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SUMMARY FOR POLICY MAKERS

GREEN ENERGY CHOICES:

The Benefits, Risks and Trade-Offs of Low-Carbon Technologies for Electricity Production

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Summary for Policy Makers

GREEN ENERGY CHOICES:

THE BENEFITS, RISKS AND TRADE-OFFS OF LOW-CARBON TECHNOLOGIES FOR ELECTRICITY PRODUCTION

This summary report highlights key findings from International Resource Panel report on: *Green Energy Choices: The Benefits, Risks and Trade-Offs of Low-Carbon Technologies for Electricity Production*.

Further detail on the methodology, sources and technologies examined as well as the findings can be found in the full report, available at www.unep.org/resourcepanel.

Foreword

Renewable energy is a cornerstone of a future of human prosperity without environmental sacrifice. The international community has recognized this. Through the Secretary-General's Sustainable Energy for All Initiative (SE4All), governments and stakeholders across the globe have demonstrated a commitment to ensuring universal access to affordable, reliable and modern energy services by 2030, while increasing the share of renewable energy in the global energy mix.

With this acknowledgment, the world community has a unique opportunity to steer investments over the next two decades towards energy systems that meet the demands of an increasing population while reducing greenhouse gas (GHG) emissions; water, air and soil pollution; and habitat loss.

This report from the International Resource Panel provides a comprehensive comparison of the greenhouse gas mitigation potential of various energy generation technologies, including hydro, solar, geothermal and wind. It also examines the environmental and human health impacts of these options, and their implications for resource use. Their impacts are compared with those of fossil fuels, including coal- and gas-fired power, with and without carbon capture and storage (CCS).

The report provides strong evidence that electricity generated from renewable sources causes substantially less pollution than that generated from fossil fuels. A business-as-usual expansion of fossil fuel-based generation would lead to increased pollution, with serious impacts on human health and the environment, and a doubling of GHG emissions by 2050. Meanwhile, renewable electricity generation produces only 5-6% of the GHG emissions of coal-fired power plants and 8-10% of those of gas-fired power plants.

The right mix of low-carbon electricity generation technologies will help to stabilise and potentially reduce pollution and impacts on the environment, including climate change and acidification. It is crucial to determine the optimal mix of these technologies, as well as policy objectives that will support these efforts. It is my hope that decision-makers will use the scientific evidence in this report to select the cleanest, safest and most sustainable mix of energy technologies for the coming decades.

Achim Steiner
UN Under-Secretary-General
UNEP Executive Director

Preface

Demand for energy is expected to double over the coming decades in order to meet the needs of a growing and developing global population. Responding to this demand will require significant investment over the next 20 years to develop and install new energy systems. With this challenge comes the opportunity to design systems and select technologies that will minimize adverse impacts on the environment, climate, and human health, as well as address the additional pressure on natural resources.

With this in mind, the International Resource Panel's experts have analysed nine key electricity generation technologies, including coal- and gas-fired power plants, technologies for solar power, hydropower, wind power, and geothermal. They examined their greenhouse gas (GHG) mitigation potential, and trade-offs in terms of environmental impacts, effects on human health, and the implications for natural resource use (including concrete, metals, energy, water and land). They also assessed the consequences of implementing the International Energy Agency (IEA) BLUE Map Scenario of a global energy mix consistent with limiting the average global temperature increase to 2°C.

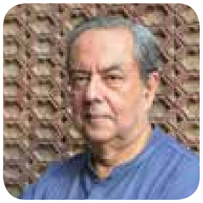
The findings are crucial in terms of helping policy-makers choose appropriate mixes of energy technologies. The modelling carried out for the report found that during the life-cycle of renewable energy technologies, GHG emissions are 5-6 percent those of coal and 8-10 percent those of natural gas fired power plants. Other damage to the environment from renewable energy technologies is 3-10 times lower than from fossil fuel based systems. Renewable energy systems also have considerable health benefits. Air pollution from renewable energy is around 10-30 percent that of state-of-the-art fossil fuel power generation. Implementation of the BLUE Map scenario would therefore see electricity generation double while GHG emissions would fall by a factor of five, and human health, ecosystem and land use would all either stabilize or decline.

However, as the findings of the report demonstrate, there are potential trade-offs to the deployment of renewable sources, including in terms of land and water use, material use, and site-specific impacts which will need to be taken into account and minimized to the extent possible in the deployment of these technologies.

Green Energy Choices will be followed by a second report, following the same approach and methodology, but examining energy efficiency technologies, including for mobility, buildings and industry.

We would like to thank International Resource Panel Members Edgar Hertwich, lead author of this report, and Sangwon Suh for their vision and leadership in coordinating this extremely important body of work.

Janez Potočnik
Co-Chair, IRP



Ashok Khosla
Co-Chair, IRP

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Introduction: Green Energy Choices as a Sustainable Development Imperative

Global demand for energy is expected to double by 2050, requiring an estimated investment of 2.5 trillion USD a year over the next twenty years in new energy installations and energy conservation initiatives[1]. Production of electricity, a major energy carrier, is currently responsible for 25 per cent of anthropogenic greenhouse gas (GHG) emissions, as well as other negative impacts on the environment and on human health. A rapid deployment of low-carbon electricity generation technologies will be needed to limit global warming to well below 2°C, the goal set by the international community at the Paris Climate Conference. Future energy scenarios suggest that the share of electricity production in the energy mix will rise, and that as nations seek to avoid and mitigate the impacts of climate change, and with an expected rise in carbon prices, final energy demand will progressively shift away from fossil fuels (gas, petrol, diesel, and coal) and towards electricity and fuels generated from sources with low carbon emissions, or renewable energy sources[2].

This context presents an opportunity for countries to carefully select the electricity production technologies in which they invest to meet the energy needs of a world population of nine billion, while at the same time reducing GHG emissions and other negative impacts. Given the scale of the investments and infrastructure development required, it will be important to strategically plan the energy mix of each country, in order to avoid technological and infrastructural lock-ins that will be difficult to change.

To choose the best technologies for a national or local energy system means that attributes other than costs and GHG emissions are also important. There is a risk that shifting the burden of curbing emissions to other parts of the economic chain may simply cause new environmental and social problems, such as heavy metal pollution, habitat destruction, or re-

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[1] IEA, World Energy Outlook 2014. 2014, Paris: OECD/IEA.

[2] Riahi, K., et al., Chapter 17 - Energy Pathways for Sustainable Development, in *Global Energy Assessment - Toward a Sustainable Future*. 2012, Cambridge University Press: Cambridge, UK and New York, NY, USA. p. 1203-1306 and Bashmakov, I.A., et al., Energy Systems, in Climate Change 2014: Mitigation of Climate Change, O. Edenhofer, et al., Editors. 2014, Intergovernmental Panel on Climate Change: Geneva.

source depletion. The ideal approach will mitigate a range of problems at the same time as maximizing the energy benefits. Before investing trillions of dollars in the large-scale development and deployment of new energy technologies, we need to understand their wider potential consequences, both positive and negative. An assessment of such impacts should form part of the "due diligence" required for such long-term investments, to avoid unintended consequences and help decision-makers select the cleanest, safest, most efficient mix – for a nation, a region or a local community.

The report of the International Resource Panel (IRP) *Green Energy Choices: The Benefits, Risks and Trade-Offs of Low-Carbon Technologies for Electricity Production* aims to support policy-makers in making choices about the technologies, infrastructures and energy sources. It does so through an analysis of the mainstream commercially available renewable and non-renewable power generation technologies[3], analysing their GHG mitigation potential, but also trade-offs in terms of:

- Environmental impacts (impacts on ecosystems, eutrophication and acidification, etc.)
- Human health impacts (particulates and toxicity)
- Resource use implications (iron, copper, aluminium, cement, energy, water and land).

The report provides a comprehensive comparison of a range of technologies, including coal and gas with and without CO_2 capture and storage (CCS), photovoltaic power, concentrated solar power, hydropower, geothermal, and wind power. It takes a life-cycle perspective, covering the production of the equipment and fuel, the operation of the power plants and their dismantling.

The work of the IRP represents the first in-depth international comparative assessment of the environmental, health and resource impacts of these different energy technologies, and is the work of an international scientific and technical experts team.

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[3] The technologies analysed were chosen because they play an important role in future energy scenarios. The choice was also strongly influenced by IEA's *Energy technology Perspectives 2010*.

Assessment Approach

This report presents an assessment of the impacts of nine main electricity production technologies on human health, ecosystem health and resource use, taking a life-cycle approach. It covers coal and gas with and without CCS, photovoltaic power, concentrated solar power, hydropower, geothermal, and wind power.

The findings are presented in the following ways:

1. A comparison and benchmarking of the environmental impacts of nine different electricity generation technologies, per unit of power production (1kWh).

2. An assessment of the global environmental, health and resource implications of implementing the International Energy Agency (IEA) BLUE Map (or 2°C) mitigation scenario[4]. The scenario envisions replacing fossil fuels with power generation from renewables on a large enough scale to keep global warming to well below 2°C, in line with the recommendations of the Intergovernmental Panel on Climate Change (IPCC) and agreement by the international community at the Paris Climate Conference. The scenario foresees a substantial expansion of wind power, photovoltaics and concentrated solar power. It also incorporates expanded gas generation capacity that is utilized for fewer hours per day to offset variations in the supply of renewable power. The use of coal is reduced substantially. It also envisions that all coal and some gas plants will be equipped with CO_2 capture and storage by 2050. The report compares the resulting global emissions rates and resource use for BLUE Map with corresponding figures for the IEA's Baseline Scenario.

The assessment focuses on impacts and resource requirements that lend themselves to quantitative comparison, although it also contains a qualitative discussion of some impacts which are considered important, but for which mature assessment approaches are not yet available, such as habitat fragmentation through hydropower dams and bird and bat collisions with wind power plants. The comparison of quantifiable impacts is based on life cycle assessment (LCA), a well-established method to address not only the impacts that occur during power production, but also impacts resulting from fuel production and the production, construction, maintenance and dismantling of the power equipment. LCA methods assess the contribution of pollutants to specific environmental mechanisms, such as climate change through radiative forcing, and to broader endpoints (human health and ecosystems)[5]. It uses an integrated model capable of reflecting regional specificities in the IEA's nine regions. The assessment combines physical and economic data in order to achieve a fuller representation of life cycle impacts.

The environmental impacts of energy technologies will change as progressively cleaner technologies enter the global energy mix, driven by factors such as mitigation needs, economies of scale and accumulated experience. The analysis therefore presents results for 2010, 2030 and 2050, taking into account the energy mixes expected in those future years when the technology is manufactured, and integrating projected technological improvements leading to higher yields and efficiency for each technology type.

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[4] IEA, *Energy Technology Perspectives 2010: Scenarios and strategies to 2050*. 2010, Paris: OECD/IEA. 650

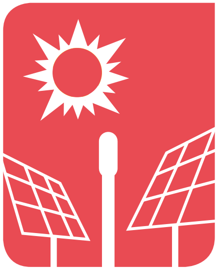
[5] Goedkoop, M., et al. *ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level*. Dutch Ministry of the Environment: The Hague, NL, 2008.

