IRENA
International Renewable Energy Agency

Accelerating the Energy Transition through Innovation

WORKING PAPER
based on global REmap analysis

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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. This report and other supporting material are available for download through www.irena.org/remap

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For further information or to provide feedback, please contact the REmap team at remap@irena.org.

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ABBREVIATIONS

°C	degrees Celsius
ACEC	Africa Clean Energy Corridor
ARPA-E	Advanced Research Projects Agency-Energy
ASG	Asia Super Grid
ATS	Administrator of the Trading System
bcm	billion cubic meters
BECCS	biomass-fired CCS
BELC	Business Environmental Leadership Council
bln	billion
BOF	blast oxygen furnace
CAGR	compound annual growth rates
CCGT	combined cycle gas turbine
CCS	carbon capture and storage
CDP	Carbon Disclosure Project
CEM	Clean Energy Ministerial
CENEF	Center for Energy Efficiency
CEPI	Confederation of European Paper Industries
CHP	combined heat and power
CNG	compressed natural gas
CO_2	carbon dioxide
COP21	21st session of the Conference of the Parties to the United Nations Framework Convention on Climate Change
CSI	Cement Sustainability Initiative
DARPA	Defense Advanced Research Projects Agency
DHC	district heating and cooling
DoE	US Department of Energy
DRI	direct reduced iron
EAF	electric arc furnaces
EBRD	European Bank for Reconstruction and Development
EEB	Energy Efficiency in Buildings
EERE	Energy Efficiency and Renewable Energy
EJ	exajoule
EU	European Union
EUR	euros
EV	Electric Vehicle
FAO	Food and Agriculture Organization of the United Nations
GABC	Global Alliance for Buildings and Constructions
GACC	Global Alliance for Clean Cookstoves
GBPN	Global Buildings Performance Network
Gcal	gigacalories
GCCSI	Global Carbon Capture and Storage Institute
GDP	gross domestic product
GEIDCO	Global Energy Interconnection Development and Cooperation Organization
GFEC	gross final energy consumption
GHG	greenhouse gas
GJ	gigajoule
Gt	gegatonnes
GW	gigawatt
GWh	gigawatt-hour

IAI	International Aluminium Institute
ICT	information and communications technology
IEA	International Energy Agency
INDC	Intended Nationally Determined Contribution
IPS	Integrated Power System
IRENA	International Renewable Energy Agency
ISA	International Solar Alliance
km²	square kilometres
kV	kilovolts
kW	kilowatt
kW	kilowatt
kWh	kilowatt-hour
LCOE	levelised cost of energy
LEED	Leadership in Energy and Environmental Design
m	metres
m²	square metres
m³	cubic metres
MMBtu	million british thermal unit
MRV	monitoring, reporting and verification
Mt	megatonnes
Mtoe	million tonnes of oil equivalent
MW	megawatt
n. d.	no date
OECD	Organisation for Economic Co-operation and Development
PJ	petajoule
PV	photovoltaic
R&D	research and development
REmap	Renewable energy roadmap analysis by IRENA
SEFF	Sustainable Energy Financing Facilities
SE4All	Sustainable Energy for All
T&D	transmission and distribution
TEC	Technology Executive Committee
TES	Thermal Energy Storage
TFEC	total final energy consumption
thm	tonne of hot metal
TJ	terajoule
toe	tonnes of oil equivalent
TWh	terawatt-hour
UN	United Nation
UNFCCC	United Nations Framework Convention on Climate Change
ULCOS	Ultra–Low CO_2 Steelmaking
UPS	Unified Power System
US	United States of America
USD	United States dollar
VRE	variable renewable energy
WACEC	West Africa Clean Energy Corridor
WBCSD	World Business Council for Sustainable Development
WSA	World Steel Association
WWEA	World Wind Energy Association
yr	year

EXECUTIVE SUMMARY

Objective of this working paper

This working paper aims to shed light on the conditions needed to nurture low-carbon technology innovation. By assessing current status and future needs for such technologies, it seeks to identify the elements of a flexible policy framework for innovation, broadly suitable to enable decarbonisation of the energy sector between now and 2050.

With these aims in mind, the potential and cost of emissions-abatement through low-carbon technologies has been assessed in 13 different sectors of the energy system, spanning both power generation and the end-use sectors of energy demand. In addition, international initiatives promoting the required innovation have been mapped for each sector.

Specific findings for each technology and sector, in turn, are translated into high-level policy recommendations to spur low-carbon technology innovation. The envisaged of cultivation of effective, case-specific innovation policies would do much to help countries meet international climate goals, such as those set forth in the 2015 Paris Agreement.

This assessment builds on and expands the analysis prepared at the request of the G20 Presidency (IEA and IRENA, 2017), which looks at how the energy transition could occur and how it would result in deep decarbonisation by 2050. It also builds on earlier REmap work by the International Renewable Energy Agency (IRENA) that had a 2030 focus. The multifaceted "REmap" constitutes IRENA's global roadmap to double the share of renewables in the energy mix by 2030, based on a detailed analysis of countries, regions and sectors focused on the period until 2030 and until 2050.

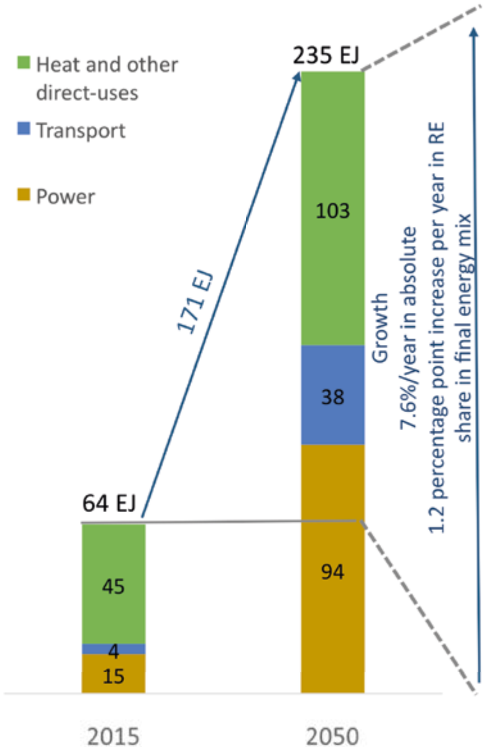
Navigating the energy transition

The world needs a decarbonised energy sector by the second half of the century. IRENA's analysis shows that energy efficiency and renewable energy have the potential to achieve 90 % of the emissions reductions needed by 2050 with renewables accounting for two-thirds of primary energy supply in 2050, growing from 16 % today. To deliver on the above goals, the growth of the renewable share in total final energy consumption needs to rise seven-fold, from 0.17 % per year between 2010 and 2015 to 1.2 % per year on average until 2050. The annual improvement rate of energy intensity – total supply of primary energy per unit of gross domestic product measured in power purchasing parity – needs to nearly double from in the level of the past two decades.

The good news is that for around two-thirds of the total energy supply, economically and scalable solutions are available. However, in many cases the deployment rates for renewables, particularly end-use sectors -transport, industry and residential and commercial buildings-, are currently too slow to achieve the emissions reduction patterns needed to decarbonise the energy sector by 2050. Faster progress is urgently needed. Governments have important roles in enabling these changes by for example providing credible long-term policy objectives and ensuring a level playing field where energy prices properly reflect all societal costs. But the role of governments goes beyond general market framework conditions.

In many energy applications, the necessary technologies are available today, so the important next step is the development of enabling policy frameworks in place to scale up their deployment. There are however energy demands in end-use sectors that are responsible for a third of the emissions in the Reference Case in 2050 – the baseline of this study, where several technology options are emerging but are yet to reach their economic and technical viability. Technology innovation along with enabling policy, financial and social measures will be crucial to creating viable transition pathways and reaching the global decarbonisation objectives. Action today is a matter of urgency, as a full-scale energy transition takes decades due to the different technology development steps, the long lifespan of the existing capital stock and the current role of fossil fuels in all aspects of economies and lifestyles.

Figure ES 1: Required compound annual growth rate in renewable technology options by 2050

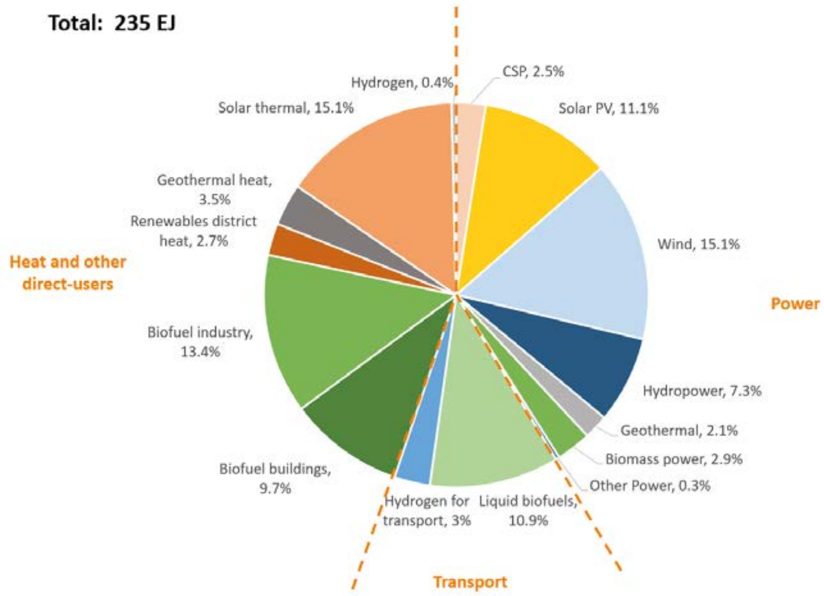


Required compound annual growth rate per technology

Power	
Solar PV	11.1%
Wind	8.1%
Hydropower	1.2%
Geothermal	9.1%
Biomass power	4.7%
Other Power	17.3%
Transport	
Liquid biofuels	5.5%
Hydrogen for transport	20.6%
Heat and other direct-uses	
Biofuel buildings	-1.2%
Biofuel industry	3.9%
Renewables district heat	4.9%
Geothermal heat	6.9%
Solar thermal	8.8%
Hydrogen	13.7%

Based on IRENA estimates

Figure ES 2: Renewable energy technology deployment in 2050



Based on IRENA estimates

Note: EJ = erxajoules. CSP = concentrated solar power

Key findings

According to IRENA's analysis, based on accelerated but feasible adoption of renewables (the REmap case), the decarbonisation of the energy system requires a growth of renewable energy technologies between 2015 and 2050, expressed in final energy terms, from 64 exajoules (EJ) per year to 235 EJ per year. To put this in perspective, the world uses today around 340 EJ of final energy from all types of energy sources, including renewables, fossil fuels and nuclear.

When expressed in primary energy terms, total renewable energy supply would cover two-thirds of the global primary energy supply in 2050. In this case, total primary energy supply growth remains nearly flat throughout the 2015–2050 period, as a result of improvements in energy intensity. The contribution of renewable energy technologies to the incremental energy intensity improvements represents a quarter of the total savings, and the remainder three-quarters come from energy efficiency technologies.

The needed growth to achieve this would come from a mix of all renewable energy technologies. In end-use sectors, solar thermal and bioenergy predominantly drive the growth. In the power sector, wind and solar PV grow the fastest. These are shown in Figure ES 1 for each renewable energy technology. For most technologies, installed capacity will grow by just below 10 % per year. A few emerging technologies would grow by around 20 % per year. These figures indicate that achieving the required rate of growth of renewables to decarbonise the energy sector is challenging but conceivable.

IRENA's analysis indicates that sectors with the least progress in innovation for decarbonisation are those where proper policy incentives and long-term perspectives are lacking. This includes heavy industry as well as freight transportation and aviation. Governments have the ability to change this situation and should consider the immediate action that can stimulate innovation and enable private sector to effectively play its role. Policy makers' actions can include global sector-based approaches or other types of policy frameworks that address competitiveness and carbon leakage concerns. Mobilising the innovation capacity of the private sector is of prime importance, as comparative agility makes private development investment a key driver of innovation. Flexibility in innovation policy design is important: the portfolio of low-carbon technologies may change as the technology progress and transition pathways evolve. Continuous monitoring and adjustments will be needed.

Innovation policy frameworks need to ensure that focus in balanced between support to technologies and to areas beyond technology. Integrating high shares of renewables requires innovations in all components of the energy system including new system operations, innovative market designs and regulations, out of the box business models, and the enabling infrastructure to integrate renewables in energy systems. For example, renewable power technologies open the door to consumers to become an active power market player. However, the enabling infrastructure (such as smart meters), new regulations allowing consumers to also become producers, and business models to maximise revenues need to emerge as well.

Policy recommendations

To achieve the decarbonisation goal in the energy sector, bold and urgent action is required in the following four areas:

1. **Nurture innovation:** This is crucial for the decarbonisation of the energy sector

Innovation is one of the key factors that will drive the energy transition process and decarbonise the energy sector. At its core, innovation is the application of new technologies and practices with enhanced and desirable features.

Limiting climate change to below 2 °C implies a reduction of energy related carbon dioxide (CO_2) emissions of nearly 70 % from 2015 levels. Many governments and other organisations have recognised that the world is under investing in innovation if we are to achieve the cost reductions and performance improvements at the pace needed to transition the world's energy systems to low carbon by 2050.

All sectors will require continued improvements in existing low-carbon technologies and in some cases, the emergence of breakthroughs or a major change in production processes will be vital. Innovation for energy transition needs to balance general support measures that is not technology specific and technology of sector specific support. As cost reduction for low-carbon technologies is an overriding priority for innovation, a suite of emerging technology solutions will offer significant impacts in energy sector decarbonisation. However, the required transformative innovation must not target technology development alone. It also must be aimed at creating new businesses and new jobs, helping industries to flourish, and providing additional economic opportunities to increase wealth.

Designing innovation policies is not straightforward. Currently they are often input-driven instead of outcome-oriented. In this case, constant monitoring and output measurements are needed. Moreover, a sole, correct innovation path cannot be singled out. Therefore, governments should focus on enabling private sector innovation.

2. **Pursue power-system integration:** Renewable power already has a strong business case, but achieving its potential requires additional efforts in innovation for systems integration

The power sector has a strong business case for deployment of renewables, which can achieve more than a third of the incremental emissions reductions needed from renewables by 2050. This is possible with renewables representing 80 % of the total electricity generation, and variable renewable electricity (VRE) covering half of all generation in 2050, according to the REmap case.

In fact, renewable generation technologies in the power sector are already economically viable, and innovation, together with economies of scale, will continue to reduce their costs, making the business case even stronger. The next step, therefore, is to focus innovation efforts on integrating high shares of VRE, such as solar Photovoltaic (PV) and wind, in power systems. At present, countries like Denmark, Germany, Portugal, Spain and Uruguay have proven that VRE shares higher than 25 %, on an annual basis, in power systems are feasible to manage. These countries have even managed short periods of time with VRE shares close to 100 % (IRENA, 2016). The integration of VRE has been enabled by such flexibility options as grid strengthening, 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 is not yet certain. Innovation in systems integration will reduce the costs of enabling technologies, such as energy storage and grid infrastructure. Enablers are based on innovative approaches for operating power systems, designing markets and creating business models. Such innovations will make it possible to create reliable and affordable power systems that are predominantly based on renewable energy.

3. **Decarbonise end-use sectors:** This requires a combination of electrification, technology breakthroughs and sector-specific global agreements

The electrification of end-use sectors offers a win-win situation in reducing emissions while also supporting the integration of higher shares of VRE in power systems. Beyond electrification, there are currently no economically viable emission reduction solutions available for sectors such as iron and steel making, cement production, chemicals and petrochemicals production, maritime transport, aviation, freight, or the replacement of non-sustainable traditional biomass. Industry and buildings are the most challenging sectors, followed by some transport modes. These sectors require new technology solutions to be developed and then to be commercialised quickly. There are, therefore, urgent research and development (R&D) needs for energy efficiency and renewable energy solutions. New policies are also needed, because for example energy-intensive industries have been largely exempt from current ambitious climate policies due to real international competitiveness issues and potential carbon leakage. New buildings need to be of the highest efficiency, while the retrofitting and refurbishment of existing ones has to be is accelerated. Buildings and city designs should facilitate renewable energy integration. In transport, cross-border regulations of jetfuels in aviation and bunker fuels (any type of fuel used for the maritime and aviation sectors) for maritime transport are yet to be addressed. In these cases, the priority should be on creating the appropriate global sector-specific innovation incentives to address the challenges at the sources and develop sustainable alternatives. The analysis indicates that a global carbon price higher than USD 60 per tonne of CO_2 would make most technology options cost effective in the 2050 time frame.

4. **Expand innovation beyond R&D:** Innovation efforts must encompass the complete technology lifecycle and all aspects of renewable energy integration. Governments play a key role in setting the right framework

Increased R&D investments are important, as are market pull incentives, but either one in isolation with a limited focus will not bring the needed results. Efforts to increase innovation must cover the complete technology life cycle, including demonstration, deployment (technology learning) and commercialisation stages. Furthermore, the innovation ecosystem should extend across a whole range of activities, including creating new market designs, building innovative enabling infrastructure and creating new ways to operate energy systems, establishing standards and quality control systems, and implementing new regulatory measures.

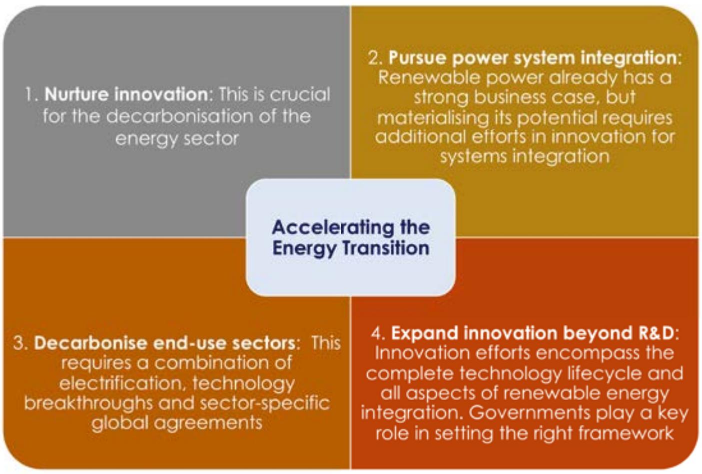
In order to encourage initiatives in innovation, in particular in the private sector, governments have a key role to play in setting an ambitious agenda and ensuring a proper framework for innovation. Basic and applied research in academia and government labs are both critical in terms of providing expertise, skilled staff and development capacity.

Innovation can reduce the cost of technologies to economically viable levels. A holistic innovation framework can also help to overcome other barriers that have hampered deployment of decarbonised energy approaches. These barriers include pricing schemes that benefit competing options, lack of enabling infrastructure to deploy the technologies, access to capital for the build-up of industrial capacity, and limited efforts targeted to demonstration and learning of technology to enable scalability. Especially interesting opportunities exist at the crossroads of information and communications technology (ICT) and energy technology. In addition, bioenergy offers a wide range of options that need to be further developed and deployed. For bioenergy, governments should put the emphasis on creating sustainable, affordable and reliable supplies of biomass feedstocks.

The opportunities from international co-operation can benefit individual governments as well as to achieve a decarbonisation of the energy sector. Developing successful, goal-oriented science, technology and innovation programmes is of paramount importance. International co-operation also creates a platform where experiences and best practices in renewable energy technology innovation are shared and transferred across countries. In this, existing international efforts in the climate context, such as Mission Innovation, Clean Energy Ministerial, United Nations Framework Convention on Climate Change (UNFCCC) Technology Expert Meetings (TEM) and the Breakthrough Energy Coalition, should be further strengthened. But innovation for renewable energy is driven by more than climate change. IRENA's Work Programme for innovation and technology considers economics, jobs creation, local air pollution and other key drivers. A broad perspective on energy transition benefits open new windows of opportunity. IRENA's work with its approximately 150 member countries underlines the need to consider specific national needs and priorities.

Innovation in renewable energy and energy efficiency technologies, stimulated by government-driven efforts, would bring major benefits beyond decarbonising the energy sector (IEA and IRENA, 2017). It would, moreover, increase wealth, promote social inclusion and improve environmental quality and health.

Figure ES 3: Strategy for accelerating the energy transition



Source: IRENA

1. INNOVATION FOR ENERGY TRANSITION: WHAT DO WE MEAN?

New global developments that affect the energy sector

At the twenty-first session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21), countries adopted the Paris Agreement. Under the historic 2015 climate deal, countries have set out to begin reducing global emissions from a peak level as soon as possible and to reach net-zero emissions in the second half of this century. The Paris Agreement also sets the objective of keeping the global average temperature rise "well below 2 degrees Celsius (°C) and to pursue efforts to limit this to 1.5 °C". Although the precise temperature threshold that can be maintained is uncertain in practice, achieving the goal of curbing global warming in a cost-effective manner will clearly be complex and will require significant effort.

The United Nations' Sustainable Development Goal number 7 seeks to ensure universal access to modern energy by 2030, to double the rate of energy efficiency improvement by 2030 and to significantly accelerate deployment of renewable energy. Coupled with the Paris Agreement, these international frameworks for action demonstrate that the transformation of the energy sector is indispensable and inevitable if the world is to meet the objectives of sustainable development and climate change abatement. The global energy transition is also critical to enhance local air quality and reduce health impacts. It can simultaneously create jobs, reduce dependence on imported fuel, empower vulnerable populations through access to clean, affordable and reliable energy, and increase social inclusion and access to education.

Few people would have imagined the scale and pace of the energy transition that we are witnessing today. Renewable energy deployment has considerably increased thanks to reduced cost and record new investments in power generation from renewables. Energy efficiency improvements are picking up, and we see important synergies emerging with renewable energy. Many countries are proving that the ongoing energy transition has multiple positive social, economic and environmental impacts.

Previous analysis from the International Renewable Energy Agency (IRENA) indicates that a global energy transformation towards renewables is necessary due to its economic, social and environmental benefits, we are not yet on this path (IRENA, 2016). Existing and new policies as well as markets driven by the positive business case for renewables will result in a rapid rise of its share in power generation. But important challenges remain in the end-use sectors of most countries: buildings (residential and commercial), industry and transport. The share of renewables and low-carbon energy sources is moving at a slow pace in those sectors, and innovation, carbon pricing and other policy frameworks will be key to accelerate progress, especially in direct uses of fuels in deep water maritime transport, heavy freight and aviation.

The global share of renewable energy is on the rise. In 2015, the share of renewables in primary energy supply was about 16 %, and the share of renewables in electricity generation was 24 % (IEA and IRENA, 2017).

Renewable energy technologies for the electricity sector have witnessed rapid progress in recent years. The cost of solar PV has fallen by 80 %, and the cost of wind by 30 %, over the last five years. Recent auctions for new renewable power generation capacity have yielded spectacular results, with solar PV and onshore wind offers below USD 3 cents per kWh, while offshore wind has been offered below USD 7 cents per kilowatt-hour (kWh), including grid connection.

In addition, the performance of technologies has also improved. For instance, taller wind turbines can reach better quality wind resources, which increases the energy yield, for instance. Because of these developments, renewable energy technologies are increasingly competitive in a growing number of places. For instance, wind is today economical throughout the United States of America (US) which was not true a decade ago. The latest offshore wind power auction in Germany produced a winning bid without any need for public support.

It is important to mention that enabling technologies continue to evolve and to strengthen the deployment of renewable energy technologies. ICT has made it possible to create smart grids that can deal with high shares of variable renewable power. New electric devices in the end-use sectors have the potential to reduce and eventually displace fossil fuel consumption, as well as to enhance performance. Electric vehicles (EVs) are a good example: They use a third of the energy and accelerate faster than conventional cars. Their absence of exhaust gases and their reduced noise are critical benefits in an urban environment. As EVs become more competitive in terms of price and range, these additional benefits compared to internal combustion engines (ICE) would make them the preferred option in the market.

Technological changes that are reducing carbon emissions are already occurring. But the change is not happening fast enough to meet the energy and climate policy objectives. A more rapid transition is needed.

What is the energy transition?

The energy transition is the pathway for transforming the global energy sector from fossil-based to zero-carbon by the second half of this century. There are many routes to such a destination, with different combinations of technologies and policies that can be implemented. The objective is to identify the best strategies to guide the transition so that it happens in the optimal manner, maximising economic and social benefits, wealth creation and inclusion of all stakeholders.

The outcome document of the second International Forum on Energy Transitions (IFET) clearly states the central role, in the energy transition, of an accelerated deployment of energy efficiency and renewable energy technologies. That deployment would build on enabling energy policy frameworks that consider energy systems thinking, encompassing energy supply and demand (NEA and IRENA, 2016). The energy transition will be enabled by information technology and includes smart technology, policy frameworks and market instruments.

The energy transition requires clear objectives and stable policy frameworks to reduce risk and ensure sufficient access to low-cost capital. Reductions in the cost of renewable energy supply depend on technology innovation, but also on low-cost financing and streamlining of approval processes to minimise project cost. A significant potential can be unleashed to reduce renewable energy project costs further. If the Paris Agreement is put into practice effectively, it can provide a more stable policy environment in favour of renewable energy and energy efficiency, thus reducing the risk profile of renewable energy project development (IEA and IRENA, 2017).

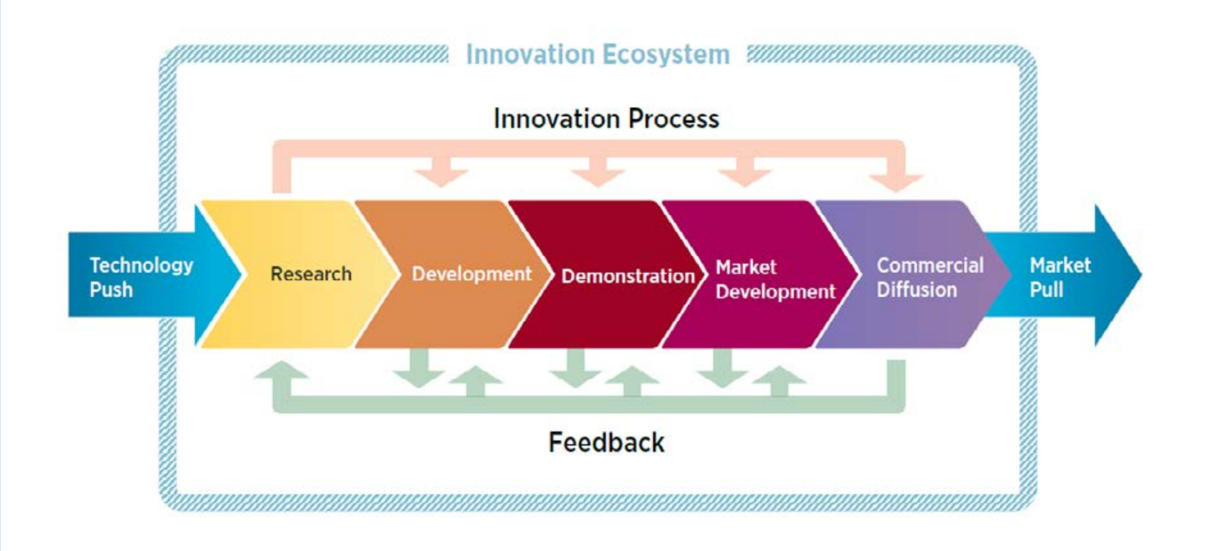
What is innovation?

Innovation is one of the key factors that will drive the energy transition process in decarbonising the energy sector. At its core innovation is the application of new technologies and practices with enhanced and desirable features.

Innovation in renewable energy encompasses the changes that help overcome barriers and result in an accelerated deployment of renewables (IRENA, 2017). It includes, among other things:

- technology breakthroughs that provide renewable solutions to sectors where at present no cost-effective alternatives to conventional energy technologies exist
- improvements to the existing renewable technologies, which reduce cost and stimulate deployment
- new business models and engagement of new actors across energy systems, allowing for a profitable scale-up of renewable technologies
- new types of financing that reduce cost and enhance access to funds
- enabling policy and regulatory innovations that provide incentives for market access and growth

Figure 1: Energy sector innovation cycle



Source: IRENA

The urgent need for solutions to decarbonise the global energy sector requires combining various policy instruments across the whole technology lifecycle, from R&D to market scale-up.

Status of the energy transition

Limiting climate change to below 2 °C implies a reduction of energy related carbon dioxide (CO_2) emissions of nearly 70 % from 2015 levels. Globally, more than 32 gigatonnes (Gt) of energy-related CO_2 were emitted in 2015. These emissions will need to fall continuously to 9.5 Gt by 2050 to limit warming to no more than 2 °C above pre-industrial levels. IRENA's analysis based on REmap concludes that energy efficiency measures and renewable energy will deliver the lion's share, about 90 %, of the emissions reductions needed to decarbonise the global energy system. CO_2 emissions from industrial processes and waste management of synthetic and organic materials must be reduced at the same time. More countries are increasingly recycling plastics, but waste-to-energy or landfilling remain mainstream across the globe and yet, no solutions exists for plastics that accumulate in the ocean that leak from end-of-life collection. The world needs an energy transition between now and 2050. IRENA's analysis demonstrates that the reduction in emissions can be achieved with a net positive economic impact, as discussed in Section 2, through the increased deployment of renewable energy and energy efficiency in G20 countries and other countries globally.

Many governments and other organisations have recognised that the world is under investing in innovation if we are to achieve the cost reductions and performance improvements at the pace needed to transition the world's energy systems to low carbon by 2050.

Objectives of this working paper

The overarching objective of this working paper is to assess the status of and future needs for low-carbon technologies and provide a basis for identifying the elements of a flexible framework that nurtures their innovation for enabling the decarbonisation of the energy sector between now and 2050.

The new energy landscape, with a view to 2050, is detailed in a report prepared by IRENA jointly with the International Energy Agency (IEA). The report looks at how the energy transition could occur, and how it would result in deep decarbonisation (IEA and IRENA, 2017). The study was released at the Berlin Energy Transition Dialogue (BETD) in March 2017. It was previously commissioned by the German Government, which holds the 2017 G20 Presidency, to inform the G20 Energy and Climate Working Groups about what this energy transition would mean in terms of investments. Based on IRENA's

REmap, the analysis shows that renewable energy and energy efficiency measures are the key elements of the energy transition and would accomplish 90 % of required CO_2 emissions reductions, and achieving this would require an additional investment of 0.4 % of the global average GDP between 2015 and 2050. IRENA and IEA assessed the decarbonisation pathways independently but converged on renewable energy and energy efficiency as the most important strategies for the decarbonisation.

The analysis in this working paper details 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 achieve the energy transition in a cost-effective manner. IRENA's REmap global modelling framework is the basis of the analysis. It provided one core case that would limit 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. This technology discussion is complemented with a qualitative assessment of what innovation is required beyond technology to decarbonise the global energy system.

This working paper contains the following elements:

- detailed sector by sector analysis for the decarbonisation of the energy system
- summary of the status and developments in renewable energy sector innovation, describing on-going efforts and gaps, and identifying discrete priority innovation needs for the energy transition by sector and by technology
- quantification of the relevance of individual sectors and the cost effectiveness of technology options
- a qualitative discussion of the non-technology innovation needs in the energy sector

For this purpose, this study considers the following starting points:

- Innovation is driven by more than research and development (R&D). It also includes enabling policy and regulatory frameworks, technology push and market pull.
- R&D spending on renewable energy now is about USD 10 billion per year. A major increase in R&D investment is needed. The Mission Innovation, for instance, calls for a doubling of public R&D in clean energy.
- Technology innovation must be accompanied by innovation in infrastructure, system operation, and business models and regulation – so-called systemic innovation.
- While the renewable power sector is attracting significant attention, end-use sectors continue to be overlooked. More attention needs to be focused on those sectors.

The challenge of any innovation discussion is to be solidly founded in technical detail while being relevant on the general policy analysis level. This working paper tries to bridge the gap between experts and generalists.

The discussion in this working paper is split into three parts:

- overview of the global energy transition needs for decarbonisation between now and 2050 (Chapter 2)
- an energy transition roadmap based on the abatement potential of low-carbon technologies by sectors: where are we today, and what do we need (Chapter 3)
- enabling policy frameworks for innovation that will accelerate energy transitions (Chapter 4)

The main body of text is supported by two Annexes. Annex A elaborates existing international initiatives that accelerate innovation on the level of specific sectors and technologies. Emphasis is put on those that help to overcome the "valley of death".

In Annex B detailed results are presented of a comprehensive assessment of the status of innovation and innovation needs across sectors and technologies. Information is presented in a standard format that allows comparison across sectors and technologies with very different characteristics. The information presented in both annexes can help to inform innovation policy design.

The results of this working paper can inform several agendas. Initially, the aim is to provide inputs for an innovation agenda for decarbonisation that can inform the G20 decarbonisation agenda. But the outcomes of this paper are expected to contribute to existing international efforts on innovation in the climate context, and make suggestions for priorities in international cooperation.

Box 1: Recent International Initiatives on Clean Energy Innovation

At the COP21 in Paris, the initiatives Mission Innovation and Breakthrough Energy Coalition were launched.

Mission Innovation (MI) is a global initiative of 22 countries and the European Union to dramatically accelerate global clean energy innovation. MI's goal is to develop and scale breakthrough technologies and substantial cost reductions. MI members have pledged to double their public clean energy research and development investment over 5 years.

Seven innovation challenges have been identified as priorities where countries will cooperate. These are listed in Chapter 4. A work programme will be tabled for approval at the Mission Innovation Ministerial meeting in Beijing, 7–8 June 2017.

For more information, see http://mission-innovation.net/

Breakthrough Energy Coalition was announced at COP21 aiming at private sector engagement to accelerate the cycle of innovation through investment in early stage innovations. The initiatives groups private investors willing to put patient and flexible risk capital for new technologies, which may provide meaningful returns on investment in the long-haul. One year after the COP21 the Breakthrough Energy Fund was launched. This is a USD 1 billion fund provided by a partnership of 28 high net worth investors committed to fighting climate change by investing in clean energy innovation. Breakthrough Energy Fund is providing capital with a 20-year time horizon, but is looking for a return on its investment. The group is spearheaded by Bill Gates. They have divided the landscape into Grand Challenges in five fields that are the biggest contributors to global greenhouse gas emissions: electricity, transportation, agriculture, manufacturing and buildings. Within each of these Grand Challenges several Technical Quests have been identified, different areas where research and investment might bring us closer to an emission-free future.

For more information, see http://www.b-t.energy/

The sector-specific approach creates a basis for an informed public-private sector discussion with stakeholders. It informs the global community on innovation needs in renewables that require more attention, and identifies priorities for the work of IRENA in this field.

2. ROADMAP FOR ENERGY DECARBONISATION

In this section the REmap case for 2050 is elaborated. The section is intended for an audience that is not yet familiar with the study Perspectives for the Energy Transition (IEA and IRENA, 2017). It elaborates the key insights from an IRENA perspective and it pinpoints the key sectors where a greater innovation effort is needed.

The findings show that we need a ten-fold reduction of the carbon intensity of energy between now and 2050. This has a profound effect on energy supply mix, with renewables growing to two thirds of the total global primary energy supply. What remains are around just below 10 Gt of emissions in 2050 that are concentrated in the industry sector and transport. In industry it's the production of energy intensive commodities that poses the main challenge: iron making, cement making, and the production of chemicals and petrochemicals such as nitrogen fertilisers, plastics and synthetic fibres.

Renewable energy and energy efficiency constitute the bulk of decarbonisation

Achieving a global energy transition that limits global temperature change to less than 2 °C is technically feasible. (IEA and IRENA, 2017), IRENA has analysed what this energy transition would look like from a technical, policy and business perspective. It would be achieved largely by the accelerated deployment of renewable energy and energy efficiency measures (Box 2). The analysis of the International Energy Agency (IEA) conducted with a separate model, but using similar assumptions, have arrived at the same conclusion. The findings are therefore robust.

Energy related CO_2 emissions were 32.3 Gt in 2015 (IEA 2015c). Based on current plans and policies (the Reference Case), these emissions could grow to 37 Gt and 40 Gt per year by 2030 and 2050, respectively. By contrast, in the REmap case, energy and materials efficiency improvements would reduce emissions by about 4 Gt by 2030, about 30 % of the emissions

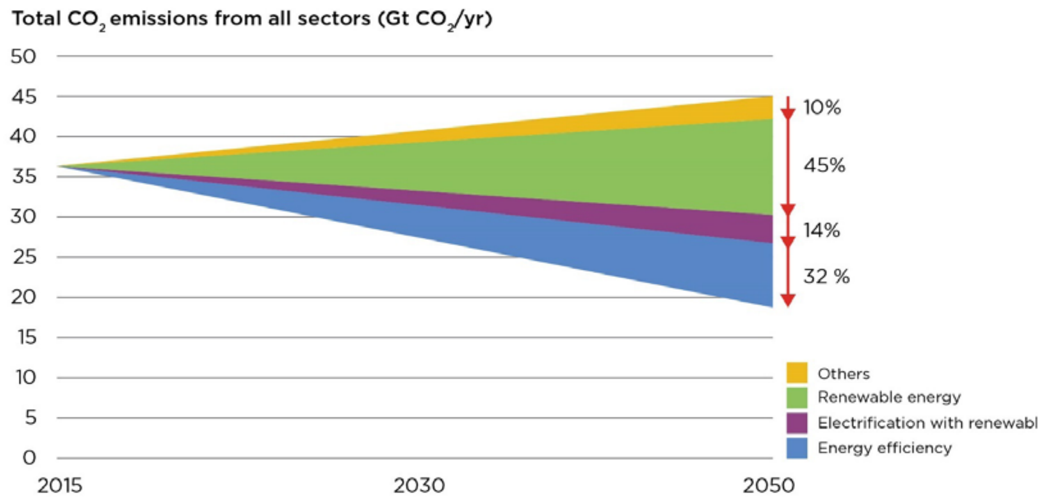
Box 2: Terminology overview

2015 "base year" – 2015 is the start year of the analysis.

Reference Case – the path set by current plans and policies: The analysis is carried out from the bottom up, based on country energy use projections. These projections are provided at the level of end-use sectors, with a breakdown by individual energy carriers. The Reference Case is the most likely case based on planned policies and expected market developments for each country's energy sector between 2015 and 2050. The Reference Case also includes energy demand forecasts made available by the national energy plans of the G20 countries. Where such data are unavailable, information from credible third-party sources was used. Some accelerated commitments relating to renewable energy and energy efficiency improvements are already accounted for under the Reference Case.

REmap – a path of accelerated adoption of renewables: This is the case where the additional potential for renewable energy, energy efficiency, carbon capture and storage, and other low-carbon technologies such as material efficiency improvements are deployed on top of the Reference Case. The assessment is done to achieve an emission pathway in line with the Paris Agreement goals, with a > 66 % probability of holding warming below 2 °C. This pathway requires a carbon emissions budget of 890 Gt CO_2 in the 2015–2100 period, reaching zero emissions in 2060.

Figure 2: CO_2 emission abatement potential of renewable energy and energy efficiency, 2015–2050, with REmap



Based on IRENA analysis in the source: IEA and IRENA, 2017

Note: 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 in 2050 would be at 40.5 Gt and 9.5 Gt per year in the Reference Case and REmap, respectively.

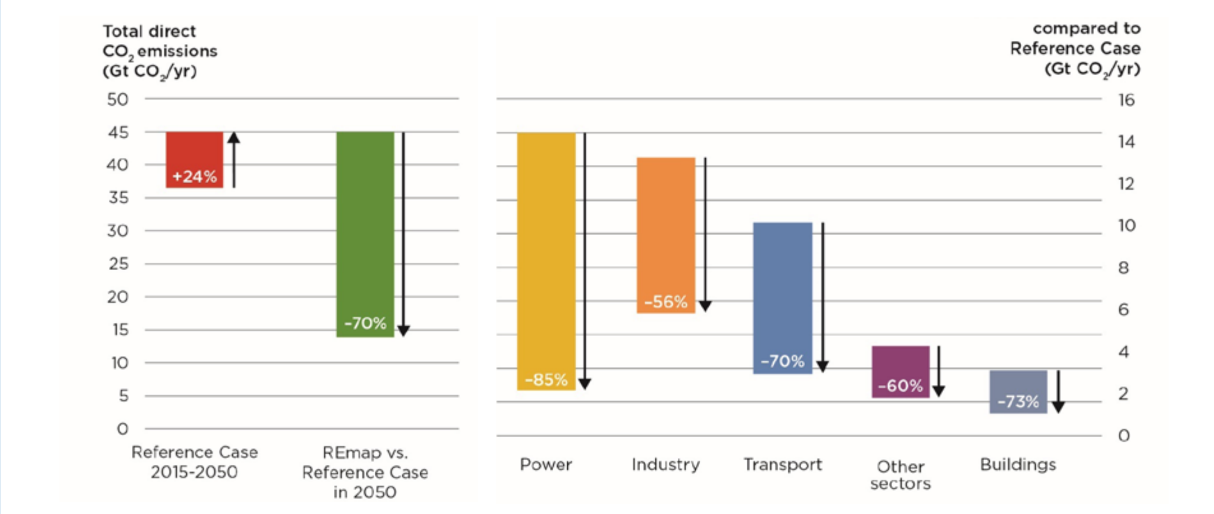
Renewables can account for half of total emissions reductions in 2050, with another 45 % coming from increased energy efficiency and electrification.

reductions needed. Electrification would cut another 1.5 Gt, or 10 % of what is needed. Renewable energy options that were identified based on the bottom-up analysis of the G20 countries would reduce emissions by another 10 Gt. Together, these measures, 2030 emissions would fall to 25.5 Gt in 2030, while the remaining fossil fuel combustion would emit about 20 Gt of CO_2 emissions per year).

That level is sufficient to put the world on a 2 °C pathway in 2030. But to keep the world on this pathway, efforts would need to be strengthened further between 2030 and 2050. This would require energy-related CO_2 emissions to drop to below 10 Gt by 2050, which would be 70 % lower than 2015 levels and 31.5 Gt less than in the Reference Case. About half of these reductions would come from renewable energy technologies. Energy efficiency improvements and electrification would account for the bulk of the other half. The remaining 10 % of reductions would come from additional measures in industry, notably carbon capture and storage (CCS), material efficiency improvements (that partly stem from improved processes) and structural changes. IRENA has considered the deployment of CCS for the industry sector only, especially for those sectors that emit CO_2 in high concentration from their processes, such as iron and steel, cement and chemical and petrochemicals production (Gale 2017). This choice was made as renewable energy and energy efficiency technologies alone are insufficient to results in significant emission reductions.

