THE TRUE COST OF FOSSIL FUELS:

SAVING ON THE EXTERNALITIES OF AIR POLLUTION AND CLIMATE CHANGE

This brief quantifies air pollution and climate change externalities related to fossil fuels and the extent these can be reduced with higher uptake of renewables. For this purpose, the analysis compares global energy demand between now and 2030 through two cases: first, based on current and planned energy policies; and second, by doubling the share of renewables in the energy mix within 15 years.

The reduction of pollution and climate impact through rapidly increased use of renewable energy by 2030 could save up to USD 4.2 trillion per year worldwide, 15 times the associated costs of doubling the share of renewables. Today's energy markets, however, do not adequately value climate impact or air pollution. Energy and environmental policies need to correct for these externalities.

KEY FINDINGS

» **External costs related to the use of fossil fuels stem from many causes.** These include pollution and *environmental degradation* resulting from the extraction of resources; indoor and outdoor *air pollution* due directly to fuel combustion as well as non-combustion emissions such as those from industrial processes; and the negative impact of *extreme weather events* caused by global warming.

» **Doubling the renewable share in the global energy mix can result in significant savings of fossil fuels.** Compared to the 2030 Reference Case, coal, oil and natural gas supplies can be reduced by 22%, 11% and 11%, respectively, while primary renewable energy supply could increase by up to 46% over the coming 15 years.

» **Modern renewables include multiple types of sustainable, cost-effective bioenergy and biofuels, which comprise crucial elements in the energy transition.** The envisaged scale-up of modern renewables also allows for the phase-out of traditional bioenergy uses that involve unsustainable fuel gathering and toxic combustion.

» **Reduced use of fossil fuels allows the avoidance of carbon dioxide (CO_2) emissions and air pollutants.** With the renewable share doubled, particulate matter ($PM_{2.5}$) emissions that result in serious adverse effects on human health would be reduced by 33% compared to today's levels. Likewise, emissions of mono-nitrogen oxides (NO_x), sulphur dioxide (SO_2), ammonia (NH_3) and volatile organic compounds (VOCs), all of which have serious health effects, would also be lower than today's levels. Doubling the share of renewables, combined with significant increases in energy efficiency, would halve energy-related CO_2 emissions in 2030, in comparison to current and planned energy policies.

» **These substitutions would reduce externalities by at least USD 1.2 trillion per year and as much as USD 4.2 trillion per year by 2030, in comparison to current policies.** Much of this reduction relates to indoor and outdoor air pollution.

» **Doubling renewables in the global energy mix could save up to 4 million lives annually by 2030.** This compares with 3.7 million premature deaths from ambient air pollution and 4.3 million deaths from household air pollution in 2012, according to World Health Organization (WHO) figures.

INTRODUCTION

This brief quantifies air pollution and climate change externalities related to the combustion of fossil fuels and bioenergy around the world. The assessment is part of a broader analysis undertaken by the International Renewable Energy Agency (IRENA) to lay out a roadmap to double the share of renewables in the global energy mix by 2030. IRENA's *REmap* analysis spans 40 countries that account for 80% of total global energy demand.[1]

The analysis, carried out in consultation with experts from each country, looks at the developments in global energy demand between now and 2030 for two cases. The first is the Reference Case, which focuses on renewable energy deployment according to today's country plans and current and planned energy policies. The second case identifies renewable energy technology options that could double the renewable energy share in the global energy mix by 2030.

Emissions of air pollutants and CO_2 emissions are quantified for the 2010-2030 period, and their cost to human health, agricultural crops and the environment is assessed. This has been done based on a range of carbon prices for the world as a whole, and on the damage costs of pollutants differentiated by country and sector.

With renewables doubled in the energy mix, the resulting reduction of air pollution, both indoors and outdoors, would offer large financial savings estimated to be between USD 1 trillion and USD 3.2 trillion per year in 2030, compared to the Reference Case (*i.e.* business as usual). Annual savings related to climate change could amount to between USD 200 billion and USD 1 trillion depending on how carbon emissions are priced. In total, these savings are at least four times—and as much as fifteen times—higher than the costs associated with doubling the share of renewables in the global energy mix by 2030.

These tremendous savings, however, will not occur without policy change. Energy markets generally do not adequately value or account for externalities related to climate change and air pollution (Parry *et al.*, 2014). Energy and environment policies, therefore, must be re-designed to correct for these externalities.

POLLUTION AND CLIMATE EFFECTS DUE TO FUEL COMBUSTION

The combustion of fossil fuels and traditional uses of bioenergy is a major source of local air pollution. SO_2, NO_x and $PM_{2.5}$ are some of the main pollutants. These pollutants can cause adverse human health effects, but they can also cause reduced agricultural yields, damage to forests and fisheries (acid rain), and damage to buildings and infrastructure. The majority of adverse impacts, however, are found to be on human health. Worldwide, some 8 million people per year die prematurely from indoor and outdoor air pollution caused by energy consumption for heating, cooking, power generation and transport.

Currently, the external effects of energy supply and use related to climate change and air pollution are in the order of USD 2.2 trillion – USD 5.9 trillion per year. In comparison, the cost of global energy supply is in the order of USD 5 trillion per year.[2] According to European Commission estimates, the external costs of air pollution in the European Union (EU) alone ranged between USD 330 billion and USD 940 billion in 2010 (Verheye, 2014).

