly wind and solar PV will be the lowest in all G20 countries well before 2030 and outcompete all other sources of power generation even as early as 2020. G20 countries intending to be in the group of global leading economies based on broad industrial growth require a least cost energy system, which is from now onwards based primarily on solar PV and wind energy. Such a system will also be supported by storage technologies, a high level of overall system efficiency and electrification strategies for all energy sectors, including mobility.

The troika comprising Germany the current host, China the previous host, and Argentina the next host, of the G20 presidency has the opportunity to lead the G20 to focus on the global promotion of renewable energies. Some economies are leading providers of renewable energy technologies, and other governments have taken considerable measures to create conducive environment for renewables. However, a few countries are yet to take any significant steps in incorporating these sustainable sources of energy. Some policy directions to further the G20's ongoing efforts to foster a global energy transition include:

- Accelerating the phase out of fossil fuel subsidies.
- Shifting investments away from carbon intensive infrastructure.
- Reforming global power markets for greater flexibility through incorporation of high shares of renewables complemented by various storage technologies and electro-mobility.

Contents

Chapter 1: Global Energy Transition and the G20

- Globally the energy transition is gaining momentum with increasing shares of renewables, mainly wind and solar PV.
- Costs of electricity generation from solar PV and wind are falling drastically, causing major changes in the dynamics of power markets across the world and more so in G20 countries.
- The G20 countries exert significant influence on matters of global relevance and therefore have an opportunity to shape the energy transition.

This introductory section lays out the aspects that make the energy transition the most vital component in addressing climate change and the weight of G20 countries in influencing decisions that can shape the global energy markets. The United Nations adopted two historically significant agreements in 2015: the Paris Climate Agreement [11] and the 2030 Agenda for Sustainable Development [12]. Governments agreed to a long-term target of keeping 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 [11, 13]. 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. On the other hand, 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 for a significant acceleration of renewable energy deployment. As 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, the successful outcome of these international agreements will depend on a rapid transition of the global energy system [14].

Economies around the world face the complex challenge of tackling climate change whilst ensuring 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 opportunity 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, South Korea, Turkey, the United Kingdom (UK) and the United States of America (USA)[1].

[1] G20 Information Centre - www.g20.utoronto.ca\\g20whatisit.html

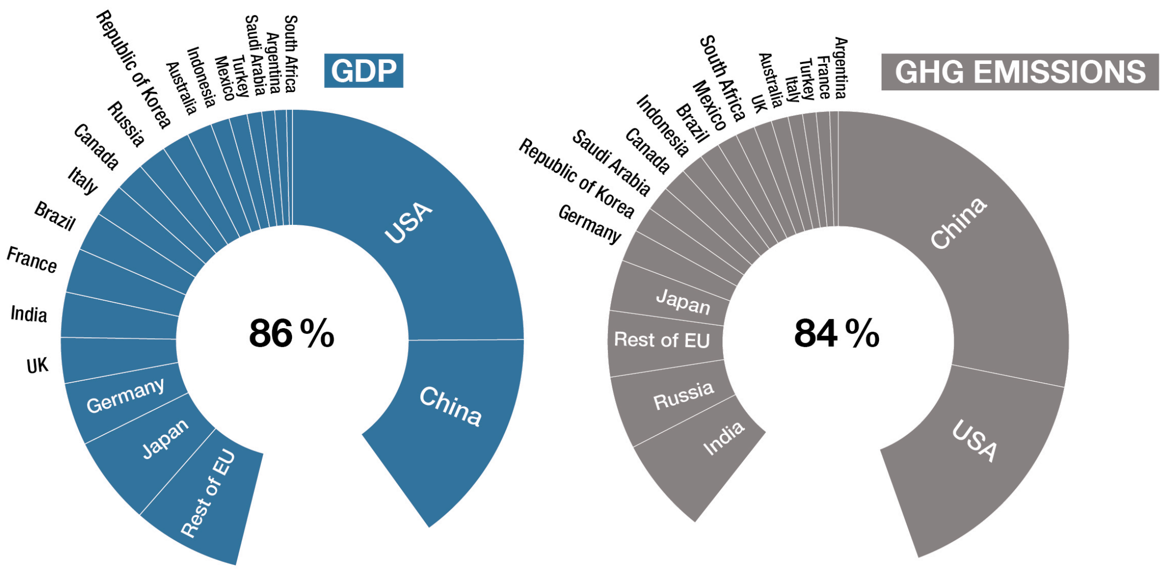


Figure 1: G20 share of Global GDP and Greenhouse Gas (GHG) Emissions [15,16]

These member countries account for 86% of the global gross domestic product (GDP), more than three quarters of global energy demand and 84% of GHG emissions from the energy sector as indicated in Figure 1.

World renewable power capacity including hydro has doubled since 2007, from around 1000 GW to about 2,017 GW by the end of 2016 [5, 7]. The addition of renewable power capacity in the year 2016, nearly 140 GW, was equivalent to 55% of all generating capacity added globally, the highest proportion in any year until now [1]. Investments in renewable power capacity were roughly double those in fossil fuel generation capacity in 2016, and this has been the trend for the last 5 years. The proportion of global electricity coming from renewable sources including hydropower has risen from around 25.3% in 2015 to 27.7% in 2016, and has prevented around 1.7 gigatonnes of GHG emissions, which substantiates the decoupling of economic growth from fossil fuels [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 has happened in the G20 nations as indicated in Figure 2. Hence, any collective move by the group will have substantial effects on global energy markets.

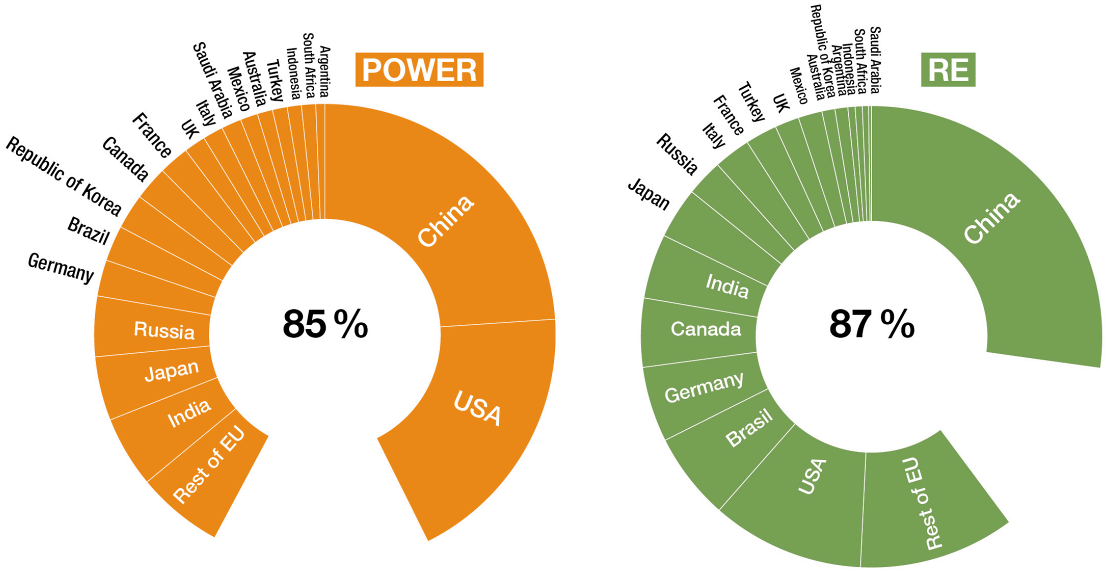


Figure 2: G20 share of Global Power Consumption and share of renewable energy (RE) installed capacity [16, 5]

A rapid transition of power systems in the G20 nations is more than a necessity, 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 and batteries, because of their rapidly increasing deployment, is well documented and demonstrated by overall investments in renewable electricity remaining quite flat between 2011 and 2015 despite annual capacity additions rising by 40% according to BNEF data [1]. An 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% [17]. Biomass for power, hydropower, geothermal and onshore wind can all now provide electricity competitively compared to fossil fuel-fired electricity generation. The LCOE of solar PV has fallen by more than 60% between 2010 and 2016 based on preliminary data, so that solar PV achieved a very competitive level at the utility scale [8].

Technology and finance are strong determinants of future societal paths, and while society's current systems of allocating and distributing resources and prioritizing efforts towards investment and innovation are in many ways robust and dynamic, there are some fundamental tensions with the underlying objectives of global sustainable development. Technological innovation 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 [14]. In this context, as costs are a vital indicator for planning and decision making of government's around the world, this LUT study commissioned by Greenpeace analyses the costs of power generation in G20 nations in the present context and from a future perspective for the year 2030. It involves determining the levelised cost of electricity for different power generation technologies for 2015 and for the situation in 2030, exploring options for storage and increasing the flexibility of power systems. It also considers the effects of externalities like additional costs of GHG emissions, health related costs amongst other societal costs and subsidies on the levelised costs of power generation in G20 nations. A cost efficient energy transition should be oriented to investment cycles with a view to deep decarbonisation, close to net zero emissions by the middle of the century, hence the study further explores various long-term energy scenarios with a cost perspective. Further, it summarizes the policy perspectives of G20 nations and identifies the most ideal policy measures to pursue large-scale deployment of renewables in order to achieve a cost effective power system in the future.

The G20's energy agenda has been evolving in recent years. The task of the G20 summit in Germany in 2017 and thereafter in successive summits would be to seize the momentum of the Paris Agreement and the SDGs to foster collective action towards a sustainable, decarbonised and affordable global energy system [103]. Investments in efficiency and renewable energy are expected to become the norm, as investment in fossil based power generation will be an exception with clearly defined timelines for an exit. 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 G20 members are highly diverse, often with very divergent interests in the energy spectrum. 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.

Chapter 2: Technological Options for Power Generation

- The power sector remains the most dynamic area of growth amongst all energy markets, as electricity is the world's fastest-growing form of end-use energy consumption.
- The trends over the past few years have been showing that solar PV and wind are the most preferred power generation technologies driven by the decreasing costs of both.
- More than 607 GW of new coal-fired power plant projects around the world have been on hold for the last year and a majority of them are in developing nations of the G20.
- The nuclear share of the world's electricity generation has remained stable around 10.7% since declining steadily from a historic peak of 17.6% in 1996.

This section presents the current status of the global power sector with additional emphasis on G20 countries, and further examines the range of power generation options from relatively new sources such as wind and solar to conventional coal, gas and nuclear. Investment and cost development trends of these technologies are further analysed across the G20 countries. Global demand for energy continues to rise, led by fast paced growth in developing and emerging countries and reflecting an expanding global economy, rapid industrialization, increasing urbanization, population growth and enhanced energy access. At the same time, the negative social, economic and environmental impacts that have resulted from heavy reliance on fossil fuels are now compelling governments to seek more sustainable options to meet energy demand while sustaining the required economic growth. The power sector remains the most dynamic area of growth amongst all energy sectors, as electricity is the world's fastest-growing form of end-use energy consumption. This has been the case for at least the last 3 to 4 decades and will most likely be for the future due to the shift-to-power megatrend observed in almost all energy sectors, such as with electric vehicles, electric heat pumps, electricity-based desalination and electricity-based chemical production currently under research. Power systems have continued to evolve from isolated, non-competitive grids to integrated national and even international networks.

2.1 Power generation options for the future

In line with global trends, the expansion of renewables is mainly concentrated in the electricity sector, which has reached up to 2017 GW of installed capacity in 2017 [7].

The global installed capacity of renewable power in the previous year was nearly 140 GW, of which 54 GW was wind power and 75 GW was solar power [5]. Trends over the past few years have been showing that solar PV and wind, including both onshore and offshore, are the most preferred power generation technologies driven by the decreasing costs of both. Solar PV has continuously outperformed expectations, in particular those of the International Energy Agency [18], which may continue for the years to come [19].

Overview of wind power development

Wind power technology has continued to evolve since the very first installations in the late 1980s, driven by various factors, like increasing global competition, continual research and development to make turbine manufacturing more efficient and cheaper, optimising power generation at lower wind speeds and going offshore in recent times. The global installed wind power capacity is nearly 490 GW [20], out of which 475 GW is in the G20 countries and amongst which a few have the major share as indicated in Figure 3 below. It further indicates that most of the G20 nations are yet to realise their full wind power potentials.

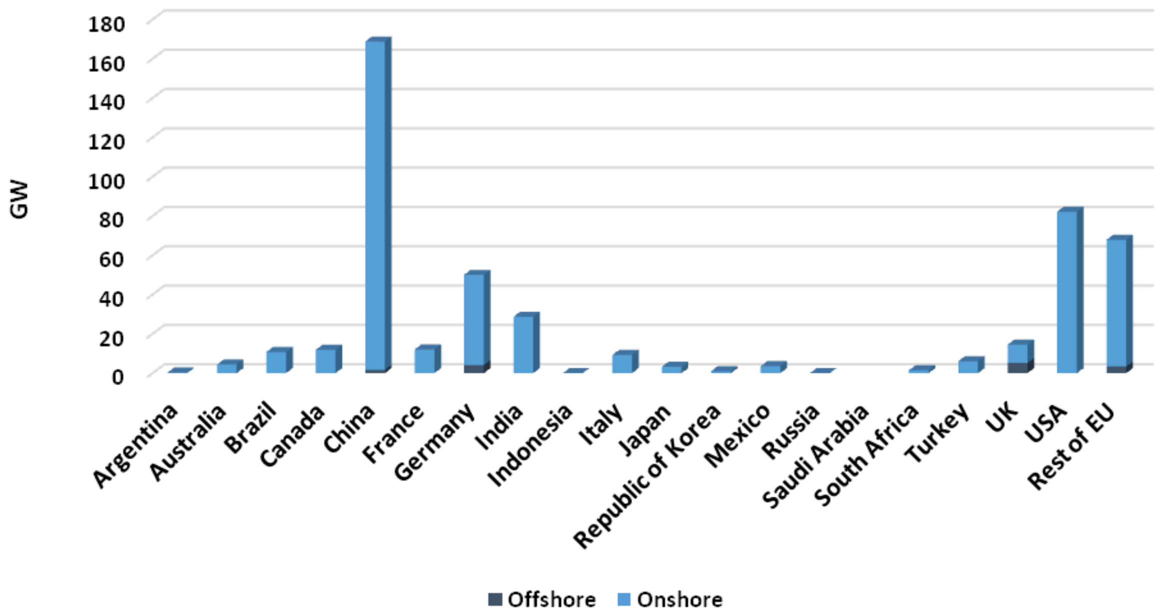


Figure 3: Total installed capacity of Wind Power across the G20 by the end of 2016 [20]

In the past few years, offshore wind installations have gained significant momentum, and the majority of these are located in waters off the north-western European coast, with UK leading the pack, closely followed by Germany. The remaining capacity is located largely in China, Denmark, the Netherlands and Belgium. However, other countries are setting ambitious targets for offshore wind, and development is starting to take off in some of these markets as costs continue to drop.

Wind power is an increasing contributor to the reduction in GHG emissions, and will be more so in the future. The sector continues to attract a large share of investments and is creating hundreds of thousands of jobs worldwide, and those are set to rise dramatically. The fact remains that wind is one of the least cost options in many markets for new power generation, and this is even before factoring in environmental and health costs. Nevertheless, challenges continue to persist for wind power – both onshore and offshore – including lack of transmission infrastructure, delays in grid connection, the need to reroute electricity through neighbouring countries, issues with public acceptance in some regions, and curtailment where regulations and current management systems make it difficult to integrate large amounts of wind energy fast enough. As shares of wind power are set to increase further, G20 countries must also take steps to create power systems that can integrate large amounts of variable wind energy by exploring smart grids, storage technologies and other grid management mechanisms.

Overview of solar power development

Solar power has been developing over the last few decades. Initially, concentrated solar thermal power (CSP) was the preferred utility-scale technology, but solar PV technology has taken over all other technologies in the past few years and is now considered the most attractive of mainstream technologies. Last year, for the first time, there were significantly more gigawatts of solar power added in comparison to all other power-generating technologies in the world.

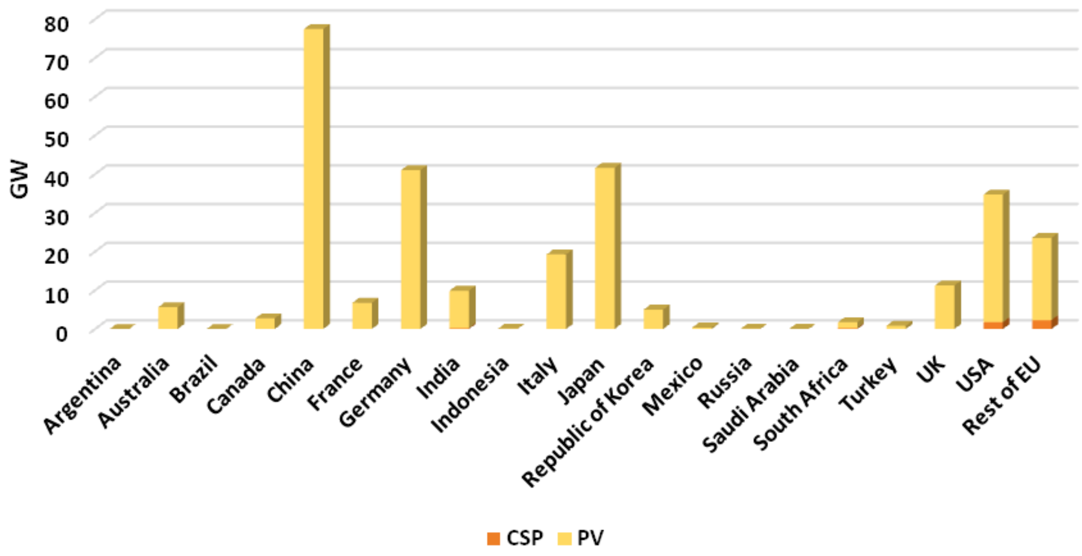


Figure 4: Total installed capacity of Solar Power across the G20 by the end of 2016 [5,21,22]

Figure 4 shows the installed capacity of solar power across G20 countries, which is around 282 GW, and globally the installed capacity is around 308 GW[7]. Clearly a few countries are adopting solar PV more predominantly, and many countries, despite having huge potentials and lying in the Sun Belt area of the world, are yet to adopt to this technology.

