IRENA
International Renewable Energy Agency




TURNING TO RENEWABLES: CLIMATE-SAFE ENERGY SOLUTIONS

#Renewables4Climate

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

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About this publication

This publication brings together four briefs prepared by IRENA for COP23, the 23rd Conferences of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC), which took place in Bonn, Germany, on 6-17 November 2017. The IRENA Coalition for Action helped to bring partners and stakeholders together through "#Renewables4Climate", a global initiative to raise awareness about renewable energy as a key solution to climate change.

For further information or to provide feedback: publications@irena.org

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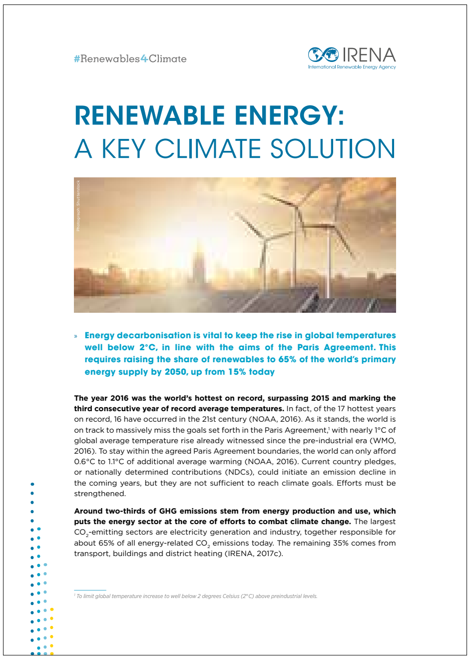
INTRODUCTION

The Paris Agreement has called for reducing carbon emissions worldwide. But to sufficiently limit the rise in global temperatures, energy use would have to be completely decarbonised in less than 50 years, even amid the expected tripling of the world's economy by 2060. This means renewable energy – already growing fast over the past decade – must grow at least seven times faster.

This set of briefs, prepared by the International Renewable Energy Agency (IRENA), highlights challenges and opportunities as the world seeks climate-safe energy solutions. IRENA produced the four briefs for **COP23** – the 23rd Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC), held in Bonn, Germany on 6-17 November 2017.



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RENEWABLE ENERGY:
A KEY CLIMATE SOLUTION

» **Energy decarbonisation is vital to keep the rise in global temperatures well below 2°C, in line with the aims of the Paris Agreement. This requires raising the share of renewables to 65% of the world's primary energy supply by 2050, up from 15% today**

The year 2016 was the world's hottest on record, surpassing 2015 and marking the third consecutive year of record average temperatures. In fact, of the 17 hottest years on record, 16 have occurred in the 21st century (NOAA, 2016). As it stands, the world is on track to massively miss the goals set forth in the Paris Agreement,[1] with nearly 1°C of global average temperature rise already witnessed since the pre-industrial era (WMO, 2016). To stay within the agreed Paris Agreement boundaries, the world can only afford 0.6°C to 1.1°C of additional average warming (NOAA, 2016). Current country pledges, or nationally determined contributions (NDCs), could initiate an emission decline in the coming years, but they are not sufficient to reach climate goals. Efforts must be strengthened.

Around two-thirds of GHG emissions stem from energy production and use, which puts the energy sector at the core of efforts to combat climate change. The largest CO_2-emitting sectors are electricity generation and industry, together responsible for about 65% of all energy-related CO_2 emissions today. The remaining 35% comes from transport, buildings and district heating (IRENA, 2017c).

[1] *To limit global temperature increase to well below 2 degrees Celsius (2°C) above preindustrial levels.*

A combination of renewables and energy efficiency measures will be essential to keep the temperature rise "well below 2°C" (as per the Paris Agreement). To meet this essential goal, renewables must grow to 65% of global energy supply by 2050, compared to the current 15%, IRENA's analysis indicates. Around two-thirds of current greenhouse emissions stem from energy production and use, making decarbonisation in this sector crucial to meeting international climate goals. The first brief in the set looks more closely at the challenge of **energy decarbonisation**.

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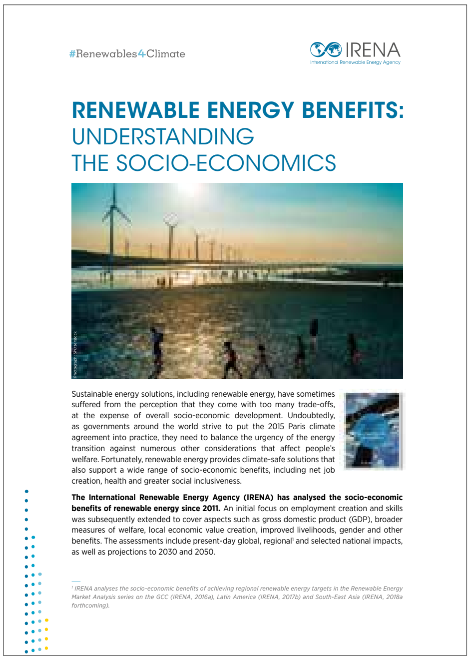

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RENEWABLE ENERGY BENEFITS:
UNDERSTANDING
THE SOCIO-ECONOMICS

Sustainable energy solutions, including renewable energy, have sometimes suffered from the perception that they come with too many trade-offs, at the expense of overall socio-economic development. Undoubtedly, as governments around the world strive to put the 2015 Paris climate agreement into practice, they need to balance the urgency of the energy transition against numerous other considerations that affect people's welfare. Fortunately, renewable energy provides climate-safe solutions that also support a wide range of socio-economic benefits, including net job creation, health and greater social inclusiveness.

The International Renewable Energy Agency (IRENA) has analysed the socio-economic benefits of renewable energy since 2011. An initial focus on employment creation and skills was subsequently extended to cover aspects such as gross domestic product (GDP), broader measures of welfare, local economic value creation, improved livelihoods, gender and other benefits. The assessments include present-day global, regional[1] and selected national impacts, as well as projections to 2030 and 2050.

[1] *IRENA analyses the socio-economic benefits of achieving regional renewable energy targets in the Renewable Energy Market Analysis series on the GCC (IRENA, 2016a), Latin America (IRENA, 2017b) and South-East Asia (IRENA, 2018a forthcoming).*

Governments around the world need to balance the urgency of the energy transition against numerous other considerations that affect people's welfare. Fortunately, renewable energy provides climate-safe solutions that also support a wide range of socio-economic benefits, including net job creation, health and greater social inclusiveness. The second brief in the set outlines IRENA's analysis of **socio-economic benefits**.

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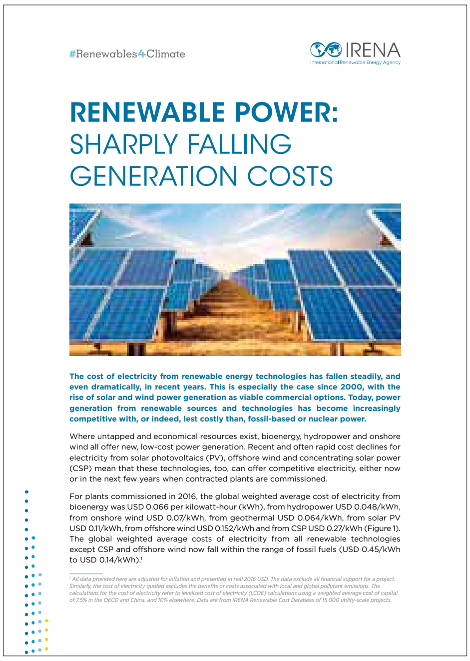

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RENEWABLE POWER:
SHARPLY FALLING GENERATION COSTS

The cost of electricity from renewable energy technologies has fallen steadily, and even dramatically, in recent years. This is especially the case since 2000, with the rise of solar and wind power generation as viable commercial options. Today, power generation from renewable sources and technologies has become increasingly competitive with, or indeed, lest costly than, fossil-based or nuclear power.

Where untapped and economical resources exist, bioenergy, hydropower and onshore wind all offer new, low-cost power generation. Recent and often rapid cost declines for electricity from solar photovoltaics (PV), offshore wind and concentrating solar power (CSP) mean that these technologies, too, can offer competitive electricity, either now or in the next few years when contracted plants are commissioned.

For plants commissioned in 2016, the global weighted average cost of electricity from bioenergy was USD 0.066 per kilowatt-hour (kWh), from hydropower USD 0.048/kWh, from onshore wind USD 0.07/kWh, from geothermal USD 0.064/kWh, from solar PV USD 0.11/kWh, from offshore wind USD 0.152/kWh and from CSP USD 0.27/kWh (Figure 1). The global weighted average costs of electricity from all renewable technologies except CSP and offshore wind now fall within the range of fossil fuels (USD 0.45/kWh to USD 0.14/kWh).[1]

[1] All data provided here are adjusted for inflation and presented in real 2016 USD. The data exclude all financial support for a project. Similarly, the cost of electricity quoted excludes the benefits or costs associated with local and global pollutant emissions. The calculations for the cost of electricity refer to levelised cost of electricity (LCOE) calculations using a weighted average cost of capital of 7.5% in the OECD and China, and 10% elsewhere. Data are from IRENA Renewable Cost Database of 15 000 utility-scale projects.

Meanwhile, the cost of electricity from renewable energy technologies has fallen steadily, and even dramatically, in recent years. This is especially the case since 2000, with the rise of solar and wind power generation as viable commercial options. Today, power generation from renewable sources and technologies has become increasingly competitive with, or indeed, lest costly than, fossil-based or nuclear power. A third brief looks more closely at renewable energy's **sharply falling costs**.

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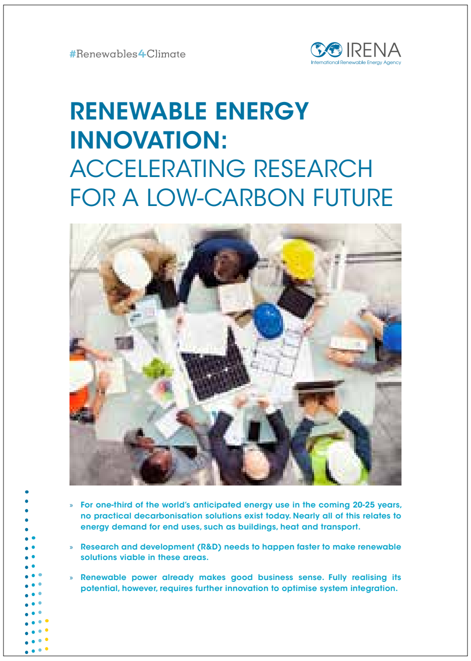

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RENEWABLE ENERGY INNOVATION:
ACCELERATING RESEARCH FOR A LOW-CARBON FUTURE

- For one-third of the world's anticipated energy use in the coming 20-25 years, no practical decarbonisation solutions exist today. Nearly all of this relates to energy demand for end uses, such as buildings, heat and transport.
- Research and development (R&D) needs to happen faster to make renewable solutions viable in these areas.
- Renewable power already makes good business sense. Fully realising its potential, however, requires further innovation to optimise system integration.

Even so, for one-third of the world's anticipated energy use in the coming 20-25 years, no practical decarbonisation solutions currently exist. Research and development (R&D) needs to happen faster, particularly to make renewable energy viable for a wider range of end uses in buildings, heat and transport. Renewable power also requires further innovation to optimise system integration. The final brief in the set highlights the need for **accelerating research**.

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Photograph: Shutterstock

BRIEF 1:
A KEY CLIMATE SOLUTION

» **Energy decarbonisation is vital to keep the rise in global temperatures well below 2°C, in line with the aims of the Paris Agreement. This requires raising the share of renewables to 65% of the world's primary energy supply by 2050, up from 15% today**

The year 2016 was the world's hottest on record, surpassing 2015 and marking the third consecutive year of record average temperatures. In fact, of the 17 hottest years on record, 16 have occurred in the 21st century (NOAA, 2016). As it stands, the world is on track to massively miss the goals set forth in the Paris Agreement,[1] with nearly 1°C of global average temperature rise already witnessed since the pre-industrial era (WMO, 2016). To stay within the agreed Paris Agreement boundaries, the world can only afford 0.6°C to 1.1°C of additional average warming (NOAA, 2016). Current country pledges, or nationally determined contributions (NDCs), could initiate an emission decline in the coming years, but they are not sufficient to reach climate goals. Efforts must be strengthened.

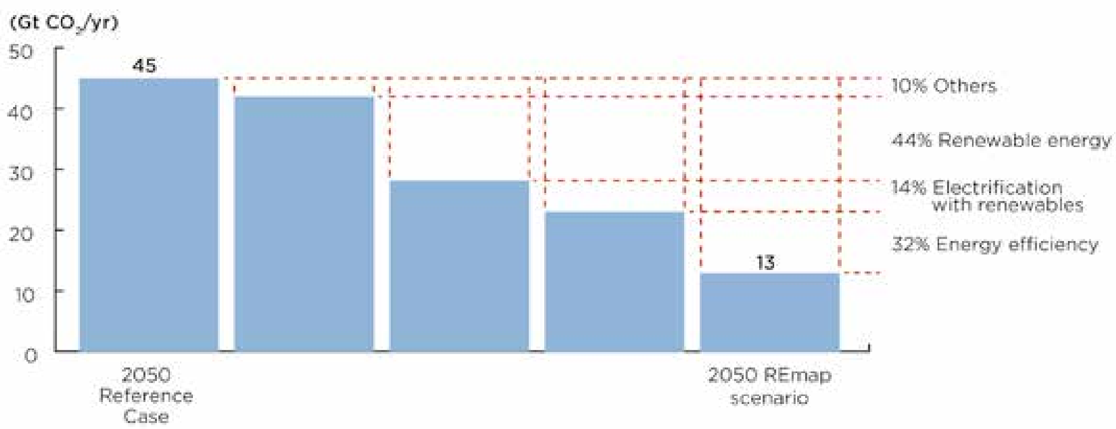
Around two-thirds of GHG emissions stem from energy production and use, which puts the energy sector at the core of efforts to combat climate change. The largest CO_2-emitting sectors are electricity generation and industry, together responsible for about 65% of all energy-related CO_2 emissions today. The remaining 35% comes from transport, buildings and district heating (IRENA, 2017c).

