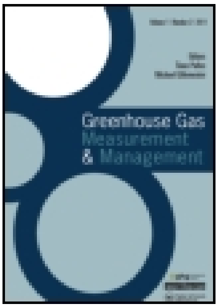

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A new tool to quantify carbon dioxide emissions from energy use and the impact of energy policies

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A new tool to quantify carbon dioxide emissions from energy use and the impact of energy policies

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A new tool to quantify carbon dioxide emissions from energy use was developed to provide a simple and transparent framework to quantify the impact of a single policy or a suite of policies on global carbon dioxide emissions. The model was tested for the period 1996–2009 by comparing with the reported emissions from the International Energy Agency. The resulting projections were within 1%, averaged for the 14-year period of historic (reported values). The tool was then employed to model carbon dioxide emissions for a suite of 495 enacted climate and energy policies under three different economic growth scenarios. Projected 2020 carbon dioxide emissions for business as usual were 42.6 ± 2.1 $GtCO_2$. Due to the impact of the full suite of policies, 2020 emissions fell to 35.2 ± 2.1 $GtCO_2$. Lastly, the emissions of the largest 10 CO_2 emitters were compared with their Copenhagen targets to provide context. Considering the transparency of the tool presented herein and its ability to model a single policy or a large set of climate and energy policies, it could prove useful to policy-makers and other stake-holders.

Keywords: emission modelling; energy policy; energy; climate policy; policy modelling; emissions trends

Introduction

Increased levels of atmospheric greenhouse gases impact Earth's heat balance, leading to changes in climate (IPCC, 2007). The primary contributors to this human-induced warming are emissions of carbon dioxide (Canadell et al., 2007; Friedlingstein et al., 2010; Le Quéré et al., 2012). A single sector, energy use, is responsible for the bulk of these emissions, accounting for 65% of greenhouse gas emissions (IEA, 2011a, 2011b, 2011c) and almost 75% of carbon dioxide emissions (Baumert, Herzog, & Pershing, 2005). Energy-related activities accounted for 94% of carbon dioxide emissions in the USA in 2010 (US Environmental Protection Agency, 2012). While deforestation, land-use change, cement production, and non-CO_2 greenhouse gases can represent an important fraction of total GHG emissions in some countries, the large contribution of emissions related to energy justifies a focus on this sector. To this end, many countries have enacted policies that aim to either reduce energy consumption by increasing efficiency or to replace CO_2-intensive fuel sources with low- or zero-carbon sources, such as renewables.

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The role of the energy sector in CO_2 emissions is expressed by the Kaya identity (Kaya, 1990) which relates a country's emissions (CO_2) to the total primary energy supply (TPES), the gross domestic product (GDP) and population (Pop):

$$CO_2 = \left(\frac{CO_2}{TPES}\right) \times \left(\frac{TPES}{GDP}\right) \times \left(\frac{GDP}{Pop}\right) \times Pop. \quad (1)$$

The different terms of the identity refer to critical components of the interplay of energy and carbon emissions. CO_2/TPES is the carbon intensity of the energy mix, TPES/GDP is the energy intensity of the economy, and GDP/Pop is the size of economy on a per-capita basis of the given country. Emissions shift in response to trends in all terms. Policies to reduce emissions aim to decrease carbon intensity or energy intensity while maximizing GDP. Generally speaking, reductions in carbon intensity occur through shifts towards low-carbon energy sources while those in energy intensity through efficiency measures (such as transportation fuel efficiency standards or building regulations). Reductions in energy intensity can also arise from underlying changes in the structure of the economy, such as a shift away from heavy manufacturing towards a service-oriented economy, but individual policies tend to focus on efficiency measures when trying to address energy intensity.

Drawing inspiration from the identity presented in Equation (1), this article presents a tool to project emissions from energy use and to quantify the first-order impact of energy-related policies on global and national emissions: a simple bottom-up model of the global energy system. The simplicity of the model and the transparency of the assumptions make it possible to quantify the reduction in emissions due to policies, whether existing, proposed, or hypothetical. A scenario for projected carbon dioxide emissions from energy, assuming full compliance of an existing suite of policies, is presented here as an example of the tool's analytical powers.

Unlike integrated assessment models, which include all the processes that impact GHG emissions, such as land-use change, agricultural practices, energy use, shifts in population, and technology development (Van Vuuren et al., 2011), this tool focuses solely on energy use. Though lacking the ability to assess these important processes, the current model is also free of the many assumptions required to characterize and simulate them.

Energy-economy models also focus primarily on the energy system; they provide a broad overview of energy dynamics and take into account technology interactions and the effect of market forces, such as carbon taxes, on emissions. The Energy Information Administration's National Energy Modelling System,[1] for example, incorporates energy resources, prices, and other characteristics of US energy markets into their calculations of emissions. These energy-economy models require considerable detail and assumptions to fully represent energy supply and demand, since many decisions that determine energy markets are made by individuals and private companies.

By contrast, the approach presented here makes the simplifying assumptions that the current fuel mix undergoes no changes in the Business as Usual (BAU) scenario and that there is full compliance for all policies. For example, fossil fuels are simply replaced by renewable energy sources or lighting standards are enforced, as dictated by policy language. Obviously, this approach misses trends that are not explicitly legislated by policies, such as the market-driven phase-out of old coal plants and the growth of natural gas, or the competition and synergies of technology options. This approach also fails to capture the behaviour of individuals or companies that respond, for example, to changing oil prices. However, its transparency provides a very straightforward BAU scenario, allowing clear isolation of the impact of a single policy or an aggregated set of policies.

The model is based on the energy balances compiled by the International Energy Agency (IEA). Future projections assume that the evolution of energy supply and consumption depend on a handful of simple variables. In the BAU scenario, energy use maintains the same mix of fuel sources and grows according to country-specific GDP growth rates, modified only by an overall improvement in energy efficiency. To verify the soundness of this approach, a hindcast BAU simulation of the period 1996–2009 was carried out. Once verified, the BAU was projected for 2020. A policy suite compiled by Deutsche Bank Climate Change Advisors (2012) was then applied to the BAU to quantify the impact of policies on emissions in the year 2020.

Methodology

Base data and critical assumptions

The base energy data in the model come from the IEA world energy balances (IEA, 2012) on a country-by-country basis. This includes world aviation and marine bunker energy use, which are accounted for globally within the IEA database. The energy balance from the IEA was formed into an energy matrix of 21 energy flows (e.g. electricity plants, road, residential, and commercial) and 10 energy products (e.g. coal, oil, gas, hydro, nuclear, wind, solar, etc.) for each country.[2] TPES for each country is the sum of the primary energy supply of all products. The sum of the TPES of all countries plus bunkers and international aviation represents the global TPES. Given that emissions are derived directly from a country's energy balance, the model presented here is sensitive to the chosen base year. Therefore, we use all the years for which the actual energy balances are available, as it allows the model to correctly capture exogenous factors (such as the financial crisis of 2007–2008) and their impacts on actual energy use.