There are other sources of CO_2 emissions besides those from fossil fuel combustion. These include fugitive emissions (*e. g.* gas flaring), industrial and agriculture process (*e. g.* ammonia feedstock, PFC, HFC,SF_6) and clinker emissions, and emissions from other sources (*e. g.* waste incineration, biofuels) (Olivier *et al.*, 2015)). Land use emissions are excluded from this assessment. These sources add another 3.5 Gt CO_2 per year in 2015. The largest share of emissions comes from process emissions and clinker, which totalled 2.2 Gt in 2015. Under REmap, these emissions grow to 4 Gt in 2050, compared to about 5 Gt in the Reference Case. The reductions in emissions are achieved through the use of industrial CCS for clinker making and from the avoided combustion of plastic waste because of increased recycling. All these emissions need to be reduced significantly, on top of the energy sector abatement efforts.

Figure 3: CO_2 emissions abatement potential by sector, 2015–2050, with REmap



Based on IRENA analysis in the source: IEA and IRENA, 2017

Notes: CO_2 emissions include energy-related emissions (fossil fuel, waste, gas flaring) and process emissions from industry. If only fossil fuel emissions were displayed, excluding waste and gas flaring, then in this figure, CO_2 emissions in 2050 would be 40.5 Gt and 9.5 Gt per year in the Reference Case and REmap, respectively.

By 2050, total energy-related CO_2 emissions should be below 10 Gt. CO_2. Emissions from the power and buildings sectors will be almost eliminated. Industry and transport would be the main sources of emissions.

All sectors must contribute to decarbonisation

The largest CO_2-emitting sectors are electricity generation and industry. They are responsible for about 65 % of all energy-related CO_2 emissions today. The remaining 35 % comes from transport, buildings and district heating. Buildings have a low share, but this increases if indirect emissions related to electricity use are included. The sector breakdown of CO_2 emissions stays roughly constant between 2015 and 2050 under the Reference Case (see Figure 3).

Under REmap, electricity generation sector emissions would fall to around 2 Gt per year by 2050, a decrease of 85 % compared to the 2015 level. This is achieved by an aggressive deployment of renewable energy technologies, especially solar and wind. These renewable technologies would generate more than 80 % of all electricity by 2050. Natural gas and nuclear would generate the remaining 20 %. The decrease in power sector emissions is also an outcome of demand side measures in industry and buildings to reduce electricity use for heating and cooling.

In the REmap case, building emissions would decrease by about 70 % by 2050. Transport and industry are the two most challenging sectors. Transport's emissions would be halved, while industry would become the largest remaining emitter.

Renewable energy will be at the heart of the energy transition

Renewable energy now accounts for 24 % of global power generation and 16 % of primary energy supply. To achieve decarbonisation, the report finds that, by 2050, renewables should be 80 % of power generation and 65 % of total primary energy supply.

The energy sector transition needs to go beyond the power sector, however, to include all end-use sectors. Renewables need to provide the majority of power generation in 2050, with continued rapid growth especially of solar and wind power in combination with enabling grids and new operating practices. But in addition, the buildings, industry and transport sectors need more bioenergy and more solar heating and electricity from renewable sources that substitute conventional energy. Electric vehicles need to become the predominant car type by 2050. Liquid biofuels production must grow ten-fold. High efficiency all-electric buildings should become the norm. Deployment of heat pumps must accelerate and a combined total of 2 billion buildings will need to be either be new-builds or go through deep retrofits. The rate of renewables deployment needs to increase seven-fold, from 0.17 % per year in recent years to 1.2 % per year. At the same time, energy intensity improvements need to accelerate. For the world as a whole, energy intensity improved by 1.3 % per year between 1990 and 2010. That rate accelerated to 1.8 % per year between 2010 and 2015. We need a further improvement to 2.5 % per year for the coming decades.

Both in the power sector and in the end use sectors, significant synergies exist between renewable energy and energy efficiency. In the power sector, power generation from many types of renewables is assumed to be 100 % efficient in international energy statistics. That represents a significant improvement over fossil power plants, which achieve between 25 % to 85 % efficiency. Electric vehicles are three times as efficient as conventional gasoline and diesel cars. Heat pumps achieve efficiencies four to five times higher than condensing gas boilers.

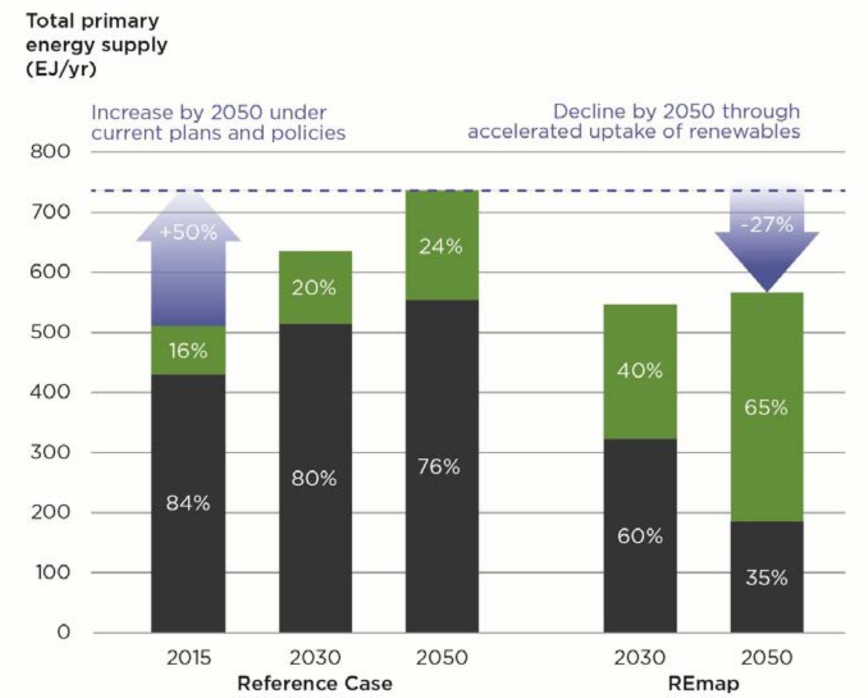
As a result, the accelerated deployment of renewables can strengthen energy efficiency, while the accelerated deployment of energy efficiency means energy demand is reduced, so the same amount of renewable energy results in a higher share of renewables.

A significant change in the global energy supply mix

The total energy demand in 2050 under REmap would be similar to today's level. But the supply mix would change substantially, compared to both current mix and to the Reference Case.

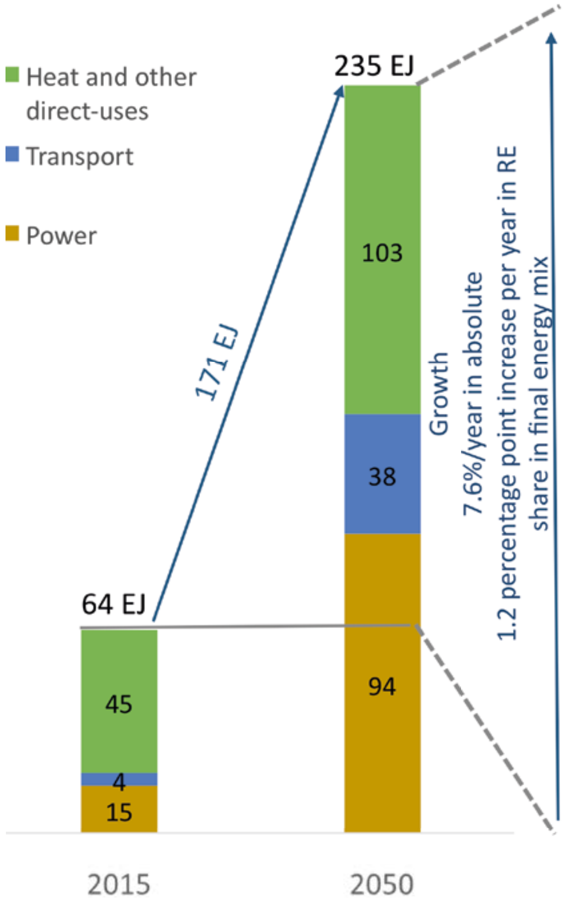
In the Reference Case, the total primary energy supply is estimated to grow by more than 50 % between 2015 and 2050. This is equivalent to an average annual growth rate of about 1.2 % per year, roughly half of the rate seen in the past two decades. Despite this slowdown, the total primary energy supply would increase to about 835 exajoules (EJ) by 2050 in the Reference Case. This demand is equivalent to the current size of 6 and one half China. Just under 80 % of this total would still be supplied

Figure 4: Global total primary energy supply in the Reference Case and REmap, 2015–2050



Based on IRENA analysis in the source: IEA and IRENA, 2017

Figure 5: Required compound annual growth rate in renewable technology options between 2015 and 2050



Required compound annual growth rate per technology

Power	
Solar PV	11.1%
Wind	8.1%
Hydropower	1.2%
Geothermal	9.1%
Biomass power	4.7%
Other Power	17.3%
Transport	
Liquid biofuels	5.5%
Hydrogen for transport	20.6%
Heat and other direct-uses	
Biofuel buildings	-1.2%
Biofuel industry	3.9%
Renewables district heat	4.9%
Geothermal heat	6.9%
Solar thermal	8.8%
Hydrogen	13.7%

Based on IRENA estimates

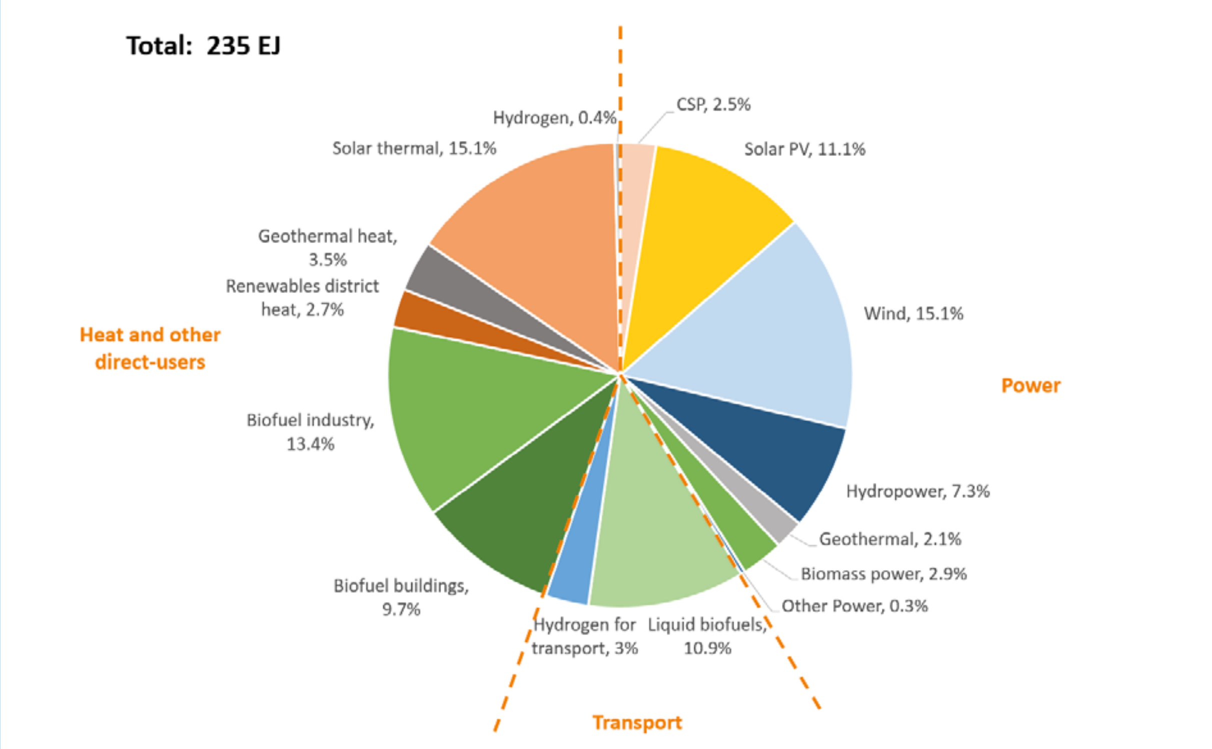
Renewables would be the largest source of energy supply under REmap in 2050, representing two-thirds of the energy mix. This requires the share of renewable energy to increase by about 1.2 % per year, a seven-fold acceleration compared to recent years. 46 % of the total renewable energy growth from 2015 to 2050 would be deployed in the power sector, 20 % in the transport sector and 34 % in the heat and other direct-uses sector.

by fossil fuels in 2050, down slightly from today's level of 84 %. If current national energy plans remain unaltered, renewable energy would bring little change in the supply mix, since those plans mainly reflect market trends.

Under REmap, the total global primary energy supply in 2050 would reach 635 EJ per year in 2050, only marginally higher than today's level and 26 % less than in the Reference Case. Total non-renewable energy use would be reduced by 67 % to 180 EJ, compared to 560 EJ in the Reference Case. The share of renewable energy in the total primary energy supply grows to about 65 % by 2050 (Figure 4).

The needed growth to achieve this would come from a mix of all renewable energy technologies. In end-use sectors, solar thermal and bioenergy predominantly drive the growth. In the power sector, wind and solar PV grow the fastest. These figures are shown in

Figure 6: Renewable energy technology deployment in 2050



Based on IRENA estimates

Note: EJ = exajoules. CSP = concentrated solar power

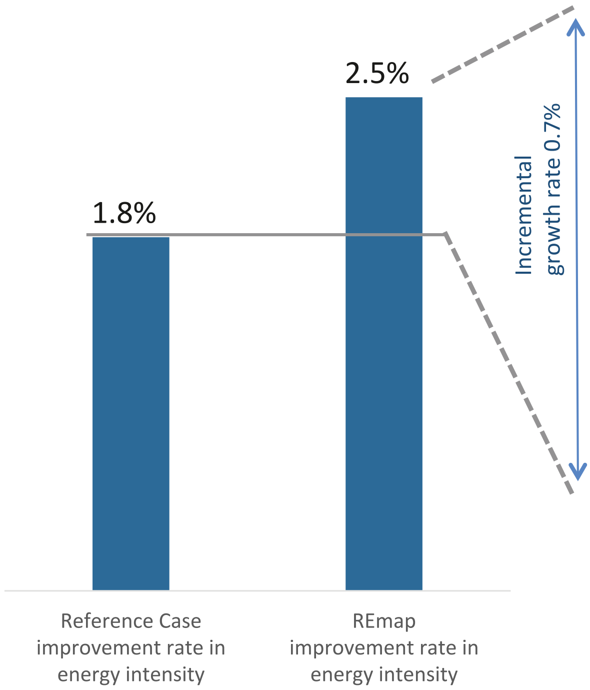
Figure 5 for each renewable energy technology. For most technologies, installed capacity will grow by just below 10 % per year. A few emerging technologies would grow by around 20 % per year. These figures indicate that achieving the required rate of growth of renewables to decarbonise the energy sector is challenging but conceivable.

Under REmap, total primary energy supply volumes remain more or less flat between 2015 and 2050. Global GDP, however, triples over this period. As a result, energy intensity drops from about 5 gigajoules (GJ) per USD to 2.1 GJ per USD between 2015 and 2050.[1] This is equivalent to an energy intensity improvement rate of around 2.5 % per year, a doubling compared to the trends observed between 1990 and 2010. In 2015, the improvement rate was 1.8 %, which is still much lower than what is required to reach the 2050 goal.

Figure 7 shows the factors that cause energy intensity to either decline or increase in 2050 in the REmap case compared to the Reference Case. Accelerated deployment of renewables causes energy intensity to decline by a third (in part because of net savings in primary energy use of 8 %), whilst energy efficiency contributes to the other two-thirds. On the other hand, CCS in industry requires heat for solvent regeneration as well as for compression and pumping of CO_2. These processes increase the primary energy demand by 7 % in total. The additional demand for energy offsets some of the decline in energy intensity improvements.

1 The reverse of this indicator yields energy productivity where output is divided by energy consumption.

Figure 7: The contribution of renewable energy to global energy intensity improvements in REmap, 2015–2050



Contributors to energy intensity reduction

Renewable Energy	**24%**
Heating/fuels	4%
Power	4%
Electrification in transport	22%
Power for electrification & CCS	-6%
Energy Efficiency	**76%**
Heating/fuels	53%
Power	22%
CCS penalty	-1%
Structural changes	2%

Based on IRENA estimates

In addition to energy efficiency, renewable energy significantly contributes to energy intensity improvements.

The energy transition is affordable and makes economic sense

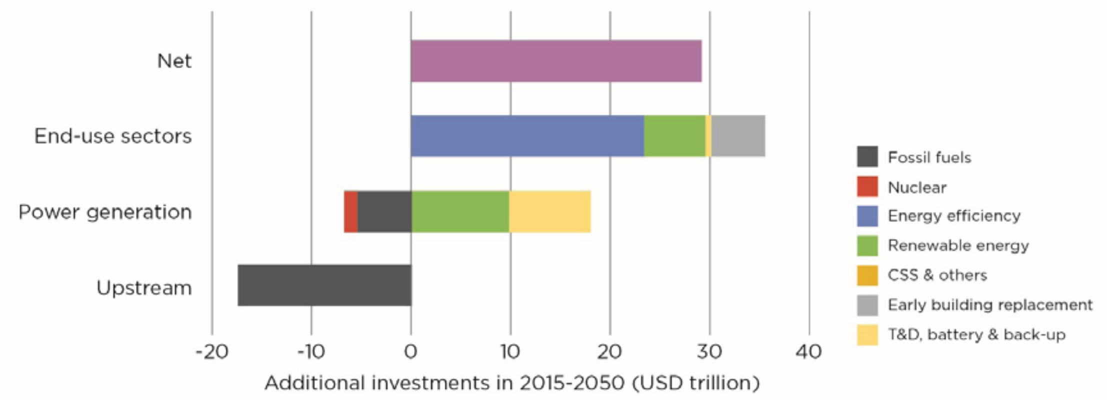
The economic case for the energy transition has never been stronger. Today around the world, new renewable power plants are being built that will generate electricity for less cost than fossil-fuel power plants. And through 2050, decarbonisation would create more new jobs in renewables and energy efficiency than those lost in fossil-fuel sectors.

IRENA has assessed the pathways for emissions reductions and concluded that energy efficiency and renewable energy account for 90 % of the emissions reduction potential. This is complemented with CO_2 capture and storage where needed, notably in industrial processes (fertilisers, iron making and cement making).

In 2016, nearly USD 290 billion was invested in renewable power (excluding large hydropower) (BNEF, 2017). These investments in new capacity will need to be scaled up significantly to enable decarbonisation of our energy system. Renewable energy alone, however, will not suffice. Energy efficiency investments will also be needed along with significant investments in other low-carbon technologies. Under the Reference Case, IRENA's analysis estimates cumulative investment needs in energy supply and demand assets of 128 trillion between 2015 and 2050. The decarbonisation transition in REmap would require an additional USD 29 trillion in cumulative investment over the same period, as shown in Figure 8.

The incremental investment needs in electricity generation or in fuel supply in the REmap case are relatively small (*i.e.* 0.4 % of GDP in 2050). This

Figure 8: Additional investment needs, 2015–2050, based on Reference Case and REmap



Based on IRENA analysis in the source: IEA and IRENA, 2017

Note: electric vehicle charging infrastructure, hydrogen pipelines and refueling stations are included. Electrification also includes additional costs for electricity generation growth.

Meeting the 2 °C target requires investing an additional USD 29 trillion between 2015 and 2050 compared to the Reference Case. The largest additional investment needs are in energy efficiency, followed by renewables. The total investment cost, however, is reduced by the avoided investments in the upstream sector and in fossil-fuelled power generation.

is partially explained by the significant growth of renewable energy power generation investments in the Reference Case, as well as higher efficiency in the REmap case compared to the Reference Case, which reduces the need for additional energy supply. The bulk of the additional investment needs will be in end-use sectors, including buildings, industry and transport. Increased implementation of all types of low-carbon technologies will be needed in end-use sectors, notably energy efficiency in buildings. Supply side investments (upstream and power supply) remain at the same level as in the Reference Case. The savings from avoided investments in fossil fuels, in upstream and electricity generation sectors, add up to USD 25 trillion.

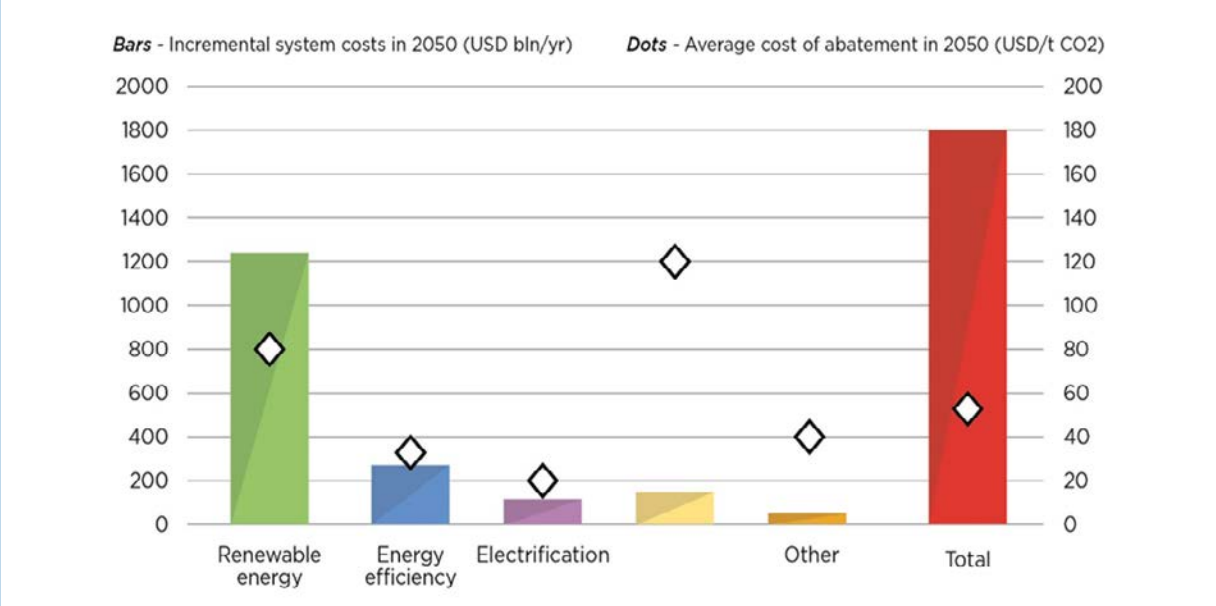
While the total energy investment needed for decarbonising the energy sector is substantial – USD 0.83 trillion per year between 2015 and 2050 – it amounts to a small share (0.4 %) of global GDP. Furthermore, IRENA's macroeconomic analysis suggests that the energy transition investments create a stimulus that, together with other pro-growth policies, will:

- boost global GDP by 0.8 % in 2050, while in a worst-case case (full crowding out of capital), would still create a positive impact of 0.6 % since the effect of pro-growth policies (i.e. carbon pricing with revenues recycled in order to lower income taxes) is still favourable

- the energy sector (including energy efficiency) would also employ around 6 million more workers in 2050 compared to the Reference Case. The new jobs in the renewable energy sector would more than offset job losses in the fossil fuel industry, with further jobs being created by energy efficiency activities. Overall GDP improvement also will induce additional job creation in other economic sectors

- improve human welfare through important additional environmental and health benefits thanks to reduced air pollution. There are also other environmental benefits such as reduced freshwater or groundwater use, but these have been excluded from the scope of this work.

Figure 9: Incremental cost and the average of abatement by category of technology option in REmap, 2050



Based on IRENA analysis in the source: IEA and IRENA, 2017

When abatement is measured as cost per tonne of CO_2, energy efficiency is the most economically viable, followed by renewable energy. The bulk of the system costs lie in renewables and end-use sector electrification technologies, such as electric vehicles and electric heating and cooling systems in buildings.

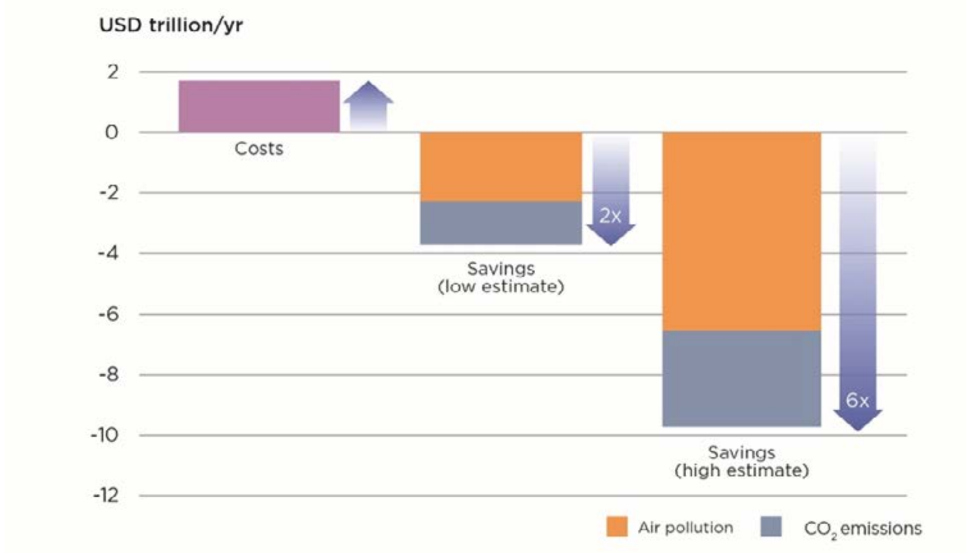
When the additional investments are annualised considering a 10 % discount rate and the respective lifetime of individual technologies, and any additional operation and maintenance (O&M) costs are included, the portfolio of technologies identified in REmap requires incremental system costs on top of the Reference Case of about USD 1.8 trillion per year in 2050 globally. This assumes a crude oil price of USD 80 per barrel. In the REmap analysis, CO_2 emissions are reduced by about 31.5 Gt per year in 2050 compared to the Reference Case. This translates to an average cost of USD 60 per tonne of CO_2 emissions abated.

This cost, however, varies significantly among the technologies contributing to reduced emissions, as shown Figure 9. The most expensive technology is CCS for industry, where the abatement cost is USD 120 per tonne of CO_2. Energy efficiency measures, by comparison, have much lower costs: around USD 35 per tonne of CO_2. Abatement costs of electrification (excluding any investments associated with charging infrastructure) and renewable energy are estimated at USD 22 and USD 75 per tonne of CO_2.

A significant potential exists to increase the renewable share in primary energy supply to 30 % by 2030 and 65 % by 2050. Renewables improve welfare in ways that are not captured by GDP, such as reduced health impacts from fossil fuel combustion. Welfare gains for society could also come from increased energy access, helping to generate sustainable livelihoods and better quality of life in rural areas. Therefore, a holistic approach is needed that factors in all externalities, including the environmental and health benefits of decarbonisation through the integration of renewables. The analysis concludes that such a development, a key element of the global transition of the energy sector towards a sustainable one, is not only affordable but also that the benefits exceed the cost by a factor of 2–6: USD 4–10 trillion of benefits compared to USD 1.8 trillion incremental system costs. Notably, health benefits will be significant, by a factor two higher compared to climate change abatement benefits.

Comparing costs and reduced externalities for 2050 shows the scale of the savings from increased share of renewables and higher shares of energy efficiency combined with other low-carbon technologies.

Figure 10: Costs of decarbonisation compared to reduction of externalities, 2050



Based on IRENA analysis in the source: IEA and IRENA, 2017

Benefits from reduced externalities exceed the costs of decarbonisation by a factor between two and six in 2050. Health benefits from reduced air pollution alone exceed the costs.

These technologies would also reduce external cost of non-renewable energy use on human health and climate change. When these reduced externalities are considered, total benefits would be between two and six-times greater than the incremental system costs of decarbonisation, which are estimated to be USD 1.8 trillion per year worldwide in 2050 (Figure 10). In absolute terms, reduced externalities can bring benefits of up to USD 10 trillion annually by 2050. Outdoor air pollution is a major externality, and it accounts for about two-thirds of this total. CO_2 reductions are also important, but their relative importance depends on the assumed social costs of carbon (here, between USD 50 and USD 110 per tonne CO_2 in 2050).

An energy transition based on renewables and energy efficiency implies an energy system which is much more capital-intensive, with upfront investment costs representing a higher share of the total cost. This has important implications for policy makers. Successfully achieving the transition would require adequate financing mechanisms, new business models and solid policies that encourage consumers and companies to invest in the required assets (*e.g.* electric vehicles, better insulated homes, solar panels). Developing policies to internalise external costs has to regarded in conjunction with pricing externalities. The analysis in this working paper merely refers to the impact of renewable energy technologies (pathways with more efficient non-renewable energy uses, for example, have not been considered).

On a sector level, the effect of implementing decarbonisation varies, but all sectors imply incremental system costs. The largest savings from reduced externalities are found in the power sector, mainly due to the drop in the use of coal. Transport would see the second-highest reduction in externalities, largely because of the higher assessment of air pollution costs stemming from the combustion of fuels in urban environments. In buildings there are some savings from CO_2-related externalities, but overall there is a slight increase in air pollution related externalities as the share of bioenergy for heating increases while gas use decreases. In total, when quantifying the cost and reduced externalities together, all sectors except buildings result in moderate to significant savings with a decarbonised energy system in place.

In economic terms, there are also synergies between energy efficiency and renewable energy which would reduce the cost of emissions abatement. For instance, higher levels of energy efficiency would require less renewable energy capacity to supply the same energy service, thereby reducing the related investment needs.

The energy transition gap: Technologies and sectors that require more innovation

The level of energy transition that has been achieved in individual sectors varies. While renewables deployment in the power sector has progressed well over the past years (see Figure 11), the same cannot be said for all end-use sectors (residential and commercial buildings, manufacturing industry and transport). In these end-use sectors, progress and technology successes have been mixed. For instance, lighting has become more efficient in most countries, but energy efficiency improvements in industry have not gone beyond the business as usual for decades. All sectors will require continued improvements in existing low-carbon technologies and in some cases, the emergence of breakthroughs or a major changes in production processes will be vital. The required transformative innovation must not target technology development alone. It also must be aimed at creating new businesses and new jobs, helping industries to flourish, and providing additional economic opportunities to increase wealth.

Box 3: Denmark to reach 100 % renewable with wind power, sector coupling, efficiency and innovation

Denmark has embarked on an energy transition to 100 % renewable energy in all sectors by 2050. By 2020, at least half of Denmark's electricity will be generated by wind power. By 2050, the country aims to have an energy system independent of fossil fuels. Besides renewables, improvements in energy efficiency and an enabling environment through the coupling of electricity and end-use sectors will be key.

From the earliest days of Denmark's energy transition, policy makers understood the importance of giving citizens a stake in clean energy projects. The country created a grant programme in the 1980s that covered 30 % of the initial capital costs of wind projects. This has resulted in the development of local cooperatives, giving individuals and households a chance to invest in wind energy projects. Five years after the programme started, the cooperatives' 100 000 investors were responsible for nearly 90 % of all turbines installed in Denmark. After more than 10 years, not only do investors have their money back, they also receive a 7 % annual return on their investment.

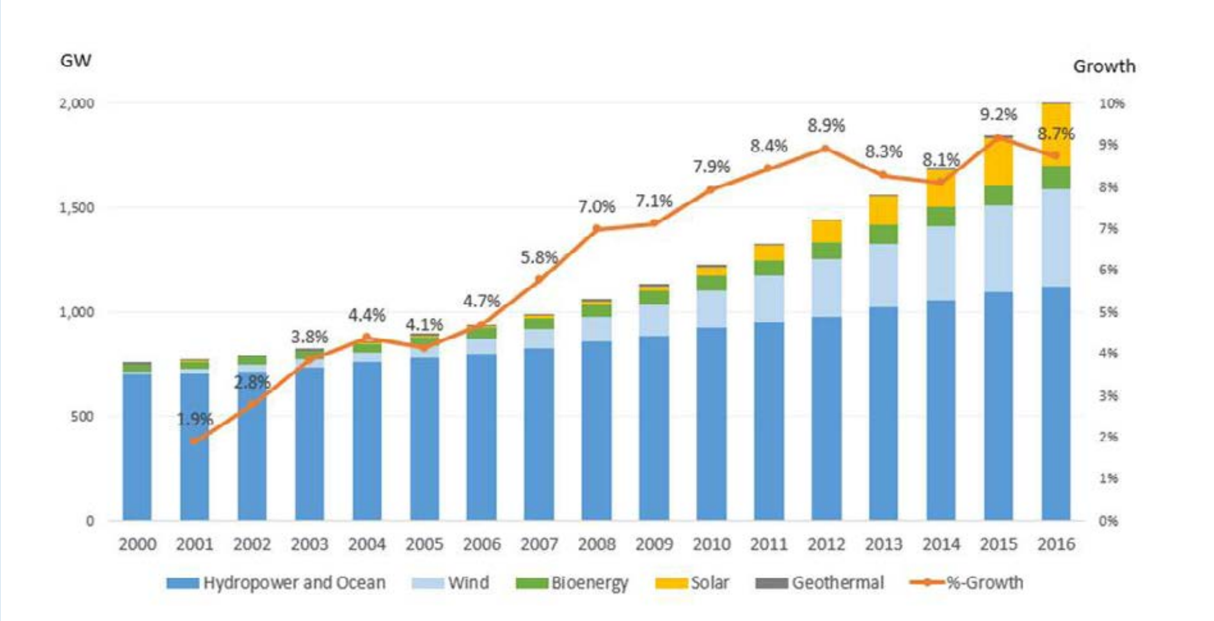
Another lesson from Denmark is the opportunity to reap the efficiencies of district heating and cooling. Denmark's decision many years ago to deploy district heating systems represents a key element of its energy transition. District systems can be much more efficient than the more common model of having every residence or business provide its own heat through decentralised systems. District systems can also be powered with solar systems, representing an exciting new frontier. An example of a solar-based district heating system is the one located in Dronninglund. It has a capacity of 26 megawatts (MW), covering around 40 % of the annual heat demand. Dozens more solar systems have been installed or are in the works across Denmark. Copenhagen also has launched a district cooling system that draws cool water from the city's harbour to pre-chill water destined for buildings with large cooling loads. The city estimates district cooling reduces electricity consumption by 80 % compared to conventional air conditioning.

Unleashing the creativity of public-sector entrepreneurs can lead to innovative solutions for decreasing the carbon footprint by sector coupling. For example, a local water service company has developed a technology to utilise renewable energy from wastewater, a waste product that is viewed nearly everywhere else as a problem to be managed. The company turned wastewater and other organic material into fertiliser for agricultural crop production, and also produced renewable heat and electricity.

Denmark's stories and its innovative solutions to tackle energy sector decarbonisation represent good practices for countries to follow in their own energy transitions.

IRENA's report released in 2017, "Renewable energy in district heating and cooling (DHC): A sector roadmap for Remap" examines the renewable DHC potential to drive the energy transition. (IRENA 2017d)

Figure 11: Renewable power capacity additions, 2000–2016



Source: IRENA

Renewables account for more than half of annual power generation capacity additions since 2012. Renewable power share is growing at a rate close to 10 % per year.

For end-use sectors that account for around one third of direct emissions in the Reference Case in 2050, the pathway for deep emissions reductions is not evident or there are no economic scalable solutions available that can be ramped up (see Figure 12). The areas without currently viable options include:

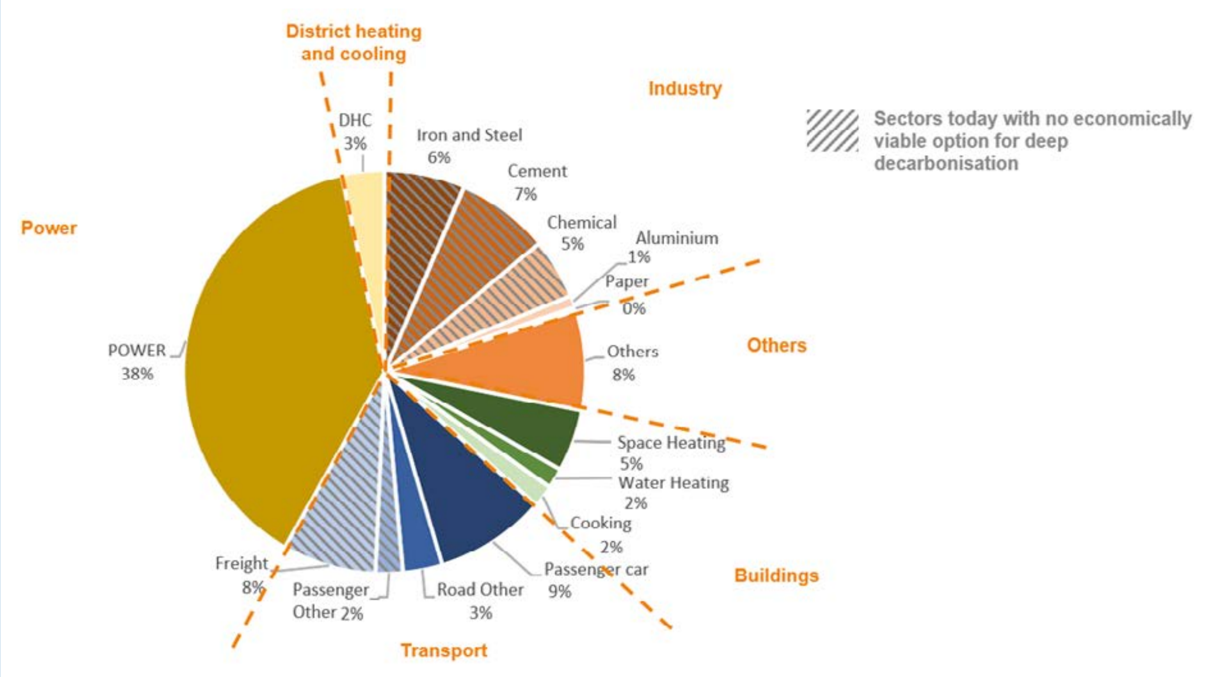
- iron and steel making
- cement making
- chemical and petrochemical production (notably production of synthetic and organic materials)
- waste handling and emissions from non-energy use of fossil fuels
- maritime transport
- aviation
- long-range freight
- replacement of non-sustainable traditional biomass

These sectors all have non-technical barriers for emissions reductions. In industry for example, international competitiveness and carbon leakage have been major concerns. As a result, these sectors have been largely exempt from ambitious emissions reduction efforts. To some extent this is also the case for transportation of goods. This raises the question of whether governments should focus on finding technology solutions or creating a better enabling environment for innovation so the private sector receives the right incentives.

While there are encouraging signs in other sectors, such as personal electric vehicles, the transition is still at an early stage. Nevertheless, for these solutions, the performance needs to be enhanced and their costs should be reduced. Higher costs of the required technologies result in additional uncertainty about the right direction. One example is the competition between electric vehicles and hydrogen fuel cell vehicles in markets such as Japan.

Certain other aspects also need attention from a systems operations perspective. For example, a power system that largely operates based on renewables with high shares of variable renewables is a new concept. The Nordic countries are demonstrating the possibility of safely relying on high shares of renewables up to close to 50 %. However, the precise

Figure 12: Breakdown of global CO_2 emissions by sector, 2015



Based on IRENA estimates

Around one third of direct energy emissions in the Reference Case in 2050 currently offer no economically viable option for decarbonisation.

setup and operation of systems with shares higher than 50 % on an annual basis are still not entirely resolved.

Also, certain critical technologies with multiple outputs need to change. For example, oil refineries produce gasoline, diesel and naphtha but also other products such as LPG (an important cooking fuel in many countries), bitumen (the “glue” for asphalt roads) and heavy fuel oil (currently used for ship bunkering). A transition away from oil fuels thus raises such questions as how future roads will be constructed.

Innovation beyond technology

As the technology to drive the transformation in the energy sector is develops and reaching commercialisation, the next stage to scale-up the transformation requires to integrate these technologies in dynamic energy systems. This was the focus of the first IRENA Innovation Week (IRENA 2016b) held in Bonn on 10–13 May 2016, and the Ministerial Roundtable at IRENA’s 7th Assembly in January 2017 (IRENA 2017c) The integration of high shares of renewables in energy systems calls for a holistic innovation approach, from technology to infrastructure, system operation, market, regulation, and business innovation.

Technology innovation needs to be complemented by business models tailored to the commercialisation of novel technologies. Successful emerging companies in the power domain, for example in the PV market, are not necessarily coming up with a more efficient or cheaper type of solar panel. They come up with a business model that sells large numbers of small systems, thereby allowing the firm to purchase components at relatively low cost in bulk. However, regulations also need to enable small and distributed power generators to be able to participate in the power market. These examples show how innovative business models can create impact, as technology breakthrough technologies can, when appropriate enabling policies and regulations are in place.

In addition to the technical aspects, there is a need to rethink and innovate on energy markets, regulation, policy and business models. Policies have evolved from feed-in-tariffs, to premium tariffs and auctions. In fact, recent auctions have shown to be an effective approach in many countries that have resulted in cost reductions in renewable electricity production. Market design and regulations would need to support investments in generation adequacy and system flexibility.

Information and communication technologies are opening the door to new ways of making business and designing markets in the electricity sector.

Box 4: US renewable energy R&D – Shifting emphasis from invention to deployment

Over the 35-year period from the US Department of Energy's (DoE) inception at the beginning of fiscal year 1978 through 2012, federal funding for renewable energy R&D amounted to about 17 % of the energy R&D total, compared with 15 % for energy efficiency, 25 % for fossil, and 37 % for nuclear (Sissine, 2012).