One of the recent innovative developments in renewable power is the siting of two or more different technologies at the same location, making use of shared land, grid connections and maintenance, which reduces intermittency. Around 5.6 GW of these hybrid renewable power projects have been built or are in development worldwide, including hydro-solar PV, wind-solar PV, PV-solar thermal, solar thermal-geothermal and biomass-geothermal [23]. For countries that aim to utilise locally available resources and promote sustainable economic growth, renewable electricity generation is becoming increasingly attractive. Further, estimates from IRENA show that doubling the global share of renewables by 2030 would save up to 4.2 trillion USD annually from the avoided expenditures of air pollution and climate change, which can benefit economies around the world, more so for the G20.

2.2 Power generation options in transition

Since the industrial revolution around the mid of last century, the fossil fuel sector has contributed substantially to global economic growth, initially with coal and later with oil and gas at the forefront of economic expansion. For most of the past 40 years, the industry produced consistent revenues and offered attractive investment value with usually a promising outlook. Along with fossil fuels, nuclear energy has played a vital role, at least in some of the developed nations and now in China, to meet the massive power requirements. However, the industry has been plagued with serious issues ever since the Chernobyl disaster and began an accelerated decline after the Fukushima meltdown. Reactor installation has slumped until the recent rejuvenation occurring in China.

Coal-fired power plants currently fuel around 40% of global electricity [6], while in some countries it contributes much higher shares. On the other hand, it is also the most polluting form of power generation with not only GHG emissions but also deadly air pollutants[2]. It also results in the depletion of forests for coal mining and causes detrimental environmental impacts [24,25]. Natural gas is yet another fossil fuel resource that will continue making a significant contribution to the world energy

[2] Such as SOx, NOx, particulate matter, heavy metals and others which are the leading cause of lung cancer and other adverse health impacts.

economy. The cleanest of all the fossil fuels, natural gas is plentiful and allows for flexible operation of power plants. It is the preferred fuel option in the most efficient power generation technologies, such as the Combined Cycle Gas Turbine (CCGT), with conversion efficiencies of up to 62%. The reserves of conventional natural gas have grown by 36% over the past two decades and its production by 61%, led by shale gas exploration in North America, which has excited gas markets around the world [16]. Nevertheless, concerns remain on the mid-term ability of the gas sector to cover the demand [26]. Increasingly, processes of attaining gas, such as fracking, are causing adverse environmental impacts and are also linked to causing earthquakes, which increases the overall risks. World nuclear power generation increased by 1.3% in 2016 [27], reversing a decade-long decline, driven mostly by the Asia-Pacific region. In absolute terms, nuclear output remains broadly at the same level as before, but its relative share in power generation has decreased, mainly due to the Fukushima nuclear accident and ongoing economic challenges for the nuclear industry induced by massive cost overruns all around the world.

Overview of nuclear power development

There are currently around 440 nuclear power reactors operating in 31 countries worldwide, with a combined capacity of over 385 GW [27]. However, only 402 reactors have been in operation in mid-2016 representing a total capacity of about 348 GW, whereas the difference is shut down for a longer period (long-term outage), mainly in Japan but also in Taiwan and Sweden, and it remains unclear whether this capacity will be available in future at all [27]. The nuclear share of the world's electricity generation has remained stable around 10.7% since declining steadily from a historic peak of 17.6% in 1996. These nuclear capacities are mostly in the G20 countries, with a large number in the USA, France, Russia, China, Japan, and South Korea as shown in Figure 5.

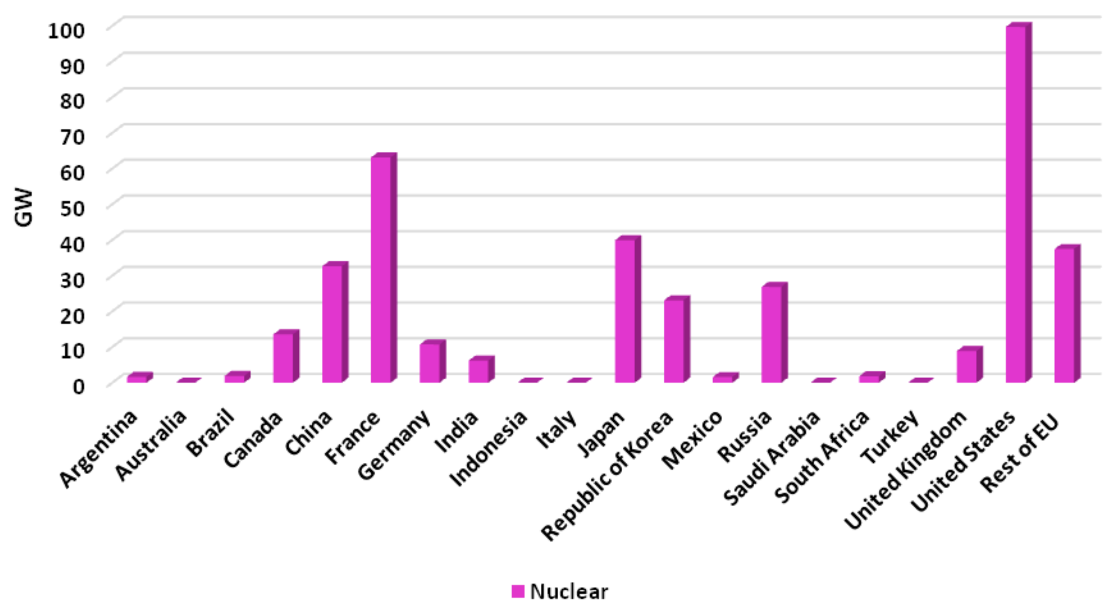


Figure 5: Installed capacity of Nuclear Power across the G20 at start of 2017 [27]

Many of the traditional nuclear and fossil fuel based utilities are struggling with a dramatic plunge in wholesale power costs, diminishing client base, declining power consumption, high debt loads, increasing production costs at aging facilities, and stiff competition, especially from renewables.

Overview of coal and gas power development

Coal continues to be the backbone of global power generation, making up 40% of global electricity generation. Global coal consumption declined for the first time this century in 2015, falling 2.7%. The total capacity of coal-fired power stations meanwhile went up by 54 GW and that of gas-fired generators by 37 GW in the year 2016 [6]. These are net figures, representing the difference between the new assets coming on to the market in 2016 and old ones shutting down.

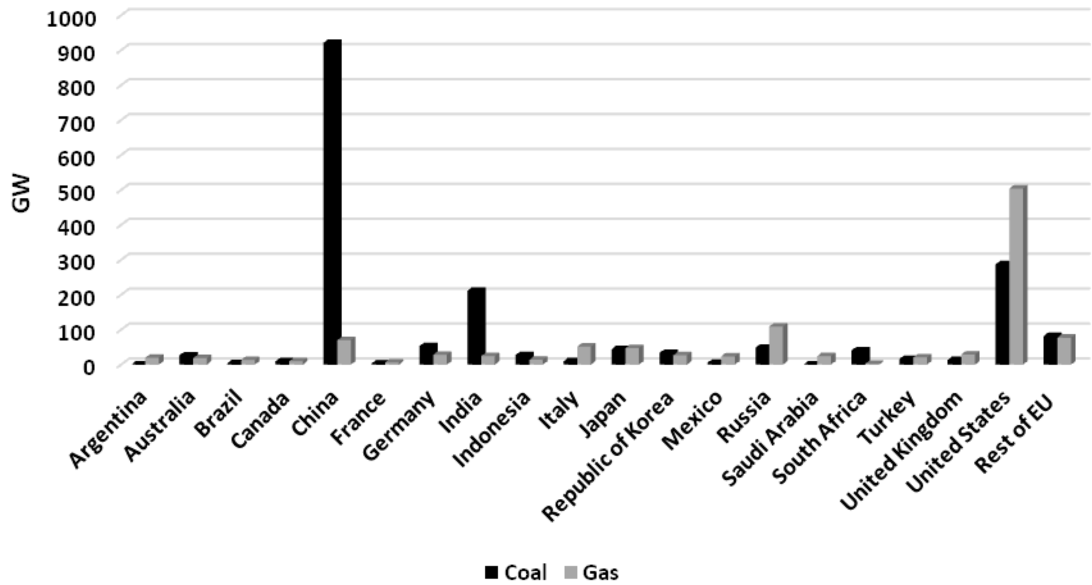


Figure 6: Total installed capacity of Coal and Gas Power across the G20 [6]

According to estimates from Bloomberg New Energy Finance (BNEF), global commissioned coal power plants represented 87 GW, and decommissions 33 GW in 2016 [1]. Generally, most of the new coal assets were in developing and emerging countries and most of the closures occurred in developed economies. There has been net divestment of coal-fired power plants of about 33 GW in Europe from the year 2000 – 2015 [28]. Coal demand has been moving to Asia, where emerging economies with growing populations are seeking affordable and secure energy sources to power their economies. However, this is the contradiction of coal — while it can provide essential new power generation, it can also lock-in large amounts of GHG emissions and expensive investments for decades to come. Hence, stranded-asset risk in fossil-fuel holdings is very much clear, present and growing. One of the biggest sovereign wealth funds, the 880 bUSD Government Pension Fund Global (GPFG) of Norway has divested from 11 coal companies based on the likelihood that their business model was no longer sustainable. The World Bank along with other central banks, such as the Bank of England, with the Financial Stability Board and the European Systemic Risk Board are following suit, suggesting that there are already financial arguments for avoiding investments in companies that have exposure to potential stranded assets [29,30,31,32]. In line with this trend, many coal-fired power plants have been on hold for the last year as shown in Table 1, and a majority of them are in developing nations of the G20.

Table 1: Coal power capacity on hold across the G20 and global [105]

Country	Coal Power on hold (GW)
China	441.7
India	82.5
Turkey	17.6

Country	Coal Power on hold (GW)
Indonesia	8.4
EU28	7.0
South Korea	1.2
South Africa	1.5

CCS

"CCS may be, politically, an easy way out of having to make more difficult and sustainable choices."

- Spreng, Marland, Weinberg, 2007

Carbon capture and storage (CCS) has been promoted as an option to create and maintain sinks of carbon which aid in lowering levels of CO_2 in the atmosphere. While the idea of CCS is certainly appealing, in practice it remains unproven and uncertain as a long-term solution. Spreng et al. [33] dub CCS "a Faustian Bargain par excellence", suggesting that it can aid in the extension of the fossil-fuels era, but also greatly extends the period over which CO_2 is emitted to the atmosphere, hardly a durable solution. Further, CCS requires a long-term commitment, extending to generations that have not yet been born, to the vigilant monitoring and management of the captured CO_2. It must be pointed out that the magnitude of this burden, and the chance of leakage back to the atmosphere, becomes greater as stored levels of CO_2 increase. As such, the more reliance on CCS there is, the greater the risk and intergenerational burden.

There are several important issues related to fossil fuel based CCS that make it incompatible with the need to create net zero emissions in global energy systems. First, the extraction, refining and transport of fossil fuels results in carbon emissions upstream from the fuel use in a power plant. Second, CCS technology results in a lower overall efficiency of a power plant, thereby necessitating the use of more fuel (and more upstream, generation and downstream emissions). Third, carbon capture efficiency from flue gas streams is typically in the range of only 50-90% [34,35], meaning that there are significant emissions of CO_2. Fourth, leakage of captured carbon can occur in the transport and deposition phases of the CCS process downstream. The full extent of this leakage is not currently well understood. Lastly, the permanent storage of CO_2 has not been definitively demonstrated. Leakage from downstream repositories occurs, the full extent of which is also not well understood. The result is that fossil fuel based CCS will result in positive emissions, perhaps even significant positive emissions.

There are three more possible options that currently show more promise than fossil fuel based CCS. These are bioenergy with CCS (BECCS), CO_2 direct air capture CCS (DACCS) and carbon capture and utilization (CCU). BECCS involves the capture and storage of biogenic forms of carbon (e.g. from the combustion of forestry or agricultural residues), and so eliminates almost all of the upstream emissions. Biogenic carbon represents a closed loop in the carbon cycle, whereby emissions are offset by other growing plants so long as forestry and agricultural operations are sustainable. Similarly, DACCS involves the atmosphere as the source of carbon, so there are no upstream emissions. Energy is needed to capture the carbon from air, but this heat and electricity can be derived from sustainable sources in order to maintain net zero emissions. Finally, CCU involves utilizing the capture carbon to create hydrocarbons needed in a number of essential processes. CCU can be performed in combination with carbon captured from either bioenergy or direct atmospheric sources. The captured CO_2 is then combined with hydrogen obtained from the electrolysis of water (H_2 and O_2 from H_2O) to produce synthetic fuels, such as synthetic methane (CH_4). This methane or comparable synthetic fuels can then be used directly as a fuel, or to produce longer chain hydrocarbons that can be used as industrial raw materials or liquid fuels for transport [36]. In a best case scenario, BECCS and DACCS may also offer net negative emissions provided that challenges surrounding the permanence of CO_2 storage can be mitigated. It should be noted that negative emissions schemes have recently been described as a questionable, "late-regrets magic bullet" that would not provide the best chance to meet the Paris Agreement targets [37].

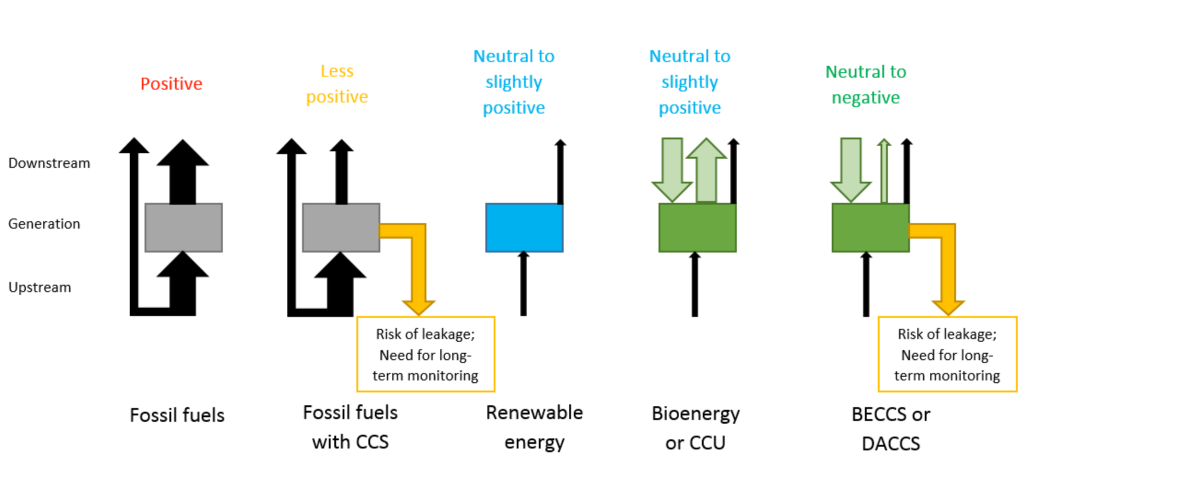


Figure 7: Carbon balance for different generation technologies. Adapted from [38]*. CCS-Carbon capture and storage; CCU-Carbon capture and utilization; BECCS-Bioenergy carbon capture and storage; DACCS-Direct air carbon capture and storage*

Fossil fuels are increasingly facing competition from renewable and alternative technologies in both the power and transportation sectors. While pressure remains on the part of utilities and power companies to resist change and defend the old order, more efficient and profitable strategies will acknowledge that the power generation economy across most parts of the world is in transition and that old power generation models are becoming increasingly unviable [39]. The financial metrics of the oil and gas sector indicate revenue declines, lower profit margins, decreasing shares of capital investments, significant project cancellations and asset write-downs. Hence, these conventional power generation models along with nuclear power plants are seemingly unattractive to institutional investors, as large pension funds, private insurance companies and banks are divesting. Overall, nuclear energy along with coal, oil, and gas power generation assets pose a significant risk of becoming stranded, with a huge burden in the near future as renewables continue to generate low cost electricity [4].

2.3 Power generation mix of G20 countries

In all G20 countries except for Germany, the UK and the Kingdom of Saudi Arabia, hydropower makes up the largest share of renewable power capacities as indicated in Figure 8.

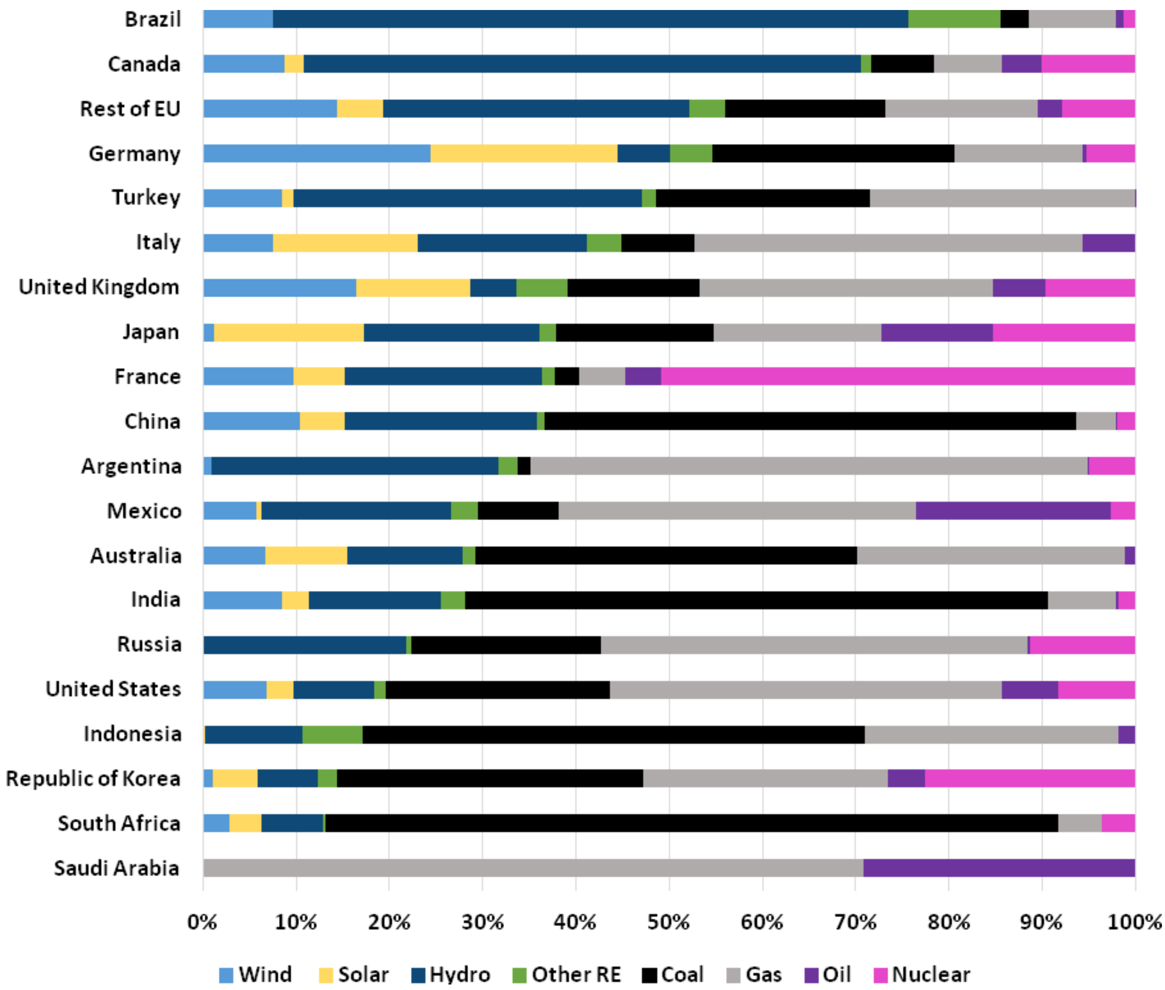


Figure 8: Shares of different power generation capacities across the G20, with Brazil at the top having the highest share of renewables and Saudi Arabia at the bottom with the lowest share [5,27,6,9].

