EXECUTIVE SUMMARY

PERSPECTIVES FOR THE ENERGY TRANSITION

Investment Needs for a Low-Carbon Energy System

About the IEA

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate was – and is – two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy for its 29 member countries and beyond. The IEA carries out a comprehensive programme of energy co-operation among its member countries, each of which is obliged to hold oil stocks equivalent to 90 days of its net imports.The Agency's aims include the following objectives:

- Secure member countries' access to reliable and ample supplies of all forms of energy; in particular, through maintaining effective emergency response capabilities in case of oil supply disruptions.
- Promote sustainable energy policies that spur economic growth and environmental protection in a global context – particularly in terms of reducing greenhouse-gas emissions that contribute to climate change.
- Improve transparency of international markets through collection and analysis of energy data.
- Support global collaboration on energy technology to secure future energy supplies and mitigate their environmental impact, including through improved energy efficiency and development and deployment of low-carbon technologies.
- Find solutions to global energy challenges through engagement and dialogue with non-member countries, industry, international organisations and other stakeholders.

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. www.irena.org

Executive Summary

Authors: International Energy Agency and International Renewable Energy Agency

Scope of the study

Investment is the lifeblood of the global energy system. Individual decisions about how to direct capital to various energy projects – related to the collection, conversion, transport and consumption of energy resources – combine to shape global patterns of energy use and related emissions for decades to come. Government energy and climate policies seek to influence the scale and nature of investments across the economy, and long-term climate goals depend on their success. Understanding the energy investment landscape today and how it can evolve to meet decarbonisation goals are central elements of the energy transition. Around two-thirds of global greenhouse gas (GHG) emissions stem from energy production and use, which puts the energy sector at the core of efforts to combat climate change.

Against this backdrop, the German government has requested the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) to shed light on the essential elements of an energy sector transition that would be consistent with limiting the rise in global temperature to well below two degrees Celisius (2°C), as set out in the Paris Agreement. The overarching objective of this study is to analyse the scale and scope of investments in low-carbon technologies in power generation, transport, buildings and industry (including heating and cooling) that are needed to facilitate such a transition in a cost-effective manner, while also working towards other policy goals. The findings of this report will inform G20 work on energy and climate in the context of the 2017 German G20 presidency.

The analyses in this report are framed by several key questions which include:

- How can the energy sector achieve a transition to a decarbonised, reliable and secure energy sector at reasonable costs?
- What are the investment needs associated with the energy sector transition and how do investment patterns need to change to reach a low-carbon energy system?
- What are the co-benefits for other energy policy objectives that could result from an energy sector transformation?
- Assuming a timely and effective low-carbon energy sector transition, what is the outlook for stranded assets? What is the impact for stranded assets if action is delayed and the transition is sharper?
- How does the trend of declining costs for renewables and other low-carbon energy technologies, as well as acceleration of efficiency gains, support the decarbonisation? How can policy accelerate this development?
- What are the roles of carbon pricing and the phase-out of fossil fuel subsidies in ensuring a cost-effective decarbonisation of energy systems?
- What are the roles of more stringent regulations, better market design and/or higher carbon prices for the energy sector transition?
- What is the role of research, development and demonstration, and how can early deployment of a broad array of low-carbon technologies support an efficient and effective energy sector transition?

In order to address these questions, the IEA and IRENA separately have examined the investment needs for energy sector pathways that would foster putting the world on track towards a significant reduction in energy-related GHG emissions until the middle of this century. Each institution has developed one core scenario that would be compatible with limiting the rise in global mean temperature to 2°C by 2100 with a probability of 66%, as a way of contributing to the "well below 2°C" target of the Paris Agreement. Both the IEA and IRENA analyses start with the same carbon budget for the energy sector. But the pathways to reaching the goal differ between the two analyses: the modelling analysis conducted by the IEA aims at laying out a pathway towards energy sector decarbonisation that is technology-neutral and includes all low-carbon technologies, taking into account each country's particular circumstances. The analysis conducted by IRENA maps out an energy transition that stresses the potential of energy efficiency and renewable energy sources to achieving the climate goal, while also taking into consideration all other low-carbon technologies.

While IEA and IRENA base their energy sector analyses on different approaches and use different models and/or tools, there are similarities in high-level outcomes that support the relevance for a pathway and framework for a timely transition of the global energy sector. In the following sections, key findings from the analyses of each organisation are presented.