Simulations

The period 1996–2009 was chosen for the hindcast runs, 2009 being the latest year with data available in the IEA database at time of download. A hindcast projection was generated using the method described in the BAU section below. The available energy data from the IEA database were then compared with our hindcast projection. The policy simulation was conducted for the period 2007–2020. For this study, the BAU scenario was computed using the published energy balances for the years 2007, 2008, and 2009, and E_n (and TPES) was projected from 2010 to 2020 (using the method described in the BAU section below). Since the energy balances for the years 2007, 2008, and 2009 are available from the IEA, the policy simulation forecasted values start in the year 2010. 2007 and 2008 are included because some policies start at those dates. The BAU energy supply or demand was modified as specified by the policies.

All BAU simulations (hindcast and future projections) assume a fixed energy mix determined by the first year of the study period. The assumption of a fixed proportion of energy sources is equivalent to assuming that each energy source grows at the same rate as the overall energy system. The validity of this assumption was assessed by comparing observed changes in the energy mix for hydro, solar, wind, and geothermal for a set of countries for which there were data. While the growth rate of these products is not always the same as that of the overall energy system on an individual country basis, it is a good approximation for the world simulation. The policy simulations deviate from the assumption of fixed energy mix when addressing targets that refer to the energy mix as stated in the policy language.

Energy to CO_2 conversion

Once the energy balance for each country is known, energy is converted to CO_2 emissions by multiplying each energy product (e.g. coal, oil, and gas) by the corresponding emission factors. The Intergovernmental Panel on Climate Change (IPCC) emission factors were not used because they distinguish between different products for each fuel type (e.g. anthracite vs. bituminous coal), which are not identified in the IEA world energy balances used in this study.[3] Instead, the effective emission factors used in this model (Table 1) are derived from the IEA World Energy Outlook 2011 (WEO; IEA, 2011a, 2011b, 2011c) by dividing total fuel emissions for Organisation for Economic Co-operation and Development (OECD) and non-OECD countries by their respective total fuel primary energy demand for the 2009 period.[4] It was assumed that all petroleum products are derived from crude oil, and the same effective emission factors were applied to these two energy products. The effective emission factors computed in this manner are consistent with the more disaggregated IPCC values.

Renewable sources (hydro, solar, wind, geothermal, and biomass) and nuclear energy were assigned an effective emission factor of zero (i.e. no CO_2 production per unit of fuel consumed). Due to the complications associated with analysing life-cycle emissions from biofuels, biofuels are considered carbon neutral, consistent with the IPCC Guidelines for Greenhouse Gases Inventories (1996) used by the IEA. This zero-emissions assumption for biofuels is an oversimplification and like the assumption of full compliance of policies, this can be thought of as a 'best-case scenario'.

Calculating the BAU scenario

As the basis of the emissions' calculations, the model generates a BAU scenario, which represents energy consumption and associated CO_2 emissions in the absence of new policies (the BAU assumes that whatever policies that are established, the current energy mix will maintain it). The hindcast is a BAU scenario, and the BAU for the projections to 2020 is the baseline onto which energy policies are applied. To construct the BAU, the IEA energy balances (IEA, 2012) for each country in the world are grown following Equation (2) by multiplying our flows and products by the GDP growth rate (GDPGr) and an Autonomous Energy Efficiency Improvement (see *Autonomous energy efficiency improvement* section below), referred to as AEEI. This assumes a constant energy mix for all projected time points

$$E_n = E_{n_0} * (\mathrm{AEEI})^n \prod_{i=1}^{n} (\mathrm{GDPGr}_i). \tag{2}$$

In Equation (2), E_{n_0} is the starting point of the forecast. For the policy simulation, E_{n_0} is the energy balance for the year 2009, the most recently published numbers from the IEA at the time of download for this study. For the hindcast run, E_{n_0} is 1996.

If the GDP growth rates used for the forecast are constant through time, as with the CAGR published by the IEA, the TPES for a given country is obtained by the aggregation of the

Table 1. Effective emission factors for OECD and non-OECD countries in million tons of CO_2 per million tons of oil equivalent ($MtCO_2$/mtoe).

	Effective emission factors ($MtCO_2$/mtoe)	
Fuel type	OECD members	Non-OECD members
Coal	3.8	3.8
Crude oil	2.6	2.7
Petroleum products	2.6	2.7
Gas	2.3	2.2

Note: Derived from the IEA World Energy Outlook 2011.

energy balance E_n which is defined as

$$E_n = E_{n_0} * (\text{GDPGr})^n * (\text{AEEI})^n. \tag{3}$$

Once the energy balance of a country E_n has been forecast for the study period (1996–2009 for the hindcast and 2009–2020 for the policy run), the fuel mix is converted to CO_2 emissions by multiplying each fuel type by the emissions factors in Table 1 as described in the *Energy to CO_2 conversions* section.

GDP growth rates

Energy consumption and economic growth are strongly coupled (Friedlingstein et al., 2010; Quadrelli & Peterson, 2007; Raupach et al., 2007), and the growth rate of a country's economy is fundamental to forecasting the growth of its TPES.

For the hindcast simulation, International Monetary Fund (IMF) historic growth rates from the year 1996 to 2009 for each country were applied. For countries not reported by the IMF, constant growth rates (i.e. North Korea and Cuba), regional growth rates (for Latin America, Africa and Asia), or parent country growth rates were used (i.e. Gibraltar uses Spain's GDP rates and Netherlands Antilles uses that of the Netherlands).

Future growth rates of GDP are uncertain, as they depend on the unconstrained predictions of economic and population growth. Therefore, two different sources for our future projections were used: the GDP growth rates published by the IMF (2012) heareafter IMF and the regional estimates published by the IEA on its WEO (IEA, 2011a, 2011b, 2011c). The IMF set is composed of historic GDP growth rates for 2007–2010,[5] forecast rates for the years 2010–2017, and a three-year running mean from previous years for 2018–2020. The WEO set uses projected compounded annual growth rates for some countries and the regional forecast for the countries for which individual growth rates are not provided.

Autonomous energy efficiency improvement

As described in the *Calculating the BAU* section above, an AEEI factor was used when projecting TPES. The AEEI describes the natural tendency of economies to see reductions in energy intensity (TPES/GDP) as time progresses (Kaufmann, 2004). Energy intensity is a key factor in the Kaya identity and is a target for policies to improve efficiency such as energy standards for building and transportation. AEEI refers however to non-policy-driven reductions in intensity, which can arise from many different factors, and trends in one country do not automatically translate to another. For example, in one country the AEEI might be driven by improvements in the efficiency of energy technologies or from the learning rates seen in certain industries, while other countries might be experiencing foundational shifts in the economy (e.g. the transition from heavy industry towards a service-oriented economy) which will reduce energy use per unit of GDP. The assumed value of the AEEI significantly impacts future projections, especially for longer forecasting periods. In this study, several AEEI assumptions were explored.