However, non-hydro renewable electricity sources, in particular wind and solar energy, have rapidly increased their shares in recent years. Germany had the largest share of non-hydro renewable energy in its electricity mix, which accounts for nearly 30% of total power generation and more than 50% of installed capacity as indicated in Figure 8, while China had the largest total installed capacity at almost 245 GW of non-hydro renewable energy at end of 2016 [5]. India is following suit and has made significant policy shifts to pursue renewables, which already make up roughly 28% of the total power capacity, including hydropower as shown in Figure 8. In Russia, Turkey and Saudi Arabia, on the other hand, the development of non-hydro renewables remains quite nascent. In Brazil, electricity supply has significantly relied on hydropower and biofuels to represent a significant share of the energy consumption, along with its use in the transport sector. Whereas, in Argentina wind power has been steadily gaining momentum with installed capacities around 300 MW and set to increase with recent auctions of around 2400 MW and at very competitive costs of around 45 €/MWh [13]. In the aftermath of Fukushima renewables kicked in to fill the power gap, and solar PV accounts for 4.4% of net generation in Japan [40,41], meanwhile South Korea is still highly reliant on fossil and nuclear fuel imports, but recent reports suggest renewables will play a prominent role in the future as the country plans to shift away from coal and nuclear [42].

Similarly, Indonesia is heavily reliant on fossil fuels while showing recent interest in adopting renewables. In South Africa, fossil fuels still constitute the major share of power generation, while efforts have started to get wind and solar energy ramped up. In Mexico, renewables struggle to make substantial inroads despite their competitiveness, but there have been recent policy shifts that could enable larger shares to enter the power markets. Canada, despite having a high share of hydropower and a relatively less polluting power system, has failed to ride the renewables wave with very few wind and solar initiatives. However, the Province of Ontario, Canada, was amongst the vanguard of regions to eliminate electricity generation from coal in 2014. In Australia renewables are riding on the initial build-up of wind power, which contributes around 5% of generation, and many large-scale renewables are set to go onto the grid in 2017 [43]. Moreover, the highest share of residential and commercial PV self-consumption in any G20 county has been achieved in Australia, now contributing to 4% of the country's total electricity demand [7,21,22]. In the UK, Italy, France and the rest of EU renewables are making big strides. Offshore and onshore wind are growing in the UK, and solar is contributing significant shares in Italy, but showing currently only very limited progress. Whereas in the USA, renewables are making significant inroads in many states with both wind and solar contributing to almost 10% of generation capacity in the USA. The state of California is in the global lead of any large state with 13% solar energy supply of total demand, despite the current political challenges facing the sector in the USA [44].

Chapter 3: Flexibility and Storage

- Energy storage and flexibility of the power system enable the optimal use of renewable energy resources and therefore decrease overall energy system costs.
- The integration of renewable energy generation and the electrification of the transport sector provide more flexibility in power systems and increase levels of storage options.
- Battery storage is one of the most widely used energy storage technologies in a vast range of applications, and it is expected to become the main energy storage technology.
- A rapid cost reduction of lithium-ion battery storage is forecasted due to increase in demand, mostly related to the spread of electric vehicles and PV self-consumption over the coming years.
- Power-to-gas is a technology that links the power grid with the gas grid by converting renewable electricity to renewable based gas fuel, and in turn provides seasonal storage options.

This section discusses the role of energy storage and flexibility options in energy systems with high shares of renewables and the impact on final energy costs. As the share of electricity generation from variable renewable energy resources increases globally, and more so in G20 countries, the need for technologies and policies to control and manage the intermittency of renewables also rises. The performance of renewable energy technologies, in particular those based on solar and wind, are dependent on weather conditions. This creates uncertainty about investment in renewable power technologies. Energy storage is one of the most feasible solutions to overcome this challenge [45]. In addition to storage, supply and demand side management, interconnected grids and sector integration are other types of flexibility that can help tackle the intermittent nature of variable renewable energy resources. In the sections that follow, the current installed and the most promising future energy storage capacities for G20 countries are discussed.

Energy storage and flexibility of the power system enable the optimal use of renewable energy resources and therefore decrease the cost of energy generation. This can be explained by the fact that surplus electricity can be stored in energy storage technologies and used later during peak times or when the demand for electricity increases. Hence, the need for additional renewable capacity is reduced due to a better management of the system. In addition, improvement to transmission and distribution grids, supply-side and demand-side resources, and operational measures are among the ways renewable variability can be balanced.

The main drivers for the improvement of energy storage systems are the integration of renewable energy generation and the electrification of the transport sector. Among all storage technologies, the need for lithium-ion battery storage has increased dramatically due to the introduction of plug-in electric vehicles, such as plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs). It has been forecasted that the installed global battery energy storage capacity will soar from 1.7 GW in 2016 [7] to over 14 GW by 2020 [46] and 25 GW by 2028 [47]. However, pumped hydroelectric storage (PHS) has, by far, the highest share of energy storage installed capacities today. The energy storage options that follow are compressed air energy storage (CAES) and sodium-sulphur batteries [48]. It should be highlighted that PHS is limited by topological location and has a relatively low power to energy density, which makes it more suitable for stationary, large-scale applications. Japan, China, the United States and Europe are the largest operators of PHS, which mostly balance the inflexibility of nuclear power and partly coal plants.

Figure 9 presents the global share of the current installed capacity of all storage technologies. With respect to G20 members, the total storage capacities installed by the end of 2016 are shown in Figure 13. PHS is the dominating technology with around 130 GW, followed by thermal storage, electro-chemical storage, electro-mechanical storage and hydrogen storage.

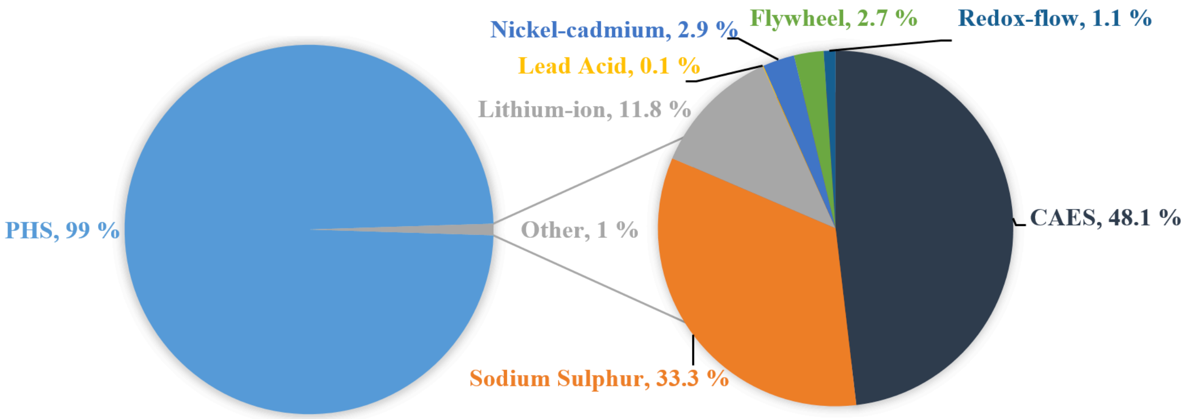
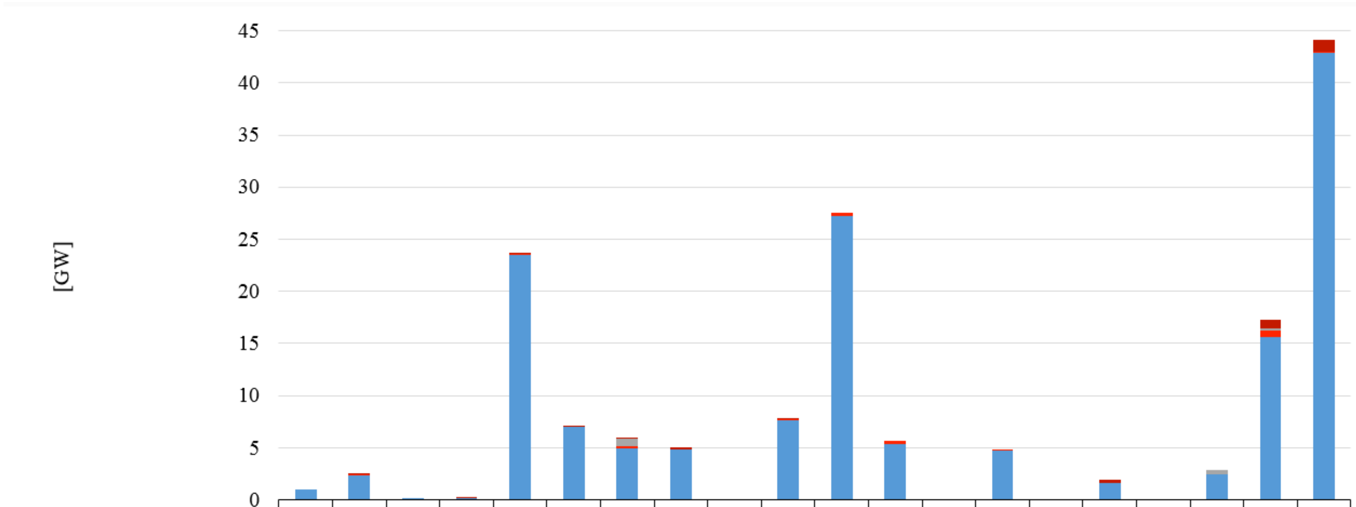


Figure 9: Global storage installed capacity for electrical energy [48]



	Argentina	Australia	Brazil	Canada	China	France	Germany	India	Indonesia	Italy	Japan	Republic of Korea	Mexico	Russia	Saudi Arabia	South Africa	Turkey	United Kingdom	United States	European Union
Thermal storage	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.8	1.1
Hydrogen storage	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Electro-mechanical storage	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.2	0.1
Electro-chemical storage	0.0	0.0	0.0	0.0	0.1	0.0	0.3	0.0	0.0	0.1	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0
PHS	1.0	2.4	0.1	0.2	23.5	7.0	4.9	4.8	0.0	7.7	27.2	5.4	0.0	4.7	0.0	1.6	0.0	2.4	15.6	42.9

Figure 10: The current storage installed capacity in the G20 countries [49–51]

Battery storage

Battery technologies have evolved to play a crucial role in our daily lives from the operation of watches to balancing megawatts of power load. The rechargeable battery is one of the most widely used energy storage technologies in vast range of applications, such as energy management, power quality, transmission congestions relief, transportation systems and energy tariff cost management. The major electro-chemical batteries can be classified as follows: lead-acid battery, lithium-ion battery, sodium-sulphur battery and flow systems. Nevertheless, lithium-ion batteries are currently experiencing the fastest growth among the other options and being used in small- and large-scale applications [52]. The high cycle efficiency (up to ~97%) makes lithium-ion superb in comparison to lead-acid batteries with ~63-90% cycle efficiencies. In addition, lithium-ion batteries have a high energy and power density, which leads to widespread use in portable devices, such as laptops and smartphones, and promises potential in the transportation sector and small-scale applications [52].

The United States and the Republic of Korea contributed 0.4 GW to the global electro-chemical storage capacity, in particular lithium-ion battery, by 2016. The two countries had the largest energy storage capacity additions in 2016, with 0.2 GW per country [7]. The next leading contributors are Japan and Germany with almost 0.1 GW each of electro-chemical energy storage capacity and South Africa with almost 0.1 GW of thermal energy storage capacity [7,50]. Despite the relatively low non-pumped hydro storage capacity in China, it is expected that the Chinese government will increase the battery storage capacity through the pilot programme. This programme has been launched in 2016 to cover curtailment of solar and wind energy in three regions in the Northern part of China [7]. In addition, several other G20 countries are experiencing a rapid growth of battery storage, such as the Netherlands (part of EU28), the United Kingdom and Australia.

A rapid cost reduction of global lithium-ion battery storage is forecasted due to increase in demand, mostly related to the spread of electric vehicles, over the coming years [53]. It has been reported that the cost of battery storage decreased drastically from about 1000 USD/kWh in 2010 to 227 USD/kWh in 2016 [54]. This enables automakers and manufacturers to speed up production of electric vehicles. As a result of high competition in the market, the price of batteries will drop significantly. According to Bloomberg New Energy Finance, battery pack prices are expected to fall further to 100 USD/kWh by 2030. However, Tesla is one step ahead of others and claims to be able to achieve a battery cost of 100 USD/kWh by 2020 [55]. As a consequence, Li-ion battery storage will have a significant role in the future as the costs decline sharply.

A fully sustainable electricity system scenario with hybrid renewable energy and storage technologies has been modelled using the “LUT Energy System model” [56]. The model is a linear optimization model, in an hourly resolution, with the target function of minimizing the annual system cost (further explanation can be found in section 5). The results of regional and global simulations clearly indicate that the role of battery storage is remarkable almost all around the world and complements the high penetration in particular of solar PV but also wind power.

With respect to G20 countries, the share of battery storage is significant when the generated electricity from solar PV is quite high. As can be seen in Table 2, China, India and the USA have the largest electricity generation from solar PV and battery storage. Thus, battery storage is found to be the best match with solar PV in an energy system with high shares of renewables. However, the situation is slightly different for the case of Saudi Arabia, where most of the electricity generated is either used by the country itself, exported to neighbouring countries through HVDC grid lines, or stored in gas storage through the power-to-gas process (see below) due to the low costs of already existing sites. It is estimated that G20 countries can achieve a 100% renewable energy system, where battery storage accounts for 11% of the total electricity generation in the power sector. This emphasizes the substantial impact of battery storage on the electrification of all sectors powered by renewables.

Table 2: Total battery storage output and electricity generated from solar PV and wind energy for the power sector, modelled and optimised by the LUT energy system model [56]

	Solar PV [TWh]	Wind energy [TWh]	Battery storage [TWh]	Share of PV and wind of total generation [%]	Share of battery output of demand [%]
Argentina	48	126	10	37/38	5
Australia	108	133	26	44/32	9
Brazil	312	47	77	56/4	9
Canada	98	864	25	19/57	4
China	3,498	3,981	1,090	51/35	13
France	132	290	38	39/34	6
Germany	165	364	36	54/36	7
India	1,303	349	413	70/17	20
Indonesia	132	0	34	64/0	11
Italy	152	22	27	64/7	8
Japan	653	384	134	74/21	13
Republic of Korea	304	92	105	81/15	19
Mexico	447	247	130	60/29	17
Russia	88	785	0	18/59	0
Kingdom of Saudi Arabia	127	389	5	26/72	23
South Africa	127	231	18	89/9	6
Turkey	232	165	72	56/28	14
United Kingdom	207	93	21	57/17	5
United States of America	1,709	2,474	419	51/39	9
European Union	1,015	1,722	228	47/28	6
G20 total	10,201	11,990	3,695	52/33	11

Additionally, electric vehicles can be used to overcome the variability of renewable electricity in the future. It is projected that the share of electric vehicles will increase noticeably over the next decade [57,58]. As a result, high economic and social benefit is expected to be achieved for grid operators and vehicle owners. Lower running costs, less maintenance costs, and health benefits are the main drivers for the surge in interest in electric vehicles. Furthermore, there would be environmental advantages in the long-term due to diminishing fossil fuel usage in the transport sector. Reflecting the growing interest in electric vehicles, several countries have passed laws to ban internal combustion engine based cars in the coming decades. Germany and India set a target to ban fossil fuel powered cars from 2030 onwards [59] and encourage customers to replace old vehicles with electricity-based, newer ones. Norway, the Netherlands and China are the other countries that plan to take action against fossil-based cars in the near future and most likely faster than Germany and India.

Electric vehicles can work also as distributed resources where power can be flexibly charged when not needed for the power sector (smart charging) or even returned to the grid (vehicle-to-grid, V2G), if needed. The grid can be utilized by battery-powered or plug-in battery electric vehicles. The higher V2G participation in the renewable electricity based system leads not only to reduced need for generation capacity, but also for less need for other storage capacity, particularly seasonal storage. Seasonal storage refers to the storage of energy for days, weeks or months to secure energy supply during seasonal lapses in energy supply or unpredictable energy supply and demands of the energy system [60].

Power-to-X

Power-to-X (PtX) refers to conversion or bridging technologies that take electricity from the power sector and provide it in suitable form to other sectors, such as the chemical or transport sectors. In addition, electricity can be converted through PtX to other forms of energy for storage and reconversion. The X in the terminology can refer to fuels or chemicals in gaseous or liquid phase, such as hydrogen, methane, Fischer-Tropsch liquids, ammonia, methanol, dimethyl ether (DME) and many more, in particular feedstock chemicals.

Among all PtX technologies, power-to-gas (PtG) is the most well-known and commercialized technology that links the power grid with the gas grid by converting renewable electricity to renewable based gas fuel via two main steps [61–63]:

- hydrogen production by water electrolysis
- hydrogenation of sustainable CO or CO_2 to CH_4 via the methanation process.