Carbon budget

The average global surface temperature rise has an almost linear relationship with the cumulative emissions of carbon dioxide (CO_2). This useful relationship has resulted in the concept of a remaining global "CO_2 budget" (the cumulative amount of CO_2 emitted over a given timeframe) that can be associated with a probability of remaining below a chosen temperature target.

The Paris Agreement makes reference to keeping temperature rises to "well below 2°C" and pursuing efforts to limit the temperature increase to 1.5°C. However it offers no clear guidance on what "well below 2°C" means in practice, or what probabilities should be attached to the temperature goals.For the purpose of this report, it was chosen to focus on a scenario with a 66% probability of keeping the average global surface temperature rise throughout the 21st century to below 2°C, without any temporary overshoot. Understanding the associated CO_2 budget consistent with this definition is a critical consideration for modelling the pace and extent of the energy sector transition (Table ES.1). To generate an estimate of CO_2 budget for a 66% chance of staying below 2°C, it is necessary to estimate levels and rates of non-CO_2 emissions. For the purpose of this study, non-CO_2 emissions originating from non-energy sectors rely on the scenarios from the database of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). With these assumptions, for the purpose of this study, we estimate that the CO_2 budget between 2015 and 2100 is 880 gigatonnes (Gt). This lies towards the middle of the 590 – 1 240 Gt CO_2 range from a study discussing CO_2 budgets commensurate with a 66% chance of staying below 2°C.

Table ES.1 • Energy sector CO_2 budget in the decarbonisation scenarios developed by the IEA and IRENA in this study

(Gt CO_2)	2015 - 2100
Total CO_2	880
Industry processes	-90
Land use, land-use change and forestry	0
Energy sector CO_2 budget	790

It is important to recognise that the 66% 2°C scenarios explored in this report keep the temperature rise below 2°C not just in 2100 but also over the course of the 21st century. It does not permit any temporary overshooting of this temperature in any year. The main reason for this working assumption is that permitting a temporary overshoot of a specific temperature rise before falling back to this level in 2100 would imply relying on negative-CO_2 technologies (such as direct air capture, enhanced rock weathering, afforestation, biochar and bioenergy with carbon capture and storage) at scale sometime in the future. The assessment of the implications of widespread adoption of bioenergy with carbon capture and storage (BECCS) for land-use requirements or the potential uptake of non-energy technologies for CO_2 removal is outside the scope of this report.

Nevertheless, many of the scenarios assessed by the IPCC in its Fifth Assessment Report that aim to limit the specific temperature rise in 2100 to 2°C rely heavily upon BECCS such that the global energy sector as a whole absorbs CO_2 emissions from the atmosphere by the end of the century. The scenarios developed in this study are therefore ambitious in terms of the timing and scope of required energy emissions reductions for meeting the 2°C goal as they offer no possibility to delay CO_2 emissions reduction until negative-emissions technologies are available at scale. Nevertheless, the scenarios offer the possibility for achieving more stringent climate targets in the future, should negative-emissions technologies become available.

To arrive at an *energy sector only* CO_2 budget for the 66% 2°C scenario it is necessary to subtract from the total CO_2 budget those CO_2 emissions not related to fossil fuel combustion in the energy sector. These emissions predominantly arise from two sources: industrial processes and from land use, land-use change and forestry (LULUCF). For the latter, the outlook for CO_2 emissions from LULUCF used in this study are based on the median of 36 unique decarbonisation scenarios analysed by the IPCC. For this study, the assumption is that CO_2 emissions from LULUCF fall from 3.3 Gt in 2015 to zero by mid-century. LULUCF subsequently becomes a net absorber of CO_2 over the remainder of the 21st century, and, as a result, cumulative CO_2 emissions from LULUCF between 2015 and 2100 are close to zero.

The net effect of these two factors is to reduce the total CO_2 budget from 880 Gt to an energy sector only budget of 790 Gt. The challenge is stark: by means of comparison, current Nationally Determined Contributions (NDCs) imply that, until 2050, the energy sector would emit almost 1 260 Gt, i.e. nearly 60% more than the allowed budget.