[1] *To limit global temperature increase to well below 2 degrees Celsius (2°C) above preindustrial levels.*

The energy sector needs a total overhaul, with a transformation from fossil-based to zero-carbon energy production by the second half of this century. Today, 84% of energy use comes from fossil fuels, with 16% derived from renewables (IRENA, 2017c). Analysis by the International Renewable Energy Agency (IRENA) shows how, through accelerated uptake, 65% of energy use could come from renewables by 2050. This would be enough for countries to meet the Paris Agreement climate goals. Renewable energy currently represents about 25% of global electricity generation, with the rest generated by fossil fuels, according to IRENA's global energy roadmap, known as "REmap". Around 80% of all electricity in 2050 could be generated by renewable energy (IRENA, 2017c).

The transformation to a sustainable energy system with high shares of renewables would meet climate goals and pay for itself. It would lead to USD trillions in economic growth between now and 2050, and the health, environmental and climate benefits would save up to six times more than the additional costs associated with reconfiguring the energy sector, all while creating millions of jobs in the process (IRENA, 2017c).

Figure 1: CO_2 emissions reduction potential from all sectors under current plans and policies vs. accelerated uptake of renewables in 2050



Notes: Gt = gigatonnes; yr = year. CO_2 emissions include energy-related emissions (fossil fuel, waste, gas flaring) and process emissions from industry. If only fossil fuel emissions were displayed in this figure, CO_2 emissions would start from 32 Gt in 2015 and would reach 40.5 Gt and 9.5 Gt per year in 2050 in the Reference Case and REmap, respectively. The Reference Case (also called the baseline or business-as-usual), is the most likely case based on current and planned policies and expected market developments. It reflects NDCs if they are already an integral part of a country's energy plan, which is the case for around 60% of total global primary energy supply. The 2050 REmap scenario is a low-carbon technology pathway that goes beyond the Reference Case for an energy transition in line with the aims of the Paris Agreement. [2]

Accelerated deployment of renewable energy and energy efficiency measures form the key elements of the energy transition. Recent analysis shows that the world can meet around 90% of the decarbonisation needed to stay within the Paris Agreement boundaries through accelerated deployment of renewable energy and energy efficiency, with the remaining 10% to be met by other low-carbon solutions (IRENA, 2017c).

[2] Technologies covered under REmap include: renewable energy technologies for energy and as feedstock for production of chemicals and polymers; energy efficiency measures and widespread electrification that also improves efficiency; carbon capture and storage for industry; material efficiency technologies such as recycling.

Energy-related CO_2 emissions from all sectors totalled 36 Gt in 2015. These need to fall to 13 Gt in 2050 to achieve the REmap scenario, a reduction of 70% compared to the Reference Case, under which emissions are estimated to reach 45 Gt in 2050. Renewable energy could provide 44% of these reductions (20 Gt per year in 2050), as illustrated in Figure 1. To enable this dramatic emissions reduction, the share of renewable energy must rise from around 16% of the primary energy supply in 2015 to around 65% in 2050.

Renewable technologies could generate more than 80% of all electricity by 2050, with the remaining 20% generated by natural gas and nuclear. By 2050, emissions from electricity generation would plummet by 85% in the REmap scenario, despite the fact that electricity generation is expected to increase by nearly 80% (IRENA, 2017c).[3] Coal-based power generation would cease altogether. Besides increasing shares of renewables, the decrease in power sector emissions is also due to energy efficiency measures taken in industry and buildings to reduce electricity use for heating and cooling. Emissions in the buildings sector would decrease by about 70% by 2050. Transport emissions would be halved, while industry would become the largest emitter of CO_2.

» **Two-thirds of global greenhouse gas (GHG) emissions stem from the production and use of energy. This puts the energy sector at the core of efforts to combat climate change**

The current electricity system evolved over many decades with fossil fuels at the centre. New power generation technologies require a new electricity system that is flexible and allows the integration of variable sources, such as solar and wind energy. Electricity generation from these variable renewables fluctuates according to resource availability and may not coincide with demand. This can cause difficulties in matching supply and demand, requiring flexibility to deal with variability. A range of flexibility options exist and will be needed as the role of variable renewables grows.

Under REmap, the share of wind and solar in power generation would increase to 52% by 2050, requiring a range of flexibility options to ensure grid stability, including time-of-use electricity pricing, adaptation of market designs and new business models. Additional interconnectors, flexible fossil fuel generation and demand-side response can also increase flexibility, thus enabling higher shares of variable renewable energy. An often-discussed flexibility option is storage, which comes in many forms. Today, around 4 700 gigawatt hours (GWh) of electricity storage exists, 96% of which comes from pumped hydro (IRENA, 2017b). Under REmap, 11 900-15 300 GWh of electricity storage is expected by 2030, with only 51% from pumped hydro.[4] With an average battery pack of 50 kilowatt hours (kWh) per vehicle, electric vehicles alone could provide about 8 000 GWh of battery storage by 2030.

[3] Electricity generation is anticipated to increase to 43 000 terawatt hours (TWh) per year by 2050, up from 24 100 TWh in 2015.
[4] Reference Case estimates 6 600-7 800 GWh of storage by 2030.

This would help to accommodate higher shares of wind and solar through flexible charging, when there is surplus generation and electricity prices are low. To achieve the conditions needed for electric vehicles to provide significant benefits to electric power systems by 2030, IRENA estimates that 160 million electric vehicles will be needed worldwide by then (IRENA, 2017a).

While the power sector holds great potential for renewables, electricity accounts only for around 20% of final energy use today. As a result, IRENA analysis points to an essential role for renewable energy technology deployment in end-use sectors. Such a role is especially important because together they account for approximately 80% of all global energy demand today. In the end-use sectors, REmap shows that the renewable energy share can grow to 78% in buildings, 38% in industry and 53% in transport by 2050 (IRENA, 2017c).[5] In transport, the number of electric vehicles needs to grow and new solutions will need to be developed for freight and aviation. New buildings will have to meet the highest efficiency standards, while existing buildings must be rapidly renovated. Buildings and city designs should facilitate renewable energy integration.

The energy transition can fuel economic growth and create new employment opportunities. The renewable energy sector alone could support around 26 million jobs in 2050,[6] with new job creation in renewables and energy efficiency more than offsetting job losses in the conventional energy sector (IRENA, 2017d). In fact, net energy sector employment in the REmap scenario (including in energy efficiency) would be higher by 6 million additional workers in 2050 compared to the Reference Case (IRENA, 2017c). Furthermore, global GDP would be 0.8% higher in 2050 compared to the Reference Case, a cumulative gain of USD 19 trillion from 2015 to 2050.[7] This overall improvement in GDP would induce additional job creation in other economic sectors as well.

The energy transition is technically and economically feasible. Drastic cost reductions have been instrumental in the unprecedented scale-up of renewable energy we are currently witnessing. Among the most transformative developments of the current decade has been the dramatic and sustained improvement in the cost-competitiveness of renewable electricity generation technologies. Technology learning and the opening up of new markets in countries with high resource potential continue to make renewables increasingly attractive.

» Nine-tenths of the necessary emissions reduction can be achieved through accelerated uptake of renewables and energy efficiency

Since the end of 2009, solar photovoltaic (PV) module prices have fallen by around 80% and the price of wind turbines by 30-40% (IRENA, 2016). Biomass for power, hydropower, geothermal and onshore wind technologies can all now provide electricity that is competitively priced compared to fossil fuel-fired electricity generation. The levelised cost of electricity from solar PV fell by more than 68% between 2010 and

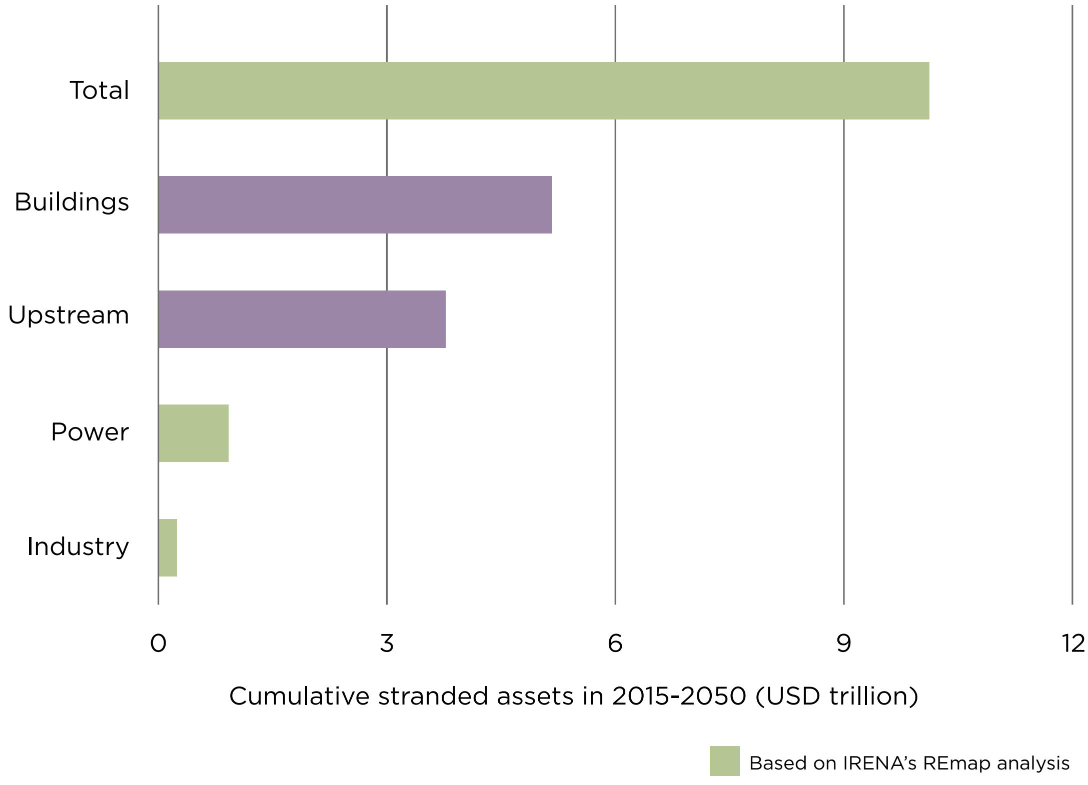
[5] Including the use of electricity and district heat sourced from renewables.
[6] Up from 9.8 million today.
[7] The main driver of the global economic surge is the investment boost from the high capital requirements of renewables and energy efficiency. Upfront investment constitutes, for both, a larger share of total lifetime cost than it does for fossil fuel-based technologies.

2016, meaning it is also increasingly competitive with conventional power generation technologies at utility scale. Onshore wind has witnessed an 18% decline in its levelised cost of electricity since 2010, while offshore wind has seen a 9% decline over the same period. IRENA analysis predicts further substantial cost reductions in the coming decade (IRENA, 2016).

Cost reductions have opened the door to an energy transition that makes economic sense. Early action, however, is essential to capitalise on the economic opportunities available while avoiding the future costs of stranded assets. Delayed policy action would result in significant asset stranding in comparison to an energy transition where accelerated renewable energy and energy efficiency deployment begins today.

Early action is critical to reduce the stranding of economically valuable assets.[8] Delaying decarbonisation of the energy sector would require higher levels of investment to achieve the same objectives and would double stranded assets. In the REmap scenario, cumulative stranded assets from 2015 to 2050 would total USD 10 trillion, coming largely from buildings that need to be replaced because of low energy efficiency, and upstream energy infrastructure and assets (gas, oil and coal that must stay in the ground). This would double to USD 20 trillion to reach the same emissions objective by 2050 if effective mitigation policy was delayed by only one decade (IRENA, 2017e). To put this into context, USD 20 trillion is approximately 4% of global wealth in 2015 terms.[9]

Figure 2 Buildings and upstream fossil reserves and infrastructure will form the lion's share of assets stranded in the energy transformation



[8] *Assets that have become obsolete or non-performing, but must be recorded on the balance sheet as a loss of profit.*
[9] *Estimated at USD 250 trillion (Credit Suisse, 2015).*

The buildings sector will be the most affected, experiencing the largest amount of asset stranding on a global scale, at approximately USD 5 trillion under REmap. Upstream energy is the second-largest sector by size of stranded assets, at approximately USD 4 trillion under REmap. In order to avoid stranded assets by accelerating the deployment of renewables and energy efficiency, as envisaged under REmap, sectors will require appropriately low-cost and long-duration financing to realise the required investments and retrofits. Without this finance, delayed action is more likely to prevail, whether there are strong macroeconomic incentives to make such investments or not (IRENA, 2017e).

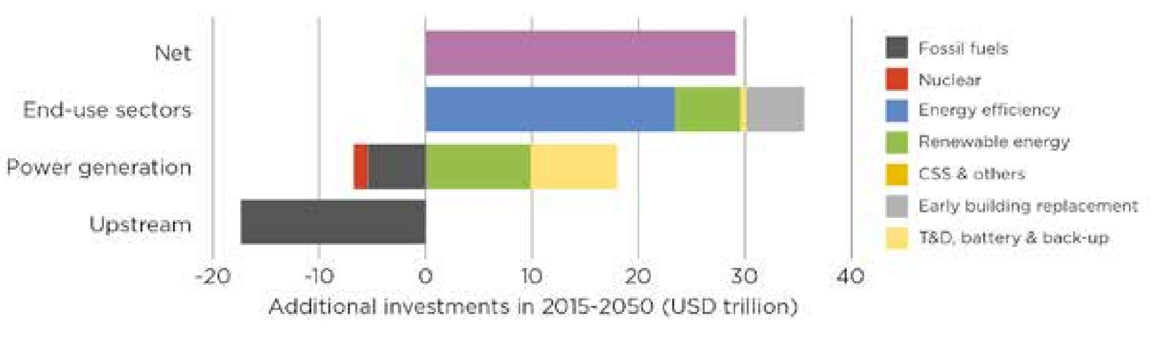
» **The resulting energy transformation would boost global gross domestic product (GDP) by 0.8% in 2050 – a cumulative gain of USD 19 trillion in the period 2015-2050**

The benefits of the energy transition for human health can also be expressed in monetary terms. Reducing human health impacts and CO_2 emissions from the combustion of fossil fuels would save between two and six times more than the costs of decarbonisation, which are estimated at USD 1.8 trillion per year in 2050 (IRENA, 2017c). Reduced outdoor air pollution accounts for two-thirds of the benefits. These numbers demonstrate that investment in decarbonisation would pay for itself purely from the human health benefits, leaving aside the further benefits of reduced climate-related impacts. Welfare gains to society could also come from increased energy access, helping to generate sustainable livelihoods and better quality of life in rural areas.