DoE R&D for energy efficiency and R&D amounts to USD 1.175 billion in 2014. This includes nearly USD 250 million for solar and biomass each, USD 88 million for wind and around USD 50 million for geothermal and water power. The requested budget for 2015 is 10–20 % higher. There is also R&D sponsored by individual states. In comparison, General Electric alone spent USD 2.1 billion on energy infrastructure research in 2011 (all forms of energy) highlighting the importance of the private sector in energy related R&D.

In addition, in 2014 the DoE announced a USD 4 billion in loan guarantee program available to innovative renewable energy and efficient energy projects (US DoE, 2014d). The program is aimed at supporting market ready technologies.

ARPA-E, or Advanced Research Projects Agency-Energy is a US government agency that was set up in 2007 and to promote and fund research and development of advanced energy technologies. A key goal of ARPA-e is to support technologies in early development stage to move into the market place. It is modelled after the Defense Advanced Research Projects Agency (DARPA).

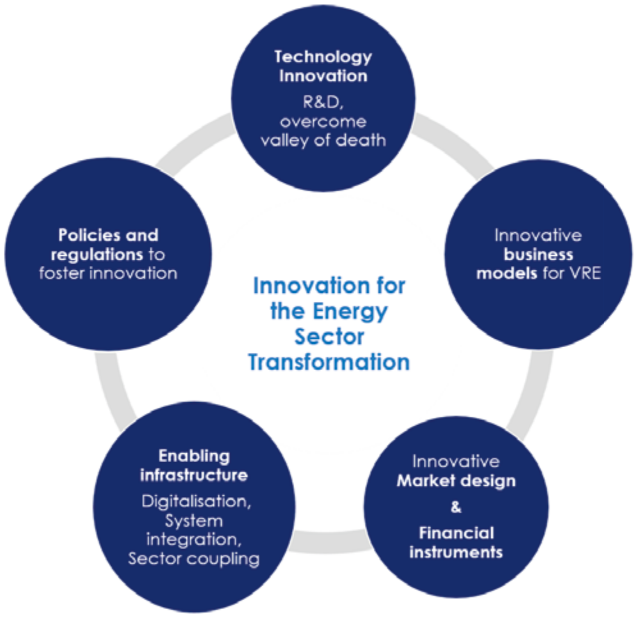
ARPA-E is intended to fund high-risk, high-reward research that might not otherwise be pursued because there is a relatively high risk of failure.

ARPA-E was created to fund energy technology projects that translate scientific discoveries and cutting-edge inventions into technological innovations, and accelerate technological advances in high-risk areas that industry is not likely to pursue independently. It does not fund minimal improvements to existing technologies; such technology is supported through existing DoE programs, such as those of the DoE Office of Energy Efficiency and Renewable Energy (EERE).

ARPA-E funding comes in relatively small amounts, typically USD 0.5–10 million per project. Government agencies, academia and private individuals can apply. Several rounds have been held dispersing grants typically up to USD 100 million each. 362 projects have received more than USD 900 million through ARPA-E's programs and open solicitations.

Twenty-two of the projects that have received about USD 95 million in federal funding have raised a collective USD 625 million in private-sector investment. And while venture investment is one way to measure success in the green technology field, it's far from the only one. Some ARPA-E grant-winning companies have done well raising venture capital funding and landing customers and partners on their own. Private sector leverage should be a priority for further expansion. However, the question at the moment is to which extent ARPA-E will be affected by changes in the local policy in the US.

Figure 13: Holistic innovation approach for the energy transition



Source: IRENA

From mobile pre-paid models in off-grid systems, to mobile apps design for smart electric vehicle charging, and the use of blockchain technology, used for transactions with bitcoins, for trading megawatt-hours between independent suppliers and consumers of renewable power. Some markets are implementing retail tariff reforms, moving from large electricity blocks and long periods of stable prices and once-a-year meter readings, towards real-time prices.

A holistic innovation approach and its implications for the transformation of the power sector, will be analysed in-depth in a forthcoming IRENA study on, the Innovation Landscape for the Power Sector Transformation.

3. TECHNOLOGIES AND POTENTIAL BY SECTOR

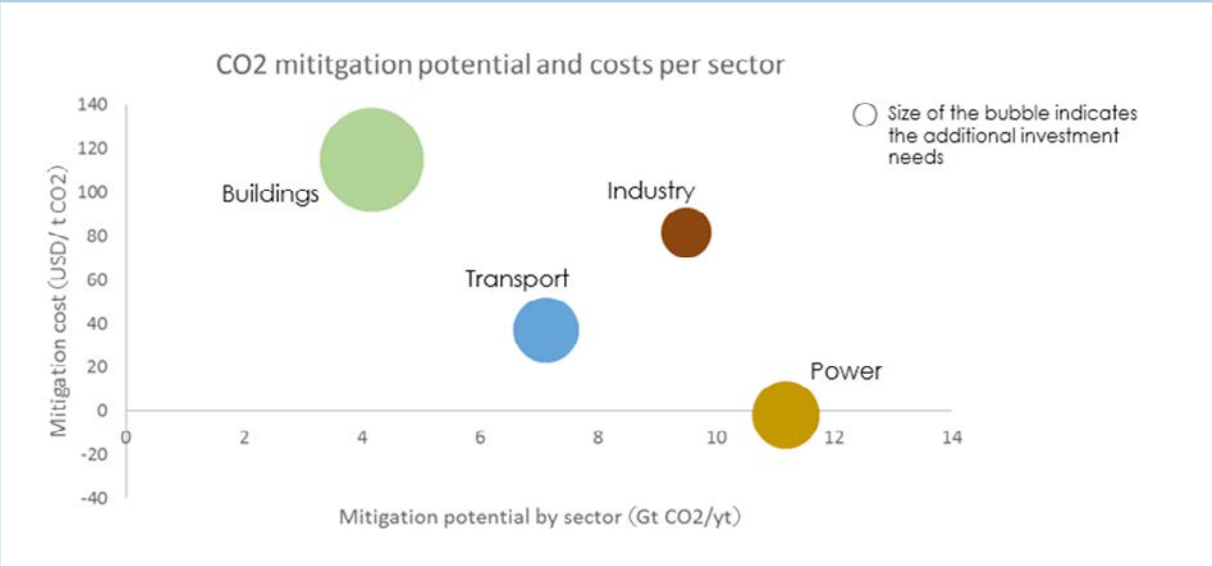
This chapter elaborates the findings on a sector and technology level. The current state of innovation is compared with the innovation needs given the 2050 objective. Based on this analysis innovation bottlenecks are elaborated. Also the market growth opportunities and the cost of innovation are elaborated. This section is intended for an audience of sector experts seeking to view sector-sector efforts with a global energy transition perspective. It is intended, also, for global energy and climate policy makers seeking to pinpoint the best focus areas for innovation.

Annex B contains a detailed overview of the emission reduction potentials, split into 12 sectors across energy supply and demand. This overview is based on literature review and expert consultations. Baseline trends are assessed based on physical demand growth and structural change. This is followed by an assessment of technology options and economic emissions-reduction potential, the future role of renewable energy supply, and the investment needed to realise this.

For each category the emission reduction potentials have been assessed across the following categories:

- structural change (that changes the useful energy service or the need for materials production, without affecting the utility of the service to the consumer)
- technical energy efficiency
- electrification with renewable electricity
- use of other fossil carbon free energy vectors
- accelerated deployment of renewable energy
- CCS

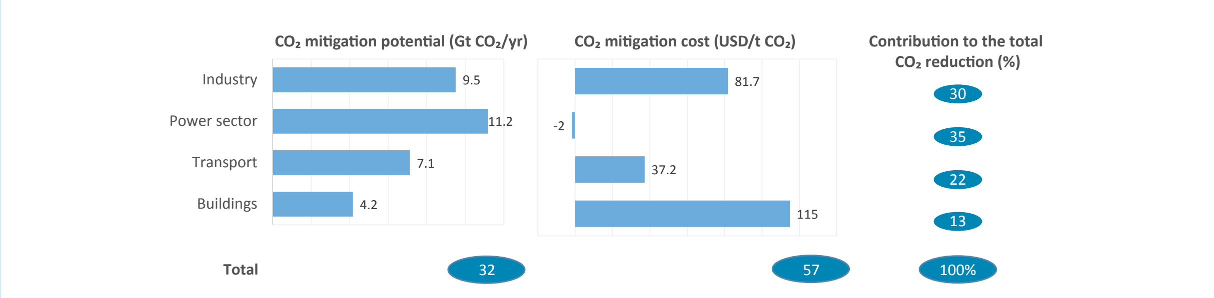
Figure 14: Correlation of abatement potential and costs per sector by 2050



Based on IRENA estimates

The highest potential for renewables and decarbonisation can be found in the sector with lowest cost. The power sector presents a strong business case for deployment of renewables. Industrial process and buildings heating are the most challenging. The largest investments for decarbonisation will be needed for buildings, but these yield limited reductions at high cost.

Figure 15: Abatement potential and costs per sector by 2050



Based on IRENA estimates

The largest emissions reduction potential exists in the power and industry sectors. The average abatement cost of technologies is highest in the buildings and industry sectors.

The implications regarding the relevance of technology solutions for global emissions abatement as well as hotspots for accelerated innovation efforts are summarised in Table 1 in this chapter.

Abatement potential and costs by sector and technology

A consolidated view of the sector analysis in this study, depicted in Figure 14, shows that the power sector has the highest CO_2 emission abatement potential. It also is the most cost-effective in terms of average marginal abatement cost. The technology options to decarbonise transport are close to being economically viable, with a significant abatement potential. Industry represents a very significant part of the abatement potential; however, the abatement cost of the identified technology options remains substantially high. The buildings sector would make a smaller, but still significant, contribution to the decarbonisation of the energy sector as a whole. The average abatement cost and the need for additional investments are higher in buildings than in any other type of energy use. The overall conclusion is that the required decarbonisation in the power sector looks viable, and is close to viable in the transport sector. But big challenges remain are in the transport and buildings sectors. The analysis also shows that the higher the absolute abatement potential, the lower the cost of abatement. This indicates that implementation should be facilitated first with the power sector, followed by transport and industry and finally buildings.

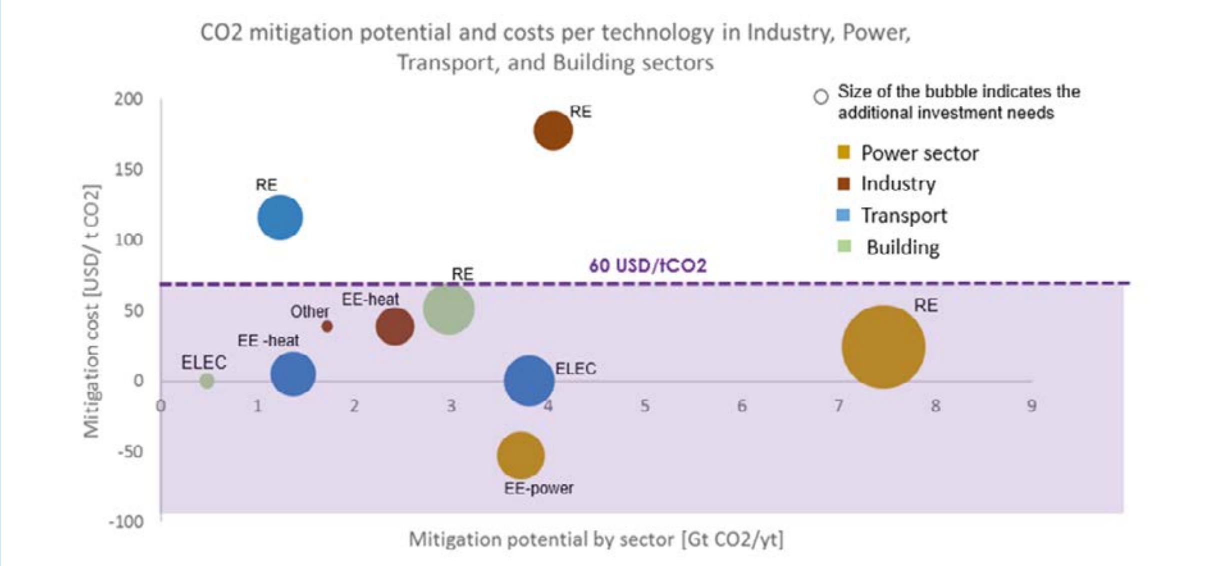
The power sector would contribute up to 35 % of total emissions reductions in energy by 2050, as shown in Figure 15. The power sector also has the lowest average abatement cost. Some costs are even negative, indicating that the transformation in the power sector already is cost-effective. The industry sector closely follows the power sector in terms of abatement potential, accounting for 30 % of total emissions reductions in energy by 2050.

The average abatement cost of the technology options for industry remains considerably higher than for the power and transport sectors, above USD 80 per tonne of CO_2. The transport sector would account for 22 % of the reduction in CO_2 emissions, with an average marginal cost of abatement around USD 37 per tonne of CO_2. As previously mentioned, the buildings sector shows the highest abatement costs, USD 115 per tonne of CO_2, and its abatement potential would account for 13 % of total emissions reductions.

In addition to the overview of the four sectors, various technology options need to be examined. Those options can be grouped into: Renewable energy, energy efficiency in heating, energy efficiency in power, electrification of end-use applications, carbon capture and storage, and other industry-related options such as efficiency in materials and process improvements.

Figure 17 and Table 1 show the abatement potentials by type of option. The chart shows the key significance of renewable energy for overall emissions reduction. The shape of the cost supply curves, available in the Annex, also varies among the options. There are significant cost-saving options in energy efficiency, but high costs for CCS and a pattern of continually rising costs for renewable energy options.

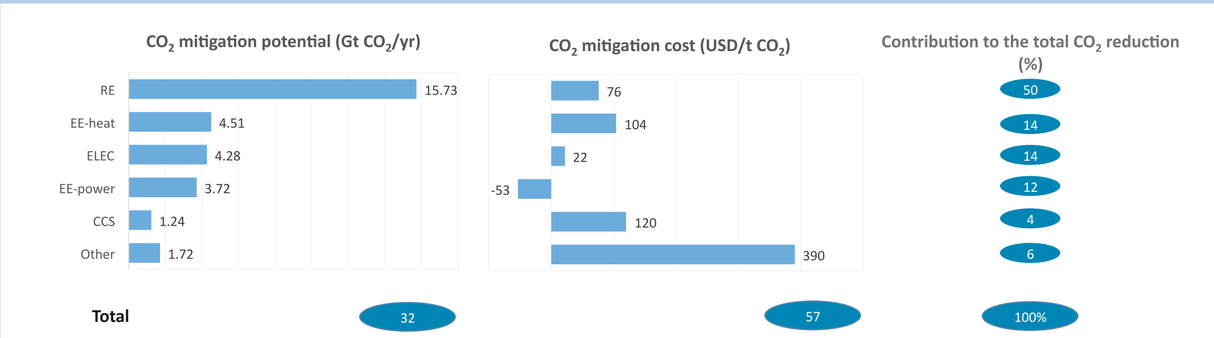
Figure 16: Relation of abatement potential and costs by technology by 2050



Based on IRENA estimates

A CO_2 price above USD 60 per tonne could unlock most of the potential for low-carbon technologies to decarbonise the energy sector. Transport and buildings may require regulation or subsidies that supplement a carbon price.

Figure 17: Abatement potential and costs per technology by 2050



Based on IRENA estimates

Renewable energy would represent half of the emissions reductions required to meet global climate goals. Energy efficiency accounts for bulk of the other half, followed by CCS and other low-carbon technologies such as material efficiency improvements.

Table 1: Technology options per sector with scaling up multiplier, 2015–2050.

	CO_2 abatement potential compared to the Reference Case in 2050	Growth index installed capacity 2015–2050	Compound annual growth rate 2015–2050	Innovation speed	Innovation opportunities
	(Gt CO_2/yr)	2015 = 1	(%/yr)		
Power sector					
Hydropower (incl. pumped hydro)	0.0	1	0.9		Retrofit existing plant; river basin planning; floating PV
Solar PV	2.6	29	10.1		Building integrated PV
Solar CSP	0.8	144	15.2		Cost reduction; low cost thermal storage; HT – solar thermal applications
Onshore wind	3.0	11	7		Arctic conditions; on site blade manufacturing; kites
Offshore wind	0.4	33	10.5		Floating wind
Biomass power (incl. waste, landfill gas)	0.0	4	4.1		Sustainable, reliable, affordable biomass feedstock
Geothermal, ocean/tide/wave	0.8	30	9.5		Deep geothermal; resilient and economic wave technologies
International interconnector capacity	Enabling	5			Roll-out ultrahigh voltage; economic underground lines
Smart grids	Enabling	x			Standardised smart meters; equipment responding to price signals
Battery storage	Enabling	20 921	32.9		Cost reduction; seasonal electricity storage
Energy efficiency in end-uses	4.8	2			
Demand side response/ demand side management	Enabling	x			Better understanding of potentials and their deployment
Industry					
DRI iron making hydrogen	0.1	11			Hydrogen energy systems at scale
DRI iron making gas + CCS	0.01	15			More demonstration plant
Blast furnace iron making + CCS	0.6	x			Demonstration plant
Blast furnace iron making biomass	0.4	16			Biomass supply at scale

New cementing materials and clinker substitutes	0.3	1		● (red)	Standards and applications
Clinker kilns + CCS	0.6	100		● (red)	Demonstration plant
Clinker kilns biomass	0.3	11		● (red)	
Biomass as fuel + feedstock for synthetic organic materials and recycling	2.4	20	8.9	● (red)	Biochemicals economics
Hydrogen ammonia production	0.00	1 000		● (red)	Hydrogen energy systems at scale
Gas ammonia production + CCS	0.1	100		● (red)	
Other renewable energy	0.9	6		● (red)	
Material efficiency	1.4	2		● (red)	Standards
Energy management systems ISO 50 001	2.4	3		● (yellow)	
CO_2 transportation and storage infrastructure	Enabling			● (yellow)	Acceptance; MRV of retention
Biomass supply at scale	Enabling			● (yellow)	Sustainable, affordable, reliable
Transport				↔ (yellow)	
Electric vehicles	3.8	676	20.5	● (green)	High performance low cost batteries
Hydrogen vehicles	0.5			● (red)	High performance low cost hydrogen vehicles
Conventional biofuels	0.1	4		● (yellow)	
Advanced biofuels	0.6	600	5.9	● (red)	Economic jet fuel
Energy efficiency	2.1	2		● (yellow)	
Biomass supply at scale	Enabling			● (yellow)	Sustainable, affordable, reliable
Buildings				↔ (yellow)	
Zero energy buildings	0.2	100	28.6	● (yellow)	Need for more stringent regulation
Energy renovation existing stock	0.5	3		● (red)	
District heating/cooling with renewables	1.0	6		● (yellow)	Strengthen renewable energy component
Clean cooking using renewables	0.2	17	8.5	● (yellow)	Roll-out at scale; enabling policy frameworks
Solar assisted water/space heating systems	1.9	19	8.7	● (yellow)	Roll-out at scale; enabling low temperature building energy systems
Heat pumps	0.4	58	12.3	● (yellow)	Roll-out at scale; enabling low temperature building energy systems
			On track	● (green)	
			Lagging but viable	● (yellow)	
			Not viable at the current pace	● (red)	

The sector analysis in Annex 2 identifies a number of technologies that could play important roles in the decarbonisation of the energy sector, but that need further development before they are scaled up. These technologies include:

- Technologies enabling a high share of variable renewable power in electricity systems. Goal is to ensure adequacy of supply and flexibility in terms of systems operation. The merger of ICT technology and power sector technologies offers special opportunities.
    - Seasonal storage – This is important for locations where renewables supply features a strong seasonality, for example solar PV at higher latitudes. One way to deal with this is to broaden the supply mix but there can also be a role for seasonal storage. In many countries hydro reservoirs provide such function but the potential is limited and site specific. Batteries are not suited for seasonal storage. Other chemical or thermal storage strategies can be considered.
    - Super grids that take advantage of the benefits of geographical distribution of renewables. China has made great progress in connecting its Western power generation with demand centres in the East. There are now plans to expand this strategy on a global level. Part of the challenge is political and economic, as witnessed by the demise of the Desertec Industry Initiative that aimed to use the solar and wind potential in North Africa for European consumers. But part of the challenge is also technical. For example, new transmission lines are controversial in many countries. Germany has decided to put large parts of the needed new transmission capacity underground, as a compromise to overcome opposition. Today this raises cost significantly and there are limitations regarding the capacity of such underground lines.
    - Power-to-X approaches that offer efficient uses for electricity supply surpluses. "X" can refer to energy carriers including hydrogen, synthetic natural gas and methanol. It's imperative to build on the characteristic strengths of such energy carriers, for example high energy density (eg methanol for shipping or hydrogen for seasonal underground storage or synthetic natural gas for exiting gas distribution systems).
    - Digitalisation of power systems (smart grids)
    - Market models that provide real time price signals to encourage demand response
    - Standardised off-grid solutions for rural areas and remote locations – this offers important potential to reduce cost. For example, Russia is exploring standardised diesel/renewable hybridisation solutions for mini-grids for communities across its remote Siberia and Arctic regions.

- High-performance low-cost batteries for electric vehicles. Electrification of end use sectors can allow higher levels of sector coupling between the electricity sector and end use sectors. Electric vehicles can play a key role. Battery performance is rapidly improving in terms of drive range and recharging time. However further improvements are needed for accelerated deployment. Fundamentally new electricity storage concepts are being explored such as ultra-super-capacitors but also continuous improvement of lithium based batteries is needed. Li-ion battery manufacturing capacity is ramping up from 21 gigawatt-hours (GWh) at end-2016 to 170 GWh planned for 2020. Economies of scale and continuous technology improvement will drive battery cost reductions. Battery innovation needs to be complemented by systems integration strategies where EVs facilitate integration of higher VRE shares. Smart charging and strategic location choices will be needed for charging points so vehicles are charged when VRE electricity is abundant. Also electric two- and three-wheelers and autonomous EVs may result in a trend away from conventional cars as preferred but energy inefficient transportation mode.

- Advanced biofuels and biochemicals and biomaterials. Advanced biofuels from lignocellulosic feedstock offers important deployment potential especially for applications in trucks, aviation and shipping where electricity is not an option. At the same time around one tenth of all oil and gas liquids is used for production of plastics and synthetic fibres, in the order of 400 Mt per year. Significant efforts are aimed at producing existing commodity materials from biomass (eg bioethylene, biomethanol and aromatics from lignin) as well as development and deployment of new types of biomaterials. Also processing of wood to engineered materials continues to develop and opens up new fields of applications. In all cases economics pose a problem at today's low oil and gas prices.

- New cement types that reduce cement clinker needs. Cement clinker is the key component of Portland cement. Its production from limestone is a major cause of process CO_2 emissions. Substitution of cement clinker with other materials with similar properties has been explored for some time. Economics and scale have been challenges for rapid deployment, as well as building and infrastructure construction regulations that rely on well proven materials.

- Scalable biomass supply and logistics. Sustainable, affordable and reliable biomass supply is a major barrier for large scale deployment. Part of the challenge is to develop sufficiently large commodity markets. Global pellet markets are today on the order of 20 million tonnes per year, a small fraction of total bioenergy or energy supply. Better logistics to collect and commoditise a distributed and heterogeneous resource are critical. It's no coincidence that large biomass power plant can be found in port areas where a broad range of resources can be accessed.

- Solar cooling with cold storage – especially in developing countries cooling demand is poised to rise rapidly. Solar energy can be used to provide the cooling but cold storage is needed for cost effective deployment is batteries are to be avoided. For example, district cooling distribution systems can be used to store cold.

- New marine shipping solutions – shipping creates special challenges. A diverse range of options can be deployed from electric propulsion for short range to wind aided systems and liquid or gaseous fuels for long range. There is a trend to introduce natural gas for shipping that can be supplemented with biogas or hydrogen.

- Solar thermal and other renewable solutions in the urban environment – this technology is well established but the roll-out is very uneven across the world. Moreover, the current focus is on residential hot water applications, but industrial applications also deserve more attention. Increasingly there is attention for integrated hybrid systems that combine solar heating with heat pumps of for example bioenergy. Solar water heating is receiving competition from solar PV heat pump systems. The analysis indicates that solar thermal represents a significant share of total renewables potential.

- Renewables-based clean cooking solutions that meet consumer needs – while clean cooking solutions have been deployed for years the success has been mixed. It's critical that more attention is paid to renewable supply solutions instead of natural gas and LNG as to avoid technology lock-in.

- CO_2 capture and storage (CCS) for cement clinker production, iron making, waste incineration and biomass processes. CCS development has been lagging and cost are high compared to many renewables options. However, for certain process emissions that is no viable alternative. Moreover, biomass with CCS is widely considered a backstop option that could play a role to bridge the gap between "well below 2 degrees" elaborated in this report and the 1.5 degrees objective that is also included in the Paris climate agreement.

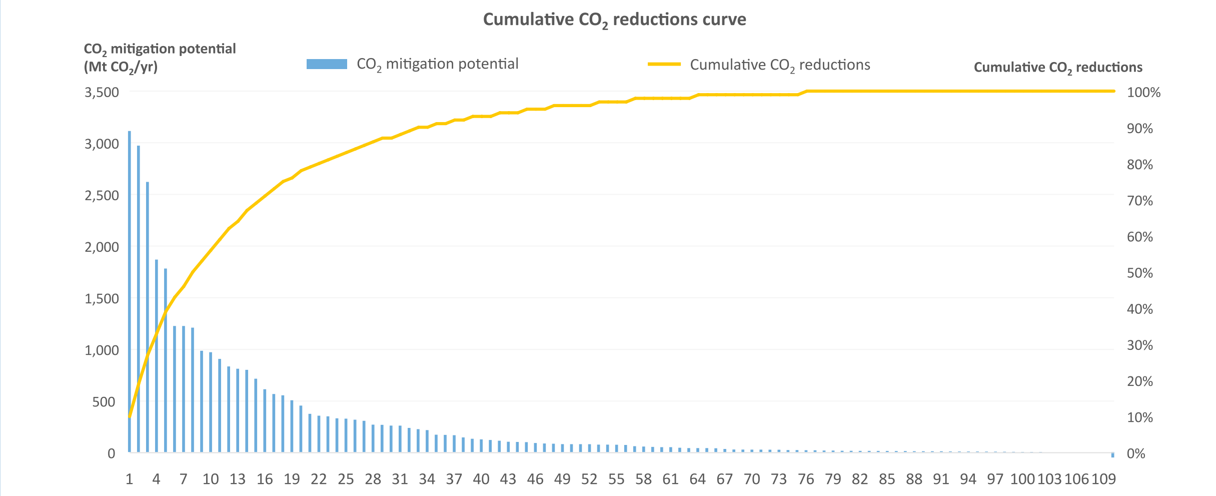
Box 5: A Dutch national project turns houses energy neutral, funded by the energy bill

The past few years, making houses energy neutral has becoming a reality. Nul op de Meter ("zero on the meter") is a Dutch national project initiated by the government to renovate existing houses and apartments so that they become energy neutral. It is a holistic systemic deep renovation concept using smart services aimed at developing smart energy-based communities. It creates energy-neutral housing by reducing energy consumption and maximising the use of renewable energy. The houses are made energy neutral by using heat pumps, PV-panels, air ventilation systems with heat recycling, plastic window frames with triple glazing and façade insulation that is 30 cm thick.

At present, buildings consume around 30 % of the Netherlands' total energy. That is why builders, suppliers and municipal representatives have joined forces to initiate an innovative housing renovation project. The programme's aim is to make 111 000 Dutch rental flats energy-efficient over the next few years. The programme is already underway: four major Dutch construction companies and six housing associations signed contracts for the first 11 000 flats in 2013.

How does the plan work? Over 15 years, an average Dutch family spends € 35 000 (USD 38 710) on energy. This money can be used to create an energy-neutral home. Instead of paying their energy bills, the tenants pay a similar amount to the housing corporations that own the houses. With this money, the corporations pay building companies to retrofit the houses, which after renovation have net zero energy costs. For this project, the building companies have developed renovation procedures that are highly cost-effective.

Figure 18: Ranking of technology options that contribute to decarbonisation of the global energy sector



Based on IRENA estimates

The top 10 low-carbon technologies account for two-thirds of the emissions reductions needed for the decarbonisation.

Contributions of technology solutions

The identified technology options for the decarbonisation of the global energy system can be ranked from sector-specific findings. The technology options are sorted based on their CO_2 abatement potential, from the highest to the lowest (see Figure 18).

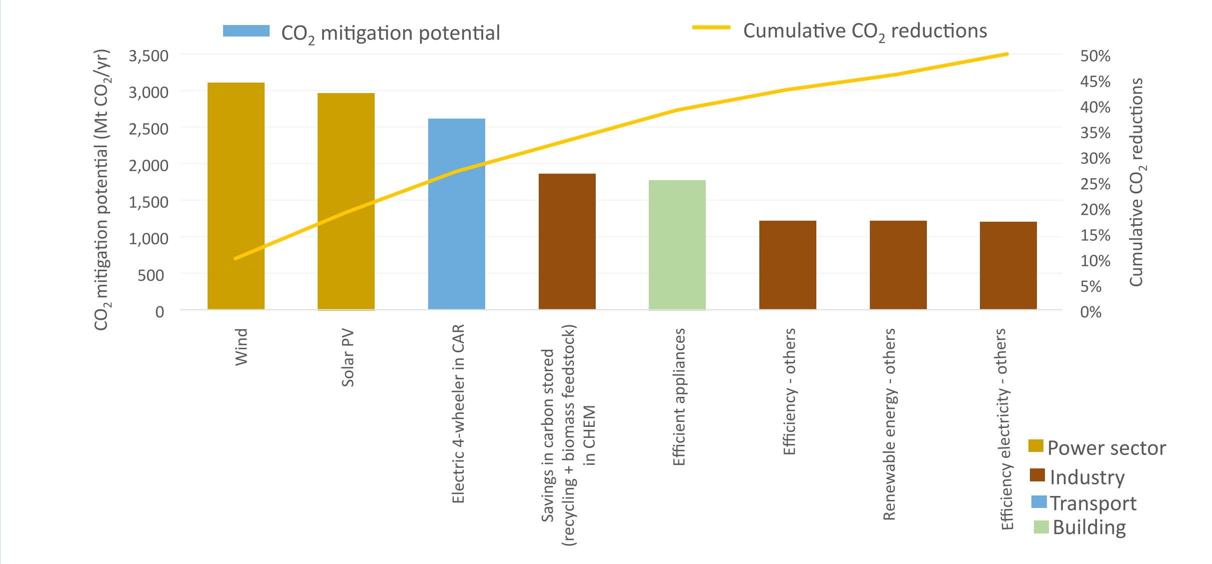
One-third of the abatement potential by 2050 would come from four of the 110 technology options: wind power, solar PV, electric vehicles for passenger transport and saving the carbon stored during plastics production in the chemical industry. 90 % of the abatement potential would come from 33 of the technology options. These emissions reductions are in power, transport, buildings heating and cooling, and in industry, notably from the energy-intensive sectors of iron and steel, and chemical and cement production.

Most of the technology options to achieve 90 % of CO_2 emissions reductions by 2050 have a moderate cost of abatement, below USD 50 per tonne of CO_2. Some options for industry and the aviation are clearly more expensive, with cost of abatement higher than USD 100 per tonne of CO_2. This information also shows the different innovation needs for each sector. In the case of energy efficiency measures with negative abatement costs, such as the deployment of efficient appliances and efficient electric motors in industry, efforts can be focused on national plans for the rollout of such technologies. In the case of the power sector, innovation on systems integration and infrastructure would be crucial. The high abatement costs in industries such as chemical and iron and steel, as well as in the aviation sector, mean that more R&D and demonstration plants are needed to push the technology towards the marketplace.

Considering the marginal cost of abatement of the different technology options, a carbon price above USD 50/tCO_2 would enable the implementation of most technology options in the power sector, and several options for the other sectors. A USD 100/ tCO_2 price would enable the implementation of most of the technology options, leaving the few costliest in the buildings, transport and industry sectors to be enabled by other mechanisms such as regulations.

The cost supply curves, available in the Annexes, provide important information about which technologies would require policy support to improve their economic viability. These technologies fall under the area "costs" and they result in a total incremental system cost of USD 2.1 trillion per year in 2050. To improve the economic viability of these technologies, different measures need to be implemented. One of them is providing subsidies. Some improvements will also happen by learning investments and some will require corrections to the market. One instrument

Figure 19: Key technology options that contribute to the majority of decarbonisation in the global energy sector



Based on IRENA estimates

The top eight technologies represent half of the total emission reductions needed. Wind, solar PV, electric mobility for passenger cars, plastics recycling and efficient appliances represent more than one-third.

Box 6: Deutsche Post is taking a leading role in electric vehicles deployment

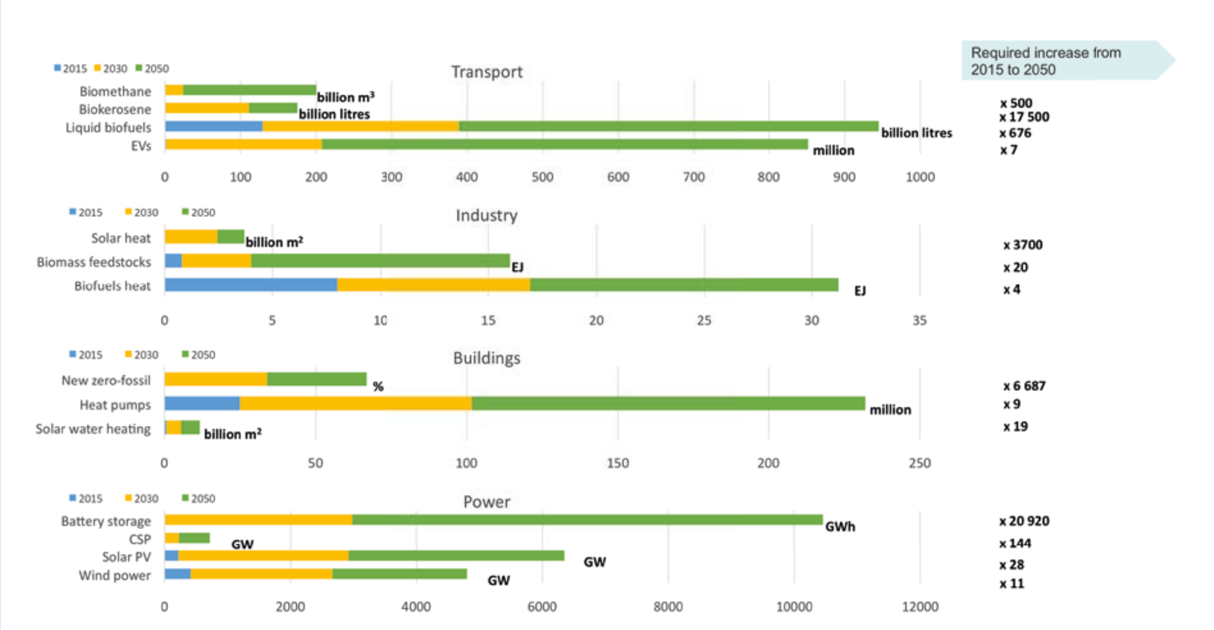
The internationally-operating postal and logistics group Deutsche Post DHL, based in Germany, has been developing and manufacturing its own electric delivery vans since 2014. Deutsche Post's goal is simple but ambitious: electrifying its entire fleet of nearly 47 000 vehicles, which travel thousands of kilometres per day delivering mail and packages to thousands of clients in urban and rural areas. The benefits, which include reducing both urban air pollution and noise, would be significant.

Deutsche Post is currently operating 2 500 electric vehicles in Germany that deliver mail and parcels. In the Netherlands, there are 100 electric delivery cars active. These energy-efficient vehicles represent the company's efforts to respond to the growing market for packages and the growth of online shopping in a fully sustainable way.

As part of the group's e-mobility strategy, the company has begun to produce its own electric delivery vans. In 2014, Deutsche Post acquired the start-up Streetscooter, a spin-off of the University of Aachen, which had been developing a small four-wheeled electric van with a range of up to 120 kilometres. In 2016, the first 2 000 such electric cars were produced.

Now, the group is planning to expand production to 20 000 electric vans in 2018. To achieve that, a second plant is being built in North Rhine-Westphalia. The price of the electric delivery van is low enough that the postal and parcel company is able to sell these "Streetscooters" to third parties. The business strategy of producing a simple vehicle without any gadgets has enabled the Streetscooters business to grow faster than traditional car manufacturing, which typically involves designing in more features and producing more expensive models.

Figure 20: Technology deployment needs by sector and application in REmap compared to the present status, 2015–2050



Based on IRENA estimates

Decarbonisation potential in end-use sectors remains largely untapped.

to correct for market distortions is a carbon price. Carbon prices are today typically used in the power generation or the industry sectors. For instance, if one assumes a carbon price of USD 60 per tonne of CO_2 in 2050, all low-carbon technologies for power generation covered in this assessment reach cost-competitiveness. Technologies that remain more expensive are typically located in end-use sectors.

If the same carbon price were applied for technologies identified for the industry sector, only about half of them would be cost-competitive. Likewise, in buildings and transport, many renewable energy technologies remain costly by 2050. In transport, for instance, national emission policies and regulations aimed at the local level (*e.g.* tighter emissions regulations for internal combustion vehicles that encourage deployment of electric vehicles) can improve the cost-competitiveness of some costly technologies. 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).

4. POLICY PRIORITIES FOR ENERGY INNOVATION

This section is intended for policy makers that are in charge of the design of an innovation framework.

Innovation for energy transition needs to balance general support measures that is not technology specific and technology of sector specific support. This section attempts to provide some practical guidance how to achieve this in practice, based on a synthesis of general innovation theory and the practical challenges that have been identified for energy transition.

Annex A contains an overview of existing initiatives to abate GHG emissions and promote renewable energy across the 12 energy sectors that have been identified. This overview is intended as an aide in the identification of gaps and areas that require strengthening. Where possible references have been included that allow an assessment of the type of activities and contacts for each activity. The overview does not claim to be comprehensive nor does it reflect an endorsement of specific initiatives.

What the overview shows is that in many areas a large number of initiatives exist. However, their objectives and achievements to date and plans for rollout are in many instances not obvious. This complicates an assessment of what gaps exist. Such assessment would constitute a study by itself, beyond the scope of this report. Conducting such assessments and repeating them regularly is strongly advised, as it will help to avoid overlap, achieve added value for new initiatives and ensure effective and efficient use of additional innovation resources.

Reducing the cost of low-carbon technologies.

The main goal of the innovation efforts in low-carbon technologies is to ensure cost competitiveness of renewables without the need for subsidies. In that way, innovation will contribute to maintaining an accelerated scaling up of low-carbon technology, irrespective of fossil fuel price volatility and independent of climate policy agreements.

Internalising costs due to climate impact would unlock mass deployment of low-carbon technologies.

Today, energy markets are distorted by fossil fuel subsidies and by external effects of fossil fuel use on health and the global climate that are not reflected in the prices of fossil fuels. To create a level playing field, these effects should be priced appropriately. As shown in this working paper, a carbon price of USD 60 per tonne CO_2 would enable most of the low-carbon technology options for decarbonising the energy sector to be cost competitive. Alternatively, the analysis suggests that the human health benefits alone are greater than the costs of decarbonisation. But the pricing of health benefits will vary widely across countries and localities.

Efficiency must go hand-in-hand with renewables.

Energy intensity improvements include gains from the implementation of energy efficiency technologies and structural change. The analysis shows that one quarter of the potential incremental energy intensity improvements can be attributed to the accelerated deployment of renewable energy. Meanwhile, energy efficiency technologies are widely available, but require strengthening of implementation efforts.

Saleable solutions are needed for building renovation and retrofits.

Innovation is not only related to new equipment and processes. There is a significant opportunity for renovation and refurbishment of existing capital stock.

More biomass is needed.

Biomass continues to represent a big part of the renewable energy solutions, particularly for challenging sectors like transport and industry. The technology continues to develop on the path to commercialisation, as in the case of advanced biofuels. But feedstock costs and logistics continue to be major challenges. Innovative solutions for the biomass supply chain thus are urgently needed to unlock the potential of bioenergy.

A suite of emerging technology solutions that offer significant impacts requires additional innovation efforts.

The analysis identifies a number of technologies that could play important roles in the decarbonisation of the energy sector, but that need further development before they are scaled up. These technologies include:

- technologies enabling a high share of variable renewable power in electricity systems:
    - seasonal storage
    - super grids that take advantage of the benefits of geographical distribution of renewables
    - power-to-X approaches that offer efficient uses for electricity supply surpluses
    - digitalisation of power systems (smart grids)
    - market models that provide real time price signals to encourage demand response
    - standardised off-grid solutions for rural areas and remote locations
- high-performance low-cost batteries for electric vehicles
- advanced biofuels and biochemicals and biomaterials
- new cement types that reduce cement clinker needs
- scalable biomass supply and logistics
- solar cooling with cold storage
- new marine shipping solutions
- solar thermal and other renewable solutions in the urban environment
- renewables-based clean cooking solutions that meet consumer needs
- CCS for cement clinker production, iron making, waste incineration and biomass processes

Creating new market opportunities.

Decarbonisation of the energy sector will not only address climate change. It also offers opportunities for wealth creation, social inclusion, the broader participation of stakeholders and achieving Sustainable Development Goals. Innovation planning must therefore include a "win-win-win" solutions mindset that covers all of these additional opportunities.

The most attractive new solutions may be found at the interface of different areas, such as between the energy sector and ICT. But this supply side perspective must be complemented with a demand side perspective that considers whether innovations can be identified that provide multiple benefits or offer solutions for specific niches.

Some industries require global, sector-specific agreements.

The aviation, shipping, iron and steel, cement, chemical and petrochemical sectors cannot be transformed through national policies due to their global nature. For those sectors, global agreements for the deployment of technology solutions are indispensable. At the present time, the lack of such global agreements has caused industry to refrain from investing in low-carbon technologies and processes due to uncertainties about the return from such investments and competitiveness concerns.

The wide range of overlapping national and international initiatives makes innovation gaps complex to identify. Better mapping is needed.