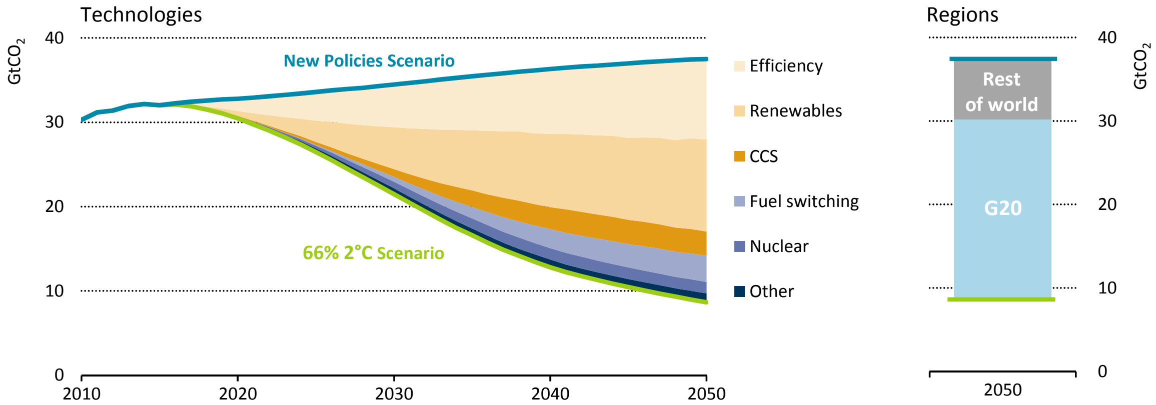
IEA findings

Limiting the global mean temperature rise to below 2°C with a probability of 66% would require an energy transition of exceptional scope, depth and speed. Energy-related CO_2 emissions would need to peak before 2020 and fall by more than 70% from today's levels by 2050. The share of fossil fuels in primary energy demand would halve between 2014 and 2050 while the share of low-carbon sources, including renewables, nuclear and fossil fuel with carbon capture and stoage (CCS), would more than triple worldwide to comprise 70% of energy demand in 2050.

The 66% 2°C Scenario would require an unparalleled ramp up of all low-carbon technologies in all countries. An ambitious set of policy measures, including the rapid phase out of fossil fuel subsidies, CO_2 prices rising to unprecedented levels, extensive energy market reforms, and stringent low-carbon and energy efficiency mandates would be needed to achieve this transition. Such policies would need to be introduced immediately and comprehensively across all countries in order to achieve the 66% 2°C Scenario, with CO_2 prices reaching up to US dollars (USD) 190 per tonne of CO_2. The scenario also requires broader and deeper global efforts on technology collaboration to facilitate low-carbon technology development and deployment.

Improvements to energy and material efficiency, and higher deployment of renewable energy are essential components of any global low-carbon transition. In the 66% 2°C Scenario, aggressive efficiency measures would be needed to lower the energy intensity of the global economy by 2.5% per year on average between 2014 and 2050 (three-and-a-half times greater than the rate of improvement seen over the past 15 years); wind and solar combined would become the largest source of electricity by 2030. This would need to be accompanied by a major effort to redesign electricity markets to integrate large shares of variable renewables, alongside rules and technologies to ensure flexibility.

Figure ES.1 • Global emissions abatement by technology and region in the 66% 2°C Scenario relative to the New Policies Scenario



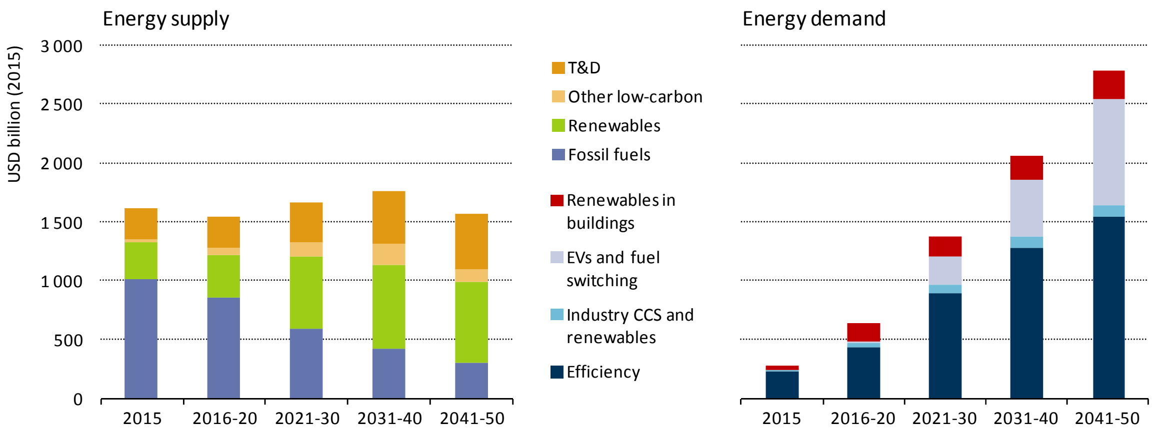
Note: The New Policies Scenario reflects the implications for the energy sector of the NDCs of the Paris Agreement.

