

## **The true cost of fossil fuels: Externality cost assessment methodology**

Background to the brief, “**The true cost of fossil fuels: Saving on the externalities of air pollution and climate change**” (IRENA 2016). Together, these two documents form part of the analysis behind *REmap*, IRENA’s roadmap aimed at doubling renewables’ contribution to the world’s energy mix by the year 2030

## 1. Introduction

This background document explains the methodology applied to estimate the external costs associated with the consumption of energy carriers (*e.g.* fossil fuels, modern bioenergy and traditional uses of bioenergy). The analysis is carried out for the years 2010 and 2030. The external costs estimated are those arising from the use of assessed fuels and include both combustion and non-combustion emissions, but not taking into account the life cycle by which these fuels are produced, transported, used to generate energy and finally disposed of.

The external costs from generation of electricity, heat and mechanical energy for transport arise from the emissions produced in the form of fine particulate matter (PM<sub>2.5</sub>), mono-nitrogen oxides (NO<sub>x</sub>), sulphur dioxide (SO<sub>2</sub>), volatile organic compounds (VOCs) and ammonia (NH<sub>3</sub>). In this assessment, three emission effects were covered: 1) health effects arising from outdoor exposure; 2) health effects arising from indoor exposure in the case of traditional use of bioenergy; and 3) effects on agricultural yields<sup>1</sup>. Additionally, the external costs associated with social economic impacts of carbon dioxide (CO<sub>2</sub>) are estimated.

The methodology to estimate external costs consists of three key calculations, carried out in sequence:

- 1. Emission factors for local pollutants by sector.** Emission factors reflect the emissions of different pollutants in kilotonnes per petajoule (kt/PJ) of energy used. This calculation is done separately for the years 2010 and 2030, for each pollutant, country and sector. Of course, emission factors change over time on account of changes in technology. An analysis of these changes is carried out, showing where (*i.e.* in which countries and sectors) to expect changes in emissions per unit of energy.
- 2. Costs per tonne of fuel.** This part of the methodology involves updating estimates of external costs in United States dollars (USD) per tonne.<sup>2</sup> This step, based on the "ExternE" methodology, takes account of recent work on health and other external costs and the subsequent costs of carbon (OECD, 2012; US Government, 2013). The estimates are made first for local air pollutants in European Union (EU) countries, where the original ExternE estimates of cost per tonne were made, and subsequently for all other REmap countries. As a separate exercise, the external costs of carbon are estimated. A range of values is derived from the most recent work in this area (US Government, 2013).
- 3. External costs from fossil fuels.** This final step involves applying the updated costs to the estimates of emissions from fuel use by sector and country. This is done for the year 2010

<sup>1</sup> The main external emissions effects of fossil fuel combustion (excluding CO<sub>2</sub>) are those on human health in the form of premature mortality and morbidity. They 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. The basic study used to make the estimates for this report was the CAFE study (Holland *et al.*, 2005), which covered health and agriculture, but not materials and ecosystems.

<sup>2</sup> All economic data are expressed in real 2010 USD.

(the base year of REmap analysis) and again for each of the two case scenarios in 2030, in order to derive estimates of the total external costs of fossil fuel use by country.

## 2. Emission factors for local pollutants by sector

The emission factors are estimated in kt/PJ for the different type of fuels drawing on the database made available by the International Institute for Applied Systems Analysis (IIASA).<sup>3</sup> The database provides detailed emission (PM<sub>2.5</sub>, NO<sub>x</sub>, SO<sub>2</sub>, VOCs and NH<sub>3</sub>) data for power generation, industry, transport and buildings (covering residential, commercial and public) sectors delivered from their scenario analysis for present and for the future years.<sup>4</sup> For this report, a weighted average of each kind of emission was calculated, taking fuel use by subcategory. Emission factors provide data on emissions during generation but not during other phases of the life cycle.