For the hindcast run, a unique AEEI value for each country was used. This factor was derived from historic OECD energy intensity data (OECD, 2011) for the 40 major emitter countries, whose emissions represent 80% of total world emissions. A compound average growth rate (CAGR) was computed using the historic trend in energy intensity within each country's energy system (increasing efficiency in all cases, i.e. negative CAGR) for the period 1999–2009. This fixed CAGR was used to attenuate the total projected TPES for each country during the hindcast period 1996–2009.

For low-emitting countries, i.e. those that are not part of the set described above, a 1.5% decrease in energy intensity per year suggested by Lackner and Sachs (2005) was used. The implicit assumption is that divergence between the actual and fixed AEEI for these countries would have a minimal impact on global emissions.

For the policy simulation, the model was run under three different AEEI conditions, which are assumed constant throughout the simulation period. In the first, the largest AEEI value (i.e. greatest efficiency improvement) was chosen from sets one and two on a country-by-country basis. In the second, the Lackner–Sachs value cited above (1.5%/yr) was applied to all countries in the world. In the third set, half of the historic CAGR of energy intensities from the period 1999 to 2009 (reported by the OECD[6]) was used. These three sets represent a decreasing range of efficiency values with corresponding emission estimates: low emissions (for the highest AEEI value), medium (Lackner–Sachs), and high (half of the historic AEEI).

Calculating policy impacts

The impact of a suite of 'bottom-up' policies on world CO_2 emissions by the year 2020 was examined using the methods described in the *Policy simulation* section below. 'Bottom-up' policies are defined as those that aim to reduce energy consumption (e.g. efficiency policies) or to increase the renewable share of a specific energy flow within a country's energy balance (e.g. installed capacity of renewable infrastructure electricity generation and increased use of biofuels in the road sector). In contrast, economy-wide emission targets (such as the Copenhagen Accord or the Kyoto protocol), which do not outline a roadmap of how reductions are to be implemented, are not considered in our simulations. In this manner, focus is shifted from ambiguous economy-wide emission targets, and centres attention on policies that specifically describe how the energy mix is to be modified.

Policy database

The policy database compiled by Deutsche Bank Climate Change Advisors (2012) consists of 495 energy sector policies from 69 different countries, including state-level policies for Australia, the USA, and Canada. Energy sector policies can aim to lower emissions by reducing the quantity of energy used, e.g. energy-efficient light bulbs or fuel economy standards (considered energy efficiency targets) or they can decrease the proportion of fossil-fuel energy in favour of zero-or low-emission fuels, e.g. renewable portfolio standards (RPS) or renewable energy targets. Renewable energy targets aim to reduce carbon intensity of the energy system, CO_2/TPES in Equation (1), while efficiency standards aim to reduce the energy intensity of the economy, TPES/GDP in Equation (1). Of the 495 policies, 314 are renewable energy targets and 181 are efficiency standards.

Policies were classified according to their language and their impact on the energy matrix after full compliance. This approach yielded 10 different categories, some of which include subcategories (Table 2).

Results

Hindcast simulation

The hindcast simulation (1996–2009) of world emissions was run using the effective emission factors described above and was compared with the CO_2 emissions from fuel combustion reported by the IEA (2011a, 2011b, 2011c).[7]

Table 2. Policy types, description, and subcategories.

Policy type	Description	Subcategories	Description	Number of policies
Electricity renewable portfolio standards (ERPS)	Policies that call for a certain per cent or installed capacity of renewables specifically applied to electricity generation. To compute the impact of these policies in addition to the energy matrix we used the electricity shares of the countries published by the IEA on their World Energy Balances	ERPS	Considers all sources of renewable energy including nuclear power when applying the policy to the energy matrix	110
		ERPS product	Considers only a specified source of renewable energy	53
		ERPS exclusion	Excludes a specified source of renewable energy	13
RPS	Policies that call for a certain per cent of renewables applied to the whole energy system, not only power generation, this per cent can be applied to TPES or total primary energy consumption depending on the policy language	N/A	N/A	60
Appliances	Policies that call for a per cent reduction of energy consumption from certain appliances. These policies only affect the total final consumption on residential or commercial sectors reflecting in a decrease in the power generation flows in the energy matrix using as the ERPS the electricity shares. Being efficient policies they decrease electricity supply across all energy products	N/A	N/A	37
Heating	Policies that call for a per cent of renewables applied to the heat supply. They only modify the energy matrix flow related with heat supply. For a combined heat and power plant only the percentage associated with heat production is modified	N/A	N/A	6
Energy intensity	Policies that call for a reduction of energy intensity defined as TPES/RealGDP. These policies modify TPES of the country	N/A	N/A	4
Close Plants	Policies that call to close specified energy products power plants. This policies redistribute the electricity shares from the selected products to the remaining ones	N/A	N/A	2

(*Continued*)

Table 2. Continued.

Policy type	Description	Subcategories	Description	Number of policies
Biofuels	Policies that call for a certain volume or per cent of biofuels in the transportation sector. They modify Total Final Consumption of road transport flows in the energy matrix	N/A	N/A	72
Natural gas utilities	Policies that call for a specific yearly efficiency improvement in natural gas power pants. Policy is modelled by reducing the TPES into the electricity flow while keeping the output the same	N/A	N/A	7
Fuel efficiency	Policies that increase the fuel efficiency of motor vehicles (e.g. CAFÉ Standards in the USA). They reduce the energy consumption across all energy products in the road transport flow only. To compute these policies, we assume that 10% of the fleet is renewed and affected by the policy each year after policy is enforced	N/A	N/A	60
Consolidated emissions	Represents a mixed set of policies. It includes different types of policies that call for emission reductions from specific sources and in specific terms. Depending on the policy, the reduction will be applied to different flows in the energy matrix	Type 1	Associated with power plants only modifies electricity and heat flows of TPES	2
		Type 2	European Union policies that affect flows not included in the EU Emission Trading Scheme	29
		Type 3	Emissions reductions from Residential sector Energy Consumption	1
		Type 4	Associated with reductions from Coal Power plants supply	39

A comparison between the two data sets shows an R^2 of 0.98, thus demonstrating close agreement between the simulation and observations. The simulation presents an initial offset in 1996 of ~735 $MtCO_2$ (3.2%) from the observed IEA emissions; this is the largest difference between the two, followed by that observed in 2004. The offset over the 14-year time series is 1% on average, with a maximum offset of 3.5%.

Offset from baseline

The initial offset from IEA emissions data could arise from differences in the energy data of our model or from differences in emission factors, since the IEA uses the IPCC (1996) emission factors. Two different data sets for world TPES were compared to evaluate whether the energy data are the source of the offset: (1) the IEA's TPES provided in the *CO_2 Emissions from Fuel Combustion* (2011a, 2011b, 2011c), referred to as 'IEA TPES'; and (2) the model projected TPES,[8] referred to as 'World projection'. The two data sets were essentially identical in 1996 (Figure 2). Thus, the initial offset (1996) seen in Figure 1 is concluded to result not from the underlying energy data, but rather from the effective emission factors that convert those data into CO_2 emissions.