Key message • G20 countries provide almost three-quarters of the emissions reductions in 2050 between the 66% 2°C and New Policies Scenarios.

A deep transformation of the way we produce and use energy would need to occur to achieve the 66% 2°C Scenario. By 2050, nearly 95% of electricity would be low-carbon, 70% of new cars would be electric, the entire existing building stock would have been retrofitted, and the CO2 intensity of the industrial sector would be 80% lower than today.

A fundamental reorientation of energy supply investments and a rapid escalation in low-carbon demand-side investments would be necessary to achieve the 66% 2°C Scenario. Around USD 3.5 trillion in energy sector investments would be required on average each year between 2016 and 2050, compared to USD 1.8 trillion in 2015. Fossil fuel investment would decline, but would be largely offset by a 150% increase in renewable energy supply investment between 2015 and 2050. Total demand-side investment into low-carbon technologies would need to surge by a factor of ten over the same period. The additional net total investment, relative to the trends that emerge from current climate pledges, would be equivalent to 0.3% of global gross domestic product (GDP) in 2050.

Figure ES.2 • Average annual global energy supply- and demand-side investment in the 66% 2°C Scenario



Note: T&D = transmission and distribution; EVs = electric vehicles; CCS = carbon capture and storage.

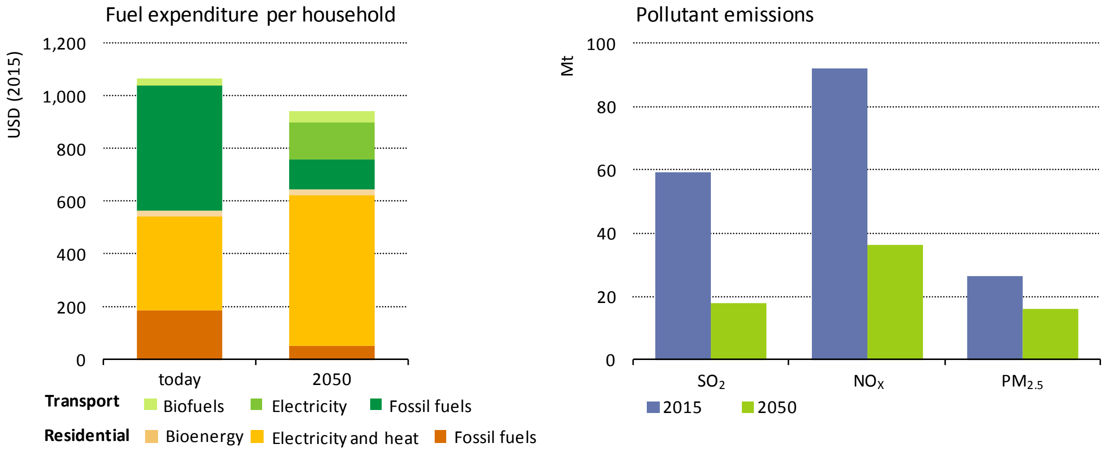
Key message • The level of supply-side investment remains broadly constant, but shifts away from fossil fuels. Demand-side investment in efficiency and low-carbon technologies ramps up to almost USD 3 trillion in the 2040s.

Fossil fuels remain an important part of the energy system in the 66% 2°C Scenario, but the various fuels fare differently. Coal use would decline most rapidly. Oil consumption would also fall but its substitution is challenging in several sectors. Investment in new oil supply will be needed as the decline in currently producing fields is greater than the decline in demand. Natural gas plays an important role in the transition across several sectors.

Early, concerted and consistent policy action would be imperative to facilitate the energy transition. Energy markets bear the risk for all types of technologies that some capital cannot be recovered ("stranded assets"); climate policy adds an additional consideration. In the 66% 2°C Scenario, in the power sector, the majority of the additional risk from climate policy would lie with coal-fired power plants. Gas-fired power plants would be far less affected, partly as they are critical providers of flexibility for many years to come, and partly because they are less capital-intensive than coal-fired power plants. The fossil fuel upstream sector may, besides the power sector, also carry risk not to recover investments. Delaying the transition by a decade while keeping the same carbon budget would more than triple the amount of investment that risks not to be fully recovered. Deployment of CCS offers an important way to help fossil fuel assets recover their investments and minimise stranded assets in a low-carbon transition.

