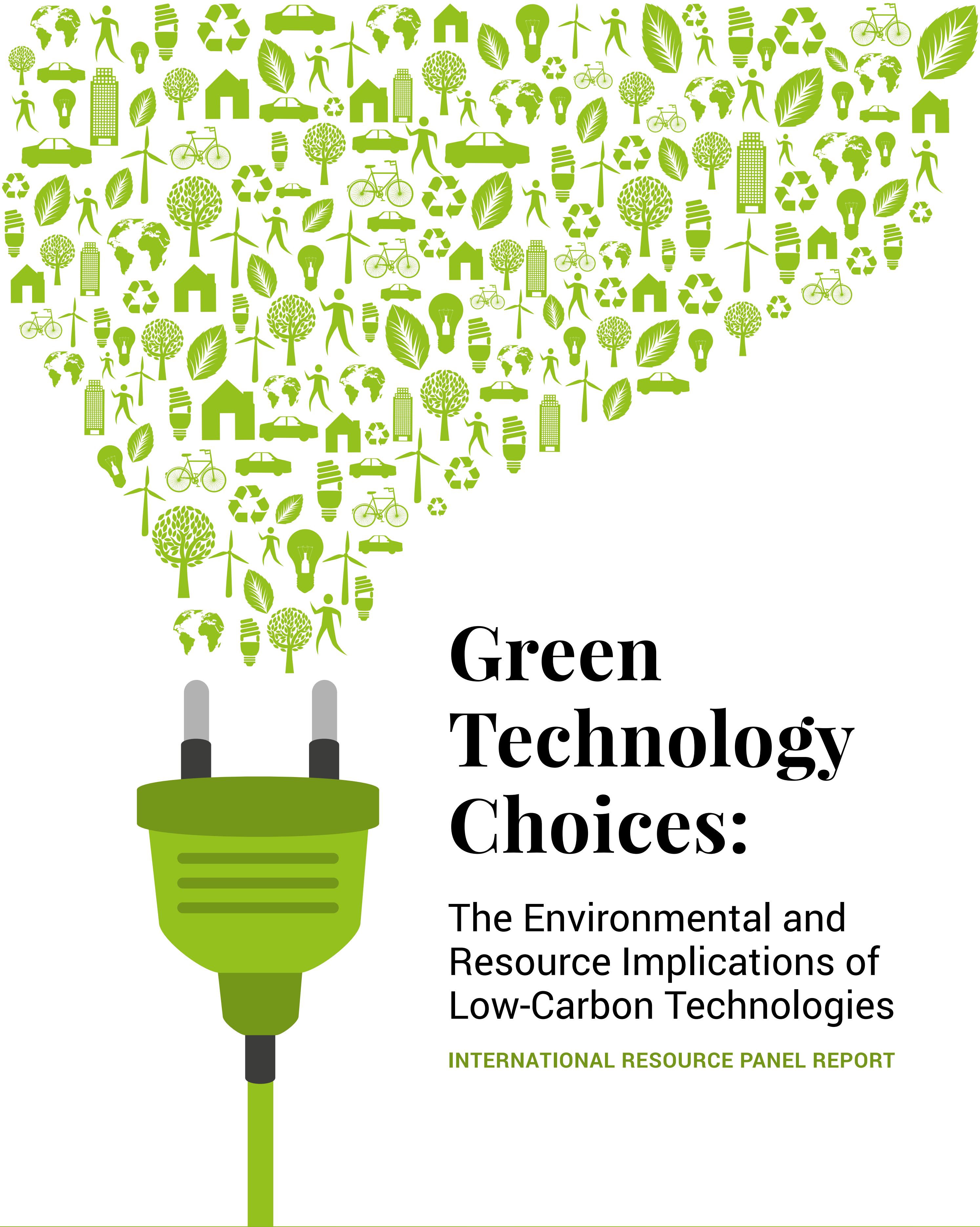
UN environment

International Resource Panel



Green Technology Choices:

The Environmental and Resource Implications of Low-Carbon Technologies

INTERNATIONAL RESOURCE PANEL REPORT

Acknowledgements

Authors: Sangwon Suh (Bren School of Environmental Science and Management, University of California, Santa Barbara), Joseph D. Bergesen (Bren School of Environmental Science and Management, University of California, Santa Barbara), Thomas Gibon (Norwegian University of Science and Technology (NTNU)), Edgar G. Hertwich (Yale University), Michael Taptich (University of California, Berkeley)

We thank the following scholars who contributed some of the data used in this report: Severin Beucker (Borderstep Institute; Yasunori Kikuchi (University of Tokyo); Łukasz Lelek (Polish Academy of Sciences); Eric Masanet (Northwestern University); Nydia Suppen (Center for life cycle assessment and Sustainable Design, CADIS); Leena Tähkämö (Aalto University).

We would also like to take this opportunity to acknowledge those that provided their valuable time to carrying out the external peer review of the report: Geoffrey P. Hammond, Lars J. Nilsson, Stefan Thomas, Fabian Wagner, Thomas Wiedmann, as well as others who preferred to stay anonymous.

We would also like to extend our thanks to International Resource Panel member Seiji Hashimoto, who acted as Peer Review Coordinator for this report.

We thank Jacqueline Aloisi de Larderel, a member of the International Resource Panel for her advice and support to this work. Special thanks go to Janez Potočnik and Alicia Barcena, the co-chairs of the International Resource Panel.

The International Resource Panel Secretariat Team provided essential coordination and support, especially Shaoyi Li, Zura Nukusheva-Béguin, Lowri Angharad Rees, Peder Jensen.

The full report should be referenced as follows:
IRP (2017): Green Technology Choices: The Environmental and Resource Implications of Low-Carbon Technologies. Suh, S., Bergesen, J., Gibon, T. J., Hertwich, E., Taptich M. A report of the International Resource Panel. United Nations Environment Programme, Nairobi, Kenya.

Design/layout: Anna Mortreux
Printing: UNESCO
Cover photos: ©gst/Shutterstock
ISBN number: 978-92-807-3655-7

DTI/2109/PA

Green Technology Choices:

The Environmental and Resource Implications of Low-Carbon Technologies

INTERNATIONAL RESOURCE PANEL REPORT

Preface

Limiting climate change to well below 2°C will require unprecedented aggressive decarbonisation of global electricity generation and deployment of demand-side low-carbon energy technologies in the coming decades. Moreover, meeting Sustainable Development Goal 7 "Ensure access to affordable, reliable, sustainable and modern energy for all" will require substantially increasing the share of renewable energy in the global energy mix and doubling the global rate of improvement in energy efficiency by 2030. Achieving these targets will necessitate a profound transformation of how energy is supplied and used around the world. With this challenge comes the opportunity to design systems and select technologies that will minimize adverse impacts on the environment and climate, as well as address the additional pressure on natural resources.

Energy efficiency and demand-side technologies are often viewed as desirable due to their potential to reduce greenhouse gas emissions while also saving costs. But how much do we know about other environmental impacts of a large-scale deployment of these technologies? What are the benefits (or costs) from the life-cycle perspective? By how much can the gains from energy efficient technologies be multiplied if combined with decarbonisation of electricity production?

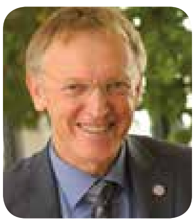
Tasked with building and sharing knowledge on how to improve management of the world's resources, the International Resource Panel (IRP), which provides independent, coherent and authoritative scientific assessments on the use of natural resources, turned its attention to understanding the impacts of such a transformation in energy production and use options, not only on greenhouse gas emissions but also on the environment and natural resources.

With this report, the Working Group on Environmental Impacts of the International Resource Panel provides, for the first time, a comprehensive global-scale assessment of the benefits, risks, and trade-offs of energy efficiency technologies and their combined effects when deployed alongside low-carbon electricity supply technologies.

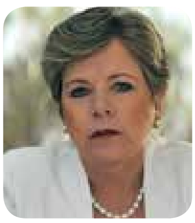
The results of the report show that the majority of efficiency technologies, used for mobility, buildings and industry, bring environmental co-benefits beyond greenhouse gas mitigation, including reduced impacts on the environment, health and natural resources. However, some technologies may generate higher impacts than the baseline technology for certain regions and for certain years.

The analysis also sheds light on the interactions between supply-side and demand-side low-carbon technologies since without decarbonizing electricity supply, the benefits of some energy efficiency technologies cannot be realized. For example, extensive electrification of passenger transport in the regions that generate electricity from fossil fuels leads to an increase—rather than a decrease—in environmental impacts and natural resource pressures, which illustrates the importance of doing both together.

We are very grateful to Sangwon Suh, Joseph D. Bergesen and other co-authors for their contribution to this extremely important body of work. We would also like to thank the authors of the background studies published in the companion issue of the Journal of Industrial Ecology. We are confident that this report together with another IRP report, *Green Energy Choices: The Benefits, Risks and Trade-Offs of Low-Carbon Technologies for Electricity Production*, will help to design policies for mitigating potential and unintended consequences of large-scale changes towards a low-carbon society.



Janez Potočnik
Ljubljana, Republic of Slovenia
Co-Chair, International Resource Panel



Alicia Bárcena
Santiago, Chile
Co-Chair, International Resource Panel

Foreword

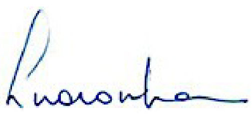
It is sometimes said that the future belongs to electricity. Electricity is clean at the point of consumption, easy to adjust up and down, and incredibly versatile. The key environmental requirement is that the production of electricity is also clean. This was the theme of a previous International Resource Panel report entitled "*Green Energy Choices: The Benefits, Risks and Trade-Offs of Low-Carbon Technologies for Electricity Production"*. Because the supply of clean electricity is still limited, it is important also to look at the demand for electricity to ensure that the available supply is stretched as far as possible. Thus, efficient energy technologies are critical in combatting climate change.

That is why different initiatives around the globe have been promoting energy efficient technologies. For example, Southern Africa faces rising energy demands due to economic development and increased use of appliances, increased access to electricity and low availability of energy efficient household appliances on the market. As the region generates 75% of its electricity from fossil fuels, this growing electricity demand will also greatly increase CO2 emissions. Several Southern African countries are acting collectively to develop an action plan for the region to leapfrog to energy efficient lighting, appliances and equipment. While the energy and climate change benefits of these technologies are clear, the understanding of their impacts on environment, human health, and natural resources has been limited. This new report, produced by the International Resource Panel, closes this knowledge gap by quantifying the environmental and natural resource implications of 60 supply and demand-side technologies in nine regions of the world, and therefore help different regions like Southern Africa make an informed transition.

The report confirms that under a 2-degree Celsius scenario, low-carbon energy technologies alleviate the pressure on both water and land by 2050 when compared to a 6-degree Celsius scenario. Moreover, the introduction of these technologies help by reducing particulate matter, which causes air pollution, as well as toxic emissions, which affect human health. Low-carbon energy technologies however, also require significant volumes of metal resources by 2050 for additional infrastructure and wiring needs. Thus, promoting these technologies would be beneficial not only for climate change mitigation, but also to reduce our impact on health, environment and natural resources use, with the exception of metals consumption.

For the first time, thanks to this report, companies and countries making the decision about which energy efficient technology to use, have clear, comparative, science-based information about not only their greenhouse gas reduction benefits, but also about other positive and negative impacts that these technologies represent. This will allow them to avoid the trade-offs and unintended consequences arising from the large scale deployment of new technologies. Protecting human health and managing the natural resource base while combatting climate change is fundamental to long-term social and economic development, as well as to eradicating poverty and increasing equality. Only with the solid scientific assessments like this one we will be able to build the truly sustainable future to which we aspire.

I would like to express my gratitude to the International Resource Panel, under the leadership of the Co-chairs Alicia Bárcena and Janez Potočnik, for coordinating this significant scientific effort.



Ligia Noronha
Director
Economy Division
UN Environment

Contents

Glossary

air pollution
The introduction into Earth's atmosphere of one or more substances (particulates, gases, biological molecules), or other harmful chemicals, materials or physical conditions (such as excess heat or noise) in high enough concentrations to cause harm to humans, other animals, vegetation or materials. Air pollution may come from anthropogenic or natural sources. (UNFCCC)

anthropogenic emissions
Emissions of pollution associated with human activities, including the burning of fossil fuels, deforestation, land use changes, livestock, fertilization, etc. (IPPC SYR Appendix)

battery electric vehicle (BEV)
Battery electric vehicles (BEVs) in this report refer to passenger vehicles powered entirely by electrically recharged battery packs. Such vehicles use electric motors in place of internal combustion engines.

biomass
Renewable energy from living (or recently living) plants and animals, e.g. wood chippings, crops and manure. Plants store energy from the Sun while animals get their energy from the plants they eat. (IEA)

building energy management system (BEMS)
See **demand-side energy management**

building shell
The building envelope – also known as the building shell, fabric or enclosure – is the boundary between the conditioned interior of a building and the outdoors. The energy performance of building envelope components, including external walls, floors, roofs, ceilings, windows and doors, is critical in determining how much energy is required for heating and cooling. (IEA)

carbon dioxide (CO_2)
A naturally occurring gas, also a by-product of burning fossil fuels from fossil carbon deposits, such as oil, gas and coal, of burning biomass and of land use changes and other industrial processes. It is the principal anthropogenic greenhouse gas (GHG) that affects the Earth's radiative balance. It is the reference gas against which other GHGs are measured and therefore has a Global Warming Potential (GWP) of 1. (IPPC SYR Appendix)

carbon [dioxide] capture and storage (CCS)
A process consisting of separation of carbon dioxide from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere. (IPPC SYR Appendix)

carbon dioxide equivalent
A metric measure used to compare the emissions of the different GHGs based upon their GWP. GHG emissions in the United States are most commonly expressed as "carbon dioxide equivalents," which are CO_2 equivalents measured in terms of the mass of carbon and not carbon dioxide. GWPs are used to convert GHGs to carbon dioxide equivalents. (UNFCCC) In this report GWP100 is used for carbon dioxide equivalency. See also **global warming potential**, **greenhouse gas**.

climate change
Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the United Nations Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes. (IPPC SYR Appendix)

coal
Refers to a variety of solid, combustible, sedimentary, organic rocks that are composed mainly of carbon and varying amounts of other components such as hydrogen, oxygen, sulfur and moisture. Coal is formed from vegetation that has been consolidated between other rock strata and altered by the combined effects of pressure and heat over millions of years. Many different classifications of coal are used around the world, reflecting a broad range of ages, compositions and properties. (IEA)

co-generation
The simultaneous generation of both electricity and heat from the same fuel, for useful purposes. The fuel varies greatly and can include coal, biomass, natural gas, nuclear material, the Sun or the heat stored in the Earth. (IEA)

consumption
The use of products and services for (domestic) final demand, i.e. for households, government and investments. The consumption of resources can be calculated by attributing the life cycle-wide resource requirements to those products and services (e.g. by input-output calculation). (IRP)

demand-side technologies
Demand-side technologies are broadly defined to include the following: (1) deploying energy efficient technologies (e.g. using light-emitting diode bulbs) that provide the same service while consuming less energy, (2) the deployment of infrastructure like improved building shell insulation that reduces the need for heating and cooling energy, and (3) fuel and mode switching (e.g. using electric vehicles or public transportation to replace petroleum vehicles).

demand-side energy management
Demand-side energy management in this report refers to a variety of technologies and approaches used to reduce energy demand by consumers. This includes Building Energy Management Systems (BEMS) that can control heating energy consumption at the apartment or room level by adapting to usage patterns, weather predictions and building design. BEMS can also control other building functions such as lighting and ventilation.

ecosystem
A system of living organisms interacting with each other and their physical environment. The boundaries of what could be called an ecosystem are somewhat arbitrary, depending on the focus of interest or study. Thus, the extent of an ecosystem may range from very small spatial scales to, ultimately, the entire Earth. (IPPC SYR Appendix)

ecotoxicity
Ecotoxicity is the potential toxicological damage to ecosystems posed by the release of pollutants into the environment.

electricity generation
The total amount of electricity generated by power only or combined heat and power plants including generation required for own use. This is also referred to as gross generation. (IEA)

electricity production
The total amount of electricity generated by a power plant. It includes own-use electricity, as well as transmission and distribution losses. (IEA)

energy, heat

Heat is obtained from fuels combustion, nuclear reactors, geothermal reservoirs, capture of sunlight, exothermic chemical processes and heat pumps which can extract it from ambient air and liquids. It may be used for heating or cooling or converted into mechanical energy for transport vehicles or electricity generation. Commercial heat sold is reported under total final consumption with the fuel inputs allocated under power generation. (IEA)

energy, renewable

Energy that is derived from natural processes (e.g. sunlight and wind) that are replenished at a higher rate than they are consumed. Solar, wind, geothermal, hydro and biomass are common sources of renewable energy. (IEA)

energy, solar

Solar radiation exploited for hot water production and electricity generation by: flat plate collectors, mainly of the thermosyphon type, for domestic hot water or for the seasonal heating of swimming pools; photovoltaic cells; or, solar thermal-electric plants. (OECD)

energy

The amount of work or heat delivered. Energy is classified in a variety of types and becomes useful to human ends when it flows from one place to another or is converted from one type into another. Primary energy (also referred to as energy sources) is the energy embodied in natural resources (e.g., coal, crude oil, natural gas, uranium) that has not undergone any anthropogenic conversion. This primary energy needs to be converted and transported to become usable energy (e.g. light). Renewable energy is obtained from the continuing or repetitive currents of energy occurring in the natural environment, and includes non-carbon technologies such as solar energy, hydropower, wind, tide and waves, and geothermal heat, as well as carbon neutral technologies such as biomass. Embodied energy is the energy used to produce a material substance (such as processed metals, or building materials), taking into account energy used at the manufacturing facility (zero order), energy used in producing the materials that are used in the manufacturing facility (first order), and so on. (IPPC SYR Appendix)

energy efficiency

Energy efficiency is a way of managing and restraining the growth in energy consumption. Something is more energy efficient if it delivers more services for the same energy input, or the same services for less energy input. (IEA)

eutrophication potential

An aggregate measure of the contribution of effluents to eutrophication. In this publication's impact assessment methods, phosphorus is treated as the limited nutrient for freshwater eutrophication and the freshwater eutrophication potential captures the contribution of different forms of phosphorus to freshwater eutrophication. Nitrogen is considered the limiting nutrient of marine ecosystems and the marine eutrophication potential captures the contribution of different forms of nitrogen to marine eutrophication.

flash furnace-based copper smelting

Flash furnace-based copper smelting is a process by which copper is extracted from sulfur-containing ore. Flash smelting processes are among the best available technologies for copper smelting, generally requiring less energy and producing less air pollution than older shaft furnace processes. (Collins)

fossil fuels

Carbon-based fuels from fossil hydrocarbon deposits, including coal, peat, oil, and natural gas. (IPPC SYR Appendix)

gas, natural

Underground deposits of gases consisting of 50—90% methane (CH_4) and small amounts of heavier gaseous hydrocarbon compounds such as propane (C_3H_4) and butane (C_4H_{10}). (UNFCCC)

global warming potential (GWP)
An index, based upon radiative properties of well mixed GHGs, measuring the radiative forcing of a unit mass of a given well mixed GHG emission in today's atmosphere integrated over a chosen time horizon, relative to that of carbon dioxide. The global warming potential represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing thermal infrared radiation. The Kyoto Protocol is based on GWPs from pulse emissions over a 100-year time frame. (IPPC SYR Appendix)

global warming
The observed increase of the global average temperature as a result of human and other activities, including through the increased concentration of GHGs such as CO_2 from energy. (IEA)

greenhouse gas (GHG)
Any gas that absorbs infrared radiation in the atmosphere. Greenhouse gases include, but are not limited to, water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrochlorofluorocarbons (HCFCs), ozone (O3), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). (UNFCCC)

heat
Form of kinetic energy that flows from one body to another when there is a temperature difference between the two bodies. Heat always flows spontaneously from a hot sample of matter to a colder sample of matter. This is one way to state the second law of thermodynamics. (UNFCCC)

hydropower
The electrical energy derived from turbines being spun by fresh flowing water. This can be from rivers or from man-made installations, where water flows from a high-level reservoir down through a tunnel and away from a dam. (IEA)

information and communications technology (ICT)
Information and Communication Technology refers to technologies that provide access to information through telecommunications. It is similar to Information Technology (IT) This includes the Internet, wireless networks, cell phones, and other communication mediums, in addition to personal computers and other consumer electronics.

life cycle
Life cycle is a concept used to describe the environmental burden (resource requirements and environmental impacts) of products and services from the cradle to the grave, i.e. along the extraction-production-consumption-recycling-disposal chain. (IRP)

life cycle assessment (LCA)
Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. [IEC (ISO 14040:2006, definition 3.2)]

life cycle inventory (LCI)
The second step of life cycle assessment wherein extractions and emissions, the energy and raw materials used, and emissions to the atmosphere, water and land, are quantified for each process, then combined in the process flow chart and related to the functional basis. (UNEP)

light-emitting diode (LED)
A solid state device embodying a p-n junction, emitting optical radiation when excited by an electric current (Electropedia).

light-source technologies
Light-source technologies use electricity or other energy sources to provide artificial illumination. This includes incandescent lamps, light-emitting diode (LED) lamps and luminaires, compact fluorescent lamps (CFLs), fluorescent luminaires, kerosene lamps and a variety of other technologies not included in this report.

luminaire

Apparatus which distributes, filters or transforms the light transmitted from one or more lamps and which includes, except the lamps themselves, all the parts necessary for fixing and protecting the lamps and, where necessary, circuit auxiliaries together with the means for connecting them to the electric supply (electropedia).

low-carbon technologies

In this report, low-carbon technologies refer to a wide array of technologies used to reduce the GHG emissions of energy supply and/or use (i.e. demand). Low-carbon electricity supply technologies produce low—or zero—GHG emissions while operating. On the demand side, this includes energy efficiency technologies that reduce energy consumption and alternative fuel technologies, for instance battery electric vehicles.

nitrogen oxides (NOx)

Gases consisting of one molecule of nitrogen and varying numbers of oxygen molecules. Nitrogen oxides are produced, for example, by the combustion of fossil fuels in vehicles and electric power plants. In the atmosphere, nitrogen oxides can contribute to formation of photochemical ozone (smog), impair visibility, and have health consequences; they are considered pollutants. (UNFCCC)

oil

As defined by the IEA, includes crude oil, condensates, natural gas liquids, refinery feedstocks and additives, other hydrocarbons (including emulsified oils, synthetic crude oil, mineral oils extracted from bituminous minerals such as oil shale, bituminous sand and oils from coal-to-liquid and gas-to-liquid) and petroleum products (refinery gas, ethane, liquefied petroleum gas, aviation gasoline, motor gasoline, jet fuels, kerosene, gas/diesel oil, heavy fuel oil, naphtha, white spirit, lubricants, bitumen, paraffin waxes and petroleum coke). (IEA)

particulate matter formation

Particulate matter is a type of air pollution that, when inhaled, can cause health problems leading to morbidity and mortality. Fine particulate matter, defined as having a diameter less than 10 µm (PM_{10}) or less than 2.5 µm ($PM_{2.5}$), is a mixture of organic and inorganic substances that come from both natural and anthropogenic sources. Secondary particulates can be formed in the air from emissions of sulfur dioxide (SO_2), ammonia (NH_3), nitrogen oxides (NO_x), and others emissions.

photovoltaic (PV)

Directly convert solar energy into electricity using a photovoltaic cell; this is a semiconductor device. (IEA)

power

The rate of doing work, rate of electrical or mechanic energy flow.

power, electric

Electric energy produced by hydro-electric, geothermal, nuclear and conventional thermal power stations, excluding energy produced by pumping stations, measured by the calorific value of electricity (3.6 TJ/GWh). (OECD)

radiative forcing

A change in the balance between incoming solar radiation and outgoing infrared (i.e., thermal) radiation. Without any radiative forcing, solar radiation coming to the Earth would continue to be approximately equal to the infrared radiation emitted from the Earth. The addition of GHGs to the atmosphere traps an increased fraction of the infrared radiation, reradiating it back toward the surface of the Earth and thereby creates a warming influence. Typically, radiative forcing is quantified at the tropopause in units of watts per square meter of the Earth's surface. (UNFCCC)

rebound effect

The rebound effect happens when a positive eco-innovation on the micro level leads to negative impacts on the meso/macro level. This can happen due to a change in consumer behaviour, i.e. consumers using more of an efficient product, which – at least partly - outweighs the efficiency improvements per unit of that product. (IRP)

2-degree Celsius Scenario

The 2-degree Celsius scenario lays out an energy system deployment pathway and an emissions trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2°C. The 2-degree scenario limits the total remaining cumulative energy-related CO_2 emissions between 2015 and 2100 to 1 000 GtCO2. The 2-degree scenario reduces CO_2 emissions (including emissions from fuel combustion and process and feedstock emissions in industry) by almost 60% by 2050 (compared with 2013), with carbon emissions being projected to decline after 2050 until carbon neutrality is reached. (IEA)

6-degree Celsius Scenario

The 6-degree Celsius Scenario is largely an extension of current trends. Primary energy demand and CO2 emissions would grow by about 60% from 2013 to 2050, with about 1 700 GtCO2 of cumulative emissions. In the absence of efforts to stabilize the atmospheric concentration of GHGs, the average global temperature rise above pre-industrial levels is projected to reach almost 5.5°C in the long term and almost 4°C by the end of this century. (IEA)

TABLE i **Resources** for definitions

Publisher	Publication	Link*
Collins	Collins English Dictionary	https://www.collinsdictionary.com/dictionary/english/flash-smelting
IEA	Glossary	http://www.iea.org/about/glossary/ http://www.iea.org/topics/energyefficiency/ https://www.iea.org/publications/scenariosandprojections/ https://www.iea.org/publications/freepublications/publication/technology-roadmap-energy-efficient-building-envelopes.html
IEC	Electropedia	http://www.electropedia.org/
IPCC	Glossary of Terms used in the IPCC Fourth Assessment Report	https://www.ipcc.ch/publications_and_data/publications_and_data_glossary.shtml
IRP	Draft Glossary of Terms Used by the International Resource Panel	https://www.wrforum.org/uneppublicationspdf/draft-glossary-terms/
OECD	Glossary of Statistical Terms	http://stats.oecd.org/glossary/
UN Environment	Resource Efficiency, Consumption	http://web.unep.org/resourceefficiency/resources/glossary
UNFCCC	Glossary of climate change acronyms	http://unfccc.int/essential_background/glossary/items/3666.php
UNFCCC	Glossary for Greenhouse Gas Emissions Inventories	http://unfccc.int/resource/cd_roms/na1/ghg_inventories/English/8_glossary/Glossary.htm

Executive Summary

The Paris Agreement has set an ambitious goal of limiting the global mean temperature increase to below 2 degrees Celsius, and, if possible, under 1.5 degrees Celsius. Achieving this goal requires an unprecedented transformation of the way energy is supplied and used throughout the world, including a rapid deployment of low-carbon electricity generation technologies on the supply side, and acceleration of energy efficiency improvements on the demand side. Although the climate change benefits of these low-carbon technologies on both the supply and demand sides are well established in the literature, their implications on other environmental impacts and natural resources are yet to be fully understood. Addressing this gap, the International Resource Panel (IRP) of the United Nations Environment Programme commissioned a series of report on the long-term global transition to low-carbon technologies and their environmental and resource implications. The first report, *Green Energy Choices* (1) evaluated the low-carbon electricity supply technologies. The current report evaluates energy efficiency and demand-side technologies as well as the combined impacts of supply-side and demand-side technologies when deployed together.