Realising the energy transition requires increased innovation and investment, along with new business models and market designs. Innovations must be shared, perfected and widely replicated by others. International collaboration can accelerate innovation through increased research and development (R&D) and investment in clean energy. In particular, greater attention needs to be paid to end-use sectors (buildings, industry and transport), where important opportunities exist.

Innovation and the accelerated deployment of low-cost renewable energy, energy efficiency, widespread electrification and information and communications technologies are essential to accelerating this energy transition. Investments made in power generation equipment and related infrastructure today, as well as over the coming decades, are going to have to bring deep emissions cuts by 2050. This is especially true for long-lived investments, such as in buildings, industrial production facilities, power plants, transport infrastructure and others. Otherwise, the risks of continued carbon lock-in will be high. Transport and industry will be the two most challenging sectors, with substantial investment and innovation required.

Figure 3: Additional investment needs for the energy transition compared to current plans and policies



Notes: These components add up to additional investment of USD 54 trillion. However, there are also avoided investments in both fossil fuel and nuclear electricity generation capacity, as well as in the upstream sector (exploration and production steps in the fossil fuel supply chain). Those avoided investments add up to USD 25 trillion, resulting in net investment of USD 29 trillion. T&D = transmission and distribution.

Net additional investment needs for the energy transition are estimated at around USD 29 trillion between 2015 and 2050, on average about USD 830 billion per year. While investment in power generation and upstream fuel supply remains at the same level, additional investment is concentrated in the end-use sectors. Additional R&D efforts in renewables will bring down further the cost of zero-carbon technologies and decrease the overall cost of decarbonisation. Unfortunately, R&D investment in renewable energy technologies has not grown in the last seven years. Moreover, most R&D investment in renewables continues to focus on power sector technologies (such as solar and wind) rather than on technologies for end-use sectors (such as biofuels and biomass), where they are urgently needed. To enable the energy transition, higher R&D investment is needed to find technology solutions for sectors where more innovation is required, such as end use. While overall energy investment requirements are substantial, net positive impacts go beyond the energy sector, from human health and wellbeing, to employment growth in related industries and overall economic growth (IRENA, 2017c).

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BRIEF 2:
UNDERSTANDING THE SOCIO-ECONOMICS

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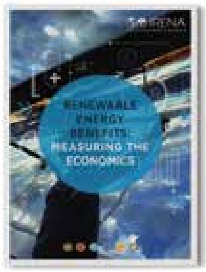
Sustainable energy solutions, including renewable energy, have sometimes suffered from the perception that they come with too many trade-offs, at the expense of overall socio-economic development. Undoubtedly, as governments around the world strive to put the 2015 Paris climate agreement into practice, they need to balance the urgency of the energy transition against numerous other considerations that affect people's welfare. Fortunately, renewable energy provides climate-safe solutions that also support a wide range of socio-economic benefits, including net job creation, health and greater social inclusiveness.



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[1] IRENA analyses the socio-economic benefits of achieving regional renewable energy targets in the Renewable Energy Market Analysis series on the GCC (IRENA, 2016a), Latin America (IRENA, 2017b) and South-East Asia (IRENA, 2018a forthcoming).

IMPACTS ON GLOBAL GDP AND WELFARE

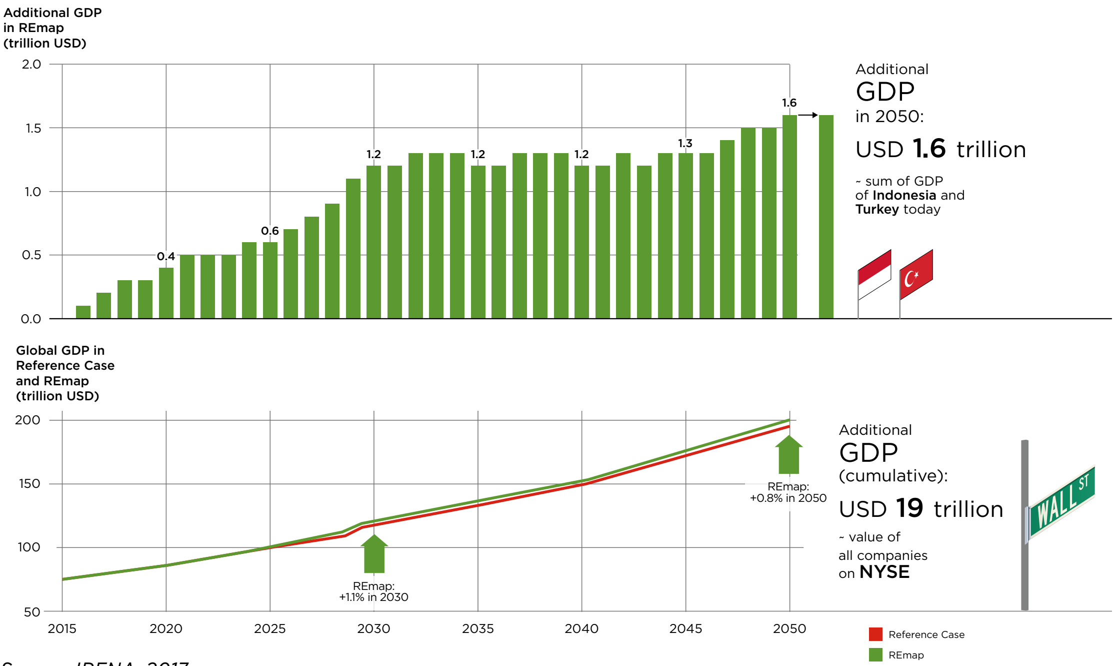
In addition to supporting climate stabilisation goals, a significant uptake of renewables and energy efficiency measures offers important macroeconomic benefits. In the analysis prepared under the German G20 Presidency, IRENA found that reducing global carbon dioxide emissions in line with the Paris Agreement would boost GDP by 0.8% in 2050, relative to a reference case (IRENA, 2017a). This translates into a cumulative gain of USD 19 trillion, roughly equivalent to the combined market capitalisation of all companies listed on the New York Stock Exchange (see Figure 1). The increase in economic activity is stimulated by the investment in renewables and energy efficiency as well as by enabling policies, including carbon pricing and the recycling of revenues from reduced income taxes.

However, indicators such as GDP alone do not capture the full spectrum of human welfare gains. A fuller accounting of benefits includes dimensions such as employment, health, education, reduced greenhouse gas emissions and changes in material consumption (see Figure 2).

Most immediately, welfare gains are the result of reduced negative externalities such as pressure on ecosystems (less mining of coal and less drilling for oil and gas) and impacts on human health (lower exposure to air and water pollutants stemming from fossil-fuel use). In addition, there are positive social impacts in the form of employment and income gains.

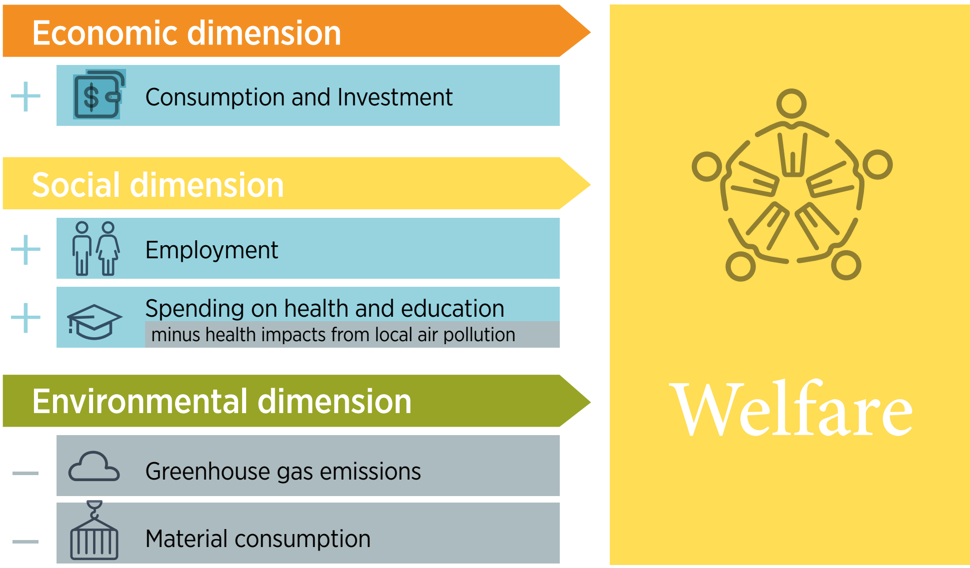
Increasingly, the deployment of renewable energy is recognised as a tremendous opportunity that helps to diversify a country's skill base, boost its industrial development and support societies' broad developmental priorities. According to IRENA estimates, the expected increase in human welfare from the deployment of renewables is close to 4%, far exceeding the 0.8% rate of improvement in GDP. Savings from reduced health and environmental externalities, which are not fully reflected in conventional economic accounting systems, far offset the costs of the energy transition.

Figure 1: Projected increase in global GDP to 2050



Source: IRENA, 2017a.

Figure 2: Welfare improvements – key dimensions



Source: IRENA, 2017a.

Because employment is essential for wage generation and thus for the well-being of individuals and their families, the creation and retention of jobs is of critical importance in any measure of socio-economic development. Wage and salary income – especially from well-paying jobs – permits people to make the purchases that translate into stable demand for goods and services, contributing to healthy local and national economies. The measure of employment thus goes far beyond direct jobs in the renewable energy sector and indirect jobs in the supply chain, also encompassing so-called induced jobs in the wider economy.

GROWTH IN RENEWABLE ENERGY JOBS

IRENA's *Renewable Energy and Jobs – Annual Review* undertakes yearly estimates of global employment in the sector since 2013 The 2017 edition concludes that direct and indirect renewable energy employment has expanded to 8.3 million people worldwide. In addition, there are an estimated 1.5 million jobs in large hydropower (direct only), for a combined total of 9.8 million jobs. Large hydropower jobs have seen a decline in recent years, reflecting a slower pace of new installations and a rise in labour productivity (IRENA, 2017c, 2016c, 2015, 2014, 2013).

The energy sector as a whole is traditionally male-dominated. Findings from an IRENA survey (IRENA, 2016c) suggest that **women** at present represent on average **35% of the labour force** in the modern renewable energy sector – a share higher than in the conventional energy sector. An additional online survey conducted with partners at Bloomberg New Energy Finance and the Clean Energy Business Council (BNEF, CEBC and IRENA, 2017) focused on the Middle East and North Africa region. It confirmed findings from other parts of the world that women continue to face challenges due to a range of attitudinal and structural factors. These include a lack of background in the STEM (science, technology, engineering and mathematics) fields, dated perceptions of gender roles, discrimination in pay and the glass ceiling for managerial positions. Redressing the situation will require a number of initiatives, including offering greater flexibility in the workplace, policies to facilitate child raising, and greater support for women through mentorship and training.

Women in renewables still face workplace challenges due to entrenched attitudes and structural factors

Photograph: Shutterstock

RENEWABLE ENERGY EMPLOYMENT IN SELECTED COUNTRIES

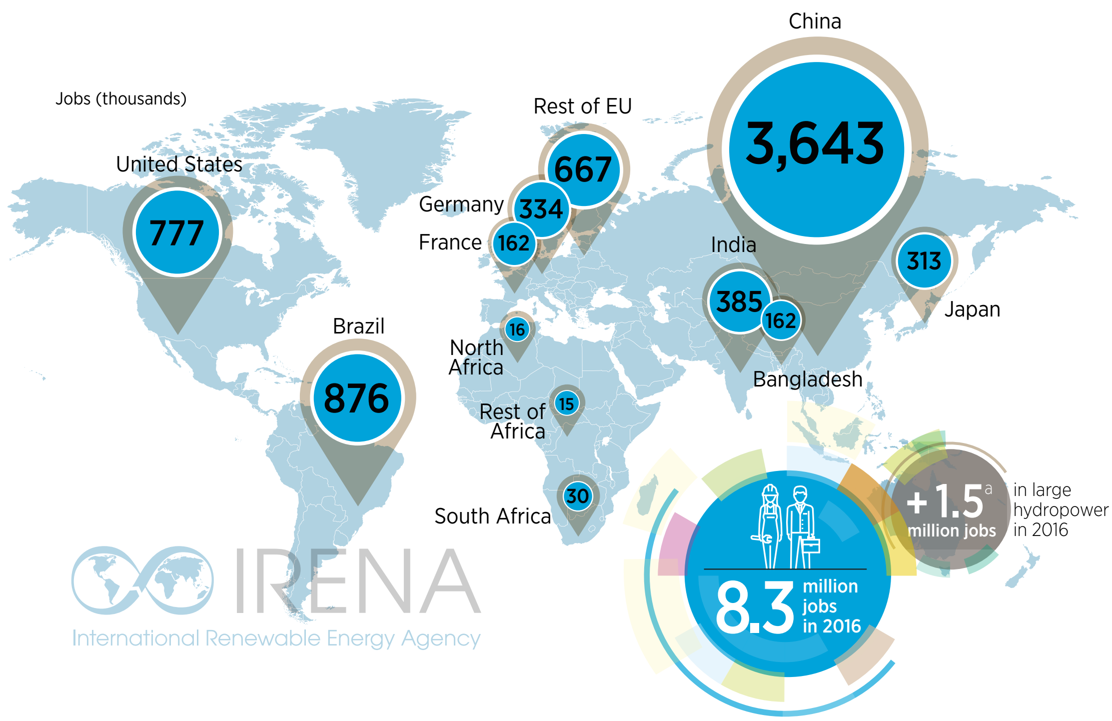
China, Brazil and the US are leading employers in the renewable energy sector (see Figure 3). Recent years have seen a considerable shift towards **Asian countries**, whose share of global renewable energy employment rose from 50% in 2013 to 62% in 2016. This shift is the result of two factors. Strong deployment policies have led to the emergence of dynamic domestic markets, and industrial policies have supported the growth of globally competitive manufacturing facilities, especially in the solar photovoltaics (PV) industry.