An analysis of emission factors reveals several interesting findings:

1. There is considerable variation in emission factors across countries for a given pollutant and a given sector, reflecting different energy and pollution-control technologies in different countries. The data show the largest variation<sup>5</sup> for the following factors:
  - In the **power generation sector**, coal and bioenergy have high coefficients of variation for all pollutants. For oil, emissions of SO<sub>2</sub> can vary significantly; for gas, emissions of NH<sub>3</sub> also show notable variation.
  - In **industry**, coal shows variation in emission factors for PM<sub>2.5</sub> and NH<sub>3</sub>, while gas has high variation for SO<sub>2</sub> and NH<sub>3</sub> and bioenergy for PM<sub>2.5</sub>.
  - For **transport**, coal has a high variation in emission factors for all pollutants. Oil has a high variation for PM<sub>2.5</sub>.
  - For **buildings**, gas has a high variation for PM<sub>2.5</sub> and SO<sub>2</sub>, but the emission factors are very small. Modern bioenergy has a high variation in emissions per unit energy of VOCs.
2. Comparing the 2010 and 2030 emission factors, a significant improvement in efficiency for all sectors is apparent, reflecting a combination of improvements in combustion technology and stricter emissions controls. For power generation, a reduction in emission factors exists for all pollutants except NH<sub>3</sub>, where the amounts involved are very small. For other fuels, the most noteworthy change is the increase in emission factors for PM<sub>2.5</sub> and VOCs from oil, along with the higher emission factors for PM<sub>2.5</sub> from modern bioenergy. Since modern bioenergy use increases in REmap, it contributes to the reduction of benefits of renewables.

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<sup>3</sup> The Greenhouse Gas – Air Pollution Interactions and Synergies (GAINS) Global database (<http://gains.iiasa.ac.at/gains/GOD/index.login>) was made accessible for this project at the courtesy of International Institute of Applied Systems Analysis (IIASA). IRENA thanks to the colleagues at IIASA who made this possible. Emission factors were available for most, but not all, countries. For Nigeria and South Africa, a figure that represents the entire Africa was provided. For Saudi Arabia and the United Arab Emirates (UAE), a representative figure for the whole Middle East was used.

<sup>4</sup> The values are taken from ECLIPSE\_V5a\_CLE\_base scenario, the latest scenario as of August 2015.

<sup>5</sup> The variability was calculated as the coefficient of variation (CV) of the emission factors across the countries.

3. For industry, there are modest improvements in most emission factors, especially those for PM<sub>2.5</sub> from coal and bioenergy, reflecting improvements in technology. There is a notable reduction in SO<sub>2</sub> from oil as well. Emissions of NH<sub>3</sub> rise per PJ but the figures are very small in the first place.
4. For transport, there are major reductions in NO<sub>x</sub>, SO<sub>2</sub>, VOCs and NH<sub>3</sub> from oil and gas, also reflecting the use of less polluting technologies.<sup>6</sup>
5. For buildings, there are small improvements in emission factors for all pollutants from all sources, especially PM<sub>2.5</sub> and VOCs.

The implications from these figures are that fossil based technologies become more environmentally benign and the external costs from fuel use will decrease per emissions over the period of the analysis. The magnitude in improvements varies by pollutant and fuel type and not all fuel types show an improvement. For example, coal's emission factor is decreasing<sup>7</sup> in all uses while the emission factors for bioenergy are estimated to improve less for power generation. These factors have to be taken into account when making an assessment of energy and environmental policies.

### 3. Costs per tonne of fuel

This calculation, based on the ExternE methodology, takes account of recent work on health and other external costs and the subsequent costs of carbon. The estimates are made first for local air pollutants in EU countries and then for other REmap countries.

#### 3.1 Costs from local air pollutants related to outdoor air pollution

The basic source of the cost estimates s per tonne of emissions is the Clean Air for Europe (CAFE) programme report (Holland *et al.*, 2005), which gives average costs for the pollutants of interest, by country for the (then) 25 Member States of the EU (EU-25). These averages were derived by running dispersion models for each country and estimating aggregated health and crop costs.<sup>8</sup> These figures are expressed in 2005 Euros (EUR), which were then converted to 2010 USD.<sup>9</sup> The 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.

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<sup>6</sup> For transport, the database did not provide any emission factors for bioenergy. In that respect, the calculations here underestimate changes in emissions as a result of the shift to bioenergy.

<sup>7</sup> Looking at the impacts from efficiency improvements in coal-based power generation plants alone, the resulting emission factors could even be even lower; however, post-combustion emission controls reduce the overall efficiency of plants, thereby offsetting some of these efficiency gains.

<sup>8</sup> Effects on materials and ecosystems are not included in the assessment. Likewise, agricultural impacts found to be negligible in previous studies have also been excluded.

<sup>9</sup> See: <http://www.oanda.com/currency/historical-rates/> and <http://www.usinflationcalculator.com/>.