The generated CH_4 is called synthetic natural gas (SNG) and can be used for all purposes met by fossil natural gas today, since there is chemically no difference. In addition, hydrogen can be used as a storage to hold renewable electricity and reuse it when is needed. The importance of PtG for supporting high shares of renewable energy has been discussed at length in academia and industry [61,62]. The technology is already in a commercialization phase in several countries, and further improvements are needed to decrease the cost. Germany is one of the most progressive producers of renewable methane in the world, followed by several countries in the EU, the USA, Argentina, and Japan [64]. Audi [65], part of Volkswagen, is one example of active companies in this field as it has invested in a PtG facility with an installed capacity of 6.4 MW to produce SNG in Germany. The product is then sold as Audi e-gas. In a scenario-based study [56], with the target function of a 100% renewable energy system globally, PtG is found to be an important technology to fill the gap between electricity generation and demand, especially for those countries that are rich in wind resources. In this research, SNG production costs are in the range of 46 - 119 €/MWh_{th} for 2030 technical and financial assumptions, which is competitive with natural gas if environmental costs are taken into consideration.

An analysis of synthetic fuel production for Europe by 2030 was carried out using hybrid PV-wind power plants in the Maghreb region, and the results demonstrate that the production of sustainable fuel is technically feasible [36]. Further, several studies discuss the production of synthetic fuel through renewable energy power plants [66–69]. However, restrictions on fossil fuel subsidies and targets for GHG emission cost are required in order to have the renewable electricity based SNG and diesel cost competitive with the current natural gas and fossil diesel prices. A similar study has been implemented for synthetic diesel production at sites of the highest cumulative PV and wind potential in the world [70]. The findings reveal that renewable electricity based diesel costs 135 USD (101.5 €) per crude oil equivalent barrel using a renewable electricity based power-to-liquids (PtL) value chain, which is higher in cost than the conventional diesel in today's markets. Nonetheless, several factors might change the cost in the long term. Environmental concerns for fossil fuels, fuel quality and increasing efficiencies through further improved PtL production processes will open further markets in the future [71].

In addition to the discussed technologies, there are other types of synthetic fuels that might become important for the transition to a more sustainable energy system, such as Methanol (MeOH), dimethyl ether (DME) and other hydrocarbons. Methanol is one of the most widely used chemical feedstocks in industry, with a growing role as a fuel. Traditionally, methanol is mainly produced from natural gas, and DME is derived from methanol. However, methanol and DME can be produced synthetically, and directly from sustainable sources of CO_2 and renewable electricity based hydrogen [72,73].

Flexibility via energy storage

The role of storage in the future energy system is significant due to several reasons. Energy storage is not limited to the size of application and is used in a wide range of applications from small- to utility-scale. Further, they can be used as a partial substitute of grid extensions. The need for energy storage depends on the level of renewable energy deployment [74]. The higher the share of renewable energy, the more flexibility options are required to balance the system. With a sharp increase in the installation of renewable electricity systems, at prices that rival those of nuclear and fossil fuel based power plants, hundreds to thousands of gigawatts of charging and discharging capacity would be needed to provide a sufficient level of flexibility to the final energy system.

In a conventional energy system, the need for meeting power demand has been supplied through usage of multiple power plants at the same period of time, which together are able to provide adequate electricity to satisfy the demand. However, increasing capacities of solar and wind energy might lead to inflexibility of the power system on the supply and/or demand side.

Providing flexibility for the electricity system through peak-load shifting has been discussed in scientific literature [75–77]. Loads sometimes cannot be regulated, and in such situations energy storage systems can accomplish the process by shifting the load profiles. In this process, energy storage is charged when power plants are powering minimal load and the cost of electricity consumption is low. Therefore, the stress on the grids is decreased by suppling adequate electricity during the high peak demand period.

Concentrated solar power (CSP) with thermal energy storage has been found to be one of the best solutions for a region with high direct normal irradiation. However, in most cases, CSP cannot compete on price with solar PV due to the rapid decline of PV system costs and lower operating costs [78]. The renewable electricity generated during energy-rich times can be stored in energy storage, in particular batteries, and utilised when there is not enough renewable electricity generation to cover demand. Energy storage can help to increase the reliability of an energy system with high shares of variable renewable electricity. Moreover, improvement in overall power quality, reduction of the total energy system costs, and support for managing the transmission and distribution grids are the other positive impacts of energy storage.

Chapter 4: Level playing field: No more hiding behind subsidies

- Fossil fuel subsidies have resulted in continued damage to the environment, technological lock-in, increasing GHG emissions, reduced efforts to achieve energy efficiency, shortages of fuels, increased budget deficits, and disproportionate negative impacts on the world's least affluent populations.
- Reliance on future carbon capture and storage represents great risk and uncertainty on social, environmental and economic grounds.
- In order to account the full cost of energy generation, efforts must be made to take the wide variety of social, environmental and other costs into consideration, and estimates of these externalities for fossil fuels alone are in the range of several trillion USD annually on a global level.

In this section, the full costs of fossil fuels and nuclear power are exposed and assessed. Through the use of three distinct Info boxes, information will be summarised about subsidies for fossil fuels and nuclear power, further costs related to carbon capture and storage, and external costs that are often unaccounted when determining the costs of energy generation. This report attempts to internalise many of the direct and indirect subsidies allocated to all technologies in LCOE calculations. However, many were difficult or impossible to quantify. It will be clear from the discussion below and results from section 7 of this report that the overall costs of fossil fuels and nuclear power to society appear much greater than those for renewable energy. In addition, it will be shown how global society has been exposed to exceptional health and financial risks. What is more, it will be shown that future generations may be expected to assume great responsibility related to carbon storage, waste management and other schemes that were devised even before they were born. Certain costs are being paid, or will be paid, that are not often explicitly seen, and are not always part of the discourse involved in making energy related decisions. The significant extent of these costs should not be denied and must become more prominent in energy discourse as the global transition towards sustainability progresses.

It is also clear that subsidies are a barrier to establishing a level playing field upon which renewable energy technologies can compete in the coming global energy system transition towards sustainability. The G20 has repeatedly acknowledge this fact in Communiqués and Declarations going back to the 2009 G20 Summit in Pittsburgh [79], but greater actions are needed. The resulting harm and risk from fossil fuels and nuclear power must no longer be subsidised.

Fossil fuel and nuclear subsidies

"Inefficient fossil fuel subsidies encourage wasteful consumption, distort markets, impede investment in clean energy sources and undermine efforts to deal with climate change."

- G20 Pittsburgh Leaders Statement, September 2009 [79]

Depending on definitions and the methods of calculations, estimates of global, annual subsidies for fossil fuels range from approximately 500 bUSD [80] to 5.3 trillion USD [81]. At the heart of the matter is whether such subsidies should be defined narrowly as so-called "pre-tax subsidies", which represent the difference between the consumer cost of fuel and the opportunity cost of fuel supply, or more broadly as "post-tax subsidies", which also include a greater range of environmental damage and general consumer taxes [81]. What is consistent, however, with each new report are the strong social, environmental and economic bases for eliminating fossil fuel subsidies in order to enable the transition towards a more sustainable global energy system. Moreover, there seems to be little doubt that fossil fuel subsidies have resulted in continued damage to the environment, technological lock-in, increasing GHG emissions, reduced efforts to achieve energy efficiency, shortages of fuels, increased budget deficits, and disproportionate negative impact on the world's least affluent populations [82,83].

Distinguishing between the two major categories of subsidies above is important, as a broader context offers an interesting perspective. Indeed, estimates show a slight decreasing trend globally in pre-tax subsidies, but a significantly increasing trend in post-tax subsidies (Figure 11).

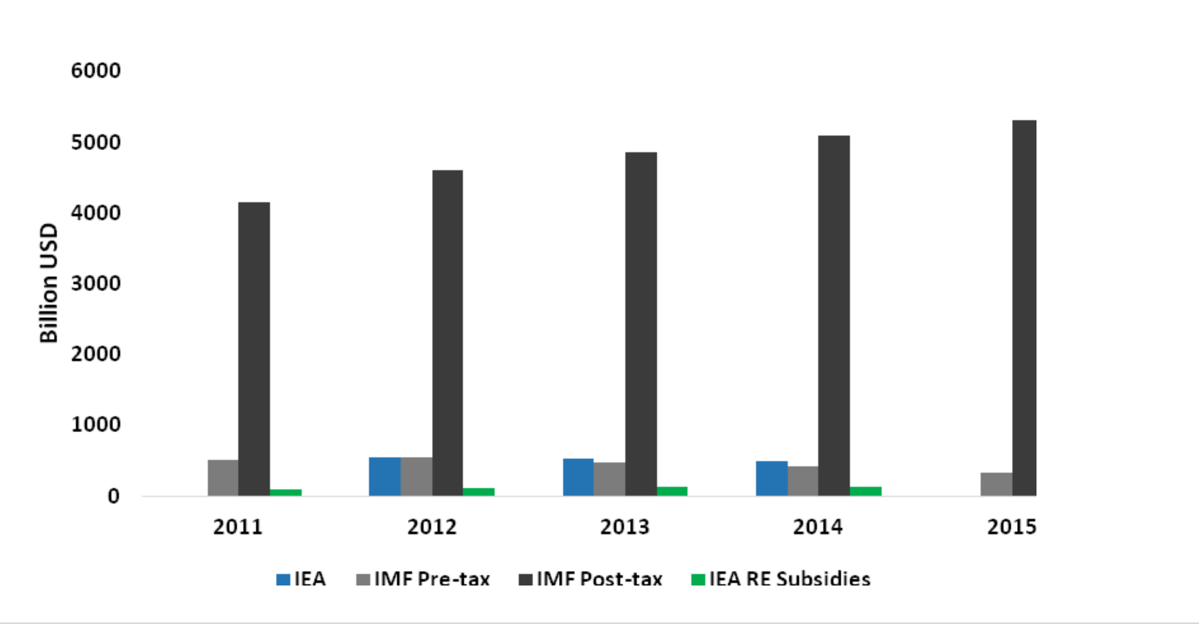


Figure 11: Global estimates from the International Energy Agency (IEA) and the International Monetary Fund (IMF) of annual fossil fuel and renewable energy subsidies (in bUSD). Adapted from [80,81]

Subsidies for the global nuclear power industry are much more difficult to quantify, as they rarely involve direct cash payments. Instead, they often shift costs, risks and burdens from the nuclear industry to society as a whole, thereby distorting market choices that might otherwise favour more sustainable options [84].

It is often neglected that many leading world economies make great efforts to defend their energy security through the use of their militaries. For this reason, a portion of military expenditures can arguably be accounted as a subsidy for securing overseas supplies of energy. It is estimated that the military costs for the USA to secure Persian Gulf oil supplies was approximately 6.8 trillion USD for the period of 1976 to 2007 [85]. Further, Delucchi and Murphy [86] conclude that, were there no oil in the Persian Gulf, combined wartime and peacetime defence expenditures by the USA might have been reduced by 27-73 $bUSD_{2004}$ per year, of which 6-25 $bUSD_{2004}$ is attributable to motor vehicle use alone.

A thorough investigation of nuclear power subsidies was completed by the Union of Concerned Scientists [84]. Although the analysis was specific to the context of the USA, similar subsidies can be seen worldwide. Table 3 provides an overview of such subsidies. Of importance is that Koplow [84] determined that total subsidies (ranging from 42 to 114 USD/MWh) often exceed the value of energy produced at nuclear power plants.

Table 3: Overview of subsidies to nuclear power. Adapted from [84]

Category		Examples
Output-linked support	Market cost support	Purchasing mandates and agreements
	Output payments	Nuclear production tax credit
Subsidies to factors of production	Capital-based	Reactor loan guarantees Accelerated depreciation Recovery of construction/work-in-progress Government research and development Tax exemptions for public reactors No required rate of return Subsidized site approval and licencing costs Transfer of stranded asset liabilities Traditional rate regulation Regulatory-delay insurance
	Labour-based	Shifting of health-related liabilities to taxpayers
	Land-based	Reduced property tax burdens
Input-linked subsidies	Uranium	Subsidized access, bonding on public lands Percentage depletion of uranium extraction Legacy costs of mining, milling sites National/central uranium-stockpile management
	Enrichment services	Below-market sales from government-owned facilities Tariffs on imported enriched uranium Environmental remediation costs
	Cooling water	Free or subsidised use of large amounts of cooling water
Security and risk management subsidies		Cap on accident liability **Reduced liability insurance** Unequal sharing of risk vs. reward Increased risk of nuclear weapons proliferation Increased risk of terrorism at nuclear power plants
Decommissioning and waste management subsidies		Tax breaks for reactor decommissioning Nationalisation/centralisation of waste management Incomplete remediation of site to green field Burden on future generations of long-term monitoring or exposure

Of notable importance is the limited insurance liability that nuclear power plants have. Thus, much of the liability for large accidents may fall firmly on the whole of society, even at a global level. Such is the case for large scale nuclear catastrophes such as Chernobyl or Fukushima, whose effects have been felt around the world.

There are several schemes globally that assign liability to the operators of nuclear installations, such as the Vienna Convention on Civil Liability for Nuclear Damage, Paris Convention on Nuclear Third Party Liability, Brussels Supplementary Protocol, Joint Protocol, Convention on Supplementary Compensation for Nuclear Damage, and the USA's Price Anderson Act (among many other national Acts). However, the common thread in each scheme is that liability on the part of the operators is capped, thus socializing any liability that exceeds the cap. In the USA, the cap is now 13.6 bUSD per incident. However, given that recent estimates for the ultimate cost of the Fukushima disaster are now in the range of 166 bUSD [87] to 180 bUSD [88], it is clear that public liability for accidents can be enormous. This liability must even be shared by other nations. In the case of Chernobyl, the aggregated cost shared between Ukraine, Belarus and Russia has been estimated to be 700 bUSD over the last three decades [89]. The probability of an event on the "dragon king scale" of Chernobyl or Fukushima is estimated to be 50% every 60 to 150 years. Of no less importance is that smaller events occur on an annual frequency [87].

One of the very few studies on the economic value of the liability insurance subsidy for the nuclear industry had been done by insurance mathematicians in Germany, concluding a subsidy in the range of 510 – 8710 €/MWh depending on assumptions and matching the technical lifetime of nuclear power plants [90]. It should be emphasised that this subsidy exceeds the economic value of the generated electricity by a factor of 10 – 100.

Little is done to account the socialization of risk as a major subsidy to the nuclear industry. What is more, this risk has increased in recent years. Combined with the risk of dragon king accidents that are unintentional, are increasing risks of intentional terrorism targeted towards nuclear plants. The need to defend against such risks will also have a cost. To this end, nuclear plant construction will need to be much more robust in order to withstand acts of terror, such as 9-11 type incidents. It has been argued that the need to modify nuclear plant design to increase security has been a major issue leading to the bankruptcy of Westinghouse Electric Company in the USA [88]. Combating this problem will most certainly lead to even greater costs for nuclear power. In addition, increases in defence spending to safeguard nuclear power plants should be seen as a direct subsidy; although, such costs are quite difficult to estimate.

In short, the totality of direct and indirect subsidies for fossil fuels and nuclear power must be more fully recognized, accounted and eliminated in order to provide a more level playing field for all forms of energy generation in the future. Despite the great rhetoric witnessed in several recent G20 summits, enduring subsidies continue to undermine efforts to create more sustainable energy systems on a global level.

Further costs of CCS

"There has been considerable optimism with respect to the development of plants for carbon capture and storage (CCS). The results, however, are disappointing."

- Emhjellen and Osmundsen [91]

The overall feasibility of CCS remains questionable on several fronts. On the one hand, it remains challenging to find economically viable projects for CCS due to its high cost. On another, a large-scale demonstration on par with what would be needed to deliver significant climate change mitigation has thus far not been achieved. Lastly, the focus on the carbon budget may overshadow other aspects of environmental and human health.

The economic viability of CCS is questionable. As is shown in section 7 of this report, the costs of CCS are significantly higher than alternatives. This observation is in line with another recent comparison [92]. Moreover, one of the flagship CCS plants in the USA, years behind schedule and billions of dollars over budget, acknowledged that a profit may never be seen [93]. Until serious market issues related to CO_2 production, transport and storage can be overcome, CCS will remain too high a risk for investors over the coming decades [94]. Overcoming these obstacles in the absence of an established, supportive market led by government subsidies seems unlikely as CCS "is marginal in economic terms and at the same time very capital intensive" [91].

To achieve the emissions reductions necessary to keep to well within the 2°C target of the Paris Agreement, the amount of carbon that will need to be captured, transported and safely stored will be massive. According to Bullis [95] "the impact of carbon capture will be limited by the sheer scale of infrastructure needed to store carbon dioxide", not to mention the infrastructure needed to transport and store it. Further, Bullis (ibid.) projects that global energy systems would need a CCS industry capable of processing roughly double the volumes of the current oil industry, "an industry that took 100 years to develop". At the moment, the CCS industry remains unproven on a full commercial scale [96]. Leung et al. (ibid.) point out that the roughly 73 larger CCS projects worldwide would need to grow to more than 3000 by the year 2050 in order to reach the reduction target. Further, they caution that while some advancements have been made in CCS technology, "comprehensive CCS projects involving large scale capture and storage are not operational". Again, this operationalisation seems highly unlikely given the current absence of a clear positive business case for investment.

Furthermore, O'Brien [97] claim that it is dangerous to focus too much on CO_2 mitigation, which is essentially just an environmental contract. They caution that such a contract would be "unlikely to change anything" (ibid.) as it would serve to reinforce the power and economic structures that are the root cause of climate change. Indeed, too much reliance on CCS may obscure focus on non-carbon emissions from fossil fuels that are a direct threat to human health (see Info box below on External costs). O'Brien et al. (ibid.) argue that climate change must not be analysed on a single level, and therefore must go beyond CO_2 in order to decrease energy system vulnerability and increase system resilience. Fossil fuel based CCS will still result in other harmful emissions despite advances in pollution control technology. Reliance on CCS does little or nothing to decrease overall energy system vulnerability, as it represents financial, social and environmental risk. It should not be the place to look for resilience or sustainability.

External costs

"The planet is fine. Compared to the people, the planet is doing great!"