China remains the single largest employer with 3.6 million renewable energy jobs. In **India**, record deployment of solar and wind capacities has been driven by both national- and state-level policy instruments. Solar photovoltaic (PV) panel and module manufacturing is also taking off in **South_East Asian countries**, such as **Malaysia**. Others in the region, particularly Indonesia, Malaysia, Thailand and the Philippines, have been adding jobs in the biofuels sector.

Brazil has the largest number of biofuels jobs of any country, but mechanisation of sugarcane harvesting is limiting the growth of employment. In all of Latin America, around 2 million people are working in the renewable energy sector, with biofuels in the lead, followed by hydropower and by fast-growing wind industries in Brazil and Uruguay.

In the **US**, employment growth is driven primarily by wind and solar. Both industries benefit from multi-year extensions of federal investment and production tax credits, along with state-level net metering and renewable portfolio standards.

Figure 3: Renewable energy employment in selected countries, 2016



Source: IRENA, 2017c.

Several member states of the **European Union (EU)** were among renewable energy's early twenty-first century pioneers. However, competitive pressures and adverse policy changes, especially since 2008, have led to significant job losses in solar PV, while Europe's wind industry continues to be a global leader.

In other parts of the world, available information on employment remains limited. In **Africa**, IRENA estimates a conservative 62 000 jobs. South Africa, due to its successful auctions, is the largest employer, with Egypt, Kenya and Morocco making significant strides. Expanding energy access will help boost employment numbers.

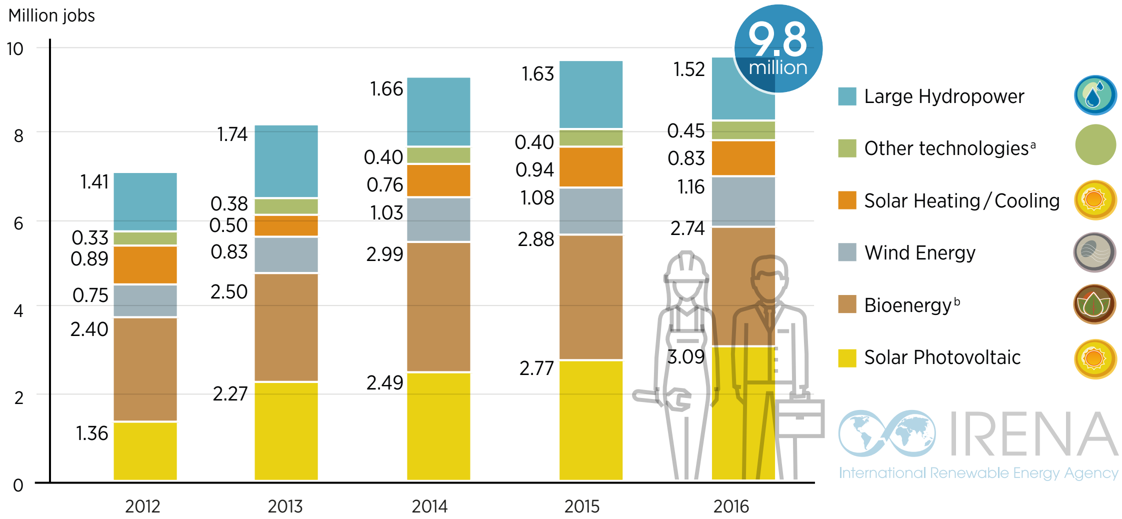
Photograph: Shutterstock

EMPLOYMENT AND OCCUPATIONS BY TECHNOLOGY

At 3.1 million jobs, **solar PV employment** grew by 12% in 2016 and has more than tripled since 2011 (see Figure 4). The industry is followed by the liquid biofuels sector (growing at a slower rate of 3% to 1.7 million jobs), and by the wind industry, growing by 7% to 1.2 million jobs.

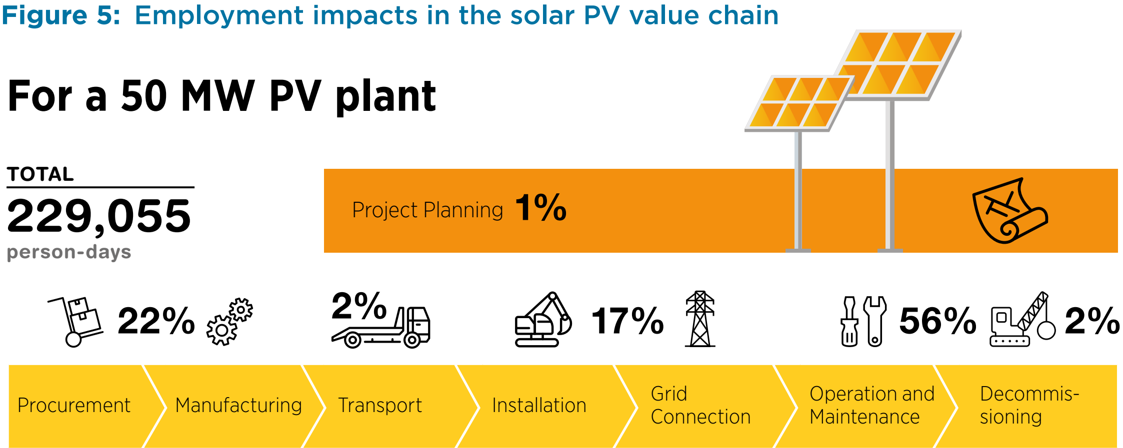
IRENA's *Leveraging Local Capacity for Solar PV* (IRENA, 2017d) analysed the occupational patterns and skills needs of a typical **50 megawatt (MW) solar PV project**. In total, some 230 000 person days are needed along the value chain (see Figure 5). Operations and maintenance account for 56%, manufacturing for 22%, and construction and installation for 17%. Construction workers (35 500 person days) and factory workers and technicians (32 000 person days) are among the most prominent occupations. Many of the occupations that can be filled locally – especially in construction – do not require highly renewables-specific skills and thus offer convenient entry points for employment.

Figure 4: Growth in global renewable energy employment by technology, 2012-2016



Source: IRENA, 2017b.

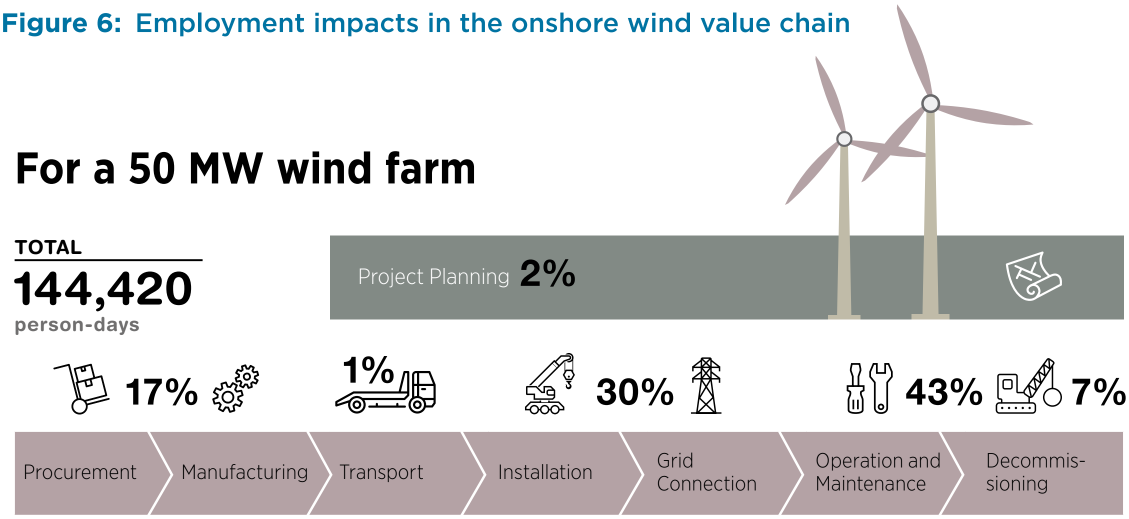
Figure 5: Employment impacts in the solar PV value chain



Source: IRENA, 2017c.

In the **wind power** industry, a strong pace of new installations – particularly in China, the US and Germany – resulted in a 7% increase in global employment to reach 1.2 million jobs. IRENA's *Leveraging Local Capacity for Onshore Wind* (IRENA, 2017e) found that a typical 50 MW project requires a total of 144 000 person days, with operations and maintenance representing 43%, construction and installation 30%, and manufacturing 17% (see Figure 6). Construction workers (26 600 person days) are the single largest occupational contingent, followed by factory workers (close to 12 500 person days).

Figure 6: Employment impacts in the onshore wind value chain



Source: IRENA, 2017d.

OCCUPATIONAL PATTERNS AND SKILLS

As IRENA's Leveraging Local Capacity reports (IRENA, 2017d, 2017e) indicate, the renewable energy sector encompasses a broad range of occupations and skills requirements. Filling some of these positions can be a challenge. Indications are that skills gaps already exist and could grow as the sector continues to expand (IRENA, 2013). Unalleviated, this could hinder the smooth transition towards a cleaner energy economy, contributing to project delays or even cancellations, cost overruns and faulty installations, which could reduce acceptance of renewables.

In this context, better co-ordination of approaches and policies between the industry and the education sector, including the integration of renewables modules into training classes, is essential. Adequate public financing for renewable energy education and training also carries great importance.

To a certain extent, the renewable energy sector can draw on skilled personnel from other industries, such as semiconductors, electrical equipment, shipbuilding and glass manufacturing. The German experience suggests that former shipyard workers can apply their know-how to building bases and towers for offshore wind farms (Fornahl et al., 2012; Hülsen, 2012).

The renewable energy sector can draw on skilled personnel from other industries

Some skill sets in fossil-fuel industries are transferable and adaptable to the renewable energy sector. Workers from the offshore oil and gas sector possess valuable expertise for offshore wind projects (CBI, 2012). Drilling experts from the petroleum sector can be employed in geothermal development. Further, the skills of electrical engineers, electrical technicians, electricians and information technology specialists employed in operating fossil-fuel power stations can be adapted to operating renewable power plants (EC and ILO, 2011). In the US context, research has found complementarities in occupational patterns and skill sets in the coal and solar industries (Louie and Pearce, 2016).

Photograph: Shutterstock

NET JOB EFFECTS AND FOSSIL-FUEL JOB LOSS

As the energy transition accelerates, growth in renewable energy employment appears set to remain strong. IRENA's analysis finds that the sector could employ around 25 million people worldwide by 2050 (IRENA, 2017a). New job creation in renewables and energy efficiency would more than offset the job losses in the conventional energy sector. In fact, net energy sector employment would be higher by 6 million additional workers in 2050 compared to the reference case – the result of shifting investment patterns and differentials in labour intensities.

In recent years, the renewable energy sector has continued to create jobs, whereas the conventional energy sector has struggled to retain them. In the US, the solar PV sector added workers almost 17 times as fast as the overall economy during 2016 (Solar Foundation, 2017).

Rising automation, overcapacities, industry consolidation and shifts towards cleaner energy are resulting in job losses in the fossil-fuel sector. China is preparing for the layoff of 1.3 million coal miners (Yan, 2016); India's largest coal company has shed 36% of its workers since 2002/03 (Statista, 2017); and the coal industry workforce in Europe and North America has been shrinking for many years. The global oil and gas industry is also confronting job losses due to low oil prices and oversupply, with at least 440 000 people laid off in 2015 and 2016 (Jones, 2017).

LOCALISING THE VALUE CHAIN AND ENSURING COMMUNITY BENEFITS

A number of countries have pursued policies to localise portions of the renewable energy value chain and thus to boost the domestic share of employment generation (Kuntze and Moerenhout, 2013). Local content policies typically require that a specified portion of a renewable energy project be sourced from domestic suppliers. To be successful, domestic content policies need to be part of a broader industrial policy to develop viable supply chains and supporting infrastructure; be linked to training and skill-building efforts; and be sufficiently attuned to technology trends and market dynamics.

Manufacturing of renewable energy equipment is concentrated in a limited number of countries. But the IRENA study on *The Socio-economic Benefits of Solar and Wind Energy* (IRENA and CEM, 2014) shows that in other parts of the value chain, more than half of jobs can be localised, in part by leveraging existing industries. Policy mechanisms are key to maximising the various socio-economic benefits of renewable energy development.

Localisation of the value chain is, to some extent, a precondition of generating community benefits – ensuring that a certain percentage of revenue streams flows to areas that host wind and solar farms or that are involved in providing inputs to the sector. But there are other ways to generate community benefits as well. An example is monetary payments to farmers on whose fields wind turbines are erected. For instance, US wind farms annually pay USD 222 million to rural land owners; more than 70% of this sum went to low-income counties (AWEA, 2016).

Experience in countries as diverse as Kenya (Waruru, 2016) and Mexico (Wood, Lorzano Medecigo and Romero-Hernandez, 2012) underlines the importance of awareness raising and prior consultation with host communities. In addition to providing local economic stimulus, tangible benefits that may be offered by a renewable energy project developer include the building of schools, clinics and roads; the drilling of water boreholes; and the provision of agricultural extension services.

Large-scale renewable energy projects are driven principally by national policy goals and industry interests, which do not always accord with the specific needs of local communities. To maximise socio-economic development opportunities and transformational change, policies and projects need to draw as much as possible on the local workforce, offer skills training programmes, and promote gender fairness and equality.

IRENA (2018b forthcoming) examines several case studies for evidence of such beneficial impacts. For example, the study points to Luderitz in Namibia, where the town council holds a 5% share in an adjacent wind farm and lease payments benefit the impoverished town's budget. Replicability is judged to be high, and a number of other town councils have indeed entered similar land lease arrangements with independent power producers.

Photograph: Shutterstock

EXPANDING ENERGY ACCESS

Renewable energy offers energy access in areas where grid extension is expensive or physically difficult. Access offers a range of socio-economic benefits, such as improved communications (mobile phone charging), which in turn facilitates economic transactions, assists in building rural markets and creates employment. Education and skills building are boosted by improved lighting in homes and schools. Also, energy access is important for improving health care (cold storage for medicines, use of medical equipment requiring electricity), and the use of clean renewables in place of highly polluting fuels reduces indoor air pollution (IRENA, 2012).