The resulting values were further adjusted to reflect recent development on valuation of a statistical life and their transfer function, following primarily the findings from OECD (2012). More specifically:

- Applications of updated value of statistical loss of life (VOSL) or the value of a life year (VOLY): recent studies (*e.g.* OECD, 2012) estimates are **twice as high** as in the CAFE study for the EU-25. 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.
- Application of an adjustment factor of 0.8 for transferring values from countries where original estimates were made to countries where no primary studies exist.<sup>10</sup> More specifically, the factor is defined in terms of an elasticity for GDP per capita.

The function adopted for value transfer is as follows:

$$V_{c,y2} = V_{EU,y1} \times [Y_{c,y2}/Y_{EU,y2}]^b \times [1+\Delta Y]^b$$

where  $V_{c,y2}$  = value in country  $c$  in year 2,  $V_{EU,y1}$  = value in the EU in the base year,  $Y$  = GDP per capita,  $b$  = elasticity, and  $\Delta Y$  = % change in GDP/capita. All GDP figures are taken in purchasing power parity (PPP) terms, with data taken from the World Bank database.

Table 1 summarises the above discussion, comparing cost estimates from the study by Holland *et al.* (2005) (first two columns from left) and with the new values, adjusting for inflation and increased health costs (first column from far right).

**Table 1: External costs in the EU-25 for different pollutants**

	CAFE (EUR <sub>2005</sub> /tonne)		CAFE (USD <sub>2010</sub> /tonne)		Adjusted for higher health costs (USD <sub>2010</sub> /tonne)	
	Low	High	Low	High	Low	High
PM <sub>2.5</sub>	26 000	75 000	34 430	99 318	69 205	199 630
NO <sub>x</sub>	4 400	12 000	5 827	15 891	11 712	31 941
SO <sub>2</sub>	5 600	16 000	7 416	21 188	14 906	42 588
VOC	950	2 800	1 258	3 708	2 529	7 453
NH <sub>3</sub>	11 000	31 000	14 567	41 052	29 279	82 514

Source: IRENA estimates

<sup>10</sup> For this adjustment factor, the OECD (2012) provides guidance along the following lines. First, the guidance identifies a number of issues for which no adjustment is recommended (*e.g.* age, health status, latency, risk perception). The main recommendation is that an elasticity for GDP per capita of 0.8 be applied for transferring key costs from one country to another, including those outside the EU. This implies, as an example, the following: if a country has half the GDP per capita of the EU-25 overall, its costs are reduced by a factor of 0.5. The OECD report makes this recommendation, while noting that lower elasticities have been identified in the literature, particularly in the United States<sup>10</sup>, and that, indeed, the OECD (2012) recommended using an elasticity of 0.4 in sensitivity analyses. However, it also notes that some authors have expressed a preference for higher elasticities, in excess of 1.0 (*e.g.* Hammitt and Robinson, 2012). These very different positions are in part a result of only a few studies having sought to quantify willingness to pay in countries at very different average income levels. Overall, it is concluded that the use of an elasticity of 0.8 is a reasonable reflection of the available evidence.

### 3.2 Costs associated with CO<sub>2</sub> emissions

Estimates of costs from CO<sub>2</sub> are values based on the literature covering the social costs of carbon (SCC). These costs have been reviewed in some depth in the literature (DEFRA, 2007; Anthoff and Tol, 2013; US Government, 2013). The values are based on the discounted costs arising from a tonne of CO<sub>2</sub> over the long term and therefore are sensitive to the discount rate adopted. The higher the discount rate, the lower the value attached to future costs, and hence the lower the discounted *present* value of the costs. This discounted value also increases over time as costs rise with higher levels of greenhouse gases (GHGs) in the atmosphere. The United States Government Review of 2013 is found to be the most comprehensive recent assessment (US Government, 2013).

SCC is calculated by running an Integrated Assessment Model (IAM), in which future economic output is estimated under different scenarios for GHG emissions. By running the model with the given emissions scenario, calculating the discounted present value of output and then running the model again with a small increase in emissions in the current period, a second discounted present value is obtained. Subtracting the discounted value in the second run from the first provides an estimate of the cost caused by that small increase. Dividing the cost by the change in emissions produces the today's SCC. The same calculation can be made projecting the model to 2020, 2030 etc. to get the SCC for that year.