In some sectors, numerous international initiatives have been identified, while others are only addressed by one. The purpose of sector-level initiatives, along with who participates in them, is often not clear to outsider parites. Typically, there are no timelines nor proper reporting of progress and impacts. This ambiguity acts as a barrier for innovation. More clarity is needed to pinpoint innovation needs. Preparing an in-depth overview of innovation needs at the level of sectors and technologies that goes beyond the level of general roadmaps is a first step. Technology briefs and outlook studies such as those prepared by IRENA can act as inputs for such an overview. But more specific R&D needs should be identified. There is a role for academia and research institutes in such a mapping process.

Innovation for decarbonisation requires increasing and expanding existing initiatives.

A significant overlap exists within the priority areas that have been identified in this working paper. This working paper also has identified a number of priority areas that are not yet covered by Mission Innovation (MI). Here are the seven innovation challenges set by Mission Innovation as priorities:

1. Smart Grids Innovation Challenge – to enable future smart grids that are powered by affordable, reliable, decentralised renewable electricity systems.
2. Off-Grid Access to Electricity Innovation Challenge – to develop systems that enable off-grid households and communities to access affordable and reliable renewable electricity.
3. Carbon Capture Innovation Challenge – to enable near-zero CO_2 emissions from power plants and carbon-intensive industries.
4. Sustainable Biofuels Innovation Challenge – to develop ways to produce, at scale, widely affordable, advanced biofuels for transportation and industrial applications.
5. Converting Sunlight Innovation Challenge – to discover affordable ways to convert sunlight into storable solar fuels.
6. Clean Energy Materials Innovation Challenge – to accelerate the exploration, discovery and use of new high-performance, low-cost clean energy materials.
7. Affordable Heating and Cooling of Buildings Innovation Challenge – to make low-carbon heating and cooling affordable for everyone.

These seven were selected based on mutual country interest. They are not based on a comprehensive assessment of decarbonisation innovation needs. The areas that have been identified in this working paper can complement this set of MI activities. As for the Breakthrough Coalition that was announced at COP21 in Paris, progress has been slow to date. Private sector engagement must be organised differently and more effectively to have a meaningful impact.

Innovation policies are often input driven instead of outcome oriented.

Some initiatives, as in the case of Mission Innovation, set a target focus on the innovation input. For example, the doubling of funding is the central objective. However, the question raised is whether a doubling would be in line with the targeted decarbonisation of the energy system. If this type of input-driven initiatives are pursued, measurements of the efficiency and effectiveness of innovation expenditures should become a top priority, ideally to allow cost-benefit analysis of the value of higher expenditures.

To stimulate innovation investment, governments should focus on enabling private sector innovation

First and foremost, governments must provide credible long-term policy objectives. Governments also have an important role to play in facilitating the enabling infrastructure for smart grids, electric vehicle charging stations and sustainable, affordable and reliable biomass supplies. However, governments have traditionally lacked the capacity to engage effectively in technology innovation. They lack the agility and the basic knowledge of what is needed. Therefore, it makes sense to focus on creating an enabling environment for private sector innovation by fostering basic research, providing a pool of skilled staff and enabling technical infrastructure.

Innovation should serve the needs of developing and emerging economies alike, but developing country needs pose a special opportunity.

Historically, innovation for low-carbon technology has been driven by industrialised economies. However, a large amount of future growth in energy consumption will come from developing and emerging economies, which have different economic, technology and geographical context. Energy services and technology performance needs are often very different in these developing economies, compared to developed ones. Therefore, a more significant effort is needed to find innovative solutions for developing countries. Obvious examples include clean cooking solutions and decentralised off-grid technologies for providing electricity access.

Innovation policy is broader than technology R&D.

Innovation covers the complete technology lifecycle. Increased R&D investments are important, but in isolation such limited focus will not bring the needed results. Efforts should also cover the demonstration, deployment (technology learning) and commercialisation stages. Innovations in business models, market designs, enabling infrastructure and systems operation, are equally crucial to achieve the energy transformation.

The analysis suggests that the main areas where more innovation is needed are those where, for institutional reasons, no significant pressure exists at present to innovate. For example, energy intensive industries are largely exempt from ambitious climate policies because of perceived competitiveness issues and potential carbon leakage. Bunker fuel use in aviation and marine shipping sectors is formally outside the national scope. The use of fuels as feedstock for plastics and other synthetic organic materials only results in CO_2 emissions at the waste incineration stage, too late to prevent those emissions. In all these cases, the priority should be to create the appropriate innovation incentives, instead of simply focusing on technology R&D.

ANNEX A: ONGOING INITIATIVES FOR DECARBONISATION BY SECTOR

Below a list of on-going technology innovation programmes and sector-specific initiatives that can contribute to accelerating commercialisation of low-carbon technologies and their uptake. The list in this annex is neither exhaustive nor represents an endorsement to any specific initiative. The annex serves as a starting point to explore the landscape of decarbonisation initiatives in all sectors, enabling a gap analysis and action plan to bridge the identified gaps. Stakeholders are invited to send information on additional initiatives to IRENA to continue maintaining and expanding this list.

Cross-cutting initiatives

	Examples of existing international cross-cutting initiatives
Energy Transition Coalition	• Ministerial coalition with the aim to promote the energy transition • The Coalition is established by IRENA and has the ambition to assemble countries leading in developing long term energy transition strategies to foster investments in a low carbon energy sector • China, Denmark, Germany, Indonesia, Mexico, Morocco and the United Arab Emirates, agreed to work together to establish an Energy Transition Coalition in the course of 2017
Mission Innovation (MI)	• Governmental innovation frameworks and support • MI is a global initiative of 22 countries and the European Union to dramatically accelerate the global clean energy innovation • MI's goal is to develop and scale-up breakthrough technologies and achieve substantial cost reductions. MI members aim to double public clean energy research and development investment over five years • For more information, see http://mission-innovation.net/
Breakthrough Coalition	• Private sector commercial technological solutions development • The Breakthrough Energy Coalition aims private sector engagement to accelerate the cycle of innovation through investment in early stage innovations. The initiatives groups private investors willing to put patient and flexible risk capital for new technologies, which may provide meaningful returns on investment in the long-haul • For more information, see http://www.b-t.energy/
Clean Energy Ministerial (CEM)	• Enabling policy market frameworks • CEM is a high-level governmental forum including 24 countries and one regional entity to promote policies and programmes that advance clean energy supply, improve energy efficiency and expand clean energy access by sharing lessons and best practices, thus encouraging the transition to a global clean energy economy • For more information, see http://www.cleanenergyministerial.org/

	Examples of existing international cross-cutting initiatives
IEA Technology Collaboration Programmes (TCPs)	• Pre-commercial technology information exchange • The TCPs are led by the IEA to support innovation for energy security, economic growth and environmental protection, by exchanging pre-commercial technology information. • There are 39 TCPs operating today, involving about 6 000 experts from government, industry and research organisations in more than 50 countries • For more information, see https://www.iea.org/tcp/
IRENA Coalition for Action	• Share knowledge network • The IRENA Coalition for Action forms a key international network to discuss renewable energy industry trends, share knowledge and exchange best practices for the global energy transformation. The mission of the Coalition for Action is to convene the global dialogue amongst non-governmental and governmental stakeholders to drive the energy transition forward by increasing renewable energy deployment. The Coalition brings together the private sector, industry associations, investment community, civil society and research institutes to enrich and share perspectives on renewable energy technologies, implementation strategies and evolving market dynamics • For more information see http://coalition.irena.org/

Power generation sector

	Examples of existing international initiatives for the power sector
Africa Renewable Energy Initiative (AREI)	• AREI is an inclusive effort to accelerate and scape up the harnessing of the continent's renewable energy potential, under the mandate of the African Union and endorsed by African Heads of State and Government on Climate Change • The target is to set at least 10 gigawatts (GW) of new and additional renewable energy generation capacity by 2020, and mobilise the African potential to generate at least 300 GW by 2030 • For more information, see: http://www.arei.org/
Power Africa	• Power Africa goals it to bring together the world's top companies, political leaders, and financial institutions to help overcome Africa's energy crisis. Power Africa uses collective problem solving to enable African leaders to pave their own future • Power Africa's goal is to add more than 30 000 megawatts (MW) of cleaner, more efficient electricity generation capacity and 60 million new home and business connections.

	Examples of existing international initiatives for the power sector
Global Geothermal Alliance (GGA)	• GGA is a coalition to increase the use of geothermal energy, both in power generation and direct use of heat. The initiative, facilitated by IRENA, serves as a platform for dialogue, cooperation and coordinated action between the geothermal industry, policy makers and stakeholders worldwide. The alliance aims to foster an enabling environment to attract investments in geothermal sector through providing customised support to regions and countries with geothermal market potential, as well as, facilitating the exchange of insights and experience among key stakeholders in the geothermal energy value chain. It aspires to achieve a 500 % increase in global installed capacity for geothermal power generation and a 200 % increase in geothermal heating by 2030 • For more information, see: http://www.irena.org/gga/ and http://www.irena.org/eventdocs/GGA_Global_Geothermal_Alliance_2017.pdf
SIDS Lighthouse Initiative	• The IRENA initiative facilitates coordinated support for islands to transform their predominantly fossil-based power systems to renewable energy through partnerships with public, private, intergovernmental, and non-governmental stakeholder organisations. Island partners gain access to: – Policy and regulatory advisory services; – Technical expertise in planning, identifying, structuring and executing projects; – Financing for capacity building, policy and regulatory design, early-stage transactions, and project finance; – A network to share information, knowledge and practices. • For more information, see: http://www.irena.org/, or contact: Islands@irena.org
International Solar Alliance (ISA)	• ISA aims to provide a platform for cooperation among solar resource rich countries, where global community including bilateral and multilateral organisations, corporates, industry and stakeholders can make a positive contribution to the more common goals of increasing solar energy generation in meeting energy needs • For more information, see: http://intsolaralliance.org/

	Examples of existing international initiatives for the power sector
Africa Clean Energy Corridor (ACEC) **and** **West Africa Clean Energy Corridor (WACEC)**	• The Africa Clean Energy Corridor is a regional IRENA initiative that seeks to secure the accelerated development of renewable energy potential and cross-border trade of renewable power within the Eastern Africa Power Pool and the Southern African Power Pool. The initiative builds upon the strong political commitment of African leaders to strengthen regional institutions and transmission infrastructure, forming large competitive markets and lowering costs across production sectors. The ACEC builds on five pillars, which include resource assessment and zoning, national and regional planning, enabling frameworks for investments, capacity building and public and political support • The West Africa Clean Energy Corridor builds on and aims to strengthen the ongoing efforts of promoting cross-border trade of electricity and eventually creating a regional electricity market in West Africa in line with renewable energy targets set by the Econonic Commission for West Africa (ECOWAS) and countries. Led by IRENA, the initiative has been undertaken in collaboration with the ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE), the West African Power Pool (WAPP) and the ECOWAS Regional Electricity Regulatory Authority, as well as the 14 WAPP countries and development partners • In March 2017, energy ministers at the African Union's Specialized Technical Committee on Energy, Transport and Tourism advised AU member States to integrate the concepts of the ACEC and the WACEC into their national renewable energy and climate change agendas as well as the process of the creation of a sustainable and low-carbon power markets, as part of the concluding declaration, which will be presented to the African Heads of States for endorsement • For more information, see: http://www.irena.org/
IRENA Renewable Costing Alliance	• The IRENA Renewable Costing Alliance was created to pool renewable cost data, confidentially in the IRENA Renewable Cost Database, to ensure up-to-date data on rapidly changing costs from a trusted source is available. The Alliance's data highlights the growing competitiveness of renewables, supports analysis of issues relevant to policy makers and provides an authoritative global source of cost data • For more information, see: http://costing.irena.org/
GRIDSTOR	• GRIDSTOR Recommended Practice for grid-connected energy storage is a set of documents created to give manufacturers, advisers and users a common guideline for energy storage systems of different kinds and applications • For more information, see: http://rules.dnvgl.com/docs/pdf/DNVGL/RP/2015-12/DNVGL-RP-0043.pdf
The 21st Century of Power Partnership	• The 21st Century Power Partnership aims to accelerate the global transformation of power systems. It is a multilateral effort of the Clean Energy Ministerial (CEM) and serves as a platform for public-private collaboration to advance integrated policy, regulatory, financial, and technical solutions for the large-scale deployment of renewable energy in combination with deep energy efficiency and smart grid solutions • For more information, see: http://www.21stcenturypower.org/

	Examples of existing international initiatives for the power sector
GEIDCO	• The Global Energy Interconnection Development and Cooperation Organization (GEIDCO), with its permanent office domiciled in Beijing, China, is a non-governmental, non-profit international organisation bringing together firms, associations, institutions and individuals dedicated to promoting the sustainable development of energy worldwide. The purpose of GEIDCO is to promote the establishment of a global energy integration system, to meet the global demand for electricity in a clean and green way • For more information, see: http://www.geidco.org
Asia Super Grid (ASG)	• Japan, Republic of Korea and possibly Russia into a vast interconnected power system, so that to further maximise the usage of renewable energy by taking advantage of diversity in loads and resources • For more information, see: http://apjjf.org/-John_A_-Mathews/3858

Industry

	Examples of existing international initiatives for the industry sector
Cement Sustainability Initiative (CSI)	• CSI is a global effort by 23 major cement producers with operations in more than 100 countries, aiming to explore sustainable development means for the cement industry. • For more information, see: http://www.wbcsdcement.org/
International Aluminium Institute (IAI)	• IAI membership represents over 60 % of global bauxite, alumina and aluminium production. Through the IAI, the aluminium industry aims to promote a wider understanding of its activities and demonstrate both its responsibility in producing the metal and the potential benefits to be realised through their use in sustainable applications and through recycling. • For more information, see: http://www.world-aluminium.org/
Confederation of European Paper Industries (CEPI)	• CEPI is a non-profit organisation, aiming at improving and securing pulp and paper industries competitiveness and sustainability towards EU policy makers • For more info, see: http://www.cepi.org/
CEM Corporate Sourcing Campaign	• The Clean Energy Ministerial (CEM) Corporate Sourcing of Renewables Campaign, launched in June 2016 with IRENA's support, seeks to accomplish the follow: (1) significantly increase the number of companies across the range of CEM member countries powering operations with renewable energy; (2) help make the business case for more companies, both large and small, to do so; (3) identify and deploy supportive policies and resources that can help facilitate additional deployment of renewable energy sources through corporate sourcing; and (4) recognise companies that have already made commitments and are powering operations with renewables. • For more info, see: http://www.cleanenergyministerial.org/Our-Work/CEM-Campaigns/Corporate-Sourcing-of-Renewables
RE100	• RE100 is a collaborative, global initiative of influential businesses committed to 100 % renewable electricity, working to massively increase demand for – and delivery of – renewable energy. It includes companies from all over the globe from a wide range of industrial sectors: from telecommunications and IT to retail and food • For more information, see: http://there100.org/

	Examples of existing international initiatives for the industry sector
Lawrence Berkeley National Laboratory – China Energy Group	• It is a collaboration between the Chinese and the US government and non-government partners to gain an in-depth understanding of China's industrial sector and its energy use, in order to identify opportunities to introduce US energy efficiency technologies in China • For more info, see: https://china.lbl.gov/
Sustainable Energy Financing Facilities (SEFFs) of the European Bank for Reconstruction and Development (EBRD)	• Through SEFFs, the EBRD extends credit lines to local financial institutions that seek to develop sustainable energy financing as a permanent area of business. Finance for sustainable energy projects is provided for two key areas: energy efficiency and small-scale renewable energy. • For more information, see: http://www.ebrd.com/what-we-do/sectors-and-topics/sustainable-resources/seffs.html
Carbon Disclosure Project (CDP)	• CDP is a not-for-profit charity that runs the global disclosure system for investors, companies, cities, states and regions to manage their environmental impacts, in order to prevent dangerous climate change and environmental damage. • For more information, see: https://www.cdp.net/en
Business Environmental Leadership Council (BELC)	• BELC is the largest U. S.-based group of corporations focused on addressing the challenges of climate change and supporting mandatory climate policy. • For more info, see: https://www.c2es.org/business/belc
WBCSD	• World Business Council for Sustainable Development
GCCSI	• Global Carbon Capture and Storage Institute
WWF Climate Savers	• WWF's Climate Savers Program works in partnership with companies to set and meet goals to reduce carbon emissions, advance projects to protect their resources from climate impacts, and ensure the sustainability of their core business. • Corporations partner with WWF to establish ambitious targets to voluntarily reduce their greenhouse gas (GHG) emissions within a defined timeframe • For more info, see: https://www.worldwildlife.org/partnerships/climate-savers
Ultra –Low CO_2 Steelmaking (ULCOS)	• It is a consortium of 48 European companies and organisations that have launched a cooperative R&D initiative to enable drastic reduction in CO_2 emissions from steel production. • The aim of the ULCOS programme is to reduce CO_2 emissions of today's best routes by at least 50 percent. • For more information, see: http://www.ulcos.org/en/index.php
The International network of the Promotional Product Industry (PSI) **Solomon Associates** **Brook Hunt & Associates** **Pöyry** **International Finance Cooperation (IFC)**	• Public and private advisory bodies that contribute to data collection and benchmarking initiatives in the industry sector

Transport

	Examples of existing international initiatives for the transport sector
European Industrial Bioenergy Initiative (EIBI)	• The EIBI is an industrial initiative that aim to prioritise and facilitate 'first-of-a-kind' demonstration of innovative clean energy technologies in Europe, and boost the contribution of bioenergy to the EU Climate and Energy ambitions. • For more information, see: http://www.biofuelstp.eu/eibi.html
Midwest Aviation Sustainable Biofuels Initiative (MASBI)	• MASBI brings together representatives from across the biofuels value chain to support the development of sustainable advanced biofuels market for aviation in the Midwest region. • For more information, see: http://www.masbi.org/
European Advanced Biofuels Flightpath	• It is an initiative launched by EU Commission in close cooperation with leading European airlines, in order to define a roadmap with clear milestones to achieve a target of 2 million tonnes of sustainable biofuels used in European civil aviation by 2020 • For more information, see: http://www.icao.int/environmental-protection/GFAAF/Pages/Project.aspx?ProjectID=9
Commercial Aviation Alternative Fuels Initiative (CAAFI)	• CAAFI seeks to enhance energy security and environmental sustainability for aviation through alternative jet fuels. • For more information, see: http://www.caafi.org/
Electric Vehicle Initiative (EVI)	• The initiative seeks to facilitate the global deployment of 20 million EVs, including plug-in hybrid electric vehicles and fuel cell vehicles, by 2020. • For more information, see: http://www.cleanenergyministerial.org/Our-Work/Initiatives/Electric-Vehicles
C40 City Leadership Low Emissions Vehicle (LEV)	• The initiative focuses on areas of municipal action critical for facilitating the uptake Low Emission Vehicles in cities • For more information, see: http://www.c40.org/networks/low_emission_vehicles
Urban Electric Mobility Initiative (UEMI)	• UEMI aims to help phasing out conventionally fuelled vehicles and increase the share of electric vehicles in the total volume of individual motorised transport in cities to at least 30 % by 2030. • For more information, see: http://www.uemi.net/
Partnership on Sustainable, Low Carbon Transport (SLoCaT)	• SLoCaT promotes the integration of sustainable transport in global policies on sustainable development and climate change • For more information, see: http://www.slocat.net/
New Urban Agenda at UN Habitat III	• New Urban Agenda represents a new framework that lays out how cities should be planned and managed to best promote sustainable urbanisation. • For more information, see: https://unhabitat.org/new-urban-agenda-adopted-at-habitat-iii/
Aviation Transport Action Group (ATAG)	• ATAG is an association that represents all sectors of air transport industry, working to promote aviation sustainable growth for all the benefit of our global society • For more information, see: http://www.atag.org/

	Examples of existing international initiatives for the transport sector
Nordic Initiative for Sustainable Aviation (NISA)	• NISA is a regional body with the aim of facilitating and strengthening the conditions for commercial and continuous access to sustainable jet fuels • For more information, see: https://www.icao.int/
Airports Council International (ACI) **International Air Transport Association (IATA)** **International Business Aviation Council (IBAC)** **International Coordinating Council of Aerospace Industries Associations (ICCAIA)**	• The global aviation industry's CO_2 abatement goals include carbon neutral growth from 2020 and a 50 % cut in net CO_2 emissions by 2050 compared to 2005 levels

Buildings

	Examples of existing international initiatives for the buildings sector
Leadership in Energy and Environmental Design (LEED)	• LEED is a green building certification program used worldwide, developed by US Green Building Council (USGBC) • It includes a set of rating systems for the design, construction, operation, and maintenance of green buildings, homes, and neighbourhoods that aims to help building owners and operators be environmentally responsible and use resources efficiently. • For more information, see: http://www.usgbc.org/leed
BREEAM	• BREEAM is a sustainability assessment method for masterplanning projects, infrastructure and buildings. It addresses a number of lifecycle stages such as New Construction, Refurbishment and In-Use. • For more information, see: http://www.breeam.com/
ICLEI	• ICLEI – Local Governments for Sustainability is an international association of local governments and national and regional local government organisations that have made a commitment to sustainable development. • The association was established when more than 200 local governments from 43 countries convened at its inaugural conference, the World Congress of Local Governments for a Sustainable Future, at the United Nations in New York in September 1990 • For more information, see: http://www.iclei.org/
C40	• C40 is a network of the world's megacities committed to addressing climate change. C40 supports cities to collaborate effectively, share knowledge and drive meaningful, measurable and sustainable action on climate change. • For more information, see: http://www.c40.org/

	Examples of existing international initiatives for the buildings sector
Covenant of Mayors for Climate & Energy	• It brings together thousands of local and regional authorities committed to implementing EU climate and energy objectives on their territory • New signatories now pledge to reduce CO_2 emissions by at least 40 % by 2030 and to adopt an integrated approach to tackling abatement and adaptation to climate change • For more information, see: http://www.covenantofmayors.eu/
State & Regions Alliance	• Through State & Regions Alliance, The Climate Group brings together the world's most influential state and regional governments to accelerate the global transition to a low carbon economy, though sharing expertise on innovative policy • For more information, see: https://www.theclimategroup.org/StatesandRegions
En.Lighten	• The United Nations Environment Programme (UNEP)-Global Environment Facility (GEF) enlighten initiative aims to accelerate a global market transformation to environmentally sustainable, energy efficient lighting technologies, as well as to develop strategies to phase-out inefficient incandescent lamps to reduce CO_2 emissions and the release of mercury from fossil fuel combustion • It serves as a platform to build synergies among international stakeholders, identify global best practices and share this knowledge and information, create policy and regulatory frameworks • For more information, see: http://www.enlighten-initiative.org/
Global Alliance for Clean Cookstoves (GACC)	• GACC aims at creating a thriving global market for clean and efficient household cooking solutions. • It calls for 100 million households to adopt clean and efficient cookstoves and fuels by 2020 • For more information, see: http://cleancookstoves.org/
Global Buildings Performance Network (GBPN)	• GBPN's mission is to provide policy expertise and technical assistance to advance building energy performance and realise sustainable built environments for all • The GBPN's goal is to contribute to the building sector achieving its full energy savings and CO_2 abatement potential of more than 2.1 Gt by 2030 • For more information, see: http://www.gbpn.org/
Global Alliance for Buildings and Constructions (GABC)	• GABC contributes to the common objective of the Paris Agreement of limiting global warming to well below 2 °C • For more information, see: http://www.globalabc.org/
Energy Efficiency in Buildings (EEB)	• EEB initiative brings together local building value chains to reduce the sector's climate impact and energy costs • EEB aims to double the annual investment in energy efficiency in buildings to US$ 215 billion by 2020 • For more information, see: http://www.wbcsd.org/Projects/Energy-Efficiency-in-Buildings

	Examples of existing international initiatives for the buildings sector
Buildings Efficiency Accelerator	• Building Efficiency Accelerator supports public commitments to double the rate of building efficiency, by supporting cities implementing policies, programs and projects • For more information, see: http://www.wrirosscities.org/our-work/project-city/building-efficiency-accelerator
Sustainable Buildings and Climate Initiative (SBCI)	• SBCI is a UNEP initiative, representing partnership of major public and private sector stakeholders in the building sector, working to promote sustainable building policies and practices worldwide • For more information, see: http://staging.unep.org/sbci/
Carbon Disclosure Project (CDP)	• CDP is a not-for-profit charity that runs the global disclosure system for investors, companies, cities, states and regions to manage their environmental impacts, in order to prevent dangerous climate change and environmental damage. • For more information, see: https://www.cdp.net/en
Benchmarking and Energy Saving Tool for Low Carbon Cities (BEST Cities)	• BEST-Cities is a tool developed by Lawrence Berkeley National Laboratory – China Energy Group, designed to provide city authorities with strategies they can follow to reduce city-wide CO_2 and methane (CH4) emissions. • For more information, see: https://china.lbl.gov/tools/benchmarking-and-energy-saving-tool-low
New Urban Agenda at UN Habitat III	• New Urban Agenda represents a new framework that lays out how cities should be planned and managed to best promote sustainable urbanisation. • For more information, see: https://unhabitat.org/new-urban-agenda-adopted-at-habitat-iii/

ANNEX B: SECTOR REVIEW OF INNOVATION OPPORTUNITIES

Key findings

Industry

Iron and steel

- The iron and steel industry accounted for 2.2 Gt (7 %) of all energy-sector CO_2 emissions in 2015 (excluding emissions from a number of processes, such as the production of final steel products, that would add another 0.4 Gt to raise the total to 2.6 Gt). This includes emissions from blast furnace gas use for on-site power generation as well as from lime use in iron making. In the Reference Case, total emissions would remain at today's level in 2050 (1.9 Gt for the blast oxygen furnace (BOF) route and 0.3 Gt for electric arc furnace (EAF) route).
- In the REmap case, emissions would be reduced by more than 70 % to 0.6 Gt in 2050 compared with the Reference Case. Nearly one-third of this reduction would be achieved with CCS, 27 % with renewables (biomass and renewable-hydrogen), and 40 % with energy and material efficiency measures.
- The share of renewable energy in the sector's total final energy mix would grow to 30 % by 2050 (including electricity consumption from renewable energy sources).
- The average abatement cost of these options would be USD 55/tCO_2 by 2050. Additional investment needs on top of Reference Case would be USD 1 trillion during the 2015–2050 period.
- Considerable uncertainty remains about which technology pathways would be the most feasible and effective at reducing CO_2 emissions. As a result, there is an urgent need to develop and establish new technologies and processes on a commercial scale, and to ensure they are implemented globally.

Cement

- Cement production is one of the largest sources of CO_2 emissions. Today, it represents approximately 8 % of all global energy-sector CO_2 emissions, or about 2.5 Gt per year. In the Reference Case, these emissions are projected to rise to 3.4 Gt by 2050.
- In the REmap case, emissions would be halved in 2050 to 1.8 Gt compared to the Reference Case. Around one-third of this reduction would be achieved with CCS. Renewable energy (including biofuels, alternative fuels and waste) and improvements in material efficiency would contribute 40 % of the total emissions reduction potential. The remaining one-fifth would be achieved through energy efficiency measures, such as more efficient kilns and grinding processes. Deep cuts in cement emissions require the development of clinker alternatives and CCS.
- The share of renewable energy, from sources such as biomass, in the sector's total final energy mix would reach nearly 40 % in 2050 in the REmap case.
- The average abatement cost of these options would be USD 40/tCO_2 by 2050. Additional investment needs on top of Reference Case are USD 0.9 trillion in the 2015–2050 period.
- The cement industry has already begun to explore the technologies and processes needed to increase renewable energy use, boost efficiency and find clinker alternatives, and CCS has yet to be applied to the sector. However, incentives may be needed to develop these approaches further as companies are under severe international competition.

Chemical and petrochemical

- The chemical and petrochemical sector is the largest industrial energy user. The emissions from the production of its building blocks, namely high-value chemicals in the steam cracking process, ammonia and methanol, reached 1.25 Gt per year in 2015 (including process emissions from ammonia production). Emissions from the sector are not limited to the production of chemicals, as some carbon is stored from feedstock use is subsequently released during end-of-life treatment. When related emissions from the waste sector are included, the sector's emissions rise to 1.65 Gt per year in 2015.

- In the Reference Case, with growing demand for plastics and chemicals, production of the sector's building blocks is projected to increase annually by 2.3 % between 2015 and 2050. This causes the sector's CO_2 emissions to grow from 1.65 Gt to 3.1 Gt per year in the same time period.

- In the REmap case, the sector's total CO_2 emissions (including the process emissions and waste) would drop to 1.3 Gt by 2050, representing a reduction of 1.8 Gt in 2050. About 1.1 Gt of these reductions come from material efficiency improvements. The remaining 0.7 Gt of reductions would be achieved through energy efficiency measures, renewable energy and CCS. An additional 1.8 Gt of emissions from the carbon stored in chemicals and plastics could be avoided by increased plastics recycling and the use of biomass feedstocks.

- The share of renewable energy, mainly biomass and renewable electricity used for electrolysis and other processes, would rise to one-fifth of the sector's total energy demand.

- These measures would cost USD 157 per tonne of CO_2 abated by 2050. Additional investment needs are estimated at USD 1.6 trillion between 2015 and 2050.

- The economics for many of the required measures, such as biomass use and plastics recycling, are currently unfavourable. As a result, incentives to ensure a level playing field may be needed to accelerate their deployment, in particular because the sector's demand for energy is projected to grow significantly in the coming decades.

Aluminium

- Aluminium production is the largest electricity-consuming sector of the manufacturing industry. It used more than 800 TWh per year of electricity in 2015. In addition, 1.1 EJ of fossil fuels were used for the production of alumina – feedstock for primary aluminium and for recycled aluminium production. Direct CO_2 emissions from the sector's production processes reached 340 Mt in 2015. Around two-thirds of these emissions are represented by anode use in primary aluminium smelting. In the Reference Case, the sector's annual CO_2 emissions increase to 520 Mt per year by 2050.

- In the REmap case, CO_2 emissions would decline by more than 20 % compared to the Reference Case in 2050. Around 85 % of the reductions come from anode use, since less primary aluminium is produced (after accounting for the increase in direct CO_2 emissions from switching to recycled aluminium production). The remainder is from energy efficiency measures (including gains from novel smelting technologies) and biofuels use in alumina plants. Another key step would be to continue locating plants to areas with available renewable electricity as the share of renewables increase in power generation.

- The sector would have the highest use of renewables (both renewable electricity and biomass) among all industry sectors, with the share of renewables jumping to 60 % by 2050 under REmap. This is an outcome of significant electricity use in production processes coupled with renewable power. In addition, the share of recycled aluminium production would reach half of all production.

- The average abatement cost of these options would be USD 10/tCO_2 by 2050. Additional investment needs on top of the Reference Case would be USD 0.2 trillion in the 2015–2050 period.

- A number of existing and emerging technologies already exist to reduce the electricity needed for smelting, and biofuels can easily replace fossil fuels in low and medium temperature alumina production. The challenge is to accelerate the adoption of these new approaches, especially in this sector where energy costs play a notable role in business decisions.

Pulp and paper

- The pulp and paper sector is the fourth largest industrial energy user, emitting about 90 Mt of CO_2 in 2015 (including emissions of the sector's products that are covered in this analysis). Production of paper is projected to grow by about 50 % by 2050, with energy use rising from 5.6 EJ in 2015 to 7.7 EJ by 2050. In the Reference Case, emissions actually decline 20 % by 2050, to 74 Mt per year, because of an increased share of biomass in sector's total energy mix. By 2050, biomass is estimated to represent half of all energy demand, with the rest being supplied by electricity (30 %) and fossil fuels (20 %).

- Under REmap, emissions would be reduced by 85 % by 2050, to 10< per year, compared to the Reference Case. The sector's energy demand would grow to 7 EJ by 2050, with biomass supplying 60 % of all energy demand. Half of the emissions cuts would come from carbon capture and utilisation (CCU). The other half is split between renewable energy (30 %) and energy efficiency measures (20 %).

- The share of renewable energy could rise to more than 80 %, with biofuels representing more than half of sector's energy demand and renewables-based power and district heat representing the remainder.

- These options actually save money. Estimated savings are USD 10 per tonne of CO_2 by 2050. Additional investment needs on top of the Reference Case are USD 20 billion in 2015–2050.

- Since the sector already uses large amounts of biofuels, further increasing the share is fairly straightforward. There is also a large untapped potential for energy efficiency. The fact that cutting emissions saves money means that meeting the targets in the REmap case will be less challenging than for other sectors. In fact, the sector could actually become a negative emitter of CO_2 if it employed biomass-fired CCS (BECCS).

Buildings

Heating and cooling

- The buildings sector today emits about 3 Gt of CO_2 per year in direct emissions. In the Reference Case, those emissions remain about the same in 2050, despite both an increase in residential and commercial floor area from today's 150 billion m^2 to 270 billion m^2 by 2050 (mostly in urban areas) and an increase in the energy used for space heating and cooling, which rises from 52 EJ to 70 EJ per year between 2015 and 2050. The reason emissions remain the same is the continued reduction in energy use per unit of floor area. (Heating and cooling represent 60 % of building energy use.)

- In the REmap analysis, direct emissions in the building sector drop 75 % by 2050, to 0.9 Gt per year of CO_2. Building shell improvements account for 15 % of the reductions, electrification for 15 % and direct deployment of renewables for 70 % (including deployment for cooling).

- The share of renewable energy rises significantly for space and water heating to more than 80 % by 2050. The share is even higher for cooling, since under REmap cooling is delivered either by solar systems or renewable power.

- Low-carbon technologies for buildings heating and cooling come with a wide range of options, and these technologies have a wide range of costs. There are numerous low-cost energy efficiency measures, but also significantly more expensive renovation technologies. The average abatement cost of these options is USD 150 per tonne of CO_2. More efficient cooling systems and appliances can also reduce emissions from electricity generation. If the power sector emissions reductions are included, the average cost of abatement comes down to USD 70 per tonne of CO_2. Additional investment needs between 2015 and 2050 would be USD 26 trillion. This includes USD 10 trillion in the value of stranded assets.

- It is critical that all new buildings have a high energy efficiency. Existing technologies and approaches (such as solar water heaters and renewable energy-based district heating) allow new buildings to be designed with a tenth of the thermal energy use per unit of floor area compared to existing stock. The renovation and refurbishment of existing buildings must be accelerated. This may require policies that change the market structure to increase the incentives for building owners to implement energy saving measures.

Cooking

- Cooking constitutes a significant part of residential energy use and about 3 % of the global final energy demand. Traditional wood fuels alone emit 1–1.2 Gt of CO_2-eq per year (2 % of the total global emissions), and total cooking emissions are about 4 Gt CO_2-eq per year. In terms of energy-related CO_2 emissions, cooking activities produced 0.6 Gt of CO_2 in 2015. In the Reference Case, this rises to 0.8 Gt by 2050.

- In REmap, cooking emissions fall to 0.5 Gt of CO_2, as people switch to more efficient cookstoves, such as electric stoves, which cut energy demand for cooking by three to five times, as well as reducing emissions. In addition, more renewables-based cookstoves, such as those that use modern biofuels and solar energy, are being deployed.

- The share of renewable energy declines to nearly 60 % by 2050 from about 70 % in 2015. This is largely explained by the introduction of more efficient modern biofuel cookstoves, which use less biomass than their traditional equivalents do to deliver the same cooking performance.

- A major challenge is delivering enough renewable electricity in the developing world to power efficient electric stoves, especially in rural areas. Large-scale efforts to supply renewable electricity to the developing world, therefore, would have the added benefit of reducing cooking CO_2 emissions and pollution.

District heating and cooling

- The district heating and cooling sector's CO_2 emissions were 1.2 Gt in 2015. This includes emissions from main activity producer heating plants as well as the fuels used for heat generation in combined heat and power plants. In the Reference Case, emissions grow slightly to 1.4 Gt per year in 2050. This modest growth is an outcome of the modernisation of existing systems so that they require less energy, reduced demand for heating in buildings, and a structural switch from centralised to decentralised power generation.

- In the REmap analysis, the sector's total CO_2 emissions decrease by two-thirds to 0.4 Gt by 2050. Overall demand for district heating and cooling drops because of energy efficiency measures and a shift toward more decentralised systems. In addition, about 30 % of the total energy demand is supplied by renewable energy technologies, mainly biofuels.

- Technology options under REmap come with an average cost of abatement of USD 50 per tonne of CO_2 by 2050. The additional investment needed for this transition is estimated at USD 10 billion for the 2015–2050 period.

Transport

Passenger cars

- Today, passenger cars represent just under 10 % of global CO_2 emissions, about 3 Gt per year. In the Reference Case, total energy demand in the sector rises from 44 EJ in 2015 to 66 EJ by 2050, with total CO_2 emissions increasing to 4.2 Gt per year. In the Reference Case, most cars would still use fossil fuels in 2050.

- In the REmap case, energy demand declines to 36.6 EJ by 2050, and emissions drop to 0.65 Gt CO_2 per year, an 85 % reduction compared to the Reference Case. The emissions reductions are achieved through better fuel economy, widespread use of electric vehicles and adoption of liquid and gaseous biofuels and renewables-based hydrogen.

- The share of renewable energy (from renewable electricity, biomass and hydrogen) would be nearly 70 % of total energy use in 2050. This would be comprised of 36 % renewable power, 24 % biofuels and 8 % renewable hydrogen.

- The average abatement cost of these options would be USD 27 per tonne of CO_2 by 2050 (excluding the additional cost of infrastructure for electric vehicle charging, hydrogen pipelines and refueling stations). Additional investment needs on top of the Reference Case would be USD 3.7 trillion over the 2015–2050 period. Around half of this total is related to infrastructure needs for electric vehicles and hydrogen.

- The technologies to build electric cars and create advanced biofuels already exist. The challenges to their adoption include making them more affordable (which may require policy incentives) and better connecting the transport and power sectors so that vehicle charging is aligned with the variable renewable power supply (which requires systems thinking).

Other ground passenger transport

- Worldwide, the number of total trips by bus and rail and by two- and three-wheelers is around 70 % of all trips made by passenger cars. Because of the high share of electric trains and the large number of passengers per bus or train, CO_2 emissions from these trips is even lower than those from passenger cars, and only 20 % of the total from transport, or 1.1 Gt of CO_2 per year. In the Reference Case, the total energy demand of the sector rises slightly from 15 EJ in 2015 to 19 EJ by 2050, with CO_2 emissions increasing to 1.24 Gt.

- In the REmap analysis, energy demand declines to 10.4 EJ by 2050 and emissions fall by two-thirds to 0.45 Gt per year. The reductions are due to the electrification of railways, bus transport and two-and three-wheelers, along with increased use of biofuels. Biofuels would supply about a quarter of all energy demand, with another 20 % coming from renewable electricity.

- The share of renewables would rise to more than 37 %, split into 23 % biofuels and 14 % renewable power.

- The average abatement cost would be USD 7/tCO_2 by 2050. The additional investment needs would be USD 2 trillion during the 2015–2050 period. Two-thirds of this total is related to infrastructure needs for additional railways electrification.

- Countries and cities are already moving rapidly to switch trains, buses and two- or three-wheelers from diesel or other fossil fuels to electric power. There are also significant shifts within these transport modes, for instance, from long-distance trains to buses and from one transport mode to another, such as from passenger cars to trains. Opportunities that may arise from these modal shifts must be accelerated and combined with renewable energy integration.

Aviation

- Aviation today (mainly long-distance passenger transport) is responsible for 10 % of transport's total energy demand, and for 2–3 % of total global CO_2 emissions (about 0.7 Gt CO_2 per year). Travel by airplane is expected to grow by between 3 % and 5 % per year, higher than any other transport mode. In the Reference Case, energy demand for aviation more than triples from about 10 EJ today to 24 EJ by 2050, with emissions rising to 1.6 Gt of CO_2. More than 95 % of this total is related to aviation, and a small share come from passenger shipping.

- In the REmap case, total energy demand rises to only 17 EJ by 2050 because of energy efficiency gains, while CO_2 emissions drop to 0.8 Gt per year. The reduction comes from a combination of greater efficiency and increased use of biofuels. Biofuels are estimated to supply around one-third of total aviation energy demand.

- The cost of the emissions reductions would be about USD 105/tCO_2 by 2050. The additional investment needs on top of the Reference Case would be USD 0.35 trillion in 2015–2050.

- Producing a large enough volume of biofuels for aviation is a challenge from technical, economic and land-use perspectives. Biofuels are currently at early stages of deployment, and few facilities exist that produce biofuels at commercial scale. However, energy efficiency alone won't be enough to reduce the sector's growing CO_2 emissions, and biofuels remain the only viable option. Therefore, new policies that can bridge the price gap between biofuels and petroleum-based jet fuels while also taking into account the sector's international nature are required.

Freight

- Freight transport (trucks, ships and trains) represents more than 40 % of transport's total energy demand. As the backbone of global trade (carrying 90 % of the tonnage of all traded goods), the shipping industry is projected to increase its energy use from 11 EJ in 2015 to 16 EJ in 2050. Road freight energy demand is projected to increase from 24 EJ to 30 EJ in the same time period. In the Reference Case, CO_2 emissions rise from 2.6 Gt in 2015 to 3.2 Gt in 2050 as the sector continues to rely on fossil fuels (with biofuels gaining a market share of 7 %, mainly used in trucks).

- Under REmap, freight's CO_2 emissions would decline by 65 % compared to the Reference Case, to 1.2 Gt of CO_2 per year by 2050. About 0.6 Gt per year of reductions come from the use of biofuels in trucks and ships. Another 1.5 Gt of CO_2 emissions can be cut by efficiency measures across all modes of freight transport, and more reductions come from switching to electricity, especially for freight trains and delivery trucks. But even with aggressive uptake of renewables and efficiency improvements, the sector's energy use and related CO_2 emissions will be significant.

- The share of renewables in 2050 is expected to be about 50 %.

- Average abatement costs of this technology mix are estimated at USD 40/tCO_2. Additional investment needs are estimated at USD 2.1 trillion between 2015 and 2050. Around two-thirds of this total is needed for new infrastructure for electrification and hydrogen.

- Biofuels are already being commercialised for trucks in some countries, but major barriers to widespread production and adoption remain.

The other main challenge is in the shipping sector, where there is a large price gap between cheap fuel oil and other options, such as electrifying ships.