Sustaining the livelihoods of nearly 2.5 billion people, the agriculture sector is the single largest employer in the world. Increasing productivity and incomes in the agriculture sector is one of the most effective ways to fight poverty, stimulate socio-economic development and meet sustainable development goals. Energy is a vital input, but high cost, vulnerability to price fluctuations and lack of access to modern energy is coming at a tremendous cost – entrapping rural economies in poverty, contributing to food losses of nearly one-third of total produce and affecting food security. Access to affordable, secure and environmentally sustainable energy along different segments of the agri-food chain will be necessary to underpin future growth in the sector. Energy access will positively impact agricultural productivity, reduce losses, increase resilience to climate variability and eventually contribute to greater food security (IRENA, 2016d).

Benefits occur along the entire value chain, from food production (water pumping and irrigation) and the post-harvest stage (storage, drying, refrigeration) to agro-processing and retail (IRENA, 2016d).

Irrigation typically more than doubles agricultural yields compared with rain-fed farming. Replacing diesel-powered pumps enables considerable fuel savings, as India's experience shows: the deployment of 4 000 solar pumps led to savings of 2.4 million litres of diesel fuel (IRENA, 2016e).

Refrigeration and solar dryers can help prevent the spoilage of perishable foods. For agro-processing activities such as milling and grinding grains, replacing diesel generators with renewables permits considerable fuel and time savings. In Nepal, improved water mills saved around USD 750 per farmer per year for de-husking rice. Solar rice threshers in sub-Saharan Africa are six times as productive as manual threshers.

In food preparation, solar cookers, biogas and improved cook stoves reduce food and water contamination, factors that cause several hundred thousand deaths annually. Cleaner cook stoves and cooking fuels also minimise indoor air pollution, which kills almost 4.3 million people every year. Improved cooking technologies can result in reduced deforestation from fuelwood and charcoal production as well as reduced drudgery (in India, for example, average annual household savings on fuelwood collection is estimated at 660 hours). Country-level employment information is scarce in this context, but anecdotal evidence suggests significant potential for job creation (IRENA, 2012, 2013, 2014, 2016c, 2016d).

RENEWABLES: THE WAY FORWARD

The multi-faceted socio-economic benefits of renewable energy have been gaining prominence as a key consideration for decision makers. The economy-wide impacts of the energy transition – employment, income generation, welfare improvements, gender balance and local industrial development – are becoming clearer.

In addition to the climate and environmental aspects of deploying renewable energy, maximising the social benefits is essential to ensure a just, timely and economically efficient transition. A just transition spreads the benefits of renewable energy broadly and enhances its overall acceptance in local communities and across societies.

To support an integrated approach to policy making related to renewables development, IRENA will continue to generate qualitative and quantitative evidence of the various benefits that can be generated and to analyse effective policies and appropriate business models.

Photograph: Shutterstock

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BRIEF 3:
SHARPLY FALLING GENERATION COSTS


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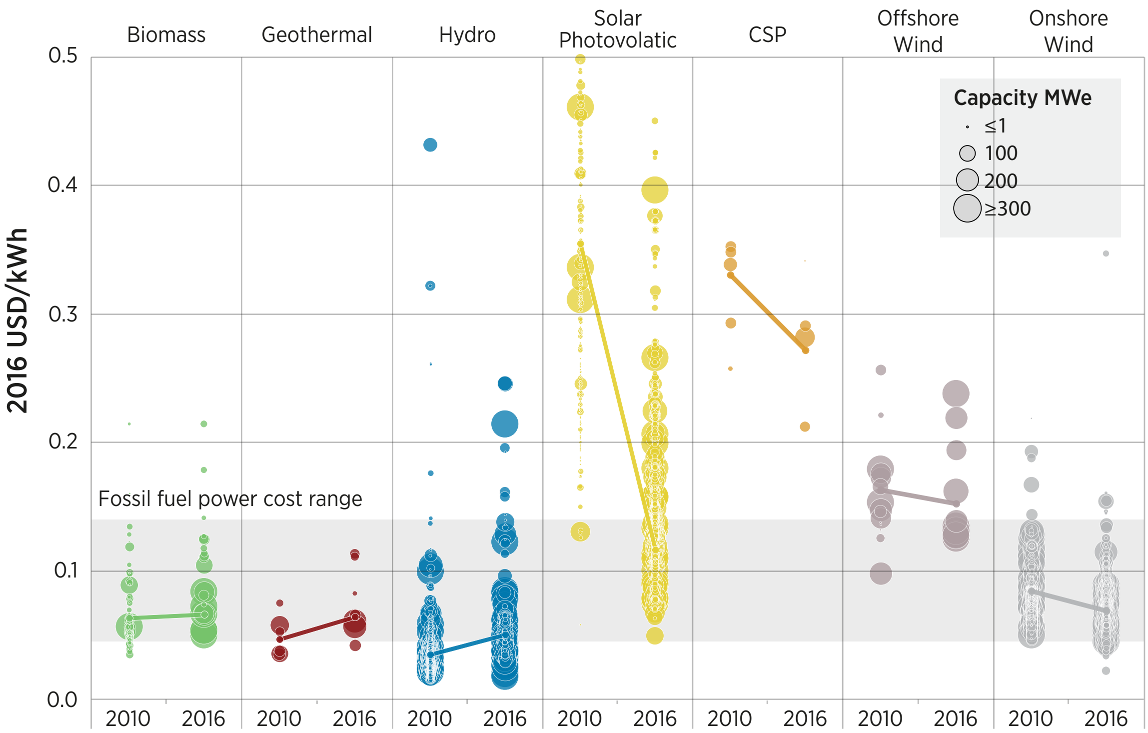
The cost of electricity from renewable energy technologies has fallen steadily, and even dramatically, in recent years. This is especially the case since 2000, with the rise of solar and wind power generation as viable commercial options. Today, power generation from renewable sources and technologies has become increasingly competitive with, or indeed, lest costly than, fossil-based or nuclear power.

Where untapped and economical resources exist, bioenergy, hydropower and onshore wind all offer new, low-cost power generation. Recent and often rapid cost declines for electricity from solar photovoltaics (PV), offshore wind and concentrating solar power (CSP) mean that these technologies, too, can offer competitive electricity, either now or in the next few years when contracted plants are commissioned.

For plants commissioned in 2016, the global weighted average cost of electricity from bioenergy was USD 0.066 per kilowatt-hour (kWh), from hydropower USD 0.048/kWh, from onshore wind USD 0.07/kWh, from geothermal USD 0.064/kWh, from solar PV USD 0.11/kWh, from offshore wind USD 0.152/kWh and from CSP USD 0.27/kWh (Figure 1). The global weighted average costs of electricity from all renewable technologies except CSP and offshore wind now fall within the range of fossil fuels (USD 0.45/kWh to USD 0.14/kWh).[1]

[1] *All data provided here are adjusted for inflation and presented in real 2016 USD. The data exclude all financial support for a project. Similarly, the cost of electricity quoted excludes the benefits or costs associated with local and global pollutant emissions. The calculations for the cost of electricity refer to levelised cost of electricity (LCOE) calculations using a weighted average cost of capital of 7.5% in the OECD and China, and 10% elsewhere. Data are from IRENA Renewable Cost Database of 15 000 utility-scale projects.*

Figure 1: Levelised cost of electricity by project and renewable generating technology in 2010 and 2016



Solar PV and onshore wind have seen very rapid cost reductions in recent decades. PV modules have experienced learning rates[2] of 18% to 22%, and module prices have fallen by around 80% since 2010. Onshore wind has experienced a learning rate of 15% for the cost of electricity delivered, as installed cost reductions (wind turbine prices have fallen 38% on average since 2009) and performance improvements have raised yields.

Between 2010 and 2016, the global weighted average cost of electricity from utility-scale solar PV plants commissioned in those years fell 69%, from USD 0.36 to USD 0.11/kWh. At the same time, the 1st and 99th percentile values fell from a range of USD 0.13 to USD 0.49/kWh to a range of USD 0.07 to USD 0.26/kWh. Recent auction and tender results suggest that the lower range could fall to just USD 0.04/kWh by 2019. Where excellent solar resources exist in the sunbelt, low-cost financing is available, and competitive installed costs and operation and maintenance (O&M) costs can be achieved. Auction results in Abu Dhabi, Chile, Dubai, Mexico and Saudi Arabia all suggest that USD 0.03/kWh will be achievable from 2019 and beyond.

Where good resources exist, onshore wind now represents one of the least-cost sources of new electricity generation capacity. The global weighted average cost of electricity from onshore wind fell 18% between 2010 and 2016, from USD 0.085 to USD 0.07/kWh, with projects regularly delivering electricity for just

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[2] Learning rates refer to the percentage reduction in cost for every doubling of the cumulative installed capacity of a technology.

USD 0.04/kWh. Recent auction results suggest costs as low as USD 0.03/kWh within the next two to three years in areas with excellent wind sites. This decline has been driven by falling wind turbine costs since 2009, as well as by increasing hub heights and larger swept areas that allow today's turbines to harvest much more electricity from the same site than turbines from five to ten years ago. Over the space of 17 years, the average capacity factor of new wind farms commissioned in Denmark doubled, while those in Brazil increased 83%, in the United States 46% and in Germany 41%.

Although recently commissioned offshore wind and CSP projects have been relatively expensive, 2016 and 2017 represented watershed years for these technologies. Both are still in the infancy of their deployment, at 13 gigawatts (GW) and 5 GW, respectively. In 2016 and 2017 the results of auctions for offshore wind delivery up until around 2022 in Denmark, Germany, the Netherlands and the United Kingdom saw the cost of electricity fall to the range of USD 0.06 to USD 0.10/kWh, which is highly competitive for new generation capacity in Europe. Similarly, CSP tenders in Australia and Dubai yielded highly competitive prices of around USD 0.07/kWh for a dispatchable, renewable generation technology that has less than 2% of the cumulative installed capacity of solar PV.

While solar and wind power technologies are commercially mature, they still have significant potential for cost reduction. By 2025 the global weighted average cost of electricity from solar PV could fall by as much as 59%, and from CSP by up to 43%. Onshore and offshore wind could see cost declines of 26% and 35%, respectively.

FACILITATING THE NEXT PHASE OF ENERGY TRANSFORMATION

Significant progress is being made in decarbonising the electricity sector, notably with the growth of the variable renewable electricity technologies, meaning solar and wind power. Experience in leading markets has demonstrated the viability of integrating high shares of these sources smoothly into existing power grids, with smart technologies helping to manage daily and seasonal variations in power supply. The focus must now increasingly shift to how to integrate renewables in the end-use sectors (heating, cooling, transport, etc.).

This need to accommodate variable energy supply while providing undisrupted output in the electricity sector, as well as efforts to integrate renewables into the end-use sectors has brought into sharp relief the significant potential, as well as crucial importance, of electricity storage to facilitate deep decarbonisation.

Electricity storage that is based on rapidly improving batteries and other technologies will permit greater system flexibility, a key asset as the share of variable renewables increases. More directly, electricity storage makes possible a transport sector dominated by electric vehicles; enables effective, 24-hour off-grid solar home systems; and supports 100% renewable mini-grids.

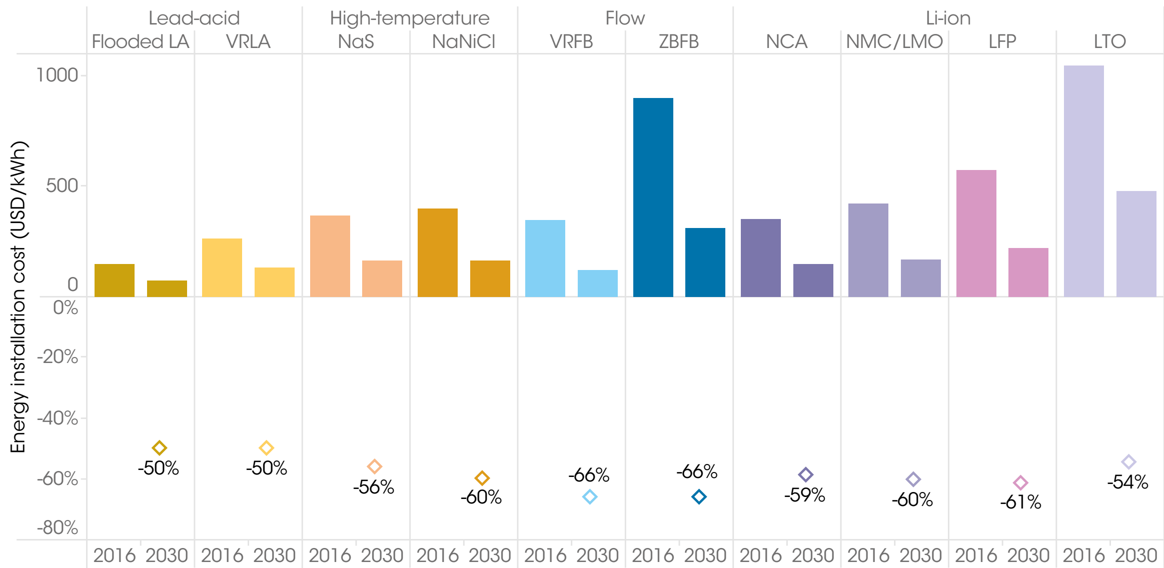
Cost reduction potential in the crucial years until 2030

Total electricity storage capacity could triple in energy terms by 2030, in tandem with rapid uptake of renewable energy. This assumes sufficient uptake to double the share of renewables in the global energy mix in less than a decade and a half. With growing demand for electricity storage from stationary and mobile applications, the total stock of electricity storage capacity will need to grow more than 150%, from an estimated 4.67 terawatt-hours (TWh) in 2017 to 12 TWh or more by 2030.

The cost reduction potential for new and emerging electricity storage technologies is significant. The total installed cost of a lithium-ion battery could fall by at least an additional 54% by 2030 in stationary applications (Figure 2). This will open up new economic markets for electricity storage, as well as increase their role in providing flexibility services to the grid.

Other battery storage technologies also offer large cost reduction potential. The total installed cost of "flow batteries" could drop two-thirds by 2030. High-temperature sodium sulphur (NaS) and sodium nickel chloride batteries also will become much more affordable. Their installed cost could fall 56% to 60% by 2030, at the same time that their performance improves. The installed cost of flywheels could fall 35% by 2030. Compressed air energy storage (CAES), although based on a combination of mature technologies, could see a 17% cost decline by 2030.