Technology Summaries

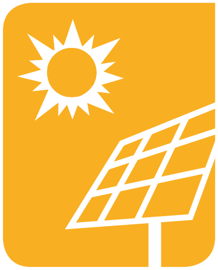
Power generation from coal and natural gas

Hydropower

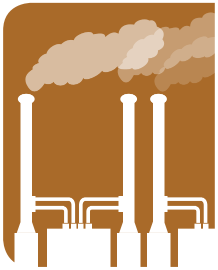
Wind power



Concentrated solar power



Photovoltaic power



Geothermal power

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POWER GENERATION FROM COAL AND NATURAL GAS

Fossil fuel combustion is currently the dominant source of the world's electricity. Given the long lifetime of mines, wells, transport facilities, and power stations and their versatile nature, fossil fuels are expected to remain an important source of electricity in the foreseeable future under most climate mitigation scenarios[6]. In many of these scenarios, CO_2 capture and storage plays an important role, allowing for a faster and less expensive transition to a low-carbon electricity system[7].

State of coal and gas technologies

While technologies for electricity production from coal and natural gas are often viewed as mature, there is in fact substantial scope for performance improvement. The maximum efficiency of power plants and combined heat and power plants has improved over the years, and but not all efficient technologies are commercially viable in all circumstances. The introduction of supercritical and ultrasupercritical coal power plants is a significant development that has raised energy efficiency from 35-37 per cent for subcritical to 43-45 per cent for ultrasupercritical plants. Integrated gasification combined cycle (IGCC) plants represent a new technological approach that achieves similar efficiencies, with the promise of further increases. Technological advances in combined heat-and-power plants and polygeneration plants include fuel-cell systems and advanced gas engines. Such systems offer greater energy efficiency but their application has so far been limited by the challenge and cost of matching the timing of supply and demand of different energy services. Smaller, more versatile units may yield fresh advances, while the use of fuel cells may increase electricity output.

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[6] Fischedick, M., et al., Mitigation Potential and Costs, in IPCC Special Report on *Renewable Energy Sources and Climate Change Mitigation*, O. Edenhofer, et al., Editors. 2011, Cambridge University Press: Cambridge (UK).

[7] Riahi, K., et al., Chapter 17 - Energy Pathways for Sustainable Development, in *Global Energy Assessment - Toward a Sustainable Future*. 2012, Cambridge University Press: Cambridge, UK and New York, NY, USA. p. 1203-1306 and Edmonds, J., et al., Can radiative forcing be limited to 2.6 Wm-2 without negative emissions from bioenergy and CO_2 capture and storage? Climatic Change, 2013. 118(1): p. 29-43.

There have been significant advances in the production of non-conventional fossil fuels with the hydraulic fracturing of shale for oil and gas production, horizontal drilling, deep-sea technology, coal seam methane extraction, and the mining of tar sands, although many of these developments are also associated with concerns about increased pollution. These technologies have made accessible oil and gas resources that were previously considered uncommercial or technically impractical, raising the amount of fossil fuels available to humans[8]. Additional resources such as deep coal, Arctic gas or methane hydrates may also become accessible in the future.

CO_2 capture and storage has seen significant development worldwide in recent years, with the first large-scale application in power generation opened in Canada in 2014. Technologies currently available at a demonstration scale include:

- chemical absorption of CO_2 from the flue gas of a power plant via amine-based solvents (post-combustion),
- physical adsorption of CO_2 from a synthesis gas (pre-combustion)
- the combustion of fossil fuels with pure oxygen, producing CO_2 and water (oxyfuel).

CCS systems require that CO_2 emitted by the burning of fossil fuels is captured in as pure a form as possible, is compressed, transported to a storage site, and injected into a suitable deep geological formation, such as a saline aquifer or a former oil and gas field. Technology and experience with such injection and subsequent storage exists from the oil and gas industry, and the monitoring and safety assessment of large-scale CO_2 storage is now being researched globally. The technology's greatest challenge lies in overcoming the combination of high investment costs and high operational costs.

Life-cycle assessment results

Conventional sub-critical coal power plants generally have higher impacts than supercritical and integrated gasification plants and much higher emissions than natural gas combined cycle plants.

The GHG emissions of modern power plants with CCS are between 22-26 per cent of those of existing coal power plants. However, in terms of particulate matter and photochemical smog emissions, which constitute the most important threats to human health, the analysis for modern plants with CCS show lower emissions than current typical coal power plants, but higher emissions than modern plants without CCS. The increased human health impacts are due to the CO_2 capture process itself, which is energy intensive and therefore leads to increased air pollution. Modern plants with CCS also demonstrate higher freshwater ecotoxicity and eutrophication compared to current plants without CCS. Therefore, while CCS technology reduces CO_2 emissions from power plants, other environmental impacts, such as particulate matter, ecotoxicity and eutrophication increase by 5-60 per cent.

While combined cycle natural gas plants have much lower GHG emissions than coal power plants, they have higher nitrogen oxide (NOx) emissions, which poses a significant risk of acidifying water bodies and soils. NOx emissions also contribute to marine eutrophication. The most important contributors to environmental impacts are the operations of the

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[8] Rogner, H.-H., et al., Chapter 7 - Energy Resources and Potentials, in *Global Energy Assessment - Toward a Sustainable Future*. 2012: Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria. p. 423-512.

power plant itself (for climate change, human toxicity, particulate matter formation and water use) and the extraction and refining of the gas (for land occupation, eutrophication, and freshwater ecotoxicity).

There is therefore a clear trade-off between climate change and other environmental impacts of coal and gas power. Technologies which reduce carbon emissions from coal and gas power plants appear to increase other environmental impacts.

Site-specific impacts from fossil fuel production

The extraction of fossil fuels is a major source of air, soil and water pollution, with impacts on ecosystems and human health. There has been recent debate over the wide range of estimates for fugitive methane emissions during shale gas production and a lack of recent, empirical data. Similarly, coal mine methane emissions vary widely across mines. Some fossil fuel production technologies, such as tar sands, also have high land and water requirements and impacts.

CO_2 transport and storage

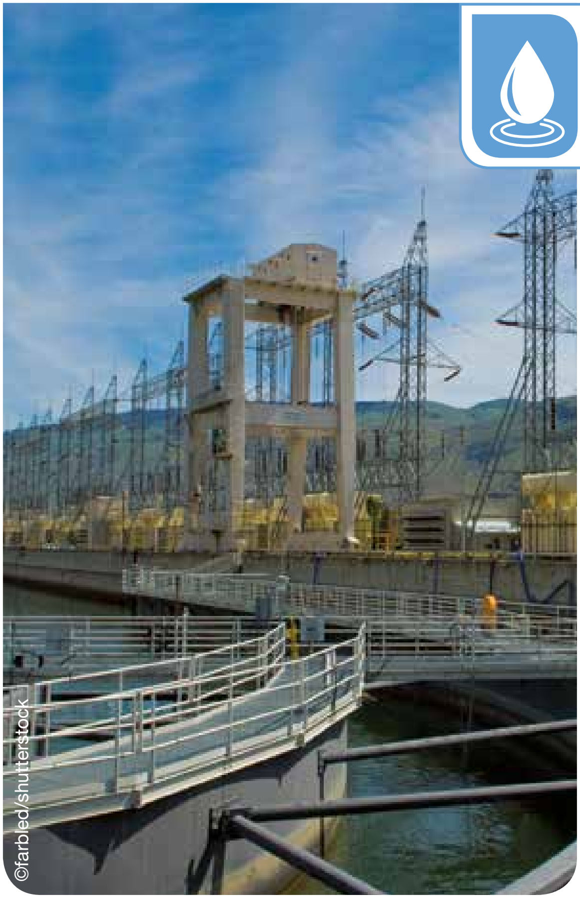
Concerns about CO_2 transport and storage under high pressure include leakage, which undermines its mitigation effectiveness and creates direct health hazards from locally high concentrations of CO_2, and the potential mobilization of toxic heavy metals in the ground through the acidification of groundwater. CO_2 reacts at the storage site with geofluids and rocks, reducing the risk of leakage. The rate of these reactions depends on the geological conditions at the storage site. The highest risk of leakage is during CO_2 injection. Options have been proposed for monitoring, verifying and accounting for potential leaks. Similarly, proposals for technologies to seal leaks exist, some of which are based on existing solutions for leaky oil and gas wells.

Summary of Impacts: COAL AND GAS WITH CCS

Climate		Human health		Ecosystem health		Resources	
Low GHG (++)	(++)	Solvent-related emissions	(==)	High eutrophication	(++)	Increased fossil fuel consumption	(++)
Substantial fugitive methane emissions	(==)	High particulate matter	(==)	High ecotoxicity	(+=)	Limited CO_2 storage volume	(++)
Concerns about CO_2 leakage	(-=)	High human toxicity	(++)				

KEY:

First symbol	(**+**) high agreement among studies	(**=**) moderate agreement	(**-**) low agreement
Second symbol	(**+**) robust evidence (many studies)	(**=**) medium evidence	(**-**) limited evidence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HYDROPOWER

Hydropower is currently the world's most important source of renewable electricity, providing 6.1 per cent of total energy supply and with the installed base growing at 3 per cent annually. The installed capacity was 874 GW in 2008. There is potential for three- to five-fold increase in hydropower production. Hydropower dams can also serve other purposes, such as water storage, irrigation and transport.

Ecological impacts

The most significant ecological impacts of hydropower are linked to habitat change due to changes in the flow regime and flooding of the reservoir area, habitat fragmentation and the obstruction of migration routes. Habitat and flow changes affect fish and other aquatic species and may threaten those adapted to river environments. Box 1 summarizes the main ecological effects, some of which can be mitigated through measures such as environmental flow control, sediment management or technical adaptations (e.g., fish ladders). Recognizing that these impacts depend on site and project characteristics; assessments need to be made on a case-by-case basis.

Box 1: POTENTIAL ECOLOGICAL EFFECTS OF HYDROPOWER PLANTS

- Obstruction of fish and other migratory aquatic species.
- Habitat change and fragmentation in riverine and shallow water ecosystems.
- Water quality reduction in the reservoir due to the growth of phytoplankton and algae and development of thermal stratification.
- Sedimentation reduces global freshwater storage capacity by 0.5-1 per cent per year and so lessens flood protection.
- Changes in flooding, sediment flow and associated nutrient deposition, affecting the extent and fertility of floodplains and deltas.
- Turbidity, sedimentation, stagnation and eutrophication of downstream waters
- Changes in the timing and volume of water flow, affecting species whose life cycle is adapted to seasonal water flow patterns.
- Reduced temperature and increased gas content (supersaturation) of water released from dams, which affects fish.

Climate impacts from hydropower

Hydropower reservoirs release significant volumes of greenhouse gases in the form of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) as a result of bacteria digesting organic matter in the reservoir. The main concern from a climate perspective is methane, which is around 30 times more potent as a climate change driver than CO_2. Although CO_2 emissions are part of the natural biogenic carbon cycle, the impact that dams have on world CO_2 emissions is still being researched and is not yet clearly quantified. The emissions from a reservoir depend on the volume of biomass and nutrients entering it, its area, age and climate; and emissions per unit of energy generated depend strongly on the reservoir area. Studies to date show emissions per unit energy can vary by several orders of magnitude between dams. Based on current data our estimate for the global methane emissions from hydropower plants is around 10 (-6/+10) million tons per year, which corresponds to 70 g CO_2e/kWh on average.

Life cycle assessment results

The material and energy required to build a hydropower plant depends entirely on its site. Reservoir volume and hydraulic head (liquid pressure) can vary enormously among plants and the environmental performance of hydropower plants can differ substantially. The plants analysed as a basis for the IRP's study have lower pollution impacts than fossil fuel-based power plants, especially for toxicity, eutrophication, and acidification. However, land occupation and metal depletion are of the same order of magnitude as those of fossil power plants.