Different pollutants arise from different energy uses. The residential sector (classed as part of buildings within the REmap methodology), for example, is responsible for substantial PM and VOC emissions. In contrast, NO_x emissions originate mainly from the transport sector and SO_2 emissions mainly from power generation. The sector breakdown of total externalities also differs by region. In Africa, the main sector responsible for pollution is the residential sector, whereas in most other regions, power generation and

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[1] *Status December 2015. The 40 REmap countries are: Argentina, Australia, Belgium, Brazil, Canada, China, Colombia, Cyprus, Denmark, the Dominican Republic, Ecuador, Egypt, Ethiopia, France, Germany, India, Indonesia, Iran, Italy, Japan, Kazakhstan, Kenya, Kuwait, Malaysia, Mexico, Morocco, Nigeria, Poland, the Republic of Korea, the Russian Federation, Saudi Arabia, South Africa, Sweden, Tonga, Turkey, Ukraine, the United Arab Emirates, the United Kingdom, the United States of America (USA) and Uruguay.*
[2] *All economic data in this brief are expressed in real 2010 USD.*

transport are the main contributors. For instance in several Southeast Asian countries, urban transport is a major contributor to air pollution. In member countries of the Organisation for Economic Co-operation and Development (OECD) a significant share of the externalities associated with outdoor air pollution come from road transport. In China, coal-based power generation and heating are the major contributors.

This brief quantifies the air pollution and climate change effects of energy use on human health, agricultural crops and the environment. Human health effects present in the form of premature disease and death (*i.e.* morbidity and mortality) that account for well over 90% of all external costs. Other costs arise through impacts on agriculture, costs to materials and impacts on habitats and ecosystems. Climate change impacts are also important, but their valuation is more uncertain than that of local air pollutants. Other external effects exist (*e.g.* noise pollution from combustion engines, which is reduced once electric vehicles are introduced); however, such effects are excluded in this study.

Coal-based processes have the highest and most adverse external effects, followed by oil. External effects are typically lowest for renewables and nuclear power. Among renewables, however, bioenergy is an exception, with pollution and climate impacts between those of fossil fuels and other renewables. External effects are especially high in the case of indoor air pollution from traditional bioenergy uses, since traditional cooking and heating typically involve minimal or no emissions control. The scale-up of renewables also involves replacing traditional bioenergy with more sustainable forms.

There is a need to understand the change in external costs that can be achieved through increased use of modern renewables, in comparison to fossil fuels and traditional uses of bioenergy. This is particularly important for the cost-benefit analyses of different technologies, since consideration of external effects can change the ranking order of investments and the net cost or savings of each technology option.

METHODOLOGY

This brief presents IRENA's assessment of the emissions and associated externalities of five local pollutants ($PM_{2.5}$, NO_x, SO_2, VOCs, and NH_3) and one global emission (CO_2) generated by fossil fuel and traditional bioenergy uses. The analysis was carried out for the period of 2010-2030.

For 2030, two cases are evaluated. One considers the development of renewables based on current and planned energy policies of countries, which constitute a "Reference Case" representing "business as usual". The second case investigates the additional potential from "REmap Options", which signify ramped-up deployment of renewable energy technologies beyond the Reference Case.

These REmap Options (determined in consultation with each country) can be further extended to a set of "Doubling Options" (IRENA's own assessment) meant to illustrate what the global energy mix could look like in 2030 with the total renewable share doubled compared to today (IRENA, 2016a). A detailed methodology of IRENA's REmap analysis can be found at www.irena.org/remap.

Three steps are followed to estimate the externalities of fuel combustion:

» Estimating emission factors for local pollutants by sector;

» Extrapolating external costs per tonne of fuel for EU countries to all countries covered in REmap, taking account of differences in their per gross domestic product (GDP); and

» Applying external costs from fossil fuel use by sector and country for 2010, for the Reference Case in 2030, and for REmap in 2030.

The emission effects covered in this assessment focus specifically on health effects arising from outdoor exposure, those arising from indoor exposure in the case of traditional use of bioenergy, and effects on agriculture. Health effects depend on the substance and the level of exposure (*i.e.* a function of ambient concentration and number of people exposed). Concentrations are a function of fuel, combustion technology and dispersion from sources to receptors. The valuation of health effects varies with income levels (measured as per capita GDP), as health expenditures relative to GDP may differ between countries.

The reference study used to make the estimates for this brief was the *Clean Air for Europe* (CAFE) study (Holland *et al.,* 2005), which demonstrated the damages per tonne of emissions on human health and agriculture. The study specifies these damages related to outdoor air pollution by pollutant and country for the (then) 25 member states of the EU (EU-25). These damage estimates were derived by running dispersion models for each country and estimating aggregated health and crop costs. The value of statistical life (VOSL) numbers used in the CAFE study were then updated using the latest study (OECD, 2012).

Values for other countries are set relative to the difference in GDP per capita between the country concerned and the average GDP per capita in the EU-25, with GDP per capita measured taking account of the purchasing power of incomes in the different countries. An elasticity for GDP per capita of 0.8 was applied for transferring key costs from one country to another.[3]

The external costs of traditional uses of bioenergy, as far as they relate to indoor air pollution, were not estimated on the basis of the costs per tonne of emissions as described above. This is because such emissions, rather than being dispersed in the atmosphere, tend to remain concentrated, resulting in a different set of health effects. Estimates were therefore derived by linking an estimate of deaths (in 2004) attributed to household air pollution (WHO, 2016) with traditional bioenergy use in households, and by applying the value of statistical life (VOSL) in line with the above-mentioned CAFE study.