TECHNOLOGIES SELECTED

This report covers 8 demand-side technologies that consist of 36 sub-technologies across three clusters: (1) buildings, (2) industry and (3) transportation. These technologies were selected based on several criteria, including their contributions to future greenhouse gas (GHG) mitigation, and the availability of data and experts essential for the assessment. Table 1 lists the demand-side technologies assessed in this report.

TABLE 1 Demand-side technologies analysed in this report.

Cluster	Technology	Sub-technology
1. Buildings	Efficient lighting	incandescent lamp, Compact fluorescent lamp (CFL), Light emitting diode (LED) lamp, fluorescent luminaire, LED luminaire, kerosene lamp
	Building shell insulation	Silica Aerogel, Cellulose, Expanded polystyrene, Foam glass, Glass wool, High density board, Polystyrene foam slab, Rock light density board, Urea formaldehyde
	Demand-side energy management	Building Energy Management System (BEMS)
	Information and communications technology (ICT)	Desktop personal computer (PC), laptop PC, smartphone, LCT TV, plasma TV
2. Industry	Copper production	Shaft furnace smelter, Outokumpu flash furnace copper smelter
	Co-generation	Natural gas-fired gas engine, gas turbine and chemically recuperated gas turbine
3. Transportation	Passenger	Petroleum and diesel car, battery electric vehicle (BEV), diesel bus, diesel train, electric train, high speed rail, aircraft
	Freight	Medium and heavy duty trucks, diesel rail, crude tanker and containership

In the previous report (1), over 20 electricity supply technologies were assessed, including renewable generation such as wind and solar and fossil fuel-based generation with carbon capture and storage. This report integrates the underlying data and models developed for electricity supply technologies with those for demand side technologies newly compiled for this report.

METHODS OF ASSESSMENT

Building on the previous report, an integrated Life Cycle Assessment (LCA) framework was developed to quantify the environmental and natural resource implications of the selected low-carbon technologies. Together with international experts, detailed, technology-specific data was collected and incorporated into the model. The penetration rates of all supply- and demand-side low-carbon technologies were estimated following the International Energy Agency (IEA)'s 6-degree Celsius scenario (baseline) and 2-degree Celsius scenario (low-carbon scenario) through 2050. The environmental and resource impacts are quantified for each of these two scenarios. Because geo-climatic and socio-economic conditions affect the mix of applicable technologies and the penetration rate of low-carbon energy technologies, the world was divided into 9 regions as defined by the IEA and region-specific parameters were used much as possible. Since technologies evolve over time, technology roadmap scenarios were incorporated to account for technology changes.

The following impact categories were considered using the ReCiPe 2008 impact assessment method (30):

- climate change (kg CO_2-eq)
- particulate matter formation (kg PM_{10}-eq)
- freshwater ecotoxicity (kg 1,4 dichlorobenzene (DCB)-eq)
- freshwater eutrophication (kg Phosphorus (P)-eq)
- human toxicity (kg 1,4 dichlorobenzene (DCB)-eq)
- metal consumption (kg Iron (Fe)-eq)
- water consumption (cubic meters (m^3))
- land occupation (square kilometres (km^2))

SUMMARY OF FINDINGS FROM COMBINED MODELLING

This section outlines the policy-relevant findings from the combined modelling of both supply- and demand-side low-carbon technologies under a 2-degree Celsius scenario.

1. Both supply-side and demand-side low-carbon technologies are needed for a substantial reduction in global GHG emissions

The results show that under the 2-degree Celsius scenario, deployment of supply-side and demand-side technologies considered in this report has the potential to reduce about 25 billion tonnes per year of GHG emissions (in CO_2-eq) by 2050 relative to the 6-degree Celsius scenario, which is about 34% lower than the GHG emissions under the 6-degree Celsius scenario (Figure i, A). Both supply-side and demand-side were essential to achieve such reduction.

2. Demand- and supply-side low-carbon technologies reduce other environmental impacts, in addition to GHG emissions

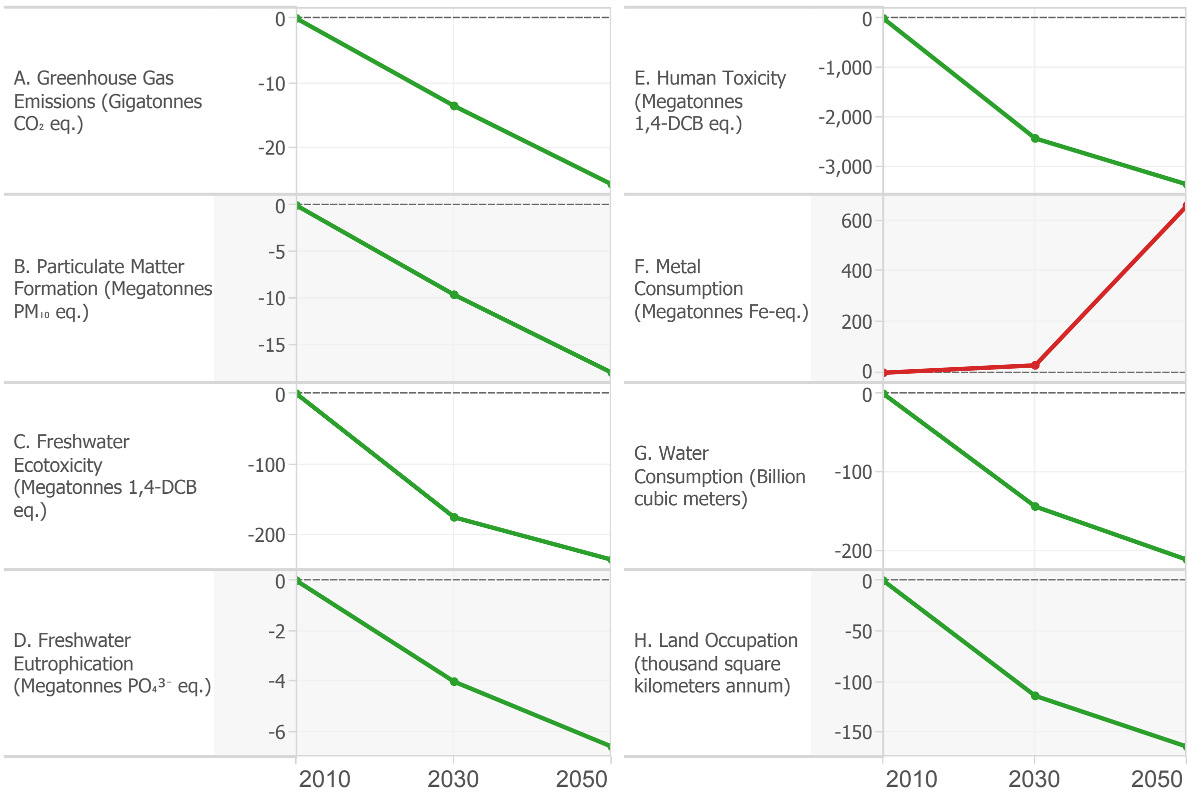
The consumption of fossil fuels for generating electricity and powering the demand-side is associated with various environmental issues, including human and ecosystem toxicity, acidification, particulate matter, and eutrophication. Therefore, reducing fossil fuel use by deploying low-carbon technologies on the supply and demand sides under the 2-degree Celsius scenario would not only help mitigate climate change but also avoid other environmental impacts, including over 17 million tonnes per year of particulate matter in PM10 equivalency and over 3 billion tonnes of human-toxic emissions measured in 1,4 DCB equivalency as compared to 6-degree Celsius scenario (Figure i B-E).

3. Low-carbon technologies also alleviate the pressure on land and water, while they may exacerbate the pressure on metallic resources

Thermal electricity generation technologies are important drivers of water consumption, and coal mining in particular occupies large areas of land. Under the 2-degree Celsius scenario, supply- and demand-side low-carbon technologies alleviate the pressure on water by over 200 billion cubic meters per year and nearly 150 thousand square kilometres of land occupation by 2050 as compared to the 6-degree Celsius scenario (Figure i G and H).

Low-carbon technologies, however, require over 600 million tonnes of metal resources (measured in iron-equivalency) by 2050 for additional infrastructure and wiring needs (Figure i F). The relative magnitude of additional metal demand by low-carbon supply- and demand-side technologies is likely small compared to the background consumption of metals caused by the rest of the economy.

FIGURE i The difference between the 2-degree and 6-degree scenarios in environmental and natural resource impacts of the selected energy supply and demand-side technologies. Negative values indicate reduction in impacts under 2-degree scenarios relative to 6 degree scenarios. All regions and all technologies selected for this study are combined.



4. The combined benefits of supply-side and demand-side low-carbon technologies are smaller than the sum of each calculated separately.

Often GHG benefits and other environmental co-benefits of low-carbon energy supply technologies are quantified assuming no additional energy efficiency improvement or additional deployment of demand-side technologies and vice versa. By incorporating both types of technologies in an integrated modelling framework, it is estimated that as much as 4.5 billion tonnes of annual GHG emissions reductions in CO_2-eq could have been overestimated by 2050 by reporting the benefits from one side only.

5. Decarbonisation of electricity should accompany electrification of transportation, especially in the regions that rely heavily on fossil fuel-based electricity.

The results show that there are wide variations in the effectiveness of low-carbon energy technologies among the 9 regions considered due largely to the underlying electricity grid-mix difference. GHG mitigation strategies through low-carbon energy technologies need to factor in such differences in order to minimize trade-offs with other environmental objectives. For example, aggressive electrification of passenger transport in the regions that currently rely on coal and oil-based electricity would lead to an increase—rather than a decrease—in greenhouse gas emissions, particulate matter, and all other environmental impacts and natural resource impacts considered in this report.

6. Efficient information and communication technologies pose higher risks of rebound effects, potentially diminishing their benefits

Saving energy and thereby fuel-costs by using energy-efficient demand-side technologies can lead to increased consumption of those services, an outcome known as the "rebound effect." The analysis show that, for most efficient technologies in the buildings cluster, more than a 100% increase in demand for the same service is needed to completely nullify the present-day environmental co-benefits of low-carbon technologies. However, an increase in demand of less than 30% could negate their environmental benefits of efficient information and communication technology and passenger vehicles. In many cases, GHG emissions and other environmental and natural resource impacts are reduced less than direct energy consumption that is reduced when using efficient demand-side technologies. For the information and communication technologies included in this report, this means that if the demand for their services increases more than 11% due to rebound, all of the environmental or natural resource impacts considered will rise even if overall energy consumption declines.

TECHNOLOGY-SPECIFIC FINDINGS

This section elaborates on the environmental and natural resource impacts and benefits of demand-side technologies in the buildings, industry and transportation clusters.

Buildings cluster

7. Efficient lighting technologies provide significant GHG emissions reductions in addition to other environmental co-benefits

The results indicate that fluorescent light and LED technologies can reduce life-cycle GHG emissions by 60-85% as compared to incandescent lights, and provide substantial other environmental and resource co-benefits in all impact categories considered. On-going efficiency improvements to LED technologies in particular, combined with decarbonized electricity generation will contribute to even more substantial GHG emissions savings and environmental benefits in the future. By 2050, 90% penetration of LED lighting, along with these expected future advances in LED efficiency and decarbonized electricity generation, would allow the global demand for lighting services to grow by a factor of 2.5 - 3 while still reducing the total amount of energy consumed for lighting according to the IEA 2-degree scenario.

8. Additional deployment of building insulation technologies shows substantial GHG benefit and other environmental co-benefits, while showing relatively small additional metals and minerals consumption.

The building insulation technologies considered in this report exhibit 20-60% reduction in the life cycle GHG emissions associated with heating and cooling when deployed in buildings in both warm or cold climates. These technologies also provide co-benefits in most of the environmental impact categories. However, using some building insulation technologies to reduce energy consumption for thermal comfort can increase the consumption of metals and other materials over the life cycle of buildings.

9. Building Energy Management Systems (BEMS) have the potential to reduce energy consumption for space heating, particularly in the regions with moderate and cold climates

Estimates show that large-scale deployment of BEMS in regions of cold and moderate climates alone have the potential to avoid up to a half billion tonnes of CO2-eq per year of GHG emissions by 2050. By reducing the need for natural gas-based or electric heating, BEMS can save more GHG emissions than required for their production and use. As a result, this technology can reduce the impacts of heating residential buildings by around 20% in 2050, and can enable co-benefits in particulate pollution, metal consumption and human and ecosystem health impacts.

10. Efficient information and communications technologies such as computers, smartphones, televisions and displays have moderate potential to reduce GHG emissions and other impacts

Information and communications technology, including computers, the internet, smart phones, gaming, and television, is consuming increasing amounts of energy worldwide. Information and communications technology can also enable energy efficiency through demand-side management and shifting to cloud-based services. For consumer electronics, the greatest environmental benefits can be achieved by replacing inefficient devices whose use-phase energy contributes the largest proportion of their total environmental impacts. Examples include efficient liquid crystal displays and plasma display panels as well as more efficient desktop personal computers. Efficient smartphones show more limited potential for environmental savings as their use phase energy consumption contributes a relatively small portion of overall impacts.

Industry cluster

11. Efficient copper production based on flash furnace-based smelting technologies can substantially reduce the GHG emissions and toxic impacts associated with copper

Replacing existing shaft furnace-based copper smelting technologies with the best available technologies, particularly flash furnace-based smelting, has the opportunity to substantially reduce the life cycle GHG emissions of refined copper while also reducing air pollution, human health impacts, and other environmental impacts. Future efficiency improvements to flash furnace-based copper refining along with the potential decarbonisation of electricity can further reduce the GHG emissions of refined copper by over 50% by 2050 relative to present-day impacts, and can lead to other environmental co-benefits.

12. Co-generation of heat and electricity using natural gas can reduce the GHG emissions and environmental impacts of industry in regions dominated by fossil-fuel electricity, although these benefits are reduced and eventually disappear as electricity is decarbonized

Distributed industrial co-generation systems that burn natural gas or diesel fuel can be used to provide process heat more efficiently while generating electricity for on-site and grid use. According to the International Energy Agency (IEA)'s scenarios, co-generation systems can save almost 2 exajoules of energy in the chemical and pulp and paper industries alone. In China, India, non-OECD Asia, Africa, and the Middle East, co-generation can reduce GHG emissions by 30-60% by generating process heat and displacing more carbon-intensive electricity. However, if electricity generation is decarbonized following the 2-degree C scenario, co-generation systems could actually increase GHG emissions and other environmental impacts in most regions by 2030.

Transportation cluster

13. Electrification of passenger transportation along with decarbonized electricity and efficiency improvements to freight modes can greatly reduce global GHG emissions and particulate pollution but may increase pressure on metal resources

Passenger and freight transportation contribute substantially to GHG emissions and air pollution around the globe. Under the 2-degree Celsius scenario, a transition towards electric passenger vehicles and trains and more efficient freight, combined with renewable and low-carbon electricity generation, has the potential to reduce total GHG emissions from passenger transportation by almost 7 billion tonnes per year compared to the 6-degree scenario, while accommodating the increased demand for passenger transportation expected by most scenarios. This transition also has the potential to reduce global particulate pollution by over 8 million tonnes per year measured in PM_{10} equivalency. Without further improvements to vehicle production and supply chain processes, high penetration of battery electric vehicles for personal transport could result in overall increases in metal demand and toxic emissions. Additionally, this analysis finds that decarbonisation of electricity should go hand-in-hand with vehicle electrification efforts to ensure GHG reductions and other environmental benefits.


©TinnyPhoto/Shutterstock.com

1. Introduction

Avoiding the most catastrophic impacts of climate change will require an urgent and substantial reduction of Greenhouse Gas (GHG) emissions over the coming decades. The Intergovernmental Panel on Climate Change underlined the need for limiting the rise in global mean temperature to under 2 degrees Celsius to avoid the most dangerous consequences of climate change, while a more ambitious target of limiting the global mean temperature increase to 1.5 degrees Celsius would be more desirable given the uncertainties around climate change (2). Following these recommendations, the Paris Agreement aims to ensure that GHG emissions will peak and begin to decline as soon as possible, reaching a balance between anthropogenic sources of emissions and natural emissions sinks by the second half of the century (3). Achieving these ambitious goals will require an unprecedented effort to deploy low-carbon technologies.

Under the 2-degree Celsius scenario, the global economy needs to limit carbon dioxide (CO_2) emissions to 16 Gt/year by 2050, which is about 42 Gt/year less than the 58 Gt/year CO_2 emissions anticipated under the 6-degree Celsius, business-as-usual scenario (4). Out of the 42 Gt reduction in annual CO_2 emissions, renewable energy, carbon capture and storage, and energy demand reductions combined are expected to contribute about 24 Gt/year. Approximately 60% of this 24 Gt reduction in annual CO_2 emission is expected to come from the energy supply-side, with the rest coming from demand-side measures (2). Clearly, a concerted effort to deploy both demand- and supply-side low-carbon technologies is crucial to meet the 2-degree Celsius target.

The diverse technologies required to meet these climate change mitigation targets have varying environmental impacts, resource requirements and costs. *Green Energy Choices*, a previous report by the International Resource Panel (1) assessed the environmental and natural resource implications of low-carbon electricity supply technologies under the 2-degree Celsius scenario. Building upon the previous report, the present report identifies the potential environmental and natural resource benefits, risks, and trade-offs of demand-side and energy efficiency technologies over the course of the International Energy Agency's 2-degree Celsius and 6-degree Celsius scenarios that cover 2010-2050 (4). A key objective of this report, in addition to assessing the environmental impacts of demand-side technologies, is to integrate the results of the previous report to understand the combined effects of low-carbon energy supply and efficient demand-side technologies when deployed together under the 2-degree Celsius scenario and the 6-degree Celsius baseline scenario. This report also highlights technologies that have significant co-benefits in their life-cycle environmental and resource impacts, characteristics that would strengthen support for GHG emission mitigation policies.

Energy efficiency and demand-side technologies are often viewed as desirable due to their potential to reduce emissions while also saving costs. Demand-side technologies, however, have rarely been deployed at their full potential even when cost savings are expected, a phenomenon referred to as the 'efficiency gap' (5, 6). For example, energy efficiency projects that require substantial upfront investment in infrastructure can make demand reductions especially challenging in developing nations where access to capital is often limited. A variety of policies and business models, such as energy service companies (ESCO), have been designed to address this gap by supporting investments in energy efficiency with partial success thus far. Closing the efficiency gap would require strengthening international cooperation, energy efficiency governance, political attention, and regulatory innovations at all levels to accelerate uptake and deployment of low-carbon technologies.

Another consideration when assessing energy efficiency and demand-side technologies is the 'rebound effect.' When demand-side technologies save energy or fuel costs, the rebound effect, that is, consuming more of the service provided by an efficient technology, can erode the energy and environmental savings gained from increased efficiency (7, 8). In developing countries, such rebound effects are expected as income increases, and can lead to greater wellbeing through, for example, increased thermal comfort, mobility and provision of lighting. Thus, it is important to assess the extent to which rebound can increase the demand for services while still ensuring the environmental and natural resource benefits of demand-side technologies and decarbonisation that are required to meet the 2-degree Celsius target.

The global transition toward low-carbon energy supply- and demand-side technologies warrants a careful assessment of the potential unintended consequences of those technologies on other environmental impacts and natural resources. Additionally, many of these low-carbon technologies are rapidly changing in terms of their capabilities, costs, and likely their environmental and resource impacts. Further, the environmental and resource co-benefits, trade-offs and costs of these technologies may also vary among regions due to differences in the level of economic development, climate, electricity generation mix and materials production systems. Therefore, it is crucial that the analysis account for temporal and regional differences when assessing the environmental and resource implications of these technologies. Lastly, since energy supply and demand-side technologies must change simultaneously, it is important to understand how changes in one can influence the environmental impacts in the life cycle of the other, possibly compounding the benefits or trade-offs of both.

This report uses life cycle assessment to quantify the environmental and natural resource impacts of GHG emissions mitigation technologies through the deployment of demand-side technologies at a global level, and integrates the results with the previous report on electricity supply technologies (1). When combined, the underlying analysis covers over 60 supply-side and demand-side technologies and their deployment in nine regions defined by the International Energy Agency at three different times: 2010, 2030, and 2050. The report also evaluates the risks of the rebound effect by deploying demand-side technologies. This report can help to design policies for mitigating the potential unintended consequences of large-scale transitions toward a low-carbon society.

In this report, the term 'demand-side technologies' is used broadly to include the following: 1) deploying energy efficient technologies (e.g. using light-emitting diode bulbs) that provide the same service while consuming less energy, 2) the deployment of infrastructure like improved building shell insulation that reduces the need for heating and cooling energy, and 3) fuel and mode switching (e.g. using electric vehicles or public transportation to replace petroleum vehicles). Specifically, this report quantifies the environmental, human health and natural resource impacts of more than 30 demand-side energy efficiency technologies across the following technological clusters:

(1) lighting,

(2) building shell,

(3) demand-side energy management,

(4) information and communications technology,

(5) copper production,

(6) co-generation,

(7) passenger transportation, and

(8) freight transportation.

This report is the second report of the series and represents the first comprehensive global-scale assessment of the life-cycle environmental and resource implications of a wide range of supply- and demand-side GHG mitigation technologies in an integrated fashion. The analysis in this report is based on coordinated research efforts that culminated in the publication of a special issue of the Journal of Industrial Ecology on demand-side technologies (9, 10). The open-source articles published in this special issue are intended to serve as the technical basis for this report, and can be referred to for additional information on the data, assumptions and more detailed technical descriptions of the results (9–15).

2. Selection of Demand-Side Technologies

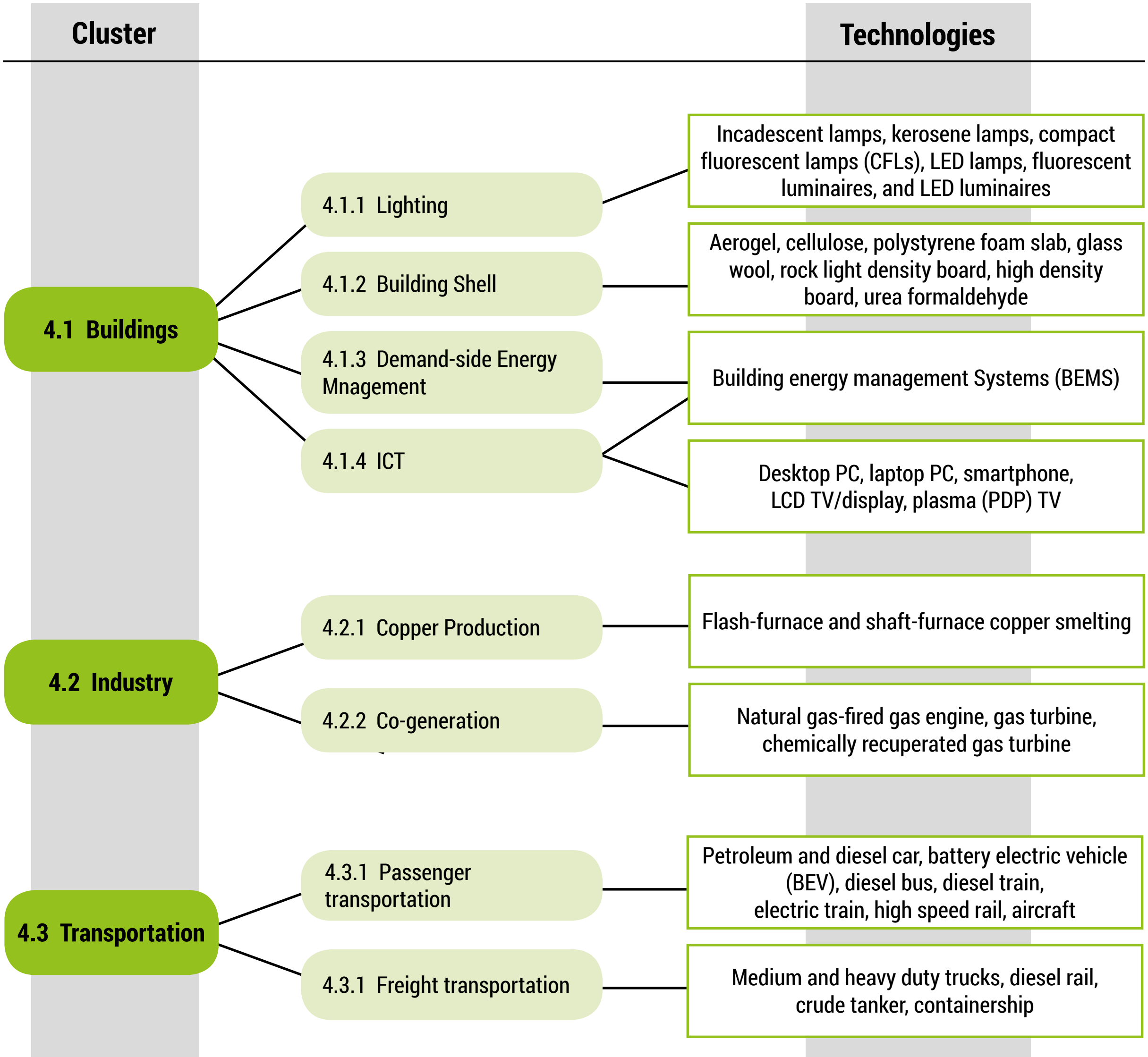
The analysis in this report already incorporates the many technologies studied in the previous International Resource Panel report on electricity supply (4) (see Table 1), and therefore elaborated here is the selection of energy efficiency and demand-side technologies. Energy efficiency and demand-side GHG mitigation technologies are numerous and diverse. Therefore, this report aims to cover many of the major technologies contributing to climate mitigation in the coming decades within the pool of available experts and resources committed to this study. First, the literature was reviewed to identify relevant low-carbon technologies. Key resources that were consulted include the Pathways to a Low-Carbon Economy by McKinsey & Company (16), the International Energy Agency's technology roadmaps (17), and previous Assessment Reports by the Intergovernmental Panel on Climate Change (IPCC) (18, 19). The technologies that contribute significantly to the overall reduction in GHG emissions were prioritized. In addition, the following criteria were considered to further narrow down the target technologies for this assessment:

- **Data availability:** the data needed for the assessment should be accessible within the resources available for this study.
- **Technological maturity:** proven technologies with higher maturity receive a priority.
- **Novelty of assessment**: technologies that have received less attention in previous literature are prioritized. In the same vein, the technologies that are already covered by existing or planned International Resource Panel reports are excluded.
- **Availability of expert contributors:** our ability to collect detailed technology-specific data depends on the availability of experts willing to contribute to our report.