Power generation

- The power generation sector emitted 13 Gt of CO_2 in 2015, about 40 % of the total global energy-related emissions. In the Reference Case, total power generation would increase from more than 24 000 TWh in 2015 to 47 700 TWh per year in 2050. Around 37 % of this total generation in 2050 would come from renewables, so annual emissions would rise only marginally from 12.7 Gt to 14.4 Gt between 2015 and 2050.

- In the REmap analysis, emissions would decline by 85 % compared to the Reference Case, to 2.1 Gt by 2050. About 60 % of the reductions are due to a significant increase in renewable power. The other 40 % of reductions come from lower demand for electricity. Under REmap, wind and solar PV would provide half of all electricity generation, and nuclear and natural gas would provide 17 %. Coal's contribution drops from 41 % in 2015 to 1 %. No CCS was foreseen.

- Overall, renewables would supply 82 % of electricity by 2050. The average cost of abatement is estimated at USD 25/tCO_2, including the costs of integrating renewable energy (estimated at USD 500 billion per year in 2050). Without those integration costs, the generation mix in REmap would result in savings of USD 44 per tonne of CO_2.

- The additional investment needs in power generation capacity on top of the Reference Case are estimated at USD 8.3 trillion during the period 2015 to 2050. Another USD 8.4 trillion of investment is needed for transmission and distribution (T&D). That includes USD 4 trillion investment in transmission and distribution lines, USD 2.7 trillion for variable renewable energy (VRE) capacity and USD 1.5 trillion for super grids. An additional investment of USD 6.3 trillion is needed for back-up capacity, including USD 0.75 trillion for battery storage.

- The high share of renewables requires that steps to be taken to ensure system flexibility. Possible steps include strengthening the grid and interconnectors, making generation more flexible, increasing demand-side management and adding storage. Solutions will vary by country, but may require both supportive policies and new business models.

Sub-sector reviews

Power generation

Sector description

Electricity is required for activities in all sectors of the economy. In buildings, a share of heating and cooling demand is supplied by electric heat pumps and other devices. The majority of household appliances and electronics use electricity. Some industrial processes, such as the production of chlorine or steel recycling, rely on electricity. Various transport modes, such as rail, trams and electric vehicles, also use electricity.

The share of electricity use in the global energy mix is about 20 % today. This share is expected to rise significantly in the future with the penetration of more electricity-based technologies and improvements in the heat demand of processes. This is important for a number of reasons. Electricity is a clean "fuel" that has no emissions when used. For instance, electric vehicles emit no CO_2 or NOX and therefore contribute to a cleaner environment. Moreover, electricity-using energy devices have significantly higher energy efficiency compared to thermal-based systems. As a result, the irreversible energy losses in conversion from one form of energy to another are significantly lower.

The power generation sector is responsible for the production of electricity from different sources of energy. It is part of a broader power system that is also responsible for transmitting and distributing the generated electricity to consumers through grids. Power can be generated from all types of fuels. Historically, coal has been the dominant fuel. For more than a century, the kinetic energy that exists in rivers or streams has also been captured in run-of-river hydropower systems. Windmills have been used starting in the early 20th century in farms in the United States (while using wind for mechanical functions, like pumping, dates back much earlier). Over many years, natural gas, fuel oil and nuclear have gained share in total power generation. Nuclear has being used since the 1950s; nearly 450 plants are in operation today worldwide. Renewable energy sources, such as solar, wind and biomass (including co-firing with coal) now are being increasingly used for electricity generation with a share close to a quarter of all generation today. The waste by-products of industrial processes, such as blast furnace gas in iron production, or any form of waste with a high energy content, are also used.

Coal and nuclear are typically used to provide baseload power to meet a continuous level of electricity demand. Likewise, hydro, geothermal and biomass can also be used to generate baseload power. These plants typically run throughout the entire year with few shutdowns, for example, only when they need to be repaired. Natural gas power plants can be used to provide baseload, but they are also typically used to meet peak loads when there is high demand and in combination with other baseload power plants. Solar and wind, on the other hand, are variable sources of electricity generation. They are not continuously available. Despite the availability of technologies and measuring systems to predict their output, they cannot always be dispatched to meet consumer demand.

The majority of consumers are connected to a power grid. Such grids typically cover a large share of a country's territory. There could be several grids in operation within a country. They can be connected to each other or they may operate in isolation from each other. Grids of different countries are also connected to each other in order to allow trade in electricity. There are also systems independent of the main grid, such as off-grid systems. These systems are smaller and provide electricity to limited number of consumers. Typically, diesel generators or hybrid systems with renewables are used in such systems. Off-grid systems can be found in islands or in rural areas.

Present energy use and CO_2 emissions

In 2015, total electricity generation reached 23 950 TWh worldwide (Enerdata 2016). Coal accounted for 41 % of all generation, followed by natural gas with a share of 22 %. Hydropower represented 16 % of the total mix, and other renewables accounted for another 7 % of the total. Nuclear accounted for 11 %. Fuel oil represents the remaining 3 %.

Starting in early 2000s, the construction of coal-fired power plants increased rapidly, averaging more than 90 GW of additional plants per year. During one period in mid-2000s, one new coal power plant was being built per week in China, a period in which the country accounted for about 90 % of all additions worldwide.[2] Over the past few years, the amount of electricity generated from coal has declined worldwide. However, there are plans to increase coal capacity. Out of 931 GW of plants announced, pre-permitted or permitted as of July 2016 (equivalent to more than 1 500 units), coal represented 349 GW. About half of the announced new coal plants are in China. But the actual markets where capacity is growing include various Southeast Asia countries, such as Indonesia and Vietnam, along with other countries that are growing rapidly and thereby require more electricity, such as India, Turkey, Pakistan and Egypt.[3]

Coal is the most carbon-intensive fuel. Today, it is responsible for more than 70 % of the sector's total CO_2 emissions of 12.7 Gt in 2015. It also accounted for about 40 % of the total global energy-related CO_2 emissions. Gas emissions accounted for 20 % of the total, followed by fuel oil emissions at 8 %.

Sector trends to 2030 and 2050

Electricity generation is projected to increase to from today's 23 950 TWh per year to about 32 500 TWh per year by 2030 and to around 47 000 TWh per year by 2050. Total power generation capacity would reach more than 12 400 GW by 2050.

This growth is explained by a number of factors. Demand will naturally rise with population growth. Increasing wealth will also increase electricity demand, because higher income countries use more electricity per capita. For example, an average person in North America uses four times more electricity than the global average. Ensuring universal electricity access also will lead to a significant additional demand. Finally, more services will be electrified, such as transport and cooking.

2 For more details, please refer to (Endcoal 2016b). http://endcoal.org/wpcontent/uploads/2016/08/GlobalOperating-2c.pdf

3 For more details, please refer to (Endcoal 2016a). http://endcoal.org/wp-content/uploads/2016/08/CountryMW-4.pdf

Reference Case: Path set by current plans and policies

The Reference Case includes the current projections of an increase in total power generation to 47 000 TWh per year in 2050. The renewable energy share of the sector would rise from today's 23 % to 31 % by 2030 and to 37 % by 2050. The increase is driven by a mix of solar PV and wind. Generation from these two sources would reach 10 120 TWh per year by 2050, representing slightly more than 20 % of the total. Gas would overtake coal to become the largest supplier of power by 2050, at 15 240 TWh per year.

REmap analysis: Technology solutions and their potential by 2050

In the REmap analysis, emissions would decline by 85 % compared to the Reference Case, to 2.1 Gt by 2050. Most of those reductions, about 60 %, would be achieved by the main class of technologies explored under REmap: renewable energy technologies. Under REmap, the renewable energy share in electricity supply would reach 60 % by 2030 and 96 % by 2050, compared to 37 % in the Reference Case. The remaining 40 % of emissions reductions would come from efficient use of electricity in buildings, industry and transport.

The sector is currently on track to meet short-term goals in the deployment of renewables, but their adoption would need to be accelerated to meet the long-term targets.

Under REmap, half of all electricity generation would be supplied by wind and solar PV, and 18 % by a mix of nuclear and natural gas. Coal's contribution would be reduced to 1 % in 2050 from 41 % in 2015. The REmap pathway also requires significant changes in the way the power sector operates. These changes are predominantly driven by the introduction of variable renewable energy sources to the mix. Under REmap, the share of wind and solar increases to 31 % by 2030 and to 52 % by 2050. The main technical challenges occur when variable renewables push demand for non-renewable generation below the minimal operating level of a country's dispatchable fleet. By requiring plants to produce less or switch off entirely in times of abundant renewable power supply, generators are presented with a difficult task in balancing supply and demand. Such high shares will require steps to be taken to ensure system flexibility. Different options can be considered to accommodate higher shares of variable renewables depending on national circumstances.

These options generally fall into four groups: strengthening the grid and interconnectors, flexible generation, demand-side management and storage.

A starting point is strengthening grid infrastructure to balance renewable energy supply patterns and demand. Grids can also be enhanced and expanded to increase the capacity to move loads over long distances when necessary. Increased interconnection capacity within countries (in particular for countries with large territory) and between countries will also be important to integrate power sectors, because interconnectors offer an important means of flexibility to the system by allowing power trading.

While dispatchable fossil fuel fleets will be largely replaced by renewable generators under REmap, the remaining fossil and nuclear (though typically the least flexible of all options) capacity offer flexible generation, supplemented with a back-up natural gas capacity of around 5 000 GW worldwide by 2050. A range of renewables, including biomass, CSP and hydro, also offer flexible generation.

Demand-side management is an important source of flexibility that may come in different forms. Primarily, it can take the form of encouraging system customers to maximise their use when supply is naturally high, for instance, when wind and solar PV are producing at their peak on windy or sunny days. Further flexibility can come from creating sector linkages between power, heating and cooling, and transport. Electricity-based heat and transport capacity are expanded greatly in the REmap case. Electric vehicles (EV) can allow for additional flexibility through smart charging, and through feeding power back to the grid when plugged in. Pilot projects are already happening in California, for example.[4] Demand response also can occur through electrification of the heating sector, for example, by shifting the supply of heat in the building sector to account for peaks in electricity supply. A common method of ensuring linkages across different sectors linkages is to use heat pumps that

4 https://www.pge.com/en/about/newsroom/newsdetails/index.page?title=20161114_pge_and_bmw_partner_on_next_phase_of_pilot_studying_advanced_electric_vehicle_charging_

can operate on a flexible schedule to supply heating or cooling services. Moreover, smart thermal grids (district heating and cooling) can effectively connect the electricity and heating sectors, adding flexibility through thermal storage.

Electricity storage is another key option for integrating higher shares of variable renewables. In the REmap analysis, electricity storage capacity reaches more than 1 000 GW by 2030, when the total installed solar and wind capacity will be 5 000 GW. This storage capacity is split into: 600 GW from electric vehicles, 325 GW from pumped hydro, 125 GW from stationary battery storage and 50 GW from second-hand car batteries.[5] Total storage capacity grows to nearly 3 000 GW by 2050, with electric vehicles accounting for majority of this total.

From a system perspective, research has shown that enhanced flexibility options to accommodate very high shares of variable renewable energy (VRE) can provide reliability at the same cost, or less, as the existing power generation mix. But for countries with existing electricity system infrastructure, there are costs associated with transforming those systems. Without any integration costs, implementing the power generation mix under REmap would bring savings of USD 325 billion per year by 2050. The savings are explained by the much lower variable costs of generating electricity with solar, wind and other renewables compared to non-renewable technologies, which have fuel costs. Incremental system costs related to the costs of integrating variable renewable energy to the power system are estimated at USD 500 billion per year, including utilisation, curtailment, storage and transmission and distribution (T&D).

Investment needs for T&D infrastructure on a global basis are estimated at USD 8.4 trillion for 2015–2050. This includes a USD 4 trillion investment in T&D to meet growing electricity demand, USD 2.7 trillion for additional VRE capacity-related T&D and USD 1.5 trillion for super grids. Investment needs for back-up capacity are estimated at USD 6.3 trillion between 2015 and 2050. For battery storage, USD 0.75 trillion investment is estimated in the same period. Some of these investments will already be made in the Reference Case; those investments amount to USD 8 trillion between 2015 and 2050. Hence, to realise the REmap potential, the additional investment needed in power system infrastructure, battery storage and back-up capacity is estimated at USD 7.5 trillion.

5 Battery storage capacity from second-hand car batteries can be higher depending on their usability, which still needs to be determined.

Table 2: Economic indicators for power generation sector

	Abatement cost (USD/t CO_2)	Abatement potential in 2050 (Mt CO_2/yr)	Abatement cost (USD/t CO_2)	Abatement cost (USD/t CO_2)
Solar PV	13	2 550	33	0.9
Wind	35	3 405	120	1.9
Geothermal	6	665	4	0.3
Concentrated solar power	15	760	11	0.3
OTEC	90	105	10	0.3
T&D, super grids				3.4
Back-up natural gas capacity				3.5
Battery storage				0.6
Total	25	7 485	180	16.3

Note: excludes the emission reduction potential from end-use sector electricity use improvements

Industry – iron and steel

Sector description

The iron and steel sector produces coils, bars, wire, cast iron and other products. The largest share of energy use is for crude steel making. Four major methods of production exist today:

- blast furnace (BF)/basic oxygen furnace (BOF)
- smelt reduction (SR)/basic oxygen furnace
- direct reduced iron (DRI)/electric arc furnace (EAF) using iron ore feedstock
- scrap/electric arc furnace (EAF)

The most commonly used processes are BF/BOF for primary steel making (where 85–90 % of the feedstock is iron ore and the rest is scrap) and electric arc furnaces (EAF) for secondary or recycled steel. BOF accounts for roughly 75 % of the total crude steel production and is responsible for the bulk of energy use and GHG emissions. DRI/EAF route has gained some market share, increasing to about 7 % of world crude steel production. Scrap/EAF accounts for 28 %.

Primary steel making (BF/BOF) consists of 5 major processes: coke making; iron ore agglomeration by sintering or pelletising; liquid iron production in BF; steel production in BOF; and final product manufacturing by casting, rolling and finishing. The blast furnace is the main process. Coal, coke and iron ore are the inputs. The outputs are liquid iron and blast furnace gas. The blast furnace gas (BFG) is then used for coke making, power generation and other processes.

Present energy use and CO_2 emissions

Coal and its products currently supply about 80 % of the iron and steel sector's fossil fuel demand. Coke and powder coal are mainly used in blast furnaces. Blast furnaces use about 350 kg of coke per tonne of hot metal (thm) produced. In addition, 125 kg of pulverised coal is injected per thm (IEA 2007; Corsten 2009).[6] Worldwide, this adds up to a total energy input to blast furnaces of 18 EJ. The process generates about 5 EJ/yr of blast furnace gas, which is typically combusted on-site for power (and heat) generation. The blast furnace gas has a high carbon intensity, so that its combustion emits about 1 Gt of CO_2 per year globally. Roughly 60 % of all blast furnace gas is combusted in power plants and the remainder 40 % in various processes of iron and steel making.

6 100 kg is about the minimum achieved where most plants require about 200 kg while using coking coal with low ash.

More than half of all iron ore is converted to sinter (IEA 2007) in a process that requires approximately 1.4 EJ/yr of solid fuels (*e.g.* coke breeze or other coal products) (IPTS/EC 2013). Steel rolling requires approximately 4.2 EJ of primary energy (IPTS/EC 2013; Corsten 2009; WSA 2015b) and fuels used in EAF require another 0.5 EJ of primary energy, mainly for scrap melting (IPTS/EC 2013). Iron casting requires about 0.5 EJ of primary energy (Saygin, Patel, and Gielen 2010). Depending on the method, between 0.5 (EAF) and 2 (BF/BOF) tonnes of CO_2 are emitted during the production of 1 tonne of hot rolled steel coil. The DRI method has lower CO_2 emissions than these other processes despite a higher energy input because it uses natural gas, which has a lower carbon intensity than coal.

The iron and steel industry accounted for 2.2 Gt of CO_2 emissions in 2015, representing 7 % of all emissions fossil fuel use worldwide. This includes emissions from blast furnace gas use for on-site power generation as well as lime use in iron making, but excludes some processes, such as the production of steel products, which would add another 0.4 Gt of CO_2 emissions.

Industry trends to 2030 and 2050

China now accounts for around half of all global crude steel production (0.8 Gt of the 1.6 Gt worldwide). The latest market reports show that China's operating capacity increased in 2016 (Custeel 2017), but some market analysts believe that production in China has peaked and will begin to decline. Meanwhile, production is increasing in other developing regions, such as India, Southeast Asia, Africa and Latin America.

Total production of crude steel is projected to rise to 2.2 Gt by 2050, with half of that produced by the EAF method in the REmap case.[7] To supply the increased feedstock needs for the EAF process, an increasing share of iron production would come from the gas and hydrogen based DRI process, a production of about 0.4 Gt by 2050. BF-based iron production would reach 1.1 Gt by 2050. The sum of total iron production from these two routes would be 1.5 Gt. The remaining 0.7 Gt of feedstock would be scrap (process and post-consumer scrap). About 0.3 Gt of scrap will also be needed for the production of primary steel in the BOF process. About 70–90 % of all input to BOF is hot metal from blast furnaces, and the remaining 10–30 % is scrap (IPTS/EC 2013).

Reference Case: Path set by current plans and policies

The Reference Case projects that the sector's energy demand will grow about 30 % from around 27 EJ in 2015 to 28 EJ in 2050. In 2050, coal and its products will continue to dominate the sector's energy mix, accounting for nearly three-quarters of the total. Gas' share will rise slightly, from 6 % to 8 %. While the electricity use share will remain the same at approximately 15 % of the total demand, no major change in renewable energy use is projected under the Reference Case. The sector's total CO_2 emissions would rise to 2.2 Gt of CO_2 by 2050 (excluding any indirect CO_2 emissions from the use of electricity).

REmap analysis: Technology solutions and their potential to reduce emissions by 2050

In the REmap case, emissions would be reduced by more than 60 % to 0.6 Gt in 2050 compared with the Reference Case. Nearly one-third of this reduction would be achieved with CCS, 27 % with renewables (largely biomass), and about 40 % with energy and material efficiency measures.

Given the high temperature levels of the production processes and the need for carbon for the chemical reaction, the only renewable energy technology alternative in iron making is biomass. Coke and coal used in blast furnaces could be replaced with charcoal derived from wood. Charcoal can also substitute for injection coal. Charcoal theoretically can also be used in high temperature (>1 300°C) sinter ovens for reducing iron ore, but there are practical limitations (IRENA 2014a; Monsen *et al.* 2001).

Efforts been made to use other carbon sources, such as waste plastic, but problems with feedstock availability and preparation needs have resulted in limited uptake. Electricity or various combustion gases can be injected into blast furnaces, but the furnace's physical structure has to be maintained. That requires using coke. In theory, the blast furnace can be replaced altogether with an electrolysis process similar to that used in primary aluminium production, but such technology is still at the R&D stage.

Because of the challenges of using renewable energy in the iron and steel industry, the greater potential for reducing emissions comes from improvements in energy efficiency. In fact, the sector has a long

7 This is somewhat higher than the World Steel Association (WSA)'s base-case case where emissions reach 2.2 Gt per year by 2050 .

Table 3: Economic indicators under REmap in 2050 compared to the Reference Case for iron and steel industries.

	Abatement cost (USD/t CO_2)	Abatement potential (Mt CO_2/yr)	Incremental system costs (USD/t CO_2)	Additional investment needs 2015–2050 (USD trillion)
Charcoal for BF & sintering	45	355	16.9	0.36
Hydrogen-DRI	185	70	12.7	0.03
Gas-DRI	25	15	0.4	0.03
Current BAT	–30	80	–2.4	0.02
Emerging technologies	40	325	13.0	0.07
Efficient motor systems	–150	72	–10.8	0.08
BAT electricity	–50	168	–8.4	0.06
Steel recycling + other material efficiency improvements	5	265	1.3	0.10
CCS	150	550	82.5	0.17
Total	55	1 900	105.2	0.92

Assumption: Discount rate: 15 % and crude oil price: USD 80/bbl.

Table 4: Global REmap case – summary of activity, energy and CO_2 emission trends 2015–2050 for iron and steel industries.

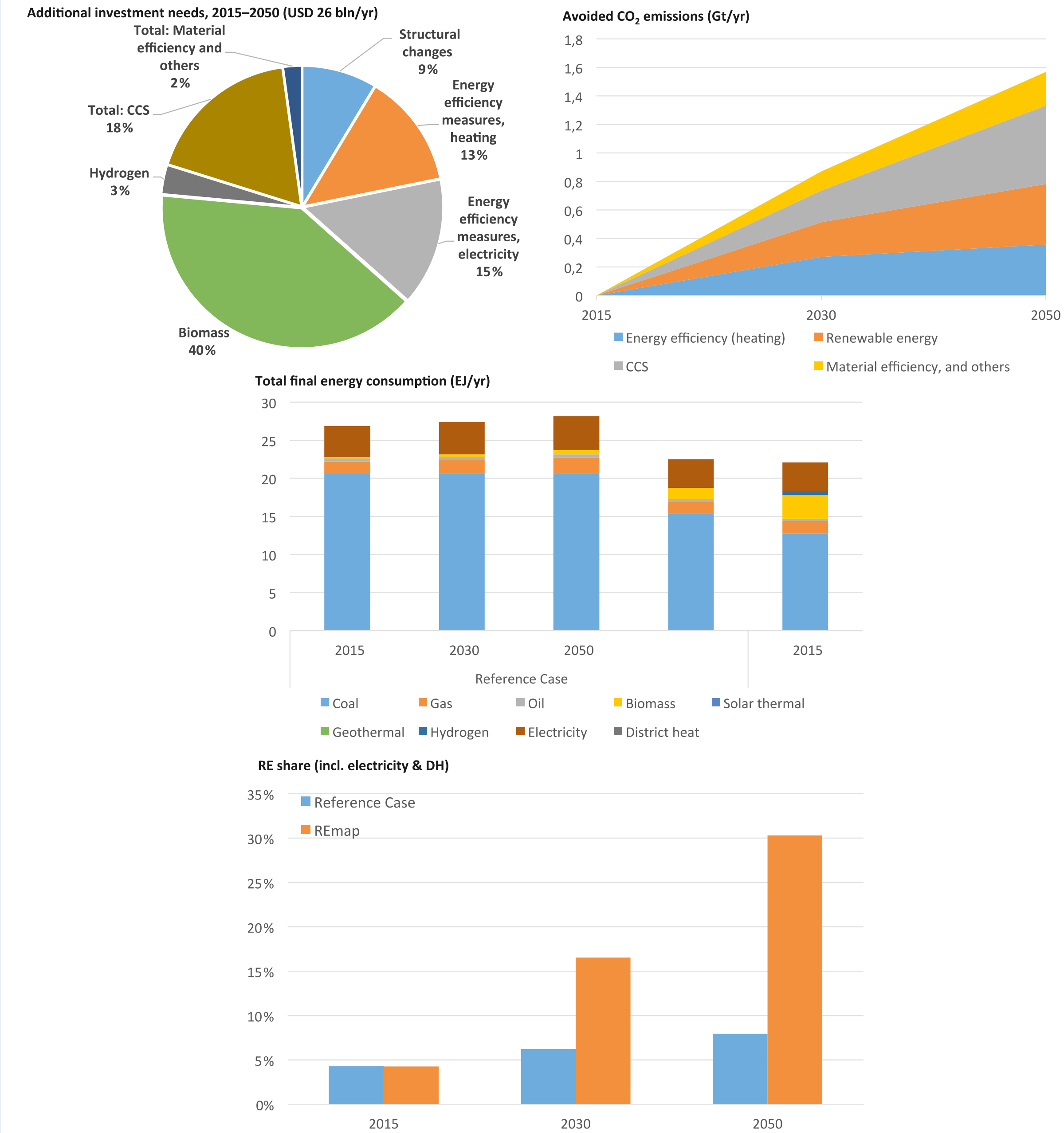
	2015	2030	2050
BF-iron production (Gt/yr)	1.2	1.1	1.1
DRI production (Gt/yr)	0.1	0.3	0.5
BOF steel (Gt/yr)	1.2	1.1	1.1
EAF steel (Gt/yr)	0.4	0.7	1.1
BOF steel (GJ/t)	18.7	15.2	13.2
Scrap/EAF steel (GJ/t)	2.7	2.2	1.9
DRI-EAF steel (GJ/t)	12.8	10.4	9.0
Total final energy consumption (EJ/yr)	26.9	22.5	22.1
CCS deployment (Gt CO_2 captured/yr)	0.0	0.2	0.6
Total direct CO_2 emissions (Gt CO_2/yr)	2.2	1.9	1.4

Note: Emissions from the combustion of blast furnace gas and emissions from limestone use are included, but indirect emissions from the generation of electricity that is consumed in processes are excluded.

history of R&D in improving energy efficiency and has developed and deployed various technologies. For example, replacing the conventional blast furnace with a process called COREX and using advanced smelting methods cuts energy use and reduces CO_2 emissions by about 20 %.[8] Using gas instead of coal for DRI also cuts emissions. Although it has been available for years, gas-based DRI is used for only about 6 % of total iron production today. Gas can also be replaced with hydrogen produced from renewable power, reducing process emissions even further.

8 http://ietd.iipnetwork.org/content/corex-process

Figure 21: Key estimates for iron and steel industries



Based on IRENA estimates

Another approach to reducing emissions would be to use carbon capture and storage (CCS). CO_2 capture processes can be integrated with iron and steel production using various solvents (Gielen 2003; Kuramochi and Turkenburg 2012).

Finally, there is a large potential to increase the production of secondary steel by collecting and recycling more of the steel in products that reach the end of their lives (Gielen and Moriguchi 2003). However, scrap availability lags behind production growth, and the relatively high costs of collection compared to the price of iron ore make the economics challenging. As a result, secondary steel from recycled products cannot entirely replace primary iron production (Neelis and Patel 2006).

Under REmap, the sector's total energy demand is estimated to decrease from 27 EJ in 2015 to 23 EJ. This reduction is driven by the introduction of energy and material efficiency measures as well as by the shift to more scrap use. Overall, the sector would use up to 20 % less energy than in the Reference Case by 2050. Coal's share of the total energy demand would drop to 60 %. Renewable energy (mainly biocoke and charcoal, but also small shares of hydrogen in the DRI process) would represent around 15 % of the total.

With improvements in energy and material efficiency, as well as the increased use of renewable energy, the sector's CO_2 emissions would still remain at around 1.4 Gt by 2050 (including the reduction in emissions from blast furnace gas combustion and lime use). That would be a reduction of 30 % compared to the Reference Case emissions of 2.2 Gt.

Adding CCS would cut CO_2 emissions further, to 0.6 Gt by 2050, for a total 60 % reduction compared to the Reference Case. Material and energy efficiency measures would account for 40 % of these reductions. CCS would represent 35 % and renewable energy technologies 25 %. This potential is in line with World Steel Association's (WSA) assessment of a 70 % reduction in 2050 (from 2.2 Gt to 0.7 Gt per year).

As Table 3 shows, the average abatement cost of these options would be USD 55 per tonne of CO_2 by 2050, and the additional investment needs over the Reference Case add up to USD 0.9 trillion in the 2015–2050 period.

Industry – cement

Sector description

Cement is produced by mixing finely ground cement clinker and other materials. Cement clinker, in turn, is produced by calcination of limestone. This process requires high temperatures of around 1 000oC. Because of the chemical reaction, this precalciner process produces emissions of around 0.5 tCO_2/t of clinker, about 60 % of the total CO_2 emissions from cement making. Total global cement production was 4.2 Gt in 2015, with clinker production of 3.1 Gt. The global clinker/cement ratio in 2015 was around 0.74 (USGS 2016a).

Present energy use and CO_2 emissions

Clinker production was responsible for 1.5 Gt of process CO_2 emissions in 2015. An additional 1 Gt of CO_2 emissions come from the energy consumed in the cement-making process, and another 0.2 Mt of CO_2 emissions come from the use of electricity. The total, about 2.5 Gt of CO_2, is about 8 % of global energy and process CO_2 emissions.

The most efficient clinker kilns currently use around 3 GJ/t of cement clinker, while older kilns use around 10–20 % more energy. Some outdated equipment can use up to double that amount. The theoretical minimum is 1.8 GJ/t clinker.

In current best practices, the preparation of feedstock materials and the grinding and mixing of products requires around 100 kWh electricity/t cement. Minor electricity uses are related to other motor drives, such as on-site compressors or fans.

Industry trends to 2030 and 2050

China accounts for more than half of global cement production. In 2015, its production of cement reached 2.36 Gt, fromabout 1.4 Gt of clinker. Chinese production is projected to decline to 1.6 Gt of cement and 0.8 Gt of clinker in 2030, with a further decline to 1 Gt of cement by 2050 (CNREC 2016). However, production is projected to grow strongly in other emerging economies. The net result will be a slight increase of global cement production to 4.8 Gt by 2030 (CemWeek 2016) and a larger increase to 5.9 Gt by 2050.

The clinker/cement ratio will depend on the future availability of clinker substitutes. The amount of one possible substitute, fly ash, is projected to decline as coal consumption for power generation declines. Similarly, the amount of blast furnace slag will also decline as new iron-making processes based on DRI will gain importance. The availability of other clinker substitutes will also be limited. As a result, the clinker/cement ratio is expected to remain constant at 0.75 for the 2015–2050 period under the Reference Case, although with the deployment of innovative clinker substitutes it falls to 0.64 under REmap by 2050.

Reference Case: Path set by current plans and policies

The Reference Case projects a growth in the sector's energy demand of approximately 30 % from about 12.3 EJ in 2015 to 16 EJ in 2050. By 2050, more than 80 % of all energy demand would be supplied by fossil fuels. Biomass and alternative fuel use would represent 9 % of the total mix by 2050, up from 2 % in 2015. The remaining 12 % would be electricity use. The sector's total CO_2 emissions are projected to rise

Table 5: Economic indicators under REmap in 2050 compared to the Reference Case for cement industry

	Abatement cost (USD/t CO_2)	Abatement potential (Mt CO_2/yr)	Incremental system costs (USD/t CO_2)	Additional investment needs 2015–2050 (USD trillion)
Biofuels, waste and other alternative fuels for clinker kilns	−30	315	−9.5	0.02
Solar thermal process heating	200	50	10.3	0.08
Current BAT	0	105	0	0.14
Emerging technologies	25	245	6.2	0.33
Efficient motor systems	−150	20	−2.6	0.01
Efficient grinding	−15	70	−1.1	0.09
Clinker substitutes	75	315	23.5	0.01
CCS (process + energy)	75	565	42.2	0.17
Total	40	1 695	69.2	0.86

Assumption: Discount rate: 15 % and crude oil price: USD 80/bbl.

Table 6: Global REmap case – summary of activity, energy and CO_2 emission trends 2015–2050 for cement industry

	2015	2030	2050
Cement production (Gt/yr)	4.2	4.8	5.9
Clinker production (Gt/yr)	3.1	3.3	3.8
Clinker energy use (GJ/t clinker)	3.5	3.0	2.3
Cement grinding electricity use (GJ/t)	0.36	0.30	0.28
Total final energy consumption (EJ/yr)	12.3	11.3	10.5
Energy-related CO_2 emissions (Gt/yr)	0.9	0.7	0.4
Process CO_2 emissions (Gt/yr)	1.6	1.1	1.3
CCS deployment (Gt CO_2 captured/yr)	0.0	0.3	0.6
CCS deployment (Gt CO_2 captured/yr)	0.0	0.2	0.6

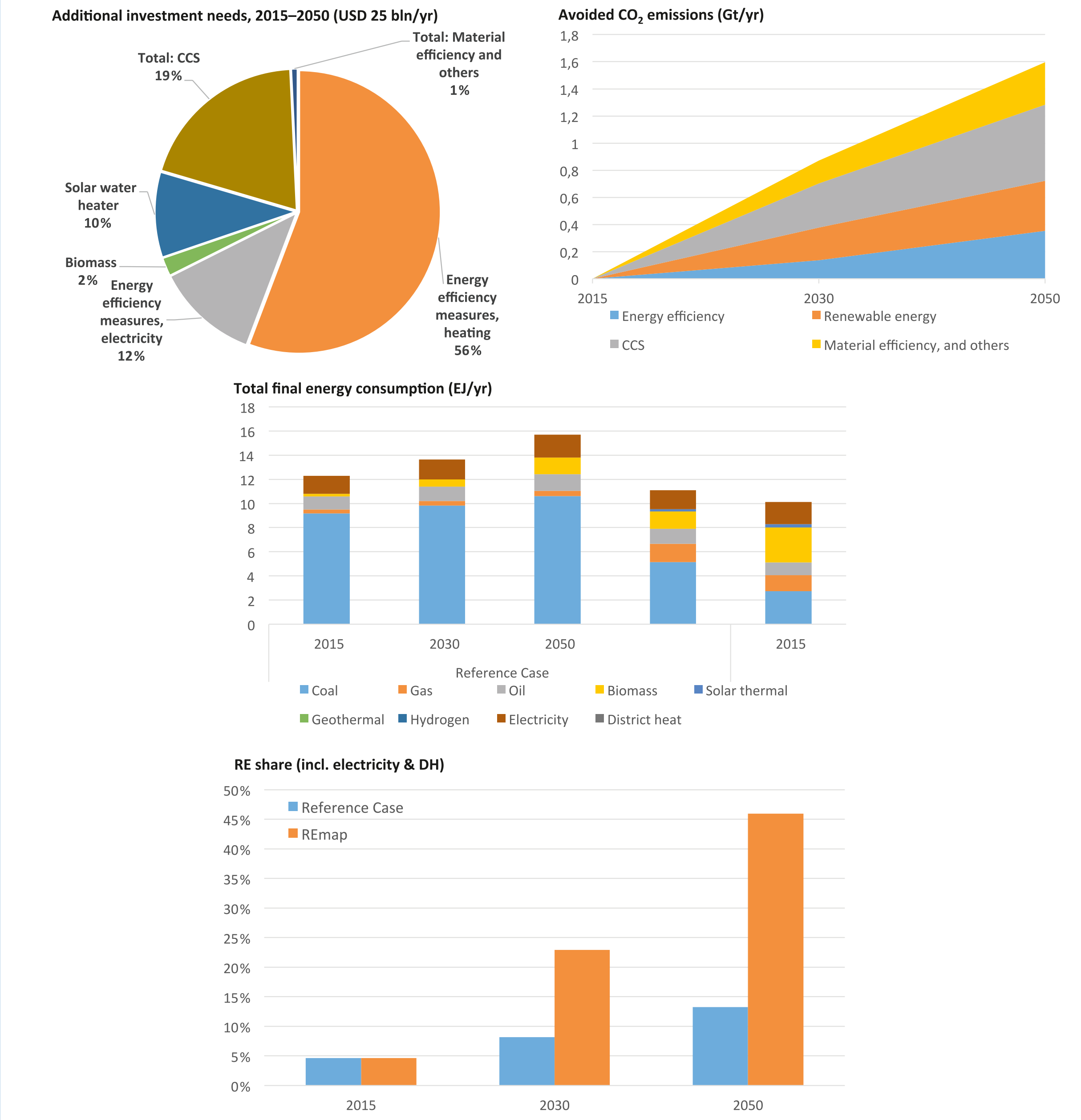
Note: Emissions from the combustion of blast furnace gas and emissions from limestone use are included, but indirect emissions from the generation of electricity that is consumed in processes are excluded.

to 3.4 Gt CO_2 by 2050 (excluding any indirect CO_2 emissions from the use of electricity).

REmap analysis: Technology solutions and their potential by 2050

Biofuels, alternative fuels and waste can replace fossil fuels to cut down the cement sector's energy-related CO_2 emissions. Emissions can also be reduced with more efficient kilns and grinding process. Deeper cuts in cement emissions, however, require the development of clinker alternatives and CCS. Under REmap, emissions would decline by 30 % compared to the Reference Case. Around one-third of these reductions would be achieved with CCS. Renewable energy and improvements in material efficiency would contribute 40 % of the total emissions reduction potential. The remaining one-fifth would be achieved through energy efficiency measures, such as more efficient kilns and grinding processes. Additional cuts in cement emissions would require the development of clinker alternatives and CCS.

Figure 22: Key estimates for cement industry



Based on IRENA estimates

Note: RE = renewable energy. DH = district heating. CCS = Carbon Capture and Storage

Cement kilns are very well suited for the use of renewable energy. About 60% of the total fuel is added in the precalciner, and the rest at the rotary kiln. Because temperatures are lower at the precalciner, it can use a variety of fuels, such as biomass, waste or other alternative fuels. Under REmap, fossil fuels would supply about half of the sector's total energy demand by 2050, compared to 86% today, and the use of biomass and alternative fuels would increase, supplying one-third of the total energy demand. This increased use of fuel alternatives would provide around 20% of the total emissions reductions in 2050.

Energy efficiency measures can also reduce energy demand and emissions in clinker making. Typical modern kilns use four- or five-stage preheating to increase efficiency. Moving to a six-stage pre-heater and precalciner process can cut fuel use even further, requiring less than 3 GJ fuel per tonne of clinker. Compared to the current level, this cuts energy by 15 %. That reduction could be doubled by 2050 with more advanced clinker-making technologies. Grinding energy demand can also be reduced by around 20 % compared to current levels, and technologies such as waste heat recovery can contribute to reducing consumption of grid electricity.

In the REmap, the specific energy demand of clinker production in 2050 is estimated to be 2.3 GJ/t. This is one-third below today's level, and close to the thermodynamic minimum. With these improvements in energy efficiency, the sector's total energy demand is estimated to be around 15 % less than today's levels under REmap, at 10.5 EJ. Energy efficiency measures achieve about a quarter of the total CO_2 emission reductions by 2050 compared to the Reference Case.

Even with these efficiency improvements, however, substantial process emissions remain. Today, the main strategy for emissions reduction is replacing cement clinker with other materials, such as volcanic ash (Pozzolana), blast furnace slag, fly ash, incinerator ash, steel making slag, glass-making slag or limestone. Depending on their material strength, however, these substitutes could affect the final cement quality. Moreover, most substitutes are not available in the quantities needed, and efforts to produce new cementing materials have not yet been commercially successful. Still, several plants for geopolymer cement production already exist. (Geopolymer cement contains silicon and aluminium, in contrast to clinker, which includes silicon and calcium). By 2050, as much as 35 % of all cement could be realistically produced from clinker substitutes. Material efficiency improvements from the increased use of clinker substitutes account for 20 % of the total abatement potential.

Finally, CCS could be used to further reduce emissions. Process emissions from calcination are highly concentrated, allowing for cost-effective capture (Kuramochi and Turkenburg 2012; Ruijven *et al.* 2016). Under REmap, CCS would be used to achieve more than one-third of the sector's total CO_2 emissions reductions by 2050.

As Table 5 shows, the average abatement cost of these options would be USD 40 per tonne of CO_2 by 2050, and the additional investment needs over the Reference Case add up to USD 0.9 trillion in the 2015–2050 period.

Industry – chemical and petrochemical

Sector description

The chemical and petrochemical sector produces chemical products that are derived from fossil fuel feedstock as well as from other inorganic raw materials. The organic chemical industry is the largest energy-using subsector. It typically uses a steam cracking process to make olefins (ethylene, propylene and butadiene) from naphtha, ethane, propane and other crude oil-derived feedstocks. The olefins are then converted to various intermediate chemicals and subsequently to a wide range of plastics, synthetic organic fibres like nylon and other polymers, which have many uses. The industry also makes solvents, detergents, paint and other products. Additional building blocks include ammonia and methanol, which are also produced from fossil fuels.

In addition to providing raw materials for the production of organic chemicals and plastics, fossil fuels are an energy source. In contrast, organic chemicals production (*e.g.* chlorine, phosphate) also consumes energy, but uses much less than the production of organics and often in the form of electricity where emissions take place outside of the sector's boundaries (Saygin *et al.* 2011).

Present energy use and CO_2 emissions

Steam cracking is by far the most important chemical process in terms of energy use. Depending on the feedstock type, high value chemical (HVC) production consumes between 60 GJ and 140 GJ of fuel per tonne of ethylene (when expressed per tonne of high value chemical, the specific consumption of fuel is lower and also the range is narrowed). About two-thirds of the fuel input is used as feedstock. The remaining one-third is used to generate process heat, which emits CO_2 when burned.

Steam crackers emit between 0.8 tonnes (for ethane) and 2.2 tonnes (for gas oil) of CO_2 per tonne of ethylene produced (Neelis *et al.* 2005). These numbers would be much lower if they were expressed in terms of tonne of high value chemical produced, which would allocate total emissions to other chemicals produced. The most efficient steam crackers are in Japan and the Republic of Korea; they are considered "best practice" plants. If the steam crackers in other parts of the world would switch to the level of best practice, they would reduce their related energy demand by between 20 % and 50 %. However, depending on the level of process integration achieved in the steam cracking process, the potential for improvement can be much higher. Some petrochemical products such as propylene and aromatics are also produced in refineries (Saygin *et al.* 2011).

Ammonia and methanol production require 30–45 GJ of energy to make a tonne of product (including feedstock use). At least two-thirds of this total remains in the product; the rest is combusted to generate process heat. The most efficient ammonia plants are in Europe and Latin America and the Caribbean, and they operate with natural gas. If all plants were as efficient as those, the total energy demand in ammonia production would be reduced by around 30–50 %.

The best-performing ammonia plants, which use a process based on steam reforming of natural gas, emit around 1.6 tonnes of CO_2 per tonne of ammonia, though emissions from inefficient plants can be as high as 2.5 tonnes of CO_2 per tonne of ammonia. When plants use partial oxidation of coal instead of steam reforming of natural gas, emissions climb to about 3.9 tonnes of CO_2. Coal-based production dominates in China, the world's largest producer. Gas-based production dominates elsewhere (Neelis *et al.* 2005; Broeren, Saygin, and Patel 2013).

Methanol production has smaller differences in energy use across countries. The production process is similar to that for ammonia, either steam reforming of natural gas or partial oxidation of oil or coal. The production processes emit between 0.4 and 2.2 tonnes of CO_2 per tonne of methanol, depending on the feedstock type.