Carbon prices were determined through a review of integrated assessment models. This suggested a range of USD 17–80 per tonne CO_2 for the year 2030 (US Government, 2013).[4]

POTENTIAL SAVINGS IN PRIMARY ENERGY SUPPLY FROM INCREASED USE OF RENEWABLES

Global demand for fossil fuels is estimated to grow by nearly 40% between 2010 and 2030, according to the Reference Case, representing the trajectory set by current energy policies. In comparison, with the implementation of all REmap Options, fossil fuel growth could fall to only 18%. With the REmap Options, coal and oil use would grow by only 9% and 12%, respectively, while natural gas would rise by 43% in the timeframe under consideration.

Total fossil and nuclear use with REmap Options would be 83 exajoules (EJ) lower worldwide in 2030 than with the Reference Case (see Figure 1). Total renewable energy use (as primary energy) would be about 46% higher with all REmap Options implemented. While the consumption of all non-renewable energy forms would range between 45 EJ and 160 EJ per year, the use of renewables would grow to about 180 EJ per year. This makes renewables—when grouped together—the largest source of primary energy by 2030.

The use of coal would be 22% lower relative to the Reference Case, reducing one of the main sources of CO_2 emissions and thus diminishing externalities from outdoor air pollution. Reductions in traditional uses of bioenergy would reduce emissions and other externalities as well.

## REDUCTIONS IN EMISSIONS FROM FOSSIL FUELS

Less fossil fuel use results in fewer emissions of air pollutants. Changes in emissions of the four major pollutants – NO_x, SO_2, VOCs and $PM_{2.5}$ – worldwide between 2010 and 2030 are provided in Figure 2. This shows an overall increase of $PM_{2.5}$, NO_x and SO_2 emissions by 6-8% between 2010 and 2030 in the Reference Case, while VOCs and NH_3 emissions decrease by about 10% in the same period. With all REmap Options, emissions of NO_x, SO_2, VOC and $PM_{2.5}$ are lower by at least 10% for SO_2 and as much as 80% for NO_x. NH_3 emissions in 2030, on the other hand, are seen as 6% higher than in the Reference Case.

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3 *An elasticity of 0.8 means that a 1% increase (or decrease) in GDP per capita results in a 0.8% increase (or decrease) in the external cost, where the external cost is as defined in the main text.*
4 *These values are averages depending on the discount rate used. The lower boundary is the result of a 5% discount rate while the upper boundary is the result of a 2.5% discount rate. There is a further, much wider range that can be derived depending on what is assumed about costs, but for this brief the above is considered a reasonable representation of the values most researchers would use in sensitivity analysis for estimation of social costs of carbon.*

FIGURE 1: GLOBAL CHANGE IN PRIMARY ENERGY USE WITH REMAP OPTIONS, 2030

Primary energy (EJ/year)

⧄ Change with REmap Options
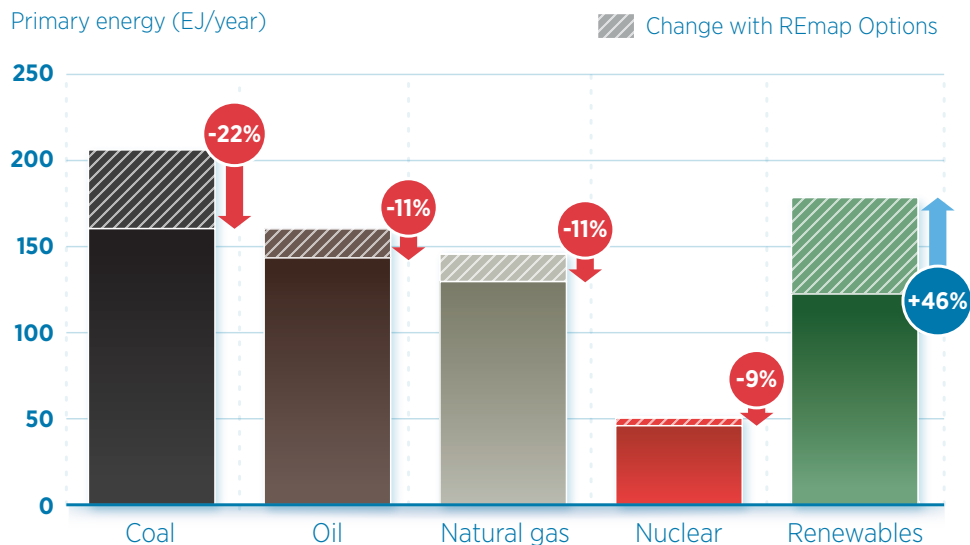
Source: IRENA estimates

The picture is not uniform, however, from country to country. $PM_{2.5}$, NH_3 and VOC emissions are significantly lower in most countries, explained by the reduction in coal use for power generation. Meanwhile, emissions increase relative to 2010 in such countries as Indonesia, Mexico, Nigeria and Turkey with the growing use of modern bioenergy[5] for power generation, and fuels with lower emissions of air pollutants, as a result of using natural gas or nuclear energy instead of coal. Modern bioenergy results in some air pollutant emissions, albeit far less than coal, and emissions of SO_2 and NO_x from modern bioenergy are typically lower than other fuels. Nuclear energy, on the other hand, offers close to zero pollutant emissions, as does natural gas when fully combusted during power production. Apart from these pollutants, however, other emissions may result from natural gas combustion such as NO_x, CO and CO_2.