As a result, 8 technological clusters were identified, under which over 30 technologies were analyzed. Some technologies with limited technological maturity or data accessibility, or technologies that have been studied extensively by previous analyses have been excluded from the scope of the assessment even if their potential to reduce GHG emissions appeared significant. Further, the technologies that have already been covered by other International Resource Panel reports (biomass, land and soil, agriculture and forest, and recycling) are also excluded.

Figure 1 shows the list of technologies examined in this report. Some of these technologies are only included in the assessment of the 2-degree Celsius scenario while only the most relevant technologies are highlighted for individual comparison.

FIGURE 1. Demand-side technologies selected for analysis and organized by cluster. Numbers represent the sections where each cluster and technology is covered.



The technologies selected in this study are, of necessity, only a subset of the entire spectrum of energy efficiency and demand-side technologies that are or will become available for GHG emission mitigation. However, these technologies are expected to contribute a substantial portion of the overall GHG emissions mitigation anticipated by the International Energy Agency scenarios for demand-side technologies.

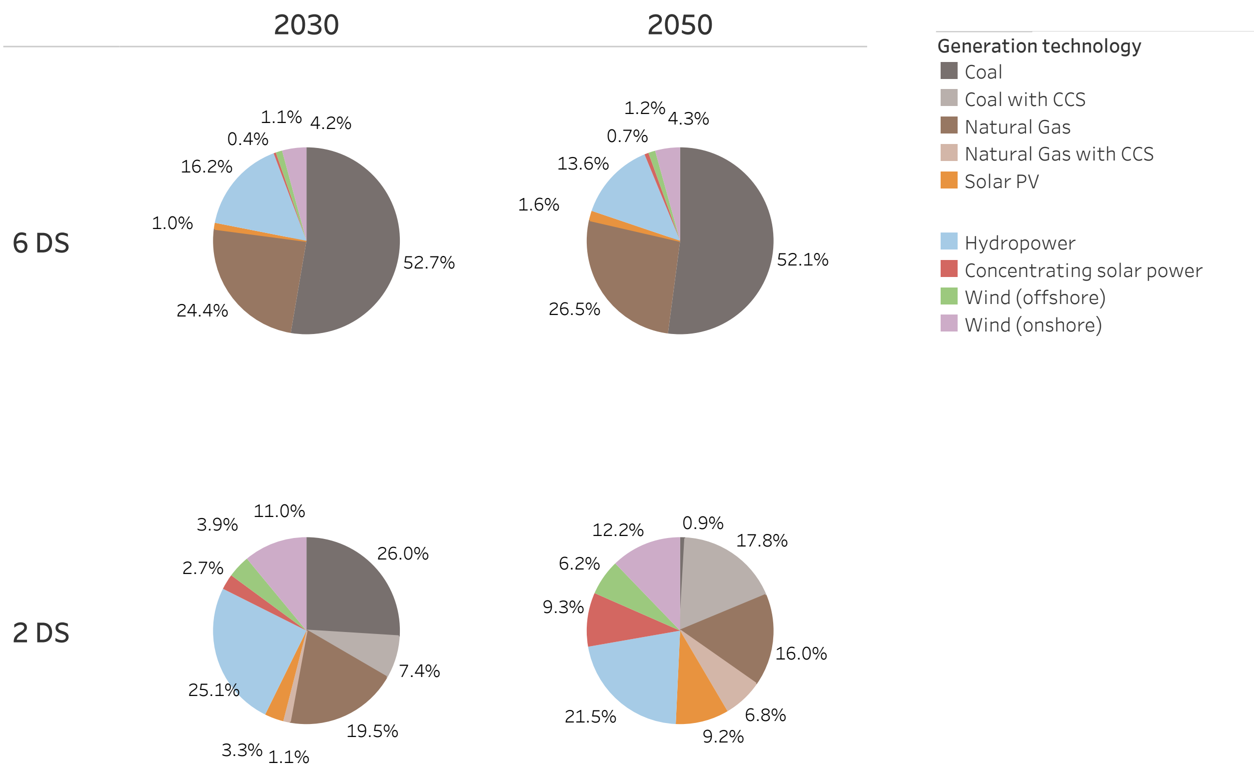
TABLE 2. Supply-side electricity generation technologies included in analysis

Fuel	Technology
Coal	Existing pulverized coal
Coal	Integrated gasification combined cycle
Coal	Supercritical pulverized coal
Coal	Supercritical pulverized coal with carbon capture and storage
Coal	Integrated gasification combined cycle with carbon capture and storage
Natural Gas	Natural gas combined cycle
Natural Gas	Natural gas combined cycle with carbon capture and storage
Photovoltaic solar	Polycrystalline silicon (ground-mounted)
Photovoltaic solar	Polycrystalline silicon (roof-mounted)
Photovoltaic solar	Cadmium telluride (ground-mounted)
Photovoltaic solar	Cadmium telluride (roof-mounted)
Photovoltaic solar	Copper indium gallium selenide (ground-mounted)
Photovoltaic solar	Copper indium gallium selenide (roof-mounted)
Concentrating Solar	Concentrating solar power– parabolic trough
Concentrating Solar	Concentrating solar power – power tower
Hydropower	360 MW dam with reservoir
Hydropower	660 MW dam with reservoir
Wind	Onshore wind
Wind	Offshore wind (steel foundation)
Wind	Offshore wind (gravity-based foundation)

3. Methods and Data

Life cycle assessment coupled with the International Energy Agency's 2-degree and 6-degree Celsius scenarios serves as the overall framework for assessing the environmental and resource implications of low-carbon technologies. Life cycle assessment is a tool to quantify the environmental and resource impacts of a product system by taking into account the total life cycle of the product from raw material extraction, to production, use, and end-of-life (20). Life cycle assessment is useful as a holistic appraisal of the environmental and resource impacts that arise from energy systems and technological transitions, and life cycle assessment results can provide policy makers an excellent spring board for the discussion of environmental trade-offs (21, 22). However, life cycle assessment findings are dependent on methodological choices and data from a wide variety of sources (21). Thus, this report attempts to provide as much transparency as possible on methods and data by using open-source articles from the *Journal of Industrial Ecology* special issue on demand-side technologies as the basis for this analysis (9). Furthermore, it should be noted that life cycle assessment studies traditionally do not offer value-based judgements comparing, for example, the trade-offs between GHG emissions reduction and resource consumption, but rather seek to organize and bring to light information on technologies' environmental impacts that can inform decision making.

FIGURE 2 **Snapshot of electricity mixes assumed under the International Energy Agency (IEA) scenarios.**
CCS=Carbon capture and storage; 2DS=2-degree Celsius scenario; 6DS=6-degree Celsius scenario; PV=Photovoltaic.



Selected technologies are evaluated based on (a) the service provided by each technology, and (b) projected total demand for the service they provide per year (e.g., passenger kilometres travelled per year). The present day and future impact results for each technology under the 2-degree Celsius and 6-degree Celsius scenarios are then calculated using an integrated life cycle assessment framework that incorporates the electricity generation technologies analysed in the previous International Resource Panel report, *Green Energy Choices*, into the supply

chain of the demand-side technologies analysed (1). This integrated analysis simulates how the impacts of providing key services using energy efficient technologies in the buildings, transport and industrial sectors will change under a transition to low-carbon electricity. This transition to low-carbon electricity encompasses all electricity used in the supply chain of producing demand-side technologies, as well as the electricity directly used by those technologies. Lastly, the additional environmental and natural resource benefits achieved under a 2-degree Celsius world are estimated by comparing the results of the 2-degree and 6-degree Celsius scenarios in 2030 and 2050, and the combined effects of demand-side and supply-side technologies on environmental and resource impacts are analysed using this scenario analysis.

Each of the technologies chosen is analysed using consistent data, system definition, and long-term electricity supply scenarios (23). Quantitative data on the bill of materials, resource use, environmental emissions, and product use and disposal patterns for the energy efficiency and demand-side technologies are collected for the present day, and, if possible, estimated for the years 2030 and 2050. Using the data collected, life cycle assessment results were computed for years 2010-2050 using an integrated hybrid life cycle assessment framework (24, 25) that combines detailed process life cycle assessment models, with multi-regional input-output analysis (23, 26). This model and its underlying data are consistent with those used in *Green Energy Choices*, the previous International Resource Panel report on supply-side technologies, allowing for a ready comparison and integration of results (1). In particular, the base year 2010 electricity mix is used for a consistent comparison of impacts between reports.

The underlying data used for the model capture variations in life-cycle impacts resulting from regional differences in electricity generation and materials production, and provide life-cycle impact results for each of the 9 International Energy Agency regions: China, India, Organisation for Economic Co-operation and Development (OECD) Europe, OECD North America, OECD Pacific (e.g. Japan, South Korea and Australia), Economies in Transition (i.e. the former Soviet Union), Latin America, non-OECD Asia, and Africa and the Middle East. Further, the environmental impacts of demand-side technologies will change as those technologies improve over time and as renewable and low-carbon technologies begin to provide a greater portion of global electricity following the electricity mix projections of the International Energy Agency's 2-degree and 6-degree Celsius scenarios (4) (See Figure 2). To accommodate these transitions, quantitative estimates of the changing resource requirements, technological capabilities, and environmental impacts of the production, use, and end-of-life of different demand-side technologies are collected from the present to 2050 using various technology roadmap scenarios and trajectories for materials and energy efficiency improvements (27–29). Notably, projections from (29) were used to model potential improvements to the energy efficiency, materials efficiency and emissions standards of bulk materials production processes and their environmental impacts from 2010-2050. Long-term improvements to both fossil fuel-based and renewable electricity generation technologies and their resultant environmental and natural resource impacts are based on the analysis done for the preceding International Resource Panel report (1).

The model and the data estimate the amount of environmental emissions and natural resources consumption by each energy efficiency and demand-side technology, referred to as the life cycle inventory. These results are then aggregated into impact categories using the ReCiPe 2008 life cycle impact assessment method (30). The present report uses ReCiPe's hierarchist perspective that considers a 100-year timeframe for impacts. The following impact categories are analysed in this study, consistent with the previous International Resource Panel report on low-carbon electricity generation technologies:

- climate change (kg CO_2-eq)
- particulate matter formation (kg PM_{10}-eq)
- freshwater ecotoxicity (kg 1,4 dichlorobenzene (DCB)-eq)
- freshwater eutrophication (kg Phosphorus (P)-eq)
- human toxicity (kg 1,4 dichlorobenzene (DCB)-eq)
- metal consumption (kg Iron (Fe)-eq)
- water consumption (cubic meters (m^3))
- land occupation (square kilometres (km^2))

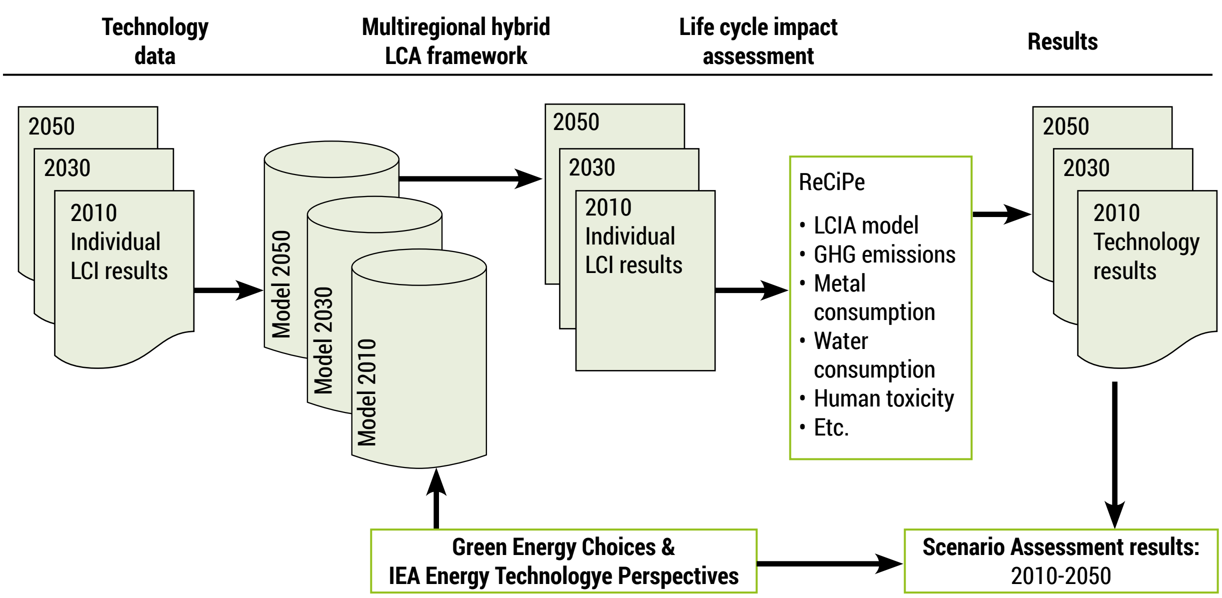
The method that aggregates pollutants emission and resources consumption is referred to as 'characterisation' in life cycle impact assessment. Each impact category uses one reference pollutant (e.g., CO_2 for climate change) or a resource (iron for metal consumption) to quantify the impacts of various pollutants or resources that contribute to the impact category using a common metric. A well-known challenge when assessing human and ecosystem toxicity is that long-term emissions of heavy metals during the disposal of sulfidic mine tailings can dominate potential impacts (31). For this reason, a common practice is to remove such emissions in the ecoinvent database (32). For metal resources, the ReCiPe method (30) puts different metals into the common unit of "kg of iron equivalent" based on the potential loss of resource quality. Resource quality is measured by estimating the cost increases from depleting the most economical sources of those metals. For example, because copper ore-grades are generally declining faster than those of iron, and thus copper consumption is weighted 43 times higher than iron. Therefore, under this method, 1 kg of copper is equivalent to 43 kg iron (Fe-equivalent). It is also important to note that the metal consumption indicator does not include all metals, but focuses on bulk metals (e.g. copper, iron, aluminium) and commonly used precious and by-product metals (e.g. gold, silver, molybdenum) and omits some of the other metals used over the life cycle of the technologies studied in this report, for example rare earth elements and other by-product metals like in indium and gallium. Resources not covered under this indicator are discussed on a technology-by-technology basis.

Figure 3 shows the overall process under which the environmental and resource impacts are calculated for each technology in 2010, 2030 and 2050 under the 2-degree Celsius and 6-degree Celsius scenarios.

It is important to note that not all demand-side technologies that are applicable under the 2-degree Celsius scenario could be modelled in the scope of this report. Other technologies, including further improvements to industrial sectors like iron, steel, and cement, and other building efficiency technologies like heat pumps, solar hot water heating, and efficient appliances are not included in the results. Furthermore, the current analysis aims to understand the overall trend of environmental and resource impacts of low-carbon technologies at a global-scale using aggregate measures through ReCiPe characterization models. Therefore, the risks of ecosystem and human health impacts associated with a pollutant in a particular location and time cannot be evaluated solely using the methods of this report. While the current study made a significant effort in collecting and analysing a large amount of data, future data collection and research regarding rare earth and by-product metal use and toxic emissions could build upon and improve the insights gained from this analysis.

FIGURE 3. The approach used for assessment of energy efficiency technologies and long-term scenarios.

Individual life cycle inventory (LCI) results refer to the compiled list of life-cycle emissions from each technology assessed. LCA=Life cycle assessment; LCIA=Life cycle impact assessment; IEA= International Energy Agency.



4. Technology-Specific Results

This section presents the life cycle assessment results for each technology in the buildings, industry, and transportation clusters. The life cycle impact assessment results for individual technologies are then compared to the environmental and resource impacts of providing the same service using the less efficient, baseline technology that they are designed to replace. For example, efficient light-source technologies are compared to standard incandescent lamps, and more efficient passenger transportation modes are compared to typical gasoline passenger cars that provide the same amount of service. The results in this section focus on the current status of technologies, while the overall comparison and scenario assessments in chapters 5 and 6 consider technological changes to demand-side technologies and the wider economy.

In this section, Figures 4-10 show the percent change in impact i from using an efficient demand-side technology j (expressed as $\Delta\, I_{ij}$). This is calculated as the difference between the life-cycle impact on impact category i of the efficient technology j (I_{ij}) and the less efficient, baseline technology j (I_{ij}) that provides the same amount of service. This difference is then divided by the impact i of the baseline technology, such that:

$$\Delta\, I_{ij} = \left(\frac{I^*_{ij} - I_{ij}}{I_{ij}}\right)\times 100\% \quad \text{(Eq. 1)}$$

Thus, a negative result represents an environmental benefit while a positive result represents an additional environmental impact for the technology-impact combination. Results are calculated for each of the 9 International Energy Agency regions, all of which are represented by the horizontal lines in each bar. The displayed results for the 9 regions vary because of differences in regional electricity mixes and materials production technologies. Each horizontal line represents the effect for one of the 9 regions, and in some cases the lines overlap because the effects are equivalent.

4.1 BUILDINGS

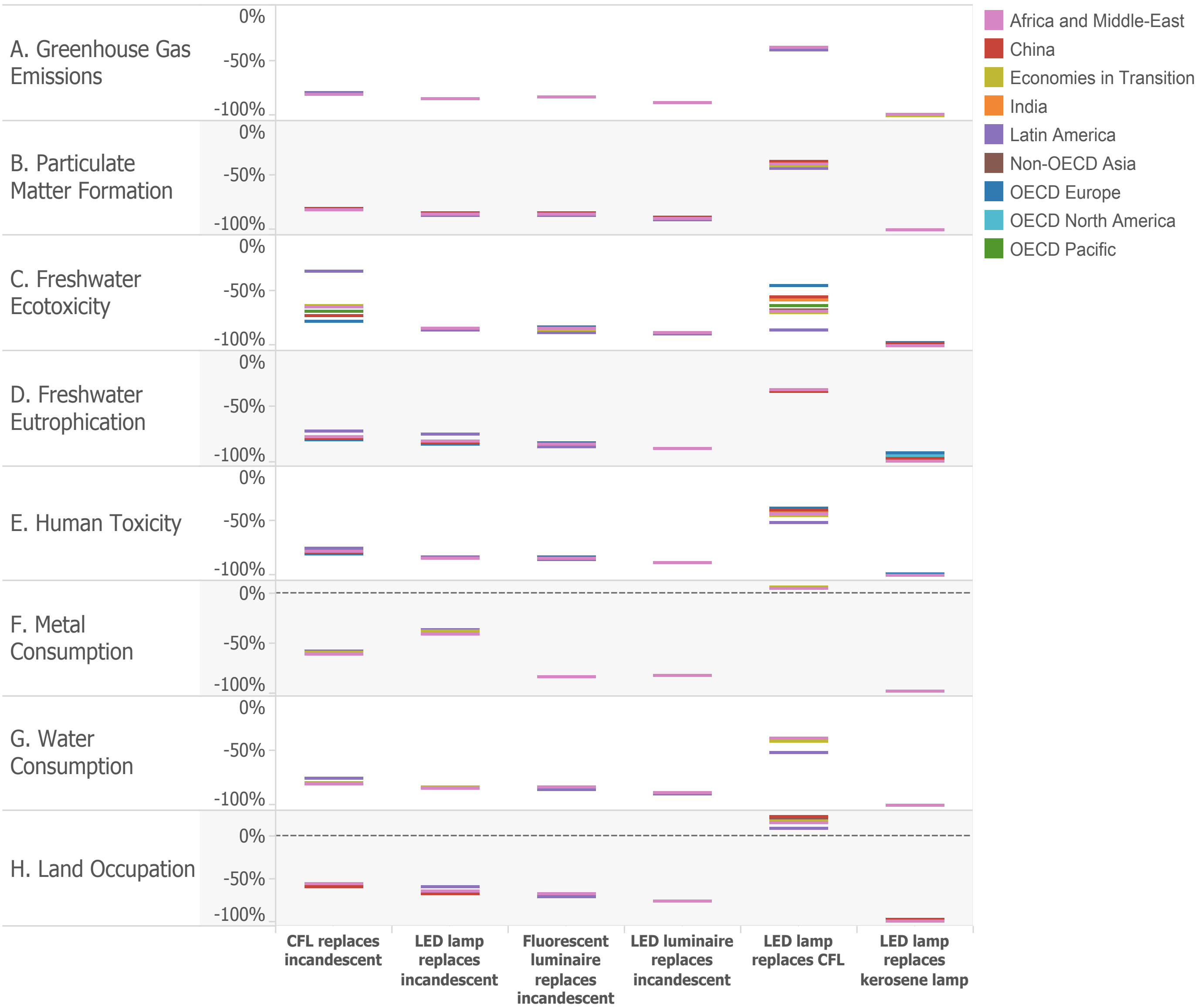
The building sector shows a strong potential for GHG emissions mitigation, with studies by others suggesting that building envelope improvements, demand-side energy management, lighting, and space and water heating could save 20-25 exajoules of energy per year globally by 2050 (27). Considering these potential savings, this report addresses efficient light-emitting diode (LED) and fluorescent light-source technologies, building insulation, and smart building energy management systems.

This section focuses on technological solutions to building efficiency, assuming that building efficiency improvements reduce energy consumption as expected. In practice, it is necessary to note that design, verification, and management are needed to ensure that efficiency measures in the building sector perform up to specifications. Case studies have shown that retrofitted green buildings have the potential to substantially reduce energy consumption and GHG emissions (33), but building retrofit projects must be monitored and evaluated on a case-by-case basis to ensure energy savings and return on investment (34).

4.1.1 Efficient Lighting

As compared to incandescent light bulbs, fluorescent and LED technologies can reduce life-cycle GHG emissions by 60-85% along with environmental and resource co-benefits in all impact categories considered. On-going efficiency improvements to LED technologies in particular combined with decarbonized electricity generation will contribute to even more substantial GHG emissions savings and environmental benefits in the future. By 2050, 90% penetration of LED lighting, along with these expected future advances in LED efficiency and decarbonized electricity generation, would allow the global demand for lighting services to grow by a factor of 2.5 - 3 while still reducing the total amount of energy consumed for lighting prescribed by the International Energy Agency's 2-degree Celsius scenario.

FIGURE 4. Change in environmental and natural resource impacts from the introduction of efficient demand-side lighting technologies within each of the 9 International Energy Agency regions compared to the indicated conventional alternatives in 2010.
CFL=Compact fluorescent lamps; LED=Light-emitting diode.



Artificial lighting currently represents around 17% of electricity demand globally (28). As the demand for artificial lighting continues to grow over the coming decades, particularly in developing countries, efficient light-sources such LEDs have the opportunity to reduce the energy required for lighting services, and thus its environmental impacts. LED light-source technologies used in residential, commercial, and industrial applications will continue to see drastic improvements in luminous efficacy (energy required per unit of illumination), leading towards a reduction in the environmental footprint of lighting. This analysis compares compact fluorescent lamps and LED lamps (commonly referred to as bulbs) and fluorescent and LED luminaires based on the amount of illumination provided over time (measured in lumen-hours). Luminaires are complete lighting units most commonly used in commercial applications.

Figure 4 shows that efficient light sources, particularly LEDs, reduce GHG emissions in all global regions at present (35–37). Improving the luminous efficacy of LEDs from around 50-100 lumens per Watt (lm/W) today to over 250

lm/W by 2050, increasing device longevity, and decarbonizing electricity under the International Energy Agency's 2-degree Celsius scenario would lead to greater than 95% reductions in the environmental impacts of providing lighting services in most impact categories (75% reduction in metal consumption) compared to incandescent lighting (11, 28, 38). By 2050, 90% adoption of LED lighting globally combined with these expected technological improvements can reduce the aggregate annual life-cycle GHG emissions of global light provision by more than a factor of seven under the International Energy Agency's 2-degree Celsius scenario (11, 27). Estimates of the technological capability and market penetration of efficient light sources show that a 2.5 - 2.9 times growth in the global demand for lighting services can be accommodated while still meeting International Energy Agency's GHG emission mitigation goals for lighting technologies and stabilizing aggregate annual metal consumption measured as by ReCiPe only 20% above 2010 levels (3, 11).

Figure 4 also shows that replacing less efficient lighting technologies with more efficient ones reduces impacts by more than half in most cases. Replacing kerosene lamps (still widely used in non-OECD regions) with LED lamps showed the most significant reductions in all environmental impact categories.

While LED technologies generally show lower metal consumption impacts than incandescent and fluorescent lighting, they may require rare earths and other critical metals including indium and gallium for LED chips (39). Fluorescent and compact fluorescent light sources, in addition to some LEDs, use phosphor coatings to produce a desirable profile of visible light. Phosphor coatings generally require rare earth metals, which can contribute to metal consumption (35). Recent and expected future advances in LEDs involve colour mixing that may eliminate the need for phosphors on LED light sources, leading to further decrease the metal requirements of LED lamps.

Figure 4 shows that variations across regions are small in most impact categories except for freshwater ecotoxicity. The inter-regional variations in freshwater ecotoxicity results in Figure 4 are associated primarily with the regional disparity in electricity grid-mixes. For example, Figure 4 shows that Latin America enjoys the least freshwater ecotoxicity benefits among the world regions from replacing incandescent light bulbs with compact fluorescent lamps because the electricity in Latin America, which is predominantly hydropower, is already relatively clean. Thus, reducing use-phase electricity consumption achieves relatively little freshwater ecotoxicity benefits. On the other hand, the freshwater ecotoxicity benefit of replacing compact fluorescent lamps with LEDs is largest in Latin America, as a significant part of the impact is associated with the electricity consumption during the manufacturing of LED lamps, the impacts of which can be mitigated when produced locally.