As explained above, constant effective emission factors were used for each of the four fossil-fuel products (i.e. the model applies a single emissions factor for coal, regardless of its composition, and a single emissions factor for crude oil and oil products). This difference in effective

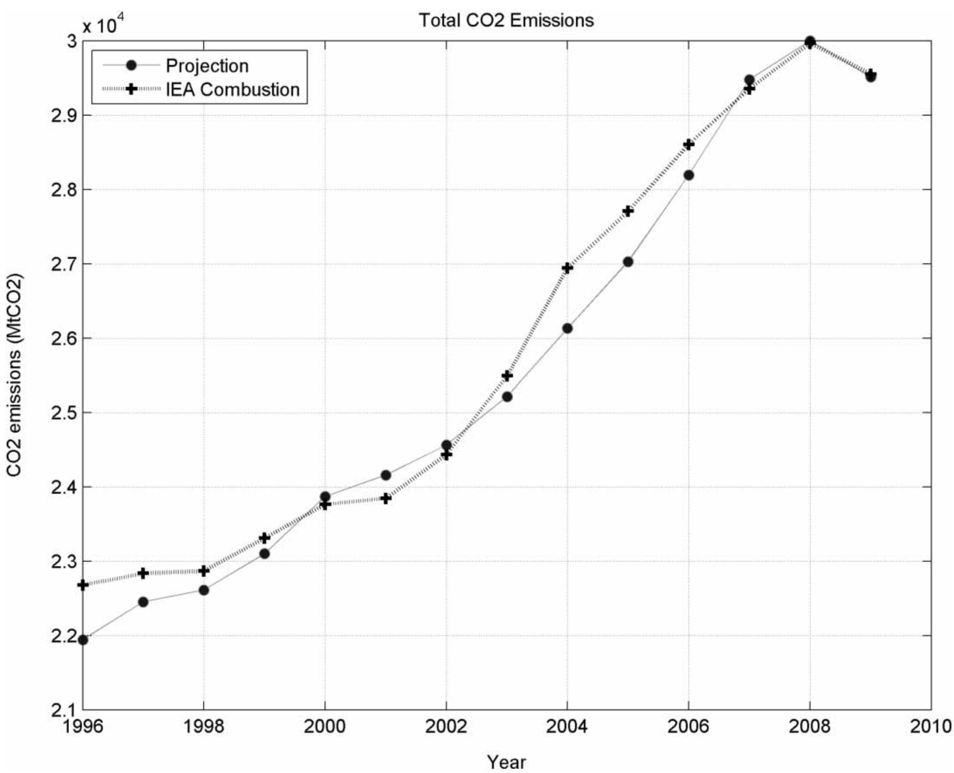

Figure 1. World CO_2 emissions from Energy Use 1996–2009. The crosses represent IEA reported values. The circles represent model projections using the effective emission factors.

emission factors is the source of the initial offset observed in 1996 in Figure 1, and likely contributes to the offset over time in varying proportions as the fuel sources grow.

The TPES projection is always about 5% higher than historic values (Figure 2), with an obvious impact on emissions. As noted, the model assumes that the proportions within the energy mix are constant through time under BAU. This assumption leads to a systematic overestimate of renewable energy sources worldwide when compared with the IEA World Energy balances (Figure 3(a)). As expected, the divergence between the projected values and the real values increases over time (Figure 3(a)). Figure 3(d), which shows the difference between the historic IEA values and the projections (using the historic values as the baseline), highlights that the largest contributor to the differences (3.6% of the total error in 2020) is the overestimation of renewables.

The projected values for fossil-fuel consumption follow the historic values closely (Figure 3(b)). The rate of increase slows after 2008 due to the global economic crisis (Friedlingstein et al., 2010). Because fossil-fuel consumption is the only activity that generates CO_2 emissions within our model (we ignore all emissions from land-use change and non-CO_2 gases), the relatively small difference (1.5% averaged over the 14 years) within this fuel type enhances the model's ability to predict future emissions from fossil-fuel consumption.

Observed TPES from nuclear energy is usually above our simulation, suggesting that the proportion of nuclear energy in the world mix increased very slightly in the study period (Figure 3(c)). The discrepancies oscillate between −5% and 2% in nuclear TPES, accounting for only 0.1% to −0.3%, of total TPES divergence (Figure 3(d)).

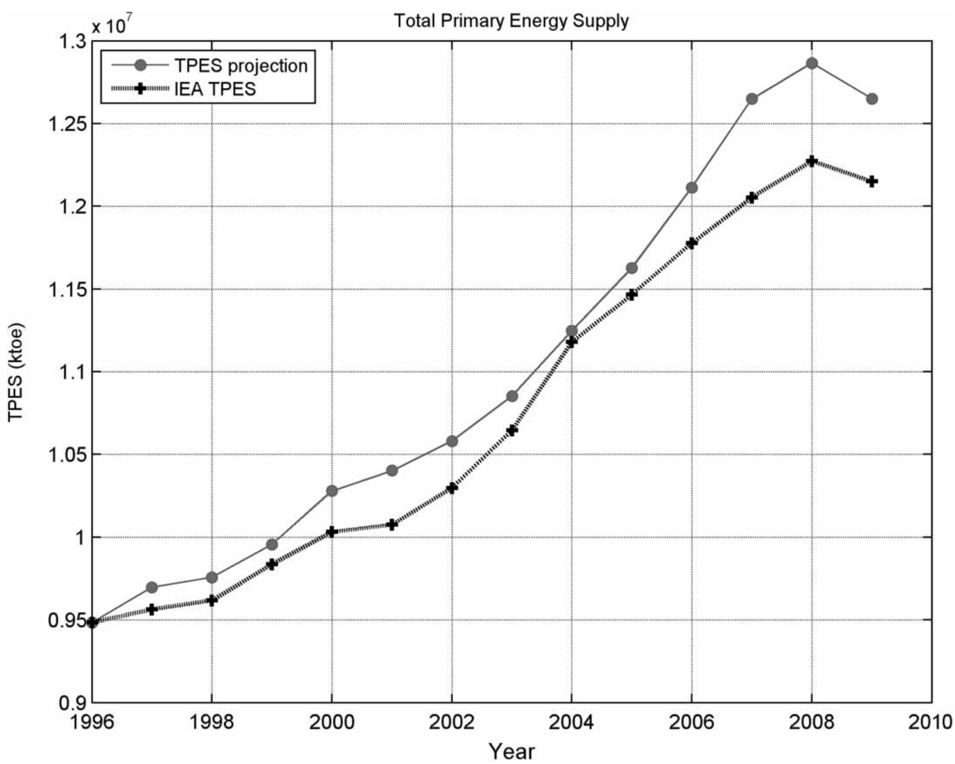

Figure 2. World TPES 1996–2009. The circles represent model projection and the crosses represent IEA reported values.