With well-designed policies, drastic improvements in air pollution, as well as cuts in fossil fuel import bills and household energy expenditures, would complement the decarbonisation achieved in the 66% 2°C Scenario. Achieving universal access to energy for all is a key policy goal; its achievement would not jeopardise reaching climate goals. The pursuit of climate goals can have co-benefits for increasing energy access, but climate policy alone will not help achieve universal access.

Figure ES.3 • Trends for selected key indicators in the 66% 2°C Scenario



Key message • The transition to a low-carbon energy sector could help achieve other key energy policy goals, such as reducing air pollution and household fuel expenditures.

IRENA findings

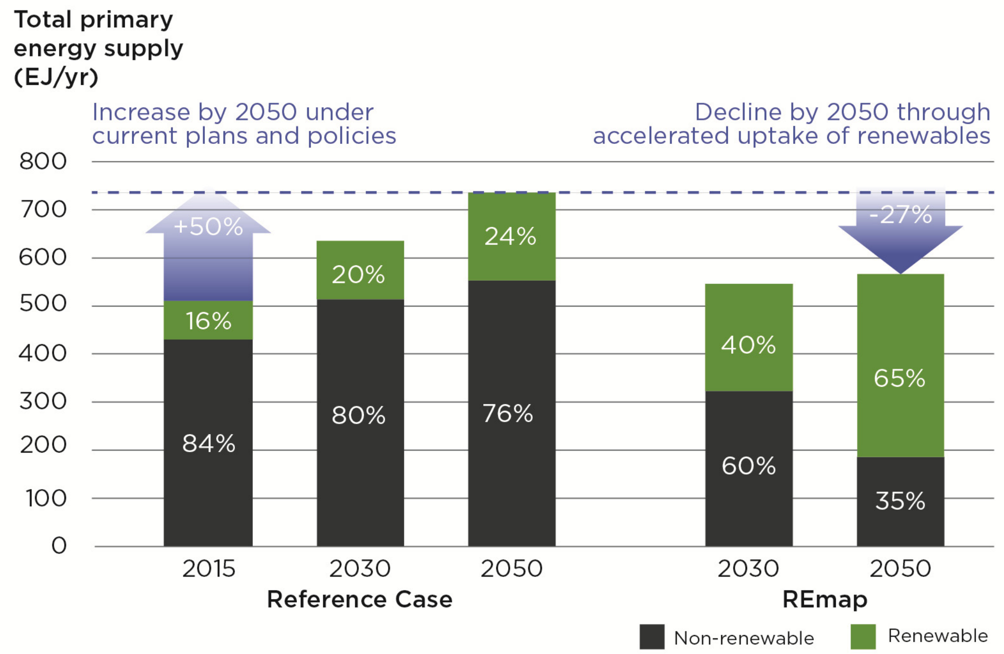
Accelerated deployment of renewable energy and energy efficiency measures are the key elements of the energy transition. By 2050, renewables and energy efficiency would meet the vast majority of emission reduction needs (90%), with some 10% achieved by fossil fuel switching and CCS. In the REmap decarbonisation case nuclear power stays at the 2016 level and CCS is deployed exclusively in the industry sector.

The share of renewable energy needs to increase from around 15% of the primary energy supply in 2015 to 65% in 2050. Energy intensity improvements must double to around 2.5% per year by 2030, and continue at this level until 2050. Energy demand in 2050 would remain around today's level due to extensive energy intensity improvements. Around half of the improvements could be attributed to renewable energy from heating, cooling, transport and electrification based on cost-effective renewable power.

The energy supply mix in 2050 would be significantly different. Total fossil fuel use in 2050 would stand at a third of today's level. The use of coal would decline the most, while oil demand would be at 45% of today's level. Resources that have high production costs would no longer be exploited. While natural gas can be a "bridge" to greater use of renewable energy, its role should be limited unless it is coupled with high levels of CCS. There is a risk of path dependency and future stranded assets if natural gas deployment expands significantly without long-term emissions reduction goals in mind.

The energy transition is affordable, but it will require additional investments in low-carbon technologies. Further significant cost reductions across the range of renewables and enabling technologies will be major drivers for increased investment, but **cumulative additional investment would still need to amount to USD 29 trillion over the period to 2050.** This is in addition to the investment of USD 116 trillion already envisaged in the Reference Case. Reducing the impact on human health and mitigating climate change would save between two- and six-times more than the costs of decarbonisation.