FIGURE 2: REDUCTIONS IN EMISSIONS OF SELECTED AIR POLLUTANTS WITH REMAP OPTIONS, 2030

Air pollutant emission (kt/yr)

REmap   Avoided with renewables   • 2010
Reference Case
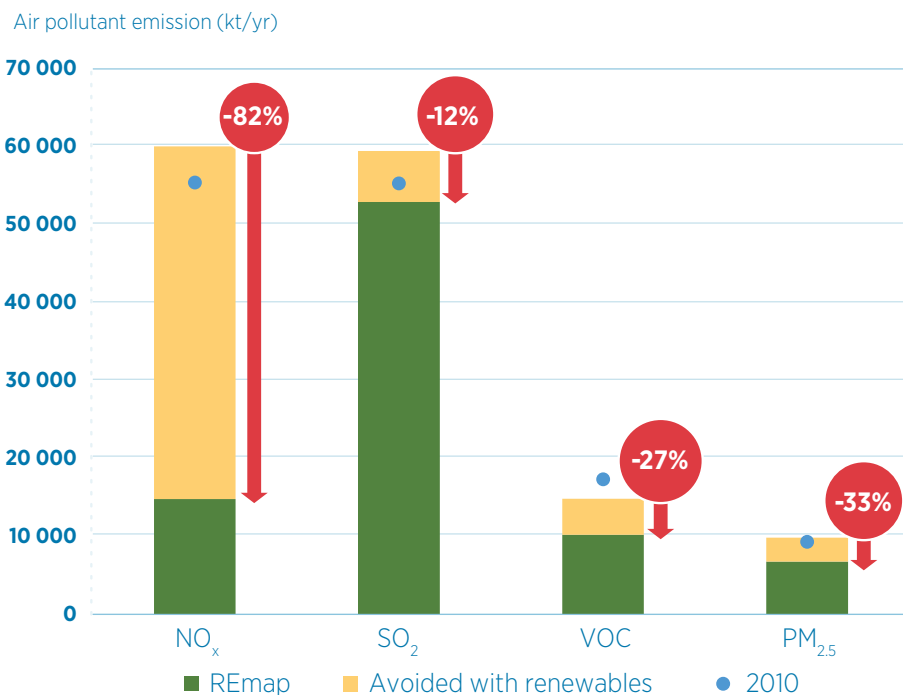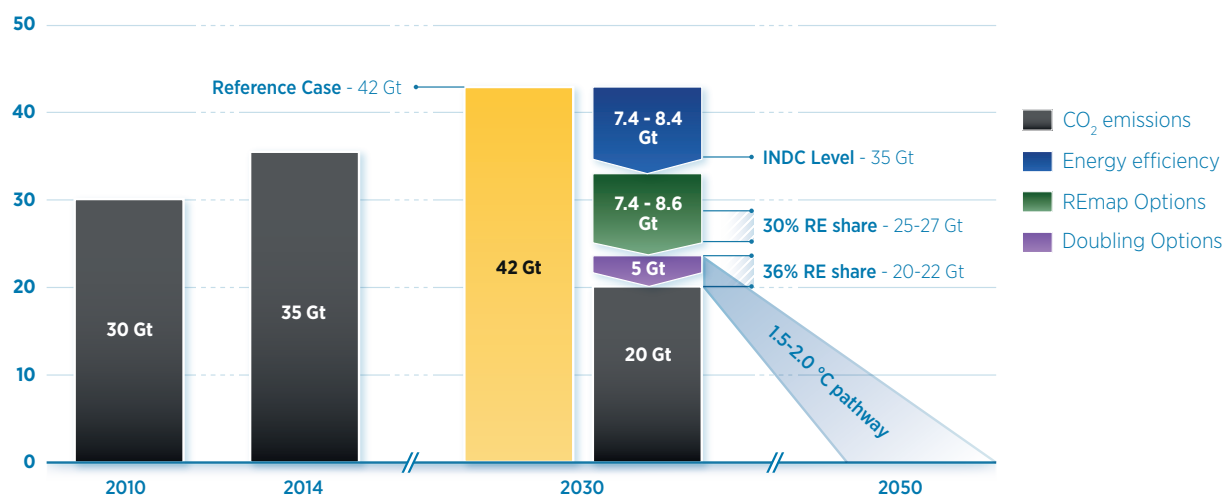
Source: IRENA estimates

[5] *There are two forms of bioenergy in use today: "traditional" and "modern". Traditional use of bioenergy includes fuelwood, animal waste and traditional charcoal. Modern bioenergy technologies include liquid biofuels produced from straw and wood, industrial co-generation and bio-refineries, biogas produced through anaerobic digestion of residues, pellet heating systems and other technologies. Some researchers also note that traditional bioenergy is usually not exploited sustainably, whereas modern bioenergy is (i.e. an equal amount to that extracted is replanted).*

When the national plans of all 40 REmap countries are aggregated and these findings are scaled up to represent the entire world, global CO_2 emissions from the combustion of fuels for energy would reach 42 gigatonnes (Gt) by 2030 in the Reference Case. Doubling the share of renewables through accelerated improvements in energy efficiency and significant uptake of renewable energy technologies could reduce the total emissions by about half, to 20-22 Gt by 2030, as seen in Figure 3. About one-third (*i.e.* 7.4-8.4 Gt) of this total reduction potential relates to energy efficiency, while two-thirds (*i.e.* 12-14 Gt) relates to renewables.