Summary of Impacts: HYDROPOWER

Climate		Human health		Ecosystem health		Resources	
Low fossil GHG	(++)	Low air pollution impacts	(=-)	Riparian habitat change (reservoir and downstream)	(++)	High water use due to evaporation	(+-)
High biogenic GHG from some dams	(==)					High land use for reservoirs	(+=)

KEY:

First symbol	(**+**) high agreement among studies	(**=**) moderate agreement	(**-**) low agreement
Second symbol	(**+**) robust evidence (many studies)	(**=**) medium evidence	(**-**) limited evidence

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WIND POWER

Wind energy is experiencing steady global growth. Over the past ten years, global installed capacity grew at an average annual rate of around 22 per cent, reaching 318 GW by the end of 2013. Most current installed capacity is onshore (98 per cent), but the offshore segment is growing. The increasing size of power plants and technical improvements are resulting in more energy harvested at lower costs. Novel technologies are also increasing generation reliability. Wind power plays an important role in practically all GHG mitigation scenarios.

Land use

Wind power plants tend to affect a much larger area than other forms of power generation because of the dispersed arrangement of the turbines in a windfarm. Much of this space, not directly taken up by the turbines, dedicated roads and other infrastructure, can be conserved as natural habitat, used for agriculture or other purposes. However a much larger area may be regarded as impacted, if indirect effects on wildlife or landscape visual quality are considered.

Wildlife mortality

The numbers of bird and bat fatalities recorded at wind farms vary widely and depend on the species, region and site characteristics. The overall ecological significance of such bird and bat mortality remains unclear and remains a topic of research and debate. Spatial planning, plant operation and other measures can potentially alleviate some of this mortality.

Rare earth elements use

Certain direct-drive wind turbines use permanent magnets containing the rare earth elements neodymium and dysprosium, although the most common wind turbine designs do not rely on such elements. In recent years, the constrained availability of rare earth elements and environmental damage caused by rare earth mining and processing have emerged as subjects of concern. Wind power faces a geopolitical risk from environmental and export restrictions by countries holding the largest strategic reserves of these materials, which is limiting access to them and could become an economic constraint[9].

Life cycle assessment results

Wind power scores from one to two orders of magnitude better than power generation from coal and natural gas (with or without CCS) for all the assessed impact categories (climate change, toxicity, eutrophication, particulate matter, smog creation, acidification, and land use) except for metal depletion. These results consider land use as the area occupied by wind farm infrastructure only, and not the spaces in-between the turbines. The total wind farm area would be two orders of magnitude higher.

Offshore wind systems consume more materials and energy than onshore, but benefit from more harvested energy and a longer lifetime. Onshore and offshore wind facilities therefore have similar lifecycle impacts, although the offshore system demonstrated higher impacts in terms of acidification, photochemical oxidants and particulate matter. The life cycle phases with the highest impacts differ between onshore and offshore systems. Production of wind turbine components contributes 70-90 per cent to all impact indicators for the onshore system but only 20-50 per cent for the offshore system. The installation, operations and decommissioning activities contribute significantly to the impact of offshore wind power. The contribution of the electrical connections is also larger than for the onshore system.

Summary of Impacts: WINDPOWER

Climate		Human health		Ecosystem health		Resources	
Low GHG	(++)	Reduced particulate exposure	(++)	Bird and bat collisions	(+=)	High metal consumption	(+=)
		Potentially reduced human toxicity	(--)	Low ecotoxicity	(=-)	Low water use	(==)
				Low eutrophication	(=-)	Low direct land use	(==)

KEY:

First symbol	(**+**) high agreement among studies	(**=**) moderate agreement	(**-**) low agreement
Second symbol	(**+**) robust evidence (many studies)	(**=**) medium evidence	(**-**) limited evidence

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[9] EC, *Critical raw materials for the EU: Report of the Ad-hoc Working Group on defining critical raw materials*. 2010, European Commission, DG Enterprise and Industry: Brussels.

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CONCENTRATED SOLAR POWER

Concentrated solar power (CSP) systems use sunlight falling on a surface kept perpendicular to the sun's rays to produce high-temperature steam for electricity generation. Areas particularly suitable for CSP are those with strong sunshine and clear skies. The global installed CSP capacity was 2.5 GW at the end of 2012. Two types of CSP plants were selected for life cycle assessment by the IRP - parabolic trough (wet-cooled), which is the most widely-applied technology to date, and power tower (dry-cooled), also known as central receiver. Other major CSP technology alternatives are linear Fresnel and dish/engine systems. Integration with low-cost thermal storage adds considerable value to CSP energy generation.

Water use

Unlike other renewable power plants like solar PV or wind, wet-cooled CSP plants require a considerable amount of water for cooling. The water use of wet-cooled CSP plants is similar to that of thermal power plants using fossil fuel. Water is also needed for cleaning the mirrors. As good CSP sites also typically occur in dry climates, water use can be a critical constraint on large-scale deployment of wet-cooled CSP. Air-cooling is technologically feasible and can reduce operational water use by about 90 per cent, but this also reduces efficiency and increases electricity production costs.

Life cycle assessment results

Generally, CSP has lower negative impacts than the global electricity mix. The main exception is its high metal depletion burden, which is greater than the mix and comparable to photovoltaic and wind power. The other exception is land use, where CSP is generally comparable with coal power, photovoltaic and wind power. The area occupied by CSP plants can seldom be combined with larger wildlife or other human uses, but CSP plants may provide valuable habitat for smaller animals and various plants and may be used for grazing.

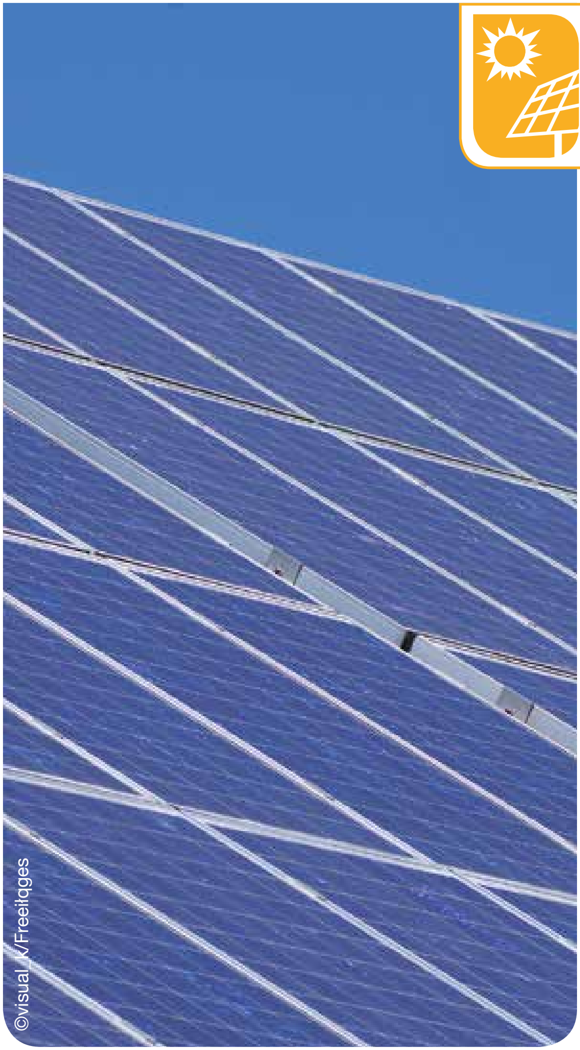
The collector system, which includes the mirrored surfaces used to concentrate direct solar radiation, causes 40-50 per cent of total impact for the tower and 30-40 per cent for the trough for most impact categories. The results depend on specific plant design, which may vary considerably depending on site features and project design.

Summary of Impacts: CONCENTRATED SOLAR POWER

Climate		Human health		Ecosystem health		Resources	
Low GHG	(==)	Low particulate matter	(=-)	Concern about heat transfer fluid	(+=)	High water use	(++)
		Low human toxicity	(=-)	Low eutrophication	(+-)	High land use	(++)
				Low ecotoxicity	(+-)		

KEY:

First symbol	(**+**) high agreement among studies	(**=**) moderate agreement	(**-**) low agreement
Second symbol	(**+**) robust evidence (many studies)	(**=**) medium evidence	(**-**) limited evidence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PHOTOVOLTAIC POWER

Photovoltaic power (PV) is growing rapidly, with total global installed capacity at 137 GW, a five-fold increase in just four years. This rapid and continued growth has been driven by the decreasing cost of PV collectors and systems. Solar insolation is abundant on the earth's surface, and even countries with predominantly cloudy skies have sufficient areas of available land and roof space for generating the large quantities of PV electricity prescribed by climate change mitigation scenarios like the IEA BLUE Map.

Photovoltaic technologies

There are a number of viable, substitutable technologies that can provide photovoltaic power. The IRP examined a cross section of mature PV technologies: polycrystalline silicon (Poly-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS). Crystalline silicon technologies are the most mature, and account for most of the PV market. CdTe and CIGS are the most mature thin film (TF) technologies and have gained market share. Thin film modules are thought to have a substantial potential for technological improvement, increasing in energy conversion efficiency and decreasing in their materials requirements over the coming decades. In addition to the technologies considered for this assessment, several emerging PV technologies (organic polymers, quantum dot, and dye-sensitized PV) may play a significant role in the PV market by 2050.

Life cycle assessment results

PV technologies show clear environmental benefits in terms of climate change, particulates, ecotoxicity, human health and eutrophication relative to fossil fuel technologies. However, PV electricity requires a greater amount of metals, especially copper, and, for roof-mounted PV, aluminium. The environmental and resource impacts of ground-mounted and roof-mounted systems have similar magnitude, despite differing technological composition. By 2030 and 2050, Poly-Si, CdTe and CIGS technologies will likely show major reductions in impacts and metal consumption due to expected increases in material efficiency of their modules and increased power generation efficiency.

Generally, thin film technologies show lower environmental impacts than crystalline silicon. Energy use during the manufacturing process contributes the most to climate change, particulates and toxicity. Crystalline silicon requires a greater quantity of electricity and has higher direct emissions during the production of metallurgical grade silicon, polycrystalline silicon wafers and modules.

The largest contributors to metal use in PV systems are the inverters, transformers, wiring, mounting and construction. Although metal use for these applications is significant, these system components are easily recycled or reused. Silicon is the second-most abundant element in the earth's crust but PV uses substantial amounts of silver as a conductor. Thin film technologies rely on semiconductor layers composed of by-product metals, namely cadmium, tellurium, gallium, indium and selenium[10]. As the thin film technologies using these elements capture larger market shares, they may encounter shortages if the recovery of these metals from primary copper and zinc production is not increased[11]. Metal supply shortage is a particular concern for tellurium in CdTe technology. Due to the toxicity of the involved metals, proper recovery and recycling is important.

Summary of Impacts: PHOTOVOLTAIC POWER

Climate		Human health		Ecosystem health		Resources	
Low GHG	(==)	Low particulate matter	(+=)	Low eutrophication	(+-)	High metal use	(+=)
		Low human toxicity	(=-)	Low ecotoxicity	(+-)	High direct land use for ground-based systems	(++)

KEY:

First symbol	(**+**) high agreement among studies	(**=**) moderate agreement	(**-**) low agreement
Second symbol	(**+**) robust evidence (many studies)	(**=**) medium evidence	(**-**) limited evidence

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[10] Byproduct metals are not produced by themselves but occur in the ores of larger-volume metals such as iron, aluminium, copper and tin. The rate of production is hence tied to those of the main product of the ore.

[11] Woodhouse, M., et al., *Perspectives on the Pathways for Cadmium Telluride Module Manufacturers to Address Expected Increases in Tellurium Price* (In Preparation). 2011, National Renewable Energy Laboratory (NREL): Golden, CO. and Woodhouse, M., et al., Supply-Chain Dynamics of Tellurium, Indium, and Gallium Within the Context of PV Module Manufacturing Costs. IEEE Journal of Photovoltaics, 2013. PP(99): p. 1-5.