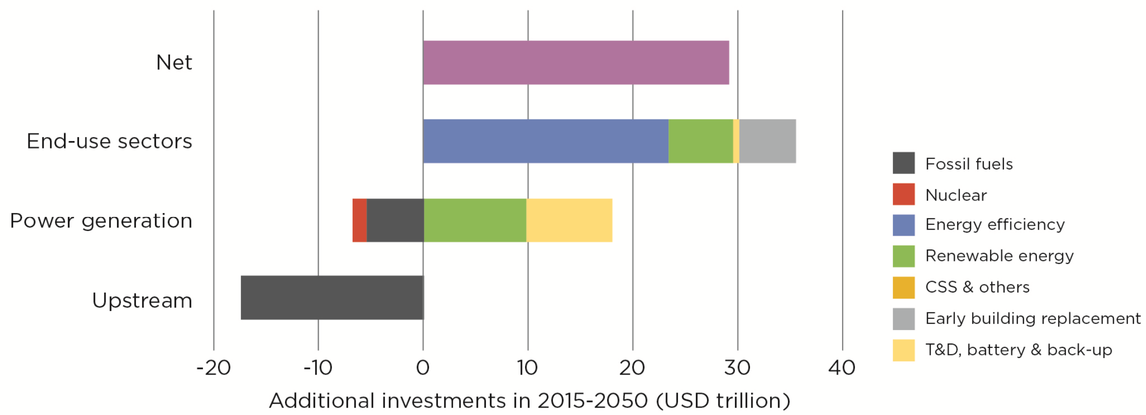
Figure ES.4 • Global total primary energy supply, 2015-2050



Key message • Renewable energy would be the largest source of energy supply under REmap in 2050, representing two-thirds of the energy mix. This requires an increase of renewables' share of about 1.2% per year, a seven-fold acceleration compared to recent years.

Early action is critical in order to limit the planet's temperature rise to 2°C and to maximise the benefits of this energy transition, while reducing the risk of stranded assets. Taking action early is also critical for feasibly maintaining the option of limiting the global temperature rise to 1.5°C. Delaying decarbonisation of the energy sector would cause the investments to rise and would double stranded assets. In addition, delaying action would require the use of costly technologies to remove carbon from the atmosphere.

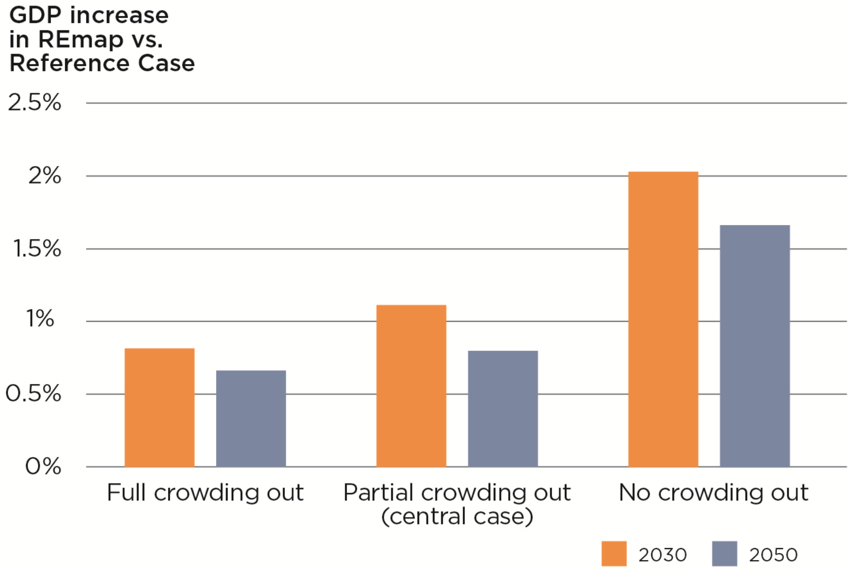
Figure ES.5 • Additional investment needs in REmap compared to the Reference Case, 2015-2050



Key message • Meeting the 2°C target requires investing an additional USD 29 trillion between 2015 and 2050 compared to the Reference Case.

The energy transition can fuel economic growth and create new employment opportunities. Global GDP will be boosted around 0.8% in 2050 (USD 1.6 trillion). The cumulative gain through increased GDP from now to 2050 will amount to USD 19 trillion. Increased economic growth is driven by the investment stimulus and by enhanced pro-growth policies, in particular the use of carbon pricing and recycling of proceeds to lower income taxes. In a worst-case scenario (full crowding out of capital), GDP impacts are smalller but still positive (0.6%) since the effect of pro-growth policies remains favourable. Important structural economic changes will take place. While fossil fuel industries will incur the largest reductions in sectoral output, those related to capital goods, services and bioenergy will experience the highest increases. The energy sector (including energy efficiency) will create around six million additional jobs in 2050. Job losses in fossil fuel industry would be fully offset by new jobs in renewables, with more jobs being created by energy efficiency activities. The overall GDP improvement will induce further job creation in other economic sectors.