FIGURE 3: GLOBAL ENERGY-RELATED CO_2 EMISSIONS

CO₂ emissions from energy (Gt/year)

Source: Based on IRENA estimates and Olivier et al. (2015)

COSTS AND SAVINGS

The estimate of the total external costs is presented with a range reflecting how each emission is valued across countries: in the base year 2010 they amounted to between 4.8% and 16.8% of global GDP (or USD 3 trillion—USD 10.5 trillion). The large range is a result of significant uncertainties for costs associated with air pollution, as well as the assumption about carbon prices. Air pollution (*i.e.* non-CO_2) externalities range between USD 1.8 trillion and USD 6.0 trillion for outdoor air pollution, plus USD 0.8 trillion—2.1 trillion for indoor air pollution (traditional uses of bioenergy). This equals 3.8—13.4% of global GDP.
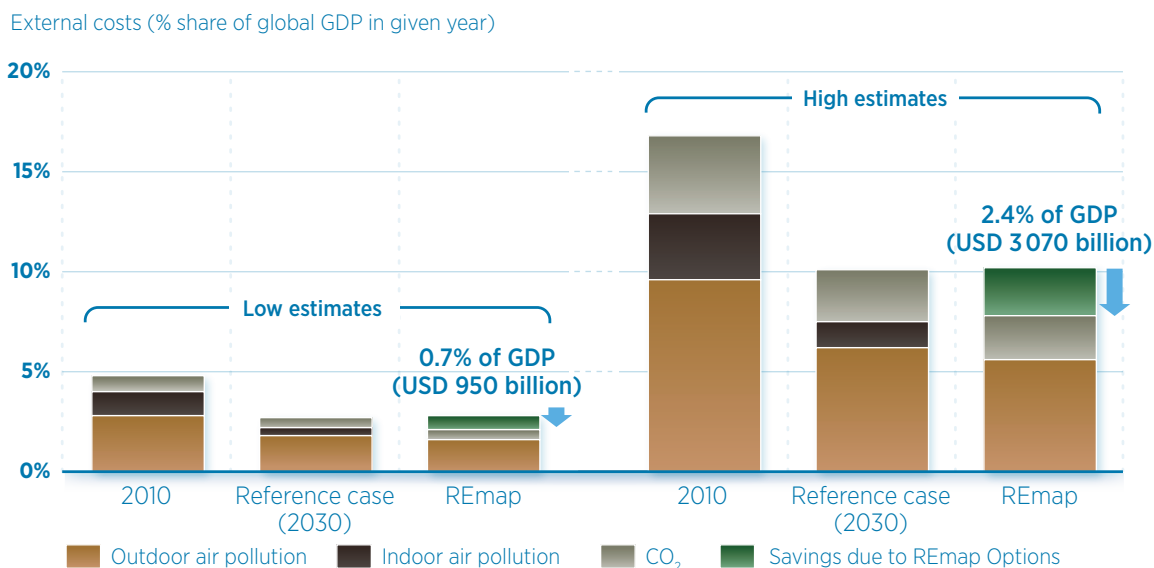
By 2030, in the Reference Case, the share of these costs as a percentage of GDP will decrease to between 2.8% and 10% of global GDP (see Figure 4). Growth in global GDP, therefore, is predicted to outpace growth in external costs (which will still occur), but the relative share of external costs as a percentage of global GDP should decrease due to the higher deployment of renewables, cleaner combustion of fossil fuels and reduced use of traditional bioenergy.

However, in absolute terms, these costs will likely still increase, as rising GDP boosts the valuation of air pollution and CO_2 impacts to between USD 3.6 trillion and USD 13.2 trillion per year in the Reference Case. Technology improvements should reduce emission factors as global energy use rises, but these two factors are of secondary importance to explain the changes. On a global level, the largest cost will come from outdoor air pollution (two-thirds), followed by CO_2 (20%) and indoor air pollution caused by traditional bioenergy use (15%).

The adoption of REmap Options lowers annual external costs (representing the sum of values for pollutants and CO_2 emissions) by between USD 0.95 trillion and USD 3.07 trillion by 2030, relative to the Reference Case (see Figure 4). This equals a reduction of 25-30% in external costs compared to the Reference Case. When the Doubling Options are included with the REmap Options, savings increase to USD 1.2-4.2 trillion, representing a 33% reduction compared to the Reference Case in 2030.

FIGURE 4: EXTERNAL COSTS AS A SHARE OF GDP AND REDUCED EXTERNALITIES WITH REMAP OPTIONS, 2010-2030

External costs (% share of global GDP in given year)

Legend: Outdoor air pollution, Indoor air pollution, CO_2, Savings due to REmap Options

Source: IRENA estimates

Figure 5 puts these savings into perspective by comparing them to the costs of doubling the share of renewables (which included both the REmap Options and Doubling Options). The technologies needed to double the global share of renewables by 2030 would cost USD 290 billion per year more by 2030 than the non-renewable counterparts for which they would substitute[6]. Total savings with renewables doubled could be at least four and as much as fifteen times higher, while net savings could amount to between USD 1.2 and USD 4.2 trillion per year by 2030.