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GEOTHERMAL POWER

Geothermal energy is thermal energy generated by and stored in the Earth. The Earth transfers about 40,000 GW of this heat to the atmosphere. Ninety-nine per cent of the earth's volume has temperatures up to 1000°C, while only 0.1 per cent of it is less than 100°C. This resource, however, is widely distributed and the power density is low (0.1W/m^2 compared to 300-500 W/m^2 for solar radiation). Heat of useful temperature is not always easily accessible from the surface, except in a few geologically active regions. Geothermal resources consist of thermal energy stored within the earth in rock, steam or liquid water. This energy source can be used both indirectly for electricity generation and directly for heating buildings, baths, greenhouses, food processing etc.

Geothermal power plants are typically 20-60 MW in size and require several wells. Plant designs vary and are determined by local resource characteristics such as whether a well is dry or has geofluids present, the temperature of those fluids, gas content, etc. Plant efficiency typically varies between 10-23 per cent and depends on the temperature of the reservoir as well as the cooling system.

Technology-specific impacts

Just as the geological circumstances vary from site to site, so do the environmental impacts of geothermal energy. The main issues to consider are summarised in Box 2.

Box 2: OVERVIEW OF THE ENVIRONMENTAL IMPACTS OF GEOTHERMAL ENERGY

LAND USE	Land use varies between 200-30,000 m^2/MW, or 0.04-6 m^2a/MWh.
GEOLOGICAL HAZARDS	Geothermal energy production is associated with extensive extraction or circulation of geofluids and/or steam, large-scale and local manipulation of the shallow and deep ground. Landslides, subsistence, fractures, explosions and changes in natural seismicity have been connected to geothermal facilities.
NOISE	High noise levels are associated with drilling and well testing.
THERMAL EFFECTS	The energy lost in the form of waste heat is around 4-10 times that in the electricity generated, and is hence higher than for fossil fuel power plants of similar capacity.
ATMOSPHERIC EMISSIONS	Geofluids contain many contaminants. Pollutants such as hydrogen sulphide (H_2S), CO_2, and CH_4 are often discharged to the atmosphere. These non-condensable gases (NCG) are released from flash-steam and dry-steam power plants, because in contrast to steam, the gases do not condense at the turbine outlet. Emissions may also include trace amounts of mercury (Hg), ammonia (NH_3), radium (Ra) and boron (B).
SOLID WASTE AND WATER EMISSIONS	Liquid-dominated high temperature geothermal fields can result in significant waste of geothermal fluids. Critical contaminants of steam emissions, such as H_2S, B, NH_3, Hg often occur in the fluids, as well as metals such as arsenic (As), lead (Pb), cadmium (Cd), iron (Fe), zinc (Zn), antimony (Sb), lithium (Li), barium (Ba) and aluminium (Al).
WATER USE	Water is used extensively in geothermal generation, especially for drilling, cooling, and to supplement steam production. The extent of cooling water use depends on the technology; air-cooled systems having a much lower water use, but also a lower efficiency and higher energy cost.

Life cycle assessment results

No generic life cycle inventory was available for the IRP assessment, so our assessment reflects a specific facility in New Zealand. Available life cycle assessments report fuel-related GHG emissions in the range of 6-50 gCO_2e/kWh, with fugitive emissions in the region of 20-770 gCO_2e/kWh. In some situations, fugitive emissions would have been released regardless of whether a geothermal plant was built and so cannot be clearly attributed to the power plant. Land use by geothermal power is modest compared to other technologies. Other emissions and resource use were often not reported in indicators comparable to the ones used in the IRP's work. Well managed projects appear to offer lower environmental impacts than fossil fuel-based power generation, but depend critically on local geological conditions. Each projects need to be evaluated individually taking site-specific factors into account.

Summary of Impacts: GEOTHERMAL POWER

Climate		Human health		Ecosystem health		Resources	
Low fossil GHG Geogenic GHG for some types	(+-) (=+)	Air and water pollution from geofluid flow in some sites	(=-)	Aquatic habitat change/pollution	(+=)	High water use for cooling	(+=)

KEY:

First symbol	(**+**) high agreement among studies	(**=**) moderate agreement	(**-**) low agreement
Second symbol	(**+**) robust evidence (many studies)	(**=**) medium evidence	(**-**) limited evidence

Comparative results

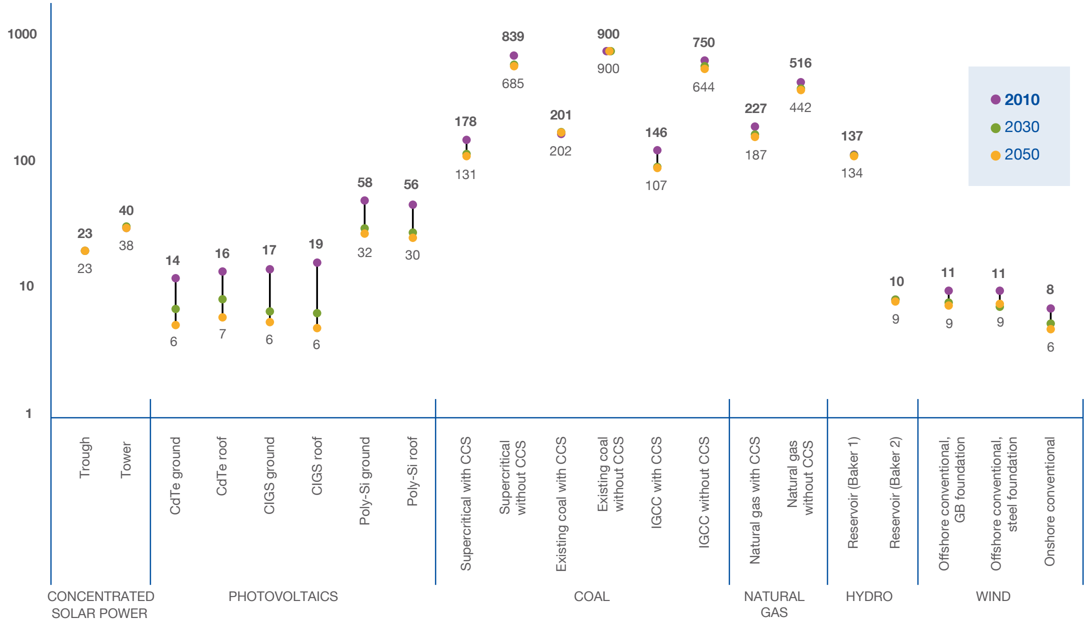
GREENHOUSE GAS EMISSIONS

Wind, photovoltaic, concentrated solar-thermal, hydro and geothermal power can achieve life-cycle carbon emissions of less than 50 grams of CO_2 per kilowatt hour (g/kWh), as shown in Figure 1. For comparison, coal power plants generate 800-1000 g/kWh and natural gas combined cycle (NGCC) plants 600 g/kWh. With CO_2 capture and storage (CCS), emissions from coal and gas power drop to 200 grams. This amounts to a reduction by up to 70 per cent in GHG emissions. Combustion at the power plant itself is still the main source of GHG emissions even with CCS, given a capture efficiency of the gas stream of 90 per cent, and additional energy is required to run the capture process and to transport and inject the CO_2.

Future GHG emissions are likely to decline as a result of a combination of factors. On the one hand, technologies may improve. In particular, further efficiency gains, improved siting and operational reliability result in more kWh generated from similar equipment. On the other hand, the penetration of a cleaner electricity mix and other advances such as cleaner material production would reduce the emissions associated with producing the power generation equipment. The numbers for 2030 and 2050 displayed in Figure 1 reflect conditions of the IEA BLUE Map scenario.

Figure 1: Life-cycle GHG emissions of different energy technologies, in gCO2e/kWh, reflecting application of the technology in Europe[12].

The numbers for future years reflect a reduction of emissions expected due to technical progress and the reduced emissions in the production of equipment following the implementation of a mitigation scenario.



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[12] Data for other regions is available in the full report. Abbreviations: CdTe – Cadmiumtelluride, CIGS – Copper Indium Gallium Selenide, Poly-Si – Polycrystalline Silicon, CCS – CO2 Capture and Storage, IGCC – Integrated Gasification Combined Cycle, GB – Gravity-Based Foundation.

HUMAN HEALTH IMPACTS

The burning of fossil fuels and biofuels is the most important cause of pollution-related human health issues. The World Health Organization's studies of the global burden of disease state that particulate matter from combustion is the most significant outdoor air pollution impact on human health, resulting in about 3.2 million premature deaths in 2010, while tropospheric ozone formed from air pollution was thought to cause 150,000 fatalities. A further 3.5 million deaths from indoor air pollution are due to respiratory infections and heart disease linked to particulate matter formed by the incomplete combustion of biomass, coal and kerosene in primitive cooking and heating stoves in developing countries[13]. Taken together, the annual death toll from air pollution is comparable with the annual death toll of the Second World War. Occupational health impacts, including accidents, also play a role in human health impacts from energy systems, while the impacts from toxic pollution to water and soil is more uncertain.

The IRP's assessment found that the exposure of humans to particulate matter per unit of electricity generated from hydropower, photovoltaics, concentrated solar power and wind power is an order of magnitude less than for modern coal and gas power plants, with or without CCS, and two orders of magnitude less than for traditional coal power plants. Particulate emissions from power plants with CCS are similar to those of similar plants without CCS, with differences ranging from a reduction of 10 per cent to an increase of 20 per cent[14]. The increase is due to the increased fuel requirements to run the CCS as well as equipment manufacturing and associated fuel chain emissions[15].

Health impacts from the toxic emissions of power generation are assessed to be larger than impacts from particulate matter. This is true especially for coal power, since the toxic effects of metal leaching from mines continues for thousands of years. However, such long-term releases are not yet considered by the WHO burden of disease studies. Coal power is about four times more toxic to humans than gas power. Among the renewable energy technologies, hydropower and onshore wind have the lowest toxicity scores.

The amine-based solvents used in post-combustion CO_2 capture, degradation products from the capture process and compounds released during capture are all potentially toxic and therefore affect the overall toxicity rating of coal with CCS. A major challenge in assessing the risks is that emissions and the composition of waste from CO_2 capture processes have not yet been made public. As a result, the understanding of the composition, toxicity and fate of CCS process emissions and products released during the waste treatment is incomplete[16]. Under some circumstances, safety limits for toxic compounds in drinking water may be exceeded[17]. According to current assessments, the health risks posed by the reported releases of

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[13] Lim, S.S., et al., *A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010*. The Lancet, 2012. 380(9859): p. 2224-2260 and Smith, K.R., et al., Chapter 4 - Energy and Health, in Global Energy Assessment - Toward a Sustainable Future. 2012: Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria. p. 255-324.

[14] Singh, B., A.H. Strømman, and E.G. Hertwich, *Comparative life cycle environmental assessment of CCS technologies*. International Journal of Greenhouse Gas Control, 2011. 5(4): p. 911-921 and Koornneef, J., et al., The environmental impact and risk assessment of CO_2 capture, transport and storage - An evaluation of the knowledge base. Progress in Energy and Combustion Science, 2012. 38(1): p. 62-86.