A unique feature of the sector is that most of carbon from the feedstocks is stored in plastics and other products, and this carbon is only released during waste incineration. Each year, about 35 Mt of plastics and fibres are incinerated, which is about 10 % of the total annual global plastics and fibres production and a quarter of these materials that reach end of their lives. Emissions from waste incineration are estimated at 0.4 Gt CO_2 per year, based on an amount of about 100 Mt of plastics and fibres combusted each year (Saygin *et al.* 2014). If these plastics were recycled instead of being incinerated, carbon emissions would be reduced significantly. Likewise, the amount of solvents that are recycled can be significantly increased.

The carbon stored in products has important implications for CO_2 emissions. This carbon is not currently included in industrial emissions statistics. But emissions are expected to rise significantly in the coming decades as both the volume of waste and the percentage of waste that is incinerated grow.

Industry trends to 2030 and 2050

Production of HVCs has now reached about 365 Mt per year (from both steam crackers and other methods such as refinery co-production), in line with the growing demand for polymers and fibres. These chemicals are typically derived from oil products, and their production is often integrated with the refinery processes in energy and material terms.

Ammonia production has reached 175 Mt per year. Ammonia is a raw material for production of fertilisers, but it is also a feedstock for a wide range of chemicals. It is mainly produced from natural gas, although China mostly uses coal. Methanol is also a raw material for various organic chemicals and it can be used as a fuel or fuel feedstock for transport. It is produced from coal, gas or oil depending on the region, and its production has reached 62 Mt per year (Broeren, Saygin, and Patel 2013).

The chemical industry is central to the global economy. The sector's outputs are used in a wide range of applications, from agriculture to packaging. Plastics have also important energy applications. For instance, they are used as insulation to cut energy demand in buildings.

A large share of the global HVC production takes place in the US, EU, Saudi Arabia and Japan. A significant share of ammonia and methanol is produced in China. With the growing demand for chemicals across all branches of the economy (packaging, automotive, agriculture, etc), their production is projected to grow on average by 2.3 % per year between 2015 and 2050. Recycling of polymers will gain importance, reducing somewhat the growing demand for virgin polymers and production of olefins (Taibi, Gielen, and Bazilian 2012; Daioglou *et al.* 2014).

Reference Case: Path set by current plans and policies

The Reference Case projects that energy use in the chemical and petrochemical sector (for chemicals selected) will double by 2050, from around 40 EJ in 2015 to nearly 85 EJ. This includes energy stored in products, which is about two-thirds of the total energy demand of the chemicals production covered in this analysis.

Nearly all the demand for energy would be supplied by fossil fuels, predominantly crude oil products. Biomass could provide about 7 % of the feedstock supply and about 1.5 % of the energy used in production processes.

The sector's total CO_2 emissions would double to 3.1 GT by 2050 (excluding any indirect CO_2 emissions from the use of electricity, but including non-energy use emissions from ammonia production and emissions from the combustion of post-consumer plastic waste).

The accounting for emissions related to the stored carbon is complex and in many cases incomplete. Waste incineration emissions are projected to increase significantly as more products enter the waste stream and landfilling becomes more problematic. Given the high energy content of waste petrochemical products, these products could also be used as fuel in power plants, cement kilns and other facilities. Without changes in the current practice of waste incineration, related annual CO_2 emissions would increase to 0.9 Gt by 2050 compared 0.4 Gt in 2015.

REmap analysis: Technology solutions and their potential by 2050

In the REmap case, the sector's total CO_2 emissions (including the process emissions and waste) would drop to 1.3 Gt by 2050, compared to 3.1 Gt per year in the Reference Case. About 1.1 Gt of these reductions would come from material efficiency improvements. The remaining 0.7 Gt of reductions would be achieved through energy efficiency measures, renewable energy and CCS. An additional 1.8 Gt of emissions from the carbon stored in chemicals and plastics could be avoided by increased plastics recycling and the use of biomass feedstocks.

Biomass is the main renewable feedstock and energy alternative for bulk chemicals production.[9] Today, around 5 % of synthetic organic materials are so-called oleochemicals derived from biomass feedstock. That percentage could be increased. In addition, biomass is a technically viable fuel option for the production processes of the sector, which typically operate at temperatures too high for other renewable energy technologies such as solar thermal or heat pumps. As a result, in new facilities, biomass can be used as both fuel and feedstock.

Biomass-based ethylene production from ethanol already has been deployed on a commercial scale. So has the production of methanol from biomass-derived feedstocks. However, large-scale production currently faces a number of challenges. With today's low oil prices, the economics for biomass-based ethylene production are highly unfavourable. Moreover, ethanol is typically produced from food crops, which competes with food production.

Ammonia production is based on hydrogen as an intermediate. The switch to renewable electricity followed by electrolysis, therefore, is technically straightforward. However, this technology has not been deployed because of high costs.

Beyond these examples, integrating renewable energy into the existing processes presents a challenge, because production is so well integrated in terms of material and energy flows in large petrochemical complexes. As a result, improvements in energy efficiency would play the major role in reducing the sector's CO_2 emissions. Recycling and CCS could also play roles by reducing the demand for new production capacity and by capturing high concentration CO_2 emissions from the production processes of ethylene and its derivatives.

As already noted, significant amounts of carbon are stored in products. Some carbon can be released during use (as in the case of urea fertiliser) or it can form into CO_2 after volatile organic carbons (VOC) are emitted from solvents or paints. Larger amounts are released during post-consumer plastic waste incineration. The production of plastics stores about 335 Mt of carbon each year. Oxidising all of this would release 1.2 Gt of CO_2 to the atmosphere. There are three ways to reduce these emissions: recycle plastics; combine waste incineration with energy recovery; or produce chemicals from carbon-neutral biomass or other feedstocks. In the REmap analysis, recycling saves about 0.4 Gt CO_2/yr in process-related CO_2 emissions, about 10 % of the total potential.[10] Better

9 CO_2 is another feedstock that can be used if produced from renewable sources. However, today it is not fully commercialised.

10 There are three recycling routes for plastics: back to monomer, back to polymer and back to feedstock. Here, the back to monomer route was assessed.

Table 7: Economic indicators under REmap in 2050 compared to the Reference for chemical and petrochemical industries

	Abatement cost (USD/t CO_2)	Abatement potential (Mt CO_2/yr)	Incremental system costs (USD/t CO_2)	Additional investment needs 2015–2050 (USD trillion)
Biofuels for HVC	40	125	4.9	0.04
Biofuels for ammonia	70	20	1.3	0.007
Biofuels for methanol	70	10	0.8	0.004
Hydrogen	180	30	5.1	0.03
Current BAT	40	150	6.1	0.02
Emerging technologies	85	280	23.9	0.35
Plastics recycling and energy recovery	65	370	24.7	0.002
CCS	200	100	20.0	0.03
Biomass-based feedstocks	250	1 865	466.3	1.12
Improvements in waste management	25	710	17.8	0.01
Total	155	3 660	570	1.61

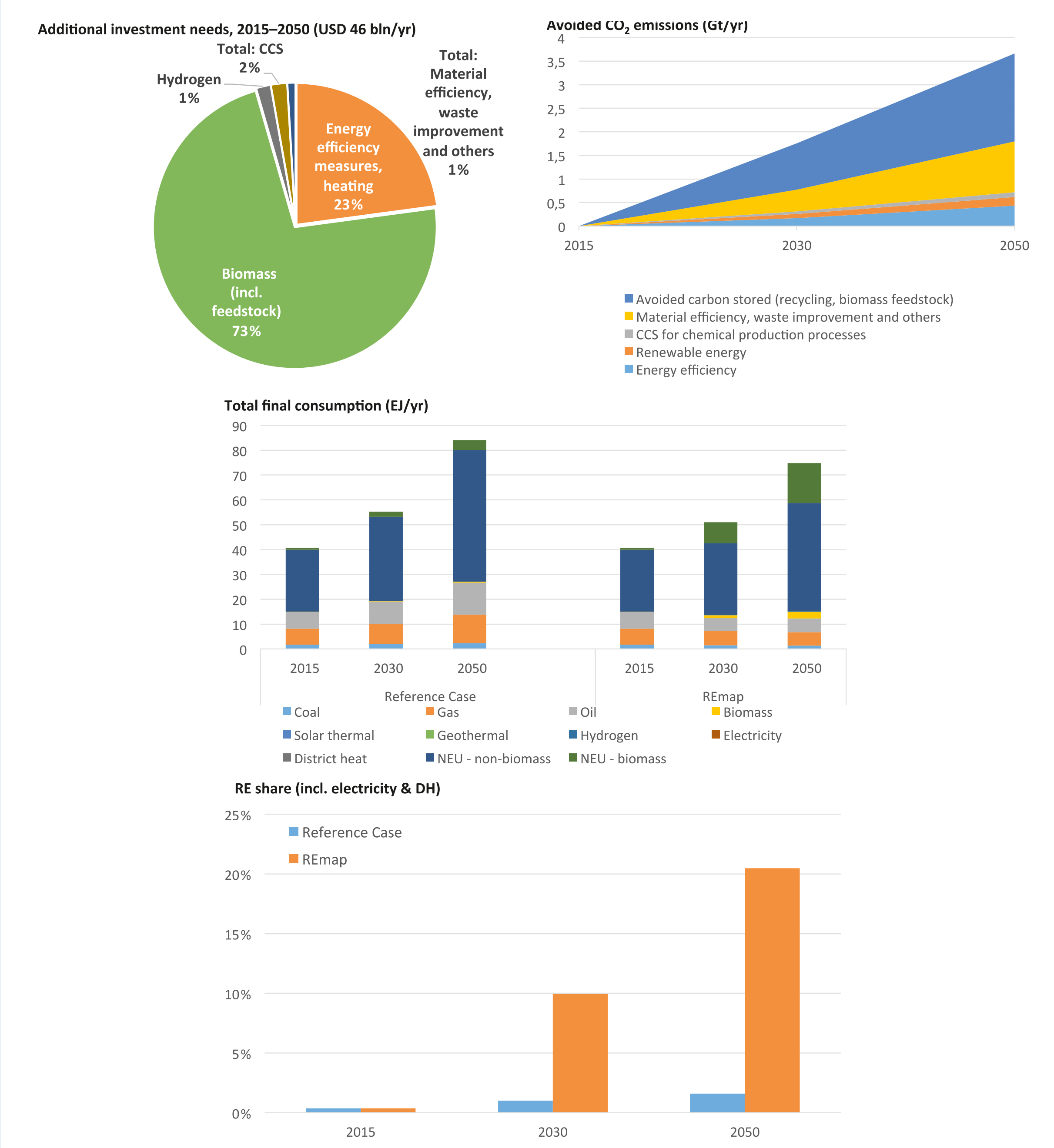
Assumption: Discount rate: 15 % and crude oil price: USD 80/bbl.

Table 8: Global REmap case – summary of activity, energy and CO_2 emission trends 2015–2050 (excluding non-energy use) for chemical and petrochemical industries

	2015	2030	2050
High value chemicals production (Gt/yr)	365	390	550
Ammonia production (Gt/yr)	175	220	290
Methanol production (Gt/yr)	60	100	195
Mechanical recycling of plastics (Gt/yr)	10	129	285
Share of plastics waste mechanically recycled (%)	8	61	84
Share of plastics waste incinerated with energy recovery (%)	25	39	16
HVC energy use (GJ/t ethylene)	30	24.3	19.4
Ammonia energy use (GJ/t)	20.0	16.2	12.9
Methanol energy use (Gt/t)	7.5	6.1	4.8
Total final energy consumption (EJ/yr)	14.9	13.7	15.4
Total feedstock use (EJ/yr)	25.8	37.3	59.4
Share of bio-based feedstock use (%)	3	23	27
Process energy CO_2 emissions (Gt/yr)	0.93	0.71	0.66
Ammonia process CO_2 emissions (Gt/yr)	0.2	0.3	0.4
Plastics waste incineration CO_2 emissions (Gt/yr)	0.4	0.3	0.2
Fossil based carbon stored in chemicals (Mt C/yr)	335	267	352

Note: Process emissions are included, but indirect emissions from the generation of electricity that is consumed in processes are excluded.

Figure 23 Key estimates for chemical and petrochemical industries



Based on IRENA estimates

plastics waste management reduces another 0.7 Gt of CO_2.

Overall, under REmap, the sector's total energy demand would grow by 85 % compared to today's level, reaching 75 EJ by 2050. Around 80 % of this total is feedstock use for chemicals production. The remaining 20 % is process energy use, which would remain at current levels. These developments show the growing importance of feedstock use in industry's total final consumption. Around three-quarters of the sector's energy demand would be from fossil fuels. The other quarter is biomass as fuel for process heat generation and as feedstock. The potential of biomass to be used as feedstock is six times greater than its potential as fuel.

In the REmap analysis, the sector's CO_2 emissions would be reduced from 3.1 Gt to 1.3 Gt per year. Another 1.8 Gt CO_2 can be avoided related to carbon stored in chemicals with increased plastics recycling and biomass-based chemicals. Renewable energy use for process heating and CCS (mainly for ammonia production and to some extent in steam crackers) would contribute 0.2 Gt and 0.1 Gt of CO_2 emission savings, respectively. Meanwhile, energy efficiency measures would reduce emissions by 0.4 Gt of CO_2 by 2050.

As Table 7 shows, the average abatement cost of these options would be USD 155 per tonne of CO_2 by 2050, and the additional investment needs over the Reference Case add up to USD 1.6 trillion in the 2015–2050 period.

Industry – aluminium

Sector description

Aluminium is produced either from bauxite (primary) or from recycling of scrap (secondary). Annual production reached 79 Mt in 2015. Two-thirds of this production comes from bauxite (53 Mt) and one-third from recycling (26 Mt).

Primary aluminium is produced using the Bayer and Hall–Héroult processes. In the Bayer process, bauxite is first dissolved at high temperatures. Then aluminium hydroxide crystals are precipitated out the solution, washed and heated to remove water. The result is aluminium oxide, or alumina. The alumina is then smelted in the Hall–Héroult process, which uses an electric current in a molten bath to produce pure aluminium. Four to seven tonnes of bauxite are used to produce two tonnes of alumina, which then yields one tonne of aluminium.

Fossil fuels are consumed for alumina production, while large amounts of electricity are used for primary aluminium smelting. Recycled aluminium production typically requires oil. Smelters also use anodes that are produced from petroleum coke or other hydrocarbon sources.

Present energy use and CO_2 emissions

Aluminium smelting does not emit CO_2 directly, because the process relies on electricity, consuming more than 800 TWh/yr in 2015. Instead, the direct CO_2 emissions from the sector come from alumina production and anode use in the smelting process. Depending on the fuel mix, alumina refining results in 0.4–1 tonnes of CO_2 emissions per tonne of alumina. The anode use results in about 4.8 tonnes of CO_2 per tonne of primary aluminium.

The efficiency of aluminium smelting has improved by about 0.5 % per year over the past two decades, with electricity use declining from more than 55 GJ per tonne of aluminium produced to about 50 GJ. The most energy-efficient smelters are located in Africa (Mozambique) and Asia (China). European and North American smelters are the least energy efficient, using about 15 % more electricity than the best facilities. There are larger differences in the energy use of alumina production, ranging from about 10 GJ (in Latin America) to 25 GJ per tonne (China).

Industry trends to 2030 and 2050

Aluminium production in China has soared from 11 % of the total global production to more than half.[11] A related trend is trying to locate smelters near sources of plentiful renewable energy, such as geothermal in Iceland or hydro in China, Norway and the western US. With growing demand for aluminium in construction, automobiles, packaging and other uses, aluminium production is projected to continue growing rapidly. By 2050, alumina production could reach more than 130 Mt per year and primary aluminium production approximately 85 Mt per year. Secondary aluminium could have a larger share in total aluminium production than it does today, reaching 50 Mt per year, equivalent to 38 % of all production. In the long run, the potential share could be as much as 50 %.

Reference Case: Path set by current plans and policies

The Reference Case projects that the sector's energy demand will grow about 36 % from around 4.1 EJ in 2015 to 5.6 EJ in 2050. By 2050, 70 % of all energy demand would be related to electricity use. The sector's total direct CO_2 emissions are projected to rise to 0.52 Gt by 2050, up from 0.34 Gt per year in 2015 (excluding any indirect CO_2 emissions from the use of electricity, but including emissions from anode use).

11 https://www.forbes.com/sites/williampentland/2016/03/29/lessons-from-the-aluminum-industry-the-hidden-cost-of-chinas-cheap-solar/#40b0d46f674f

Table 9: Economic indicators under REmap in 2050 compared to the Reference Case for aluminium industry

	Abatement cost (USD/t CO_2)	Abatement potential (Mt CO_2/yr)	Incremental system costs (USD/t CO_2)	Additional investment needs 2015–2050 (USD trillion)
Biofuels for alumina	15	4	0.07	2.1
Current BAT	–10	3	–0.03	15.9
Emerging technologies	40	10	0.41	79.4
Efficient motor systems	–150	11	–1.64	0.02
Efficient smelting	50	77	3.83	77.5
Aluminium recycling (incl. reduced anode prod)	–5	98	–0.49	34.1
Total	11	203	2.14	209

Assumption: Discount rate: 15 % and crude oil price: USD 80/bbl.

Table 10: Global REmap case – summary of energy and CO_2 emission trends 2015–2050 for aluminium industry

	2015	2030	2050
Alumina production (Gt/yr)	114	126	147
Primary aluminium production (Gt/yr)	53	58	68
Secondary aluminium production (Gt/yr)	26	46	69
Alumina energy use (GJ/t)	11.9	9.7	8.5
Primary aluminium smelting (GJ/t)	51.3	41.6	35.2
Secondary aluminium production (GJ/t)	7.0	5.7	5.1
Total final energy consumption (EJ/yr)	4.1	3.8	3.9
Energy-related CO_2 emissions (Gt/yr)	0.09	0.08	0.07
Process CO_2 emissions (Gt/yr)	0.25	0.28	0.33

Note: Process emissions are included, but indirect emissions from t generation of electricity that is consumed in processes are excluded.

Alumina production grows by around 60 % to 184 Mt per year by 2050 in order to meet the demand for primary aluminium production of 85 Mt. Recycled aluminium production doubles to 52 Mt in the 2015–2050 period.

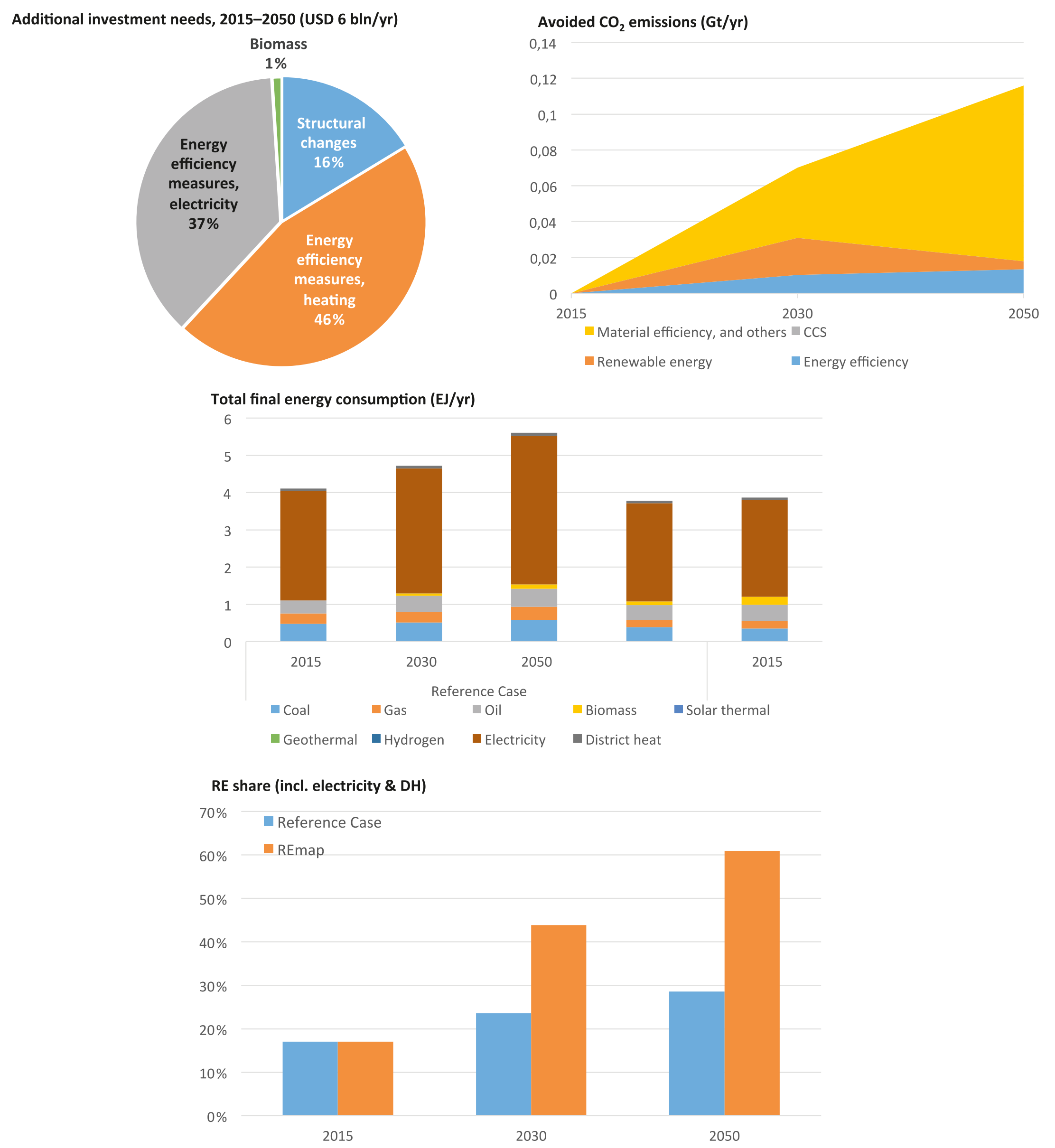
REmap analysis: Technology solutions and their potential by 2050

Under REmap, CO_2 emissions would decline by about 20 % compared to the Reference Case in 2050. Around 85 % of the reductions come from anode use, since less primary aluminium is produced. The remainder is from energy efficiency measures (including gains from novel smelting technologies) and biofuels in alumina plants. Another key step would be continuing to locate plants to areas with available renewable electricity.

There are several effective approaches for achieving emissions reductions in the aluminium sector. One is biofuels. Because the Bayer process for making alumina operates at temperatures of between 140–280 °C, biofuels can deliver the required heat, making them a good substitute for fossil fuels (IRENA, 2014). Under REmap, around 200 PJ of biomass would be used in alumina production.

Biofuels can make only a limited contribution to reducing energy use in the sector, however, because

Figure 24: Key estimates for aluminium industry



Based on IRENA estimates

the total energy demand is dominated by electricity use. But a number of existing and emerging technologies exist to reduce the electricity needed for smelting, such as lowering the voltage or using wetted drained cathodes. These technologies can reduce energy demand by up to 40 %. More savings are possible with best practice anode production technologies, which can cut the energy used for the anodes by 70 %. Overall, energy use in primary aluminium smelting could be reduced by at least one-third compared to the world average today, from 14 250 kWh per tonne of aluminium today to about 10 000 kWh per tonne.

Increasing the amount of aluminium recycling also brings major energy savings, because the process requires only 20 % of the total energy required in a typical smelter (Kermeli *et al.* 2015). The efficiency of the recycling process can also be increased, with energy demand dropping from around 7 GJ per tonne today to 5 GJ per tonne.

In the REmap case, the share of recycled aluminium in total production reaches an ambitious level of around half of the total production by 2050 (69 Mt per year). Increased production of secondary aluminium under REmap requires about 15 % more energy in absolute terms compared to the Reference Case by 2050. This is offset with the improvements in energy efficiency of primary aluminium production, where total electricity demand decreases by more than 30 % from around 4 EJ to 2.7 EJ per year.

The reduced demand for primary aluminium results in less production of alumina, thereby bringing additional reductions in energy use. There is a potential to save 15 % of the energy for alumina production, compared to the Reference Case by 2050. Total energy use for alumina production would be 2.4 EJ in REmap by 2050, a drop of 30 % from the Reference Case.

The REmap analysis also assumes that a growing share of the sector's electricity would be sourced from renewables, with that share rising to 60 % by 2050. This would be accomplished by continuing today's trend of trying to locate smelting plants in areas with abundant and affordable renewable power.

As Table 9 shows, the average abatement cost of these options would be USD 10 per tonne of CO_2 by 2050, and the additional investment needs over the Reference Case add up to USD 0.2 trillion in the 2015–2050 period.

Industry – pulp and paper

Sector description

The pulp and paper industry uses either chemical pulping or mechanical pulping processes to create pulp by separating cellulose fibres from wood, fibre crops or recycled paper. The pulp is then used to make a wide variety of paper products. Pulp production reached more than 256 Mt in 2015, with about one-third coming from recovered pulp and 25 Mt from mechanical pulp processing. Total production of paper products reached 400 Mt in 2015.[12] Recycled paper represents around 40 % of the fibre supply.

Present energy use and CO_2 emissions

The sector is the fourth largest industrial energy user, with wood being the sector's primary input. Unlike any other industry sector, the pulp and paper sector is a large generator of energy, particularly in kraft (or chemical or sulphate) pulp mills, in the form of a biomass waste product of the pulping process known as black liquor. Black liquor is typically burned in a boiler, producing heat and power either for the pulp mill itself or for the paper mill, or both if the site integrates both pulp and paper production. Currently, around half of the sector's energy demand is met by biomass residues in this way. Mechanical pulping uses energy in the form of power only, not heat.

Plants in the Asia Pacific region are efficient in using heat and electricity. Plants in North America and in economies in transition, such as Eastern Europe, use the most energy, reflecting the continuing use of older capital stock. These older plants could cut their energy demand in half if they were able to reach the levels found in the best plants in the world.

Integrated pulp and paper mills are typically more efficient than stand-alone mills, because they use about 50–60 % of the heat generated in chemical pulping for papermaking, and use more of the heat for bleaching and mechanical pulping (IEA 2007). However, they are not entirely self-reliant, getting about 10–30 % of their fuel from external sources like fossil fuels.

The efficiency of stand-alone mills could be increased close to the level of the integrated mills if the stand-alone facilities sold their excess biomass by-products and steam to third parties. Stand-alone paper and recycling mills use fossil fuels, primarily for steam generation and for drying pulp, and to some extent for lime production. In China, India and Africa, the majority of the production capacity consists of small mills.

Overall, the sector emitted about 90 Mt of CO_2 in 2015 from the combustion of fossil fuels.

Industry trends to 2030 and 2050

Production of paper is projected to grow to 750 Mt by 2050, an increase of about 85 % from today, with the production of pulp reaching 470 Mt. The share of

12 Includes newsprint, printing and writing papers and various other types of paper and paperboard.

pulp produced from recycled or recovered materials is projected to increase to 45 % from 36 % today. Mechanical pulp production could cease by 2050. There is a large potential to reduce the sector's energy use in the 2050 frame, in particular by switching to integrated mills. However, there will always be stand-alone mills processing recycled paper only.

Reference Case: Path set by current plans and policies

The Reference Case projects that the sector's energy demand will increase by about 40 %, from around 5.6 EJ in 2015 to 7.7 EJ in 2050. Energy demand grows only about half as much as the production of paper. The main reason is the increased use of integrated plants, which are more efficient than stand-alone mills.

Biomass, electricity and fossil fuels are estimated to supply equal shares of the sector's total energy demand by 2050.

The sector's total CO_2 emissions are projected to decline to 74 Mt by 2050 from 90 Mt in 2015 (excluding any indirect CO_2 emissions from the use of electricity), primarily because of increased use of biomass (but also because of improved efficiency in pulp and paper production). By 2050, biomass is estimated to represent half of all energy demand of the sector, with the rest being supplied by electricity (30 %) and fossil fuels (20 %).

REmap analysis: Technology solutions and their potential by 2050

Under REmap, emissions would be reduced by 85 % by 2050, to 10 Mt per year, compared to Reference Case.

Some of the emissions reductions come from increased use of biofuels, especially in integrated pulp and paper mills (IRENA, 2014). More than 80 % of the sector's total energy demand is low and medium temperature heat, which biomass can provide. Currently half of the sector's energy demand comes from biomass. In the REmap analysis, that increases to 60 %. In theory, it could increase all the way to 100 % if all mills were integrated. In practice, however, a few stand-alone mills are always likely to produce recycled paper only.

The Reference Case includes some energy efficiency gains, but the REmap analysis shows that there is a large additional potential. There are potential savings about 20 % in stock preparation, 8 % in forming, 5 % in pressing and 90 % in drying. However, the technologies that save heat demand in pressing and drying increase the related electricity demand by about 5–10 % (Saygin *et al.* 2013).

Although not included in this study, the sector can actually become a negative emitter of CO_2 if it employs biomass-fired CCS (BECCS). The opportunities for BECCS in various mill configurations (including possible combinations with emerging technologies such as biomass gasification) have already been investigated for years (Möllersten *et al.* 2004; Hektor and Berntsson 2007). The CCS potential identified by REmap comes from the capture of CO_2 in flues from fossil fuel-based steam generation, not from the use of biomass.

Under REmap, the sector's total energy demand grows to 7.1 EJ in 2050 compared to 5.6 EJ in 2015. For pulp making (by all technology routes), demand increases to around 3 EJ by 2050 from around 2.6 EJ per year in 2015. This is less than the level in the Reference Case (around 3.2 EJ per year in 2050) because of greater efficiency improvements. The energy demand of papermaking increases slightly from around 3 EJ in 2015 to around 4 EJ by 2050, which is also slightly less than in the Reference Case (4.4 EJ).

As Table 11 shows, the average abatement cost of these options would resulting a saving of USD 10 per tonne of CO_2 by 2050, and the additional investment needs over the Reference Case add up to USD 0.7 trillion in the 2015–2050 period.

Buildings – heating and cooling

Sector description

The buildings sector is enormously diverse, ranging from small rural houses to tall urban office buildings. A little more than two-thirds of the total global floor area of 150 billion square metres (m^2) is residential. The rest, about 40 billion m^2, is in commercial buildings.

These building use energy in five main ways:

- heating
- cooling
- hot water
- cooking
- appliances and lighting

This section focuses on the first three, heating, cooling and hot water, where the amount of energy that buildings use varies dramatically. Thanks to huge progress in the insulating qualities of buildings' walls and windows (comprising the "shell"), today's state-of-art houses barely use any heating and cooling energy. Buildings, however, are characterised by their very long average lifespans. In Europe, for example, 40 % of buildings were constructed before 1960, before there were any efficiency standards (BPIE 2011). As a result, these old buildings are typically inefficient – and the efficiency of the average building lags far behind the state of art, especially in countries with fewer new buildings. There are also regional differences in the lifespans of building. Those in Japan tend to have a much shorter lifespan than those in Europe, for instance. Combined with differences among countries in building energy efficiency standards and renovation rates, these age differences make global trends in energy efficiency differ widely.

Another important split is between the urban built environment and rural buildings. Today 50 % of the world's population lives in cities. That percentage will grow to two-thirds in 2030, and rise even more by 2050. The greater population density in cities allows the use of energy-reducing solutions that are less possible in rural areas, such as cost-effective district heating and cooling systems and renewable-powered electric public transit systems. Both low-density cities, with larger rooftop areas, and some rural areas could benefit from highly distributed renewable energy technologies, like solar roofs, and from increased use of electric vehicles.

Table 11: Economic indicators under REmap in 2050 compared to the Reference Case for pulp and paper industry

	Abatement cost (USD/t CO_2)	Abatement potential (Mt CO_2/yr)	Incremental system costs (USD/t CO_2)	Additional investment needs 2015–2050 (USD trillion)
Biofuels	15	6	0.1	0.001
Current BAT	–80	1	–0.1	0.03
Efficient motor systems	–150	42	–6.3	0.02
BAT other electricity	–25	23	–0.6	0.07
Integrated pulp and paper mills	–25	1	<0	0.49
Black liquor gasification	50	50	0.8	0.03
Energy efficient drying	35	10	0.4	0.06
CCS	150	30	4.5	0.01
Total	–10	127	–1	0.70

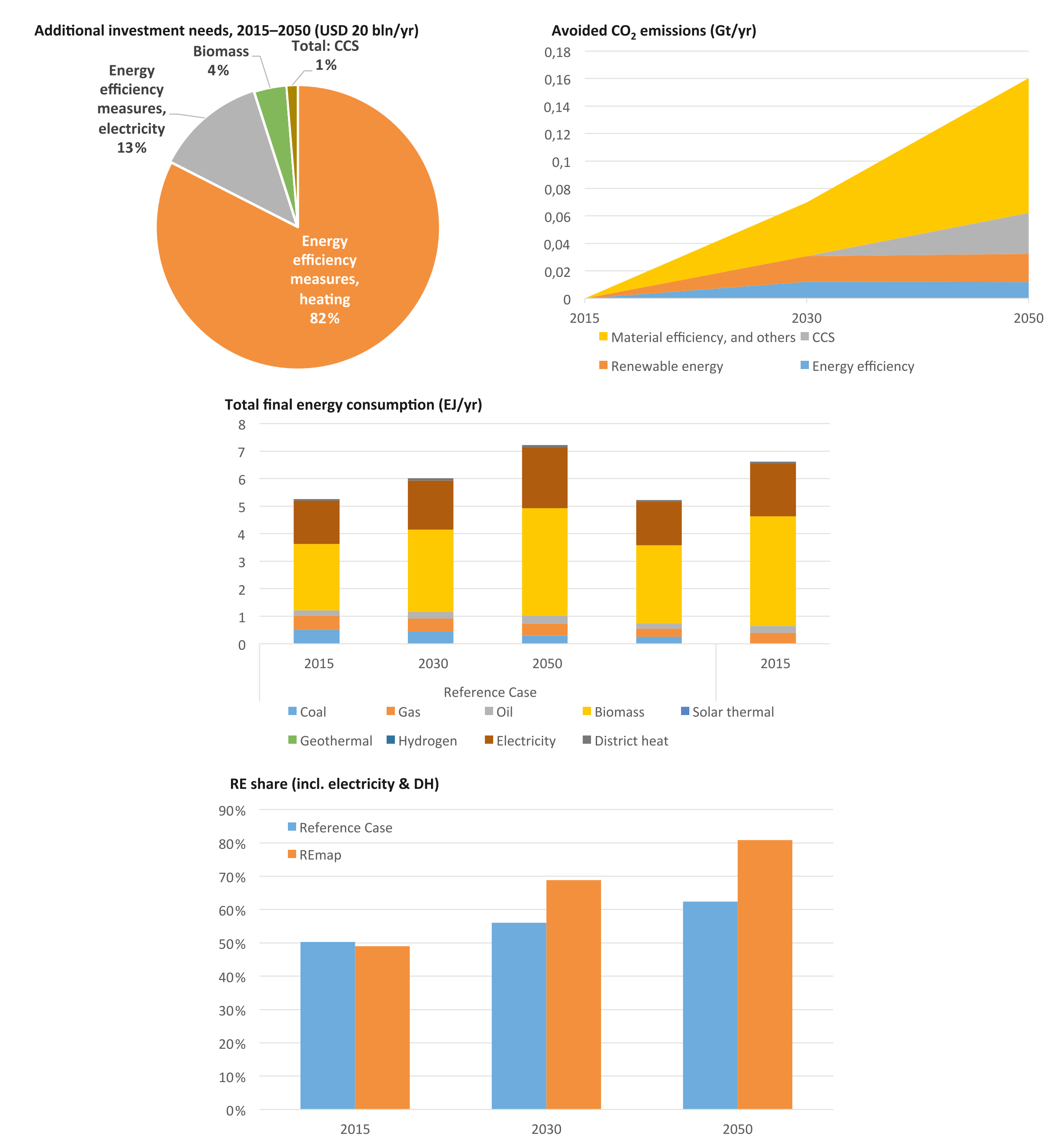
Assumption: Discount rate: 15 % and crude oil price: USD 80/bbl.

Table 12: Global REmap case – summary of activity, , energy and CO_2 emission trends 2015–2050 for pulp and paper industry

	2015	2030	2050
Chemical pulp (Mt/yr)	162	193	258
Recovered pulp (Mt/yr)	94	135	215
Mechanical pulp (Mt/yr)	25	21	11
Paper (Mt/yr)	406	520	750
Total final energy consumption (EJ/yr)	5.7	5.6	7.1
Energy-related CO_2 emissions (Mt/yr)	95	56	11

Note: indirect emissions from the generation of electricity that is consumed in processes are excluded.

Figure 25: Key estimates for pulp and paper industry



Based on IRENA estimates

As both global population and the share of people in cities rise, the world will need to build the equivalent of around 2 000 additional cities of 1 million citizens each in developing countries by 2050. These new cities will offer major opportunities for improved energy efficiency and the adoption of renewable energy technologies, since investing in such measures and technologies is easier when buildings are new..

Data on the energy use in 3 649 cities that account for 60 % of global energy demand show that renewables offer the lowest-cost supply of power in a growing number of places, without any financial support (IRENA 2016f).

Present energy use and CO_2 emissions

Today, heating demand is about 44 EJ per year. Hot water demand is 22 EJ per year and space cooling demand is 8 EJ per year. Together these add up to 61 % of all energy demand in buildings (GABC 2016), with space heating and cooling accounting for 45 % of total buildings energy use.

These three uses of energy in buildings add up to about 74 EJ per year, about 15 % of the total global energy demand. Direct emissions are about 2.2 Gt of CO_2 per year (GABC 2016). Another 3.2 Gt of CO_2 emissions per year come from the production of materials for buildings construction. These emissions are accounted for under the industry sector, such as iron and steel or cement.

Heating demand is especially high in North America, Europe, CIS and Northern China. In these areas, heating and cooling account for 70 % of buildings total energy demand, well above the global average. This share, however, has been gradually declining as building insulation has improved over time and residential equipment ownership rates have increased. Still, the US, EU and China account for two-thirds of cooling demand today.

Buildings vary not only in the amount and effectiveness of insulation, but also in the efficiency of their heating and cooling systems. Many buildings have outdated oil and gas heating systems that use 15–30 % more energy than energy-efficient modern ones.

However, updating these systems without also improving insulation is not an ideal approach. In highly insulated zero or almost zero energy buildings, heating demand is very small and the optimal heating systems will be much different than those in a poorly insulated building. As a result, simply substituting more efficient boilers for old ones (which is currently subsidised in many countries) leads to a "technology lock-in" that reduces the cost-effectiveness of very high-efficiency building shell retrofits later and causes higher energy use and emissions in the long term. To avoid this lock-in, those high-efficiency measures should be employed first to allow the use of much smaller heating and cooling systems.

Buildings energy use depends on the local climate conditions, orientation towards the sun and buildings user behavior. Buildings occupancies and indoor air temperatures are functions of user behavior. Apartments use significantly less energy per unit of floor area than do single-family dwellings. In developed countries, the floor area per inhabitant tends to be greater in rural areas than in cities (for example, floor area in rural areas is 30 % higher per capita compared to cities in Europe (BPIE 2011)) and the share of high-rise buildings is significantly greater in most cities. The situation is the reverse in developing countries.

Sector trends to 2030 and 2050

The current 150 billion m^2 of floor area worldwide is expected to grow to 270 billion m^2 by 2050 (Navigant Research 2016; Ürge-Vorsatz 2016), with the shares of residential and commercial space remaining roughly the same. (In some other case analyses, the share of commercial building area grows at a somewhat higher rate than that of residential buildings. Commercial buildings tend to use more electricity in their energy mix than do residential ones.)

The vast majority of this growth will be concentrated in developing countries, where heating demand tends to be significantly lower than the world average, but where cooling demand is expected to rise.

The energy use per unit of floor area typically falls as the quality of the building shell improves. In developing countries, however, the drop is expected to be smaller than in developed countries, because of the lower heating needs. Moreover, the expected increase in demand for cooling and appliances in developing countries may actually cause energy use per unit area to increase.

Through a combination of energy-efficiency regulations and new technology, many types of "zero energy" buildings can already be built, with the use of space heating cut to a small fraction and other heating provided by renewable energy. Such buildings are feasible in many climates.

For existing buildings, many ongoing projects show that energy efficiency can be increased substantially though renovation. The Dutch "Nul op de Meter" programme is an example (see Box 4). Annual renovation rates tend to be on the order of 1% of residential stock and around 5 % for commercial buildings. Germany aims to achieve annual 2 % renovation rates by 2030, which is double the current level. Raising these rates is a priority in many countries but is challenging. To avoid lock-in, renovations must aim to achieve near-zero energy levels.

Renewable energy solutions can be added to existing buildings as well, but the right mix of efficiency and renewable energy varies. Ideally, efficiency should come first. But energy renovations are often dependent on total refurbishment of buildings, which may happen only once every couple of decades. In some cases, therefore, renewable heating or cooling solutions can be introduced faster and can provide a good bridge until the deep renovation becomes economically feasible.

Use of renewable heating and cooling systems is well established but not widespread. Fossil fuel-based heating systems still dominate, even in situations where the lifecycle costs are significantly lower for the renewable solution. Among the reasons is a common market structure where owners pay the investment cost while tenants pay the operating cost. This distribution of cost makes it harder to implement renewable solutions, which typically have a high upfront cost. This so-called landlord-tenant problem needs to be dealt with through policy measures, such as regulation.

Other barriers to implementing renewables include space constraints and heating system technical constraints on temperature levels. In addition, there may be constraints because of mismatches between energy supply and energy use. For example, France has a high share of electric resistance heating which causes peaks in electricity demand in winter that are sometimes hard to manage.

Policy makers have recognised these challenges. The European Union heat strategy seeks to reduce heat-related energy consumption (almost 50 % of current final energy consumption) by 40–50 % and to increase the share of renewable heat from around 17 % currently to 45–55 % by 2050 (IHS Energy 2016). Such an objective seems feasible if there are high renovation rates, stringent standards for new buildings and electrification of heating. Solar thermal is another option with high potential (or even hybrid solar panels).

Overall, the average energy use for heating and cooling in North America and Europe is projected to decline by 10–20 % between 2015 and 2050, as efficiency gains are partly offset by the rapid increase in buildings floor space and increases in cooling.