4.1.2 Building Shell

The building insulation technologies considered in this report exhibit 30-50% reductions in the life-cycle GHG emissions associated with heating and cooling when deployed in buildings in either warm or cold climates for most regions. The greatest reductions can be observed for buildings that require both cooling and heating in developing regions with typically low levels of existing insulation (i.e. Asia, India, Africa, and the Middle East). Insulation technologies also provide co-benefits in most of the environmental impact categories. However, using some building insulation technologies to reduce energy consumption for thermal comfort can increase the consumption of metals and other materials over the life cycle of buildings.

A majority of existing buildings will still be standing in 2050, particularly in the developed world. Retrofits to building envelopes, namely added insulation, can help reduce energy demand for space heating and space cooling. Present-day insulation technologies can be effective at achieving energy savings, and emerging technologies like silica aerogels may become increasingly viable for achieving energy and environmental savings in the future with minimal insulation thickness as their insulation efficacy improves (40, 41).

Throughout the world, improving building shell insulation has the potential to save 6 exajoules of energy per year out of a total of 40 exajoules for all space heating and cooling by 2050 under the International Energy Agency's 2-degree Celsius scenario compared to business-as-usual (4). Retrofitting existing buildings with additional insulation requires producing, installing, and disposing of such insulation materials, which contribute to environmental impacts.

In this study, life-cycle models are constructed using life cycle assessment databases and literature (32, 41), and the environmental and natural resource impacts of the following common building insulation materials are compared:

- rock board (mineral wool) insulation,
- polystyrene foam slabs,
- glass wool,
- cellulose, and
- silica aerogels.

Silica aerogels are an emerging type of insulation material that are already in commercial use. In the long term, aerogels are expected to insulate buildings' walls and windows with minimal thickness compared to today's average technologies, but few estimates of their comprehensive life-cycle impacts exist (41, 42). The potential future environmental and resource impacts of producing silica aerogels are based on estimates of their long-term potential thermal performance from peer-reviewed literature as well as potential improvements in production processes estimated from life cycle assessment sources (41, 42). For scenario analysis, the present and future mix of space heating provided by natural gas, electricity and biomass in each region was provided by the International Energy Agency scenarios (27).

The energy savings gained by adding insulation to buildings depend on climate as well as the amount of insulation present in existing buildings, also referred to as a building's thermal resistance which is measured in terms of R-value (m^2 Degree-Kelvin/Watt). Data on heating degree-days and cooling degree-days for major cities of warm and cold climates in each region, along with estimates of typical R-values of walls and ceilings in existing residential and commercial buildings (43–51) were used to estimate the baseline energy consumption for heating and cooling in each region considered for analysis. The reduced heating cooling demand in each region were then calculated for existing average residential and commercial buildings with an additional R=1 m^2K/W, which represents an aggressive improvement to building insulation. It is important to note that energy savings from additional insulation follow the law of diminishing returns, meaning that adding another R=1 of insulation would save less energy than the initial retrofit (27). Appendix tables A3 and A4 list the major cities considered in each IEA region and their estimated annual energy savings from added insulation. Based on these calculated energy savings and the expected 15-year insulation lifetime Figure 5 presents the relative change in environmental impacts of heating and cooling typical buildings by adding an additional R=1 m^2 Degree-Kelvin/Watt using different insulation types. The results presented in Figure 5 apply to buildings in major cities with warm and cold climates in each of the nine International Energy Agency regions as compared to the life-cycle impact of using natural gas boilers

for heating and electricity for cooling. Other energy sources are commonly used for space heating, including electricity and biomass, are considered in the scenario analysis but not presented here as a basis for comparison. It is important to note that modelled energy efficiency gains from insulation and other measures are sometimes not realized fully because of occupancy behaviour or inadequate design and construction. Often, monitoring and verification are needed to ensure efficient building performance (52).

FIGURE 5. Change in environmental and natural resource impacts of heating and cooling buildings in each of the 9 International Energy Agency regions by the introduction of building insulation technologies compared to typical buildings using natural gas boilers and electric cooling.

CFL=Compact fluorescent lamps; LED=Light-emitting diode.

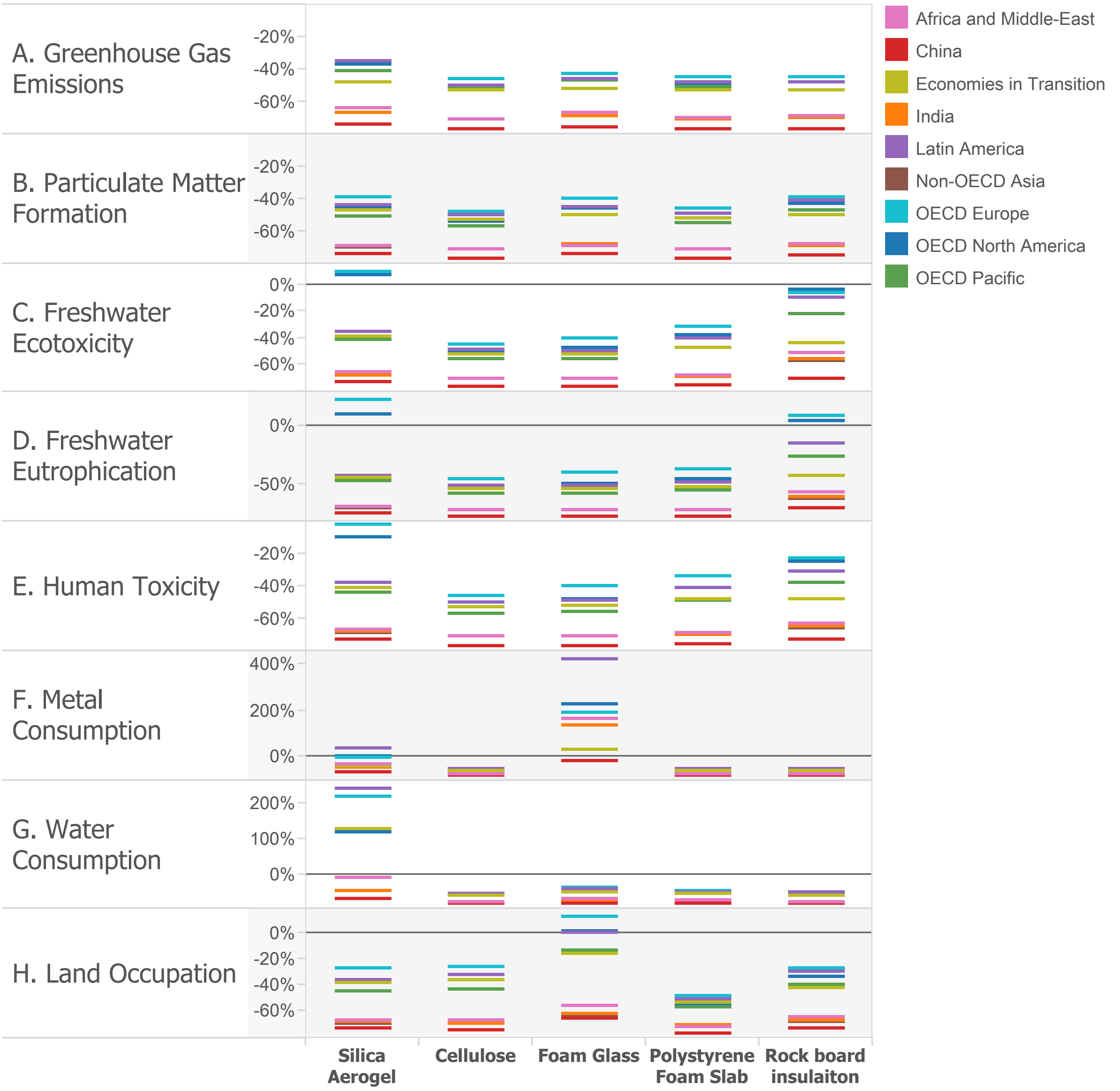


Figure 5 indicates that most insulation technologies can provide energy savings with lower life-cycle environmental and resource impacts than providing heating with natural gas or electricity or cooling with electricity. Heating oil was not considered in this analysis. Some technologies like current silica aerogels and foam glass insulation materials, however, require more metals in 2010 than heating from natural gas. Higher metal consumption for

foam glass insulation shown in Figure 5 is due to the metal inputs that are either melted and used as additives in the glass oven (e.g. manganese) or are consumed through wear during the production process (molybdenum electrodes and chromium trimming blades). In some regions silica aerogels show higher particulate matter formation due to the contributions from coal-intensive electricity of those regions. Silica and solvent production are reasonably energy intensive processes, and as the particulate matter emissions from natural gas heating, which is the denominator (I_{ij}) of Eq.1, is already low, the relative impact of silica aerogels on particulate matter emissions becomes higher.

As shown in Figure 5, insulation technologies exhibit large inter-regional variations in the results. In particular, China, India, Africa, Middle East and Developing Asia show largest environmental co-benefits from insulation for most of the impact categories considered. This is due to the typically lower level of building insulation in these regions (46-51).

While the environmental payback of building shell retrofits should be evaluated on a case-by-case basis, this analysis provides evidence that building shell retrofits can generally achieve environmental savings in buildings requiring heating or cooling in all climates and International Energy Agency regions. Improved roof and wall insulation is just one of several ways to improve building energy performance. This report does not cover all possible energy saving measures such as improved windows and doors, thermal mass, and passive design that could further reduce energy consumption for space heating and cooling.

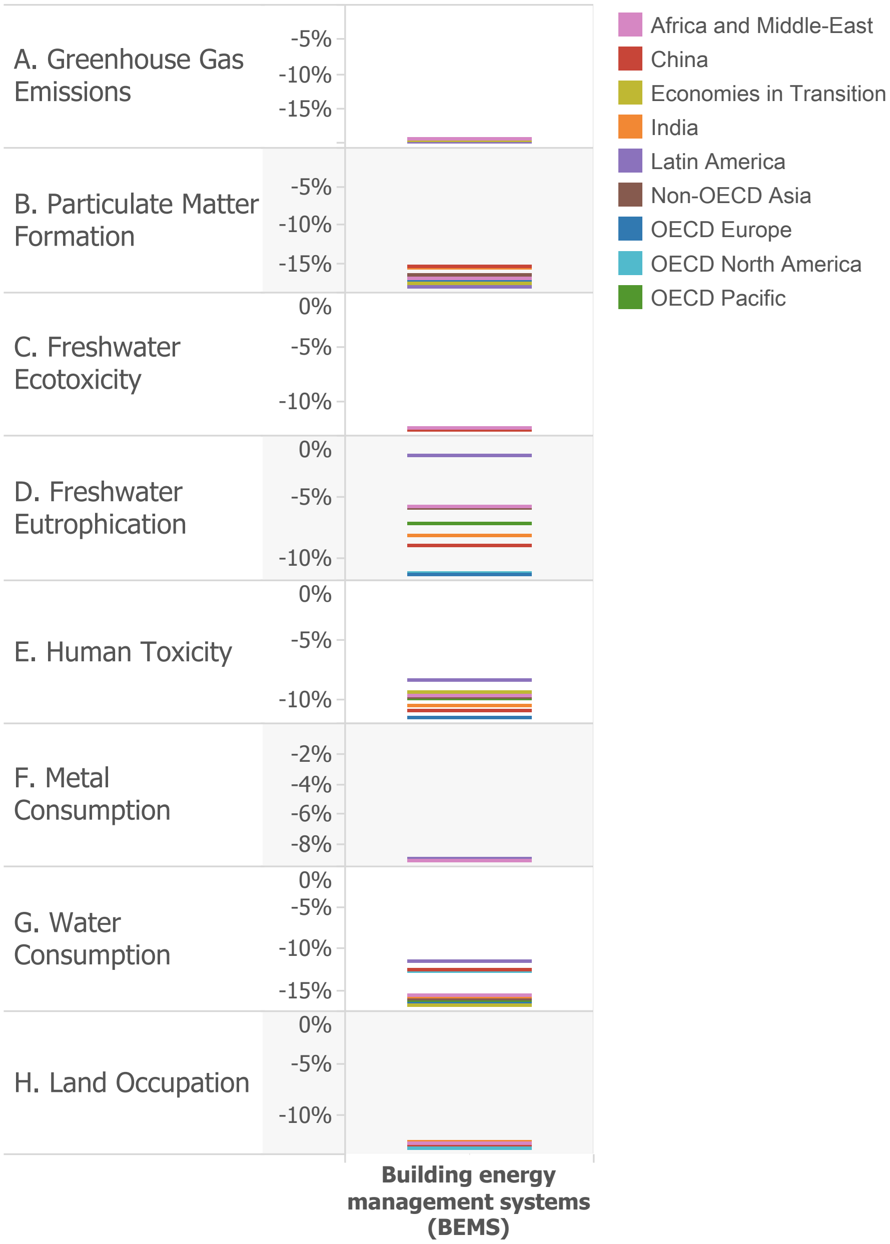
4.1.3 Demand-Side Energy Management

Demand-side energy management technologies, specifically the Building Energy Management Systems analysed in this report, have the potential to reduce energy consumption for space heating in regions with moderate and cold climates at a low upfront cost by adapting heating energy consumption to weather patterns, user demand profiles and building physics. Estimates show that large-scale deployment of Building Energy Management Systems in regions of cold and moderate climates have the potential to avoid up to a half billion tonnes of GHG emissions per year by 2050. By reducing the need for natural gas-based or electric heating, Building Energy Management Systems can save more GHG emissions than required for their production and use, and enable co-benefits in particulate pollution, metal consumption and human and ecosystem health impacts.

Building Energy Management Systems are a potentially viable technology for reducing energy consumption and GHG emissions in countries with cold and moderate climates that have a large stock of multi-story buildings with central heating systems. Previous assessments have shown that smart thermostats and Building Energy Management Systems can potentially save 20-40% of space heating energy (53–56). The Building Energy Management Systems considered in this report can control heating energy consumption at the apartment or room level by adapting to usage patterns, weather predictions and building design. Building Energy Management Systems can also control other building functions such as lighting and ventilation, however this chapter focuses on their ability to reduce heating energy consumption. Building Energy Management Systems can be combined with most existing space heating systems, as well as other efficiency measures like building insulation, and they are attractive due to their low up-front costs. The life cycle assessment presented in this report is based on information from Building Energy Management Systems manufacturers on the material composition of devices (57, 58) and generic life cycle inventory data for electronic components assembled by Beucker and colleagues (12). Energy savings are estimated based on reported savings from deployed Building Energy Management Systems that include not only smart thermostats but devices that can control heating demands on a room level in complex building structures (53, 54). Using Building Energy Management Systems to manage a typical 100 m^2 apartment would consume around 35 kWh per year of electricity while saving a conservative estimation of 4000 kWh of space heating demand per year per 100 m^2 apartment if deployed in cool regions (around 30% of heating energy) (12). These assumed savings fall within the range of the 20-40% energy savings measured and reported in literature for contemporary Building Energy Management Systems of similar complexity (56). In this case, potential net life-cycle emissions savings range from approximately 0.4 kg CO_2-eq for every kWh of heating demand saved when avoiding natural gas heating to over 1 kg CO_2-eq for every kWh of heating demand saved when avoiding electrical resistance heating in regions with GHG intensive electricity generation (12). These per kWh savings would translate to around 20% reductions in the GHG emissions from heating typical multi-level residential buildings in moderate and cold climates. Figure 6 shows the potential change in the life-cycle impacts of heating a typical building in each region.

The introduction of Building Energy Management Systems can substantially lower life-cycle GHG emissions and environmental impacts in most impact categories and regions when compared typical apartment buildings using natural gas heating. In older buildings in countries with cold and moderate climates Building Energy Management Systems can sometimes contribute to energy savings comparable to those of insulation, and could save as much as a half billion tonnes of CO_2-eq per year in 2050 if deployed in around 360 million individual homes or apartments (12). Although this report focuses on the application of Building Energy Management Systems in reducing heating demand in multi-level buildings in moderate to cold climates, where case studies have observed substantial energy savings (56), it is important to note that Building Energy Management Systems can also be deployed in warmer climates and used for the reduction of cooling energy consumption. The variation among the regions in Figure 6 is relatively minor and can be explained by the differences in the underlying electricity mix associated with the production and the use of the Building Energy Management Systems and devices.

FIGURE 6. Change in environmental and natural resource impacts from the introduction of Building Energy Management Systems (BEMS) in apartments heated by natural gas boilers compared to a typical apartment in each of the 9 International Energy Agency regions in 2010.



Systems can sometimes contribute to energy savings comparable to those of insulation, and could save as much as a half billion tonnes of CO2-eq per year in 2050 if deployed in around 360 million individual homes or apartments (12). Although this report focuses on the application of Building Energy Management Systems in reducing heating demand in multi-level buildings in moderate to cold climates, where case studies have observed substantial energy savings (56), it is important to note that Building Energy Management Systems can also be deployed in warmer climates and used for the reduction of cooling energy consumption. The variation among the regions in Figure 6 is relatively minor and can be explained by the differences in the underlying electricity mix associated with the production and the use of the Building Energy Management Systems and devices.

Results show deploying Building Energy Management Systems can lead to environmental co-benefits in all impact categories considered. By 2030 and 2050, projections show that using Building Energy Management Systems will result in even greater co-benefits in human and ecosystem toxicity, eutrophication and natural resource impacts, as the electricity used to operate Building Energy Management Systems and produce their components becomes cleaner under the 2-degree Celsius scenario. A limitation of this analysis is that the interaction between Building Energy Management Systems and added building insulation is not accounted for. When deployed together, actual co-benefits would be less than the arithmetic sum of the two applied separately. Thus, current analysis uses conservative estimates for energy savings from both technologies to minimize the error associated with the interactions between them.

4.1.4 Information and Communications Technology

Information and communications technology, including computers, the internet, smart phones, gaming, and television, is consuming increasing amounts of energy worldwide. Not only do these devices consume energy during use, but they are responsible for an increasingly large consumption of energy due to the upstream operation of data centers and network infrastructure. However, information and communications technologies can enable energy efficiency through demand-side management and shifting to cloud-based services. For consumer electronics, the greatest environmental benefits can be achieved by replacing inefficient devices whose use-phase energy contributes the largest proportion of their total environmental impacts. Examples include efficient liquid crystal displays and plasma display panels as well as more efficient desktop computers. Efficient smartphones show a more limited potential for environmental savings as their use-phase energy consumption contributes a relatively small portion to their overall impacts.

Information and communications technologies are rapidly growing in terms of their energy demand globally (59). Information and communications technologies can be economically and socially transformative, and can contribute to a growth in energy consumption as well as to energy efficiency (60). Data centers, driven by the growth of the internet, accounted for 1 to 1.5% of global electricity use by 2010 (61), and consumer electronics are estimated to account for as much as 12% of residential electricity use in the United States, highlighting the importance of end-use efficiency to reduce the energy consumption and environmental impacts associated with electronics (62).

For these reasons, electronic products have been the focus of significant policy attention due to concerns of operational and stand-by energy use, toxic material content, and concern over pollution associated with informal recycling. Recent research has demonstrated the increasing importance of information and communications technologies compared to household appliances, with televisions and personal computers playing prominent roles (63–65). The main reason for the increasing importance of information and communications technologies is the increasing number of devices in households, the high rate of acquisition of those devices, and the relative importance of impacts associated with the production of those products compared to their operational energy use (63–65). Teehan and Kandlikar (2012) dispute the relative importance of manufacturing for desktops, pointing to underestimates for impacts of the use phase (66). Other researchers, however, see a similar risk of underestimation of manufacturing (67).

Since the beginning of semiconductor production, information and communications technologies have seen a steady pace of innovation that continues to this day. New equipment with improved performance and new application areas is being continuously developed. Several studies of new technologies indicate that these technologies bring reduced environmental impacts per unit performance compared to those that preceded them

(63, 68–70). These advances in energy efficiency, however, do not usually lead to reduced energy consumption but rather result in increased use of products with improved performance. Tracing the evolution of the performance attributes of laptops and their resulting material requirements, Kasulaitis and Babbitt found that gains in the performance of chips, disks and batteries have led to more powerful computers and not to reduced material demand (65).

This section analyses the environmental impacts of replacing inefficient electronic devices with more efficient versions of the same technology, comparable to those promoted by efficiency programs like the United States Department of Energy's ENERGY STAR (71). The devices considered are efficient plasma and liquid crystal displays, laptop and desktop computers, and smartphones. Data for constructing life cycle inventories were collected from various sources for each type of device: desktop computers (72–76), laptop computers (76, 77), liquid crystal and plasma displays (72, 74–76), and smartphones (76, 78, 79). Use-phase energy consumption and lifetimes for efficient and conventional devices were based on data from the ENERGY STAR program (71, 80).

FIGURE 7. **Change in environmental and natural resource impacts from the introduction of efficient information and communications technologies compared to conventional alternatives in each of the 9 International Energy Agency regions in 2010.**

PC= Personal Computer; LCD=Liquid Crystal Display; PDP= Plasma Display Panel.

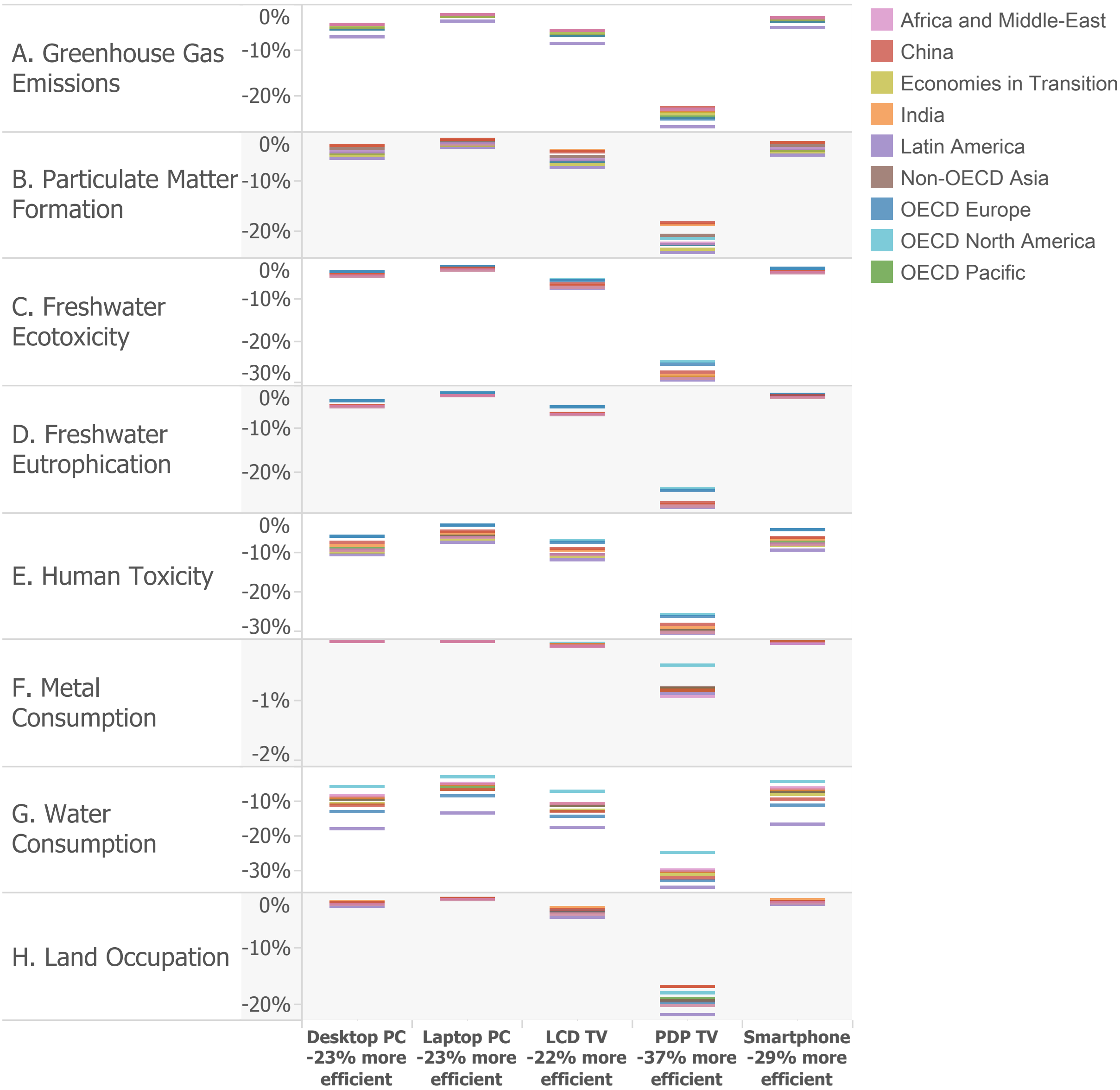


Figure 7 shows the relative impact of using efficient electronics as replacements for less-efficient versions of the same devices. Most efficient technologies, when used as replacements for conventional versions, show small reductions in overall impacts compared to their conventional counterparts. While electricity consumption is reduced by 22-37% for these devices, environmental impacts for most impact categories are reduced by less than 10-20%. The environmental benefits of more efficient electronics vary depending on the contribution of use-phase electricity to overall life-cycle impacts. For example, smartphones are used for only 2-3 years, and only a very small fraction of their life-cycle GHG emissions is from electricity consumption during the use phase, as has been indicated by this analysis and by environmental reports published by smartphone producers (81). The relatively small inter-regional differences in Figure 7 are due to differences in the electricity mix associated with the production and use of the information and communications technologies.

These results suggest that measures besides energy efficiency improvement, for instance improved material efficiency, would be needed to further reduce the impacts of many information and communications technologies. Technologies with longer life spans whose use-phase energy consumption contributes more to overall impacts, such as efficient liquid-crystal displays, tend to show greater potential reductions from improved energy efficiency.

While this analysis focuses on a limited set of efficient consumer electronic devices, it is important to note that information and communications technologies can also enable energy efficiency in addition to simply consuming energy. For example, the section on demand-side management discussed how information and communications technologies controlling heating demand could reduce energy consumption. Additionally, while data centers are growing in energy consumption globally, they also have the potential to reduce overall energy consumption by end-users. For example, one case study found that shifting all video viewing in the United States to streaming could save 162 petajoules of primary energy and around 8.6 million tonnes of CO_2 emissions (82).