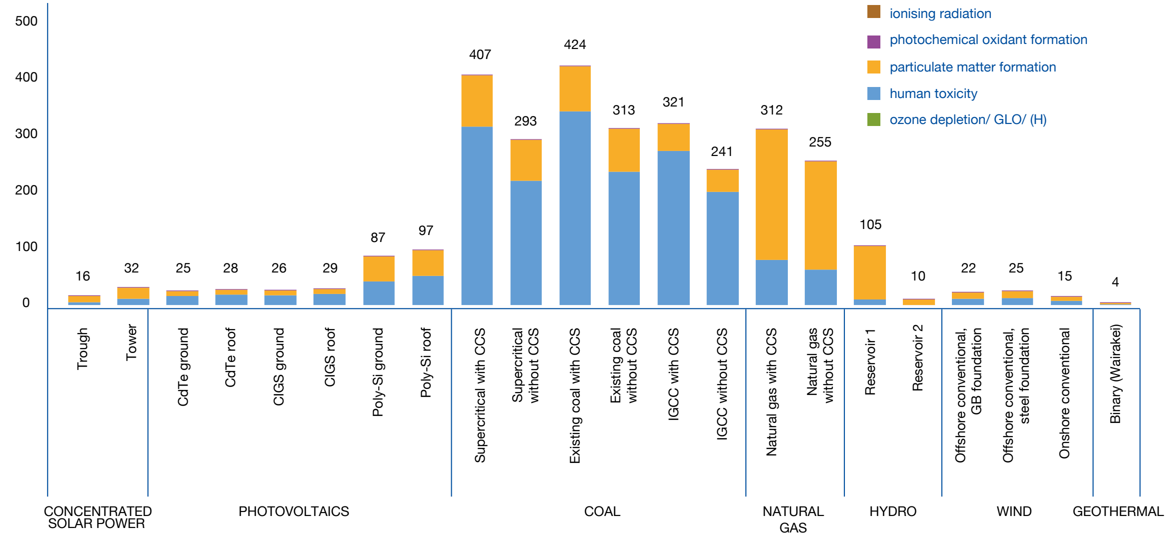
[15] Ibid

[16] Da Silva, E.F. and A.M. Booth, *Emissions from postcombustion CO2 capture plants*. Environmental Science and Technology, 2013. 47(2): p. 659-660.

[17] Op cit at 13 and and Veltman, K., B. Singh, and E.G. Hertwich, *Human and environmental impact assessment of postcombustion CO2 capture focusing on emissions from amine-based scrubbing solvents to air*. Environmental Science and Technology, 2010. 44(4): p. 1496-1502.

nitrosamines, nitroamines and formaldehyde are within the range of health risks of toxic emissions from fossil power plants without CO_2 capture[18]. In life cycle assessments, emissions from fuel production and the manufacturing and installation of the necessary equipment are of equal or larger importance than direct emissions during the capture process[19]. An increase of 40-80 per cent in human toxicity impacts of fossil power plants with different CCS approaches has been reported, relative to their non-CCS counterparts. However, there is still a degree of technological uncertainty about the exact CCS solutions to be implemented and an insufficient understanding of emissions, reactions, and toxicity of the chemicals involved.

Figure 2: Human health impact in disability adjusted life years (DALY) per 1TWh of electricity generated, for Europe 2010[20].



In this report, we do not include the potential human health impact from climate change in general, which other research suggests will be higher than the human health impact from particulate matter or toxic emissions[21]. The other impact pathways on human health, such as photochemical oxidant (ozone) formation, ionizing radiation, and ozone depletion, had negligible impacts.

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[18] Veltman et al.(op cit at 17)

[19] Op cit at 14

[20] Data for other regions is available in the full report. Abbreviations: CdTe – Cadmiumtelluride, CIGS – Copper Indium Gallium Selenide, Poly-Si – Polycrystalline Silicon, CCS – CO2 Capture and Storage, IGCC – Integrated Gasification Combined Cycle, GB – Gravity-Based Foundation.

[21] Op cit at 5

IMPACTS ON ECOSYSTEMS


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Fossil fuel-based power plants impact on the natural world in a number of ways. They substantially increase atmospheric nitrogen concentrations and mobilize phosphorus contained in coal, thereby contributing to the eutrophication of terrestrial, freshwater and marine ecosystems. They further cause impacts through the emission of toxic pollutants such as mercury, and acidifying and organic chemicals that cause regional and local impacts, or impacts on particular species. Climate change and ocean acidification, both linked to carbon emissions from burning of fossil fuels, are likely to substantially impact ecosystems by destroying the habitat of many species faster than these species can adapt or move[22].

The mining and production of metals and cement cause some of the same pollutants as the mining and combustion of coal. Material requirements are therefore an important consideration in the assessment of renewable energy and CO_2 capture technologies. Pollution from mining, material processing and manufacture of equipment contributes to eutrophication, acidification and toxic impacts. A comparison of life cycle impacts indicates that CCS leads to a modest increase in pollution-related ecosystem damage as compared to fossil fuel plants without CCS, due to the need to produce and install additional equipment and infrastructure. Three of the CCS systems covered in this report use amine-based solvents that increase ammonia emissions and thus contribute to eutrophication and acidification. Increased fuel use for the capture process causes further increases in eutrophication. Specific emissions from the CO_2 capture plant do not appear to be grounds for special concern, but it is important to pay attention to waste treatment. However, the availability of emissions data related to capture plants is sparse.

Renewable energy technologies have significantly lower impacts in terms of pollution, and the emissions from material production for and the manufacture of renewable technologies are much lower than the combined emissions from natural gas-powered plants, or for the mining, transport, and combustion of coal, as well as the waste treatment of ash. The production of photovoltaic cells causes terrestrial and marine ecotoxicity. The pollution impacts from hydropower, wind power and CSP are small by comparison.

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[22] Emberson, L., et al., Chapter 3 - Energy and Environment, in *Global Energy Assessment - Toward a Sustainable Future*. 2012: Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria. p. 191-254.

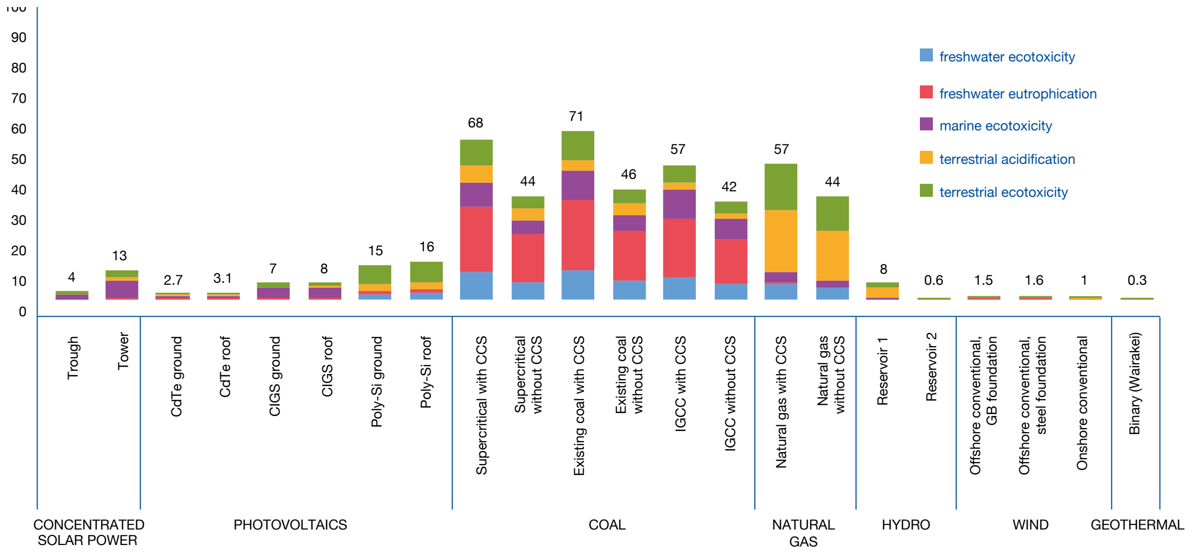

Figure 3: Ecosystem impacts in species-year affected per 1000 TWh of electricity following different damage pathways, reflecting Europe 2010 [23].

Concerns about the biodiversity impacts of low-carbon energy systems mostly relate to habitat change caused by land use, water use, and the physical modification of the environment through structures such as dams, wind farms, solar installations and power lines. Habitat change is the main driver of local and global species extinction today. Agriculture and human settlements are today the most important causes of habitat change. There are, however, significant ecological concerns over habitat change resulting from the large-scale deployment of low-carbon technologies. The complexity of comparing the impacts on a variety of species and ecosystems on a common scale, and the fact that habitat change in particular is an issue that is very specific to the site and project design parameters makes a quantitative assessment difficult. Land use requirements is therefore used as an indicator for potential habitat change. The larger the land use, the greater the potential level of habitat change. The actual habitat change incurred, however, depends also on the specific project and site. For example, photovoltaic power may be produced in fertile valleys and pristine nature areas, or on rooftops and along highways. The IRP's analysis shows the intensive land use requirements for hydropower, coal-fired power, CSP and PV. The lowest land use requirements are for power from natural gas combined cycle facilities, wind power and roof-mounted PV, where the roof area is not considered since the primary land use is attributed to the building itself. For direct land use associated with wind power, we consider only the area occupied by the turbine itself, its access

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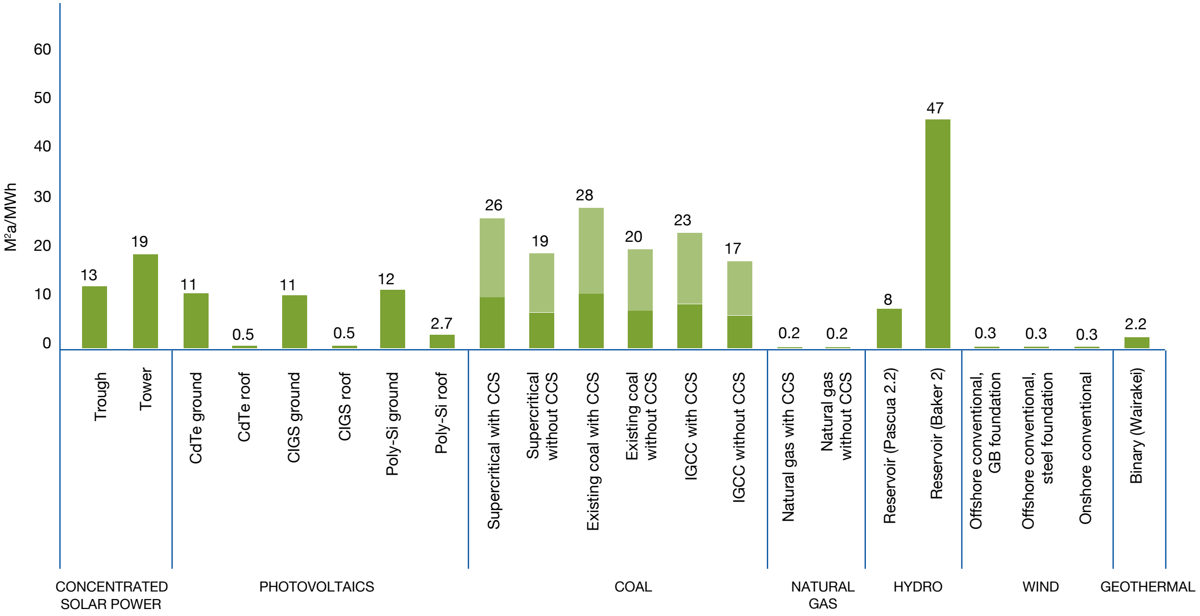
[23] Data for other regions is available in the full report. Abbreviations: CdTe – Cadmiumtelluride, CIGS – Copper Indium Gallium Selenide, Poly-Si – Polycrystalline Silicon, CCS – CO2 Capture and Storage, IGCC – Integrated Gasification Combined Cycle, GB – Gravity-Based Foundation.

roads and other installations, but not the land in between, because this land can be used as pasture, agricultural land or wilderness, with some restrictions. For hydropower, the global average land use attributed to the reservoir is 100 m^2a/MWh[24] and is hence larger than the specific hydropower installations analysed in this assessment. Of course, not all land use is equivalent. The land use associated with open-pit coal mines or sealed surfaces of PV solar panels may have a greater ecological impact than the open water areas of hydroelectric reservoirs or the hardwood forest growing timber for underground coal mines. The ecological properties of the land during occupation vary significantly, as does the value of a site prior to its occupation.