- George Carlin, American comic

In order to account the full cost of energy generation, effort must be made to take the wide variety of social, environmental and other costs into consideration. Table 4 introduces the components of these costs, many of which vary significantly on a global scale, and represent a wide range of costs that are inherently difficult to determine and validate. Nonetheless, several studies have attempted to internalise the external costs of energy generation, most notably the ExternE study in Europe [98], Rafaj and Kypreos [99], Rentizelas and Georgakellos [100], Epstein et al. [24], and Buonocore et al. [25]. These studies have focussed on the ultimate social costs related to emissions of radiation, particulate matter, heavy metals, nitrogen oxides, sulphur oxides, and carbon dioxide equivalents. However, many other pollutants and effects are noted.

Table 4: Components of costs to be internalised in LCOE calculations. Adapted from [98]

Category	Pollutant/Burden	Effects
Fatal effects on human health	Particulate matter (PM_{10}, $PM_{2.5}$); SO_2; O_3	Reduction in life expectancy
	Heavy metals	
	Benzene; Benzo-[a]-pyrene; 1,3-butadiene; Diesel particles; Radionuclides	
	Accident risk	Fatal risk from traffic, home and workplace accidents
	Noise	Reduction in life expectancy
Non-fatal effects on human health	Particulate matter (PM_{10}, $PM_{2.5}$); SO_2; O_3; CO	Hospital admissions; Respiratory and pulmonary problems; Restricted activity days; Congestive heart failure
	Heavy metals	Cancer risk; Loss of IQ of children
	Benzene; Benzo-[a]-pyrene; 1,3-butadiene; Diesel particles; Radionuclides	Cancer risk; Osteoporosis, ataxia, renal dysfunction
	Accident risk	Non-fatal risk from traffic, home and workplace accidents
	Noise and visual disturbance	Sleep disturbance; Hypertension; Heart problems
Effects on buildings	SO_2; Acid deposition	Ageing of buildings
	Combustion particles	Soiling of buildings
Effects on	NO_x; SO_2; O_3	Changing crop yields

crops	Acid deposition	Increased need for liming
	N, S deposition	Fertilising effects
Environmental effects	SO_2; NO_x, NH_3	Acidity and eutrophication; Potentially Disappeared Fraction (PDF) of species
	Radiation	Permanent changes to land
	Land use change	PDF of species
Effects on global warming	CO_2; CH_4; N_2O	Coastal impacts, changing energy demands and economic impacts due to temperature change and sea level rise
Other social effects	Fossil fuels	Increased global competition and conflicts over resources; impact on energy security
	Nuclear power; radioactive waste	Increased risk of nuclear accidents or terrorism; nuclear weapons proliferation; intergenerational dilemma of long-term waste disposal
	Wind and solar power	Impacts on landscape and property values; risk of falls from height; overall social acceptance

Two important ethical issues arise from these effects. The first is an intergenerational issue. In essence, the full impact of many of these effects may not fully be felt for long periods of time, perhaps decades. We therefore must ask whether it is right for polluters of today to impact citizens of tomorrow, some of whom may have not yet been born. The second important issue relates to the fact that these impacts are not equally shared. In fact, as many of these effects are felt over great distances, people who have little to do with the pollutant or burden may be the main ones feeling their effects. In other cases, those who live close to the source of the pollutant or burden may feel disproportionate effects. This is in contrast to many nations' basic right of equal protection under the law. What is worse is that there is increasing evidence that the world's most vulnerable people may be disproportionately feeling these impacts [97].

As shown above in Figure 11, estimates of externalities for fossil fuels alone are in the range of several trillion USD annually on a global level. In this report, we endeavour to internalise many of these costs in LCOE calculations as fairly as possible. However, it must be noted that the process of monetizing pain, suffering, quality of life, and death is inherently despicable and inaccurate. What is more, such risks, burdens and costs can be avoided. Stronger actions towards developing sustainable energy systems globally will result in mitigating much more than climate change. This must start with the acknowledgement that we do not only need to save the planet, we desperately need to save ourselves.

Chapter 5: Global scenarios, growth of renewables and system cost

- The need for an energy transition is crucial and driven by high global population growth, increasing energy demand, diminishing fossil fuel resources, rising environmental concerns and significant global renewable energy potential, especially solar and wind resources.
- Future global energy scenarios are widely discussed based on different assumptions, methodologies and targets from national to global levels that reflect the diversity of views.
- Only those global energy scenarios with targets of 100% renewable energy based systems are expected to have the least-cost due to sharp decreases in costs of solar PV and wind power.
- The increasing adoption of variable renewable energy and new power system designs based on high shares of renewable generation eliminate the dependence on costly and less flexible traditional baseload generation.

In this section, nine global energy studies, some with multiple scenarios, are examined. The selected reports are among the most well-known studies regarding global energy transitions. The aim of this section is to provide insight into each global energy system report in a nutshell and to show how different assumptions and targets can create different results. Finally the question of what may be the long-term share of renewable energy for the global energy supply is discussed. Global energy scenarios are widely discussed based on different assumptions, methodology and targets from a national to global level [101]. Royal Dutch Shell, due to their close ties with the fossil fuel industry, receives contributions to reports from the fossil fuel companies. Meanwhile, Greenpeace [102] focuses on renewable energy with the aim of an entirely sustainable energy system for the world, using a mix of experts from renewable energy industries and academia. Researchers and scientists also work on energy scenarios with diverse goals for either an overnight scenario or scenarios played out over several years [56,103,104].

Due to the variation in assumptions and targets, transparency is one of the most important elements for the creation of global energy system scenarios. For instance, unrealistic assumptions have been made concerning the future costs of solar photovoltaics (PV). This leads to an unrealistically high cost of PV in the future that is similar to the current cost in some countries [105]. Therefore, the final cost of the system with high shares of PV would be much higher in such systems compared to other future energy systems analysis where more detailed and realistic assumptions are used. In fact, the lower cost assumptions for non-renewable options can lead to considerable amounts of fossil fuel or nuclear shares in the future energy system analysis.

Given more realistic financial assumptions by 2030, LCOE for renewable energy resources in the G20 countries is estimated to be lower than or comparable with fossil fuels, nuclear power and fossil fuels with CCS technology (see next section for more details). Thus, for those global energy system analyses that lack a 100% renewable energy based system, the LCOE is expected to be higher than an entirely sustainable energy based system. This can be better understood via Table 5 at the end of this section, which lists the share of renewable energy for G20 countries in all selected studies. A lower share of renewable energy resources indicates a higher average LCOE than that for a 100% renewable energy system.

Each study is described briefly below and a summary discussion will follow.

Royal Dutch Shell

The New Lens Scenarios is the name of report published by Royal Dutch Shell [106]. The demand for water, energy and food is forecasted to further increase by 40%-50% till 2030. Two scenarios are investigated called “Mountains” and “Oceans”. The Mountains scenario highlights the role of governments whose wise foresight helps to develop small cities and change the transportation infrastructure. It is expected that the passenger road market will be almost oil-free by 2070 and affordable hybrid hydrogen vehicles may dominate. Increasing the natural gas contribution to the global primary energy source is the main character of this scenario. Despite the remaining untapped gas resources in the world, tight/shale gas, which forms around 15% of the current global gas production together with Coal Bed Methane (CBM), is expected to experience a tremendous growth starting from the middle of the 21st century. Along with the development of methane hydrates, this is presumed to further expand gas supply growth for the longer term. It is summarized that increasing nuclear and biomass contributions to final energy sources and accelerating CCS technology will lead to a carbon-free electricity sector in the long term.

The Oceans scenario describes a more decentralized world where energy demand leaps, developing economies continue to grow and power is more widely distributed, with tough governments to agree on critical decisions. Tight/shale gas and CBM are no longer the major contributors to the final energy mix, except in North America. Natural gas, oil and coal have almost the same share in comparison to solar energy by 2060. At the end of the 21st century, fossil fuel accounts for 21.5% of the total energy sources, and oil has the highest share by around 10%. Solar energy dominates the system with about 38%. The scenarios also explore the paradoxes and pathways countries face and identify key features of a possible geopolitical transition. Gasoline and diesel-fuelled vehicles become more important due to advanced combustion engine technologies, followed by an affordable hybrid vehicle with smaller batteries.

Natural gas resources and CCS technology are considered as two main options for the energy sector in the Shell report. Lack of one of these two resources is said to lead to increases in GHG emissions higher than would be allowed to reach the 2 °C goal. Surprisingly, the role of renewable energy is almost half of the total energy by 2060 in the Mountains scenario, and in the more optimistic scenario, Oceans, solar becomes the dominant technology after 2070. The geographical locations of renewable energy resources, the long distance from resources to consumption centres, and massive land area requirements are the main arguments of this report to justify the low share of renewables in the future. Moreover, it is highlighted that modern renewable energy resources can most likely fulfil the demand of the power sector, which has the lowest energy demand among all sectors today. However, the use of renewable energy resources in other sectors, such as the chemical and transport sectors, is limited.

International Energy Agency (IEA)

With respect to the Paris Agreement reached at the 21st Conference of the Parties (COP21), the IEA in its Energy Technology Perspective (ETP) report [107] claims to show enormous opportunity for a number of cost-effective and sustainable energy resources available in every corner of the world. It is mentioned that a massive change is required in the energy sector in order to achieve a cost-competitive energy system. The 2 Degree Scenario (2DS) is introduced to elaborate how such a large-scale transition is possible via low-carbon technologies. The final results reveal a 30% reduction in energy demand and 70% decrease of GHG emissions in the energy sector by 2050. The main factors that contribute to this transformation are electrical efficiency (38%), renewable energy (32%), CCS (12%) and nuclear energy (7%). Three different scenarios (no CCS, hiRen, hiNuc) were included in the 2010 and 2012 released reports.

The WEO report [108] is the flagship publication of the IEA, commonly discussed as the most well-known source for global energy projections and analysis. The report includes a "450 scenario", which is supposed to draw a pathway to reach the 2 °C target. Among hydrocarbon resources, the natural gas contribution to final energy production continues to increase further, while the shares of oil and coal decline. The need for oil is expected to constantly rise until 2040, mainly due to difficulties in finding a substitution in the petrochemicals industry, aviation and road freight transport. In addition, the battle against climate change and 'diversifying' the fuel mix leads coal consumption to remain almost constant over years. Therefore, renewable energy and natural gas are found as best options to meet global energy demand growth by 2040. Overall, fossil fuels and nuclear continue to stay as a main energy resource in the future energy system, and projected growth rates of renewables are quite conservative.

World Energy Council (WEC)

Two scenarios are investigated in the World Energy Scenario report [109], named “Jazz” and “Symphony”. In 2050, the global population is anticipated to grow by 26% in the Jazz scenario and 36% in the Symphony scenario, compared to the year 2013. Similarly, GDP per capita, mobility and total primary energy demand will continue to rise in both scenarios. Energy efficiency and energy conservation are considered as two main elements in dealing with energy supply to support steady demand growth. The primary energy mix in 2050, however, will not experience a dramatic change and fossil fuels will continue to dominate the market. With a 77% share of fossil fuels in the total primary energy source, the Jazz scenario has the lower share compared to the Symphony scenario, where fossil fuels account for 59%. Similar to the Mountains scenario in the Shell report, unconventional gas dominates the energy system. PtG is introduced as one of the potentially greatest game-changers in both scenarios. A PtG breakthrough is assumed to occur from 2035 onwards in the Jazz scenario and earlier in the Symphony scenario. However, the year in which the PtG breakthrough occurs in the Symphony scenario is not reported explicitly.

International Institute for Applied Systems Analysis (IIASA)

“Global Energy Assessment” [110] is the report of the IIASA group published in 2012. The report stresses the main global challenges and their connection to energy, how to provide energy security for all considering the available technologies and resources, how to reduce the level of GHG emissions and air pollution, and also the role of governments, institutions and organizations to achieve a sustainable energy future. To address and solve the current energy system challenges, 41 pathways are examined to achieve all the goals listed in the report. There are three main scenarios called “Efficiency”, “Mix” and “Supply”, each with different assumptions and targets. In the Efficiency scenario, for example, by 2050 energy per capita decreases by approximately 31% in both developed and emerging countries compared to 2005. However, it is assumed that energy per capita increases even further, by around 3% in the Supply scenario. The study emphasizes all aspects of sustainability for choosing the suitable technologies for a radical transformation in the energy system. Nuclear energy and CCS are not considered in this category. The integrated analysis presents a holistic, macroeconomic view of the energy sector. Meanwhile, energy technologies are discussed less in detail.

German Advisory Council on Global Change (WBGU)

“Exemplary” is the name of the scenario developed and analysed by WBGU [111]. This scenario is based on an IPCC scenario and focusses on the 450 ppm target. The core assumptions of this scenario are future energy demand, population and economic growth. As such, sustainability goals can be reached without need for massive changes in the present patterns of energy use. Access to modern, affordable and efficient energy services, decreasing air pollution, preserving land and marine ecosystems, phasing out nuclear power projects and sustainable use of bioenergy under specific limits are the main criteria in this scenario. CCS technology is projected to become commercialized by the 2040s and phased out again by 2100. It is found that 50% of the total energy production will come from renewable energy resources by 2050.

World Wide Fund for Nature (WWF)

The “Ecofys” [112] scenario deals with a number of critical challenges globally regarding economic, political, environmental and social issues. The main goal of the report is to achieve a 100% renewable energy based system worldwide by 2050. Nevertheless, 95% of final energy is sourced by sustainable resources and the remaining 5% comes from coal and natural gas – both have equal shares as presented in the report. The main goals listed in the report are the following: providing reliable electricity for all, decreasing the need for fossil fuels through supplying sustainable energy to cover all demands, preventing climate change, and phasing out nuclear power due to several harmful impacts. According to the scenario, energy demand by 2050 will drop by 15% and 20% compared to 2005 and 2010, respectively. More efficient forms of transport systems, better constructed buildings as well as more energy efficient and recycled material use in the industry will help to do more with less. In the energy mix, solar PV is projected to have the highest potential at around 200 EJ/year, followed by CSP, wind onshore and wind offshore. Bioenergy utilization, with around 180 EJ/year of primary energy, is much higher than what is introduced as sustainable use of biomass by WBGU and Greenpeace. A 4 trillion € saving is expected by 2050, obtained through improved energy efficiency and decreased fuel costs in comparison with the BAU scenario. However, more capital costs are needed to invest in the installation of renewable energy and increase the installed capacity. The transition to renewable energy is found as the best solution to decrease global GHG emissions by at least 80% in 2050.

Greenpeace

Two scenarios are investigated in the latest editions of the energy [r]evolution [102] report series published by Greenpeace: “Energy [R]evolution” and “Advanced Energy [R]evolution”. According to the report, if fossil fuels and nuclear power are still considered the main options for electricity generation, moving towards a fully sustainable energy system is wishful thinking among many energy experts and engineers. However, increasing global mean temperature and GHG emissions, diminishing hydrocarbon resources and rapidly declining costs of renewable energy promote a 100% renewable energy vision. Since the first edition of this report in 2005, the costs of renewables, in particular solar PV and wind power, have declined significantly. The latest editions highlight the relevance of the low costs to the energy transition. Increasing energy efficiency is noted as a cheap solution compared to investments in new forms of energy from scratch. A radical change in the entire global transport sector from the fossil fuels based system to renewable electricity directly, or via synthetic fuels indirectly, is needed to phase out GHG emissions. It is expected that overall electricity demand continues to increase further from around 18,860 TWh/year in 2012 to 37,000 TWh/year in 2050 in the Energy [R]evolution scenario. In contrast, energy use slips back by almost 47% in the Advance Energy [R]evolution scenario by 2050 compared to the reference scenario, with regards to both primary and final energy demand. PV and wind will dominate the growing market share starting from 2020, with CSP, geothermal and ocean energy complementing these resources. The pathway is defined to supply 83% and 100% of the total energy production by renewables in the Energy [R]evolution and Advanced Energy [R]evolution scenarios, respectively, by the year 2050. A smart energy system, energy storage capacities, demand side management and other relevant factors need to be developed to increase the flexibility and reliability of the energy system. It is highlighted that economic or technical barriers are not significant to block the path towards an entirely renewable based energy system. However, cooperation of governments, policy makers, NGOs, institutions and society as a whole is required to reach this target.

Jacobson et al.

The scenario developed in this report [113] is called Water, Wind and Sunlight (WWS), which aims to provide a clean and sustainable energy for all energy dependent sectors in 139 countries. It is planned to reach 80% zero-emitting energy by 2030 and 100% by 2050. The new energy system offers millions of new jobs, reduces air pollution, combats global warming, provides accessible and reliable energy for all, even those in energy poverty, and several more benefits. Energy costs are expected to reduce and stabilize over time. All energy sectors are assumed to be electrified, or direct heat is to be used with existing technologies. Energy demand in the WWS scenario is lower than in the study’s

BAU scenario. A mix of WWS energy technologies is proposed to generate the power demand needed for all 139 countries. It is concluded that onshore 5 MW wind turbines are the leader among all renewable energy technologies, providing 23.5% of the total energy of all countries. The next sources of energy generation are 50 MW utility-scale solar PV power plants (21.4%) and offshore 5 MW wind turbines (13.6%). Initially, 50 states of the US were modelled [113] on the basis of high spatial and temporal resolution with detailed energy technology analysis. However, the new report for the whole world was developed taking average annual capacity factors into consideration.

Breyer et al.

Similar to Jacobson et al., this study [56] can be classified in the science and research based scenario analysis category, where a group of researchers address the main issues of the existing energy system globally and introduce scenarios to tackle challenges. The world is divided into 145 sub-regions, including countries with multiple regions, individual countries, and merged countries. The subdivision is applied according to the population, area, electricity demand, electrical power grid structure, and geopolitical status of the countries. The main objective of the study is the transition of the global energy system towards an entirely sustainable one based on the Paris Agreement. In this way, a mix of renewable energy based on the availability of the resources and storage options, national electricity demand and costs, and applied constraints and assumptions are considered as input data to optimize the best possible energy system at the minimal costs to support all the electricity demand. The "LUT Energy System Model" is based on a linear optimization of energy system parameters, and is able to provide hourly resolution data to analyse electricity generation in every hour of a year. Thus, it makes the work easier for energy experts to monitor and find the best technologies for electricity generation.

The developed scenarios are named "region-wide", "area-wide" and "integrated", and all are applied for the year 2030 for a fully sustainable energy system. In the region-wide scenario, the regions are independent and the energy system is rather distributed. However, electricity trade among neighbouring sub-regions is allowed in the area-wide scenario. This means that each region can not only supply its own electricity demand, but can also transfer excess electricity through HVDC power lines to adjacent regions. Both scenarios are designed to only provide electricity for the power sector. The integrated scenario fulfils demands for power, water desalination and non-energetic industrial gas sectors. In addition, similar to the area-wide scenario, electricity exchange between sub-regions is allowed.