Reference Case: Path set by current plans and policies

The near doubling of total buildings floor area by 2050 will increase the demand for heating and cooling. At the same time, however, greater efficiencies are expected to lower the average demand by more than 1 % per year in the 2015–2050 period, from 140 kWh/m^2 to 100 kWh/m^2. As a result, total demand is projected to increase by only 37 %, from 74 EJ in 2015 to 100 EJ in 2050.

Direct emissions of CO_2 from heating and cooling remain stable at around 2.4 Gt per year by 2050 compared to 2.2 Gt in 2015. This is mostly due to the introduction of more efficient buildings rather than to an increase in the share of direct renewable energy.

The renewable energy share in all applications does increase, however. In space heating, the share increases from around 20 % in 2015 to 27 % by 2030. For water heating, the share is already at around 50 % today (mainly because of the uses of traditional biomass in developing countries). This share increases to 60 % by 2050. Biofuels account for more than 30 % of all the energy used for water heating. Solar water heaters represent about 12 % of the total energy demand. For space heating, direct applications of geothermal and biofuels would have a 20 % share in 2050, up from 15 % today. Solar cooling systems account for 5 % of all cooling demand by 2050 under the Reference Case.

Finally, there is a notable trend towards the electrification of heating, mostly in the form of heat pumps. The share of electricity increases from around 22 % to 31 % in the 2015–2050 period. Around 40 % of this electricity consumption is sourced from renewable power under the Reference Case by 2050.

REmap analysis: Technology solutions and their potential by 2050

Priorities for implementing low-carbon technologies in the sector are (in order):

- zero or near-zero new energy buildings
- deep energy efficiency retrofits of existing buildings (to close to near-zero levels)
- operational energy efficiency: installation of buildings energy management systems, commissioning, reduction of heat load in areas where cooling matters, good practice buildings use, reduction of urban heat islands
- electrification of energy services coupled with renewable power
- direct integration of renewable energy

- district heating and other forms of renewable-derived energy carriers
- seasonal heat and cold storage

In the REmap analysis, direct emissions in the buildings sector drop 75 % by 2050 compared to the Reference Case, to 0.9 Gt per year of CO_2. Building shell improvements account for 15 % of the reductions, electrification for 15 % and direct deployment of renewables for 70 % (including deployment for cooling).

As mentioned in the list above, the top priority in the REmap case is improving energy efficiency through the renovation of existing stock and the construction of efficient new buildings in order to reduce demand for heating and cooling in buildings. Lower demand for energy then requires less additional capacity for renewable energy, making it easier to supply that demand with renewables.

Space and water heating

Renewable energy options for heating (space and water) include decentralised equipment in buildings and centralised generation for district heating systems. Decentralised solid biofuel-fired boilers (*e.g.* wood pellets and chips) are a mainstream technology today. To minimise air pollution, however, cities must implement codes and standards to ensure clean combustion.

Solar thermal systems have been used for decades for water heating, and to some extent also for space heating. Some countries, such as Israel and Cyprus, have achieved a significant share of solar water heating. Around 400 GW solar thermal capacity was installed globally in 2015, using both flat plate systems and vacuum tube systems. China accounts for the vast majority of the global market in terms of installed capacity. Elsewhere the technology is still not widely spread, despite often-excellent solar irradiation conditions and favourable economics. Quality control regarding equipment and installation is critical to assure market acceptance (IRENA 2015f).

Heating and Cooling

The energy demand for cooling is expected to rise faster than the demand for heating because of rapidly growing demand for air conditioning in the developing world, which is being accelerated by climate change. As a result, the introduction of more efficient approaches and equipment for cooling can have a large impact in slowing that growth.

In warm climatic zones especially, the cooling demand can be reduced drastically by a combination of shading, lowering the amount of heat produced inside buildings, improving insulation and recovering heat in ventilation systems. With such measures, the cooling demand of a terraced house in Madrid can be reduced by 85 %, for example.

Various renewable energy solutions exist for buildings heating and cooling:

- Heat pumps are already well established. About 85 % of new Austrian residences and 45 % of new German residences use heat pumps. Most are air-to-air heat pumps, but some are geothermal (extracting heat from the ground). Hybrid systems that combine an air-source heat pump with a high-efficiency condensing gas boiler are also being installed, especially in unrennovated homes. Costs are reduced by using gas – where the required infrastructure is already in place – to cover peak heating needs.
- Many gas boiler systems in Europe are connected to rooftop solar thermal installations that feed in hot water for heating and for other applications.
- Seasonal storage of heat and cold may be needed to allow buildings and industry to adjust consumption over time. Charging a heat or cold storage system during high solar irradiation periods or wind peaks avoids curtailment in times when variable renewable electricity generation exceeds demand. At present, distributed thermal energy storage (TES) in buildings mainly consists of buffer storage systems to accumulate heat from electric heaters (and to a lesser extent, from solar heat) in hot water tanks. Adding such a heat buffer allows for domestic hot water production at night. Various other options for TES exist, such as storing heat underground (*e.g.* in boreholes or caverns), using phase change materials (*e.g.* freezing and melting ice), or employing chemical reactions (IRENA and IEA-ETSAP, 2013).
- District heating with renewable energy is increasing. In 2014, only about 5 % of total district heat worldwide was supplied by renewable energy. In some countries, however, such as Denmark and Switzerland, renewable energy provides more than 40 % of the district heat, and systems are approaching 100 % in Baltic countries using biomass boilers. Renewable energy has a potential of providing 30–35 % of district heating in Japan

and the US, and nearly 50 % in district cooling in the UAE. Use of biomass and residual heat from waste incinerators is already widely deployed, more recently sometimes in combination with seasonal solar heat storage. A recent trend is the merger of heat networks, for example in the West of the Netherlands and the Ruhr Area in Germany. Those mergers create large heat networks with many million clients that can connect to a variety of heat sources. But while district heating has been found to be the lowest-cost source of renewable heat, large-scale retrofits will take many years.

- Biomass pellet and solid biomass heating systems are mainstream technologies that have been long used to provide space heating. They are characterised by high energy efficiency.

As noted in the discussion above, improving energy efficiency (by constructing new near-zero energy buildings and deeply retrofitting the shells of existing buildings) is critical. Under REmap, half of the total energy used in the buildings sector would be used in efficient new buildings by 2050. A large share of the remaining demand would be in existing buildings that have been significantly renovated to improve their energy efficiency. Such renovations can cut energy demand by 70 % compared to the average level today. With the renovation rates assumed in REmap, heating and cooling demand in buildings drops by about 70 % by 2050 compared to 2015 level.

The combination of improved efficiency and increased renewables would reduce the sector's total direct CO_2 emissions to 0.3 Gt per year by 2050, 2.1 Gt fewer than in the Reference Case. This excludes any reductions from indirect CO_2 emissions. If these are accounted for, another 0.8 Gt CO_2 emissions in the power sector can be mitigated by 2050 from more efficient uses of electricity for cooling. About 60 % of all CO_2 emissions savings in buildings compared to the Reference Case are related to renewable energy, and the remainder are from energy efficiency (including electrification).

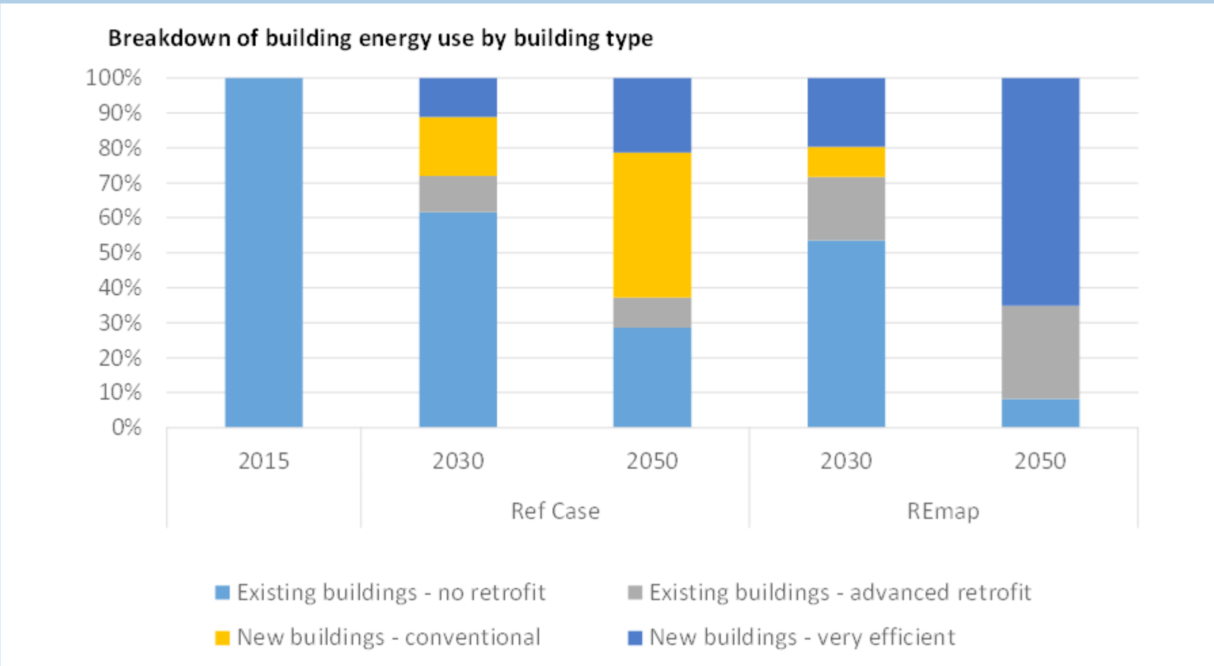
As Table 13 shows, the average abatement cost of these options would be USD 150 per tonne of CO_2 by 2050, and the additional investment needs over the Reference Case add up to USD 27 trillion in the 2015–2050 period.

Buildings – cooking

Sector description

Cooking accounts for around 21 EJ of the energy demand in the buildings sector worldwide today.

Figure 26: Building energy use by building type



Based on IRENA estimates

Table 13: Economic indicators under REmap in 2050 compared to the Reference Case for buildings sector

	Abatement cost (USD/t CO_2)	Abatement potential (Mt CO_2/yr)		Incremental system costs (USD/t CO_2)	Additional investment needs 2015–2050 (USD trillion)
		Space heating/ cooling	Water heating		
Smart home system	–285	19	8	–7.7	0.9
Early replacement of condensing gas boiler	–160	38	47	–13.7	0.2
Draught proofing	–180	19	24	–7.7	2.6
Floor insulation	–35	96	24	–4.2	3.6
Early replacement of condensing gas boiler with hybrid/heat pump	–100	38	47	–8.6	0.04
Loft insulation	15	38	8	0.7	1.4
Wall insulation	500	77	–	38.5	2.8
Double glazing	300	50	–	15.0	1.8
Insulation doors	2 000	8	–	15.4	0.3
Heat pumps	–15	256	57	–4.7	0.2
Stranded assets	1 650	163	37	335	10
Solar water heating	25	830	117	26.7	0.2
Efficient cooling system	–50	275	–	–13.6	0.7
Solar cooling	75	982	–	73.6	2.8
Total	150	2 891	369	443	26.9

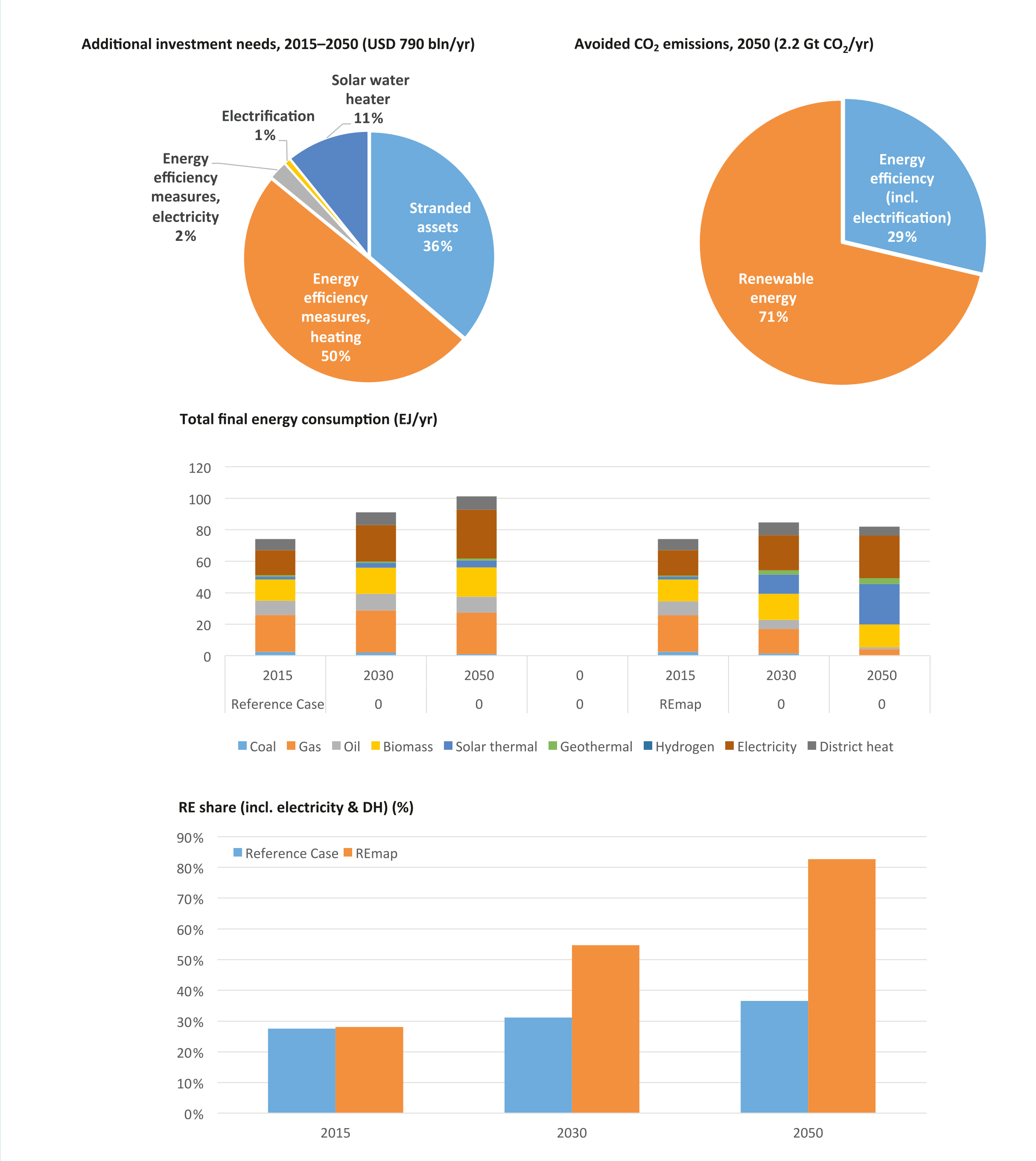
Assumption: Discount rate: 15 % and crude oil price: USD 80/bbl.

Table 14: Global REmap case – summary of activity, energy and CO_2 emission trends 2015–2050 for buildings sector

	2015	2030	2050
Floor area residential (bln m^2)	106	152	204
Floor area commercial (bln m^2)	38	51	65
Space heating energy residential/ commercial (kWh/m^2)	75	52	23
Water heating energy residential/ commercial (kWh/m^2)	40	35	26
Cooling energy residential (kWh/m^2)	16	18	23
Heating energy residential energy efficiency building shell (%)	0	36	61
Biomass heating share (%)	21	23	24
Electric heating/cooling share (%)	22	27	33
District heating share (%)	9	10	8
Cooling energy residential energy efficiency building shell (%)	0	36	61
Total final energy consumption (EJ/yr)	74	85	82
Total CO_2 emissions (Gt CO_2/yr)	2.2	1.4	0.3

Note: indirect emissions from the generation of electricity that is consumed in processes are excluded.

Figure 27: Key estimates for buildings – space heating and cooling



Based on IRENA estimates

That is about 6 % of global final energy use. Around 2.5 billion people, a third of global population, rely on traditional forms of bioenergy, such as wood, charcoal, agricultural waste and animal dung, for cooking. This biomass has a total energy content of 17 EJ, and is typically unsustainably sourced. In addition, coal is still used in some countries, though its use is decreasing. All of these solid biofuels are major sources both of carbon emissions and of indoor and outdoor air pollution.

Cleaner alternatives, such as LPG, kerosene and natural gas, are also used worldwide. In addition, about 50 million biogas stoves have been deployed, notably in China and India. Cooking with electricity is gaining importance, with the increasing use of electric stoves, glass ceramic built-in hobs (“Ceran”), induction cooking and microwave ovens. The use of these cleaner alternatives is increasing, notably in cities (80 % of people using biomass are in rural areas).

The energy use varies by cooking technique. The many different types include charcoal grilling, ovens, grilling devices, rice cookers, steaming, frying, boiling and pressure cooking. The technique varies depending on the type of food, on people’s different tastes and on other factors.

The most efficient form of cooking is electricity, with an efficiency level of around 80 %. By comparison, oil products and gas have efficiencies of around 60–65 %. Inefficient cookstoves that use traditional forms of bioenergy and coal have efficiencies as low as 20 %. As a result, modern biomass cooking stoves can reduce energy demand by half compared to traditional stoves.

Present energy use and CO_2 emissions

Cooking accounts for a major share of global traditional biomass use. About 60 % of the renewable energy used in buildings today is traditional bioenergy, mainly in the form of cooking on open fires in the developing world, especially in rural areas. About 18 % of urban populations in developing countries still use fuelwood and charcoal for cooking, and in the least developed countries, this share reaches close to 70 %.

In developed countries, about 5–8 % of residential electricity use is related to cooking (Lapillonne, et al 2015). Hobs and ovens play an important role in Europe and North America, while Asia has different cooking habits.

In India, Southeast Asia and Africa, cooking accounts for more than 75 % of per capita urban energy use. The share is even higher in rural areas. In China, around half of per capita energy use is related to cooking (Daioglou et al 2012).

Cooking is an important source of direct CO_2 emissions. The use of traditional wood fuels results in emissions of 1–1.2 Gt CO_2-eq per year, representing about 2 % of total global emissions. The combustion of all traditional forms of bioenergy together is responsible for 4 Gt CO_2-eq per year, including methane emissions from these fuels. There also are indirect CO_2 emissions from the generation of electricity used in cooking.

Studies show that the deployment of 100 million state-of-the-art improved cookstoves could cut emissions by about 98–161 Mt CO_2-eq per year.

Electric cooking is widespread in emerging and developed countries, but its uptake varies widely. Romania uses almost zero electricity for cooking, for example, while Portugal uses more than 1 000 kWh per year per dwelling (Lapillonne, et al 2015). The European average is around 250 kWh/yr per household (Almeida *et al.*, 2011). Electric cooking is also frequent in Latin American urban areas. In South Africa, 85 % of urban households now use electricity for cooking, 73 % in Zimbabwe and 40 % in Mongolia (ESMAP 2015). In Ecuador, the government decided in 2014 to promote induction cooking through financing support and free electricity during the first month. It aims to reach 3.5 million systems by the end of 2017 (Scherffius 2015). As solar and wind power capacity is set to expand in most of these countries, indirectly more of the energy used for cooking will be supplied by renewable energy.

Sector activity trends to 2030 and 2050

Final energy demand for cooking increases with population growth and increasing wealth, but decreases significantly when a switch occurs from traditional biomass to other types of energy or from combustion-based cooking methods to electric stoves. Also, convenience prepared foods tend to reduce energy needs. As a result, while the total amount of cooking (the “useful demand”) is projected to double by 2050, the final energy demand per unit of useful energy is projected to fall by one-third, primarily from the phase out of traditional biomass stoves (Bailis *et al.* 2015). The net impact of these trends is decreasing energy demand for cooking.

Reference Case: Path set by current plans and policies

In the Reference Case, demand for final energy related to cooking falls to 25 EJ from 30 EJ by 2050, but CO_2 emissions rise from 0.6 Gt in 2015 to 0.75 Gt per year in 2050. This is explained by the increased share of fossil fuels (gas, LPG and kerosene) used for cooking.

REmap analysis: Technology solutions and their potential by 2050

In the REmap case, cooking emissions are lower than in the Reference Case, at 0.5 Gt of CO_2 by 2050, as millions of people switch from the traditional forms of bioenergy to modern biomass cookstoves and electric stoves. These modern cookstoves, using bioenergy or electricity (which can be generated by renewable power), are a key solution.

The challenge for widespread deployment of electric cooking in developing countries is the need for large amounts of electricity, which requires a powerful grid connection. A Ceran plate with four hobs typically has a capacity of 1.5 kilowatts (kW) and may require 0.5–1.5 kW during operation. Clearly, a rooftop solar PV system of 100 W is inadequate to meet such demand. So while electric cooking may offer the best way to transition to renewable energy for countries with adequate grids, other solutions will be needed in some developing countries.

One of those solutions is biogas. Today, 50 million home biogas installations for cooking are in operation. Around 45 million of these are located in China. India has four million, of which two million are thought to be in operation. Elsewhere, uptake has been slower. In areas such as the south of India, where biogas for cooking has been used for some time, the biogas is produced from organic waste in digesters ranging in size from the household scale (1–5 kg per day) to large-scale (up to 100 tonnes/day) (Vögeli and Zurbrügg 2008). In Nepal, biogas has been used in cooking for more than 60 years, mainly in rural settings. The country now aims to build 2 500 biogas plants in urban locations between 2012 and 2017 (Government of Nepal 2012). These plants will use biodegradable waste to produce cooking gas and electricity (The Kathmandu Post 2015).

For solid biomass, programmes to provide cleaner and more efficient charcoal and wood cookstoves are underway in Ghana, Kenya and Mali. Ethanol cooking is also prevalent in selected urban areas in Africa. About 200 000 cookstoves have been sold in Ghana and Nigeria that use cellulosic ethanol made from sawdust (Green Energy BioFuels, n. d.). Today in Africa, around 10 % of all biomass cooking stoves are

Table 15: Economic indicators for cooking

	USD/GJcooking	Application
Fossil @20 USD/GJ	24	Urban, rural
Electric Ceran @10 UScents/kWh	27	Urban
Biogas	10	Rural with animal husbandry
Biomass clean @ 3 USD/GJ	12	Rural/ Urban
Biomass traditional @1 USD/GJ	10	Rural

Table 16: Global REmap case – summary of energy and CO_2 emission trends for 2030 and 2050 for cooking

	2015	2030	2050
Fossil (% cooking)	12	33	38
Electricity share (% cooking)	10	17	29
Biogas (% cooking)	0	5	5
Clean biomass cooking stoves (% cooking)	4	45	25
Traditional biomass (% cooking)	74	0	0
Other/fossil (% efficiency)	45	50	60
Electricity (% efficiency)	70	75	80
Biogas (% efficiency)	60	65	70
Clean biomass cooking stoves (% efficiency)	30	32	34
Traditional biomass (% efficiency)	15	22	25
Cooking final energy (EJ/yr)	21	19	16
CO_2 emissions (Gt CO_2/yr)	0.17	0.42	0.40

of the modern type. These are about twice as energy efficient as traditional ones and reduce indoor air pollution significantly. The deployment rate in Asia is higher. The Chinese National Improved Stove Program (NISP) has been the only cookstove dissemination effort to achieve broad success at scale, distributing about 130 million stoves.

Total global cooking energy demand is estimated to decrease from 21 EJ in 2015 to 16 EJ by 2050 in the REmap case. A third of these reductions are due to renewables (95 % modern biomass and 5 % solar cookstoves). About 30 % is due to electric cookstoves. The remainder is kerosene/LPG and gas use. With the remaining fossil fuel use for cooking and the growth in demand for energy, CO_2 emissions more than double under REmap from 170 Mt CO_2/yr to 400 Mt CO_2/yr. However, this is still about 20 % less than what was envisioned under the Reference Case, of 500 Mt CO_2/yr. Efficiency improvements from the substitution of traditional uses of biomass and switch to gas or electric cookstoves account for nearly all the reductions in CO_2 emissions.

Transport – passenger cars

Sector description

Passengers can travel by car, bus, train or other modes, but this section focuses on passenger car transport. Most cars are four-wheelers powered by internal combustion engines (ICE). Electric vehicles are increasing in number, but current sales represent less than 1 % of the total. Passenger car use depends highly on road infrastructure. The infrastructure is built over long periods of time at relatively high costs, and also remains in use for long periods. As a result, there is considerable infrastructure lock-in.

Present energy use and CO_2 emissions

Passenger cars represent 40 % of transport's total energy demand. Much of this (95 %) comes from fossil fuel-based gasoline and diesel, and a small share from biofuels (3 %). The remainder is compressed natural gas (CNG) (1.5 %) and electric vehicles (< 0.1 %).

The sector currently emits around 3 Gt of CO_2 per yearmainly from gasoline and diesel combustion. These emissions are just under 10 % of the total global energy-related CO_2 emissions.

Energy use and emissions can be significantly reduced by powering cars with electricity. Electric vehicles are three times more efficient than ICEs, and offer additional benefits as well. They do not emit any air pollutants or CO_2 like ICEs. They can also be sourced with renewable power, raising the share of renewable energy in both the power and transport sectors. They are quieter than ICE vehicles, reducing noise pollution and often have better performance and lower maintenance costs. Their total sales reached half a million in 2015. At the end of 2016, the total number of electric vehicles in the car stock has passed the two million mark. This rapid rise has been led by China, the US, Japan and several European countries.

Emissions can also be cut with greater use of liquid biofuels, which are today mainly used for passenger cars. Their use has reached around 128 billion litres today. Much of this is fuel ethanol produced from food crops, with a tiny share coming from residue or other non-food based advanced biofuels. The use of biomethane is around 10 million m^3, concentrated in a few countries (*e. g.* Germany, Italy, Sweden). Biofuels production has stagnated in the past few years, with investments dropping significantly compared to the mid-2000s. This trend is mainly due to low crude oil prices and growing concerns about the sustainability of growing feedstocks for biofuels.

Sector trends to 2030 and 2050

Passenger car use is expected to grow further in future decades. As population increases and people's purchase power rises with economic prosperity, the number of passenger cars will grow. Passenger cars are also a representation of status, and are generally a top priority for purchase when people have access to sufficient amounts of capital. Annual passenger-kilometres driven by passenger cars are expected to more than double by 2050 compared to today. This implies a total passenger car stock of about 2 200 million cars by 2050, equivalent to 250–300 cars per 1 000 people. Today, ownership is around 180 cars per 1 000 people, or about 1.3 billion passenger cars.

Reference Case: Path set by current plans and policies

In the Reference Case, total energy demand of the sector is projected to rise from 44 EJ in 2015 to 66 EJ by 2050. Fossil fuels are estimated to represent the majority of passenger car fuel needs by 2050. In line with the growth in demand for energy, the sector's total CO_2 emissions would increase from 3.0 Gt per year to 4.2 Gt per year by 2050.

REmap analysis: Technology solutions and their potential by 2050

In the REmap case, energy demand would decline to 37 EJ by 2050, and emissions would drop to 0.65 Gt of CO_2 per year, an 85 % reduction compared to the Reference Case. The emissions reductions are achieved through better fuel economy, the widespread use of electric vehicles, and adoption of liquid and gaseous biofuels and renewables-based hydrogen.

Automobile fuel efficiency has already improved significantly, partly because of policies to reduce pollution and to mitigate climate change, and partly because of market changes caused by periods of high oil prices. But there remains a large potential for improvement. Some additional gains are possible through advances in ICE technology. Others are made possible by technologies outside of the powertrain, such as lightweight materials, low friction tires and aerodynamic improvements from innovative vehicle designs. Depending on the car type, these measures can reduce passenger car energy demand by between 10 % and 50 %.

The vast majority of the emissions reductions that can be made in the passenger car sector, however, would come from widespread electrification. Electric cars use about one-third of the energy of ICE vehicles, and their efficiency can be further improved through the use of lightweight materials and other technologies.

The adoption of electric cars can be driven by strong technological progress, cost reductions (especially in batteries) and policy support, including purchase incentives, driving and parking access advantages, and greater availability of public charging infrastructure. If battery costs drop from their current levels of around USD 350/kWh (or for specific types even less at around USD 200/kWh) to USD 150/kWh[13], a 40 kWh battery system for electric vehicles would cost USD 6 000. While that is higher than the cost of the drive systems in today's internal combustion engine vehicles, the fuel savings would allow for short payback times. By 2050, electric vehicle costs are expected to be same or even less than the costs of ICE vehicles.

There will, however, be additional costs in building charging systems. Today in Germany, there are about six electric cars for every available public charging station. This number will increase as the number of cars grows and as charging times decrease. This number could be increased up to as many as 50 cars per charger by 2050. But more rapid growth in the number of cars would mean that thousands of new charging stations must be built, at a cost of between USD 15 000 and UDS 50 000 each.

Table 17: Economic indicators under REmap in 2050 compared to the Reference Case for transport – passenger cars

	Abatement cost (USD/t CO_2)	Abatement potential (Mt CO_2/yr)	Incremental system costs (USD/t CO_2)	Additional investment needs 2015–2050 (USD trillion)
Conventional ethanol	20	8	0.2	0.006
Advanced ethanol	190	16	2.9	0.030
Conventional biodiesel	35	8	0.3	0.003
Advanced biodiesel	200	16	3.2	0.019
Biomethane	30	6	0.2	0.011
EVs	25	2 670	66.8	0.820
Hydrogen hybrid	75	215	16.3	0.687
Energy efficiency	5	550	2.7	2.154
Total	27	3 480	92	3.73

Assumption: Discount rate: 10 % and crude oil price: USD 80/bbl.

13 https://www.greentechmedia.com/articles/read/How-Soon-Can-Tesla-Get-Battery-Cell-Cost-Below-100-per-Kilowatt-Hour

Table 18: Global REmap case – summary of activity, energy and CO_2 emission trends 2015–2050 for Transport – Passenger cars subsector.

	2015	2030	2050
Passenger, cars travel (bln passenger-km/yr)	22 920	33 880	51 690
ICE energy use (MJ/passenger-km)	1.9	1.7	1.1
EV energy use (MJ/passenger-km)	0.62	0.57	0.48
Total electricity demand (TWh/yr)	1	590	4 480
Number of EVs (million)	1.5	170	830
Conventional biofuels (bln litres/yr)	117	150	160
Advanced biofuels (bln litres/yr)	1	80	190
Biomethane (bln m^3/yr) (1 BCM = 36 PJ)		5	3
Hydrogen (EJ/yr)		1.2	2.9
Total fossil fuel use (EJ/yr)	40.9	44.5	8.9
Total natural gas use (bln m^3/yr)	18.1	14.3	0
Total energy-related CO_2 emissions (Gt/yr)	3.0	3.2	0.65

Note: indirect emissions from the generation of electricity that is consumed in processes are excluded.

The higher share of electric mobility in the 2050 passenger transport system will bring additional advantages that are not captured by this cost. One main opportunity is the linkage to the power sector, an example of an innovative systems thinking approach. Aligning vehicle charging with a variable renewable power supply results in synergies between the sectors that would improve overall systems operation.

The combination of electrification and efficiency gains from improvements in car design and material use would account for 92 % of the emissions reductions in the REmap analysis compared to the Reference Case.

The remaining 8 % of emissions reductions under REmap would come from the use of liquid biofuels, biomethane and hydrogen. Liquid biofuels could have further potential, but meeting the growing demand is a significant challenge, because of the competing uses of biofuels in other transport modes such as aviation and constraints on growing biofuels feedstocks. Advanced biofuels and biomethane, which are both made from non-food feedstocks, offer alternatives, but most production pathways are only at the early stages of commercialisation. Similarly, hydrogen is one other source of energy that is becoming more commonly used in some countries, such as Japan. However, there are large infrastructure costs associated with hydrogen. A hydrogen filling station costs around 5–6 times more than a conventional gas station, so that increasing hydrogen use would require huge subsidies. Moreover, while fuel cells are efficient at converting hydrogen to electricity in fuel cell vehicles, those efficiency gains are offset by the energy needed to produce and compress hydrogen gas (Nikkei Asian Review 2016). The choice about whether to power transport with more hydrogen or more electricity will differ between countries.

In the REmap analysis, fossil fuels would represent a quarter of sector's total energy use, a significant drop from today's level of 97 %. Biofuels would supply about a quarter of the total demand, and electricity about 44 %. The remainder 8 % would originate from hydrogen.

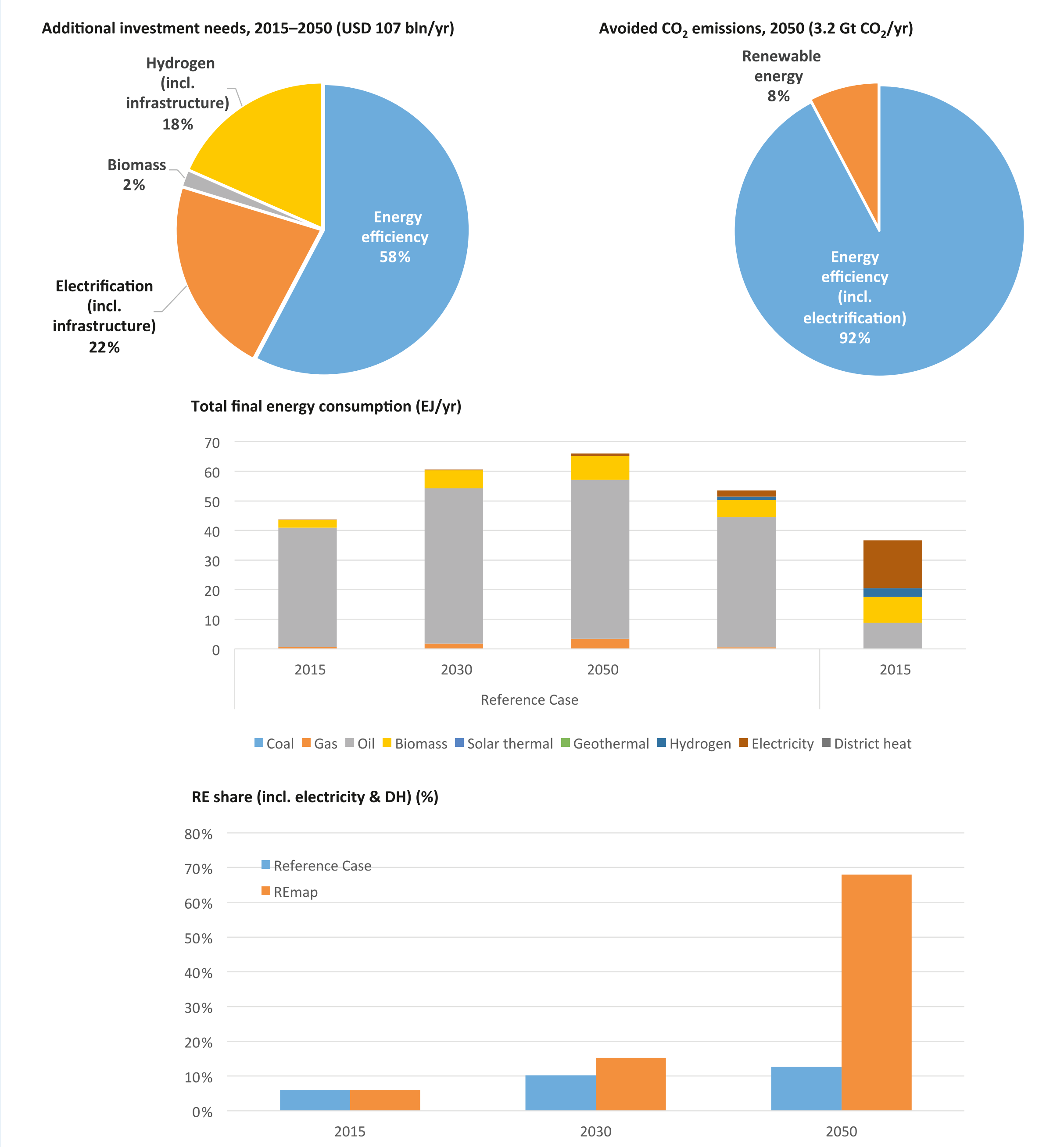
As Table 17 shows, the average abatement cost of these options would be USD 55 per tonne of CO_2 by 2050, and the additional investment needs over the Reference Case add up to USD 0.9 trillion in the 2015–2050 period.

Transport – other ground passenger transport

Sector description

Around the world, more people travel by bus, train and other public ground transport than they do by passenger car. These modes of transport are typically more efficient than a passenger car. A large bus can easily carry up to 80 people, for example, while a collective taxi that runs between districts would have less capacity than a bus, but might carry 40–60 people per ride with multiple passengers coming in and out during a trip.

Figure 28: Key estimates for transport – passenger cars



Based on IRENA estimates

Buses are used extensively throughout the world. In countries that do not have good railway networks, such as Latin American countries and the US, they are the main transport mode. In countries where railways are well established, buses are gaining popularity. One example is Germany, which recently liberalised its long-distance bus system. Worldwide, buses and similar vehicles travelled more than 10 000 billion passenger-kilometres in 2015.

In principle, trams and trains provide the same service as buses and other public road transport, but require their own separate track instead of using the same road infrastructure as passenger cars. The advantage is that they can offer more punctual transport compared to road systems, which are impacted by congestion, especially during peak hours. On the other hand, train systems have very limited flexibility and require significant time and planning to build.

In 2015, railways carried 3 000 billion passenger-kilometres. Railways have become more efficient by switching from steam engines (the last one was retired in the early 1980s) to diesel engines or electrified systems. For long-distance travel, a number of countries have also invested in high-speed trains.

There are many advantages of public transport systems. They allow people who do not own their own vehicles to travel. Reducing the need to own a car, in turn, reduces the burdens of paying for parking, fuel, insurance and car ownership-related taxes, etc. Buses and trains also allow passengers to make use of their travel time in ways they can't do while driving. The cost to the user is more explicit. Energy use per passenger-km can be much lower than for transport by passenger car.

Finally, many types of two- and three-wheelers are typically used all around the world. In 2015, more than 2 000 billion passenger-kilometres were travelled by such vehicles. The simplest is the human-powered bike. Bikes can also be upgraded to mopeds or scooters by adding an engine, typically fuelled with gasoline. Larger motorcycles can achieve the speeds and performance of a 4-wheel vehicle. Electric scooters and motorcycles have also become common all around the world, and have already been mainstream in China. Three-wheelers, which typically have more cargo space, also exist, and are used for transporting goods and food, as well as people. Most are gasoline or diesel-powered, but versions exist that run with human power. Two- and three-wheelers are common in densely populated cities (*e.g.* Beijing, Jakarta), in cities with limited road infrastructure for large cars and buses (*e.g.* the Netherlands) and in developing countries where citizens cannot easily afford cars. Their advantages are that they reduce road congestion, compared to travel by passenger cars, and are far easier to park than cars. However, they are typically less suited for long-distance travel and have less cargo capacity. Still, some of these vehicles can allow a 3-person family to travel for certain distances.

Present energy use and CO_2 emissions

The ground transport sector currently emits around 1.1 Gt of CO_2 per year. Public road transport systems account for about 90 % of this total. In terms of energy use, two- and three-wheelers or buses use one-third (or less) fossil fuel per passenger-km than a passenger car does. The models that use electricity are even more efficient, using one-third of the energy of an internal combustion engine equivalent.

Currently, the sector uses just under 15 EJ of energy per year. About 14 EJ of this is diesel. About 190 PJ of natural gas (5 billion m^3) is used, mainly in buses. Another 220 PJ (or about 60 TWh/yr) of electricity is used, mainly in railways (and to smaller extent by two- or three-wheelers, notably in China). Consumption of biodiesel is around 130 PJ (4 billion litres) today. The biodiesel is often blended with conventional diesel to be consumed in buses and other road transport modes.

Sector trends to 2030 and 2050

Like other forms of transportation, ground passenger transport using modes other than passenger cars is expected to grow. The number of passenger-kilometres by rail is projected to nearly double by 2050 compared to current levels, similar to the rate of growth in passenger transport. The growth in transport by bus and two- and three-wheelers is expected to be less. The reason is that people would rather own and use a car than take public transport, if they can afford the car. The use of two- and three-wheelers will also continue to grow in regions where they are common today, such as Southeast Asia, China, India and other developing Asian countries. High-speed railways are projected to gain a large share of the railways-based passenger transport. Currently, about 20 000 kilometres of high-speed rail routes are available. That is expected to double by 2030, as projects that are currently under construction (mainly in China) or are being planned are finalised. The total length of high-speed railways is projected to increase more than 100 000 track-kilometres by 2050.

Such growth will have impacts beyond energy and emissions. Building railways and related infrastructure is costly and requires significant time and planning. As inter-city bus systems gain an increasing share of the total passenger transport by 2050, it also will be necessary to plan for this growth by either making use of the existing infrastructure or planning new systems. One option for urban transport is to build corridors for buses that allow them to use private lanes separated from the rest of the road traffic – an approach called bus rapid transit (BRT). This would also require considerable investment and planning.

Reference Case: Path set by current plans and policies

The total energy demand of this sector is projected to reach 19 EJ by 2050, up from 15 EJ in 2015. Most of this demand will be continue to be supplied by oil products for buses and two- or three-wheelers. The use of electricity is projected to double to 3% by 2050. However, its contribution to reduce the sector's CO_2 emissions under the Reference Case is negligible. The share of biofuels increases to 9%. Overall, the sector's CO_2 emissions would increase from around 1.1 Gt per year to 1.23 Gt per year by 2050.