4.2 INDUSTRY

Numerous opportunities for improved energy efficiency exist throughout the industrial sector. Among these many possibilities, selected energy-efficient technologies were analysed, including energy-efficient copper smelting and co-generation systems that provide process heat and electricity generation. Copper production was selected because demand for copper is expected to increase under GHG mitigation scenarios, as more copper will be required to produce the renewable energy technologies and grid infrastructure that enable electricity decarbonisation. Efficient flash furnace-based technologies are the current state-of-the-art, and further improvements to energy efficiency are possible (29). When combined with low-carbon electricity generation, efficient copper refining technologies have the potential to reduce GHG emissions per metric tonne of copper refined by over 50% compared to today's inefficient shaft furnace technologies, while also reducing air pollution, human health impacts, and other environmental impacts (14). Industrial co-generation allows for more efficient generation of process heat by using natural gas to concurrently generate heat and electricity. Co-generation can be an effective and environmentally benign GHG mitigation strategy when replacing conventional industrial boilers in countries with carbon-intensive electricity mixes (15).

4.2.1 Copper Production

Replacing existing shaft furnace-based copper smelting technologies with best available technologies, particularly flash furnace-based smelting, can substantially reduce the life-cycle GHG emissions of refined copper while also reducing air pollution, human health impacts, and other environmental impacts. Future efficiency improvements to flash furnace-based copper refining along with the potential decarbonisation of electricity can further reduce the GHG emissions of refined copper by over 50% by 2050 relative to current impacts, and lead to other environmental co-benefits.

Literature has already explored the material and energy efficiency potential of iron, steel, and cement production. For example, a number of studies have explored the benefits for energy efficiency, particulate reduction, and sulfur dioxide reduction of more efficient steel production processes in China, India, and the European Union (83–85). However, expected material and efficiency improvements in steel *production* technologies will not be

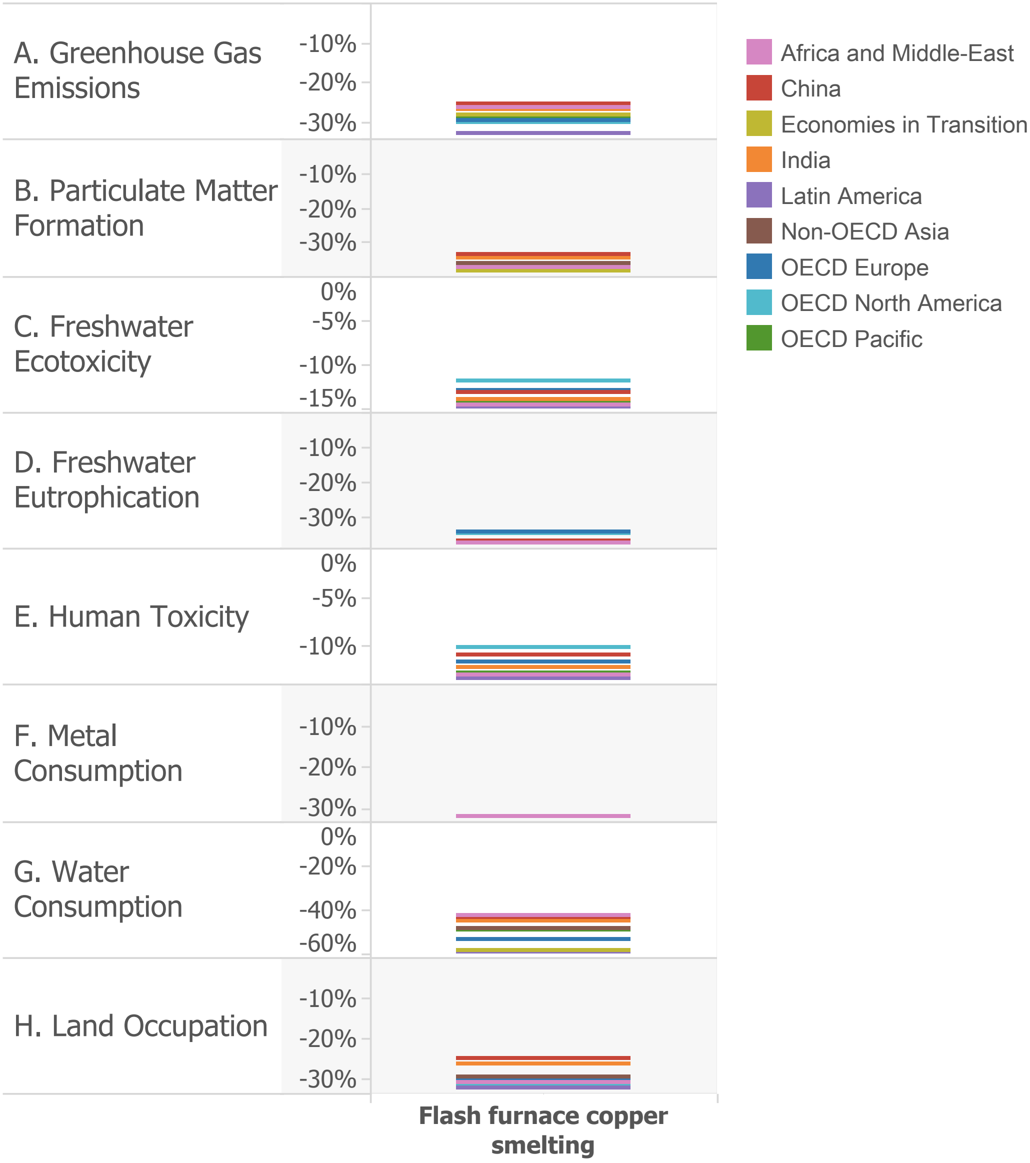
sufficient to decrease GHG emissions by 50% if demand doubles by 2050 (86). In this case, material efficiency improvements are needed in the use phase, such as light-weighting, substitution, product life extension, re-use and re-manufacturing (86).

While copper production does not contribute as much to global GHG emissions as iron, steel and aluminium, increased demand for copper is a likely consequence of a transition towards low-carbon electricity generation (26) renewable technologies require higher initial investments in infrastructure than fossil-based power systems. To assess the tradeoffs of increased up-front emissions and reduced operational emissions, we present, to our knowledge, the first global, integrated life-cycle assessment (LCA. This increased copper demand is mainly due to the increased need for grid infrastructure and renewables generation, and is a key contributor to the human and ecosystem health impacts of such technological shifts (26, 87)renewable technologies require higher initial investments in infrastructure than fossil-based power systems. To assess the tradeoffs of increased up-front emissions and reduced operational emissions, we present, to our knowledge, the first global, integrated life-cycle assessment (LCA. Furthermore, existing life-cycle databases include limited data on copper production, and therefore new, reliable and up-to-date life-cycle data on copper technologies is a valuable contribution to the literature. Thus, this report chooses to focus on quantifying the environmental benefits of state-of-the art and increasingly efficient copper production technologies, namely pyro-metallurgical smelting technologies that produce refined copper. Data on the input requirements and emissions from the KGHM Polska Miedź S.A, Glogow I and II smelting facilities in Poland are coupled with electricity and materials production in the nine International Energy Agency regions and used to compare the environmental impacts of shaft and flash furnace-based smelting technologies (14). While the construction of KGHM II is an example of new, more energy efficient copper smelting around the world, efficient copper smelters can be slow to replace older, less efficient smelters due primarily to the high upfront investments required to build smelters (88). Additionally, this analysis accounts for likely technological changes to flash-furnace smelting technologies (current best available technologies) and changes to the electricity generation mix from 2030 to 2050 to forecast the long-term impacts of efficient copper production.

The results show that for most impact categories the flash-based technology can achieve significantly lower environmental impacts than a shaft furnace. For example, the flash-based technology in 2010 generates on average a 24% lower impact than a shaft furnace per tonne of copper produced. For GHG emissions, transitioning from shaft furnace-based copper production to more efficient flash furnace technology can decrease emissions by 29% in 2010, 50% in 2030 and 56% in 2050 (14) relative to today's technology. In addition to GHG emissions, flash-furnace copper smelting shows substantial benefits in other indicators, notably particulates, eutrophication, water consumption and metal consumption.

Flash furnace copper smelting technologies use additional electricity while reducing onsite fuel consumption as compared to conventional shaft furnace technologies. Therefore the potential for flash furnace copper smelting to reduce GHG emissions is higher in the regions with low-carbon electricity grid-mix such as Latin America (Figure 8).

FIGURE 8. Change in environmental and natural resource impacts per unit of copper produced from the introduction of flash furnace copper smelting technologies compared to conventional shaft furnace technology in each of the 9 International Energy Agency regions in 2010.



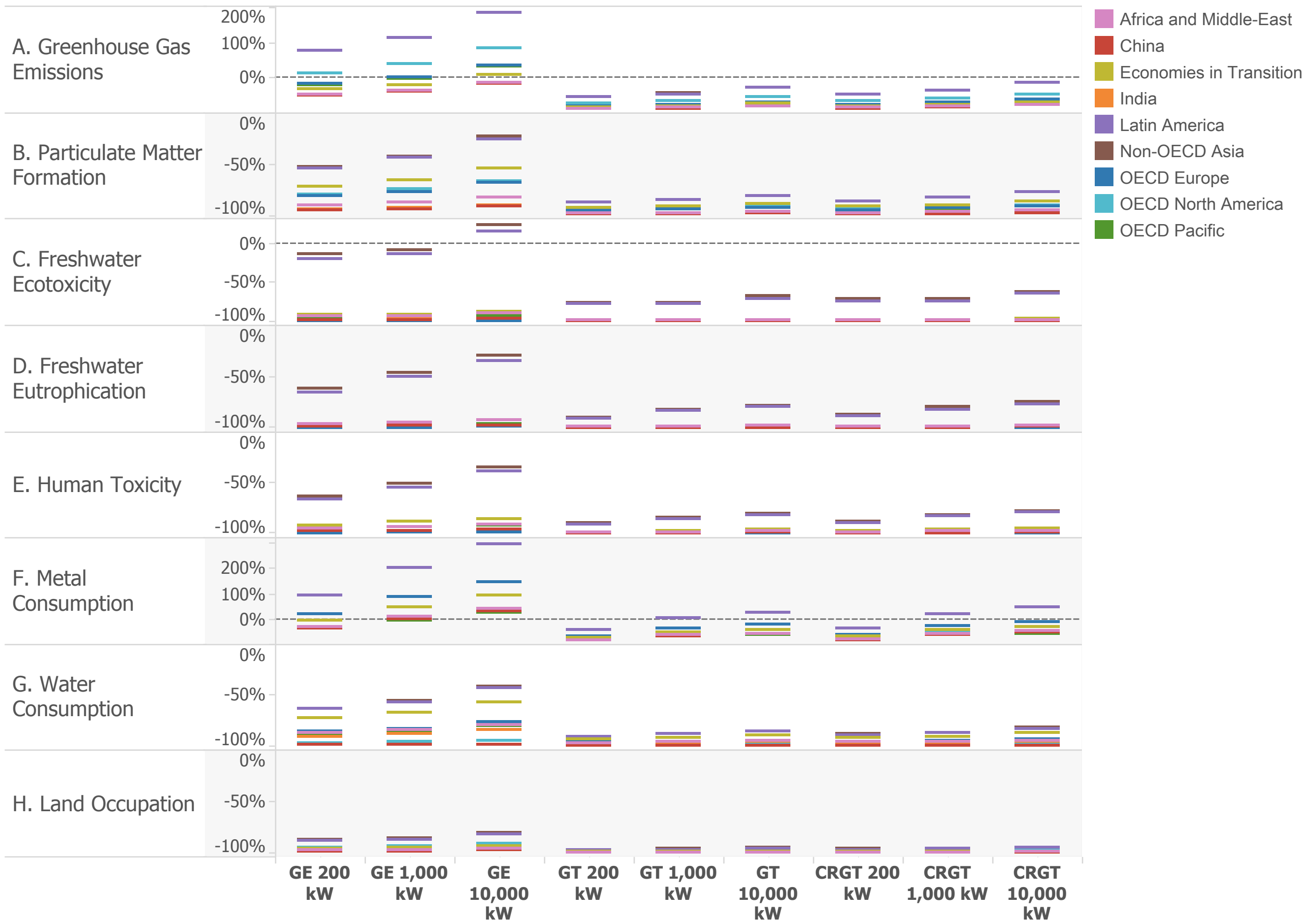
4.2.2 Co-generation

Distributed industrial co-generation systems that burn natural gas or diesel fuel can be used to more efficiently provide process heat while generating electricity for on-site and grid use. According to the International Energy Agency's Energy Technology Perspectives, co-generation systems can save almost 2 EJ of energy in the chemical and pulp and paper industries alone. In China, India, non-OECD Asia, Africa, and the Middle East, co-generation can reduce GHG emissions by 30-60% when displacing more carbon-intensive electricity and compared to industrial boilers that generate heat only. If electricity generation is decarbonised following the International Energy Agency's 2-degree scenario, co-generation would become less effective at reducing GHG emissions in the long term.

The deployment of distributed co-generation can be an effective strategy in industrial applications to generate process heat more efficiently while also generating electricity that can be used internally or to offset grid generation. The International Energy Agency identifies co-generation as a particularly important demand-side measure for reducing energy consumption in the chemical and pulp and paper industries (4). According to the International Energy Agency's 2-degree Celsius scenarios, co-generation can save up to 1.75 exajoules of energy per year globally in the chemical, petrochemical, and pulp and paper industries alone (4).

FIGURE 9. Change in environmental and natural resource impacts from the introduction of 200, 1,000 and 10,000 kW natural gas co-generation systems compared to conventional electricity generation in each of the 9 International Energy Agency regions in 2010.

GE = gas engine, GT = gas turbine, and CRGT = chemically recuperated gas turbine.



This section examines the potential of using distributed energy sources in future energy systems, following the International Energy Agency's 2-degree and 6-degree Celsius scenarios. This analysis quantifies the environmental impacts and benefits of industrial co-generation systems of varying capacity, generating varying proportions of electricity and heat (15). Figure 9 compares the impacts of generating process heat while displacing grid electricity using co-generation systems in all 9 regions defined by the International Energy Agency. Because co-generation systems produce both electricity and steam, these results account for the benefits of avoiding the need to burn natural gas to produce steam using industrial boilers. In the near term, the greatest environmental benefits come from co-generation systems deployed in regions with GHG-intensive electricity generation, such as China, India, non-OECD Asia, the economies in transitions, and Africa and the Middle East (15). The largest increases in GHG emissions are seen in Latin America, where current electricity generation relies heavily on hydropower. Similarly, smaller GHG benefits are observed for OECD countries in North America, Europe and the Pacific. In all regions co-generation systems also have the potential to provide environmental co-benefits in particulate matter formation, ecotoxicity, eutrophication, and land occupation. If electricity generation is decarbonised following the 2-degree Celsius scenario, the GHG benefits of co-generation achieved by displacing grid electricity would be eliminated, suggesting that natural gas-based co-generation without carbon capture and storage would only be effective as a short-term, transitional measure to reduce energy consumption, GHG emissions, and environmental impacts from industry. These results are consistent with previous research analysing the GHG benefits of co-generation in the residential and industrial sectors (89).

Inter-regional differences in the results (Figure 9) can be explained by the underlying grid-mix differences. For example, the environmental co-benefits of co-generation systems, if any, is the smallest in Latin America, where the existing electricity grid is cleaner.

It is notable that in some regions scaling up of co-generation using bagasse and agricultural residue as feedstock, which can potentially displace fossil-based electricity, may offer climate change mitigation and environmental co-benefits. Co-generation with biomass feedstock, however, remains to be assessed.

4.3 TRANSPORTATION

Passenger and freight transportation contribute substantially to GHG emissions and air pollution around the globe. Under the International Energy Agency's 2-degree scenario, a transition towards electric passenger vehicles and trains and more efficient freight, combined with renewable and low-carbon electricity generation, has the potential to reduce total GHG emissions from passenger transportation by up to 1.5 billion tonnes CO_2-eq per year while accommodating increased demand for passenger transportation projected by many scenarios. High penetration of battery electric vehicles for personal transport could result in overall increases in metal demand, and toxicity without further improvements to vehicle production and supply-chain processes. Decarbonisation of electricity should go hand-in-hand with vehicle electrification efforts to ensure GHG reductions and other environmental benefits.

The global transport sector can significantly reduce the carbon-intensity of both passenger and freight vehicle fleets by 2050 through a portfolio of approaches that aim to improve vehicle fuel efficiency and lower overall supply-chain emissions (3). The majority (66-99%) of life-cycle GHG emissions associated with transportation are generated during the production, distribution, and utilization of transportation fuels (13). New technologies, such as vehicle light-weighting and downsizing, thermodynamic cycle improvements, hybridization, and aerodynamic improvements, represent proven technological strategies for reducing


©NickStarichenko/Shutterstock.com

fuel usage and thereby 'well-to-wheel' environmental impacts. However, to reach the climate change mitigation targets of the 2-degree Celsius scenario, increased electrification of passenger transportation in combination with low-carbon electricity generation is crucial. The analysis of transportation in this report also explores how these technological transitions may shift environmental impacts from mobile sources of pollution to supply-side energy production systems. The shift of GHG emissions from mobile sources to stationary ones through electrification may also accommodate economies of scale for carbon capture and storage technologies applied to larger fossil fuel-based power plants.

Sustainable transport policies will have varying effects on environmental and resource impacts around the world due to differences in fleet characteristics (e.g., vehicle age, stock turnover rates, supply-side technology deployment). Research suggests that the largest opportunities for per passenger-kilometre reductions in the carbon-intensity of vehicles occur within developing nations (e.g., non-OECD) due to generally lower present-day fleet average fuel efficiency for private automobiles, public transit, and freight transit (13).

4.3.1 Passenger and Freight Transportation

This section analyses the life-cycle environmental and resource footprint of both passenger and freight transportation following the 2-degree Celsius scenario based on data collected by Taptich and colleagues (13). In total, 14 vehicle types were assessed across five passenger transportation modes (automobile, bus, rail, high-speed rail, and airplane), three freight modes (medium heavy-duty and heavy heavy-duty trucks, rail, and oceangoing vessel), and five fuel pathways (gasoline, diesel, heavy- fuel oil, jet fuel, and electricity). Other alternative transportation fuels such as biofuels were considered but were ultimately excluded due to uncertainties regarding system scalability (e.g., material sourcing and infrastructure expansion) and adoption (90, 91). Fuel efficiency improvements within each region reflect current and projected industry standards, technological projections, and energy and emissions reduction goals (92–97).

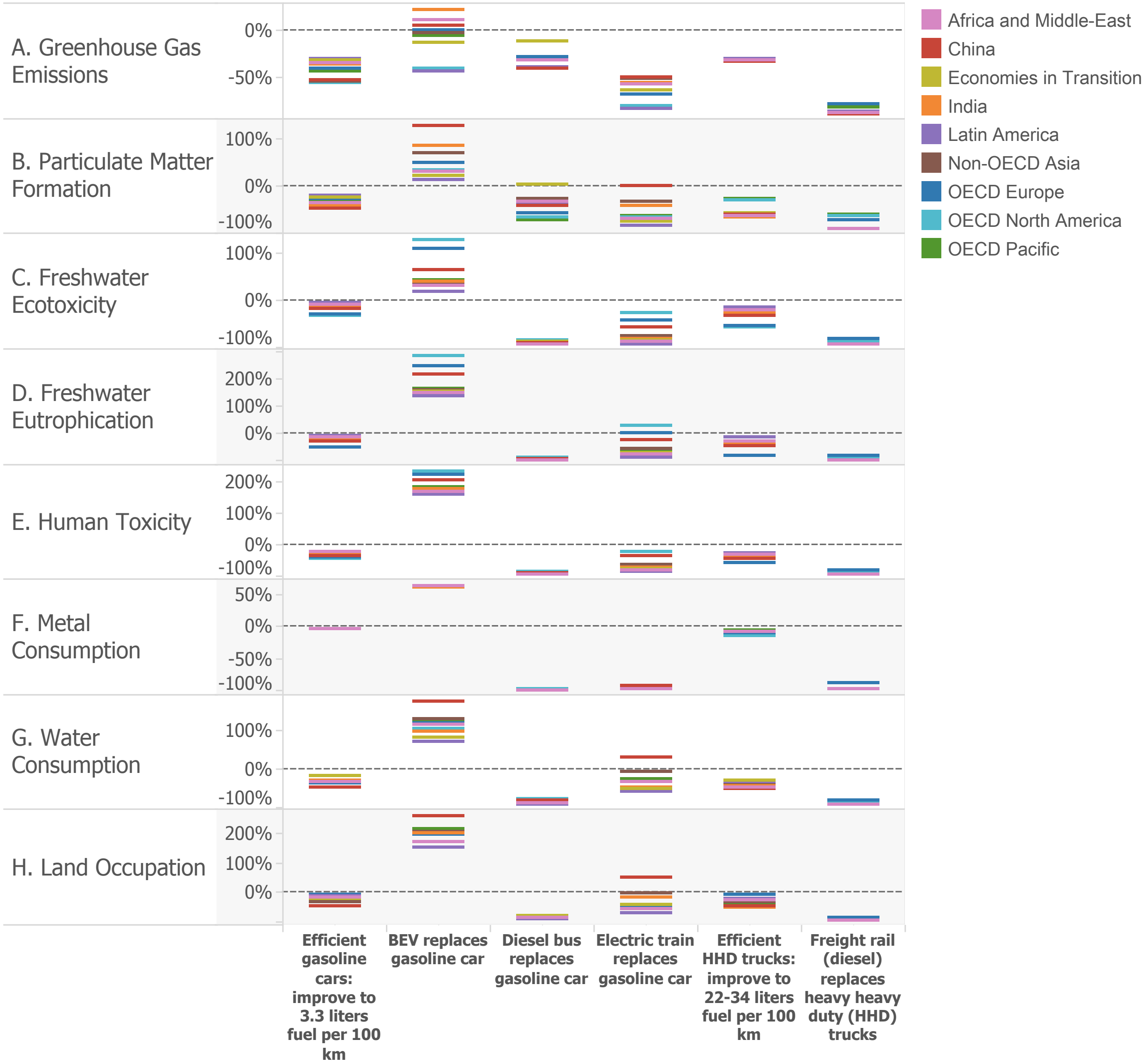
Estimates of aggregate demand for passenger and freight transportation were based on various projections by the Intergovernmental Panel on Climate Change (97) of vehicle-kilometres travelled, tonne-kilometres shipped for freight transportation, and current transportation mode shares. These scenarios generally expect passenger transportation in non-OECD countries to grow at a faster rate than in the OECD, where passenger transportation would need to level off or decline to help reach climate change mitigation targets of the 2-degree Celsius scenario. For transportation, the Intergovernmental Panel on Climate Change projections were used to supplement the International Energy Agency scenarios which did not provide regional projections of passenger and freight demand. Next, the International Energy Agency's 2-degree Celsius offered a likely picture of vehicle electrification, projecting that battery electric and plug-in hybrid electric vehicles could make up 75% of vehicle sales by 2050 (4). For an alternate baseline scenario, the shares of electric, gasoline and diesel passenger vehicles were assumed to remain the same as the present while improving in fuel economy, and that public transportation and air travel would not increase as a percentage of passenger-kilometres travelled.

Figure 10 presents the environmental impacts of efficient passenger and freight transportation options in 2010 compared to average gasoline vehicles and average heavy duty trucks in each region. These estimates encompass all well-to-wheel processes, vehicle manufacturing, and maintenance, including battery manufacturing for battery-electric and plug-in hybrid electric vehicles (98, 99), as well as end-of-life processes. These results compare the impacts of replacing vehicles of regional average fuel efficiency with more efficient modes (namely electric vehicles and public transit that would displace passenger transportation using gasoline cars). Results show that in regions like India, Africa and Middle-east, and China with GHG intensive electricity, present day battery-electric vehicles technologies do not help mitigate GHG emissions, echoing the results of Hawkins and colleagues (99). This is due to the high carbon intensity of grid electricity in those regions, where coal power plants are the largest contributor to the life-cycle GHG emissions of battery-electric and plug-in hybrid electric vehicles.

It is important to note that the present day GHG benefits of shifting passenger transportation to diesel buses depend heavily on ridership and average fuel efficiency of regional fleets, with higher ridership providing greater environmental benefits.

FIGURE 10. Change in environmental and natural resource impacts from the introduction of efficient passenger transportation and freight transportation modes compared to the stated fossil-based alternatives in each of the 9 International Energy Agency regions in 2010.

BEV=Battery electric vehicle. HHD=Heavy Heavy Duty .



In some other impact categories, particularly metal consumption, human toxicity and freshwater ecotoxicity, current estimates of battery-electric vehicles life cycles show increased impacts. Battery-electric vehicles show higher metal consumption and ecotoxicity due to the increased demand for copper and metals used in the vehicle's battery. These results are consistent with previous studies that have investigated the life cycles of battery-electric vehicles (99, 100). Electric vehicles do not directly emit substances contributing to freshwater eutrophication, but the emissions of phosphates during the disposal of tailings from copper and coal mining in the supply chain of vehicles have the potential to contribute to this impact category. It is important to note, that the number of estimates of battery-electric vehicles life-cycle emissions is limited, with most life cycle studies in the literature focusing only on energy and GHG emissions. Furthermore, expected future improvements in battery-electric and plug-in hybrid electric vehicles fuel efficiency and decarbonisation of electricity might reduce many of these impacts (13, 98, 99). More fuel-efficient heavy heavy-duty trucks vehicles show potential environmental benefits in comparison with average freight fleets, as does a shift from freight trucks to freight rail (diesel). While shifting freight transportation to rail may save emissions and environmental impacts on a tonne-kilometre basis, it is important to note that not all freight can be replaced by rail. One of the limitations of our vehicle comparisons is that this methodology ignores specific transactional processes needed to facilitate mode switching (e.g., infrastructure expansion, differences in network topology, etc.) (101). Another limitation is that this chapter considers limited improvements in vehicle fuel economy without expressly considering measures such as light-weighting of cars using high-strength low-alloy steel or the use of complex superalloys in the hot parts of jet engines and gas turbines, making higher combustion temperatures and better fuel efficiency possible.

Lastly, scenario results (presented in chapter 6) are used to show the potential reduction of the GHG intensity of passenger and freight transportation following the 2-degree Celsius scenario by 2050. GHG emissions reduction is likely to occur more slowly in freight transportation than in passenger modes around the world by 2050. One reason for these forecasted differences is that longer vehicle lifetimes (e.g., 30 years for rail, aircraft, oceangoing vessel, and heavy heavy-duty trucks) and infrastructure design choices (e.g., non-electrified rail) lock in the technologies available within freight modes for longer periods of time, thereby reducing the uptake of newer, more efficient technologies. Results indicate that the greatest environmental benefits occur within electrified passenger rail, following a ~0.8% per year improvement in fuel efficiency and electricity decarbonisation (following the International Energy Agency's 2-degree Celsius scenario). Scenario analysis in the following sections shows that the developing world could see larger reductions in particulate matter formation (PM_{10}-eq) by passing on-road vehicle emission standards at levels comparable to those found in OECD countries today.