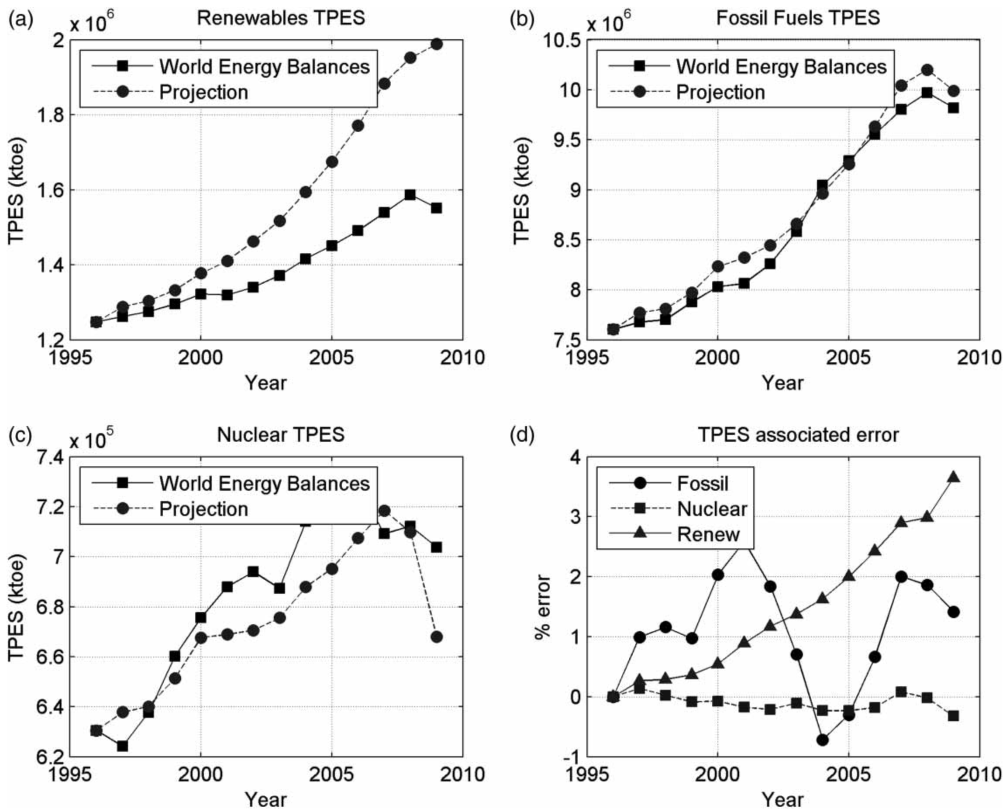

Figure 3. TPES for 1996–2009 from (a) renewables; (b) fossil fuels; and (c) nuclear power. Squares show the IEA World Energy Balances; circles are the model projections. (d) Offset between the IEA World Energy Balances and the projection associated with each energy source.

Policy simulations

BAU sensitivity

As noted, two estimates of GDP growth rate (WEO vs. IMF) and three potential values for AEEI factors (the 'best-case scenario' factor in which the largest observed AEEI was applied, the Lackner–Sachs factor, and half of the historic CAGR factor) are employed when analysing policies. Six runs of the model were performed in order to capture the effect of these factors on the projected baseline. Table 3 gives the world 2020 emissions for the six different runs.

In order to account for the 1% error found in the hindcast run, ±1% uncertainty was incorporated to each of the six model runs for a total of 12 emission pathways. A multi-run mean (the

Table 3. 2020 World BAU emissions from fossil fuels under different assumptions.

	IMF growth rates	WEO growth rates
Autonomous efficiency improvement	*2020 Emission* ($MtCO_2$)	*2020 Emission* ($MtCO_2$)
'Best-case scenario'	42,443	41,542
Lackner–Sachs	42,634	41,732
Half CAGR	44,364	43,399

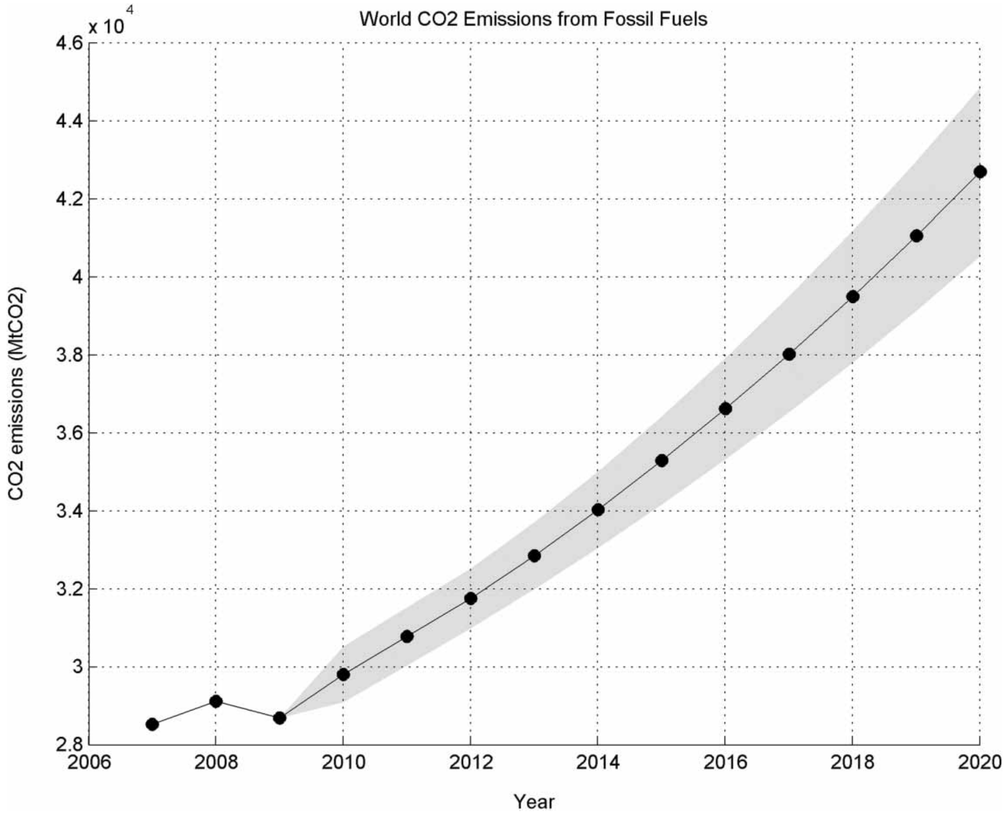

Figure 4. Projected world BAU CO_2 emissions from energy use for 2007–2020. The shaded envelope depicts the uncertainty range at the 95% confidence level.

average of the 12 emission pathways) was used to generate the BAU which reached 42.6 ± 2.1 $GtCO_2$ in 2020 (Figure 4). As expected, the uncertainty range increases with time.

Policy impacts

The impact of the policies is estimated as the difference between the projected BAU emissions and those resulting from modifying the energy mix according to the policies. As discussed above, the full compliance assumption is generally optimistic and represents a 'best-case scenario' view. On the other hand, the 'cascading' effect of renewable policies on certain sectors or industries could well be underestimated because technological synergies are not taken into account. For example, India is expected to double its renewable targets because of market forces and regional conditions (Obiko, 2012) while the model only captures what is explicitly stated in the policy.