Figure ES.6 • Global GDP impacts in different cases of crowding out of capital



Notes: Partial crowding out is modelled by forcing savings to be at least 50% of investment. Full crowding out imposes savings to be equal to investment. Null crowding out does not impose any relation between savings and investment.

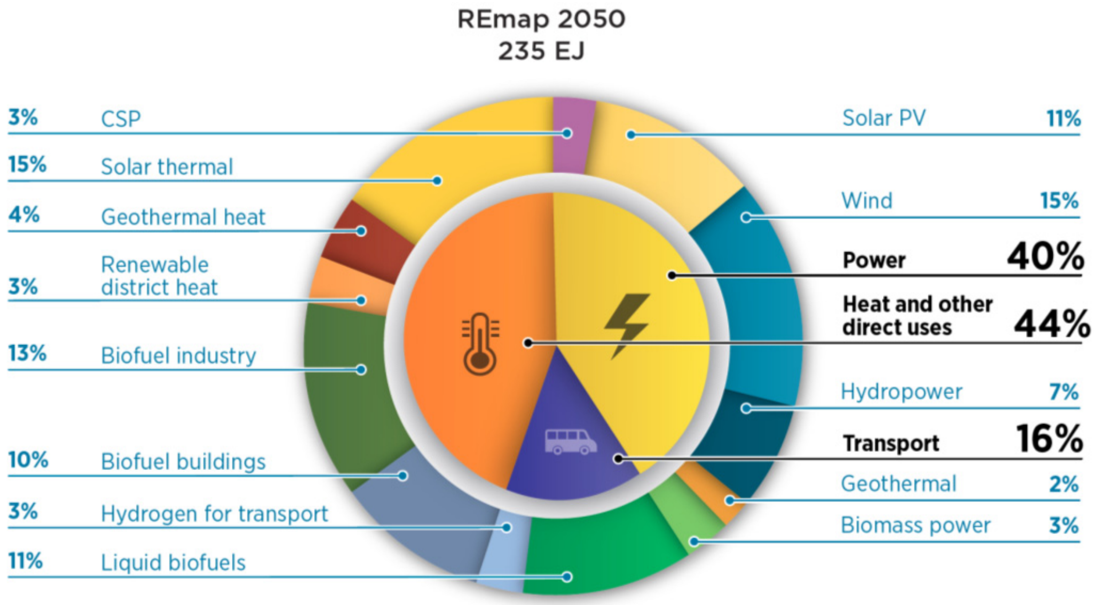
Key message • **Global GDP will be boosted by around 0.8% in 2050 (USD 1.6 trillion). In a worst-case scenario (full crowding out of capital), GDP impacts are smalller but still positive (0.6%) since the effect of pro-growth policies is still favourable.**

Improvements in human welfare, including economic, social and environmental aspects, will generate benefits far beyond those captured by GDP. Around 20% of the decarbonisation options identified are economically viable without consideration of welfare benefits. The remaining 80% are economically viable if benefits such as reduced climate impacts, improved public health, and improved comfort and performance are considered. However, today's markets are distorted – fossil fuels are still subsidised in many countries and the true cost of burning fossil fuel, in the absence of a carbon price, is not accounted for. To unlock these benefits, the private sector needs clear and credible long-term policy frameworks that provide the right incentives.

Deep emission cuts in the power sector are a key opportunity and should be implemented as a priority. Sectoral approaches must be broadened to system-wide perspectives, to address the main challenge of reducing fossil fuel use in end-use sectors. The power sector is currently on track to achieving the necessary emissions reductions, and its ongoing efforts must be sustained, including a greater focus on power systems integration and coupling with the end-use sectors. In transport, the number of electric vehicles needs to grow and new solutions will need to be developed for freight and aviation. It is critical that new buildings are of the highest efficiency standards and that existing buildings are rapidly renovated. Buildings and city designs should facilitate renewable energy integration.

Increased investment in innovation needs to start now to allow sufficient time for developing the new solutions needed for multiple sectors and processes, many of which have long investment cycles. Technology innovation efforts will need to be complemented by new market designs, new policies and by new financing and business models, as well as technology transfer.

Figure ES.7 • Final renewable energy use by sector and technology in REmap, 2050



Key message • Under REmap, final renewable energy use is four-times higher in 2050 than it is today. Power and heat consume about 40% and 44% of the total renewable energy, respectively.