The impacts of climate change taken into account vary from one model to another. The study by the US Government (2013) is primarily based on three IAM used by the US government, namely, DICE, FUND and PAGE (see the original study for more details of these models). All include the cost caused by sea level rise, agriculture and energy (*e.g.* higher demand for energy for space cooling but less for space heating). These also include additional costs of health treatment resulting from higher temperatures and extreme events. Models vary in the cost function they use (*i.e.* the link between emissions and climate change and between climate change and costs) and there is an element of arbitrariness about the functions. These models, although useful, do have their limitations:

- 1. Incomplete treatment of non-catastrophic costs:** Current IAMs do not assign value to all important physical, ecological and economic impacts of climate change and it is recognised that, even in future applications, a number of potentially significant cost categories will remain non-monetised, such as ocean acidification (not quantified in any of the three models) and species and wildlife loss.
- 2. Incomplete treatment of potential catastrophic costs:** Cost functions may not capture the economic effects of all possible adverse consequences of climate change: 1) potentially continuous “tipping point” behaviour in Earth systems; 2) inter-sectoral and inter-regional interactions, including global security impacts of high-end warming; and 3) imperfect substitutability between cost to natural systems and increased consumption.
- 3. Uncertainty in extrapolation of costs incurred from high temperatures:** estimated costs are far more uncertain under more extreme climate scenarios.

- 4. Incomplete treatment of adaptation and technological change:** Models do not adequately account for potential adaptation or technological change that might alter the emissions pathways and resulting costs.

Based on a thorough review of the different models, this document produces a range of USD 11.6-54.7/t CO<sub>2</sub> rising to USD 16.8-80/t CO<sub>2</sub> in 2030.<sup>11</sup> It should be noted that these costs from CO<sub>2</sub> are additional to costs from local pollutants.

#### **4. External costs of modern fuels and traditional uses of bioenergy**

This final calculation applies updated costs per tonne of fuel (as calculated above in Section 2) to the estimates of emissions from fuel use by sector and country (calculated in Section 1). This is done for 2010 (the base year of REmap analysis) and again for each of the two cases in 2030. The result indicates the total external costs of fossil fuel use by country.

##### **4.1 External costs of modern fuels by pollutant and country**

Estimates of costs from the actual and forecast emissions by sector and country are made with the original CAFE unit costs and with the new unit costs. In order to estimate this for 2030, it is necessary to estimate the change in per capita income between 2010 and 2030. The change is based on GDP per capita projections by IRENA, which are based on countries' national plans. The same projections are used for both 2030 Reference Cases and REmap 2030. The GDP effect of higher shares of renewables is excluded from this assessment.

GDP projections for 2030, however, were not available for all countries from their national plans. Missing data were collected from the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5). This report identified five 'Shared Socioeconomic Pathways' (SSPs), which describe possible futures in terms of the evolution of society and the natural system over the coming century. These qualitative narratives are labelled as: "sustainability" (SSP1), "middle of the road" (SSP2), "fragmentation" (SSP3), "inequality" (SSP4) and "conventional development" (SSP5) (O'Neill *et al.*, 2014). The narratives are converted into projections of GDP, population and urbanisation and

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<sup>11</sup> These values are averages depending on the discount rate used. The lower bound is the result of a 5% discount rate while the upper bound is the result of a 2.5% discount rate. There is also a much wider range that can be derived depending on what is assumed about costs, but for this study the above is considered a reasonable representation of the values most researchers would use in SCC sensitivity analyses.

are available from IIASA<sup>12</sup>. For this study, an average of the sustainability (SSP1)<sup>13</sup> and conventional development (SSP5)<sup>14</sup> scenarios were taken.

Table 2 gives the corresponding values of GDP per capita based on PPP exchange rates for the selected countries in 2010 and 2030. The costs for the EU-25 countries were based on the detailed values from the CAFE data, updated to be expressed in real 2010 USD and for 2030 adjusted to reflect the change in GDP per capita as provided in Table 2. An elasticity of costs with respect to per capita GDP of 0.8 was taken.