Inter-regional differences in the results are influenced by several factors, including existing emissions standards, fuel standards, and the regional electricity grid-mix. China, for instance, has relatively strict NOx standards for gasoline vehicles, and therefore replacing them with battery-electric vehicles powered mainly by coal electricity can lead to increases in overall particulate matter emissions. There are important differences, however, between particulate matters emitted by mobile and stationary sources in terms of their potential exposure to humans, which will be elaborated further in section 6. Figure 10 also shows that battery-electric vehicles replacing gasoline cars increase water consumption and land occupation impacts, where the most significant increases are observed in the regions relying heavily on coal-powered electricity. Replacing gasoline cars by battery-electric vehicles also increases other impacts such as freshwater ecotoxicity and human toxicity. For these categories, however, replacing gasoline car by battery-electric vehicles results in higher impacts among the OECD regions as compared with non-OECD regions. This is due to the relatively high toxic impacts associated with battery supply chain and production, which are normalised by relatively low toxic impacts of the existing supply chain and production of gasoline cars produced within the OECD regions.

It is also notable that part of the co-benefits outlined in this section could be negated due to increased congestion, and lags in infrastructure developments and urban planning in some regions.

5. Comparison Among Technologies

5.1 OVERALL COMPARISON

In this section, energy efficiency and demand-side GHG mitigation technologies are compared based on the percent impact reduced when providing the same function as their conventional, less efficient alternatives.

Figure 11 presents the environmental and resource effects of a subset of 20 energy efficiency and demand-side technologies in 2010, 2030 and 2050 under the 2-degree Celsius scenario compared to baseline technologies in the same year. Negative numbers in Figure 11 represent environmental impact reductions by demand-side technologies and positive numbers represent potential trade-offs. Each horizontal line within a bar represents the impact of the demand-side technology in one of the 9 International Energy Agency regions (see chapter 3 for list of regions). Some columns show less than 9 lines due to overlapping results. Such regional variations arise from the differences in the underlying regional electricity grid-mixes and production technologies. While it is possible for some technologies to displace more than one type of fuel or energy source, technologies are organized based on the energy source they most likely displace: natural gas, electricity and petroleum. For example, building insulation technologies are compared to natural gas, but they can also save electricity or biomass used for space heating or cooling. Results presented for 2030 and 2050 account for expected future improvements to the demand-side technologies as well as changes in the underlying electricity mix under the 2-degree Celsius scenario. Such results are compared to the baseline technologies in the same year, which also incorporate the expected future changes and improvements under the 2-degree Celsius scenario. Therefore, both the efficient technology and baseline technology have undergone technological improvements and use lower carbon electricity in 2030 and 2050.

Saving Natural Gas

Columns 1-6 include the demand-side technologies such as building insulation and Building Energy Management Systems that primarily reduce the need for heating with natural gas. Changes in environmental and resource impacts are calculated by comparing the energy consumption required for heating and cooling a building with added insulation to that of an average building.

Saving Electricity

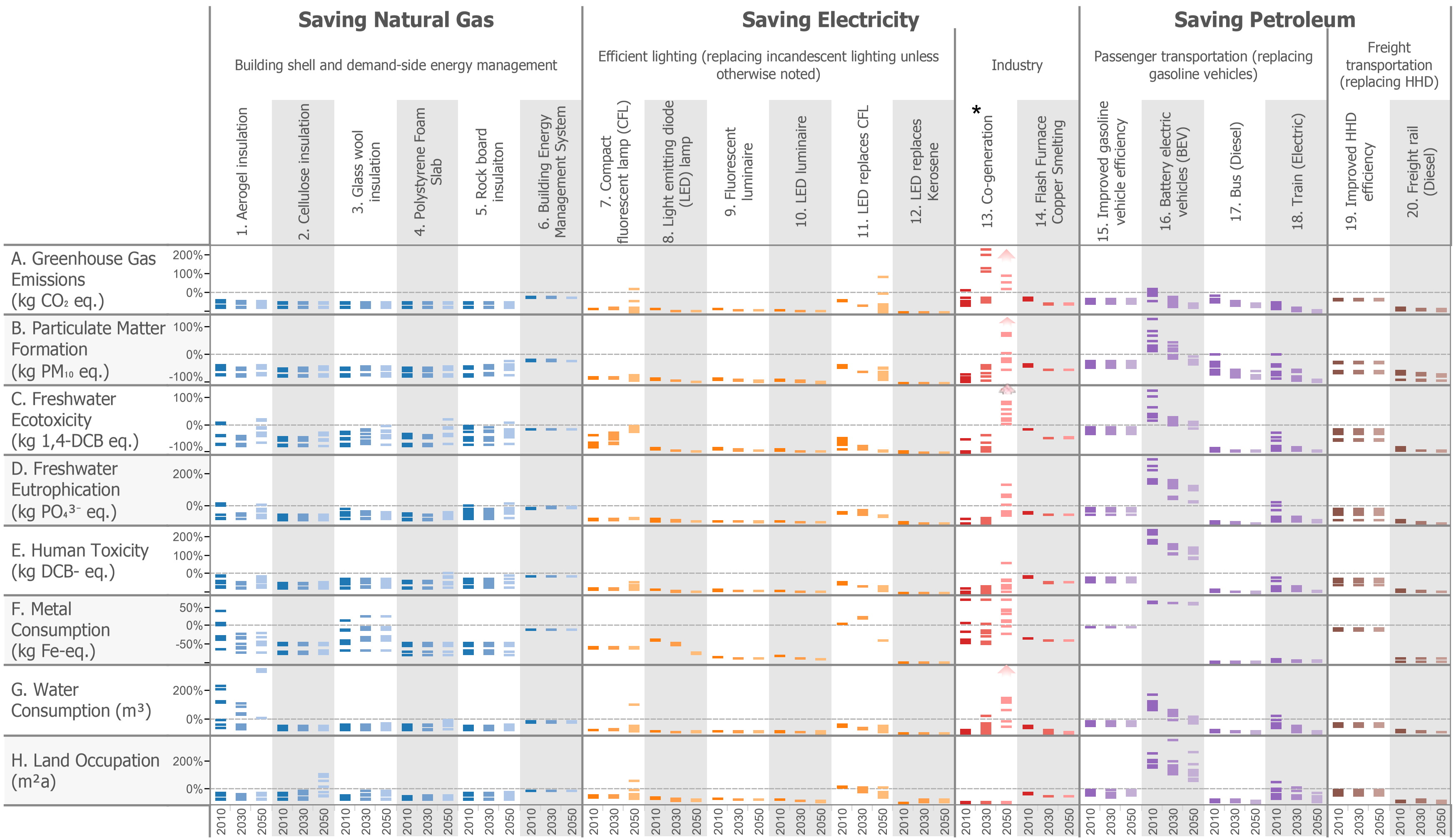
Columns 7-14 include technologies that primarily save electricity, including efficient lighting, co-generation and efficient copper production. Lighting technologies are compared to incandescent lights (unless otherwise noted) on a lumen-hour basis. Co-generation generates electricity while also providing process heat for industry, and is compared to grid electricity generation. Efficient flash-furnace copper production saves electricity per tonne of copper produced, but also other energy carriers used in smelting such as natural gas.

Saving Petroleum

Columns 15-20 include efficient and low-carbon passenger and freight transportation modes that reduce the consumption of petroleum (i.e. gasoline or diesel). Passenger transportation technologies are compared to an average gasoline vehicle in each region on the basis of a passenger-kilometre travelled. Freight technologies are compared to average heavy duty trucks on the basis of a tonne-kilometre transported.

FIGURE 11. The effects of demand-side technologies on environmental and natural resource impacts compared to selected baseline technologies in the same year under the 2-degree Celsius scenario.

*LED= Light emitting diode; CFL= compact fluorescent lamp; BEV=battery electric vehicle; HHD=heavy duty trucks. *Some very large results for co-generation in 2050 were excluded from the figure, as such high results would obscure the differences in other technologies. Arrows denote that some regions had results higher than shown here.*



The demand-side technologies considered in this report generally reduce GHG emissions and other impacts in most global regions and all years considered. These environmental and resource benefits are evident from Figure 11, which shows a majority of the results reside below zero. At the same time, however, it is clear that some of the technologies may generate higher impacts than the baseline technology for certain regions and for certain years. Also, there are noticeable regional and temporal variations in the results for some technologies (e.g. columns 13 and 16). For example, the impacts of battery electric vehicles (see column 16) relative to baseline gasoline vehicles in 2010 vary depending on the differences in the emissions intensities of the underlying regional electricity mixes. The production of materials, in addition to the use phase, also plays a role in the variability of the results among regions. For example, water consumption by aerogel insulation varies significantly among regions due to the substantial quantity of electricity required for silica production and the regional differences in water consumption required for electricity generation.

Figure 11 also indicates that the benefits and trade-offs of demand-side technologies often change significantly over time. Therefore, a technology that reduces GHG emissions or other impacts today does not necessarily do the same in the future (see columns 7 and 16). For example, co-generation technologies (column 13) reduce environmental and resource impacts in most categories and regions in 2010, but they begin to show much higher impacts as compared to baseline technologies by years 2030 and 2050 under the 2-degree Celsius scenario. This reversal of benefits is caused by the decarbonisation of the electricity that would be displaced by co-generation in 2030 and 2050 under the 2-degree Celsius scenario, in which the shares of renewables rise substantially.

Furthermore, there are some trade-offs observed among the impact categories considered. For example, battery electric vehicles (column 16) in 2030 and 2050 show fewer GHG emissions (row A) compared to the baseline, while they consistently consume more metals (row F). This follows the trend observed in the previous report on electricity supply, that a large scale transition toward low-carbon technologies requires more metallic resources but fewer fossil resources compared to the technologies and infrastructure of today (1, 26).

In general, however, the technologies that reduce energy consumption in the building and industrial sectors, namely insulation, lighting, demand management and efficient copper refining tend to provide the greatest resource and environmental benefits relative to the technologies they displace (see columns 1-14). For instance, insulation technologies considered in our study can save between 30% and 70% GHG emissions when added to typical buildings that use natural gas for heating and electricity for cooling (see columns 1-5). LED lighting technologies provide even greater GHG savings than building insulation when displacing kerosene (column 12), which is still common in many developing regions, or incandescent lights that are rapidly being phased out in the developed world (columns 8). Efficient lighting options also provide environmental benefits in all impact categories presented.

Some of the building shell technologies considered, on the other hand, require greater quantities of metals throughout their life cycles, when applied to the buildings that use natural gas for heating (see columns 1 and 3, row F).

Reducing petroleum consumption through fuel-efficiency improvements in transportation (columns 15-20) shows 30-55% reductions for gasoline passenger vehicles and around 30% reductions for heavy duty freight trucks in 2010 if best available technologies are promoted and tougher fuel efficiency standards are implemented. Similarly, shifting freight transport from trucks to rail (column 20) can reduce GHG emissions by more than 75% in all regions while providing additional benefits in all other impact categories considered. The relative reductions decrease by 2030 and 2050 as the typical baseline vehicles being replaced become more efficient under the 2-degree Celsius scenario.

Shifting from gasoline vehicles to battery electric vehicles (column 16) shows GHG benefits of around 0-12% in OECD regions, Developing Asia and the Economies in Transition, with up to 40% reductions possible in Latin America due to the prevalence of hydropower in the electricity grid. Battery electric vehicles would increase GHG emissions by 6-22% in India, China and Africa and Middle East due to their GHG intensive electricity mixes in 2010. These results reflect the established knowledge that hybrid and battery electric vehicles do not save GHG emissions in regions with fossil fuel-intensive electricity generation (13). Battery electric vehicles also show greater land occupation, primarily due to the substantial land requirements of coal mining required for coal-fired electricity generation. These land occupation impacts for battery electric vehicles are reduced by 2030 and 2050 but remain higher than those of gasoline vehicles due to the continued presence of coal-fired electricity with carbon capture and storage assumed under the 2-degree Celsius scenario. Further, battery

electric vehicles tend to show greater potential ecotoxicity and human toxicity impacts due to the disposal of mine tailings in the production of metals and materials for those vehicles. Battery electric vehicles also show higher particulate pollution over their life cycle in 2010 due to the particulates emitted by power plants. However, as electricity generation is decarbonised under the 2-degree Celsius scenario, battery electric vehicles begin to see substantial savings in terms of particulate emissions by 2030 and 2050. It is important to note that the human toxicity and particulate matter impact categories are both related to different aspects of human health, and the benefits and trade-offs under each category must be weighed carefully. Results suggest that a transition toward more electric transportation under the 2-degree Celsius scenario would potentially lead to decreased pollution from mobile sources (i.e. particulates from gasoline and diesel vehicles) while increasing pollution from stationary sources (e.g. power plants and mines). The implications of particulate pollution and human toxicity results for passenger transportation will be discussed in more detail in Chapter 6. Understanding such trade-offs and mitigating unintended adverse consequences would be important for the transition toward a low-carbon society.

5.2 REBOUND EFFECT

One of the concerns about using energy efficient technologies to reduce global energy consumption and GHG emissions is the rebound effect (102). Because many energy efficient technologies provide the same service at a lower cost, they can lead to increased consumption of the same service, called the direct rebound effect. Also, money saved through the use of more efficient technologies may increase the consumption of other goods or services, resulting in so-called indirect rebound effects (also called income effects) (103–105). Third, some have hypothesized that a fall in the real price of energy as a result of improved efficiency can lead to increased macroeconomic growth, referred to as the economy-wide rebound effect (7, 106). Because the increased demand for goods and services through lower costs can stimulate economic development, the implications of the rebound effect must be carefully considered. While these rebound effects have the potential to lessen or completely cancel out the environmental benefits achieved by the deployment of more efficient technologies (7, 107), rebound effects can improve quality of life, particularly in developing countries, by potentially providing services like thermal comfort, lighting and mobility at a lower cost. Thus, policy measures such as carbon taxes or changes in behaviour and consumption patterns have been explored as possible solutions to mitigate the rebound effect (8), but may need to be balanced with development goals.

Empirical estimates of rebound can vary greatly by technology and by study (107). In the context of long-term scenario analysis, rebound effects would be expected but are difficult to estimate given the uncertainty of long-term projections of the costs of energy and energy-efficient technologies. This section provides an overview of literature in regards to the rebound effect of the technologies considered in this report, and presents a sensitivity analysis estimating the magnitude of direct rebound effect that would be needed to cancel out the environmental benefits or the efficiency technologies considered in this report.

In the area of lighting, the amount of lighting services consumed worldwide has seen a remarkable relationship to gross domestic product throughout history (108, 109), the implication being that lighting greatly improves quality of life. Hence, and substantial growth is expected in demand for lighting over the next 40 years, particularly in developing countries. Technological improvements to LED technologies and the anticipated high penetration of LEDs by 2050, combined with low-carbon electricity generation, can accommodate a certain amount of inherent rebound, (perhaps a 2.5 to 3 times growth in lighting services) while still meeting the 2-degree Celsius scenario goals (11), but this does not consider indirect rebound effects that could lead to other increased environmental impacts from consumption, as has been suggested in recent literature (110–113). A review of econometric studies by Sorrell and colleagues suggests that the long-run rebound from efficient lighting and other appliances may range from 32-49% (43).

Estimates of the direct rebound in OECD countries for efficiency gains in space heating range from a 10% to 30% increase in heating demand, but have been observed as high as 60% in some studies in the United Kingdom and Canada (107). Similarly, rebound from efficiency improvements in space cooling range from 0%- 26% (107).

For transportation, increased environmental impacts from direct rebound effects have been observed for more efficient conventional and hybrid vehicles. For current electric vehicles, the higher capital costs of new battery

electric vehicles can actually lead to decreased environmental pressures from decreased use (114), but this trend may not continue if the costs of electric vehicles decline in the future.

One way to gauge the risk of rebound effects on the environmental benefits provided by efficient technologies is to estimate the amount of additional consumption of a service that would completely cancel out the environmental savings achieved by that technology. The break-even rebound threshold is defined as the minimum additional use of an efficient technology (percent) that erodes all environmental benefits that it provides in a particular impact category. The higher the break-even rebound threshold, the more secure the environmental benefits, because a greater rebound is needed to eliminate the benefits. These results can be interpreted such that an increase in demand for a service greater than the break-even rebound threshold value would eliminate the environmental benefits achieved by using the more efficient technology. Examples of this type of rebound would include using efficient lighting more often, increasing the illuminated area in a home or workplace, or purchasing a more efficient television with a larger screen. Because efficient technologies provide different relative benefits in different impact categories, it is useful to understand how an increase in consumption of a service from the deployment of an efficient technology may still show benefits in one category while increasing impacts in another. Break-even rebound threshold values shown in Figure 12 are calculated according to Eq. 2.

The impact of providing a service using an efficient technology j is represented by I^*_{ij}, and the impact of providing that same service with a less efficient, baseline technology j is I_{ij}. The break-even rebound threshold for technology j and impact category i is calculated by subtracting the impact of the efficient technology I_{ij} from the impact of the baseline technology I_{ij}, all divided by the impact of the efficient technology I^*_{ij}.

$$\text{BERT} = \begin{cases} \left(\dfrac{I_{ij} - I^*_{ij}}{I^*_{ij}}\right) \times 100\% , & \text{if } I^*_{ij} < I_{ij} \\ \text{not applicable} , & \text{if } I^*_{ij} \geq I_{ij} \end{cases} \quad \text{(Eq. 2)}$$

For example, if I_{ij} = 5 kg CO_2-eq. and I_{ij} = 10 kg CO_2-eq. then break-even rebound threshold = 100%. This result indicates that a 100% increase in demand would completely erode the environmental savings achieved by the efficient technology. Break-even rebound threshold results are calculated for each of the 9 International Energy Agency regions.

Figure 12 presents break-even rebound threshold estimates for efficient technologies in 2010. Green represents a high break-even rebound threshold and red and orange a low break-even rebound threshold. Values in Figure 12 represent the median value of the break-even rebound threshold in the 9 International Energy Agency regions. To enhance to clarity of the figure, extreme break-even rebound threshold values (greater than 250%) are represented by solid green bars. Efficient technologies showing no environmental benefit in a particular impact category are excluded from Figure 12 and are represented by solid white bars. For building improvements (building envelope and efficient lighting), a large increase in consumption of services (100% or greater) is needed to erode the environmental savings achieved for most impact categories. The required rebound would be larger than direct rebound effects estimated in literature. A notable exception is Building Energy Management Systems, where an increase in heating demand of 10-24% would be needed to erode environmental impact reductions achieved by energy savings. Another exception is metal consumption for some insulation and lighting technologies, suggesting that only a moderate rebound could result in increased metal consumption if those technologies are used for energy savings. Transportation technologies replacing gasoline-fuelled personal automobiles would require a small or decreased amount of passenger kilometres travelled to achieve environmental savings in some impact categories. An example of this is the median case of battery electric vehicles, where only a 2% increase in demand for passenger transportation is needed to erode the GHG emission savings. An exception to this is GHG emissions savings by battery electric vehicles in regions with less carbon-intensive electricity mixes, including the OECD European, Pacific and North American regions as well as Latin America. Interestingly, reduced demand for passenger travel using battery electric vehicles has been observed due to their higher upfront costs at present (114).

FIGURE 12. Additional consumption of the same service needed to cancel out the benefits of efficiency technologies in 2010 (Break-Even Rebound Threshold). Percentages and colours represent the median value among the 9 regions evaluated. White cells represent not applicable cases where the impact of the efficient technology is already greater than the conventional technology. Break-even rebound threshold values greater than 250% (low risk) are represented by solid green bars.

BEMS=Building Energy Management System; CFL=Compact fluorescent lamp; LED=light-emitting diode; ICT=information and communication technologies; PC=personal computer; LCD=liquid crystal display; PDP=plasma display panel; BEV=battery electric vehicle; HHD=heavy heavy duty.

Median Value 0% – 250%

	Building shell and demand-side energy management						Efficient lighting						ICT					Industry		Passenger transportation				Freight	
	Aerogel insulation	Cellulose insulation	Glass wool insulation	Polystyrene Foam Slab	Rock board insulaiton	BEMS	CFL	LED lamp	Fluorescent luminaire	LED luminaire	LED replaces CFL	LED replaces Kerosene	Efficient Desktop PCs	Laptop PC	LCD TV	PDP TV	Smartphone	Co-generation	Efficient copper production	Improved gasoline vehicle	BEV	Bus (Diesel)	Train (Electric)	Improved HHD vehicle	Freight Rail Diesel
A. Greenhouse Gas Emissions	89%	109%	107%	108%	108%	24%					60%		5%	2%	7%	30%	3%	113%	38%	66%	2%	45%	159%	45%	
B. Particulate Matter Formation	100%	126%	106%	119%	94%	21%					64%		4%	2%	6%	29%	3%		58%	48%		61%	184%	131%	
C. Freshwater Ecotoxicity	66%	121%	97%	86%	75%	14%	219%				170%		4%	2%	7%	40%	3%		16%	11%				25%	
D. Freshwater Eutrophication	85%	127%	110%	115%	71%	8%					55%		5%	2%	7%	38%	3%		58%	17%			130%	39%	
E. Human Toxicity	74%	124%	100%	92%	87%	11%					73%		10%	6%	11%	42%	8%		14%	32%			194%	44%	
F. Metal Consumption	36%	107%	63%	109%	108%	10%	145%	64%								1%		56%	46%	2%				5%	
G. Water Consumption		115%	97%	93%	104%	19%					63%		10%	6%	13%	43%	7%		92%	45%			46%	66%	
H. Land Occupation	75%	74%	105%	127%	69%	14%	125%	183%	203%				2%	1%	3%	24%	2%		43%	19%			62%	30%	


©MijeShots/Shutterstock.com

6. Assessment of the 2-degree Celsius scenario

This chapter presents the life-cycle environmental and resource effects of deploying demand-side technologies along with decarbonized electricity generation under the International Energy Agency's 2-degree Celsius scenario compared to the impacts of the 6-degree Celsius scenario. Under the 6-degree Celsius scenario it is assumed that low-carbon electricity generation technologies and energy efficiency and demand-side technologies will be deployed at a slower rate than under the 2-degree Celsius scenario, and the performance of these technologies improves under both scenarios. Thus, it is crucial to note that the results presented in this section counts only the *additional* benefits or impacts from deploying supply- and demand-side technologies under the 2-degree Celsius scenario above and beyond those achieved by the on-going improvements expected under the 6-degree Celsius scenario.

The total annual demand for energy services and materials, as well as the potential annual energy savings from efficiency from 2010 to 2050, are estimated primarily from the projections of the 2-degree Celsius scenario of the International Energy Agency's Energy Technology Perspectives (4). Annual demand projections for passenger and freight transportation are based on various projections by the Intergovernmental Panel on Climate Change (97), and a likely scenario for the electrification of passenger transportation was also provided by the International Energy Agency's 2-degree and 6-degree Celsius scenarios (4). Further details on the sources used to estimate the annual demand for services and level of deployment of efficient technologies is presented in Appendix Table A2.

It is important to realize that the reductions from the supply-side and the demand-side technologies cannot be simply calculated as a simple arithmetic sum of the two calculated independently. That is because the marginal environmental and resource benefits of additional energy efficiency diminish as the underlying energy supply technology becomes cleaner or less resource intensive. Likewise, the marginal benefits of cleaner and more resource efficient energy supply technology diminish as end-use energy efficiency increases, thereby lowering energy demand. Our scenario analyses integrate such aspects by using integrated hybrid model that combines both supply- and demand-side changes in a unified framework (23, 24). The term "overlapping effect" is used to describe the environmental impact reduction (or increase) that is shared between improved efficiency and decarbonised electricity. For example, the total reduction in GHG emissions by the clusters analysed in this report by 2030 is around 6 Gt. Demand-side measures alone would reduce emissions by about 4.8 Gt of GHGs, while decarbonisation alone would reduce emissions by about 4 Gt. In this case, the overlapping effect is quite substantial, accounting for 2.8 Gt, or almost half of the total reduction in emissions. Failing to account for this overlapping effect when adding up GHG emissions reductions from different sources like low-carbon electricity and energy efficiency could overestimate total potential reductions. Such effect can only be evaluated when the supply- and demand-side technologies are modelled simultaneously, in an integrated fashion, as performed in this analysis.

In some cases, GHG emission reductions and other environmental benefits are materialised through the interactions between supply-side and demand-side technologies. Electrification of passenger vehicles, for example, has a significant potential to reduce GHG emissions. However, without decarbonising electricity supply, the benefits of electrifying passenger vehicles cannot be materialised across all International Energy Agency regions. The result for the particulate matter formation category, for example, shows that low-carbon transportation technologies under 2-degree Celsius scenario increase the impact by 2030, while they reduce the impact by 2050 due to the differences in the mix of underlying electricity supply-side technologies. Therefore, decarbonisation of electricity should be emphasized preceding the electrification of passenger vehicles, especially in the regions of higher coal and oil-based electricity. These results suggest that a more rapid decarbonisation of electricity than proposed in the International Energy Agency's 2-degree Celsius scenario could provide additional co-benefits. For example, reaching 2050 2-degree Celsius scenario levels of renewable energy penetration by 2030, even with the same deployment of efficient demand-side technologies, could provide over 40% greater reductions in both GHG

emissions and almost 50% greater reductions in particulates. A faster adoption of low-carbon energy supply technologies would lower the overall environmental impacts of passenger transportation technologies.

Figure 13 shows the annual changes in environmental and resource impacts of deploying low-carbon energy supply and demand technologies aggregated into 8 technology clusters. Figure 14 further aggregates the results across the technology groups shown in Figure 13 and distinguishes the supply-side, demand-side and overlapping effects in the total annual changes from deploying all the low-carbon technologies analysed in this series of reports.

Figure 13 shows that the role of each individual technology in overall impact mitigation varies across the impact categories considered. For example, while efficient flash-furnace copper offers only limited potential for GHG savings in the 2-degree Celsius scenario, it can help reduce a significant amount of impacts in the toxicity categories. Also, improvements to the efficiency of freight transportation modes have the potential to contribute to global reductions in particulate matter formation that can affect both human and ecosystem health.