Figure 4: Land occupation required for the production of electricity, Europe in 2010 (for coal power, the dark green bar represents open pit mines (land use largely associated with the mine itself) and the total size of the bar reflects the land use associated with coal from underground mines. These underground mines use hard wood as structural material, which contributes most to land use)[25].



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[24] Barros, N., et al., *Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude*. Nature Geoscience, 2011. 4(9): p. 593-596.

[25] Data for other regions is available in the full report. Abbreviations: CdTe – Cadmiumtelluride, CIGS – Copper Indium Gallium Selenide, Poly-Si – Polycrystalline Silicon, CCS – CO2 Capture and Storage, IGCC – Integrated Gasification Combined Cycle, GB – Gravity-Based Foundation.

Wind power and hydropower have specific ecological concerns. Wind power can cause injury and death to birds and bats when they collide with the turbine blades. Larger areas may thus become less suitable for particular species. Hydropower affects fish and other aquatic species by erecting migration barriers, changing stream-flow and in-stream habitats. River regulation also reduces flood plains habitat. Not all wind or hydro plants cause substantial impacts, however, and some may in fact benefit local biodiversity. Offshore wind power creates new habitat for marine life, while creation of pondages and changes in flow regimes caused by some hydropower projects may benefit some fish species. Where sites and projects cause new pressures on particular species, it will be important to consider that these are additional to existing ecological pressures. There is, as yet, no clear understanding of the combined effects of these pressures, existing and new, on particular species. For example, the number of small bird deaths caused by collisions with wind power turbines is low compared to that caused by domestic cats, windows, or power lines, but large birds of prey are more frequently affected.

RESOURCE IMPLICATIONS

The dependency of economies on finite fossil fuel reserves has been a concern since the Industrial Revolution[26]. While new technology is allowing less easily accessible resources to be retrieved, this is often at higher costs, greater risks, and raises new and significant environmental issues. While the peak in fossil fuel extraction is not considered imminent[27], resources are finite and will eventually decline.

Fossil fuel power stations require a much higher energy input per unit output than low-carbon technologies, which is a reflection of both their low conversion efficiencies and high life-cycle energy requirements. CO_2 capture is an energy intensive process and increases the energy demand of power production by about one third. Renewable technologies also require the input of electricity and fuels derived from fossil or nuclear sources.

Their increased use of land, water and materials is often mentioned as a concern in the deployment of low-carbon technologies. There are also additional technology-specific resources that may potentially be in low supply, such as rare earth metals for direct-drive wind turbines, special metals for PV, silver for CSP and PV, and adequate storage space for CO_2 from CCS.

In terms of structural materials, natural gas combined cycle plants and efficient hydropower plants generally have the lowest material requirements. Concentrated solar tower technology and inefficient hydropower installations have high material requirements of approximately 8-9g of bulk materials per kWh. The remaining technologies are in the range of 1-4 g/kWh, with offshore wind power and trough CSP on the higher end and roof PV and coal power on the lower end. PV has substantial aluminium and copper requirements. Moreover, solar technologies require substantial amounts of glass. Overall, both renewable energy and CCS have higher material requirements than fossil fuel-based power. For example, photovoltaic systems require 11-40 times more copper, and wind power plants require 6-14 times more iron.

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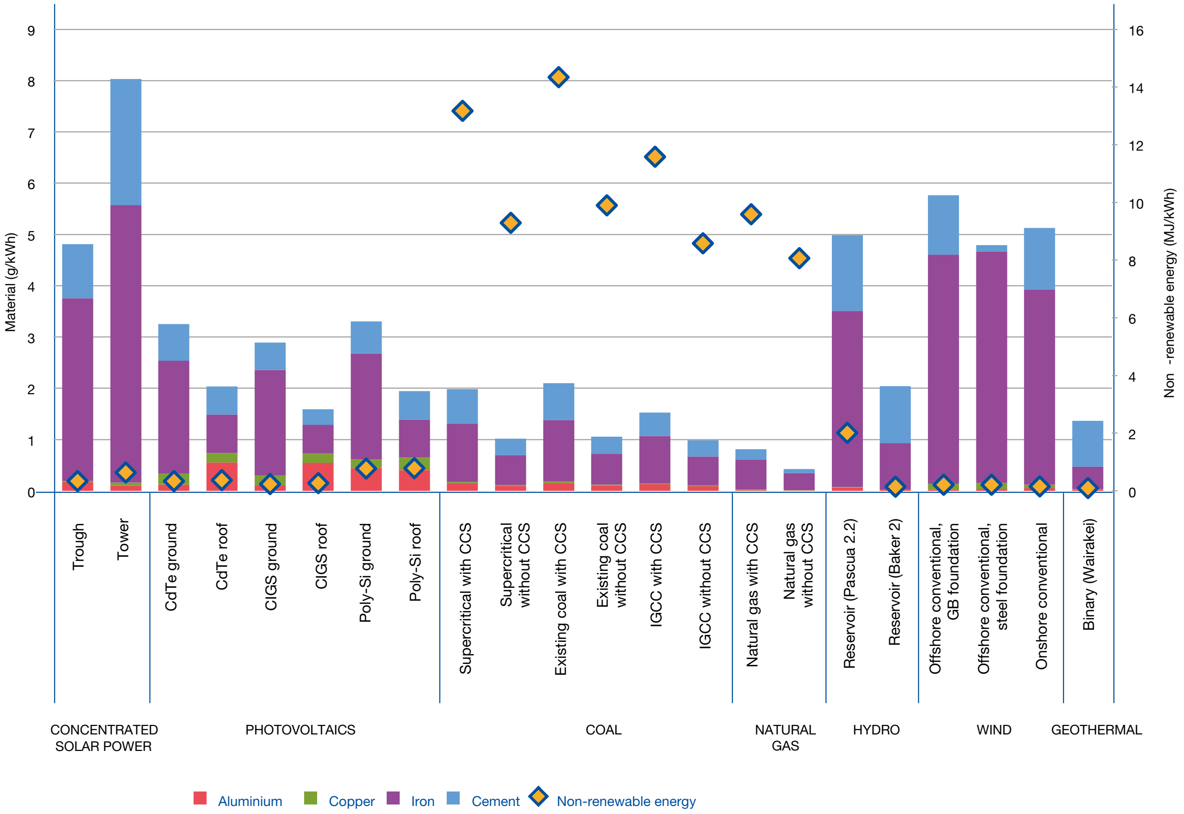
[26] Jevons, W.S., *The coal question: an inquiry concerning the progress of the nation, and the probable exhaustion of our coal mines*. 1866, London: Macmillan & Co. I,467 s.

[27] Op cit at 8

Figure 5: Bulk material and non-renewable energy requirements per unit power produced.[28]

Fossil technologies have high cumulative non-renewable energy demand (CED) and low bulk material requirements.



For conventional coal power, the amount of coal required to fuel a power plant is approximately 250 g/kWh, so the total mass flow associated with a coal fired power plant is much larger than that of a renewable power plant.

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[28] Abbreviations: CdTe – Cadmiumtelluride, CIGS – Copper Indium Gallium Selenide, Poly-Si – Polycrystalline Silicon, CCS – CO2 Capture and Storage, IGCC – Integrated Gasification Combined Cycle, GB – Gravity-Based Foundation.

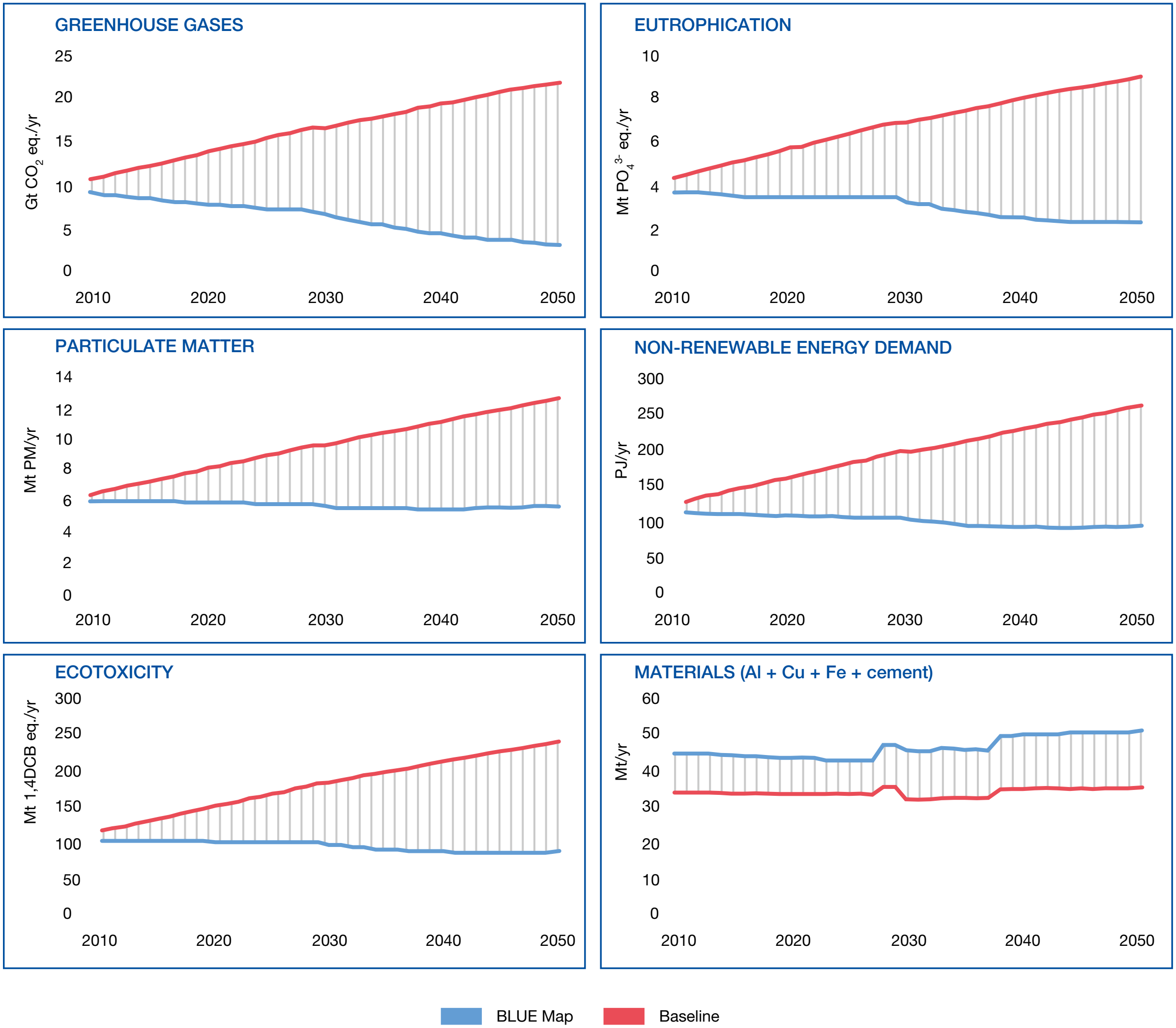
SCENARIOS FOR THE FUTURE GLOBAL ENERGY MIX

Like all climate mitigation scenarios that aim to limit global warming to 2°C, the IEA BLUE Map scenario foresees widespread adoption of a range of low-carbon electricity generation technologies by 2050 and the virtual phase-out of all coal power plants without CCS. Some electricity generation by fossil fuel-fired power plants would still exist in 2050, but most of it would be from power plants with CCS, and the remaining gas power plants without CCS would be used for fewer hours per year, serving mainly to balance variable renewable power production. As consequence of reduced coal use, GHG emissions associated with coal power would decline by 87 per cent between 2010 and 2015.