Figure 2 Battery electricity storage systems: Installed energy cost reduction potential, 2016-2030



BRIEF 4:

ACCELERATING RESEARCH FOR A LOW-CARBON FUTURE

Photograph: Shutterstock

» **For one-third of the world's anticipated energy use in the coming 20-25 years, no practical decarbonisation solutions exist today. Nearly all of this relates to energy demand for end uses, such as buildings, heat and transport.**

» **Research and development (R&D) needs to happen faster to make renewable solutions viable in these areas.**

» **Renewable power already makes good business sense. Fully realising its potential, however, requires further innovation to optimise system integration.**

INNOVATION IS CRUCIAL FOR THE DECARBONISATION OF THE ENERGY SECTOR

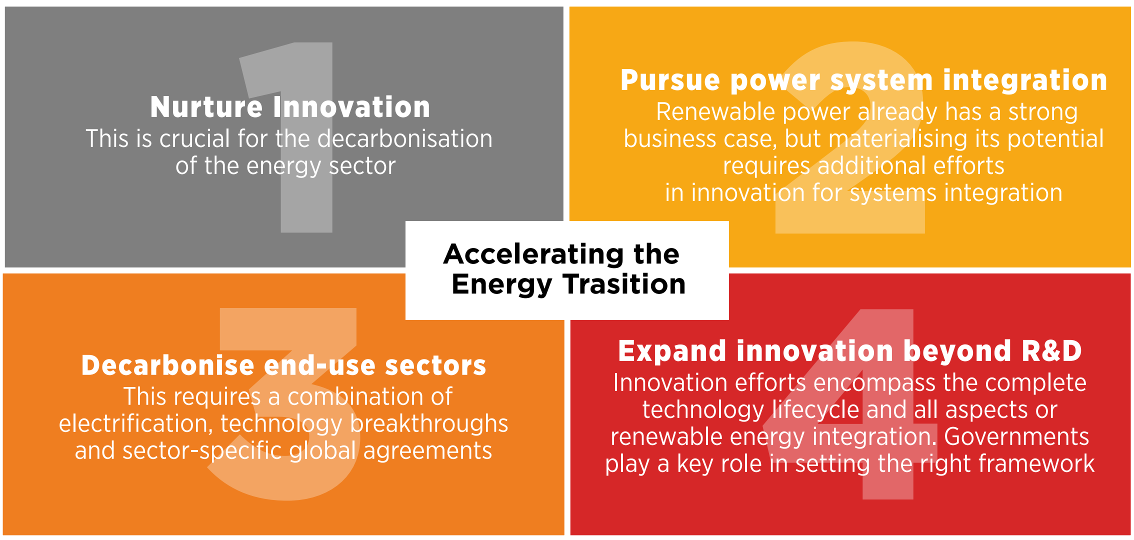
The worlds's energy transformation is accelerating. This is due to a combination of technological progress, developmental priorities and rising environmental concerns. Past experiences suggest that energy transformations were driven primarily by economic opportunity and technological development, not fuel resource scarcity. The ongoing transformation is evolving in the same vein, with innovation as one of its pillars.

The International Renewable Energy Agency (IRENA) estimates that by 2050, the accelerated deployment of renewables and energy efficiency can achieve 90% of the emissions reductions needed to achieve Paris Agreement climate goals.[1] This is, however, a major undertaking that requires significant acceleration in the deployment of existing solutions and additional innovation efforts. Given the rapid rate of change, an ongoing review is needed to focus efforts on priority areas and policy frameworks necessary to achieve energy transformation (IRENA, 2017e).

Looking beyond the power sector at total energy supply, economically scalable solutions are available for around two-thirds of supply requirements. For the remaining one-third, no solutions exist today. These solutions are needed most in end-use sectors (IRENA, 2017a).

On the one hand, we need innovation to accelerate deployment: driving cost reduction, improving performance and enabling integration of existing and emerging renewable technologies in energy systems. On the other hand, innovation is also needed to unearth and develop new technologies. Incremental improvements will continue to foster significant progress, but may not lead us to a complete transformation of the energy sector – game-changing technologies and approaches will be needed as well. Whether today's breakthroughs and early-stage technologies will become commercially available, and how soon, is difficult to determine in advance. Many new technologies for achieving decarbonisation undoubtedly have yet to be envisioned, and the solid prospects of today's solutions are no reason for inaction given the serious consequences of climate change.

Figure 1 Strategy for accelerating the energy transformation



[2] *Limit global temperature increase to well below 2 degrees Celsius (2°C) above preindustrial levels.*

Despite the encouraging progress observed in the power sector, policy makers need to further encourage both incremental R&D and breakthroughs, nurturing all phases of the technology life cycle, from early-stage research to commercialisation. Importantly, accelerating the deployment of the available low-carbon technologies requires not only continuous technology improvement, but also innovations to integrate those technologies. Innovation policy needs to be broader than technology R&D. Beyond generation technology, system integration entails innovation in infrastructure, new ways to operate energy systems, innovative business models to monetise services, and enabling policies and financial instruments. The four elements to be included in such an innovation policy framework for the energy sector are set out in Figure 1.

The growing number of initiatives that focus on innovation serve an important purpose to accelerate progress in R&D and technological innovation. But they need to align with priority areas. This brief offers the climate community suggestions for the means to refine and sharpen the innovation framework to better meet priority needs. Innovation is of paramount importance for energy transformation.

Decarbonising global energy use requires rapid innovation in electricity and other sectors

WHAT DOES ENERGY DECARBONISATION MEAN?

Decarbonisation requires global carbon intensity, the measure of an economy's carbon emissions, to be reduced by 85% over the next 35 years.[1] This clearly requires significant changes in the global energy system and the focus of this transformation should be directed toward the uptake of the most affordable and cleanest technologies.

Decarbonisation will require accelerated improvements in energy efficiency across all sectors to keep the total primary energy supply at the same level between 2015 and 2050 while the economy grows threefold in the same period. Energy efficiency is essential and the potential is large, but alone it is insufficient to achieve complete decarbonisation. Renewables are the other major component. Two out of three units of primary energy supplied must come from renewables by 2050. This requires renewables' share of total primary energy supply to increase at a rate of about 1.2% per year, an eightfold acceleration compared to the trend seen in recent years. To achieve this major increase in the share of renewables in the global energy mix, both faster deployment of available technologies and the development of new renewable energy technologies will be needed. Innovation must support both aspects (IRENA, 2017e).

[1] *Global carbon intensity CO_2 emissions per unit of GDP generated.*

MONITORING PROGRESS ON DECARBONISATION

The business case for renewable power

The power sector is by far the largest source of CO_2, accounting for about 40% of all energy-related CO_2 emissions. It is also the sector where the most significant advances are taking place. Since 2012, the bulk of capacity additions and investment in the global power sector have been in renewable energy (IEA, 2016). In 2016, 62% of added power capacity worldwide was from renewables. In the same year, solar PV capacity grew more than any other source of power generation (IRENA, 2017b). The economic case for renewable power is firmly established and is driven by rapid reductions in the cost of renewable energy. Innovation and the economies of scale have resulted in reductions of 80% in solar PV module costs over the past seven years. IRENA projects that this cost-decreasing trend will continue into the next decade (IRENA, 2016a).

Around the world, countries are raising their ambitions for renewable energy deployment. The leader in renewable energy growth, China, announced earlier this year that it was cancelling plans to build more than 100 coal plants (Mason, 2017). Saudi Arabia, as part of its newly announced 2030 vision, plans to invest up to USD 50 billion to achieve a target of 9.5 gigawatts (GW) of electricity from renewables by 2022 (El Gamal, Shamseddine and Paul, 2017). The generation of electricity from all types of renewables has currently reached about a quarter of all electricity supplied worldwide. Today, solar and wind power account for 2% and 7% of total generation worldwide, respectively. Each year the share of renewables is increasing by between 0.5% and 1% (IRENA, 2017b). Based on this trend, in 35 years renewables could supply 60% of all our electricity demand.

Countries such as Denmark, Germany, Portugal, Spain and Uruguay have proven that their power systems can manage a share of variable renewable energy (VRE)[3] higher than 25%, on an annual basis. However, there is no experience yet of countries managing power systems with a sustained penetration of VRE above 50% on an annual basis. Therefore, the next stage in innovation efforts has to address integration of very high shares of solar PV and wind. Innovation in operating and regulating power systems will offer new solutions, as well as innovative enabling infrastructure for renewable power systems based on advanced information and communication technologies (IRENA, 2015a; 2016b).

» **Analysis by the International Renewable Energy Agency (IRENA) outlines priority innovation areas by sector and technology, and for other critical areas such as policy and finance. It also provides a starting point to identify the key innovation areas to achieve decarbonisation.**

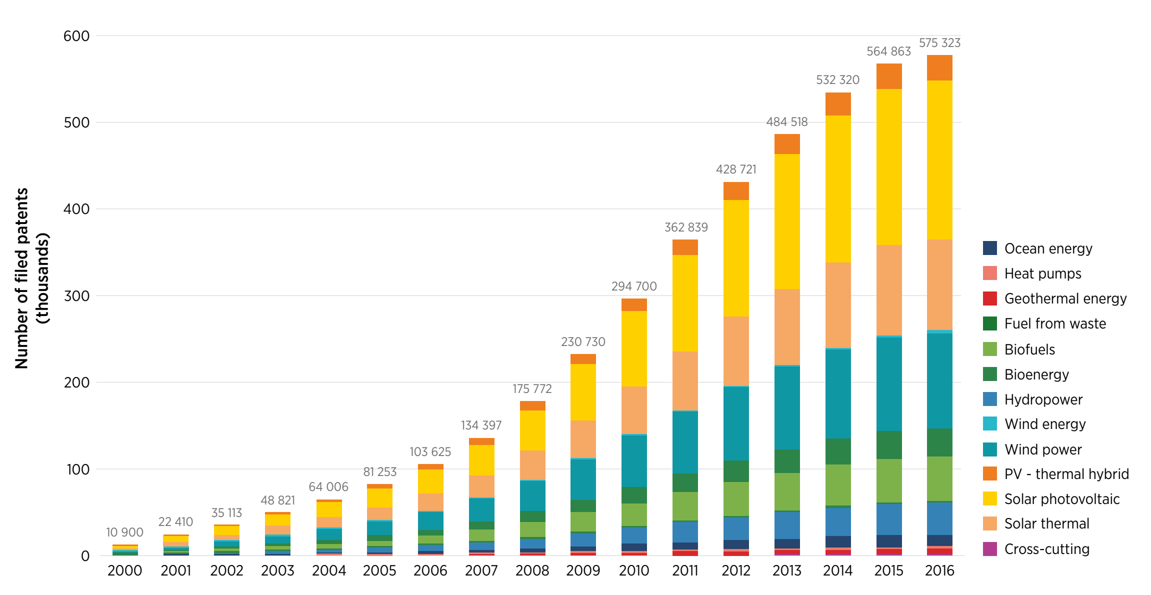
» **Technological innovation will not be sufficient. Innovation beyond technology R&D is necessary across the whole energy system, including for new system operations, innovative market design and regulation, out-of-the-box business models, and the enabling infrastructure to integrate renewables in energy systems.**

[3] *VRE mainly comprises of solar PV and wind.*

Renewable energy patent activity

Patent indicators show that renewable energy technology has experienced significant innovation in recent years (Figure 2). Renewable energy patents have grown at a rate above 12% per year since 1995, well above the average rates for other technology sectors (IRENA, 2017c). This provides a reassuring message on the prospects for future development of renewable technologies.

Figure 2 Renewable energy patents filed between 2000 and 2016



Source: http://inspire.irena.org

- **Nearly 600 000 renewables-related patents have been filed between 2000 and 2016**
- **The solar sector has seen the most progress, representing more than half of these patents**
- **Patents can help to assess the trajectory of future development**

Mixed technology success in end-use sectors

End-use sectors – industry, transport and buildings – represent 60% of all energy sector CO_2 emissions (Figure 3). So far, the deployment rates of low-carbon technologies in these sectors have been too slow to achieve significant emission reductions (IEA, 2016).

The industrial sector has managed to limit the growth of its energy demand in the past few years thanks to the continued uptake of energy efficiency technologies (IEA, 2017a). The sector is unique as fossil fuels are not only used for energy, but also as feedstock to produce plastics and fibres, where carbon is an essential building block. Moreover, industrial processes such as cement making represent around a fifth of total industrial direct CO_2 emissions (IRENA, 2017e). The share of renewables in the industrial sector has remained flat for the past few decades at around 10% (IRENA, 2014a).

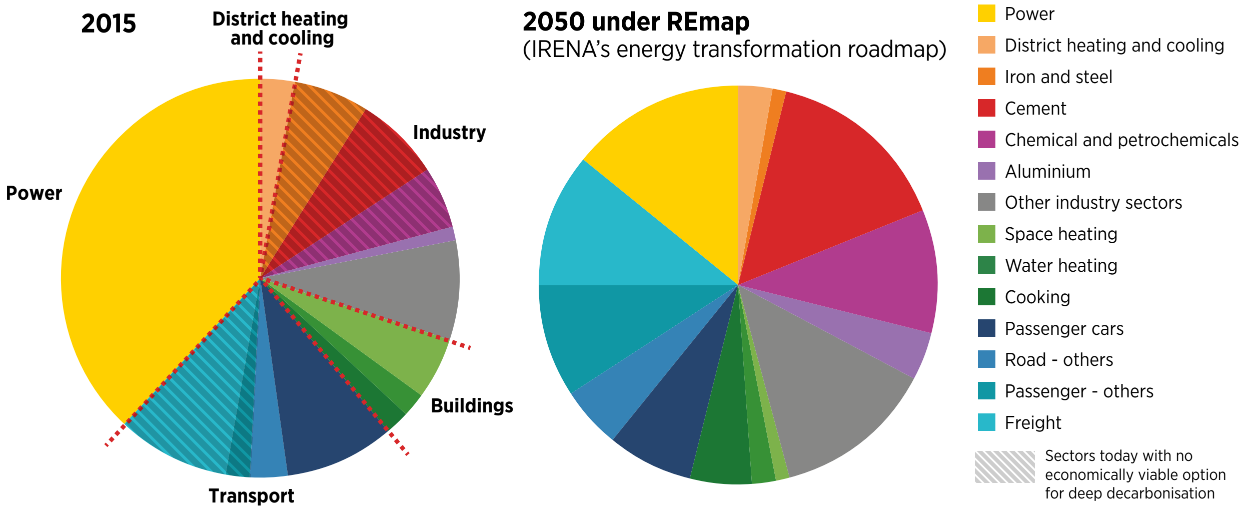
The transport sector is observing a sharp upward trend in the uptake of electric vehicles (EV). In 2016, new EV registrations hit a world record of nearly 800 000 units, around 1% of all car sales. In Norway, on average one out of every five cars sold is an EV. The 2 million threshold has now been crossed, and China, Japan and the United States (notably the state of California) account for around two-thirds of the total global EV stock (IRENA, 2017d).