Total projected savings can be split into three categories: 50-66% indoor air pollution (associated with traditional bioenergy use); 20-37% CO_2 emissions; and 13-14% outdoor air pollution. There is a significant decline in traditional uses of bioenergy with comensurate reductions in associated costs of externalities.

The low reduction of outdoor health effects is the net result of fossil fuel savings and rising use of modern bioenergy. The emission factors for $PM_{2.5}$ for modern bioenergy can be as high as for coal. The emission factors for VOC are higher than for fossil fuels, but emissions from SO_2 and NO_x are the lowest among all fuels.

With the REmap Options, modern bioenergy use would be higher for heating, power generation and transport, while substituting fossil fuels. This makes the external costs related to modern bioenergy around USD 220 billion higher, based on an average of cost ranges. That is, modern bioenergy costs in 2030 are about USD 280 billion (from a range of USD 125-440 billion) in the Reference Case; and about USD 500 billion (from a range of 225-775 billion) with the REmap Options.

By comparison, the average external costs related to fossil fuels would be lower by USD 770 billion per year, resulting in average net savings of USD 550 billion per year. These savings exclude reduced externalities relating to indoor air pollution. The Doubling Options would increase the net savings even further.
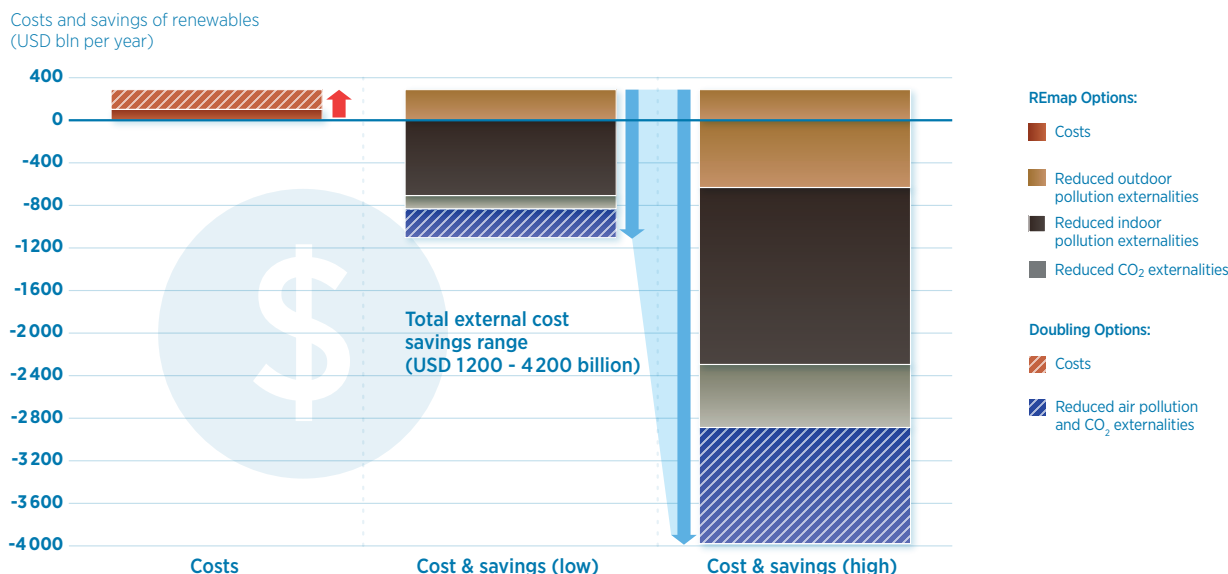
There is also some electrification and solar heat introduced in buildings, industry and transport, but the introduction of modern bioenergy dominates the energy transition in the direct fuel use of those sectors. About a third of this modern bioenergy scale-up replaces traditional bioenergy use. The net health savings from such a substitution are enormous. In industry, the reduced externalities are less significant.

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[6] This indicator accounts for the annualised costs of generating heat, electricity or transport based on capital, operation and maintenance, and energy costs. The amount needed to deliver the same amount of energy otherwise is equal to the difference between the annualised costs of all renewable energy technologies and the costs of non-renewables.

FIGURE 5: COSTS AND SAVINGS WITH THE REMAP AND DOUBLING OPTIONS, 2030

Costs and savings of renewables
(USD bln per year)

REmap Options:

Costs

Reduced outdoor pollution externalities

Reduced indoor pollution externalities

Reduced CO_2 externalities

Doubling Options:

Costs

Reduced air pollution and CO_2 externalities

Total external cost savings range
(USD 1200 - 4200 billion)

Costs — Cost & savings (low) — Cost & savings (high)

Source: IRENA estimates

On a sector level, the effect of implementing the REmap Options varies. In industry, transport, power and district heating, the REmap Options increase the costs of renewables. For buildings, the REmap Options result in savings.