Figures 13 and 14 confirm that aggressive deployment of low-carbon technologies under the 2-degree Celsius scenario have the potential to reduce not only GHG emissions but also other environmental impacts as compared to those under the 6-degree Celsius scenario. The magnitudes of reduction in the particulate matter formation and the freshwater ecotoxicity categories are particularly significant. The only exception is metallic resource consumption, where the 2-degree Celsius scenario results are higher than the 6-degree Celsius scenario. Most of the additional impacts on metallic resources consumption in this scenario are contributed by low-carbon transportation technologies such as battery electric vehicles and a transition to low-carbon electricity generation technologies such as photovoltaic and wind power. The contributions to increased metal consumption by passenger transportation, particularly battery electric vehicles, are smaller than the aggregate increase in metal consumption expected for low-carbon electricity supply as described in the preceding International Resource Panel report (1) and discussed in Hertwich et al. (26) renewable technologies require higher initial investments in infrastructure than fossil-based power systems. To assess the tradeoffs of increased up-front emissions and reduced operational emissions, we present, to our knowledge, the first global, integrated life-cycle assessment (LCA. Furthermore, the relative magnitude of additional metal demand by low-carbon supply- and demand-side technologies is likely small compared to the background consumption of metals caused by the rest of the economy (26) renewable technologies require higher initial investments in infrastructure than fossil-based power systems. To assess the tradeoffs of increased up-front emissions and reduced operational emissions, we present, to our knowledge, the first global, integrated life-cycle assessment (LCA. This does not mean that there would not be any price increases or elevated scarcity of certain metals over the course of the aggressive deployment of low-carbon technologies under the 2-degree Celsius scenario. Additional, more detailed research is needed to better understand and mitigate such unintended consequences of low-carbon technologies. Numerical results showing the potential aggregate reductions in environmental impacts between the 2-degree Celsius scenario and 6-degree Celsius scenario are presented in table A1 in the Appendix.

Figure 13 shows an overall reduction in particulate pollution under the 2-degree Celsius scenario by 2030 and by 2050, due to increased deployment of energy efficient technologies as well as decarbonisation of electricity. Much of this reduction in particulates comes from a transition towards electric vehicles combined with decarbonisation of the electricity used to charge those vehicles. The risk of human exposure to particulates can be substantially different for particulates emitted from stationary power plants versus particles from mobile sources. Human exposure to particulates can vary with population density, the height of the emission source, background pollution levels, and other geographic and weather patterns (115). A great deal of research has dealt with estimating the intake fraction of emitted particles, that is the fraction of particulate pollution inhaled by humans in different locations from different types of sources (116–119).

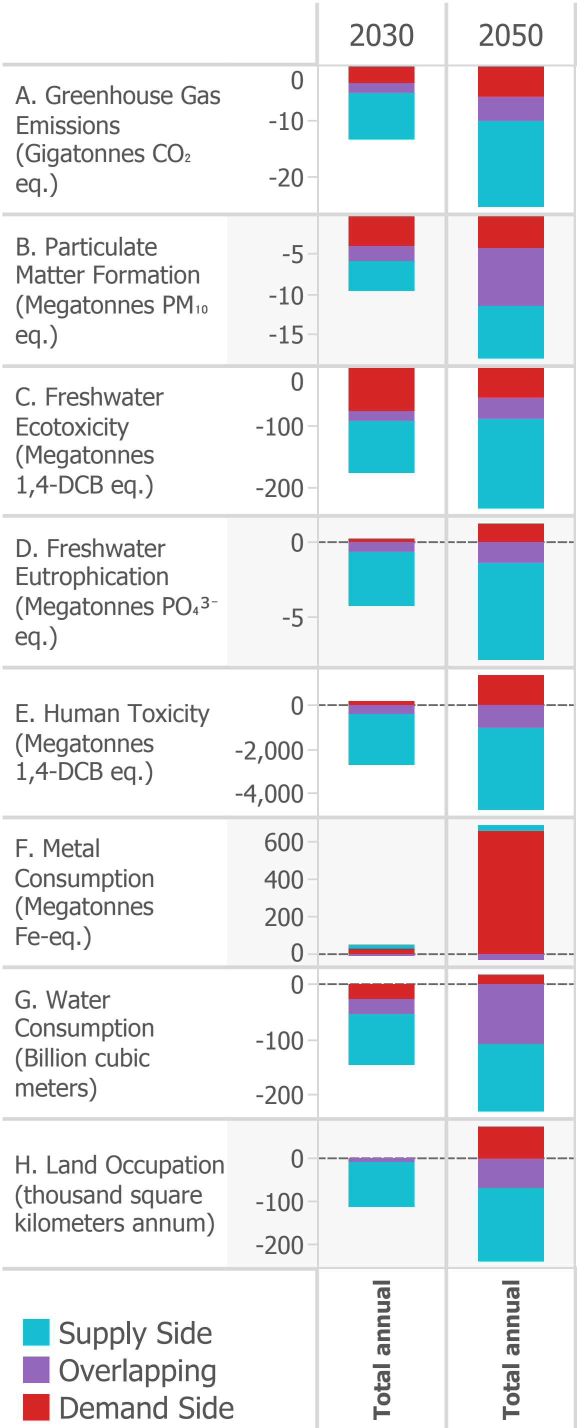
Comparing the intake fractions estimated for mobile sources to those for power plants allows us to perform a sensitivity analysis to better explore the potential change in particulate exposure and environmental benefits from transitioning towards electric vehicles over the course of the 2-degree Celsius scenario. Moriguchi et al. (120) found that for Japanese cities particulates from passenger vehicles were around four times worse than those from stationary sources. Greco et al. (118) found that primary particulates, SOx and NOx were around 1.8, 1.5, and 1.3 times worse for mobile sources in the US. Zhou et al. (119, 121) also found a higher percentage of particulates are inhaled for mobile sources in China. For the scenario results presented in Figures 13 and 14, PM formation under the 2-degree Celsius scenario is approximately 8% lower by 2030 and 15% lower by 2050. Assuming the ratio of mobile to stationary intake fractions found by Greco et al. and Moriguchi et al., the 2-degree Celsius scenario would fare 26-32% better than the 6-degree Celsius scenario in 2030, and 41%-49% better by 2050.

This result suggests that a transition from mobile sources of particulates to power plant-based sources of emissions could lead to greater environmental and human health benefits than indicated by Figures 13 and 14. It is important to note, however, that these estimates of intake fractions are based only on specific geographies and present-day conditions, meaning that further research is needed to better estimate the extent to which humans are likely to be exposed to particulates given the long-term changes in population, transportation demand, and electricity generation over the course of the International Energy Agency's scenarios.

In addition to particulates, Figure 14 also shows general reductions in other impact categories related to human and ecosystem health under the 2-degree Celsius scenario, including human toxicity and freshwater ecotoxicity. The substances and emissions that contribute to the categories of human toxicity impact human in different ways, and arise from varying processes throughout the supply chain of demand-side technologies. The higher human toxicity shown for electric vehicles warrants a brief explanation. Firstly, human toxicity should be differentiated from other impacts affecting human health, like particulate pollution which have traditionally been of most concern for transportation technologies. Potential human toxicity impacts of battery electric vehicles, on the other hand, arise from the life cycle of materials used in producing batteries and other vehicle components. Specifically, the biggest contributor to human toxicity of battery electric vehicles and all vehicles is the disposal of sulfide mine tailings from the mining of coal, copper and other metals used in the supply chain. These disposed materials include heavy metals that do not degrade over time like many toxic organic pollutants. Because the ReCiPe method equally considers the potential toxicity impacts of pollutant releases over thousands of years, even small quantities of these heavy metals that may not actually be transported to sensitive ecosystems or exposed to humans are weighted higher than initially more harmful organic pollutants, and can contribute substantially to the human toxicity and ecotoxicity indicators (31). If long term emissions for all transport technologies are ignored, however, battery electric vehicles still require more initial materials and show higher human toxicity results than conventional gasoline vehicles. This finding should be carefully weighed against the fact that battery electric vehicles, especially when coupled with decarbonized electricity, can substantially reduce particulate pollution that has traditionally been the major human health concern for vehicles.

FIGURE 13. The annual changes in environmental and resource impacts from deploying demand-side technologies globally in 2030 and 2050 under the 2-degree Celsius scenario broken down into technology groups.

FIGURES 14. The individual and overlapping effects on environmental and resource impacts from deploying demand- and supply-side technologies globally in 2030 and 2050 under the 2-degree Celsius.



7. Discussion of Policy Implications

Demand-side technologies exhibit substantial environmental co-benefits in most impact categories.

Many of the efficiency technologies available today show environmental benefits beyond GHG mitigation, including reduced impacts on the environment and natural resources. Examples of efficiency technologies with substantial co-benefits are efficient light-source technologies, flash furnace-based copper refining, added building insulation, demand management technologies, more efficient freight transportation, increased fuel-efficiency in gasoline vehicles, and co-generation in non-OECD regions. Given the benefits of these technologies, promoting these technologies would be environmentally beneficial even in the absence of policies promoting decarbonisation of electricity.

Some demand-side technologies may aggravate the pressure on metallic resources and other natural resources by more than 50% compared to conventional technologies.

Some demand-side technologies, including electric vehicles and a to a lesser extent a few building insulation technologies, may aggravate the pressure on natural resources, especially metallic resources, but the additional impacts by these technologies are relatively small compared to the rest of the economy. Battery electric vehicles, for example, increase metal consumption by around 50% compared to gasoline vehicles. This analysis shows that impacts would improve as batteries become more efficient.

Of the technologies studied, improvements to buildings, industry and vehicle fuel efficiency offer near-term environmental benefits of 20-70% compared to conventional technologies that provide the same service.

Among the technologies considered in this report, reducing natural gas combustion and electricity demand with building envelope improvements, efficient lighting and building energy management systems can offer near term environmental and natural resource co-benefits on the order of 20-70% in most impact categories considered, warm and cold climates, and developed and developing regions. Improving the fuel efficiency of conventional passenger cars and freight trucks also presents a near-term opportunity for environmental and resource benefits. Finally, industrial efficiency improvements, as exemplified by copper production and co-generation in this report can also offer substantial co-benefits at present. Co-generation at present is especially effective at reducing GHG emissions and particulates when offsetting heat and electricity production in countries with coal-based and GHG intensive electricity, particularly China and India. If electricity is decarbonised, however, the GHG benefits of co-generation would be reversed. Since these systems use natural gas or diesel to generate heat and electricity, they may increase GHG emissions in the long term under climate change mitigation scenarios like the 2-degree Celsius scenario.

Decarbonisation of electricity should go hand-in-hand with widespread vehicle electrification efforts to ensure GHG reductions and other environmental benefits

Electrification of personal vehicles is an important part of any climate change mitigation strategy but would only be effective if combined with renewable and low-carbon sources of electricity. At present, electric vehicles do not reduce GHGs in all regions, and policy makers should be made aware of local analyses of impacts before promoting electrification of transportation. Aggressive electrification of passenger transportation (75% of passenger cars in 2050), while underlying electricity generation still relies on coal and oil, may lead to an increase—rather than a decrease—in environmental impacts and natural resource pressures. These results, however, rely on only a few data sources available for estimates of the impacts other than climate change (98, 99), leaving room for further improvements. In reality, there are many other factors besides GHG emission mitigation that can influence the decision to switch to electric vehicles, such as mitigating local air pollution, reducing life-cycle costs when oil is expensive, and other social factors and consumer preferences that are not considered here. Decarbonisation of electricity also has the potential to increase the benefits of electrified public transportation options, including electric trains.

Rebound effects can diminish the environmental benefits of some technologies in some impact categories even when greenhouse gases are reduced

Saving energy and thereby fuel-costs by using energy-efficient demand-side technologies can lead to increased consumption of those services, an outcome known as the 'rebound effect.' More than a 100% increase in demand for the same service is needed to completely nullify the environmental co-benefits of low-carbon technologies achieved most efficient technologies in the buildings cluster. However, an increase in demand of less than 30% could eliminate their environmental benefits of efficient information and communication technology and passenger vehicles. In many cases, GHG emissions and other environmental and natural resource impacts are reduced less than direct energy consumption that is reduced when using efficient demand-side technologies. This means that if the demand for services increases due to rebound, some environmental or natural resource impacts will rise even if overall energy consumption declines.

Both demand-side approaches and low-carbon electricity are needed

The analyses in this series of reports suggest that both energy efficiency and demand-side technologies and low-carbon electricity generation should be deployed in tandem to meet climate change mitigation goals, as well as other environmental and resource objectives. This is evident in the scenario analysis presented here, showing the large contributions to emissions reductions of decarbonisation, deployment of energy efficiency technologies and their overlapping effect (being deployed in together).

Timely policy actions tailored to the specifics of the region are needed

The environmental and resource benefits of these efficiency technologies can vary significantly by region, impact category, and time of implementation. Achieving the potential benefits of low-carbon technologies outlined in the report depends on effective policy actions at the national and international levels to remove existing barriers and accelerate the uptake of the low-carbon technologies. In doing so, understanding the regional and temporal variations in the life-cycle impacts of low-carbon technologies can foster effective policy design that maximises the co-benefits.

8. References

1. Hertwich EG, et al. (2015) Green Energy Choices: The benefits, risks, and trade-offs of low-carbon technologies for electricity generation (UNEP International Resource Panel).
2. IPCC (2014) Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change eds Edenhofer O, et al. (IPCC, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA).
3. UNFCCC (2015) Adoption of the Paris Agreement. Report No. FCCC/CP/2015/L.9/Rev.1 (UNFCCC) Available at: http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf.
4. International Energy Agency (2012) Energy Technology Perspectives 2012 (OECD/IEA, Paris).
5. Jaffe AB, Stavins RN (1994) The energy-efficiency gap What does it mean? Energy policy 22(10):804–810.
6. Hirst E, Brown M (1990) Closing the efficiency gap: barriers to the efficient use of energy. Resources, Conservation and Recycling 3(4):267–281.
7. Greening LA, Greene DL, Difiglio C (2000) Energy efficiency and consumption—the rebound effect—a survey. Energy policy 28(6):389–401.
8. Binswanger M (2001) Technological progress and sustainable development: what about the rebound effect? Ecological economics 36(1):119–132.
9. Potočnik J, Khosla A (2016) Examining the Environmental Impact of Demand-Side and Renewable Energy Technologies. Journal of Industrial Ecology 20(2):216–217.
10. Suh S, Hertwich E, Hellweg S, Kendall A (2016) Life Cycle Environmental and Natural Resource Implications of Energy Efficiency Technologies. Journal of Industrial Ecology 20(2):218–222.
11. Bergesen JD, Tähkämö L, Gibon T, Suh S (2015) Potential long-term global environmental implications of efficient light-source technologies (accepted). Journal of Industrial Ecology.
12. Beucker S, Bergesen JD, Gibon T (2016) Building Energy Management Systems: Global Potentials and Environmental Implications of Deployment. Journal of Industrial Ecology 20(2):223–233.
13. Taptich M, Horvath A, Chester M (2015) Worldwide Greenhouse Gas Reduction Potentials inTransportation by 2050 (accepted). Journal of Industrial Ecology.
14. Kulczycka J, Lelek L, Lewandowska A, Wirth H, Bergesen JD (2015) Environmental impacts of energy-efficient pyrometallurgical copper smelting technologies - the consequences of technological changes from 2010 to 2050 (accepted). Journal of Industrial Ecology.
15. Kikuchi Y, Kanematsu Y, Sato R, Nakagaki T (2015) Distributed cogeneration of power and heat within an energy management strategy for mitigating fossil fuel consumption (accepted). Journal of Industrial Ecology.
16. Nauclér T, Enkvist P-A (2009) Pathways to a low-carbon economy: Version 2 of the global greenhouse gas abatement cost curve. McKinsey & Company 192.
17. IEA - Technology roadmaps Available at: https://www.iea.org/roadmaps/ [Accessed January 24, 2017].
18. IPCC (2001) Climate change 2001: Synthesis report: Third assessment report of the Intergovernmental Panel on Climate Change eds Watson RT, Albritton DL (Cambridge University Press, Cambridge, United Kingdom and New York, USA).
19. IPCC (2007) Climate change 2007: Synthesis report: fourth assessment report of the Intergovernmental Panel on Climate Change eds Pachauri RK, Reisinger A (IPCC, Geneva, Switzerland).
20. Guinée J, et al. (2002) Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards (Kluwer Academic Publishers: Dordrecht).
21. Hammond G (2014) Progress in Energy Demand Reduction-From Here to 2050 (Editorial). Proceedings of the Institution of Civil Engineers-Energy 167(3):89–102.

22. Čuček L, Klemeš JJ, Kravanja Z (2012) A review of footprint analysis tools for monitoring impacts on sustainability. Journal of Cleaner Production 34:9–20.
23. Gibon T, et al. (2015) A methodology for integrated, multiregional life cycle assessment scenarios under large-scale technological change. Environ Sci Technol. doi:10.1021/acs.est.5b01558.
24. Suh S, et al. (2004) System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches. Environ Sci Technol 38(3):657–664.
25. Suh S (2004) Functions, commodities and environmental impacts in an ecological–economic model. Ecological Economics 48(4):451–467.
26. Hertwich EG, et al. (2014) Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. Proceedings of the National Academy of Sciences. Available at: http://www.pnas.org/content/early/2014/10/02/1312753111.abstract.
27. International Energy Agency (2013) Transition to Sustainable Buildings: Strategies and Opportunities to 2050 (OECD/IEA, Paris).
28. US Department of Energy (2012) Solid-state lighting research and development: multi-year program plan.
29. ESU, IFEU (2008) New Energy Externalities Developments for Sustainability (NEEDS) – LCA of background processes (ESU; IFEU).
30. Goedkoop M, et al. (2009) ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. VROM–Ruimte en Milieu, Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer, www lcia-recipe net.
31. Pettersen J, Hertwich EG (2008) Critical review: life-cycle inventory procedures for long-term release of metals. Environmental science & technology 42(13):4639–4647.
32. ecoinvent (2010) Ecoinvent Database v2.2 (Ecoinvent Centre. Swiss Centre for Life Cycle Inventories, Switzerland).
33. Fowler K, Rauch E, Henderson J, Kora A (2011) Re-assessing green building performance: A post occupancy evaluation of 22 GSA buildings. Pacific Northwest National Laboratory: Richland, WA, USA.
34. Ma Z, Cooper P, Daly D, Ledo L (2012) Existing building retrofits: Methodology and state-of-the-art. Energy and Buildings 55:889–902.
35. Scholand M, Dillon HE (2012) Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products Part 2: LED Manufacturing and Performance (Pacific Northwest National Laboratory (PNNL), Richland, WA (US)).
36. Tähkämö L, et al. (2013) Life cycle assessment of light-emitting diode downlight luminaire—a case study. The International Journal of Life Cycle Assessment 18(5):1009–1018.
37. Tähkämö L (2013) Life cycle assessment of light sources–Case studies and review of the analyses.
38. Murphy Jr TW (2012) Maximum spectral luminous efficacy of white light. Journal of Applied Physics 111(10):104909.
39. Kamtekar KT, Monkman AP, Bryce MR (2010) Recent Advances in White Organic Light-Emitting Materials and Devices (WOLEDs). Adv Mater 22(5):572–582.
40. Dowson M, Harrison D, Craig S, Gill Z (2011) Improving the thermal performance of single-glazed windows using translucent granular aerogel. International Journal of Sustainable Engineering 4(3):266–280.
41. Dowson M, Grogan M, Birks T, Harrison D, Craig S (2012) Streamlined life cycle assessment of transparent silica aerogel made by supercritical drying. Applied Energy 97(0):396–404.
42. Aspen Aerogels (2011) Spaceloft® Data Sheet. Available at: http://www.tcnano-norge.no/Spaceloft_10_A.pdf [Accessed December 15, 2014].
43. Petersdorff C, Boermans T, Harnisch J (2006) Mitigation of CO2 Emissions from the EU-15 Building Stock. Beyond the EU Directive on the Energy Performance of Buildings (9 pp). Env Sci Poll Res Int 13(5):350–358.
44. Deru M, et al. (2011) US Department of Energy commercial reference building models of the national building stock.

45. US Department of Energy (2012) Estimating the Payback Period of Additional Insulation. Available at: http://energy.gov/energysaver/articles/estimating-payback-period-additional-insulation [Accessed December 16, 2014].

46. India Insulation Forum Thermal Insulation for Energy Efficiency in Buildings in India. Available at: http://beepindia.org/sites/default/files/K_K_Mitra-1.pdf [Accessed April 24, 2017].

47. Pino A, Bustamante W, Escobar R, Pino FE (2012) Thermal and lighting behavior of office buildings in Santiago of Chile. Energy and Buildings 47:441–449.

48. Thermal Insulation Association of South Africa (2010) The guide to energy efficient thermal insulation in buildings. Available at: http://www.aaamsa.co.za/images/Technical%20Publications/TIASA/TIASA%20GUIDE%202010%20Low%20Res.pdf.

49. Mahdy MM, Nikolopoulou M (2013) The cost of achieving thermal comfort via altering external walls specifications in Egypt; from construction to operation through different climate change scenarios. Building Simulation Conference France.

50. Paiho S, et al. (2013) Energy saving potentials of Moscow apartment buildings in residential districts. Energy and Buildings 66:706–713.

51. Yu S, Evans M, Shi Q (2015) Analysis of the Chinese Market for Building Energy Efficiency. Current Politics and Economics of Northern and Western Asia 24(2/3):155.

52. Collinge WO, Landis AE, Jones AK, Schaefer LA, Bilec MM (2014) Productivity metrics in dynamic LCA for whole buildings: Using a post-occupancy evaluation of energy and indoor environmental quality tradeoffs. Building and Environment 82:339–348.

53. Baggini A, Marra A (2012) Building Automation, Control and Management Systems. Electrical Energy Efficiency: Technologies and Applications:71–124.

54. Malina M (2013) Getting and keeping control–building energy management systems. Delivering Sustainable Buildings: An Industry Insider's view:145–160.

55. DENA (2010) Bericht 2010, dena Sanierungsstudie, Teil 1: Wirtschaftlichkeit energetische Modernisierung im Mietwohnungsbestand. [Report 2010, dena retrofitting survey, part 1: cost effectiveness of refurbishments in total stock of rented property.] (Deutsche Energieagentur, Berlin, Germany.).

56. Lee D, Cheng C-C (2016) Energy savings by energy management systems: A review. Renewable and Sustainable Energy Reviews 56:760–777.

57. Riedel M (2007) Mehrebenensteuerung für Energieeinspar-Contracting in Schulen und Kitas-Heizen nach Stundenplan. Pöschk, J: Energieeffizienz in Gebäuden, Jahrbuch.

58. Riedel M (2006) Hausautomation als wirtschaftliches Instrument für Energieeffizienz. Pöschk, J: Energieeffizienz in Gebäuden, Jahrbuch.

59. Delforge P (2014) Data Center Efficiency Assessment. Scaling Up Energy Efficiency Across the Data Center Industry: Evaluating Key Drivers and Barriers (National Resources Defense Council, New York, NY, US).

60. Williams E (2011) Environmental effects of information and communications technologies. Nature 479(7373):354–358.

61. Koomey J (2011) Growth in data center electricity use 2005 to 2010. A report by Analytical Press, completed at the request of The New York Times:9.

62. Urban B, Shmakova V, Lim B, Roth K (2014) Energy consumption of consumer electronics in US homes in 2013. Fraunhofer Center for Sustainable Energy Systems.

63. Ryen EG, Babbitt CW, Williams E (2015) Consumption-Weighted Life Cycle Assessment of a Consumer Electronic Product Community. Environmental science & technology 49(4):2549–2559.

64. Hertwich EG, Roux C (2011) Greenhouse gas emissions from the consumption of electric and electronic equipment by Norwegian households. Environmental science & technology 45(19):8190–8196.

65. Kasulaitis BV, Babbitt CW, Kahhat R, Williams E, Ryen EG (2015) Evolving materials, attributes, and functionality in consumer electronics: Case study of laptop computers. Resources, Conservation and Recycling 100:1–10.

66. Teehan P, Kandlikar M (2012) Sources of variation in life cycle assessments of desktop computers. Journal of Industrial Ecology 16(s1):S182–S194.

67. Vasan A, Sood B, Pecht M (2014) Carbon footprinting of electronic products. Applied Energy 136:636–648.

68. Teehan P, Kandlikar M (2013) Comparing embodied greenhouse gas emissions of modern computing and electronics products. Environmental science & technology 47(9):3997–4003.

69. Alaviitala T, Mattila TJ (2015) Engineered nanomaterials reduce but do not resolve life cycle environmental impacts of power capacitors. Journal of Cleaner Production 93:347–353.

70. Hischier R (2015) Life cycle assessment study of a field emission display television device. The International Journal of Life Cycle Assessment 20(1):61–73.

71. US Department of Energy Energy Star. Available at: http://www.energystar.gov.

72. TREN E (2005) Preparatory studies for Eco-design Requirements of EuPs „LOT 3-Personal Computers (desktops and laptops) and Computer Monitors. Final Report ". European Commission DG TREN, Preparatory studies for Eco-design Requirements of EuPs. Contract TREN D 1:1–8.

73. Deng L, Babbitt CW, Williams ED (2011) Economic-balance hybrid LCA extended with uncertainty analysis: case study of a laptop computer. Journal of Cleaner Production 19(11):1198–1206.

74. Socolof ML, Overly JG, Kincaid LE, Geibig JR (2001) Desktop Computer Displays: A Life-Cycle Assessment, Volume 1. (US Environmental Protection Agency, Washington, D.C.) Available at: http://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=200016BC.PDF

75. Aoe T, Michiyasu T, Matsuoka Y, Shikata N (2003) Case study for calculation of Factor X (Eco-Efficiency)-comparing CRT TV, PDP TV and LCD TV (IEEE), pp 650–655.

76. Andrae AG, Andersen O (2010) Life cycle assessments of consumer electronics — are they consistent? Int J Life Cycle Assess 15(8):827–836.

77. Lu L-T, et al. (2006) Balancing the life cycle impacts of notebook computers: Taiwan's experience. Resources, Conservation and Recycling 48(1):13–25.

78. Herrmann C (2008) Environmental footprint of ICT equipment in manufacture, use and end of life. Optical Communication. Available at: http://www.pe-international.com/uploads/media/Environmental_footprint_of_ICT_equipment_01.pdf.

79. Masanet E (2014) ICT data compilation.

80. Suh S (2011) Quantification of cradle-to-gate, use and end-of-life phase greenhouse gas emissions of selected EnergyStar products (Report to US Environmental Protection Agency).

81. Apple (2015) product environmental reports. product environmental reports. Available at: http://www.apple.com/environment/reports/ [Accessed August 10, 2015].

82. Shehabi A, Walker B, Masanet E (2014) The energy and greenhouse-gas implications of internet video streaming in the United States. Environmental Research Letters 9(5):054007.