The advent of EVs is going to be a game-changer for renewable power. Germany, India, Scandinavian countries and the United Kingdom are now committing to electric mobility by 2030 or 2040. China has announced an obligatory target of 10% EV in total car sales by 2019, and France and the United Kingdom have announced a ban on internal combustion engine vehicle sales by 2030. Progress in the use of transport biofuels is less promising than EVs. Biofuels today represent 2-3% of the total transport energy supply (100 billion litres fuel ethanol and 40 billion litres biodiesel) (BP, 2017; IEA, 2017b; RFA, 2017). Transport biofuel investments have been discouraged due to low fossil fuel prices and increasing sustainability concerns. Investment in new biofuel capacity has plummeted since 2009 – in 2015, it was one-tenth of that seen during the 2006/07 peak (IRENA, 2016c).

Buildings have experienced modest energy efficiency progress. They still lag in the fulfilment of their potential to reduce energy demand and increase the share of renewables. The technology and skills to build near zero energy buildings exist. However, the level of energy efficiency in many new buildings is still well below the technical potential. Renovation rates are also generally below the target level. Inefficient building stock in cold climates results in a significant amount of heating energy wasted. Related emissions are difficult to reduce without significant policy effort and financing options for citizens (IRENA, 2017e; IRENA, 2017a). Until 2014, promising growth was seen in renewable heat, notably for solar water heaters, but the world market has since shrunk (Weiss, Spörk-Dür and Mauthner, 2017). Heat pumps are another source of renewable heat, if they draw renewable power for their energy needs.

Roughly half of all renewable energy use is in the form of traditional uses of biomass – burning firewood – for water heating and cooking in buildings. Its share has been slowly decreasing in recent years, but the use of traditional biomass remains widespread, particularly in areas that lack affordable alternatives. Modern renewable solutions exist to reduce the traditional uses of biomass. The use of modern, clean cookstoves with improved solid biofuels such as briquettes and pellets can significantly improve both efficiency and indoor air quality (IRENA, 2016c). Ethanol gels, solar cookstoves and biogas are additional alternatives. Biogas is used in more than 50 million Chinese households today, thanks to a long history of development programmes that stretch back to 1960s (IRENA, 2014b). The trend in residential buildings is towards higher shares of electricity use in total energy demand, which also partly includes electric forms of cooking (IRENA, 2016c).

Figure 3 Changing breakdown of energy sector CO_2 emissions with accelerated uptake of renewables



No economically viable solutions yet exist for one-third of CO_2 emissions. Mainly heavy industry, long-haul trucking, aviation and shipping. By 2060 the world needs zero emissions. The emissions left in 2050 represent a real challenge, mainly in industry and transport.

THE NEED FOR TECHNOLOGICAL INNOVATION

The energy transformation has to be approached from a technical, policy and business perspective. It would be achieved largely by the accelerated deployment of renewable energy and energy efficiency measures (Figure 4).

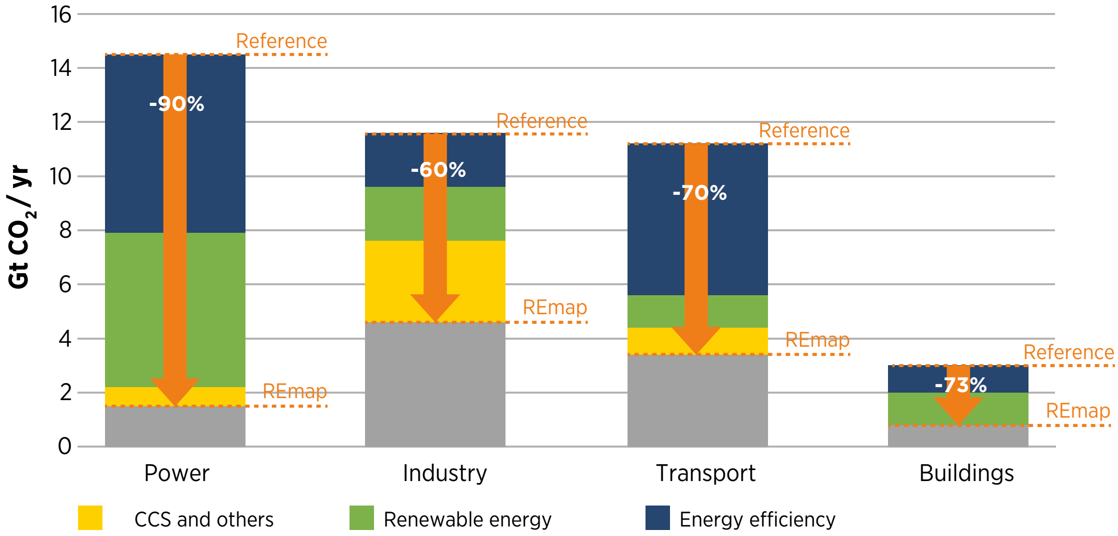
The **power sector** has the largest reduction potential, split roughly equally between renewable energy and efficiency of electricity use. Energy efficiency gains are due to reduction in demand and more efficient uses of electricity in buildings and industry.

Industry initially requires the deployment of all types of low-carbon technology, as well as efficiency in energy and resource use, followed by renewable process heat. Carbon capture and storage could also play a role for industrial processes involving high CO_2 concentration.

Transport requires a dual effort: major electrification coupled with renewable power (covered under energy efficiency) and the accelerated use of both conventional and advanced biofuels for applications where no other electric alternative exists. A modal shift from freight trucks, passenger cars and aircraft to renewable-powered electric railways will also be needed in areas where the development of such infrastructure is technically and economically feasible.

New **buildings** will need to be of the highest efficiency, while the retrofitting and refurbishment of existing ones must be accelerated. More renewable technologies must be used to supply the remaining energy needed for space heating/cooling and water heating, in combination with heat pumps and other types of electrification.

Figure 4 Technology needs for energy sector CO_2 emission reductions in 2050, compared to baseline



Reference: path set by today's plans and policies
REmap: accelerated renewable energy uptake, as per IRENA's REmap analysis

Notes: Gt = gigatonnes; CCS = carbon capture and storage

While the mix of options varies, renewable energy can play an important role in all sectors

DECARBONISATION REQUIREMENTS UNTIL 2050 AND TODAY'S GOOD PRACTICES

1. **Renewable power:** Supply 80% of power generation by 2050 from renewables (half of all generation from solar and wind) to significantly reduce coal use. Develop a combination of existing and new technologies such as storage and interconnectors, market and regulatory changes and new business models to enable this transformation.

   Today's good practices:

   - Germany maintained a power system that supplied electricity with a renewable share of 80% for several hours in 2015. Consumption of power from wind in Denmark averaged 42% in the same year.
   - Large-scale deployment of solar PV and onshore wind capacity at competitive prices in all parts of the world. Among many examples, to name but one: wind energy time shift and frequency response with sodium-sulphur batteries in Japan.

2. **Iron and steel:** By 2050, incentivise the development and accelerate the deployment of energy-efficient iron-making technologies, aiming to cover 80% of all production and achieve significant reductions in coal- and energy-intensive methods of traditional iron-making. Enhance the use of existing technologies such as scrap recovery, along with new technologies and fuels, such as renewable hydrogen.

   Today's good practices:

   - Sustainable production from plant matter, as exemplified in Brazil, where 160 small-scale blast furnaces with combined annual production capacity between 70 000 and 150 000 tonnes are producing up to 6 million tonnes of iron fired with charcoal from eucalyptus trees. Experimental work currently ongoing in other countries shows promising results. In Canada, for instance, a project aims to replace pulverised coal injection with sustainable charcoal to reduce GHG emissions by more than 20%.
   - Production of iron from the direct reduction of ore by using a reducing gas, primarily hydrogen and carbon monoxide. Initial investment and operating costs are lower than integrated steel plants. Moreoever, when hydrogen can be produced from renewable energy sources, it contributes further to emission reductions.

3. **Cement:** By 2050, increase the blending rates of clinker with its substitutes. Supply a higher share of clinker energy needs with biomass and alternative fuels. Reduce the energy demand of clinker production to approach the theoretical limit.

   Today's good practices:

   - Use of pozzolanic material and other materials (e.g. finely ground limestone, silica fume) as clinker substitutes as well as alternative fuels in clinker kilns.
   - Production of new cement types such as geopolymer cements.

4. **Chemicals and petrochemicals:** By 2050, increase the rate of mechanical recycling ten-fold and the share of biomass fuel and feedstocks to cover around a quarter of all energy demand to save on fossil fuel energy and feedstock needs for plastics production.

   Today's good practices:

   - Bioethylene, polylactic acid (PLA) and many other bio-based plastics produced in Europe, Southeast Asia, Brazil and the United States.
   - Carbon capture in nitrogen fertiliser production, as done by companies around the world.

5. **Aluminium:** By 2050, introduce new and emerging primary aluminium smelting technologies. Increase the share of recycling to cover about half of all aluminium supply to save on fuels for alumina (aluminium raw material) and electricity use for primary smelting.

   Today's good practices:

   - Most-efficient Hall Heroult smelting processes in China (in Xinjiang) and in Mozambique. Many aluminium smelters worldwide are located next to hydropower plants to source their electricity needs.
   - An aluminium smelter in Germany used as a battery to deliver up to 1.12 GW of flexible capacity.

6. **Passenger transport electrification:** By 2050, significantly ramp up EV sales to reach a share of around one-third of total passenger car stock. Triple the number of passenger-kilometres travelled by electric railways such as trams, metro and trains.

   Today's good practice:

   - Tesla Model S, BYD E6 and Chevrolet Bolt/Opel Ampera-e with driving ranges of more than 300 kilometres.

7. **Transport biofuels:** By 2050, reduce the cost of biofuels for jet aircraft by at least half with innovation and economies of scale, in order to supply more than one-third of all aviation fuels from such "bio-jet" fuels. Supply one-third of all energy demand for passenger cars and a quarter of all demand for buses from conventional and advanced liquid biofuels and biomethane.

   Today's good practices:

   - Advanced biofuel projects in China, India, Thailand and the United States.
   - Around 100 bio-jet fuel initiatives and the growing number of plants in the United States and rest of the world for production of bio-jet fuels from various routes.

8. **Buildings energy efficiency:** By 2050, utilise the potential from new buildings that will represent about two-thirds of the entire building stock. Ensure all new buildings are fossil fuel-free by 2020. Retrofit non-fossil fuel equipment or replace inefficient equipment in existing buildings in 2050 that will represent the remaining one-third of the building stock. Increase the ownership of efficient appliances and lighting that represent about one-third of buildings emissions.

   Today's good practices:

   - Total Concept method in the European Union for deep renovation of non-residential buildings in a profitable way.
   - Solar district heating/cooling in Austria, Singapore and several other countries.

9. **Buildings renewables use:** By 2050, supply one-third of all heating demand for buildings from solar water heaters. Increase the use of wood chips and pellets by more than 20 times to supply about 800 million tonnes for space and water heating.

   Today's good practice:

   - Solar water heater subsidy programme in Cyprus.

WHERE TO FOCUS INNOVATION

IRENA's analysis shows the required deployment rates for each carbon-reduction technology and sector, as well as where more R&D would be needed. Table 1 below summarises this analysis from the perspective of innovation by categorising each technology against four indicators:

- contribution to total CO_2 emission reductions in 2050 compared to a baseline
- required magnitude of capacity growth for decarbonisation
- status of innovation progress
- opportunities for innovation

Economically scalable solutions exist for two-thirds of global energy use

Questions and answers: Innovation needed for rapid energy decarbonisation

Technologies needed for decarbonisation	How rapidly is innovation progressing?	How much it contributes to decarbonisation in 2050 compared to baseline?[1]	How much capacity needs to grow in 2015-2050?[2]	What further opportunities exist for innovation?
		[%]	[multiplyer]	
Power generation				
Hydropower		0.1	1.4	Retrofit existing plant; river basin planning; floating PV
Solar PV		7.6	29	Building integrated PV
Solar CSP		2.3	144	Cost reduction; low cost thermal storage; HT solar thermal applications
Onshore wind		8.8	11	Arctic conditions; on site blade manufacturing; kites
Offshore wind		1.2	33	Floating wind
Biopower		0.1	4	Sustainable, reliable, affordable biomass feedstock
Geothermal & OTEC		2.3	30	Deep geothermal; resilient and economic wave technologies
CCS for natural gas and biomass		2.1	75	Assessment, coordination and cooperation for CO_2 storage; cost reductions for BECCS
Interconnector capacity		Enabling	5	Roll-out ultrahigh voltage; economic underground lines
Ultra high voltage DC		Enabling	-	
Smart grids		Enabling	-	Standardised smart meters; equipment responding to price signals
Battery storage [3]		Enabling	>20 000	Cost reduction; seasonal electricity storage
Energy efficiency in end uses		14.1	2	
Demand side response		Enabling	-	Better understanding of potentials and their deployment
Various negative emission technologies		-	-	
New materials for advanced battery storage		-	-	

On track
Lagging but viable
Not viable at current pace
Currently not available [5]

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		[%]	[multiplyer]	
Industry				
DRI iron making hydrogen		0.3	11	Hydrogen energy systems at scale
DRI iron making gas + CCS		0.1	15	More demonstration plant
Blast furnace iron making +		1.8	-	Demonstration plant
CCS				
Blast furnace iron making biomass		1.2	16	Biomass supply at scale; extend application from small to large capacity blast furnaces
Clinker substitutes		0.9	3	Standards and applications
Clinker kilns + CCS		1.8	100	Demonstration plant
Clinker kilns biomass		0.9	11	Biomass supply at scale
Biomass for chemicals + recycling [4]		7.0	20	Biochemicals economics
Hydrogen ammonia production		0.1	1 000	Hydrogen energy systems at scale
Gas ammonia production + CCS		0.3	100	Economies of scale
Other renewables		2.6	6	Cost reduction for solar water heaters; biomass supply at scale and accessible at low cost
Material efficiency		4.1	2	Standards
Energy management systems ISO 50001		7.0	3	
CO_2 transportation and storage infrastructure		Enabling	-	Acceptance; MRV of retention
Biomass supply at scale		Enabling	-	Sustainable, affordable, reliable
Solar thermal aluminium smelting		-	-	-
Direct conversion of CO_2 to fuels and materials		-	-	-

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		[%]	[multiplyer]	
Transport				
EVs		11.2	675	High performance low cost batteries and charging infrastructure
Hydrogen vehicles		1.5		High performance low cost hydrogen vehicles
Conventional biofuels		0.3	4	
Advanced biofuels		1.8	600	Economic jet fuel
Energy efficiency		6.2	2	New power trains and lightweight materials
Railway infrastructure for modal shift		Enabling	-	
Biomass supply at scale		Enabling	-	Sustainable, affordable, reliable
Solar passenger cars		-	-	-
Electric airplanes		-	-	-

- **On track**
- **Lagging but viable**
- **Not viable at current pace**
- **Currently not available [5]**

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		[%]	[multiplyer]	
Buildings				
Zero energy buildings		0.6	100	Need for more stringent regulation
Energy renovation and existing stock		1.5	3	
District heating/ cooling with renewables		2.8	6	Strengthen renewable energy component
Clean cooking using renewables		0.6	17	Roll-out at scale; enabling policy frameworks
Solar assisted water/space heating systems		5.6	19	Roll-out at scale; enabling low temperature building energy systems
Heat pumps		1.2	60	Roll-out at scale; enabling low temperature building energy systems
Advanced lightweight materials for construction		-	-	-
New appliance technologies such as magnetic refrigerators, breakthrough materials for insulation and advanced smart heating, cooling and appliance use and control systems		-	-	-

On track

Lagging but viable

Not viable at current pace

Currently not available [5]

Notes: BECCS = bioenergy with carbon capture and storage; CCS = carbon capture and storage; CSP = concentrated solar power; DC = direct current; HT = high-temperature; MRV = measuring, reporting and verification; OTEC = ocean thermal energy conversion; – = not known or not applicable.