As in the case of the BAU, 12 different emission pathways, using the range of GDP growth rates and AEEI factors, were simulated for the period 2007–2020. The multi-run average emission trajectory was estimated with the 95% confidence interval (Figure 5). The multi-run average world emissions in 2020 are around 35.2 ± 2.1 $GtCO_2$ for the policy scenario, putting the impact of the analysed set of policies in 2020 at 7.4 ± 2.1 $GtCO_2$.

The results described above were compared with the IEA WEO 2011 current policies and new policies scenarios. In its current policy scenario, the IEA projects CO_2 emissions from energy use

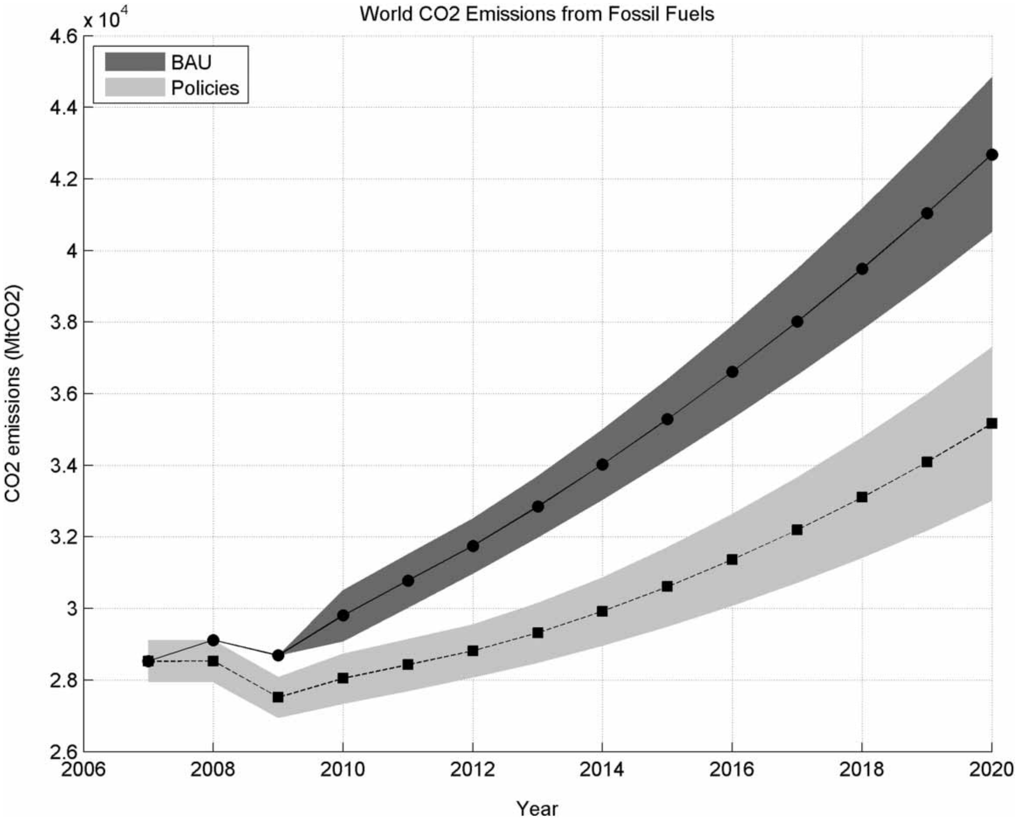

Figure 5. Projected world CO_2 emissions for BAU and for policy runs (policies) 2007–2020. The shaded envelope depicts the uncertainty range at the 95% confidence level.

at 36 $GtCO_2$ in 2020, almost 1 Gt above the mean of the model runs but within the 95% confidence level. The new policy scenario of the IEA places world emissions in 2020 at 34 $GtCO_2$, which is around 600 $MtCO_2$ below the reported mean but still within our 95% confidence level. Results are consistent with those of the IEA. It is important to mention that a direct comparison between the model's results and those of the IEA is not possible, as the suite of policies applied to the model falls somewhere between the two IEA scenarios.

In 2010 the UN Environmental Program established that emissions must be below 44 $GtCO_2e$ in 2020 to limit warming to less than 2°C total GHG (UNEP, 2010). The emission estimates from energy use reported above are already very close to this threshold although these results only consider energy emissions, which account for 60% of GHG emissions. When non-energy emissions and non-CO_2 greenhouse gases are also considered, it is unlikely that total GHG emissions will be below the UNEP threshold by 2020.

Analysis of high-emitting countries

An examination of policy impacts on the emissions of major emitting countries in 2020 was conducted, including the six largest emitters of the G8, the EU block, and the three largest emerging economies. This examination was conducted by comparing the policy impacts against each country's BAU and its corresponding Copenhagen Pledge (Figure 6).[9] Note that the Copenhagen pledges are economy-wide emission reduction targets, which include emissions associated with

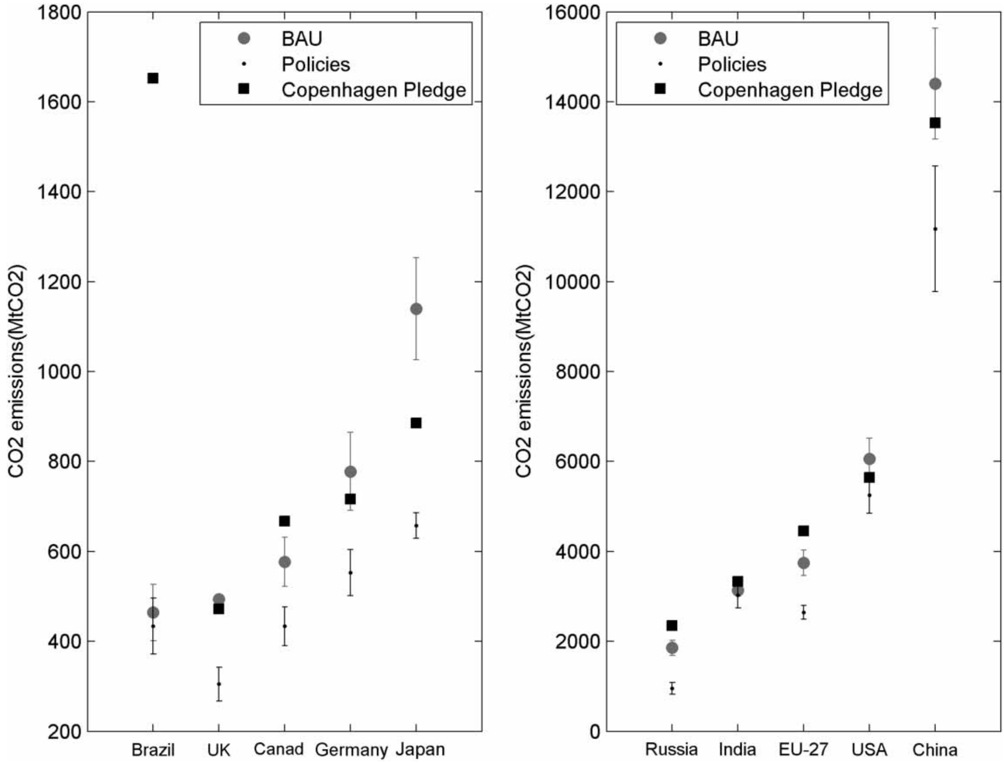

Figure 6. 2020 CO_2 emissions from energy use under BAU and after applying policies for selected countries. The emissions under the Copenhagen Pledge are included as a reference.

land-use change, cement production, and other greenhouse gases. Because the tool only deals with energy-related emissions of carbon dioxide, analysing the country results against its economy-wide Copenhagen pledge might appear misleading. However, it contextualizes the results and highlights the ambition of the energy policies with respect to a country's broader emission reduction commitments and aspirations. BAU emissions and emissions under the policy scenario overlap for Brazil, India, and the USA (Figure 5).