**Table 2: Per Capita Income in Selected Countries: 2010 and 2030 (USD<sub>2005</sub> PPP)**

	<b>2010</b>	<b>2030</b>	<b>% Growth</b>
Australia	34,621	43,603	26%
Brazil	10,079	19,114	90%
Canada	35,223	47,800	36%
China	6,819	20,163	196%
Denmark	32,379	41,392	28%
Ecuador	7,692	13,376	74%
France	29,522	39,225	33%
Germany	33,565	41,762	24%
India	3,122	8,639	177%
Indonesia	3,873	13,228	242%
Italy	27,059	33,904	25%
Japan	31,030	42,545	37%
Malaysia	13,767	23,297	69%
Mexico	11,979	21,416	79%
Morocco	4,268	12,017	182%
Nigeria	2,120	5,598	164%
Republic of Korea	26,774	52,529	96%
Russian Federation	14,182	30,210	113%
Saudi Arabia	24,864	33,883	36%
South Africa	9,516	18,977	99%
Turkey	12,671	26,294	108%
United Arab Emirates	36,480	49,712	36%
Ukraine	6,029	16,010	166%
United Kingdom	32,809	45,965	40%
United States of America	42,001	56,420	34%

Source: IRENA estimates and IIASA

<sup>12</sup> For details, see <https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=about>

<sup>13</sup> Global and national inequality falls as low-income countries develop rapidly and education levels rise. Low global growth in population is associated with low consumption of energy-intensive goods and animal products. This is partly enabled by the rapid development of environmentally-friendly technologies. Reduced fossil fuel dependency and clean energy technologies coincide with high levels of environmental awareness. Environmental governance helps to achieve goals set in implemented agreements.

<sup>14</sup> Conventional development (*i.e.* economic growth and the pursuit of self-interest) is perceived as the solution to social and economic challenges. As a result, fossil fuel dependency increases and mitigating it is difficult. However, the Millennium Development Goals (MDGs) are attained and robust economic growth, engineered solutions and highly-managed ecosystems provide a certain level of adaptive capacity.



## 4.2 Costs of indoor air pollution from traditional use of bioenergy

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 a statistical life (VOSL) in line with the above-mentioned CAFE study.<sup>15</sup> This approximation could under-estimate the degree of indoor air pollution as the number of deaths in 2010 is likely to be higher. Given this approximation, cost estimates were made for indoor air pollution in 2010 from the use of traditional bioenergy in 11 countries for which data indicate the use of such bioenergy: Brazil, China, Ecuador, India, Indonesia, Malaysia, Mexico, Morocco, Nigeria, South Africa and Turkey. For 2030, the estimates of VSL were increased in line with the growth in per capita incomes, applying an elasticity of 0.8 as discussed above. Costs are provided in Table 3.

**Table 3: Estimates of costs of indoor air pollution (USD<sub>2010</sub>/GJ)**

Country	Fatalities Per PJ	Value Per Fatality in 2010		Cost per GJ in 2010		Value Per Fatality in 2030		Cost per GJ in 2030	
		USD LB	USD UB	USD/GJ LB	USD/GJ UB	USD LB	USD UB	USD/GJ LB	USD/GJ UB
Brazil	35.70	810,405	2,431,216	28.9	86.8	1,252,739	3,758,218	44.72	134.16
China	92.40	592,859	1,778,576	54.8	164.3	696,593	2,089,780	64.36	193.09
India	118.20	317,294	951,882	37.5	112.5	699,728	2,099,183	82.71	248.12
Indonesia	35.88	377,058	1,131,175	13.5	40.6	383,023	1,149,069	13.74	41.23
Malaysia	1.14	1,042,068	3,126,203	1.2	3.6	1,160,804	3,482,411	1.33	3.98
Mexico	16.48	1,018,519	3,055,558	16.8	50.4	1,106,962	3,320,886	18.24	54.72
Morocco	4.84	407,512	1,222,535	2.0	5.9	852,380	2,557,141	4.13	12.39
Nigeria	33.87	237,211	711,634	8.0	24.1	587,088	1,761,265	19.88	59.65
South Africa	13.35	773,995	2,321,986	10.3	31.0	808,903	2,426,709	10.80	32.39
Ecuador	n.a.	687,582	2,062,746	18.61	55.84	829,143	2,487,429	22.44	67.33
Turkey	12.04	1,084,677	3,254,032	13.1	39.2	1,527,632	4,582,897	18.40	55.19

Notes to the table: LB stands for Lower Boundary and UB stands for Upper Boundary

Note: Data on deaths for Ecuador were not available. Fatalities per PJ were based on the average for countries in the region.

Source: Adapted from IRENA (2013)

<sup>15</sup> 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 cogeneration and bio-refineries, biogas produced through anaerobic digestion of residues, pellet heating systems and other technologies. Some scholars also note that traditional bioenergy is typically collected and used unsustainably, whereas modern bioenergy is used sustainably (*i.e.* as it is extracted, equal amounts are planted).

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