Key messages

1. Transformation of the energy system in line with the "well below 2°C" objective of the Paris Agreement is technically possible but will require significant policy reforms, aggressive carbon pricing and additional technological innovation. Around 70% of the global energy supply mix in 2050 would need to be low-carbon. The largest share of the emissions reduction potential up to 2050 comes from renewables and energy efficiency, but all low-carbon technologies (including nuclear and carbon capture and storage [CCS]) play a role.
2. The energy transition will require significant additional policy interventions.
    - Renewables will assume a dominant role in power generation. Skillful integration of variable renewables at very high levels becomes a key pillar of a cost-effective energy sector transition.
    - Power market reform will be essential to ensure that the flexibility needs of rising shares of variable renewables can be accommodated.
    - Ensuring access to modern energy services for those currently deprived remains a high priority, alongside improved air quality through deployment of clean energy technologies.

3. Total investment in energy supply would not need to rise over today's level to achieve climate targets, while there is significant additional investment needed in end-use sectors.
   - Investment needs in energy supply would not exceed the level of investment undertaken by the energy sector today. It requires appropriate and significant policy signals to ensure that investment in low-carbon technologies compatible with the "well below 2°C" objective becomes the market norm.
   - The additional investment needs in industry and households for more efficient appliances, building renovations, renewables and electrification (including electric vehicles and heat pumps) are significant. In order for energy consumers to reap the potential benefits of lower energy expenditure offered by the use of more efficient technologies, policy would need to ensure that the higher upfront investment needs could be mobilised.
4. Fossil fuels are still needed through 2050.
   - Among fossil fuel types, the use of coal would decline the most to meet climate targets.
   - Natural gas would continue to play an important role in the energy transition to ensure system flexibility in the power sector and to substitute for fuels with higher carbon emissions for heating purposes and in transport.
   - The use of oil would fall as it is replaced by less carbon-intensive sources, but its substitution is challenging in several sectors, such as petrochemicals.
   - CCS plays an important role in the power and industry sectors in the IEA analysis while only in the industry sector in the IRENA analysis.
5. A dramatic energy sector transition would require steady, long-term price signals to be economically efficient, to allow timely adoption of low-carbon technologies and to minimise the amount of stranded energy assets. Delayed action would increase stranded assets and investment needs significantly.
6. Renewable energy and energy efficiency are essential for all countries for a successful global low-carbon transition, but they will need to be complemented by other low-carbon technologies according to each country's circumstances, including energy sector potentials, and policy and technology priorities.
7. The energy sector transition would need to span both the power and end-use sectors.
   - Electric vehicles would account for a dominant share of passenger and freight road transport.
   - Renewables deployment would need to move beyond the power sector into heat supply and transport.
   - Affordable, reliable and sustainable bioenergy supply would be a priority especially in light of limited substitution options in particular end-use sectors
8. Technology innovation lies at the core of the long-term transition to a sustainable energy sector.
   - Near-term, scaled-up research, development, demonstration and deployment (RDD&D)spending for technological innovation would help to ensure the availability of crucial technologies and to further bring down their costs.
   - Not all of the needed emission reductions can be achieved with existing technology alone. Additional low-carbon technologies that are not yet available to the market at significant scale, such as electric trucks or battery storage, will be required to complement existing options.

- Technology innovation must be complemented with supportive policy and regulatory designs, new business models and affordable financing.

9. Stronger price signals from phasing out inefficient fossil fuel subsidies and carbon pricing would help to provide a level playing field, but would need to be complemented by other measures to meet the well below 2°C objective.

- Price signals are critical for the energy sector to ensure climate considerations are taken into account in investment decisions.
- It is important to ensure that the energy needs of the poorest members of society are considered and adequately taken into account.

10. The IEA and IRENA analyses presented here find that the energy sector transition could bring about important co-benefits, such as less air pollution, lower fossil fuel bills for importing countries and lower household energy expenditures. Both analyses also show that while overall energy investment requirements are substantial, the incremental needs associated with the transition to a low-carbon energy sector amount to a small share of world gross domestic product (GDP). According to IEA, additional investment needs associated with the transition would not exceed 0.3% of global GDP in 2050.[1] According to IRENA, the additional investment required would be 0.4% of global GDP in 2050 with net positive impacts on employment and economic growth.

1 The Organisation for Economic Co-operation and Development (OECD) analysis of how the IEA scenarios play out in the broader macroeconomic policy context will be presented in a forthcoming publication titled *Investing in Climate, Investing in Growth*.

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