In addition, Breyer et al., under the Neo-Carbon Energy project [114], have designed an online tool, called the Global Internet of Energy (IoE), which shows how 100% RE in the power sector would work all over the world for cost optimised systems. The tool is likewise structured for 145 regions in the world. The resource data are based on high temporal (1-hour) and spatial (50-km) resolution globally. This high resolution is required due to the intermittency of renewables, such as solar and wind energy, and the need for a stable electricity system. The visualisation clearly illustrates how power supply can match the demand in all hours of the year, in a least cost solution.

A summary of the discussed global energy system transition scenarios with respect to G20 countries is presented in Table 5 and Figure 12. The reference year in Table 5 is set to the year 2030 for all scenarios to make them more comparable with the scope of this report. However, a few scenarios have a target of 100% renewable energy by 2050 in specific time steps, such as Greenpeace, and some only have a target for 2050, such as Jacobson et al. In addition, a comparison of electricity generation by resources between all scenarios and the percentages of renewable energy contributed to total electricity generation are shown in Figure 12.

Comparison of energy technologies considered in all studies shows the diversity of thoughts and opinions in the future energy scenarios. With respect to COP21, some introduced scenarios aim to achieve 100% renewable energy and move towards a net zero emission world in the mid-term future.

Whereas, others argue that renewable energy is not the only solution for the required energy transition, and other alternatives such as nuclear energy and CCS are needed as well. However, the role of CCS is not globally accepted in future energy scenarios, and the overall sustainability of this technology is questionable (see sections 4 and 7). WBGU, for example, presumes fossil CCS to be commercialized in 2040s and phased out by 2100. On the other hand, the IEA provides no clear explanation regarding both nuclear and CCS capacity ramp-ups. The focus on nuclear power and CCS in global energy scenarios may be explained by the fact that the reality of sharply decreasing costs of solar PV and wind power all over the world and fast growth of installed capacity are not precisely taken into account. The same can be noted for battery storage, which is currently experiencing similar trends to solar PV and wind costs. In terms of battery storage, high costs and doubt about resource availability are the main constraints in the same studies [74]. Moreover, the increasing adoption of variable renewable energy and the opportunity for new power systems to be designed based on high shares of renewable generation eliminate the dependence on costly and less flexible traditional baseload generation [7].

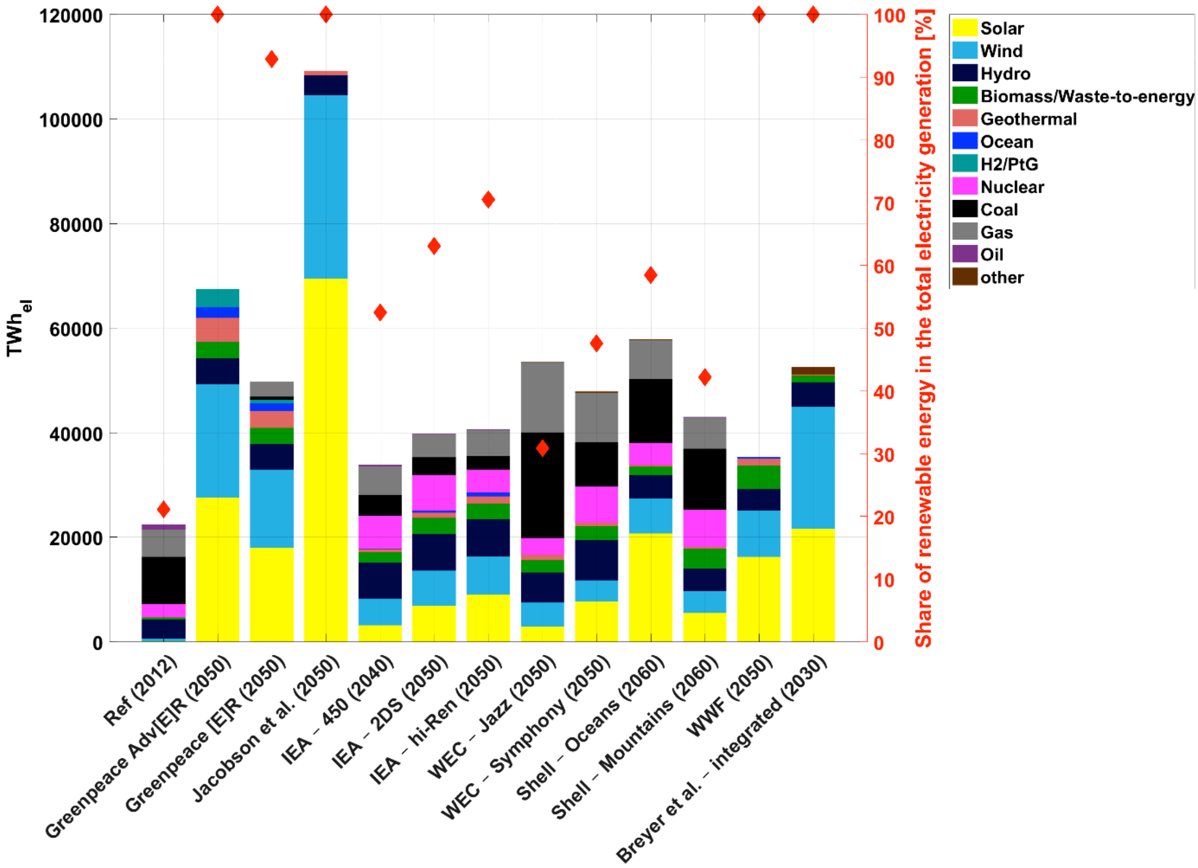


Figure 12: Electricity generation from different sources and share of renewable electricity in total generation in the assessed scenarios [101]. The reference scenario for the year 2012 is based on Teske et al. [102] For WWF and Shell scenarios the values are for final consumption; for WWS electricity generation is estimated from supplementary materials [103]; and for the rest the values are for generated electricity.

Table 5: Summary of the renewable energy shares in the global energy scenarios with respect to G20 countries. Some studies do not provide absolute numbers for all or some G20 countries, thus the cells remain blank. The colour code indicates the share of renewable energy, solar PV and wind power (onshore and offshore) in the total primary energy demand (TPED) for each scenarios. Solar PV and wind are chosen because in almost all studies and these two resources have the highest share among renewables. Green represents the share of renewables, dark yellow stands for share of solar PV and blue shows wind share in TPED.

	Global energy system scenarios														
	Royal Dutch Shell		IEA		WEC[3]		IIASA[3,4]			WBGU	WWF	Greenpeace[3]		Jacobson et al.	Breyer et al.
References	106		107,108		109		110			111	112	102		113	56
Scenarios / **G20 Countries**	Mountains [2060]	Oceans [2060]	2DS hiRen [2050]	450[3] [2030]	Jazz [2050]	Symphony [2050]	Efficiency [2030]	Mix [2030]	Supply [2030]	Exemplary [2030]	Ecofys [2050]	Energy [r]evolution [2030]	Advanced energy [2030]	WWS [2050]	Integrated [2030]
Argentina	-	-	-	72/5/8	60/27/16	70/29/12	35/5/2	56/3/2	54/3/2	-	-	78/20/16	86/26/19	100/48/35	100/30/54
Australia	-	-	-	43/18/7	49/29/12	56/41/5	13/4/4	27/4/4	38/6/3	-	-	67/32/15	72/35/16	100/43/37	100/43/49
Brazil	-	-	-	86/4/12	60/27/16	70/29/12	35/5/2	56/3/2	54/3/2	-	-	78/20/16	86/26/19	100/44/32	100/65/5
Canada	-	-	-	43/9/17	54/4/42	69/31/29	16/4/3	24/4/5	25/4/4	-	-	70/29/23	73/32/24	100/21/50	100/12/75
China	-	-	-	52/10/18	32/14/10	58/41/8	14/6/0	17/6/2	16/5/2	-	-	59/19/19	63/21/20	100/48/36	100/62/30
France	-	-	-	57/13/24	44/6/29	59/21/29	16/5/4	21/4/6	21/5/5	-	-	73/24/25	77/27/26	100/26/57	100/37/38
Germany	-	-	-	57/13/24	44/6/29	59/21/29	16/5/4	21/4/6	21/5/5	-	-	73/24/25	77/27/26	100/54/45	100/51/41
India	-	-	-	54/19/18	18/6/6	64/32/19	18/6/1	20/7/2	22/8/2	-	-	73/28/30	80/31/36	100/49/37	100/69/19
Indonesia	-	-	-	52/12/16	49/29/12	56/41/5	17/4/1	27/4/1	29/5/1	-	-	71/27/22	74/31/21	100/56/25	100/84/0

[3] The values are only available for the main regions and some countries of the world. The respective values for each region are assigned for the countries within the regions.
[4] Advanced transportation pathway with no restricted options (full portfolio), conventional transportation pathway with no restricted options (full portfolio), and advanced transportation pathway with no nuclear are presented in this report for the Supply, Mix and Efficiency scenarios, respectively.

Italy	-	-	-	57/13/24	44/6/29	59/21/29	16/5/4	21/4/6	21/5/5	-	-	73/24/25	77/27/26	100/57/26	100/63/11
Japan	-	-	-	49/24/4	32/14/10	58/41/8	13/4/4	27/4/4	38/6/3	-	-	67/32/15	72/35/16	100/86/9	100/84/13
Korea	-	-	-	43/18/7	32/14/10	58/41/8	17/4/1	27/4/1	29/5/1	-	-	67/32/15	72/35/16	100/73/15	100/88/10
Mexico	-	-	-	43/9/17	54/4/42	69/31/29	35/5/2	56/3/2	54/3/2	-	-	70/29/23	73/32/24	100/48/35	100/61/32
Russia	-	-	-	38/0/6	44/6/29	59/21/29	14/5/1	23/4/1	23/6/1	-	-	63/15/26	69/19/30	100/21/72	100/24/63
Saudi Arabia	-	-	-	21/6/7	15/13/1	46/45/0	7/4/0	8/4/1	9/5/1	-	-	63/26/14	68/32/15	100/46/42	100/44/56
South Africa	-	-	-	34/14/9	54/42/6	63/42/6	41/8/1	60/6/1	62/6/1	-	-	70/33/19	78/39/19	100/37/48	100/39/56
Turkey	-	-	-	59/12/23	44/6/29	59/21/29	16/5/4	21/4/6	21/5/5	-	-	73/24/25	77/27/26	100/49/27	100/53/36
United Kingdom	-	-	-	59/12/23	44/6/29	59/21/29	16/5/4	21/4/6	21/5/5	-	-	73/24/25	77/27/26	100/46/49	100/57/20
United States	-	-	-	39/9/17	54/4/42	69/31/29	16/4/3	24/4/5	25/4/4	-	-	70/29/23	73/32/24	100/46/38	100/49/44
European Union	-	-	-	57/13/24	44/6/29	59/21/29	16/5/4	21/4/6	21/5/5	-	-	73/24/25	77/27/26	100/44/46	100/46/31
G20 members	-	-	-	51/12/15	44/14/21	61/31/19	19/5/2	29/4/3	30/5/3	-	-	70/26/22	75/29/23	100/47/38	100/55/35
Global	14/2/1	17/3/2	71/12/18	49/11/15	40/14/18	61/35/16	12/5/2	12/5/3	12/5/2	13/1/8	42/2/5	67/25/22	73/28/23	100/48/34	100/56/33

Chapter 6: Methodology for cost calculations

- Levelised cost of electricity is the standard methodology to compare different electricity generation technologies.
- The cost calculation is expanded so that all types of cost can be included, in particular external cost.
- Cost data is collected from various sources to reflect a realistic range of levelised cost of electricity.

In order to represent the comparative annualised costs of electricity generation for different technologies on an equal footing, a levelised cost of electricity (LCOE) calculation is often employed. In general, LCOE calculations include all the costs of building and operating a power plant in relation to its 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 CO_2 emissions. However, this analysis will attempt to include the full cost of energy generation by internalising them as fairly as possible. To this end, a fuller range of costs both upstream and downstream from power plants are included in order to give a more accurate representation of the full cost 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 cost may differ significantly from its originally budgeted cost. This is due to the fact that 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 [115]. For example, a solar PV rooftop system on an individual home can be ordered from a service provider who can deliver a turn-key product within weeks. And due to the fact that 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 permitting and construction. Moreover, a recent trend has been observed in time and cost overruns that dramatically inflate the originally projected overnight cost. A case in point is the Olkiluoto 3 reactor in Finland. The first application for the 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 still not been commissioned, and recent cost estimates exceed 8.5 b€ [116,117].

The components of the LCOE calculations employed in this analysis include 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 LCOE are plant lifetimes and full load hours (FLH) of operation annually.

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

- International Energy Agency [118]
- International Energy Agency – Photovoltaic Power Systems Programme [21]

- European Commission Joint Research Centre, 2014 [119]
- Danish Energy Agency, 2016 [120]
- International Renewable Energy Agency, 2015 [121]
- European Technology & Innovation Platform – Photovoltaic (ETIP-PV) 2017 [122]
- Bongers, 2015 [123]
- Lazard, 2016 [124]
- Grausz, 2011 [125]
- Ahmad and Ramana, 2014 [126]
- World Nuclear Association, 2017 [127]
- Rafaj and Kypreos, 2007 [99]
- International Energy Agency and Nuclear Energy Agency, 2015 [128]
- Mann et al., 2014 [129]
- Schlissel, 2016[130]
- Government of India Ministry of New & Renewable Energy, 2017[131]
- Central Electricity Regulatory Commission of India, 2015 [132]
- UBS, 2017 [58]
- Pöller, Obert, and Moodley, 2015 [133]
- World Nuclear Association, 2017 [134]
- Schneider and Froggatt, 2016 [27]

Additionally, this report has endeavoured to show transparency in the calculation methods. Furthermore, the authors would be very pleased to share further information in this regard if needed.

Overview of the Methodology

The calculation of LCOE (expressed as €/MWh_{el}), representing a discounted cash flow approach for the case of constant annual cash flows, in this report is characterised by the following equation:

$$LCOE = \frac{(Capex_{Real} * crf) + Opex_{fixed} + \frac{Decommissioning\ costs}{N}}{FLH} + Opex_{variable} + LCOS + Fuel\ costs + Waste\ disposal\ costs + External\ costs + GHG\ costs$$

where,

$Capex_{Real}$ is annual capital expenditures (€/MW_{el}), which include a low and high estimate for investment and budget overruns; *$Opex_{fixed}$* are fixed operations and maintenance costs (% of capex/year); *Decommissioning costs* are expressed as a % of capex for all technologies except nuclear power plants, for which they are expressed as a value in €/MW_{el}; *N* is the operational lifetime of the technology (years); *$Opex_{variable}$* is the annual variable operations and maintenance costs (€/MWh_{el}); *LCOS* is the levelised cost of storage in €/MWh_{el} (see below); *Fuel costs* are expressed in €/MWh_{el}; *Waste disposal costs* are expressed in €/MWh_{el}; *External costs* (annual) include a range of socio-

economic costs related to energy generation (€/MWh_{el}); *GHG costs* (annual) include the full socio-economic costs of GHG emissions. 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:

$$crf = \frac{WACC * (1 + WACC)^N}{(1 + WACC)^N - 1}$$

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.

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

$$LCOS = \frac{Storage\ capacity * [(Capex_{Real} * crf) + Opex_{fixed}]}{System\ output} + \frac{Costs\ of\ battery\ losses}{System\ output}$$

All monetary values are expressed in 2015 euros, unless otherwise stated. Major components of LCOE are further described in the Appendix, and all raw calculations are available from the authors.

Chapter 7: Cost trends for solar and wind energy in comparison to conventional fuels

- Economic analyses of electricity generation are often made on an individual plant level, and therefore exclude the very real range of costs coming from the value chain that precede and follow actual generation.
- Energy from fossil fuels and nuclear power is significantly more expensive than renewable energy upon internalising impacts on human health, the environment, global warming, long-term waste management, plant decommissioning, financing and budget overruns.
- Low, median and high values of levelised cost of electricity generation in 2015 and 2030 are calculated for a variety of technologies in all G20 countries.
- Onshore wind power is currently the least cost source of electricity in most G20 countries, while utility-scale solar PV is highly competitive with conventional forms of energy generation, especially in countries with high solar irradiation.
- Renewable energy technologies offer the lowest overall cost of electricity to G20 nations in 2030 based on the results of this study.

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. This 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 involved in the variance in LCOE are capex, investment and overruns, and FLH. At the same time, fuel costs and assumptions about technology lifetimes could add slightly more 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, 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 the low FLH of peak-following gas turbines, which have an important regulatory function in any energy system.

While a full range of values were calculated for LCOE, only values below 250 €/MWh_{el} will be shown in figures below. Above this level, investments in capacity 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.

Results of calculations

Results of LCOE calculations are presented in Figures 13 to 16 for major regions of the world: the Americas, Europe, Asia, and the Middle East and Africa. In general, onshore wind energy currently shows the lowest overall LCOE, especially in regions of high latitude (either north or south). Notable exceptions exist for some regions in Asia where wind resources are less favourable and the solar resource is more favourable. In 2030, solar PV utility power plants represent the lowest LCOE of all technologies in all regions of the world with the exception of Northern Europe, where onshore wind continues to show lowest LCOE. On a global level, 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) on a global basis. Conventional fuels become significantly less competitive in 2030 when the costs of CO_2 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 synthetic methane. Carbon capture and storage offers an opportunity to reduce costs associated with fossil fuel combustion, but remains significantly higher in cost than renewable energy generation, even with anticipated cost reductions due to development of CCS technology. It needs to be noted that net zero emissions are almost impossible with fossil-fuel based CCS, but still occurring higher cost than renewable energy based energy systems. Nuclear power has already lost its competitiveness to wind and solar PV in 2015 in most G20 countries and further worsens its relative competitiveness with renewable energy in 2030 when high levels of social, environmental and economic risk are internalised in LCOE calculations.