REmap analysis: Technology solutions and their potential by 2050

In the REmap analysis, energy demand declines to 10.4 EJ by 2050 and emissions fall by two-thirds, compared to the Reference Case, to 0.45 Gt per year. The reductions would be achieved by the

Table 19: Economic indicators under REmap in 2050 compared to the Reference Case for transport – other ground passengers

	Abatement cost (USD/t CO_2)	Abatement potential (Mt CO_2/yr)	Incremental system costs (USD/t CO_2)	Additional investment needs 2015–2050 (USD trillion)
Electric railways	–260	15	–4.5	1.502
Conventional biodiesel	35	10	0.4	0.005
Advanced biodiesel	200	25	5.1	0.028
Biomethane	–15	25	–0.3	0.023
Electric bus	45	235	10.5	0.064
Electric 2-/3-wheeler	–80	90	–7.4	0.200
Energy efficiency	5	345	1.7	0.135
Total	7	745	6	2.0

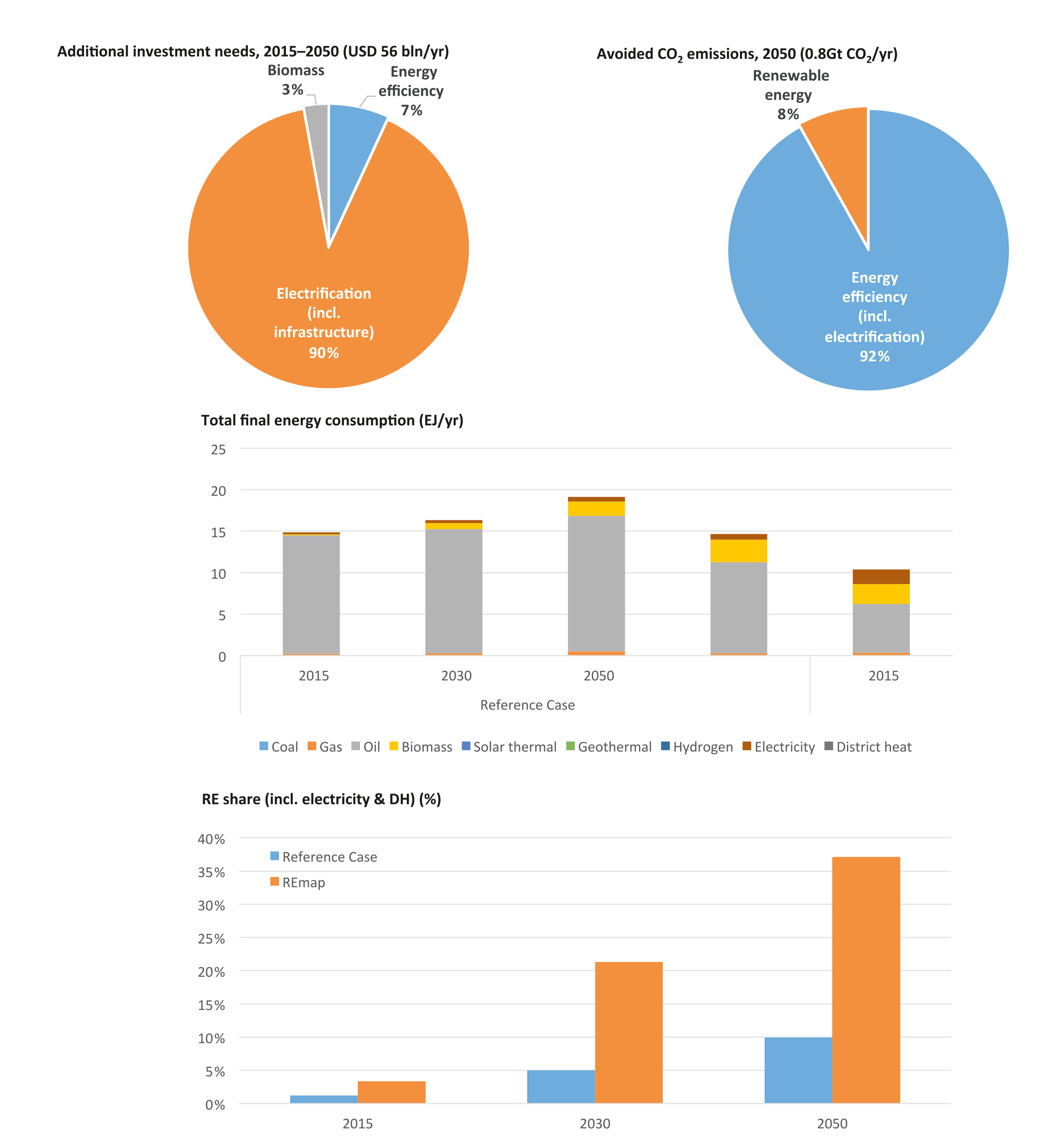
Assumption: Discount rate: 10% and crude oil price: USD 80/bbl.

Table 20: Global REmap case – summary of activity, energy and CO_2 emission trends 2015–2050 for transport-other ground passengers

	2015	2030	2050
Public road transport travel (bln passenger-km/yr)	10 650	13 760	17 560
2-/3-wheelers (bln passenger-km/yr)	2 130	2 750	3 520
Railways (bln passenger-km/yr)	3 030	3 960	5 775
Public road, 2-/3-wheelers fossil use (MJ/passenger-km)	1.00	0.80	0.60
Public road, 2-/3-wheelers electricity use (MJ/passenger-km)	0.26	0.23	0.15
Railways electricity use (MJ/passenger-km)	0.1	0.09	0.08
Total electricity demand of public road transport (TWh/yr)	60	117	347
Conventional biodiesel (bln l/yr)	14	44	26
Advanced biodiesel (bln l/yr)		38	46
Biomethane (bln m^3/yr)		2.7	13.5
Total fossil fuel use (EJ/yr)	14	11	6
Total energy-related CO_2 emissions (Gt/yr)	1.1	0.8	0.4

Note: indirect emissions from the generation of electricity that is consumed in processes are excluded.

Figure 29: Key estimates for transport – other passenger vehicles



Based on IRENA estimates

electrification of railways, bus transport and two- or three-wheelers, along with increased use of biofuels. Biomass would supply about a quarter of all energy demand, with another 20 % coming from renewable electricity.

Biofuels can be used in a range of transportation types, especially buses. The current consumption of liquid biofuels can increase to 115 billion litres by 2050, nearly three times higher than in the Reference Case. Natural gas also is being increasingly used in buses all across the world, and can be replaced by biomethane using the same infrastructure. A total potential of about 14 billion m^3 is estimated.

Electric buses have become more common, especially for urban transport, and offer an important option for future development. Many cities have announced goals of raising the share of electric buses to as high as 100 % (*e.g.* Bonn or Hamburg in Germany). Trolley buses in urban areas and sky trams in mountainous urban areas are also electrified alternatives to current road public transport systems. The typically small engines in two- and three-wheelers can also easily be replaced by electric alternatives. Their use is already prominent in China and likewise can easily be expanded in other parts of Asia.

Under REmap, electricity would account for more than 10 % of the sector's total energy use by 2050, compared to less than 1 % (only in railways) in 2015. Biofuels (both biodiesel and biomethane) would supply more than one-third of the sector's total energy demand. The remaining half is oil use.

As Table 19 shows, the average abatement cost of these options would be USD 7 per tonne of CO_2 by 2050, and the additional investment needs over the Reference Case add up to USD 2 trillion in the 2015–2050 period.

Transport – aviation

Sector description

This section covers passenger transportation in airplanes. In addition, passenger transport in ships is also briefly mentioned.

Airplanes are typically used for long-distance transportation, and can save considerable time compared to the same trips by train, car or ship. In aviation, the costs of high-specification jet fuel represent up to 30 % of the sector's total costs (international aviation fuels are not taxed). Therefore, an affordable supply of energy is crucial for the international competitiveness of airline companies.

The energy demand of aviation will grow 3–5 % per year over the coming decades as populations and economic activity increase. For example, India's aviation sector is expected to become the third largest worldwide by 2020 and the largest by 2030 (FICCI-KPMG 2016).

Travelling by ship is less common than air travel, and is often used for short trips within a city, or between neighbouring cities. While long-distance leisure cruises carry increasing numbers of passengers, the total number of trips by ship will remain low compared to tourist trips on planes. Similarly, fuel is an important component of shipping's total costs. But shipping often enjoys the availability of low-cost, low-specification fuels.

Present energy use and CO_2 emissions

About 3.6 billion people fly on airplanes each year, travelling more than 5 000 billion passenger-kilometres per year. That number is about one-third the number of passenger-kilometres made by passenger cars today. The number of trips on ships – about 340 billion passenger-kilometres per year – is much smaller.

The total CO_2 emissions from aviation and shipping were 0.7 Gt of CO_2 in 2015. Most of this is from the aviation sector, which produced about 2–3 % of the total global energy-related CO_2 emissions. This share is expected to grow over the coming decades as the aviation sector grows, tickets become cheaper and people can afford more trips.

When expressed in terms of passenger-kilometres, planes use slightly more energy than an average passenger car because they carry significantly more passengers in a single trip and move at faster speeds. Passenger ships require 3–4 times more energy than an airplane to move the same number of passengers over the same distance. Combined, these two passenger modes consume approximately 10 EJ of final energy, with about 95 % of this total from aviation. Nearly all energy use originates from fossil fuels: kerosene (or jet fuels) for aviation and heavy fuel oil for ships.

Given aviation's growing contribution to global CO_2 emissions, aviation will play a key role in meeting the international climate targets set forth in the 2015 Paris Agreement, even though the document does not specifically mention aviation emissions. Many airlines, aircraft manufacturers and industry associations have committed to voluntary, aspirational targets that would collectively achieve carbon-neutral growth by 2020 and a 50 % reduction in GHG emissions by 2050 (relative to 2005 levels).

Similarly, emissions from the shipping sector must be curbed to reduce air pollution and climate change impacts. Regulations on emissions have been mainly focused on sulphur emissions in order to reduce air pollution in specific locations. For sulphur emissions reductions, scrubbers are typically used in ships rather than cleaner fuels. However, there is also a trend in the shipping sector to shift to cleaner fuels with lower sulphur content. This has important implications for refineries and the fuel market. The International Convention for the Prevention of Pollution from Ships (MARPOL) has stipulated mandatory technical and operational measures, which require more efficient maritime energy use and, simultaneously, fewer emissions. These regulations came into force in 2013. The shipping sector itself has set targets to reduce carbon dioxide emissions by 20 % by 2020 and 50 % by 2050. Ship operators and owners, therefore, need to consider cleaner fuel and power options, including the use of renewables, to meet these targets. Cruise ships in particular burn significant amounts of fuel. A large cruise ship uses around 150 tonnes of fuel per day and can emit more sulphur than several million cars would emit in total. Some companies have reacted to the impacts of cruise ships from growing fuel use. In the period 2007–2014, several cruise lines have improved their fuel use efficiency by 24 % using better propulsion technologies and hull coatings, along with more efficient air conditioning and lighting.

Sector trends to 2030 and 2050

Aviation passenger travel is expected to grow by around three times between today and 2050 under both the Reference Case and REmap. Ships are expected to carry twice as many passengers by 2050 compared to today, but their total contribution to passenger activity will remain low. This will cause total energy demand to triple between 2015 and 2050.

Reference Case: Path set by current plans and policies

The sector's energy demand is around 10 EJ today. This is projected to more than double, reaching 24 EJ by 2050. More than 95 % of this total is related to aviation. Energy use will be dominated by kerosene and heavy fuel oils made from fossil fuels, with renewables representing 10 % of the total, at about 70 billion litres of liquid biofuels. Emissions, mostly from aviation but also a small share from shipping, would rise from 0.7 Gt of CO_2 to 1.6 Gt by 2050.

REmap analysis: Technology solutions and their potential by 2050

In the REmap case, total energy demand rises to only 25 EJ by 2050 because of energy efficiency gains, while CO_2 emissions drop to 0.8 Gt per year, about half the level in the Reference Case. The reduction comes from a combination of greater efficiency and increased use of biofuels (estimated to supply just under 30 % of total aviation energy demand).

Efficiency gains will come from improved fuel efficiency in new aircraft, from aircraft modifications and airport restructuring, from optimised navigational systems and other measures. These energy efficiency measures would be responsible for 30 % of the emissions reductions under REmap, compared to the Reference Case.

However, achieving a significant longer-term reduction of emissions will require airlines to use fuels that are renewable and sustainable, such as biofuels developed for jet aircraft. Although sustainable and clean alternative propulsion technologies are in development, such as electric- or solar-powered aircraft and the use of cryogenic hydrogen, these options are unlikely to be ready for commercial use until well after 2050. Given that aircraft have long lifespans and are very expensive, airlines typically want to use them as long as possible before replacing them. Biofuels for jet aircraft – synthetic paraffinic kerosene, with or without aromatics – are known in the industry as biojet. They are the only real option to achieve significant reductions in aviation emissions by 2050. Biojet fuels can be derived from sustainable sources such as vegetable oils, animal fats and forest residues, and existing jet engines do not require modifications for their use.

So far, 23 airlines have conducted 2 500 commercial and demonstration flights using biofuels. But today less than 0.05 % of the total jet fuel demand is met with biofuels. As of early 2016, targets for biojet production are more aspirational than legislative, with the US FAA suggesting that 3.8 billion litres of biojet could be produced by 2018, and the US Air Force hoping to have 50 % of its fuel replaced by alternative fuels by 2016 (another 3.8 billion litres). Current production costs of biojet are 3–5 times higher than costs for conventional kerosene. These fuels are also subject to stringent quality standards. Even with significant technological learning, their cost-competitiveness is likely to improve only marginally. By using a significant share of the total liquid biofuel production for aviation, the sector can achieve a 30 % share of renewable energy using about 200 billion litres of biojet. About 70 % of the total CO_2 emissions reductions in REmap, compared to the Reference Case, would be achieved through the use of biofuels.

The transition to a clean energy shipping sector requires a significant shift from fossil fuel-powered transport to energy-efficient designs and renewable energy technologies. Renewable energy can transform the global shipping fleet. One option is biodiesel. Options also exist for electrification in both retrofits to the existing fleet or incorporated into new shipbuilding and design.

The energy use of passenger transport via aviation and marine modes reached 10 EJ in 2015. By 2050, aviation demand is estimated to triple according to the Reference Case. With improvements in energy efficiency, this growth can be limited to a doubling under REmap. In line with the aviation sector long-term objectives, biofuels account for around 30 % of the sector's total energy mix. This is the only other technology option besides energy efficiency for aviation.

Overall, under REmap, the energy used in aviation will double by 2050, rather than tripling as in the Reference Case, and the sector's total CO_2 emissions would grow slightly from around 0.7 Gt in 2015 to 0.8 Gt per year by 2050 (about half of the level in the Reference Case).

As Table 21 shows, the average abatement cost of these options would be USD 105 per tonne of CO_2 by 2050, and the additional investment needs over the Reference Case add up to USD 0.4 trillion in the 2015–2050 period.

Transport – trucks and shipping

Sector description

The global economy depends on the movement of an enormous volume and variety of goods. The vast

Table 21: Economic indicators under REmap in 2050 compared to the Reference Case for transport – aviation

	Abatement cost (USD/t CO_2)	Abatement potential (Mt CO_2/yr)	Incremental system costs (USD bln/yr)	Additional investment needs 2015–2050 (USD trillion)
Biojet fuels	295	255	75	0.3
Conventional biodiesel for passenger shipping	35	1	0.01	0.001
Advanced biodiesel for passenger shipping	200	2	0.3	0.002
Energy efficiency in aviation	5	485	2.5	0.044
Total	105	740	78	0.36

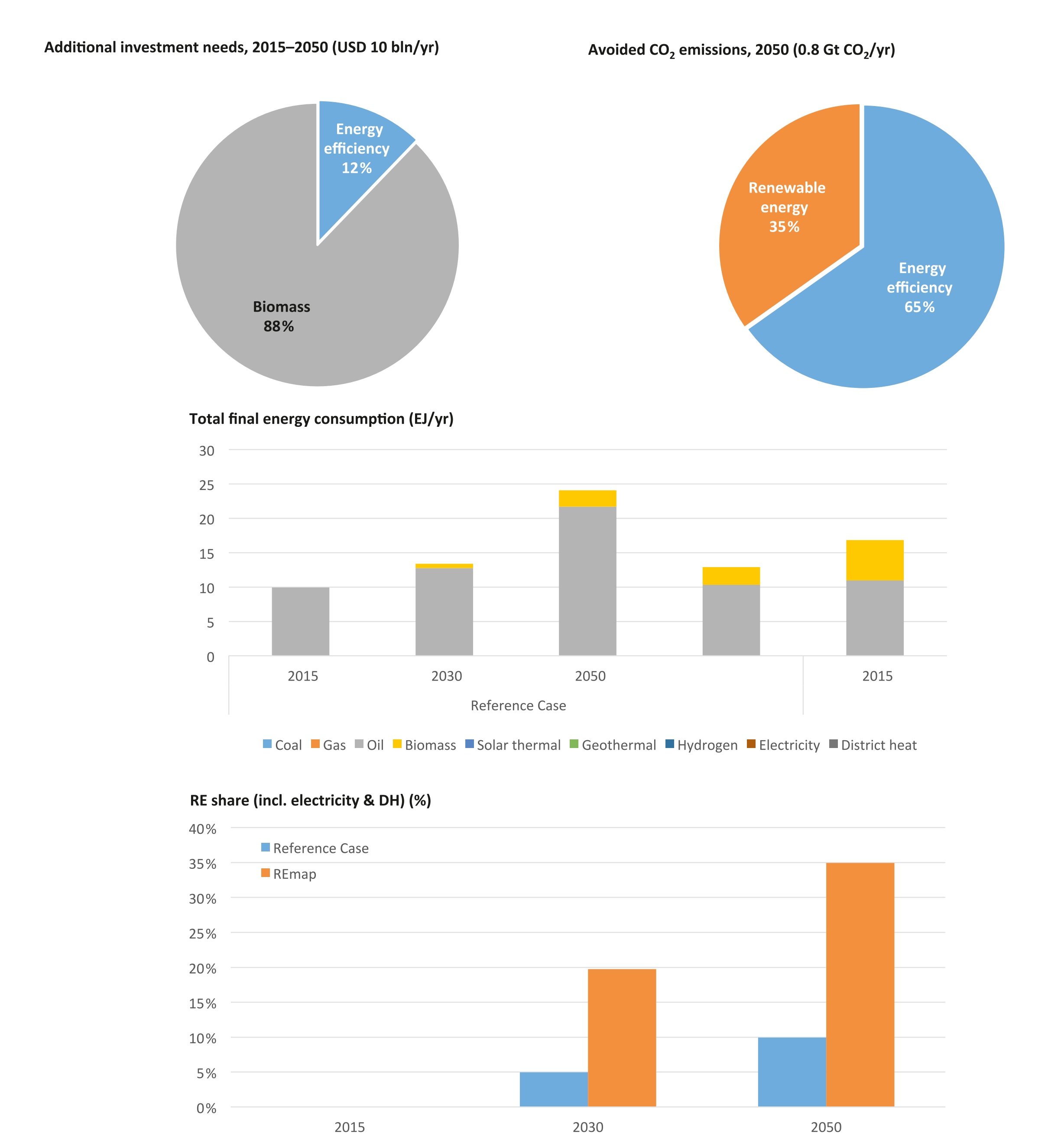
Assumption: Discount rate: 10 % and crude oil price: USD 80/bbl.

Table 22: Global REmap case – summary of activity, energy and CO_2 emission trends 2015–2050 for transport – aviation

	2015	2030	2050
Air passenger travel (bln passenger-km/yr)	5 150	7 500	15 000
Ship passenger travel (bln passenger-km/yr)	340	540	665
Aviation fossil use (MJ/passenger-km)	1.9	1.7	1.2
Passenger shipping energy use (MJ/passenger-km)	0.5	0.4	0.2
Conventional biodiesel for shipping (bln litres/yr)	0	0.3	0.6
Advanced biodiesel (bln litres/yr)		0.1	0.9
Biojet (bln litres/yr)		75	175
Total fossil fuel use (EJ/yr)	9.9	10.3	10.9
Total energy-related CO_2 emissions (Gt/yr)	0.7	0.8	0.8

Note: indirect emissions from the generation of electricity that is consumed in processes are excluded.

Figure 30: Key estimates from review of transport – aviation



Based on IRENA estimates

majority of this freight is carried by ships, but large amounts are also transported by rail and by trucks. The shipping industry is the backbone of global trade and a lifeline for island communities, transporting approximately 90 % of the tonnage of all traded goods. Annual global freight shipping tonnage increased from 2.6 billion to 9.5 billion tonnes between 1970 and 2013. In 2015, more than 50 000 billion tonne-kilometres of freight were transported by about 100 000 operating ships. Around 45 000 of these ships are cargo ships. Another 46 000 ships are used for fishing and service. There are 7 000 passenger ships (McGill, Remley and Winther, 2013). The demand for shipping is predicted to grow significantly, because of the changing patterns of global production and the increasing importance of global supply chains and international trade.

Railways are also used for freight transport. Just under 10 000 billion tonne-kilometres freight were transported by trains. Railways are often linked to other certain economic activity (*e.g.* mines) or transport hubs (*e.g.* seaports) and carry goods from one source to inland. Rail freight is, however, not as flexible as road freight, which has resulted in equal amount of freight distances being hauled by trucks, even over long distances. Road freight can be split into trucks and delivery vans. There are numerous truck types. Long-haul trucks carry containers or have an integrated trailer that can be loaded with goods. Such trucks can carry tens of tonnes of freight and are typically used to carry freight across countries and between countries. There are also light trucks that are used within urban areas or between cities to carry all different types of dry and liquid goods. Trucks are also used on-site in specific industries (*e.g.* coal mining) or at construction areas. Delivery vans carry smaller cargo. A delivery van can carry up to 15 tonnes of goods and its daily range is typically 3–5 times less than that of a long-haul truck (CE Delft 2010).

Present energy use and CO_2 emissions

The freight sector's total final energy demand was about 36 EJ 2015, and CO_2 emissions were 2.6 Gt CO_2.

A significant amount of the energy demand and CO_2 emissions from the sector comes from ships, since shipping accounts for the largest share of freight activity today. The shipping industry is responsible for about 11 EJ (or 30 %) of final energy demand of freight activity, and produces about 0.8 Gt of CO_2 per year today. This represents 15 % of the emissions of the entire transport sector (including cars and other passenger transport). The other common use of ships, for fishing, by comparison contributes only a small amount, around 35 Mt of CO_2 per year (assuming 100 litres of fuel per 1 tonne of fish, and 100 Mt of fish per year).

A single large container ship can emit as much air pollution as 50 million cars. This is because of the high sulphur content of the low-grade bunker fuel used in freight ships. The 100 000 ships now in operation burn approximately 6 million barrels of oil per day, equivalent to three times Kuwait's crude oil exports in 2016. The combustion of these fuels produces SO_x emissions of 20 million tones per year.

Around 80 % of total energy demand in shipping is related to cargo ships. The remainder 20 % is for fishing boats, as well as service and passenger shipping (McGill, Remley, and Winther 2013). There is now a regulation in place for sulphur reductions in global fuels by 2020, which will drop the maximum allowed sulphur content from 3.5 % to 0.5 %. The actual current average sulphur content is around 2.5 %. The new rule will thus achieve an 80 % reduction in sulphur emissions from shipping.

When crude oil prices were around USD 100 per barrel, the price of marine diesel oil was around USD 700 per tonne (McGill, Remley, and Winther 2013). Today the price is around USD 500 per tonne. In shipping, heavy fuel oil is predominantly used which has a current price of around USD 300 per tonne.

According to the technical regulations in the International Marine Organization (IMO) agreement that came into force in January 2013, new ships must improve their energy efficiency by 30 % by 2025 (covering 94 % of the world fleet). Under the Ship Energy Efficiency Management Plan (SEEMP), the international shipping industry aims reduce its CO_2 emissions intensity (tonne/km activity). ICS has put forward a reduction of 50 % by 2050 (IMO 2014).

Trains and trucks also carry significant amounts of goods. When it comes to the amount of freight carried per unit of distance, rail freight and road freight have similar volumes at around 10 000 billion tonne-kilometres per year. But road transport accounts for more than 60 % of the freight sector's total energy demand, though its share in total freight transport activity is around 10 %. Road freight uses more than 10 times more energy per unit activity compared to ships.

Much of the energy use for freight comes from diesel used in trucks and ships. In the EU-27, for instance, long-haul trucks account for more than a third of the total road freight sector GHG emissions. Freight truck use for regional delivery, urban delivery and at construction sites each account for 13 % of the total emissions.

Sector trends to 2030 and 2050

Total freight transport is expected to double from around 75 000 billion tonne-kilometres per year to more than 160 000 tonne-kilometres per year by 2050. Shipping freight is expected to account for three-quarters of this total, followed by road freight transport and railways.

Reference Case: Path set by current plans and policies

With the growing demand for domestic and international transportation of freight, the energy use of the sector is projected to reach 48 EJ by 2050, a 35 % increase over the 2015 level of 36 EJ. The sector would predominantly rely on fossil fuels as the main source of energy, with biofuels gaining a market share of less than 10 % to be mainly used for trucks. While shipping energy demand is projected to increase by 50 %, demand for trucks is projected to increase by around 30 % in the 2015–2050 period. Emissions are estimated to reach 3.2 Gt by 2050, compared 2.6 Gt in 2015.

REmap analysis: Technology solutions and their potential by 2050

Under REmap, freight's energy use would drop to 33 EJ (30 % less than in the Reference Case), and CO_2 emissions would decline by 65 % compared to the Reference Case, to 1.1 Gt of CO_2 per year by 2050.

For ships, the main low-carbon technology solutions in REmap are more efficient ship designs and biofuels (electrification is possible, but is not included in the analysis). Various efficient propeller technologies (*e. g.* twin propellers, contra-rotating propellers, propeller boss fin caps, etc.) can reduce fuel consumption by 5–10 %. Heat recovery systems can result in 7–12 % savings. These are technologies that can be used to retrofit the existing fleet as well as in the construction of new ships. New ships can save at least 40 % in fuel use compared to the average technology used by the current fleet (Winkler, 2007).

Biofuels can be easily integrated in all vessel types without any major modifications. In addition, ships can be powered by renewables-based electricity, wind or even nuclear (such as military submarines and aircraft carriers and icebreakers). Soft and fixed-sail technologies are already commercialised and can be used for both primary and auxiliary propulsion. Trial trips have been made with solar PV, and wind turbine integration is under research and development. There are also a number of examples of battery-electric propulsion ships (IRENA 2015d).

Additional savings can come from changes in operation. The concept of "slow steaming" emerged a decade ago during the financial crisis, enabling shipping companies to save money (since at lower speeds, fuel consumption per km can be halved compared to normal speed.) Ship size also makes a difference. A ship with cargo capacity of 10 000 TEU has a 50 % lower carbon intensity (tCO_2 per tonne-km) than a ship with a capacity of 7 000–8 000 TEU (Rodrigue 2016).

For railways, the most effective approach to reduce emissions is further electrification, provided that the electricity trains consume is supplied with renewables.

Trucks have a large potential for efficiency improvements. In the US, for example, the energy efficiency of non-light duty vehicles could be improved by 25–50 %.

Biofuels and biomethane are options for renewable energy. They are already being commercialised for trucks in some countries today, such as Sweden. Electrification is an economically viable option for delivery trucks, a rapidly growing market segment linked to the Internet economy. There are four methods to electrify the truck sector: conductive charging, inductive charging, battery swap and overhead charging.

However, the electrification of road freight faces significant challenges. In contrast to passenger cars, trucks travel over long distances. They also consume more energy, requiring larger battery packs. For a delivery truck with a 10 tonne gross vehicle weight (GVW), a battery-electric system would add 740 kg or more. But the conventional truck has on average nearly 10 times the range before it needs to refuel (1 100 km vs 120 km for the battery-electric truck) (CE Delft 2010). A long-haul truck that travels an average of 800 km/day would require a prohibitively heavy battery pack. A battery weight of 2 500 kg is realistic, but can only be achieved after 2030.

Charging technologies and infrastructure would also play important roles in the electrification of the freight sector. Plug-in charging would typically require around eight hours. This would be sufficient for electric delivery vans. Fast charging requires larger power capacities. For passenger cars, capacity is around 50 kW, which is expected to reach to around 200 kW in the coming years. For a distribution truck, a capacity of 400–2 000 kW would be required (and a connection of 10 kV).

Currently there are only a few demonstration projects for hydrogen use in trucks. Hydrogen can be used instead of diesel in a combustion engine (a few concepts have been already tried), or it can be converted to electricity in a fuel cell. A fuel cell of 300 kW size and an applicable battery for long-haul systems would suffice and would be about the same size as the engine in diesel counterparts (around 1.5 m^3). The durability of fuel cells is important and must reach around 15 000 hrs for long-haul trucks.

Currently, fuel cells have a durability of around 2 500 hrs.

In the REmap case, the freight sector's total energy demand would be only slightly higher in 2050 (at 40 EJ) than the 2015 level of 36 EJ in 2015, and 30 % lower than the projected demand in the Reference Case. Two-thirds of this is related to road freight, and 30 % related to transporting cargo by ship. The remainder 3 % is rail freight.

This decrease is driven by the significant electrification of trucks (42 % of all activity would be via electric vehicles, which would be three times more efficient than conventional trucks), and further electrification of rail. Biofuels uptake is significant in both road freight

Table 23: Economic indicators under REmap in 2050 compared to the Reference Case for transport – truck and shipping

	Abatement cost (USD/t CO_2)	Abatement potential (Mt CO_2/yr)	Incremental system costs (USD bln/yr)	Additional investment needs 2015–2050 (USD trillion)
Electric railways	–280	7	–1.9	0.213
Electric trucks	60	785	47.2	0.138
Conventional biofuels	35	40	1.4	0.017
Advanced biofuels	200	85	17.0	0.103
Biomethane	–5	220	–1.2	0.340
Hydrogen	75	300	22.4	0.757
Energy efficiency	5	720	3.6	0.444
Total	42	2 160	90	2.0

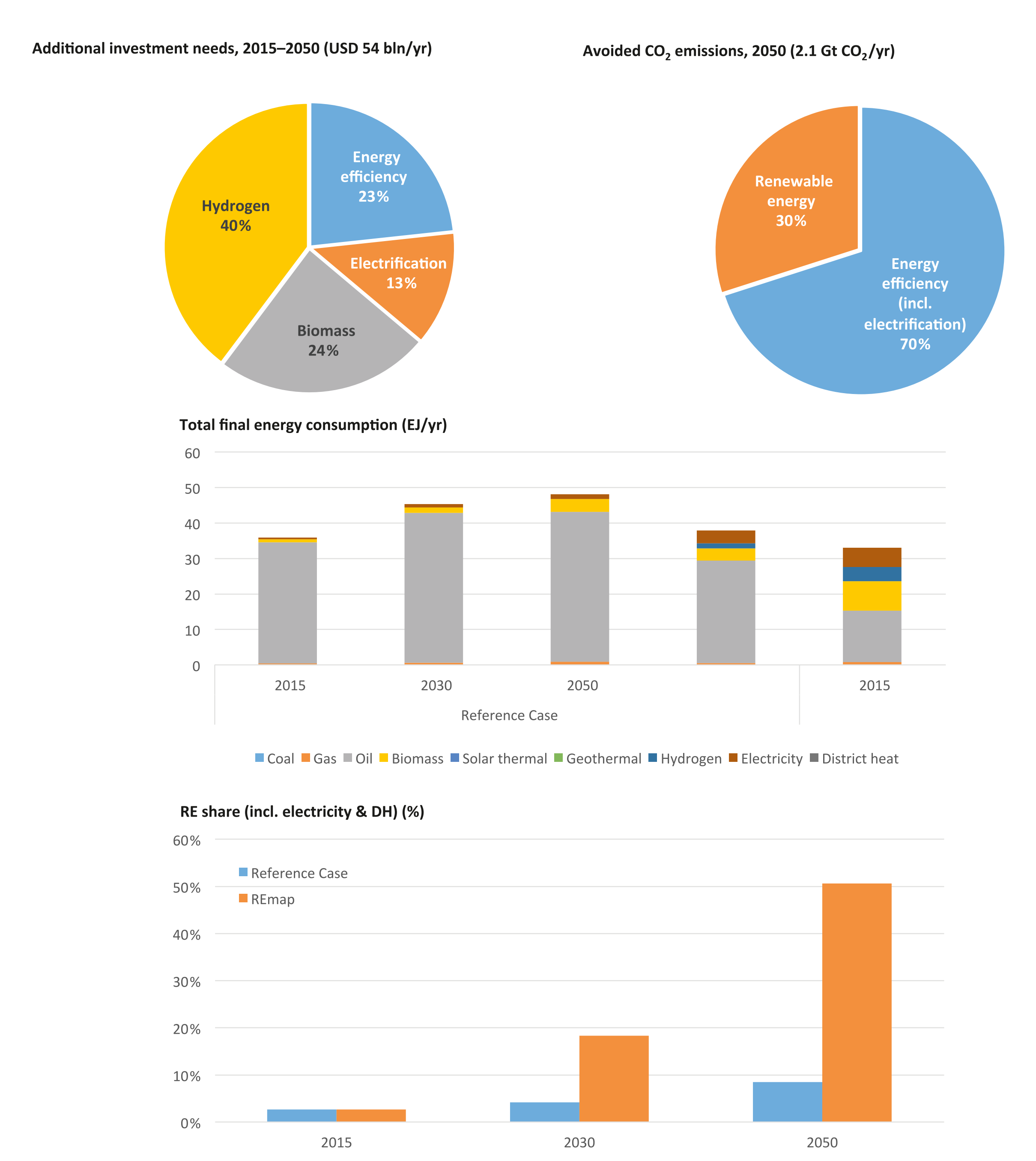
Assumption: Discount rate: 10 % and crude oil price: USD 80/bbl.

Table 24: Global REmap case – summary of activity, energy and CO_2 emission trends 2015–2050 for transport – truck and shipping

	2015	2030	2050
Road freight travel (bln tonne-km/yr)	10 370	14 590	18 900
Rail freight travel (bln tonne-km/yr)	9 680	15 000	19 500
Shipping freight travel (bln tonne-km/yr)	55 000	90 000	120 000
Road freight fuel use (MJ/tonne-km)	2.3	1.8	1.5
Rail freight electricity use (MJ/tonne-km)	0.07	0.06	0.06
Shipping energy use (MJ/tonne-km)	0.19	0.18	0.11
Conventional biofuels for trucks (bln litres/yr)	0	76	90
Advanced biofuels for trucks (bln litres/yr)		40	127
Biofuels for shipping (bln litres/yr)	0	25	145
Biomethane for trucks (bln m^3/yr) (1 bcm = 36 PJ)		45	90
Road electrification (TWh/yr)		645	1 900
Hydrogen (EJ/yr)		0.8	4.1
Total fossil fuel use (EJ/yr)	34.5	30.5	19.4
Total energy-related CO_2 emissions (Gt/yr)	2.6	2.2	1.4

Note: indirect emissions from the generation of electricity that is consumed in processes are excluded.

Figure 31: Key estimates for transport – truck and shipping



Based on IRENA estimates

and shipping, at 40 % and 25 % of each sector's total fuel mix by 2050, respectively. Hydrogen fuel cells would represent 20 % of the total energy demand of the freight sector.

These measures would cut the sector's emissions by 63 % compared to the Reference Case from 3.7 Gt to 1.4 Gt by 2050. Renewable energy accounts for 30 % of the total potential. The remaining 70 % is from energy-efficiency measures including electrification.

As Table 23 shows, the average abatement cost of these options would be USD 40 per tonne of CO_2 by 2050, and the additional investment needs over the Reference Case add up to USD 2 trillion in the 2015–2050 period.

BIBLIOGRAPHY

Industry				
Sector	**Sub-processes**	**References**		
		Production	**Specific Energy Consumption**	**Sector reviews**
Cement	Cement	(USGS 2015b; IEA 2012)	(Deger Saygin 2012)	(USGS 2016a; Amato 2013; Sumanth Reddy 2013; CNREC 2016; CSI/ECRA 2009; USGS 2015b; CemWeek 2016; Ruijven *et al.* 2016; Kuramochi and Turkenburg 2012)
	Clinker to cement ratio	(WBCS 2014)	(Oda, Akimoto, and Tomoda 2012)	
Iron & Steel	Steel	(WSA 2015a; IEA 2012; Oda, Akimoto, and Tomoda 2012)	(Oda, Akimoto, and Tomoda 2012; IEA 2007)	(Oda, Akimoto, and Tomoda 2012; IEA 2007) (CE Delft 2010; Corsten 2009; Gielen 2003; Gielen and Moriguchi 2003; Gielen and Taylor 2007; IEA 2007; IPTS/EC 2013; Kuramochi and Turkenburg 2012; Neelis and Patel 2006; Norgate *et al.* 2012; Ruijven *et al.* 2016; Deger Saygin, Patel, and Gielen 2010; WSA 2015b; Mathieson 2013; NRCAN 2013; Allanore, Yin, and Sadoway 2013; Green Car Congress 2016; O'Dette 2016; Irfan 2013; EUWID-Energy 2017; Suncoal 2017; Green-peace 2017; J. Birat 2010; J.-P. Birat and Lorrain 2006; J.-P. Birat, Lorrain, and Lassat 2008)
Pulp & Paper	Mechanic, chem-ical/Recovered paper, Fiber and Pulp/Paper (all types)	(FAO 2015; IEA 2010c, 2012)	(Deger Saygin 2012)	(IEA 2007; Deger Saygin *et al.* 2013; Hektor and Berntsson 2007; Möllersten *et al.* 2004; CEPI 2013)
Non-ferrous metals	Alumina & Aluminium	(USGS 2016b; IEA 2012, 2007)	(WAO 2015; Kermeli, Graus, and Worrell 2014)	(IRENA 2015a; Kermeli *et al.* 2015)
Chemicals & Petrochemicals	Ammonia	(USGS 2015a, 2016a)	(Deger Saygin 2012)	(Jong *et al.* 2012; Broeren, Saygin, and Patel 2013; Daioglou *et al.* 2014; D. J. Gielen and Y. Moriguchi 2002; Neelis *et al.* 2005; Deger Saygin *et al.* 2011; D. Saygin *et al.* 2014; Taibi, Gielen, and Bazilian 2012; Global CCS Institute 2016; EBTP 2012; Funk, Myers, and Vora 2013; IEA 2015b; PlasticsEurope 2016; CEFIC 2016)
	Methanol production	(IEA 2012)		
	Steam crackers	(IEA 2012)		

Transport				
Sector	Sub-processes	References		
		Activity	Specific Energy Consumption	Sector reviews
Passenger	Cars	(IEA 2010b)		(Nikkei Asian Review 2016; IRENA 2016a; Slowik 2016; Lane 2016; Difiglio and Gielen 2007; IEA 2005; Yvkoff 2016)
	Rest road	(IEA 2010b; E3MLab/ICCS 2014; IEA and UIC 2012, 2015)	(IEA 2005)	(WAVE 2017; Park 2016; Ruoff 2016; ElectRoad 2017; Mathias-son 2016; Primove-Bombardier 2017)
	Rail		(IEA and UIC 2012, 2015)	
	Aviation		(DLR 2012)	(IRENA 2017d)
	Marine			(Saltzman 2014; Vidal 2016)
Freight	Road		(DLR 2012)	(IRENA 2015d; Quak, Nest-erova, and Rooijen 2016; CALSTART 2011, 2015; Winkler 2007; McGill, Remley, and Winther 2013; IMO 2014; Rodrigue 2016)
	Rail			
	Marine			
	Aviation		(I. Hileman *et al.* 2008)	

Buildings				
Sector	Sub-processes	References		
		Activity	Specific Energy Consumption	Sector reviews
Residential	Area	(Navigant Research 2016; Ürge-Vorsatz, F. Cabeza, and Serrano 2014)	NA	NA
	Population	(World Bank 2010)		
	Household size	(Nakona 2010)		
	Space heating and cooling	NA	(Ürge-Vorsatz, F. Cabeza, and Serrano 2014; Ecofys 2015; Daioglou, van Ruijven, and van Vuuren 2012)	(Hamman 2010; Breithaupt 2016; GABC 2016; IHS Energy 2016; IRENA 2017e, 2016f, 2015f; Wachs and Singh 2016; BPIE 2011; Becchio 2013; Ürge-Vorsatz, F. Cabeza, and Serrano 2014)
	Water heating			NA
	Cooking		(IEA 2012)	(Almeida *et al.* 2011; Bailis *et al.* 2015; Daioglou, van Ruijven, and van Vuuren 2012; EU commision 2014; Burghardt 2009; Wuppertal Institute 2013; Michaelbluejay 2013; Lapillonne, Pollier, and Samci 2015; Shrimali *et al.* 2011; Bhattacharya 2012)
	Lighting and Appliances			NA

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<tr><td>Cement</td><td rowspan="2">(IEA 2009)</td></tr>
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</table>

Sector	Measure	Sub-sector	Parameters	References
Buildings	Energy Efficiency	Insulation	Additional CAPEX, Fuel cost savings, CO_2 savings, lifetime	(National Insulation Association 2016; Dr.Peter Breithaupt 2015)
		Windows		(DECC 2012; Dr.Peter Breithaupt 2015)
		Reflective roof		(US Department of Energy 2015; RoofingCalc 2016)
		Appliances – demand side		(The co-operative energy 2013)
		Appliances – improved efficiency	Additional CAPEX, energy savings	(Wada, Akimoto, and Sano 2012)
		Lighting		
		Smart home system		(DECC 2012; Dr.Peter Breithaupt 2015)
		Boilers	Additional CAPEX, lifetime, energy savings	(IRENA 2017a; Dr.Peter Breithaupt 2015)
		Heat pumps		
		Renovation cost for building types – Space heating and cooling	Additional CAPEX	(GBPN and ABUD 2015)
Power	Infrastructure	Transmission grid, storage, curtailment, utilisation	Average integration cost, discount rate, lifetime	(Scholz, Gils, and Pietzcker 2016; SMASH 2013; IRENA and IEA-ETSAP 2015)
		Distribution network		(IEA 2014a)
	Technology	Renewable generation costs and forecasts	Generation costs	(IRENA 2016c, 2015e)
		Sector review	Electricity production, proposed and operating capacity, technology data	(Enerdata 2016; Endcoal 2016a, 2016b, IRENA 2015c, 2016e; IRENA and IEA-ETSAP 2015; IRENA 2015b)
General	Technology	Global costs	Technology cost/ performance, commodity prices	(IRENA 2016d)
		REmap country specific costs		(IRENA, n.d.)
		Technology brief		(IRENA and IEA-ETSAP, n.d.)
		Bioenergy	Feedstock cost	(IRENA 2014b)

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