The increasing market share of renewable electricity would reduce the pollution impact per unit of electricity generated by a factor of two or more. In the face of continued growth in electricity supply, these improvements would enable a stabilization of emissions of particulate matter formation and ecotoxic impacts on fresh water while at the same time reducing emissions that contribute to climate change and eutrophication. The mitigation scenario would lead to a reduction of the use of non-renewable energy resources and also in land use. This downward trend contrasts with the Baseline scenario, where the increased use of coal and gas would lead to a proportionate increase in all its environmental impacts.

However, the widespread deployment of low-carbon technologies also implies increased investment in infrastructure which leads to a greater demand for iron and steel, cement, and copper. CSP and wind power plants will create additional demand for cement and iron, while PV will lead to additional requirements for copper and aluminium. However, responding to the world's energy needs in 2050 (as per the IEA's BLUE Map Scenario) would only require one year of current global production of iron and two years of current global copper production. The associated environmental impacts are low compared to the impacts of fuel production and combustion of fossil fuel-based power plants. Given that fossil fuels are the most important cause of pollution today and are likely to remain so over the coming decades even in a 2°C scenario, more effort needs to be focused on mitigating the pollution from fossil fuel production and use.

Figure 6: The employment of investigated electricity generation technologies under the IEA BLUE Map scenario ensures a stabilisation or reduction of pollution indicators at the expense of an increased material demand. The IEA Baseline scenario shows a continued escalation of all investigated pollution indicators.



ELECTRICITY GRID AND ENERGY STORAGE

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Energy resources differ in their spatial and temporal distribution. The characteristics of resources and technologies for electricity generation, as well as the characteristics of power demand, have important implications for the design of transmission and distribution systems. A high fraction of intermittent renewable sources such as wind and solar energy poses a challenge to system operation. Larger grid systems, energy storage, flexible demand, and/or the flexible operation of fossil fuel-based power can help smooth out variations in supply. However, all these responses cause additional environmental impacts. The effect of different power sources on grid operations is very system specific and varies across regions and situations. For example, various studies indicate that adjusting the operation of fossil power plants to balance the variable production of wind power can cause impacts as large as the life-cycle impacts of installing and operating the wind power plant itself. In certain situations solar power can reduce the need for peak capacity as it generates electricity at the same time as, for example, air conditioning demand peaks.

In the IEA scenarios, the investments in transmission are of a similar size to those in distribution. It is not clear, however, that a mitigation scenario requires higher grid investments than a baseline scenario, as the mitigation scenario results in a lower total energy demand.

Electricity grid extension

Connecting larger areas of generation and demand can improve system operations and allow the integration of more renewables. High capacity, high voltage lines can provide significant energy savings, allowing for more steady operation of power systems. All forms of electricity transmission incur losses, but these losses tend to be higher in systems with a weak transmission infrastructure. The construction of power lines, cables and transformer stations, however, causes a range of impacts both directly on habitat and wildlife and through the production of materials and equipment demanded. Power lines take up land and are a cause of bird deaths.

A significant impact of electricity transmission is usually the power loss, which is often on the order of 1-3 per cent for the high-voltage portion of the grid; losses in low-voltage distribution grid are commonly larger, 3-5 per cent in industrialized countries and up to 40 per cent in developing countries. The electricity transmission infrastructure is also material intensive. A hypothetical grid for large-scale utilization of offshore wind power in the North Sea would add approximately 5 gCO_2e per kWh of power.[29] Impacts from power transmission are generally low compared to impacts from power production, but they are not negligible, and the impacts of power transmission on metal demand are significant.

Flexible operation of fossil power plants

The integration of substantial amounts of intermittent renewable energy into an electricity system dominated by fossil power requires the flexible operation of the fossil power plants, including managing the losses during the ramp-up and ramp-down of power plants and the operation of spinning reserves. Various studies of systems in North America and Europe indicate that this flexibility causes additional GHG emissions on the order of 15-70 gCO_2e per kWh of wind energy introduced into

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[29] Arvesen, A. et al., Life cycle assessment of an offshore grid interconnecting wind farms and customers across the North Sea. Int. J. Life Cycle Assess. 2014, 19(4): 826-837.

a grid. The larger the grid, the lower the costs, as the variability of wind power production aggregated across larger regions is lower than at individual sites. A fundamental challenge with using fossil power plants as a back-up energy source is that it limits the share of very low-carbon technologies in the system.

Energy storage

Energy storage can deliver substantial benefits in stabilizing grid operations. Opportunities for effective electricity storage are limited, however. Pumped storage hydropower is the only technology widely used for large-scale energy storage today, offering acceptable costs and efficient storage at suitable locations. Other types of storage foreseen for systems based on a large degree of intermittent renewable power include batteries and electrolysis/fuel cell systems, flywheels, compressed air storage, super-capacitors and more. These technologies all require significant capital investment. Many systems achieve 70-90 per cent storage efficiency, but the losses increase as energy is stored on longer time scales, ranging from hours to days. There has been little analysis of the environmental and resource impacts of utility-scale energy storage options, but extending the analysis of small-scale or mobile systems gives an indication. Generally, the production of energy storage systems is material and emission intensive. As an example, the most environmentally promising battery technologies, lithium ion and sodium sulfide, emit in the order of 30-100 gCO_2e per kWh of electricity stored, over the life cycle, although impacts are expected to come down as a result of a cleaner energy mix and technology learning. Based on our limited knowledge, current electricity storage options apart from hydropower have relatively high environmental costs. The moderately high environmental costs of storage also limit the attractiveness of grid-independent systems and mini-grids based on PV or wind energy.

Flexible demand

There is substantial potential to use energy demand that is not time-dependent to control power loads. For example, water heaters, district heating systems, refrigerator and freezers could use surplus electricity where it exists in a grid and so help to better match demand to variable supply. Other loads can be switched off at moderate costs. Smart grids and meters are one way to attain this goal. Some large industrial enterprises are already entering contracts that allow utilities to disconnect them in case of power shortages. Smart grids may make such options attractive to a much wider range of customers. Preliminary analysis indicates that there are specific benefits from such strategies. However, the implementation of smart grids and meters is resource intensive, and little research exists to date on the environmental costs and benefits of flexible demand strategies.

Conclusions

The large investments required to meet the rising energy demand of a growing world population presents an ideal opportunity to make technology choices that take into account, and to the extent possible, mitigate negative impacts on the climate, ecosystems and human health.

When replacing conventional fossil fuel-based power plants, renewable energy technologies offer substantial reductions in both emissions of greenhouse gases and other pollutants, including those causing eutrophication, acidification, particulate matter and photochemical smog, and various forms of toxicity. The capture and storage of CO_2 from fossil fuel-based power plants offers a substantial reduction in greenhouse gas emissions, but without the benefit of reducing other types of pollution. Renewables also reduce dependence on finite reserves of fossil fuel.

Renewable technologies, however, lead to a number of other concerns, principally their direct ecological impacts associated with land and water use, and their increased consumption of iron, cement and copper. Similar ecological impacts related to land and water use are also associated with fossil fuels: for example, land use by coal mining is similar in scale to that of wind and solar power. Fossil power plants use somewhat less water than geothermal and concentrating solar power plants, but options such as air-cooling are now becoming available for all of these technologies. Proper project selection, design and operation may mitigate many adverse ecological impacts. The modest increase in iron and cement use associated with low-carbon technologies does not pose a serious problem given the availability of those resources and the relatively small share of total demand related to electricity systems. The use of copper and functionally important metals, however, may pose some concerns in the long term, depending on opportunities for substitution which are not yet fully understood. Overall, replacing fossil fuels with renewable energy offers a clear opportunity to reduce environmental pollution from electricity generation.

Gas and coal power will remain important for some time, not at least to balance the variable production of wind and solar power. CO_2 capture and storage technology promises to substantially reduce GHG emissions compared to conventional power plants, although emissions would still be higher than from renewable energies. CCS, however, leads to a moderate but uniform increase of most emission-related impacts and of resource use. In addition, the storage of CO_2 needs to be monitored and verified, and there is no large-scale deployment of this technology to date.

Table 1: Overview of the impacts of low-carbon technologies for electricity generation on climate, human health, ecosystems and resources, comparing state of the art power plants at well-suited locations.

The reference is the current global mix, which has high impacts compared to the levels indicated in this table.

	Climate	Human health	Ecosystem health	Resources
WIND	Low GHG (++)	Reduced particulate exposure (++) Potentially reduced human toxicity (--)	Bird and bat collisions (+=) Low ecotoxicity (=-) Low eutrophication (=-)	High metal consumption (+=) Low water use (==) Low direct land use (==)
PHOTOVOLTAICS	Low GHG (==)	Low particulate matter (+=) Low human toxicity (=-)	Low eutrophication (+-) Low ecotoxicity (+-)	High metal use (+=) High direct land use for ground-based systems (++)
CONCENTRATED SOLAR POWER	Low GHG (==)	Low particulate matter (=-) Low human toxicity (=-)	Concern about heat transfer fluid (+=) Low eutrophication (+-) Low ecotoxicity (+-)	High water use (++) High land use (++)
HYDROPOWER	Low fossil GHG (++) High biogenic GHG from some dams (==)	Low air pollution impacts (=-)	Riparian habitat change (reservoir and downstream) (++)	High water use due to evaporation (+-) High land use for reservoirs (+=)
GEOTHERMAL POWER	Low fossil GHG (+-) Geogenic GHG for some types (=+)	Air and water pollution from geofluid flow in some sites (=-)	Aquatic habitat change/pollution (+=)	High water use for cooling (+=)
COAL WITH CCS GAS WITH CCS	Low GHG (++) Substantial fugitive methane emissions (==) Concern about CO_2 leakage (-=)	Solvent-related emissions (==) High particulate matter (==) High human toxicity (++)	High eutrophication (++) High ecotoxicity (+=)	Increased fossil fuel consumption (++) Limited CO_2 storage volume (++)

KEY:

First symbol	(**+**) high agreement among studies	(**=**) moderate agreement	(**-**) low agreement
Second symbol	(**+**) robust evidence (many studies)	(**=**) medium evidence	(**-**) limited evidence

While environmentally attractive, wind and solar resources are intermittent and do not provide a continuous or readily controlled electricity output. In some regions, peak demand is correlated to peak supply, e.g., air conditioning in hot regions and sunshine, but this is not always the case. However the challenges in developing a balanced grid that integrates various energy sources are modest, as fossil-dominated systems can quickly respond to variable renewable supply. This flexible operation of fossil fuel power plants causes additional environmental impacts which are of similar magnitude to those imposed by renewables. Given the much higher pollution and climate impacts resulting from only using fossil fuels, grid integration does not compromise the environmental benefits of renewables in the medium term. However, integration challenges grow with the share of generation from intermittent renewables. Building larger and stronger transmission grids, utilizing energy storage and flexible demand, and relying on a variety of uncorrelated sources of renewable energy are all promising response strategies. Indeed, grid integration challenges provide a persuasive rationale for use of concentrating solar power alongside thermal energy storage, wave power, tidal power, and offshore wind (which deliver energy at other points in time and with a higher capacity factor than onshore wind). Few assessments are currently available on the environmental impacts of power transmission and energy storage, but they indicate that strengthening and extending electricity grids has lower impacts than the forms of energy storage investigated. Further research and development will be needed to design integrated electricity systems with average emissions below 100 gCO_2e/kWh.