For Brazil, BAU and policy runs overlap at around 430 $MtCO_2$, while the Copenhagen pledge is around 1600 $MtCO_2$. This reflects the fact that the bulk of emissions for Brazil is not energy related and so its energy policies have minimal impact on BAU. Brazil emissions from land-use change and deforestation accounted for over 1.3 $GtCO_2e$ in 2005 (World Bank, 2012) and it is estimated that two-thirds of Brazil's emissions come from land-use change and agriculture (Cerri et al., 2007). This is not reflected in the BAU shown here, which only include energy emissions. Brazil's National Plan on Climate Change includes an aggressive reduction in deforestation, but as a non-energy policy, it was not modelled and its impact is not seen in Figure 5.

India's Copenhagen pledge aims for 25% reduction in carbon intensity, putting the Copenhagen-related emissions right at the edge of energy emissions projections. Because the percentage of emissions coming from energy in India represented 75% of total emissions in 2007 (Ministry of Environment and Forests, 2010), and the difference between the Copenhagen emissions and the lower bound policy result is 21% of total emissions, it is concluded that it will be unlikely for India to meet its Copenhagen target with its current set of policies. As noted above, the cascading market effects of full policy compliance could lead to further emissions reduction.

US emissions from fossil-fuel combustion represented 94% of total CO_2 emissions in 2010 (US Environmental Protection Agency, 2012). The Copenhagen pledge, which calls for a 17% reduction in emissions from 2005 levels, sits exactly at the intersection of the lower bound BAU and the upper bound policy emissions. Other greenhouse gases emissions accounted for 1.8 $GtCO_2e$ in 2010, while Land-Use Change and Forestry (LUCF) acted as a carbon sink with around 1 GtCO2e, bringing the net number to 0.8 GTCO2e (US Environmental Protection Agency, 2012). If this number is not lowered and the fuel mix remains constant, it seems unlikely that the USA will meet its target under the given set of analysed policies. However, the recent market-driven shift away from coal towards natural gas in electricity production (which is not modelled in the policy scenarios) has shown to rapidly decrease emissions in the electricity sector (US Energy Information Administration, 2012). This trend, which is not included in the present study, might prove decisive in enabling the USA to meet its Copenhagen pledge under the current set of policies.

The Copenhagen pledge targets of individual EU countries shown here fall on the lower bound of their BAU scenario. The UK's policy suite almost halved its BAU emissions. Considering that energy-related emissions accounted for 85% of UK total emissions in 2011, their policy suite should easily bring them below their Copenhagen target. German policies lower projected 2020 emissions 200 $MtCO_2$ below BAU, even including the policy-driven phase-out of nuclear power announced after the Fukushima crisis.

Conclusion

This study presents a simple model to project energy-related CO_2 emissions under a variety of different assumptions (GDP growth rates, energy intensity improvements, and effective emission factors), which can easily be used to estimate the first-order impact of energy-related policies on global and national emissions. In assessing the tool's accuracy to forecast CO_2 emissions, a hindcast for the energy-related CO_2 emissions for the 1996–2009 period was performed. Results of the hindcast suggest that on average the 14-year time series has an offset of 1% with respect to the historic data.

The tool was then used to assess the impact of a suite of 'bottom-up' energy policies on world emissions by 2020. The impact of policies is estimated as the difference between the projected BAU emissions and those resulting from modifying the energy mix according to the policy language and targets. A multi-run mean for the BAU baseline under different GDP growth scenarios and AEEI projected world CO_2 emissions from fossil-fuel combustion to be 42.6 ± 2.1 $GtCO_2$ in 2020. After applying the set of policies included in this study, the multi-run average emissions in 2020 were found to be 35.2 ± 2.1 $GtCO_2$, putting the impact of the suite of policies in 2020 at 7.4 ± 2.1 $GtCO_2$. When comparing these results to the IEA WEO 2011 current policies and new policy scenarios, the multi-run mean of our policy scenario resulted in emissions 1 $GtCO_2$ below the IEA's current policy scenario and 600 $MtCO_2$ above the new policy scenario. Both IEA scenarios fall within our 95% confidence interval.

Trends that are not explicitly specified by policies, such as retiring old coal plants and the market-driven growth of natural gas cannot be captured in the model. Likewise, the simulations will not include growth in an energy source that exceeds the growth of GDP. That said, and even considering these simplifications, our results fall within the projections of the most complex and nuanced energy models. The ability of this tool to accurately forecast CO_2 emissions from fossil-fuel consumption when compared with historic values and other modelled future projections highlights its relevance and importance. The simplicity and transparency of its underlying assumptions make it possible for the model to compute the impact of a single policy or a large suite of policies with no modifications to the model. Because of this, the tool presented in this paper can be easily be used by academics or stake-holders to study the potential impact of individual energy policies or policy roadmaps within a national or international context.

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Notes

1. http://www.eia.gov/oiaf/aeo/overview/
2. For details of the aggregation method, see Appendix 1.
3. Energy balances with a more detailed disaggregation are available from the IEA in their ‘Extended world energy balances’. In order to reduce the complexity of the data being used, the model was based on the simpler ‘IEA world energy balances’. Although the former has more detail about each fuel type, they both report the same TPES for each country.
4. It was assumed that these factors stayed constant throughout the modelling period.
5. Another advantage of using historic GDP growth rates for 2007–2010 is that they capture the global economic recession of 2008.
6. Because the OECD discloses data for the major emitters of the world, the AEEI factor was applied on a country-by-country basis in this scenario.
7. For a discussion on model sensitivity for select countries see Appendix 2.
8. The process for projecting this TPES is identical to the one described in the ‘calculating BAU’ section and uses the historic IMF growth rates as detailed above.
9. For details on the specific target percentages in the Copenhagen Pledges see Appendix 3.

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Appendix 1. Aggregation of IEA energy balances to energy matrix

The main purpose of modifying the flows and products from the IEA World Energy Balances is to simplify the energy matrix. This simplification is based on similarities in flows or products from the IEA in order to reduce the size of the matrix.