Significant progress can be expected in the power sector. In fact, the largest savings in reduced externalities stand to be achieved in this sector, mainly due to the drop in the use of coal. Transport would see the second-highest reduction in externalities, largely because of the higher valuation of air pollution costs stemming from the combustion of fuels in urban environments that account for roughly 70% of total transport activity. Here the costs of externalities could be four times higher than in rural areas. In buildings, there are similar savings but the main driver is the substitution of traditional uses of bioenergy. In this sector, achieving significant progress will depend on whether substitution of traditional bioenergy use is pursued. The opposite is true in industry, where CO_2-related savings are higher than from air pollution. In district heating, there is a slight overall increase in the external costs associated with air pollution, but savings should result from CO_2 reductions. In total, if quantifying the cost and reduced externalities together, all sectors except district heating should result in moderate to significant savings with the REmap Options. Costs and savings by sector are presented in Figure 6.
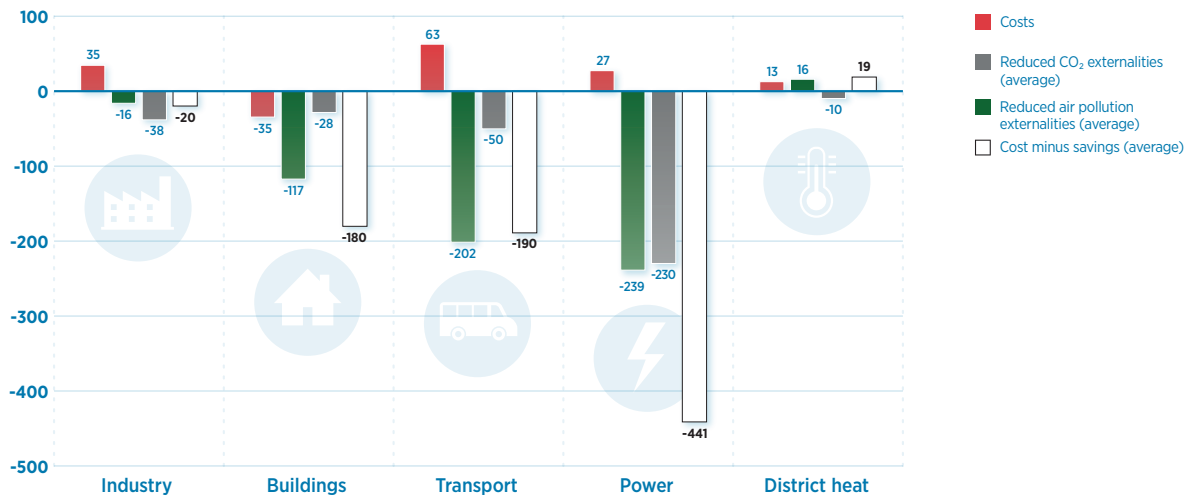
In absolute terms, China, India, Indonesia and the USA would accrue the greatest health savings, apart from the developing countries overall where traditional use of bioenergy is phased out. The countries that benefit most would be those where polluting coal power plants are substituted. Countries with high bioenergy potential in heating and transport sectors often show disproportionally small or even negative health savings, especially where natural gas is substituted (*e.g.* in the case of the Russian Federation).

Figure 6: Cost and savings with REmap Options, by sector, 2030

Costs and savings of renewables by sector in 2030
(USD bln per year)

Legend:
- Costs
- Reduced CO_2 externalities (average)
- Reduced air pollution externalities (average)
- Cost minus savings (average)

Values by sector:

Industry: 35, -16, -38, -20
Buildings: -35, -117, -28, -180
Transport: 63, -202, -50, -190
Power: 27, -239, -230, -441
District heat: 13, 16, -10, 19

Source: IRENA estimates

More details about the results of the REmap Options on a country level are provided in Figure 7. The figure shows the costs for the REmap Options and the average annual savings related to reduced externalities for indoor, outdoor and CO_2 as a share of GDP by 2030. In some countries, the REmap Options have already resulted in savings even without considering externalities. But for countries which have costs associated with the REmap Options, the savings resulting from reduced externalities are higher than the cost of the REmap Option. For most countries, the largest savings would result from reduced externalities from outdoor air pollution. For countries that have traditional uses of bioenergy, reduced externalities can be significant, as is the case for Ethiopia, Kenya and Nigeria. The reduction of externalities relating to CO_2 would have less of an impact using this median value overall, but for some countries it is an important driver, as it is for Poland, the Republic of Korea and the USA.

Figure 7: Costs and reduced externalities with REmap Options by country, 2030

Cost and reduced externalities of REmap Options
(% share of country GDP in 2030)