The key to future energy decisions lies in determining the right mix of technologies for the local or regional situation and policy objectives. This demands careful assessment of all the impact categories of the different energy alternatives, to avoid unintended negative consequences, and to achieve the most desirable mix of environmental, social and economic benefits.

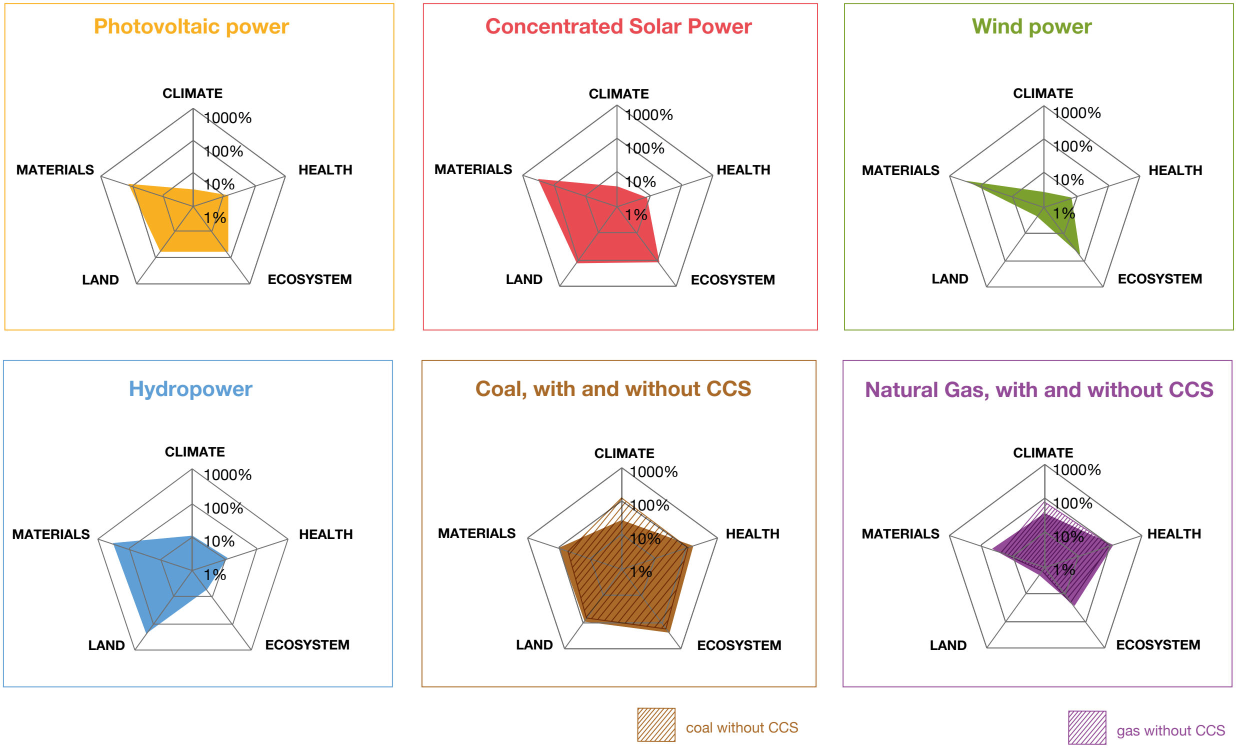
To summarize:

- Policy-makers in their policy development and decision-making process need to consider that all low-carbon technologies for electricity generation have environmental impacts, although these impacts vary in scale at different times in their life cycle, with main stages being during resource extraction, during manufacturing, during use and finally during dismantling/disposal.
- All electricity generation technologies emit greenhouse gases at some point in their life cycle.
- Fossil-fueled electricity generation causes more pollution than renewables. The combustion in the power plants is the most important cause of GHG and other air emissions, while mining of coal causes substantial soil and water pollution.
- CCS technologies are required in most 2°C scenarios and could reduce GHG emissions significantly, but increase other pollution problems by 20-80 per cent. The development of CCS technologies is currently not on track.
- Renewable generation technologies have a significantly lower pollution impacts, but a higher demand for structural materials.

Electricity generation technologies are an integral part of broader energy systems, and need to be considered as such, and not as site-specific development activities only. Resource requirements of electricity generation are influenced by growth in electricity demand, demography, and storage capacity for renewables or improvement in energy efficiency.

The report shows that lifecycle assessment is of central importance in determining the sustainability of different energy options. The Global Tracking Framework of the Sustainable Energy for All initiative[30] points out that sound criteria are needed to distinguish between different actions and technology choices in terms of their ultimate sustainability. These criteria will help ensure that overall sustainability goals are met and that actions are in line with global targets, such as Paris Agreement on climate change and Sustainable Development Goals. This report lays the foundation for developing such sustainability criteria, and so making good decisions about the energy sources that will influence the whole human future.

Figure 7: An overview over the life cycle results of different technology groups compared to the global average mix of electricity production technologies. The indicators are the use of the bulk materials (cement, iron and steel, copper, and aluminium), land occupation, greenhouse gas emissions, and the endpoint indicators for human health and ecosystems (excluding the contributions of climate change and land use, but including the production of materials.)



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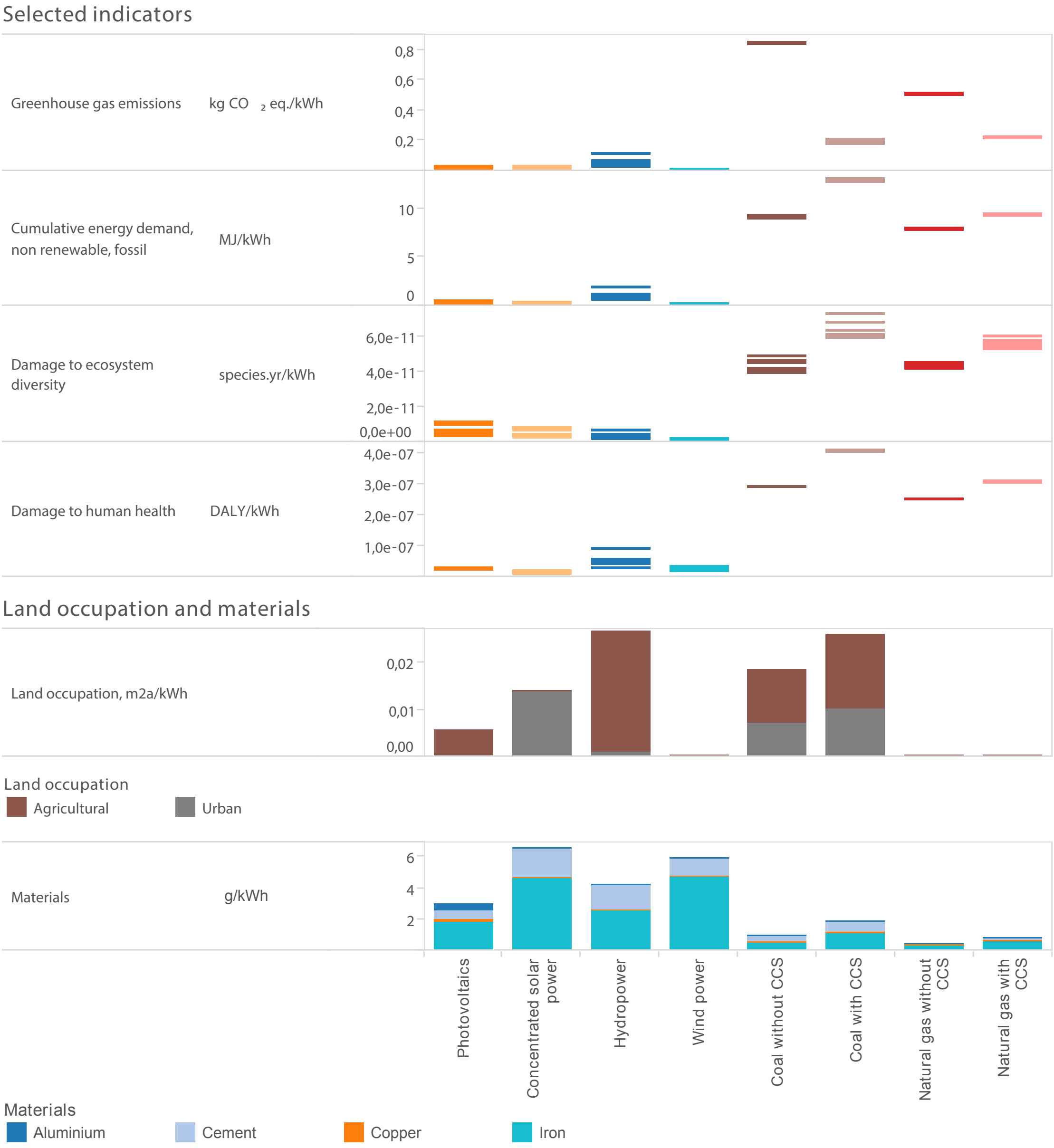
[30] SE4All is an initiative launched by the UN Secretary General gathering support by a wide range of partners to reach three complementary objectives by 2030: universal access to modern energy services, doubling the share of renewables in the global energy mix, and doubling the global rate of improvement of energy efficiency. www.sustainableenergyforall.org

Figure 8: Overview over the life cycle impacts , land occupation, and material requirements of different technology groups in the year 2010.



This summary report highlights key findings from the report of the International Resource Panel: Green Energy Choices: The Benefits, Risks and Trade-Offs of Low-Carbon Technologies for Electricity Production.

Meeting the rising energy demands of a growing world population presents an ideal opportunity to make technology choices that take into account, and to the extent possible, mitigate negative impacts on the climate, environmental and human health. The report examines the main commercially available renewable and non-renewable power generation technologies, analysing their GHG emissions, but also trade-offs in terms of:

- Environmental impacts (impacts on ecosystems, eutrophication and acidification, etc.)
- Impacts on human health (particulates, toxicity)
- Resource use implications (concrete, metals, energy intensity, water use and land use).

It provides a comprehensive comparison of a range of technologies, including coal and gas with and without Carbon Capture and Sequestration, photovoltaic solar power, Concentrated Solar Power, hydropower, geothermal, and wind power. It takes a whole life-cycle perspective, covering the production of the equipment and fuel, the operation of the power plants and their dismantling to provide:

1. A comparison and benchmarking of the environmental impacts of nine different electricity generation technologies, per unit of power production.
2. An environmental and resource assessment of implementing the IEA's Blue Map (or 2°C) mitigation scenario for keeping global warming to less than two degrees, in comparison to a baseline scenario. The scenario envisions replacing fossil fuels for power generation with renewables on a large enough scale to keep global warming to 2 degrees.

The work of the IRP represents the first in-depth international comparative assessment of the environmental, health and resource impacts of these different energy technologies, and is the work of an international scientific and technical expert team. The aim is to examine the trade-offs, benefits, and risks of low-carbon technologies in terms of GHG mitigation potential, but also their impacts on the environment, on human health and resource use in order to better equip decision-makers with the information that they require in order to make informed decisions as regards their future energy mix.

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