83. Moya JA, Pardo N (2013) The potential for improvements in energy efficiency and CO 2 emissions in the EU27 iron and steel industry under different payback periods. Journal of Cleaner Production 52:71–83.

84. Hasanbeigi A, Morrow W, Sathaye J, Masanet E, Xu T (2013) A bottom-up model to estimate the energy efficiency improvement and CO2 emission reduction potentials in the Chinese iron and steel industry. Energy 50:315–325.

85. Zhang S, Worrell E, Crijns-Graus W, Wagner F, Cofala J (2014) Co-benefits of energy efficiency improvement and air pollution abatement in the Chinese iron and steel industry. Energy 78:333–345.

86. Allwood JM, Cullen JM, Milford RL (2010) Options for Achieving a 50% Cut in Industrial Carbon Emissions by 2050. Environ Sci Technol 44(6):1888–1894.

87. Bergesen JD, Heath GA, Gibon T, Suh S (2014) Thin-Film Photovoltaic Power Generation Offers Decreasing Greenhouse Gas Emissions and Increasing Environmental Co-benefits in the Long Term. Environ Sci Technol 48(16):9834–9843.

88. Tuominen J, Kojo IV (2005) Blister flash smelting—Efficient and flexible low-cost continuous copper process.

89. Lowe R (2007) Technical options and strategies for decarbonizing UK housing. Building Research & Information 35(4):412–425.
90. McKone T, et al. (2011) Grand challenges for life-cycle assessment of biofuels. Environmental Science & Technology 45(5):1751–1756.
91. Strogen B, Horvath A, McKone TE (2012) Fuel miles and the blend wall: Costs and emissions from ethanol distribution in the United States. Environmental science & technology 46(10):5285–5293.
92. International Civil Aviation Organization (2010) Aircraft Technology Improvements (International Civil Aviation Organization) Available at: http://www.icao.int/environmental-protection/Documents/EnvironmentReport-2010/ICAO_EnvReport10-Ch2_en.pdf [Accessed November 1, 2014].
93. International Council on Clean Transportation (ICCT) (2012) Evolution of heavy-duty vehicle GHG and fuel economy standards (International Council on Clean Transportation (ICCT).) Available at: http://www.theicct.org/evolution-hdv-ghg-and-fueleconomy-standards [Accessed November 1, 2014].
94. International Council on Clean Transportation (ICCT) (2014) Global Passenger Vehicle Standards (International Council on Clean Transportation ICCT)) Available at: http://www.theicct.org/info-tools/global-passenger-vehicle-standards [Accessed November 1, 2014].
95. International Marine Organization (IMO) (2013) Technical and Operational Measures, Energy Efficiency Design Index Available at: http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Technical-and-Operational-Measures.aspx [Accessed November 1, 2014].
96. National Research Council (NRC) (2014) Reducing the Fuel Consumption and Greenhouse Gas Emissions of Medium- and Heavy-Duty Vehicles, Phase Two: First Report (Committee on Assessment of Technologies and Approaches for Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles, Phase Two; Board on Energy and Environmental Systems; Division on Engineering and Physical Sciences; Transportation Research Board; National Research Council) Available at: http://www.nap.edu/catalog.php?record_id=18736 [Accessed November 1, 2014].
97. International Institute for Applied Systems Analysis (IIASA) Energy Program (2014) AR5 Scenario Database. Available at: https://secure.iiasa.ac.at/web-apps/ene/AR5D [Accessed February 1, 2015].
98. Majeau-Bettez G, Hawkins TR, Strømman AH (2011) Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles. Environ Sci Technol 45(10):4548–4554.
99. Hawkins TR, Singh B, Majeau Bettez G, Strømman AH (2013) Comparative environmental life cycle assessment of conventional and electric vehicles. Journal of Industrial Ecology 17(1):53–64.
100. Nordelöf A, Messagie M, Tillman A-M, Ljunggren Söderman M, Van Mierlo J (2014) Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? Int J Life Cycle Assess 19(11):1866–1890.
101. Taptich MN, Horvath A (2015) Freight on a Low-Carbon Diet: Accessibility, Freightsheds, and Commodities. Environ Sci Technol. doi:10.1021/acs.est.5b01697.
102. Berkhout PHG, Muskens JC, W Velthuijsen J (2000) Defining the rebound effect. Energy Policy 28(6):425–432.
103. Hertwich EG (2005) Consumption and the rebound effect: an industrial ecology perspective. Journal of Industrial Ecology 9(1 2):85–98.
104. Borenstein S (2013) A microeconomic framework for evaluating energy efficiency rebound and some implications (National Bureau of Economic Research).
105. Font Vivanco D, van der Voet E (2014) The rebound effect through industrial ecology's eyes: a review of LCA-based studies. Int J Life Cycle Assess 19(12):1933–1947.
106. Barker T, Ekins P, Foxon T (2007) The macro-economic rebound effect and the UK economy. Energy Policy 35(10):4935–4946.
107. Sorrell S, Dimitropoulos J, Sommerville M (2009) Empirical estimates of the direct rebound effect: A review. Energy Policy 37(4):1356–1371.

108. Tsao JY, Waide P (2010) The world's appetite for light: empirical data and trends spanning three centuries and six continents. Leukos 6(4):259–281.

109. Saunders HD, Tsao JY (2012) Rebound effects for lighting. Energy Policy 49(0):477–478.

110. Chitnis M, Sorrell S, Druckman A, Firth SK, Jackson T (2013) Turning lights into flights: Estimating direct and indirect rebound effects for UK households. Energy Policy 55:234–250.

111. Druckman A, Chitnis M, Sorrell S, Jackson T (2011) Missing carbon reductions? Exploring rebound and backfire effects in UK households. Energy Policy 39(6):3572–3581.

112. Hicks AL, Theis TL (2014) An agent based approach to the potential for rebound resulting from evolution of residential lighting technologies. The International Journal of Life Cycle Assessment 19(2):370–376.

113. Hicks AL, Theis TL, Zellner ML (2015) Emergent Effects of Residential Lighting Choices: Prospects for Energy Savings. Journal of Industrial Ecology 19(2):285–295.

114. Font Vivanco D, Freire-González J, Kemp R, van der Voet E (2014) The Remarkable Environmental Rebound Effect of Electric Cars: A Microeconomic Approach. Environ Sci Technol 48(20):12063–12072.

115. Humbert S, et al. (2011) Intake fraction for particulate matter: recommendations for life cycle impact assessment. Environmental science & technology 45(11):4808–4816.

116. Apte JS, Bombrun E, Marshall JD, Nazaroff WW (2012) Global intraurban intake fractions for primary air pollutants from vehicles and other distributed sources. Environmental science & technology 46(6):3415–3423.

117. Levy JI, Wolff SK, Evans JS (2002) A Regression Based Approach for Estimating Primary and Secondary Particulate Matter Intake Fractions. Risk Analysis 22(5):895–904.

118. Greco SL, Wilson AM, Spengler JD, Levy JI (2007) Spatial patterns of mobile source particulate matter emissions-to-exposure relationships across the United States. Atmospheric Environment 41(5):1011–1025.

119. Zhou Y, Levy JI, Evans JS, Hammitt JK (2006) The influence of geographic location on population exposure to emissions from power plants throughout China. Environment International 32(3):365–373.

120. Moriguchi Y, Terazono A (2000) A simplified model for spatially differentiated impact assessment of air emissions. Int J LCA 5(5):281–286.

121. Zhou Y, Levy JI, Hammitt JK, Evans JS (2003) Estimating population exposure to power plant emissions using CALPUFF: a case study in Beijing, China. Atmospheric Environment 37(6):815–826.

122. Edelstein DL (2013) U.S. Geological Survey Minerals Yearbook (Copper) (U.S Geological Survey) Available at: tp://minerals.usgs.gov/minerals/pubs/commodity/copper/myb1-2006-coppe.pdf.

123. ICSG (2014) The World Copper Factbook Available at: http://www.icsg.org/index.php/component/jdownloads/viewdownload/170/1959.

124. Kishita Y, Inoue H, Kobayashi S, Umeda Y (2012) Development of an Integrated Model to Estimate Long-term Metal Demand Based on Sustainability Scenarios. Proc of the 10th International Conference on EcoBalance 2012: Challenges and Solutions for Sustainable Society, C2-06, Yokohama, Japan. Available at: http://www-lce.mech.eng.osaka-u.ac.jp/kishita/papers/EcoBalance2012.pdf.

9. Appendix

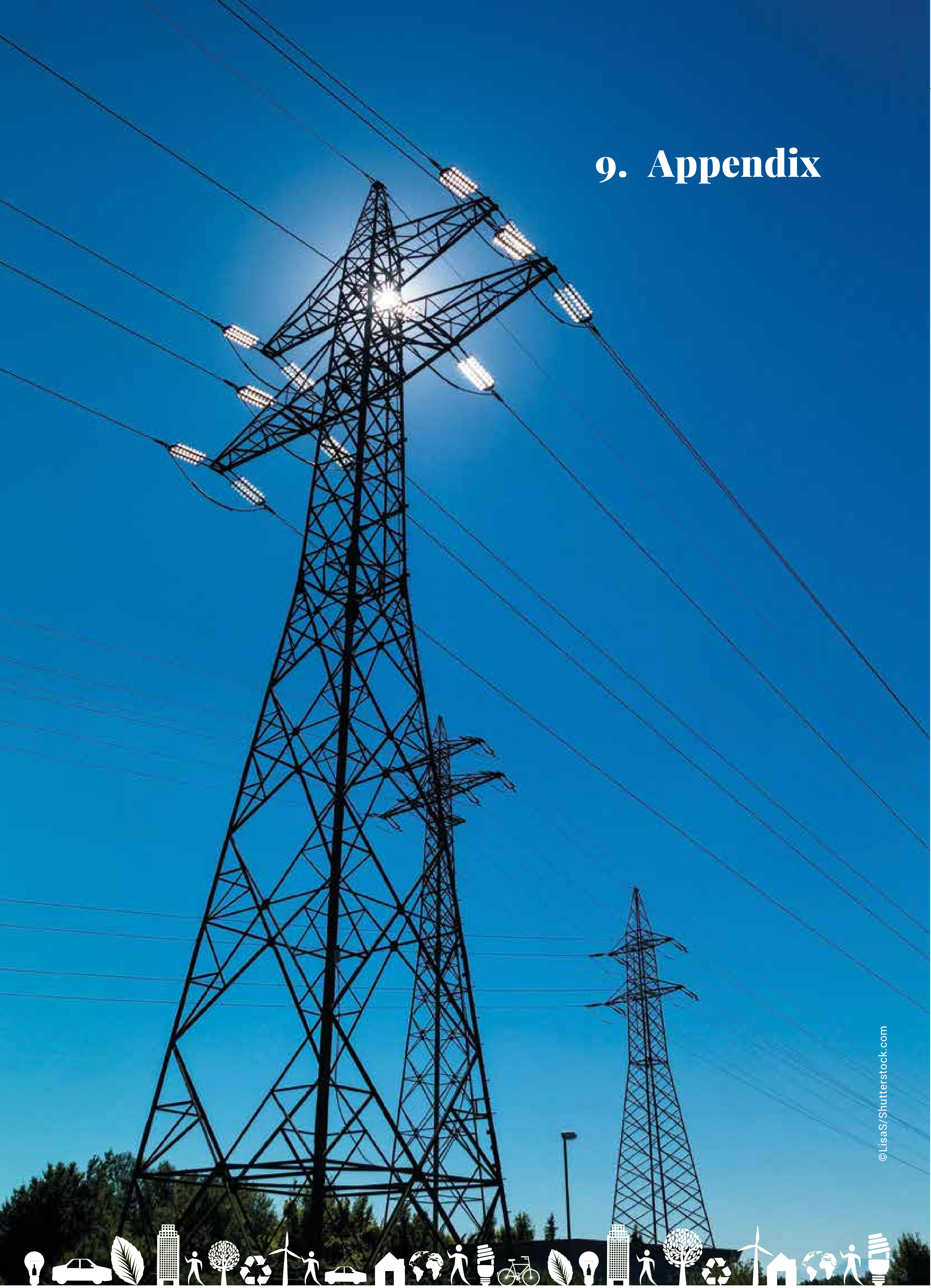


TABLE A1. Summary of scenario results. Impact reductions from efficiency technologies and electricity decarbonization. The overlapping effect shows the impact reduction that would be overestimated or underestimated by adding the individual reductions from efficient technologies and decarbonization alone.

		2030									2050								
		Efficient Lighting	Building Shell	Demand-side energy manage-ment	Coppper Produc-tion	Co-generation	Passen-ger Transport	Freight Transport	Other Decarb-onizaiton	Total reduction (+) or increase (-)	Efficient Lighting	Building Shell	Demand-side energy manage-ment	Coppper Produc-tion	Co-generation	Passen-ger Transport	Freight Transport	Other Decarb-onizaiton	Total reduction (+) or increase (-)
Greenhouse gas emissions (Megatonnes CO2-eq.)	Efficient technology	455.6	339.2	342.0	62.8	545.7	2801.1	430.1		4976.5	823.7	729.6	736.6	45.9	930.2	5959.9	859.3		10085.1
	Decarbonization	829.5	703.1	709.1	32.9	0.6	657.7	69.8	6997.3	10000.0	1484.6	1573.4	1588.4	47.5	1.7	2250.0	166.7	12887.7	20000.0
	Overlapping effect	-226.5	-34.5	-34.8	-15.7	-512.1	-657.7	-13.4		-1494.7	-633.1	-119.2	-120.3	-19.0	-1319.5	-2250.0	-51.7		-4512.8
	Total Reduction	**1058.7**	**1007.7**	**1016.3**	**79.9**	**34.2**	**2801.1**	**486.6**	**6997.3**	**13481.8**	**1675.1**	**2183.9**	**2204.6**	**74.3**	**-387.6**	**5959.9**	**974.3**	**12887.7**	**25572.2**
Metal Consumption (Megatonnes Fe-eq)	Efficient technology	20.9	0.7	1.1	194.2	3.1	-226.5	1.5		-5.0	44.2	2.1	2.8	151.8	5.0	-831.3	3.0		-622.4
	Decarbonization	3.3	4.1	6.8	0.2	0.0	16.6	0.8	-38.0	-6.2	6.0	8.1	11.1	0.2	0.0	32.2	1.4	-58.5	0.5
	Overlapping effect	-0.9	-0.2	-0.3	-0.1	0.0	-16.6	0.0		-18.1	-2.5	-0.6	-0.9	-0.1	-1.4	-32.2	-0.1		-37.7
	Total Reduction	**23.4**	**4.6**	**7.5**	**194.3**	**3.1**	**-226.5**	**2.3**	**-38.0**	**-29.4**	**47.7**	**9.5**	**13.0**	**151.9**	**3.7**	**-831.3**	**4.4**	**-58.5**	**-659.6**
Human Toxicity (Megatonnes 1,4, DCB-eq.)	Efficient technology	138.3	21.8	21.2	64.3	37.3	-159.9	16.8	0.0	139.8	164.1	42.7	40.8	40.1	142.6	-941.9	34.8	0.0	-476.8
	Decarbonisation	305.6	254.6	248.2	10.8	0.1	249.2	18.5	1579.1	2666.2	360.9	375.5	359.2	11.0	0.3	670.9	31.7	2973.3	4782.8
	Combined effect	-83.5	-15.8	-15.4	-5.1	-18.6	-249.2	-2.6	0.0	-390.2	-135.1	-38.1	-36.4	-4.4	-71.3	-670.9	-7.4	0.0	-963.5
	Total Reduction	**360.4**	**260.6**	**254.1**	**70.0**	**18.8**	**-159.9**	**32.7**	**1579.1**	**2415.8**	**390.0**	**380.1**	**363.6**	**46.7**	**71.6**	**-941.9**	**59.1**	**2973.3**	**3342.5**
Freshwater Ecotoxicity (Megatonnes 1,4, DCB-eq.)	Efficient technology	3.4	0.5	0.6	64.3	1.0	4.2	16.8		90.7	3.8	0.8	1.2	40.1	1.8	4.7	34.8		87.2
	Decarbonization	8.2	6.3	7.2	10.8	0.0	6.7	18.5	44.5	102.3	8.9	7.7	10.7	11.0	0.0	17.2	31.7	96.4	183.5
	Overlapping effect	-2.2	-0.4	-0.5	-5.1	-0.6	-6.7	-2.6		-18.1	-3.2	-0.8	-1.1	-4.4	-1.7	-17.2	-7.4		-35.8
	Total Reduction	**9.4**	**6.4**	**7.3**	**70.0**	**0.4**	**4.2**	**32.7**	**44.5**	**174.9**	**9.5**	**7.7**	**10.7**	**46.7**	**0.1**	**4.7**	**59.1**	**96.4**	**235.0**
Particulate matter (Megatonnes PM10-eq.)	Efficient technology	0.8	0.1	0.1	0.3	0.6	2.7	1.1		5.8	1.6	0.3	0.4	0.2	0.9	6.0	2.1		11.5
	Decarbonization	1.3	1.1	1.1	0.1	0.0	1.1	0.2	0.8	5.7	3.1	3.1	3.2	0.1	0.0	4.1	0.6	-0.5	13.7
	Overlapping effect	-0.4	0.0	0.0	0.0	-0.2	-1.1	-0.1		-1.8	-1.4	-0.2	-0.2	0.0	-0.9	-4.1	-0.3		-7.2
	Total Reduction	**1.8**	**1.2**	**1.2**	**0.3**	**0.3**	**2.7**	**1.2**	**0.8**	**9.6**	**3.3**	**3.2**	**3.4**	**0.3**	**-0.1**	**6.0**	**2.4**	**-0.5**	**18.0**
Freshwater Eutrophication (Megatonnes P-eq.)	Efficient technology	0.2	0.0	0.0	0.1	0.0	0.0	0.0		0.4	0.2	0.1	0.1	0.0	0.1	-0.4	0.0		0.0
	Decarbonization	0.5	0.4	0.4	0.0	0.0	0.4	0.0	2.5	4.3	0.5	0.6	0.4	0.0	0.0	1.0	0.0	5.4	7.9
	Overlapping effect	-0.1	0.0	0.0	0.0	0.0	-0.4	0.0		-0.6	-0.2	-0.1	0.0	0.0	-0.1	-1.0	0.0		-1.3
	Total Reduction	**0.5**	**0.4**	**0.4**	**0.1**	**0.0**	**0.0**	**0.0**	**2.5**	**4.0**	**0.5**	**0.6**	**0.4**	**0.1**	**0.0**	**-0.4**	**0.0**	**5.4**	**6.6**
Land occupation (thousand km2-annum)	Efficient technology	14.7	1.7	1.8	2.6	9.1	-23.3	1.0		7.6	27.3	4.2	4.8	1.9	16.8	-64.7	2.3		-7.4
	Decarbonization	2.1	2.8	3.0	0.2	0.0	3.6	1.1	101.5	114.1	34.0	31.8	37.1	1.1	0.0	38.9	3.8	94.2	241.0
	Overlapping effect	-0.6	0.3	0.3	-0.1	-1.2	-6.7	-0.1		-8.0	-16.0	-1.7	-2.0	-0.4	-10.2	-38.9	-0.4		-69.7
	Total Reduction	**16.2**	**4.7**	**5.1**	**2.7**	**8.0**	**-26.5**	**2.0**	**101.5**	**113.7**	**45.3**	**34.3**	**39.9**	**2.6**	**6.7**	**-64.7**	**5.6**	**94.2**	**163.9**
Water Depletion (billion cubic liters)	Efficient technology	12.3	1.2	1.6	1.3	19.2	15.9	2.1	0.0	53.6	20.2	2.3	3.6	0.9	26.3	31.4	4.1	0.0	88.7
	Decarbonisation	22.5	13.6	17.3	0.9	-3.7	18.6	1.9	46.8	117.9	40.8	22.7	35.9	1.3	-6.1	64.3	4.1	68.2	231.2
	Combined effect	-6.1	-0.6	-0.8	-0.4	-0.9	-18.6	-0.3	0.0	-27.8	-17.5	-1.7	-2.7	-0.5	-20.7	-64.3	-0.9	0.0	-108.4
	Total Reduction	**28.7**	**14.2**	**18.1**	**1.8**	**14.6**	**15.9**	**3.7**	**46.8**	**143.7**	**43.5**	**23.2**	**36.8**	**1.7**	**-0.5**	**31.4**	**7.3**	**68.2**	**211.6**

TABLE A2. Summary of sources used to estimate total yearly demand and energy savings for scenario analysis.

Cluster	Technologies	Sources	Comment
Buildings	Efficient Lighting	International Energy Agency's Transition to Sustainable Buildings (27) and Energy Technology Perspectives (4).	Reports provided projections on current and future energy consumption for lighting under 2-degree Celsius and 6-degree Celsius scenario.
	Building Shell Demand-side Energy Management	Transition to Sustainable Buildings (27) and Energy Technology Perspectives (4).	Reports provided estimates of current and future energy consumption for heating and cooling and projections of potential energy savings from building insulation and demand management under 2-degree Celsius scenario.
Industry	Copper Production	Edelstein (122), International Copper Study Group (ICSG) (123), Kishita et al. (124) and Hertwich et a. (103).	Baseline demand projections are based on Edelstein and ICSG. Kishita and Hertwich project increased copper demand based on demand from low-carbon energy scenarios.
	Industrial Co-generation	Energy Technology Perspectives (4).	IEA estimated potential energy savings from co-generation in the chemical and pulp and paper industries.
Transport	Passenger transportation	Intergovernmental Panel on Climate Change AR5 Scenario database (97), International Energy Agency (4).	Intergovernmental Panel on Climate Change data was used to future demand for passenger and freight transport in each region from 2010-2050 and current mode shares. Energy Technology Perspectives scenarios were used to model like future mode shares of electric vehicles under the 2-degree Celsius scenario.
	Freight transportation	Intergovernmental Panel on Climate Change AR5 Scenario database (97).	

TABLE A3. Energy savings from building shell improvements for selected cities in each region.

City	IEA region	Heating Degree Days	Cooling Degree Days	Heating Savings	Cooling Savings
		Degrees Celsius per year		kWh per additional m² insulation (R = 1 m²K/W) per year	
Beijing	China	2,570	1,377	186.45	22.83
Hong Kong	China	94	3,239	6.82	53.71
New Delhi	India	237	3,783	11.43	41.70
Mumbai	India	0	4,576	0	50.44
Kyiv	Economies in Transition	3,034	709	52.44	2.80
Moscow	Economies in Transition	3,958	499	68.42	1.97
Lima	Latin America	15	1,503	0.21	4.83
Santiago	Latin America	1,179	1,029	16.58	3.31
Jakarta	Other Developing Asia	0	4,475	0	49.32
Karachi	Other Developing Asia	57	4,119	2.75	45.40
Cairo	Africa and Middle East	145	2,873	7.84	35.52
Johannesburg	Africa and Middle East	669	1,004	26.02	8.93
Berlin	OECD Europe	2,503	514	20.10	0.94
Istanbul	OECD Europe	1,167	1,324	16.86	4.37
Los Angeles	OECD North America	356	802	10.48	5.40
Chicago	OECD North America	2,617	1,052	21.02	1.93
Seoul	OECD Pacific	2,573	1,173	20.66	2.15
Sydney	OECD Pacific	302	1,429	8.89	9.62

TABLE A4. Sources of typical building insulation R-values for cities and regions.

Region	Source for typical levels of insulation
China	Yu S, Evans M, Shi Q (2015) Analysis of the Chinese Market for Building Energy Efficiency. Current Politics and Economics of Northern and Western Asia 24(2/3):155.
India & Other Developing Asia	India Insulation Forum Thermal Insulation for Energy Efficiency in Buildings in India. Available at: http://beepindia.org/sites/default/files/K_K_Mitra-1.pdf [Accessed April 24, 2017].
Economies in Transition	Paiho S, et al. (2013) Energy saving potentials of Moscow apartment buildings in residential districts. Energy and Buildings 66:706–713.
Latin America	Pino A, Bustamante W, Escobar R, Pino FE (2012) Thermal and lighting behaviour of office buildings in Santiago of Chile. Energy and Buildings 47:441–449.
Africa and Middle East (Cairo)	Mahdy MM, Nikolopoulou M (2013) The cost of achieving thermal comfort via altering external walls specifications in Egypt; from construction to operation through different climate change scenarios.
Africa and Middle East (Johannesburg)	Thermal Insulation Association of South Africa (2010) The guide to energy efficient thermal insulation in buildings. Available at: http://www.aaamsa.co.za/images/ Technical%20Publications/TIASA/TIASA%20GUIDE%202010%20Low%20Res.pdf.
OECD Europe, North America and Pacific	Deru M, et al. (2011) US Department of Energy commercial reference building models of the national building stock.

Green Technology Choices:

The Environmental and Resource Implications of Low-Carbon Technologies
International Resource Panel Report

The Paris Agreement sets a goal of holding the global average temperature increase to well below 2 °C, and pursuing efforts to limit this to 1.5 °C above pre-industrial levels. Achieving this goal requires an unprecedented deployment of both low-carbon energy supply and energy efficient demand-side technologies in order to reduce the greenhouse gas emissions from electricity production and consumption. But what impacts will a large-scale deployment of these technologies have on other environment aspects, human health and natural resource use? Will they bring co-benefits or will they cause other unintended environmental or social problems?

In order to address these questions, the International Resource Panel developed a series of reports on the long-term global transition to low-carbon technologies and their environmental and resource implications. The first report, "Green Energy Choices", evaluated the benefits, risks and trade-offs of low-carbon technologies for electricity production.

This report is the second one of the series and examines the life cycle environmental, health and natural resource implications of large-scale deployment of energy efficiency technologies. This is the first international assessment of this type, which analyses more than 30 demand-side energy efficiency technologies across different technological clusters including lighting, buildings, information and communication technology, efficient metals processing, high-efficiency cogeneration and transportation. In addition, the combined impacts of low-carbon energy supply and deployment of efficient demand-side technologies under the 2 degree and 6 degree Celsius scenarios are assessed.

The report provides decision-makers with a better understanding of the regional and temporal variations in the life-cycle impacts of low-carbon technologies to enable them to foster effective policy design that maximises the co-benefits and to choose technologies strategically.

FOR MORE INFORMATION, CONTACT:

International Resource Panel Secretariat
UN Environment
Economy Division
1 rue Miollis, Building VII
75015 Paris, France
Email : resourcepanel@unep.org
Web : www.resourcepanel.org

UN environment
United Nations Environment Programme

International Resource Panel