Current status

Renewables

Onshore wind is currently the least cost source of electricity in most G20 countries. Notable exceptions exist in Indonesia and India, where the wind resource is not of the best quality in comparison to European and Latin American conditions. While the solar resource is excellent; and the Republic of Korea, where high domestic subsidies for nuclear power result in a least cost solution. Offshore wind is currently a rather high cost option for energy generation on a global level due to the higher costs of current technology and significant variation in the quality of the resource on an inter-annual level. In many countries, utility scale solar PV is currently highly competitive with conventional forms of energy generation on a global level, especially in countries with higher solar irradiation. This is demonstrated well in the Indian market where prices for solar PV have been decreasing substantially since the last couple of years [135], which could result in solar PV by far the least cost electricity even before 2020 at the given rate of decline [136].

Conventional fuels

Fossil fuel based energy generation currently appears relatively low in cost due to a low cost of GHG emissions imposed by many global markets which does not represent the real damage of those emissions. Coal 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, higher full load hours generally seen in gas turbine plants are a major contributor to higher LCOE. CCS technology appears very high in cost at the moment and does not represent an economically competitive option in the near term. Nuclear power appears relatively lower in cost 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 risks are included. In the case of France, where there are considerations of refurbishment investments to old nuclear power plants which could cost up to 100 b€ until 2030 [137], this indicates that costs of nuclear power generation will further increase in comparison to the rapid decline in power generation costs from renewables. The competition of low cost solar PV and wind plants already led to earlier than possible shut down decisions in the USA [138].

Trends for 2030

Renewables

Renewable energy technologies offer the lowest LCOE ranges globally in 2030. Utility scale solar PV generally shows the lowest values (16 to 117 €/MWh_{el}), 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 (16 to 90 €/MWh_{el} excluding Indonesia). This is the case in several countries at higher northern latitudes. Rooftop solar PV generally offers the next lowest LCOE (31 to 126 €/MWh_{el}), followed by offshore wind power. 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 on a utility scale (21 to 165 €/MWh_{el}) with overall market costs of electricity depending on local costs, and on a residential scale (40 to 204 €/MWh_{el}) depending on consumer costs of electricity including taxes, transmission costs, and distribution costs. Interestingly, the lowest LCOE values seen for renewable energy technologies in the G20 are seen in Argentina, where solar and wind resources are exceptional.

Conventional fuels

Fossil fuel and nuclear power generation represents higher LCOE ranges on a global basis in 2030. Firstly, gas based energy generation represents the highest LCOE values. However, it must be reiterated that many of the higher range values are the result of operational conditions for gas turbine, 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 technologies have the great potential to reduce costs associated with carbon emissions and external costs by switching to more sustainable fuels, such as biogas and synthetic methane. Secondly, coal based power represents amongst the highest LCOE values globally (115 to 186 €/MWh_{el}) when CO_2 and external costs are accounted. This trend is seen on a global level. Thirdly, nuclear power shows a wide range of LCOE values globally (62 to 152 €/MWh_{el}). Low values for 2030 are seen in China and the Republic of Korea. However, it is unclear if the reported overnight costs represent subsidised values as technology 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 [27,116,139] and the averaged cost overrun for 180 reactors has been found to 117% [140]. 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 to 205 €/MWh_{el}), and the range for CCGT CCS is (102 to 179 €/MWh_{el}).

Americas

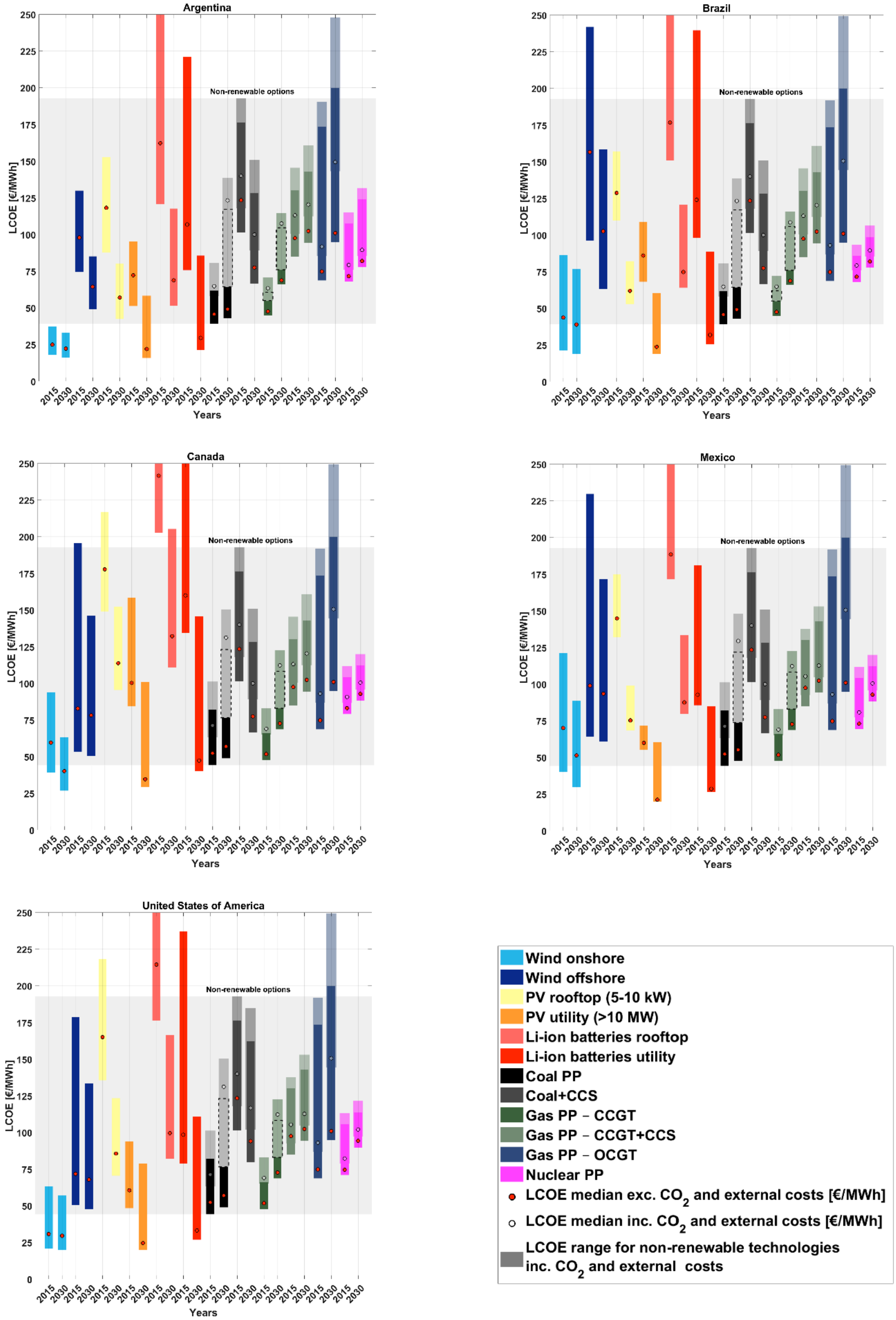


Figure 13: Results of LCOE calculations for the Americas in 2015 and 2030 (€/MWh$_{el}$).

Europe

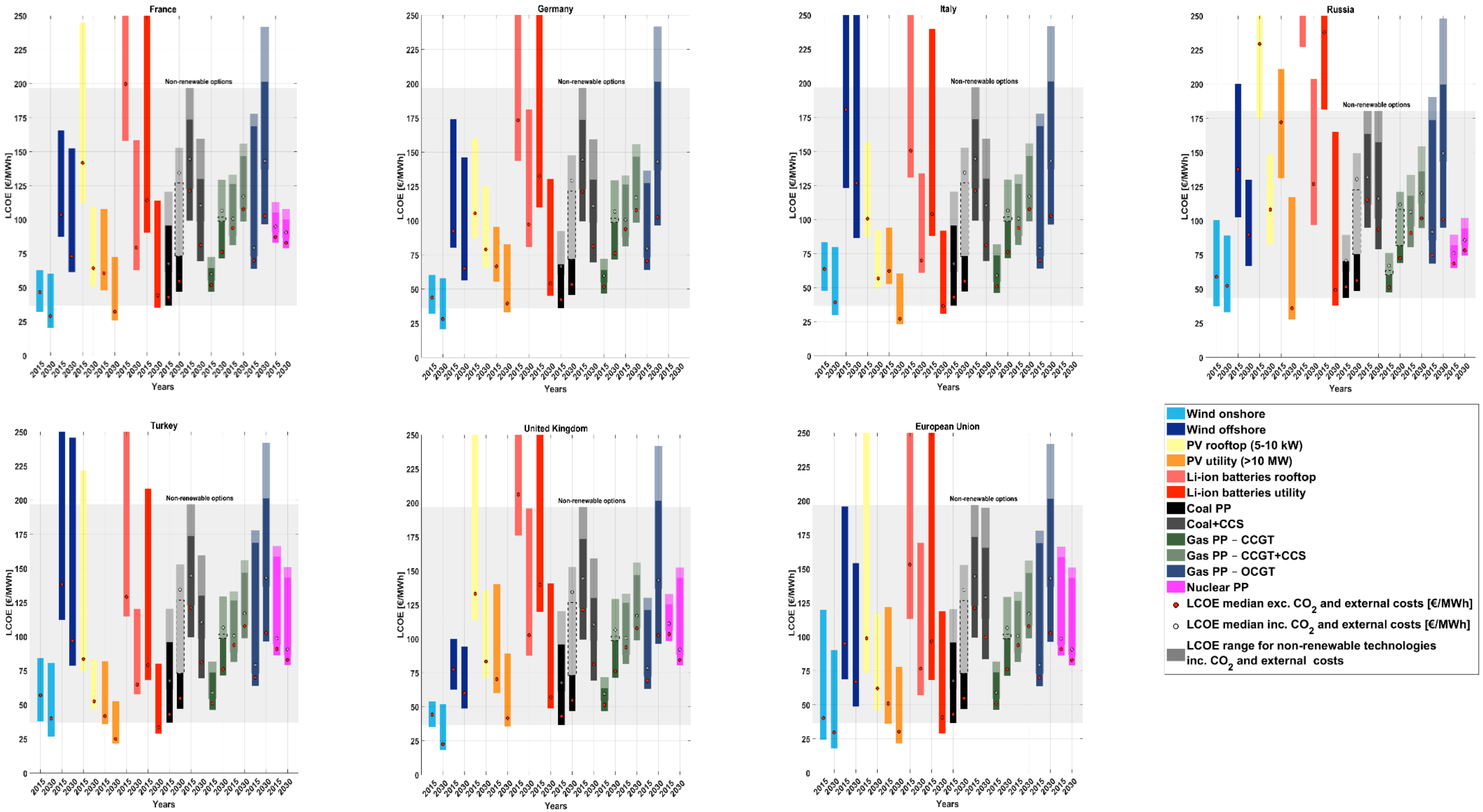


Figure 14: Results of LCOE calculations for Europe in 2015 and 2030 (€/MWh$_{el}$)

Asia

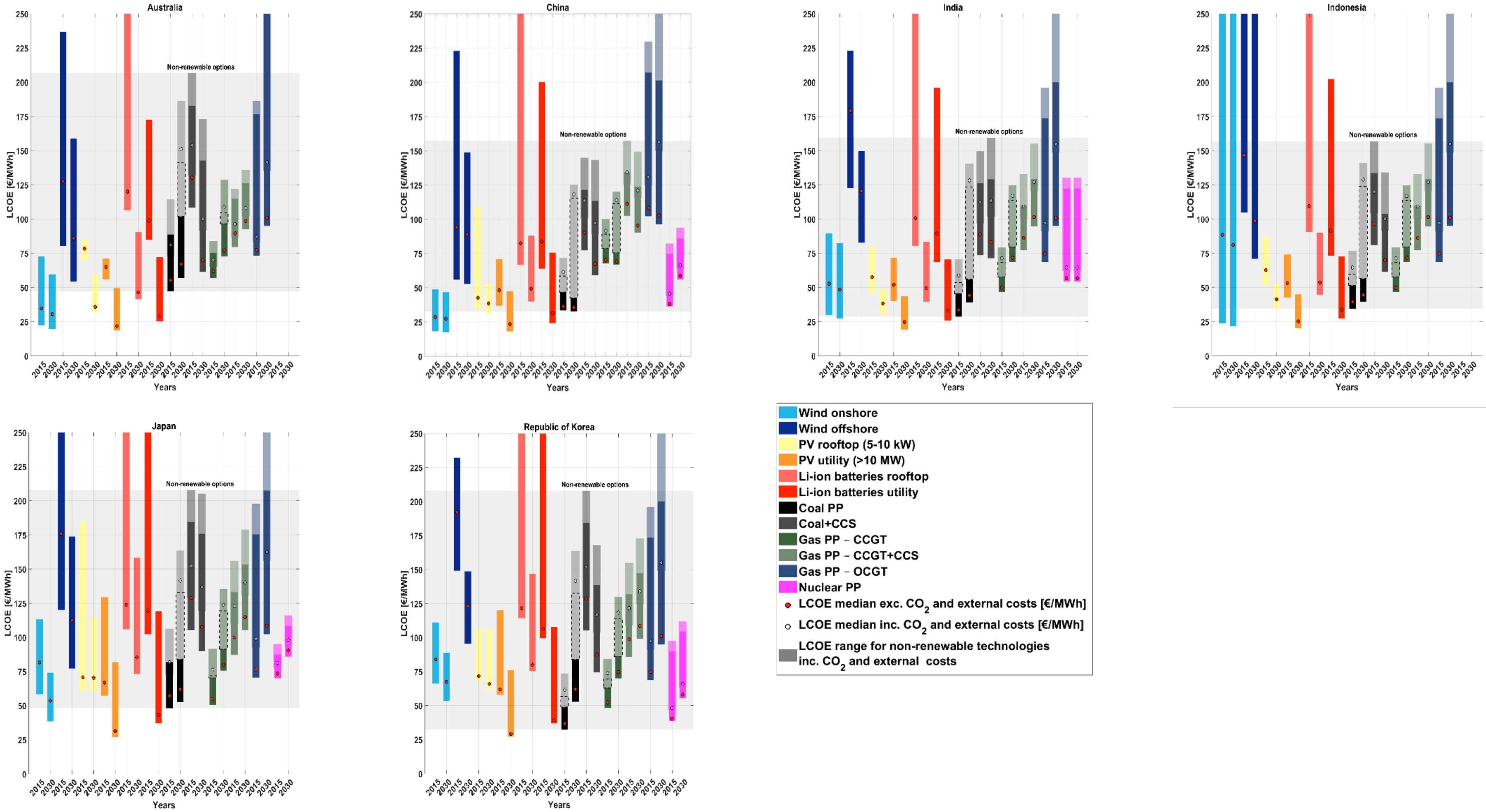


Figure 15: Results of LCOE calculations for Asia in 2015 and 2030 (€/MWh$_{el}$)

Middle East and Africa

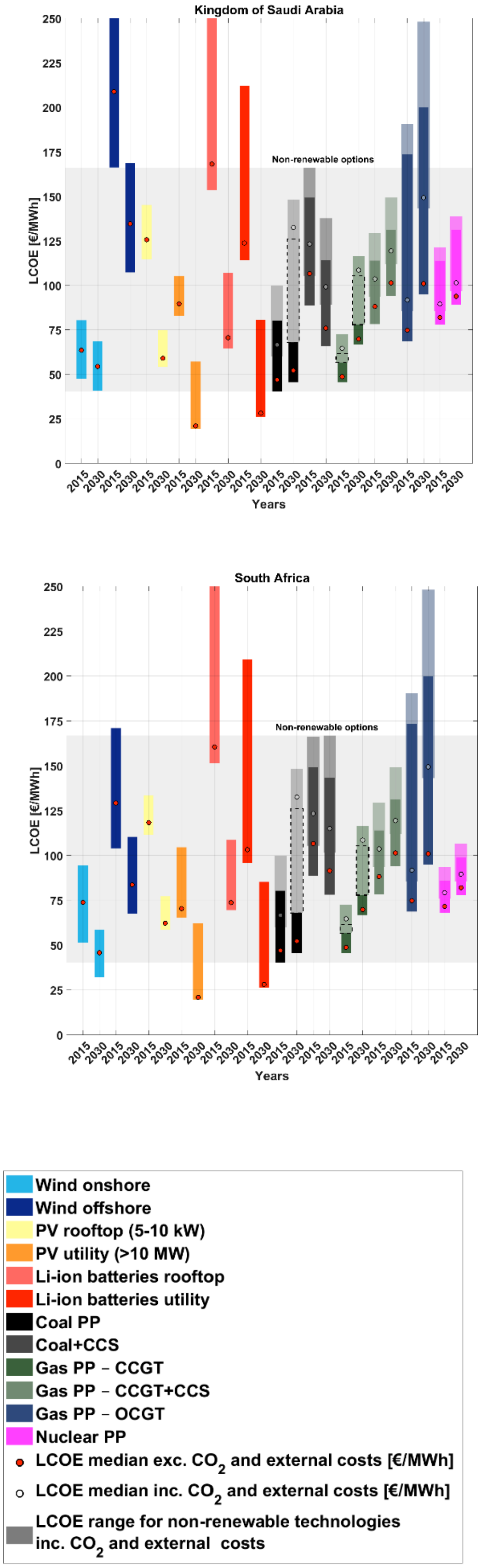


Figure 16: Results of LCOE calculations for the Middle East and Africa in 2015 and 2030 (€/MWh$_{el}$)

Implications

From the LCOE results presented in Figures 13 to 16, it is clear that RE electricity generation in several G20 countries is already lower in cost than conventional alternatives. These include the USA, Argentina, Brazil, the EU, Turkey, China and Australia. At the same time, it is expected that all G20 countries will demonstrate the full cost competitiveness of RE generation by 2030. However, it should be stressed that all countries should begin to invest in RE 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 RE capacities may be unnecessarily disruptive to electricity grids if growth is too rapid. More gradual increases in capacities over the coming decade or so can mitigate such technical disruption. Furthermore, existing industries and companies may need to adapt to the energy transition to come, and a longer transition towards 2030 may help prepare them for the task ahead. Similarly, global education systems will need to be prepared to produce future RE experts. One way to accomplish this is to involve future students, educators and tradespeople in the transition as it happens. A learning by doing approach is preferable to one which separates theory and task too greatly. Finally, eliminating external costs as soon as possible will result in improved health and well-being, particularly in countries such as India and China. 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, and it would be unwise for any to lack an appropriate sense of urgency.