Flow aggregation

The total primary energy supply of a country is extracted from 45 flows of the Country IEA World Energy Balance. These 45 flows are aggregated according to Table A1 to create the 21 flows that are used in the model. This aggregation is made based on energy use.

Table A1. International Energy Agency (IEA) flows aggregated into model flows.

IEA flow	Model flow
Autoproducer CHP plants	CHP plants
Main activity producer CHP plants	
Blast furnaces	Coal transformation
Coke ovens	
Patent fuel plants	
Commerce and public services	Commercial and public services
Losses	Distribution losses
Domestic aviation	Domestic aviation
Autoproducer electricity plants	Electricity plants
Main activity producer electricity plants	
Gas works	Gas works
Autoproducer heat plants	Heat plants
Main activity producer heat plants	
Chemical and petrochemical	Industry sector
Construction	
Food and tobacco	
Industry	
Iron and steel	
Machinery	
Mining and quarrying	
Non-ferrous metals	
Non-metallic minerals	
Non-specified (industry)	
Paper, pulp and printing	
Textile and leather	
Transport equipment	
Wood and wood products	
Liquefaction plants	Liquefaction plants
Non-energy use	Non-energy use
Agriculture/forestry	Other sectors
Fishing	
Non-specified (other)	
Other transformation	Other transformation
Domestic navigation	Other transport
Non-specified (transport)	
Pipeline transport	
Energy industry own use	Own use
Non-energy use in transport	Part of Non-energy use
Non-energy use industry/transformation/energy	
Oil refineries	Petroleum refineries
Rail	Rail
Residential	Residential
Road	Road
Statistical differences	Statistical differences
Transfers	Transfers

Product aggregation

The aggregated balances of the IEA include 10 products and 3 subproducts for energy supply. The model uses 10 of the products and 2 of the subproducts to form a set of 8 products and 2 subproducts; the aggregation is shown in Table A2.

Table A2. International Energy Agency (IEA) products aggregated into model products.

IEA product	Model product
Coal and coal products	Coal and peat
Peat	
Crude, NGL and feedstocks	Crude oil
Oil products	Petroleum products
Natural gas	Natural gas
Nuclear	Nuclear
Hydro	Hydro
Geothermal	Geothermal, solar, etc.
Solar/wind/other	
Biofuels and waste	Biomass
Heat output from non-specified combustible fuels	Not used
Electricity	Electricity
Heat	Heat

Final matrix

The final energy matrix for the model is a 21 flow by 10 product matrix as shown below (Table A3). This matrix is then projected for energy use over time.

Table A3. Mexico 1996 Energy Balance after aggregation.

Flow/Product	Coal and peat	Crude oil	Petroleum products	Natural gas	Nuclear	Hydro	Geothermal, solar, etc	Biomass	Electricity	Heat
Transfers	0	12091.228	-13504.973	0	0	0	0	0	0	0
Statistical differences	−788.852	281.2	1132.989	−8.961	0	0	0	0.024	19.35	0
Electricity plants	4389.67	0	16922.17	5603.346	2053.055	2704.012	4926.139	711.361	−13946.362	0
CHP plants	0	0	0	0	0	0	0	0	0	0
Heat plants	0	−1	0	0	0	0	0	0	0	0
Gas works	0	0	960.28	−772.716	0	0	0	0	0	0
Petroleum refineries	0	67819.882	−67471.902	0	0	0	0	0	0	0
Coal transformation	631.982	0	0	0	0	0	0	0	0	0
Liquefaction plants	0	0	0	0	0	0	0	0	0	0
Other transformation	0	0	0	0	0	0	0	0	0	0
Own use	24.704	0	6335.189	6904.286	0	0	0	0	920.63	0
Distribution losses	0	0	0	0	0	0	0	0	1999.672	0
Industry sector	1992.179	0	7529.834	8130.527	0	0	1.313	1405.171	6590.18	0
Domestic aviation	0	0	0	0	0	0	0	0	0	0
Road	0	0	30081.917	0	0	0	0	0	0	0
Rail	0	0	597.263	0	0	0	0	0	85.312	0
Other transport	0	0	592.72	0	0	0	0	0	0	0
Residential	0	0	7549.986	560.674	0	0	15.785	6691.367	2449.452	0
Commercial and public services	0	0	1316.065	183.718	0	0	10.627	0	1241.582	0
Other sectors	0	0	1827.728	0	0	0	0	0	648.698	0
Non-energy use	0	0	7234.762	6176.14	0	0	0	0	0	0

Note: Mexico 1996 Energy Balance (ktoe)

Appendix 2.

As described in the main paper, the model computes total world emissions by aggregating emissions generated by individual countries. Therefore, it is critical to understand how the model behaves on at the individual country level. Table A4 presents the average difference between the model's projected CO_2 emissions and ones reported by the IEA over the hindcast period of 1996–2009 for select major emitters.

Table A4. Average difference for selected countries between model projection and IEA data.

Country	Average difference between model projection and IEA data (1996–2009) (%)
Brazil	−3.1
Canada	2.7
China	14.8
Germany	8.1
India	−5.3
Japan	−5.9
Russia	−1.2
United Kingdom	5.1
United States	2.1

The unusually high difference seen in the case of China can probably be explained by errors in the data set. Akimoto, Ohara, Kurokawa, and Horii (2006) used satellite observations and national statistics to assert that coal consumption for the period 1996–2002 was higher than the numbers reported by the IEA, and propose that IEA numbers for this period should not be used for CO_2 inventories. The maximum offset is in 2001, when the deviation between reported emissions and our projected value is ~1 $GtCO_2$. After this period, when reported emissions begin to grow again, the difference decreases, reaching its minimum absolute value of 340 $MtCO_2$ in 2005. Recent literature (Guan, Liu, Geng, Lindner, & Hubacek, 2012) suggests that IEA emission numbers for China are still being underestimated, which suggests that our overestimated values for Chinese emissions might be closer to reality than would appear at first glance.

Appendix 3. Copenhagen pledges shown in Figure 6

The Copenhagen pledges for selected countries shown in Figure 6 of the main text are shown in Table A5.

Table A5. Copenhagen pledges for economy wide reductions for selected countries.

Country	Copenhagen pledge considered
Brazil	39% reduction in greenhouse gas emissions from BAU levels by 2020
Canada	17% reduction in greenhouse gas emissions from 2005 levels by 2020
China	40% reduction in carbon intensity from 2005 levels in 2020
European Union	20% reduction in greenhouse gas emissions from 1990 levels by 2020
Germany	20% reduction in greenhouse gas emissions from 1990 levels by 2020
India	25% reduction in carbon intensity from 2005 levels in 2020
Japan	25% reduction in greenhouse gas emissions from 1990 levels by 2020
Russia	20% reduction in greenhouse gas emissions from 1990 levels by 2020
UK	20% reduction in greenhouse gas emissions from 1990 levels by 2020
USA	17% reduction in greenhouse gas emissions from 2005 levels by 2020