Legend:
- Costs
- Outdoor air pollution
- Indoor air pollution
- CO_2
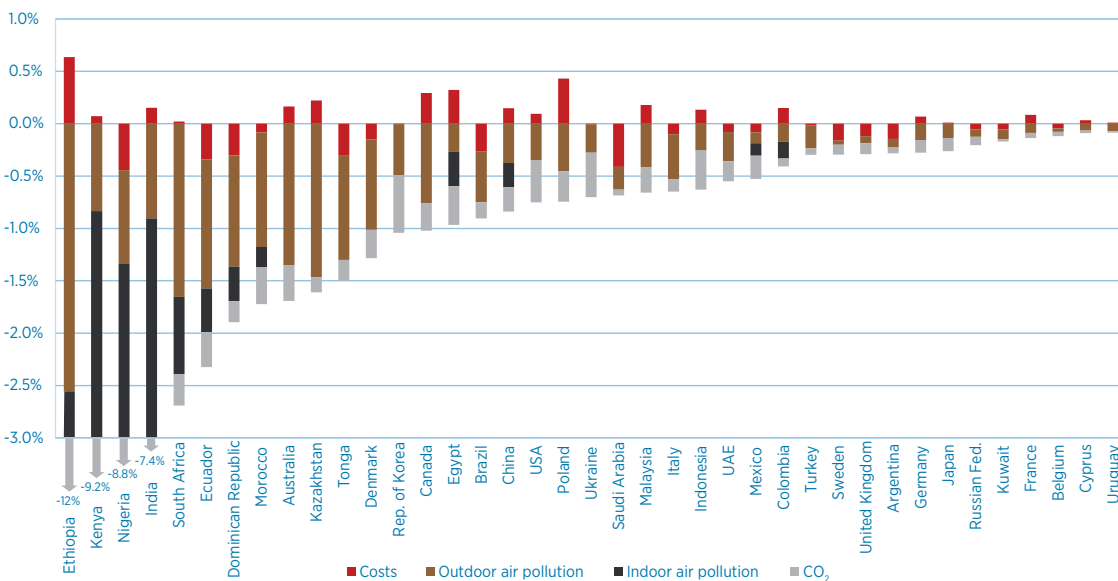
Note: The figure area is scaled to allow better visiblity of country results.
The following country ranges extend below the graph: Ethiopia: -12%; Kenya: -9.2%; Nigeria: -8.8%; India: -7.4%
The figure shows the costs and reduced externalities relating to the REmap Options, the Doulbing Options are not shown.

Source: IRENA estimates

POLICY IMPLICATIONS AND NEXT STEPS

Clearly, current market frameworks fail to adequately value the costs and savings from reduced externalities, particularly as renewables expand in the global energy mix (Parry *et al.*, 2014). If external costs are taken into account, non-renewable energy technologies would be more expensive than renewables, and that is without even considering the significant positive externalities of renewables, such as macro-economic impacts through job creation or trade (IRENA, 2016b).

While a tighter range of cost estimates is not yet possible, these costs need to be internalised in energy prices. Such valuations can help to stimulate investments in renewables that could save up to 4 million lives by 2030 and would also contribute to mitigating climate change.

A number of areas require government intervention to reduce these externalities. Internalising the costs of pollution clearly provides a better approach for setting future policy priorities. Oil, gas and coal prices are currently low and could remain so as renewables continue to grow. Governments should take advantage of this window of opportunity to internalise these large external costs. One option, as was already done in several countries and regions, is to incorporate these costs into typical market structures through financial incentives such as carbon pricing and possibly also by pricing local pollutants.

Globally, 164 countries have adopted renewable energy targets, with deployment aspirations featuring prominently in several countries' Nationally Determined Contributions (IRENA, 2015), submitted ahead of the Paris Agreement. However, countries do not necessarily consider every cost-effective renewable option that is available. Further reducing the costs of renewable energy technologies remains crucial, as does setting specific targets for both energy efficiency and renewable energy use, in order to fulfil national emission-reduction pledges.

More effective and improved regulations to limit air pollution via emission and fuel efficiency standards in transport, but also in industry and power plants, will be essential. For example, in buildings and in most urban settings, such regulations are not yet widespread and exist only to a limited extent. Hence, related regulations, including freight transport levies and others, can be adjusted to accelerate implementation. Experience from several countries has shown that air pollution regulations are expensive, but ultimately cost-effective.

While such regulations will certainly support the uptake of cleaner and more efficient technologies, policies will be needed to accelerate capital stock turnover to improve overall efficiency and increase renewable energy deployment by pushing out the polluting and old technologies from the stock. As a key renewable energy technology option, special attention will need to be paid to bioenergy, as this assessment has shown that bioenergy technologies have air pollution impacts higher than, for example, natural gas and other renewables. Particulate matter levels will need to be controlled through the development and uptake of modern, efficient bioenergy combustion technologies.

Development of national and local air pollution action plans will be key. These action plans need to be complemented with practical measures, such as the elimination of inefficient and uncontrolled use of coal for power and heat generation or the limitation or banning of internal-combustion-engine cars in cities. Action at municipal levels will be crucial, but enforcement of targets and regulations will require national governments to take the lead. While air pollution is typically a local issue, in some cases it can be a cross-boundary challenge if pollutants travel over long distances. In such cases, other forms of governance will be required to reduce its impacts.

Implementation must be governed effectively, with participation by stakeholders from all levels. Particularly important will be coordinated action and policy design by environment and energy ministries. The development of key indicators to monitor implementation (*e.g.* the particulate matter indicator covered under *Sustainable Development Goal 11: Sustainable cities and communities*) and the design of new policies will be essential.

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ABBREVIATIONS

CAFE	Clean Air for Europe
CO_2	carbon dioxide
EJ	exajoule
EU	European Union
GDP	gross domestic product
Gt	gigatonne
IRENA	International Renewable Energy Agency
kt	kilotonnes
NH_3	ammonia
NO_x	mono-nitrogen oxides (NO_x is a generic term for the mono-nitrogen oxides NO and NO_2)
OECD	Organisation for Economic Co-operation and Development
PM	particulate matter
SDG	Sustainable Development Goal
SO_2	sulphur dioxide
USA	United States of America
USD	United States dollars
VOCs	volatile organic compounds
VOSL	value of statistical life
WHO	World Health Organization

ABOUT IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international cooperation, a centre of excellence, and repository of policy, technology, resource and financial knowledge on renewable energy.

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