Chapter 8: Policy perspectives for the low-cost power system of the future

- Concerted action by G20 countries can offer an important impetus to building a sustainable, low-cost power system for the future.
- Policymakers across the G20, while tailoring to country specific strengths and weaknesses, can initiate regulatory and fiscal measures for a coherent global energy transition that internalises the risks posed by climate change, while stepping up efforts in phasing out all fossil fuel subsidies.
- The G20 can promote measures for the integration of higher shares of renewables into power systems, enable comprehensive coupling of the electricity sector with other not-yet-electrified sectors, and promote storage technologies and electric vehicles that can create new markets for renewable electricity.

To accelerate the adoption of sustainable energy, several barriers still need attention of the global community and this section presents the measures that could be initiated by G20 countries to realise a low cost energy system until 2030. Overcoming path dependencies and vested stakes in fossil and nuclear power remains challenging worldwide and especially amongst the G20 countries. At the same time, these policies need to adapt to changing market conditions such as falling technology costs as shown earlier in the report, least cost energy in the future across all G20 countries by 2030 will be mainly from solar and wind power generation technologies.

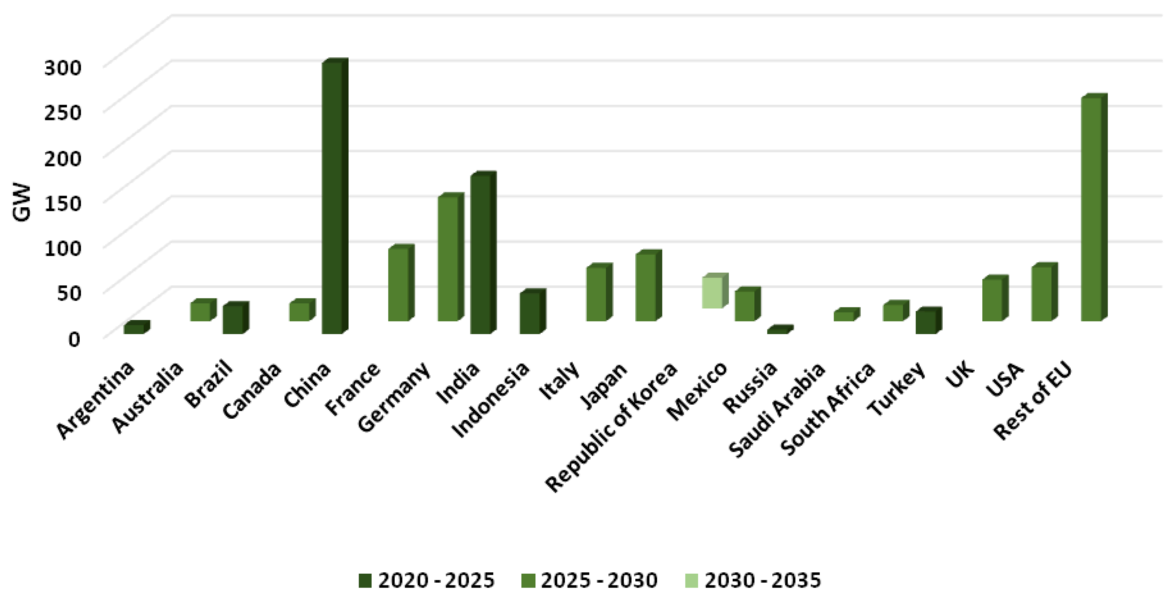


Figure 17: Renewable Power Targets of the G20 nations ranging from 2020 to 2035 [141]

Currently, all of the G20 nations have some form of renewable energy policy and plans for their development. Figure 17 shows renewable energy targets of the various G20 nations distributed according to their timeframes from 2020 until 2035. Countries that have taken measures to promote renewable energy adoption are set to take the lead in attracting investments, sustaining economic growth and creating jobs. But, to accelerate the pace of deployment in line with global sustainable development objectives, government policies will remain vital to address prevalent market-specific barriers. These barriers vary as the renewable energy sector matures.

Concerted action by G20 countries can offer an important impetus to building a sustainable and low-cost power system.

Coherent global energy transition

Competitive auctions are emerging as a potential policy tool for effective deployment in a cost-effective manner and in turn, they facilitate the decrease in technology costs globally. These auctions, often implemented jointly with other measures to incentivise renewable energy deployment, have over the past decade increased eleven-fold from six in 2005 to at least 67 countries by the end of 2016 [1]. Whether auctions can fully substitute other policy tools, such as renewable portfolio standards or feed-in tariffs, remains to be seen. Finally, each G20 country has to find its own individual set of policy tools to continuously foster renewable deployment and ensure coherence with global energy markets.

Climate risks

One of the first steps in efforts to internalise the risks posed by climate change is the full acknowledgement of these risks while making decisions related to large-scale investments, particularly in the power sector. As this is not just an environmental issue, but it is also in the economic self-interest of companies, investors, and governments to have a clear view of the financial risks presented by climate change [142]. This is particularly important in the context of power infrastructure projects, which can potentially lock-in GHG emissions over many decades, cause adverse impacts, and carry the risk of stranded assets.

Finance and Subsidy reform

In order to increase shares of investment in climate-compatible power infrastructure, countries will need to increase public expenditures and trigger market conditions necessary to attract private finance. In this context, the G20 should also build on its 2009 commitment [142] and establish deadlines for phasing out all fossil fuel subsidies and promote a net zero emission, climate-resilient development.

Integration

The growth of renewables will take place as their level of integration into the power system increases hand in hand. Specific needs vary according to the characteristics of the particular power system in a country, like the flexibility of the power mix, the robustness of the transmission and distribution systems, the availability of storage capacity, variations in demand, interconnections and dependency on power market developments in neighbouring markets, which all have cost implications [76]. Advancing capacity of new technologies that support integration would partly dependent on the ability to attract private capital from domestic and foreign resources, and G20 nations could facilitate availability of resources for such vital projects.

Sector Coupling

For G20 countries to bring the energy transition to a long-term success, efforts cannot be limited to transforming the power sector, but have to be further extended to start using renewable electricity also for heating, cooling, transport, desalination, synthetic fuels and feedstock chemicals. To unlock the full potential of renewables, converting electricity into heat/cooling, mobility or synthetic fuels will be of the utmost importance. The comprehensive coupling of the electricity sector with other, not yet electrified sectors will enable the integration of a substantially higher share of renewable energy resources, by replacing fossil fuels in households, industry and transport sectors. At the same time, sector coupling will increase energy efficiency in the energy sector as well as allow for the stronger integration of energy supply with many other sectors. Robust policies and incentive mechanisms have to be developed to enable the promotion of sector coupling practices and encouraging business models to explore this potential. In this regard many of the G20 nations can play leading roles in promoting sector coupling initiatives.

Storage and Electric Vehicles

Last year was characterised by the diversification of utilities, renewable energy companies, vehicle manufacturers and oil and gas companies into the storage industry in order to capture rapidly growing markets [7]. Beyond offering the prospect to reduce fossil fuel use in the transportation sector, electric vehicles can create a new market for renewable electricity, as they can help integrate growing quantities of renewable energy. Policies targeting both, distributed customer sited behind-the-meter storage (residential and commercial) and large-scale utility projects in front of the meter are going to play a vital role for countries to pursue a sustainable development pathway. Some of G20 countries mainly China, Germany and India have set policy directions to foster adoption of large number of electric vehicles and also completely transform the transport sector to become electric, this should have ripple effects and encourage other members of G20 to emulate.

Enhancing Cooperation

The launch of the G20's energy agenda in 2009 [13] has led to the initiation of some measures, such as establishing work streams on some of the most pressing issues, for a transition to sustainable energy: energy access, renewable energy, energy efficiency and phasing-out of fossil fuel subsidies. These are vital steps towards the implementation of SDGs and the Paris Agreement and it is, therefore, essential that the G20 deepen their engagement in all these areas. Strengthening the links to global climate mitigation efforts and embedding sustainable energy into the G20's core track on finance and economic policy could provide the necessary impetus for a strong G20 energy agenda under not only the German presidency in 2017, but for the Argentine presidency next year and subsequent presidencies in the years to follow. The progressive G20 countries should push their policies ahead, in particular in case single G20 countries refuse to cooperate.

Eventually, renewable based power is the only reasonable option, as not only is it lower in cost and more efficient but it also generates jobs and sustains economic growth. 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. It is logical from an economic perspective, an environmental perspective, a health perspective and a moral perspective.

List of Abbreviations

BAU	Business-As-Usual
BECCS	Bioenergy Carbon Capture and Storage
BEV	Battery Electric Vehicle
BNEF	Bloomberg New Energy Finance
CAES	Compressed Air Energy Storage
CBM	Coal Bed Methane
CCS	Carbon Capture and Storage
CCGT	Combined Cycle Gas Turbine
COP	Conference of the Parties
CSP	Concentrated Solar Thermal Power
DACCS	Direct Air Carbon Capture and Storage
DME	Dimethyl Ether
EU	European Union
FLH	Full Load Hours
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GPFG	Government Pension Fund Global
GW	Gigawatts
G20	Group of Twenty
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IMF	International Monetary Fund
IPCC	International Panel on Climate Change
IRENA	International Renewable Energy Agency
LCOE	Levelised Cost of Electricity
MW	Megawatt
OCGT	Open Cycle Gas Turbine
PHEV	Plug-in Hybrid Electric Vehicle
PHS	Pumped Hydroelectric Storage
PtL	Power-to-Liquids
PtX	Power-to-X
PV	Photovoltaics
RE	Renewable Energy, partly used in the sense of Renewable Electricity
SDGs	Sustainable Development Goals
SNG	Synthetic Natural Gas
TPED	Total Primary Energy Demand
TW	Terawatt
USD	Unites States Dollar
WBGU	German Advisory Council on Global Change
WEC	World Energy Council
WEO	World Energy Outlook (flagship report of the IEA)
WWF	World Wide Fund for Nature

Appendix

Detailed Methodology

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 recognized 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. 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.

The calculation of LCOE (expressed as €/MWh_{el}), representing a discounted cash flow approach for the case of constant annual cash flows, in this report is characterised by the following equation:

$$LCOE = \frac{(Capex_{Real} * crf) + Opex_{fixed} + \frac{Decommissioning\ costs}{N}}{FLH} + Opex_{variable} + LCOS$$
$$+ Fuel\ costs + Waste\ disposal\ costs + External\ costs + GHG\ costs$$

where,

$Capex_{Real}$ is annual capital expenditures (€/MW_{el}), which include a low and high estimate for investment and budget overruns; $Opex_{fixed}$ are fixed operations and maintenance costs (% of capex/year); *Decommissioning costs* are expressed as a % of capex for all technologies except nuclear power plants, for which they are expressed as a value in €/MW_{el}; N is the operational lifetime of the technology (years); $Opex_{variable}$ is the annual variable operations and maintenance costs (€/MWh_{el}); *LCOS* is the levelised cost of storage in €/MWh_{el} (see below); *Fuel costs* are expressed in €/MWh_{el}; *Waste disposal costs* are expressed in €/MWh_{el}; *External costs* (annual) include a range of socio-economic costs related to energy generation (€/MWh_{el}); *GHG costs* (annual) include the full socio-economic costs of GHG emissions. 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:

$$crf = \frac{WACC * (1 + WACC)^N}{(1 + WACC)^N - 1}$$

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 investments and a higher risk of stranded investments [143]. This risk is due to 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 [27,84,88,144], making capital more difficult to raise.

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

$$LCOS = \frac{Storage\ capacity * [(Capex_{Real} * crf) + Opex_{fixed}]}{System\ output} + \frac{Costs\ of\ battery\ losses}{System\ output}$$

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.

Capex

Overnight capital expenditures were derived from a range of internationally recognized 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 found from scientific literature to reflect the additional cost of the tracking system.

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 $Capex_{Real}$.

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 was added [128]. 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 [118,128]. For nuclear power, a low investment and overrun addition of 20% was assumed due to the longer construction time 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% [145]. 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 progressive larger over time. Currently, nuclear power plants in Finland and France seven years beyond their scheduled construction time of 5 years, and cost overruns are approximately 300% [116,139]. 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% in average and no single reactor within the planned budget had been found [146].

$Capex_{Real}$

A high and low value for $Capex_{Real}$ 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 $Capex_{Real}$ represents only the variance in the investment and overrun addition.

In three cases, values for $Capex_{Real}$ 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 $Capex_{Real}$ values for nuclear power in Argentina was based on a known cost of 5.8 bUSD for the 800 MW Atucha 3 reactor [27,134]. Interestingly, the technology provider for the Atucha 3 reactor is Chinese (CANDU), and the cost of similar projects in China are generally reported at much lower cost. 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 $Capex_{Real}$ values for China and the Republic of Korea are derived from known costs for the same technologies in other countries. The high $Capex_{Real}$ values 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 [27,134]. Likewise, the high $Capex_{Real}$ values for nuclear power in South Korea are 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. [27].

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) [147,148]. In this report 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 €/MWh_{el}.

Opex

This category is divided into fixed and variable operational and maintenance expenditures. $Opex_{fixed}$ is commonly expressed as a % 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. $Opex_{variable}$ represents costs that are directly related to the frequency and duration of plant operation. Some operations and maintenance costs, such as those related to pumps, fans and lubricating fluids, is needed only when the plant operates. In the case of batteries, a similar value to $Opex_{variable}$ is calculated based on the costs related to storage losses. These losses are a function of the energy throughput and battery efficiency.

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 [122]. 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 €/MWh_{el}. 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 [58]. 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 [124]. The competition of low cost solar PV and wind plants already led to earlier than possible shut down decisions [138]. However, the high risk profile of nuclear power plants may lead to much shorter lifetimes, due to detracted societal willingness of accepting the risk, which seems to be also well covered by liberal western constituencies, as confirmed recently by the Federal Constitutional Court of Germany [149].

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 to 2005. The procedure for estimating FLH was complex, but took into account both geographic and temporal variation of the resources. Data was derived from [150,151], 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 not 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 was limited to 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 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 would lead to higher LCOE. At the same time, this raises an important point. The LCOE for the solar PV + Battery system may not, therefore, be immediately comparable to the LCOE of the other generation technologies, but should be compared to a consumer cost of electricity in order to determine if it is low or high.

Fuel

Fuel costs were taken from projections found in Bloomberg New Energy Finance's New Energy Outlook 2015 [152] and are summarised in Table A-1.

Table A-1: Fuel cost assumptions for coal (upper) and gas (lower) in €/MWh_{th}.

BNEF	€/t		€/MWh_{th}	
	2015	2030	2015	2030
Coal Europe	45.86	64.66	5.63	7.94
Coal China	71.43	68.42	8.77	8.40
Coal India	30.08	63.91	3.69	7.85
Average			6.03	8.06

	€/MMBtu		€/MWh_{th}	
	2015	2030	2015	2030
Gas Europe	5.26	9.77	17.96	33.35
Gas Japan	6.02	10.53	20.52	35.92
Gas China	9.77	9.77	33.35	33.35
Gas USA	2.26	8.27	7.70	28.22
Average			19.88	32.71

A cost of 5.26 €/MWh_{el} for nuclear fuel [118] 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/MWh_{el}, and may vary by ±1 €/MWh_{el} globally.

Waste disposal

Waste disposal costs were considered only for nuclear power plants and were derived directly from the IEA [128]. This source reported values for each country in 2015 which included both fuel and waste disposal costs. The waste disposal cost was determined after subtracting the above fuel costs. Values reflect the economic difficulty that some countries have in safely disposing of nuclear waste (Japan, the USA and the UK).

External costs

A comprehensive review by Climate Advisers [125] of the total social cost of different forms of electricity generation determined that the work of Rafaj and Kypreos [99] 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 A-2 below. Note that values do not include external costs related to CO_2 emissions, which will be explained in the next section.

Table A-2: External costs of electricity generation excluding CO_2 costs used for LCOE calculations. From [99]. 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. EEFSU includes all Eastern European and Former Soviet Union countries. LAFM includes countries of Latin America, Africa and the Middle East.

	ASIA €/MWh_{el}	OECD €/MWh_{el}	NAME €/MWh_{el}	EEFSU €/MWh_{el}	LAFM €/MWh_{el}
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

GHG emission costs

For CO_2 emissions, a range of costs exist that represent the cost of a ton of emissions. Some of these are market based, while others are politically determined. In this report, a value of 7 €/ton of CO_{2eq} was assumed based on the market value of carbon in the EU for the year 2015. For 2030, a value of 74 €/ton of CO_{2eq} was assumed based on estimates of the social cost of carbon by the Stern Review [153]. This cost is assumed to represent the social cost of carbon based on the criteria presented in Table A-2. The recent report of the High-Level Commission on carbon price confirms CO_{2eq} emission costs of up to 74 €/ton of CO_{2eq} for the year 2030 [154]. However, it should be noted that there are a range of estimates related to the actual cost of carbon from 30 to 165 €/ton of CO_{2eq} [155].

Determining a single, universally acceptable value for GHG emissions is an impossible task, which often leads to confusion of 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 has a major role. The Stern Review [153] was amongst the first influential publications to place a social cost on carbon. This was set at 85 USD_{2007} per ton (74 €$_{2015}$/ton of CO_{2eq}) 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 carbon, even the social cost, is not static. Instead, we must accept that the cost will be higher as global atmospheric concentrations increase. What is more, a recent study [155] 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 carbon could be much higher – up to 220 USD/ton (165 €/ton of CO_{2eq}) [155].

Other technical assumptions

Wind onshore

- FLH based on power curve of a 3 MW onshore wind turbine: Enercon E101, hub height 150 m

Wind offshore

- FLH based on power curve of 3.6 MW offshore wind turbine: Siemens SWT-3.6-120, hub height 100 m

PV rooftop

- Based on scale of 5 kW_p

PV utility

- Based on scale of 50 MW_p

Li-ion batteries

- Based on power capacity of 1-3 MW and storage capacity of 0.5-1.2 MWh for utility-scale

Coal PP

- Based on supercritical, pulverised coal condensing power plant burning black coal; plant efficiency based on lower heating value

CCGT PP

- Based on combined cycle gas turbine of up to 580 MW (net); plant efficiency based on lower heating value of fuel

OCGT PP

- Based on advanced open cycle gas turbine of up to 250 MW (net); plant efficiency based on lower heating value of fuel

CCS

- Based on post-combustion capture; plant efficiency based on lower heating value of fuel

Nuclear PP

- Based on advanced light water reactor technologies in the range of 1000 to 3300 MW; plant efficiency based on lower heating value of fuel

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