[1] This column shows the contribution of each technology to the annual CO_2 emission reductions of 32.5 Gt that needs to be achieved between the baseline (45 Gt) and a scenario which explores technology pathways for deep decarbonisation of the energy sector (12.5 Gt) in 2050. The sum of contributions of all technologies adds up to 100 per cent. The CO_2 emissions include energy-related emissions (fossil fuel, waste, gas flaring) and process emissions from industry. If only fossil fuel combustion related CO_2 emissions were displayed in the table, the savings would be 31 Gt (a reduction from 40.5 Gt to 9.5 Gt in 2050).

[2] This column shows the required growth in capacity (or activity) of each technology between 2015 and 2050.

[3] The total storage capacity from electric vehicles are also included here.

[4] Four technologies are included here: biomass use to generate process heat (5 per cent of all CO_2 emission reductions covered in this category) and as feedstock for production of high value chemicals (ethylene, propylene, butadiene and aromatics) (60 per cent) and better management of plastics end of life by increased deployment of highly-efficient energy recovery (22 per cent) and higher shares of mechanical recycling (13 per cent).

[5] This category of technologies does not include data on abatement potential due to its early development stage.

Several technologies stand out for their importance to CO_2 emission reductions. Energy efficiency technologies represent about 45% of all the emission reductions that are needed. Recent results appear mixed for innovation with energy efficiency technologies. For instance, energy efficiency improvements in appliance use in buildings and motor systems in industry (both covered under "energy efficiency in end uses" category) are on track. By comparison, industrial process heating efficiency improvements and the deployment of energy-efficient buildings lag behind their potential, but have the ability to catch up and therefore can be considered viable.

IRENA's analysis confirms the validity of pursuing energy efficiency first, as "low-hanging fruit" that offers early opportunities to realise considerable potential. The case for renewables is somewhat different.

Today's successful solar PV and on/offshore wind technologies account for just below 20% of the world's total CO_2 emissions-reduction potential. Their current rates of deployment must continue at even higher rates for the next 35 years. The installed generation capacity from these technologies must grow by between 10 and 30 times worldwide from current levels. This will be needed to power a growing number of EVs, which need to grow by nearly 700 times in the same period, contributing another 11% to CO_2 emission reductions. Together with energy efficiency technologies, they constitute three-quarters of the total emission reductions needed. The undertaking will be huge, but IRENA's analysis shows these options are technically and economically feasible to implement.

"Questions and answers" tables on the preceding pages highlight some signicant challenges remaining with several renewable energy technologies. In industry, biomass use as a fuel for process heating and as a raw material for chemicals production could contribute a large share of around 5%, but utilising this potential will not be viable with the current rate of progress. Production of bio-based chemicals must exceed market volume forecasts, overcome technical barriers of system integration and close the price gap with petrochemical counterparts. This is an area that certainly requires greater technological innovation.

More R&D will also be needed for renewables, as well as for enabling technologies. Based on their potential contributions to total emission reductions, renewable hydrogen, liquid biofuels and CSP all require greater research, development and demonstration to overcome barriers. CCS research needs to focus on industry and opportunities for coupling with biomass. All these technologies would cover a further 10% of the total emission reductions needed.

Even if all these technologies are successfully deployed by 2050, accounting for about one-third of the total global energy supply, innovation will still be needed. This is the case not only for new technology options, but also for non-technology strategies. Certain energy-intensive industries and air, maritime and freight transport require particular attention.

» **For around two-thirds of the total energy supply, economical and scalable solutions are available.**

» **The power sector is on track to decarbonise, with vast untapped potential for renewable energy technologies and cost-effective options to reduce the carbon intensity of electricity for end uses to achieve deep emission cuts. These options should be implemented as a priority.**

» **The share of wind and solar photovoltaic (PV) in power systems can increase significantly to cover half of all generation by 2050. Effective integration of these variable sources will depend on accelerated innovation.**

ACCELERATING THE ENERGY TRANSFORMATION THROUGH INNOVATION

Innovation has to go beyond traditional energy technology R&D. Innovation policy frameworks will need to have a balanced focus between support for technologies and for areas beyond technology.

Innovation is needed in sectors where decarbonisation options are limited, to find the solutions needed to mitigate the remaining emissions. The sectors with the lowest progress in innovation for decarbonisation, such as heavy industry as well as freight transport and aviation, are those where proper policy incentives and long-term perspectives are lacking. In industry, it is the production of energy-intensive commodities that poses the main challenge: cement making and the production of chemicals and petrochemicals such as nitrogen fertilisers, plastics and synthetic fibres. In these sectors, international competitiveness and carbon leakage have been major concerns. As a result, they have been largely exempt from ambitious emissions reduction efforts.

Accelerating the deployment of low-carbon technologies requires the creation of a level playing field. This is especially true for technologies that are more expensive than their conventional counterparts. One instrument to improve the economic viability of technologies and correct for market distortions is a carbon price. IRENA's analysis has shown that if a carbon price of USD 60 per tonne of CO_2 was applied to industrial sector technologies, about half of the technologies would still be cost-competitive (IRENA, 2017a). However, it is uncertain whether a uniform global carbon price will be attainable in the near future. Therefore, policy makers and the private sector need to work together to devise politically viable, economic and efficient decarbonisation strategies for the industrial sector. This challenge cannot be addressed by increased R&D investment alone; it also requires global sectoral approaches to help ensure industries remain cost-competitive whilst addressing concerns over carbon leakage from production plants relocating to countries with less stringent policies. Furthermore, these sectors cannot be transformed through national policies due to their global nature. Global agreements for the deployment of technology solutions are indispensable.

In transport, national emissions policies and regulations are aimed at achieving domestic goals (e.g. tighter emissions regulations for internal combustion vehicles that encourage deployment of EVs) and can improve the cost-competitiveness of some costly technologies and increase their deployment. Market instruments, such as correcting for harmful effects of fossil fuels from air pollution externalities that are not priced, are also important (similar to a carbon price). Sectors such as freight and aviation have non-technical barriers to emission reductions. Cross-border regulation of jet fuels in aviation and bunker fuels for maritime transport has yet to be addressed. Governments must find the right balance between focusing on technology solutions and creating an enabling environment for innovation so that the private sector receives the right incentives. Stable and long-term policy objectives are essential to attract private-sector engagement.

To date, the integration of variable renewables has been enabled by flexibility options such as grid reinforcements, demand-side management, energy storage, sector coupling and flexible conventional generation. However, the optimal strategy for integrating shares of VRE higher than 50% on annual basis by 2050 is not yet known. Integrating high shares of renewables requires innovation in all components of the energy system, including new system operations, innovative market design and regulation, out-of-the-box business models, and the enabling infrastructure.

Innovation has been addressed by many organisations, industry associations and increasingly through the establishment of new initiatives. In principle, initiatives are helpful as they develop priorities for sectors to accelerate progress on innovation. In order to ensure initiatives are impactful, they must be aligned with sector-specific innovation needs. The priority areas outlined in this report can also help adjust and complement focus areas suggested by initiatives such as Mission Innovation (MI) or the Breakthrough Coalition. Innovation requires close co ordination with the private sector, where its engagement must be organised more effectively to have a meaningful impact.

A broad understanding of the technology needs for decarbonisation exists. but many pathways will be available to get there. The uncertainty is even greater when the availability of technology and time required for technology deployment are considered. Numerous solutions may already be under consideration by academia, industry and governments, but new breakthroughs will emerge in the future. For instance, in the short and medium term, liquid biofuels and efficient powertrains constitute today's solutions for aviation emission reductions. In the coming decades, however, technologies which do not yet exist, such as electric aircraft, may be developed.

Policy makers need to be informed of all the options that are available today, and which may be commercialised in the future, to make informed decisions. Decarbonisation will therefore increasingly require the creation of enabling frameworks, and innovation efforts will need to expand beyond R&D. Innovation will be needed at the system level to create new business models, develop market design, regulation and policy instruments, and to increase financing. Finally, the decarbonisation of commoditised sectors requires innovation to be accompanied by global sectoral agreements on a clear low-carbon pathway.

» **For end-use sectors – transport, industry and buildings – a combination of specific approaches will be required. Deployment rates for renewables in end-use applications need to accelerate in line with the emissions reduction pathway required to decarbonise the energy sector by 2050. In addition, broad and systems-wide electrification offers an immediate option to drive a large proportion of the change needed in end-use sectors.**

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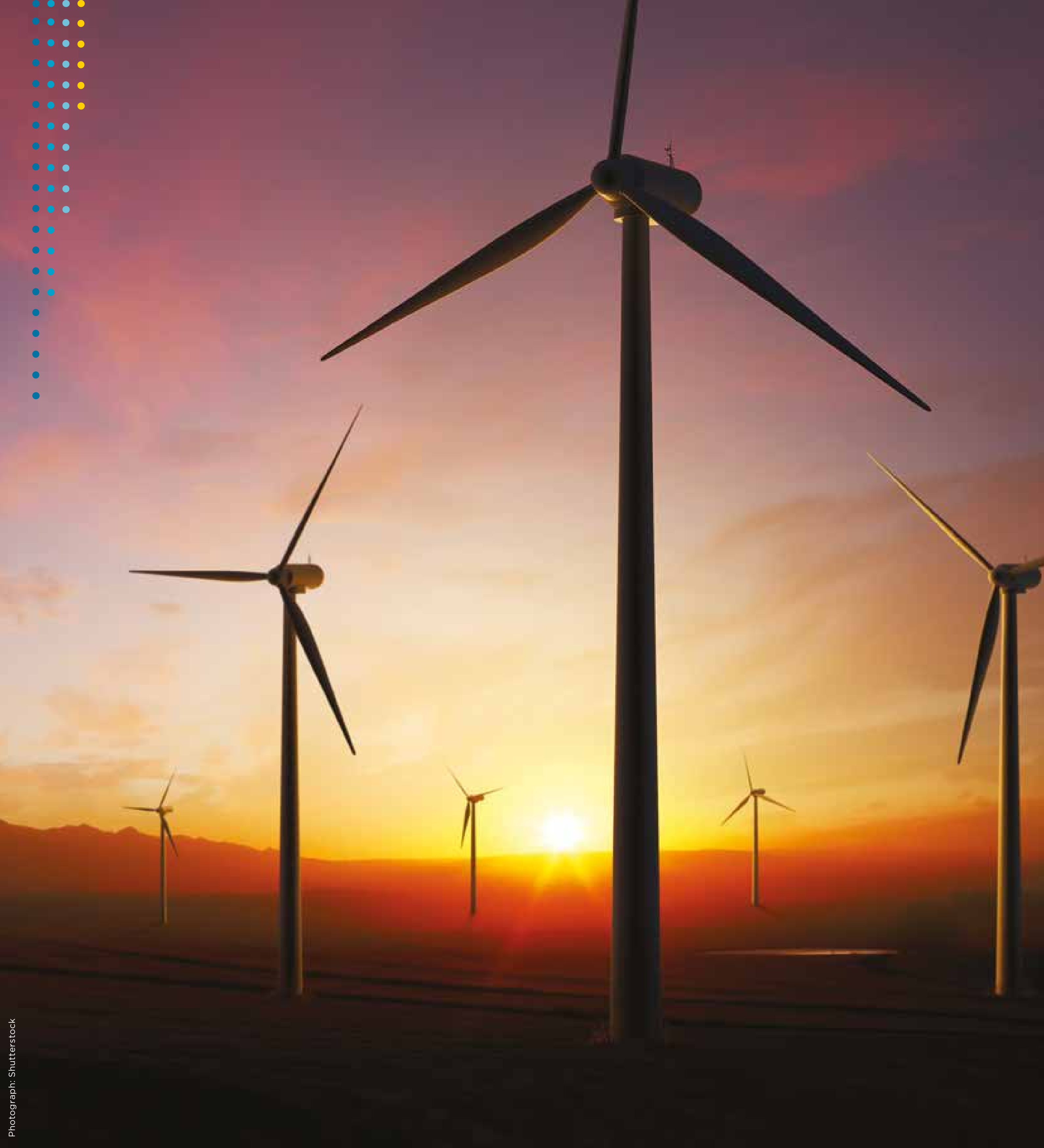
The shift to renewable sources needs to happen faster – not just in power generation but in heating, buildings and transport – to check the rise in global temperatures.



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