Supplementary Information

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1. Model Descriptions

AIM/CGE model is a one-year-step recursive-type dynamic general equilibrium model that covers all regions of the world. The AIM/CGE model includes 17 regions and 42 industrial classifications. Details of the model structure are described by Fujimori et al. (2012). The production sectors are assumed to maximize profits under multi-nested constant elasticity substitution (CES) functions and each input price. Energy transformation sectors input energy and value added as fixed coefficients of output. Power generation values from several energy sources are combined with a Logit function. Household expenditures on each commodity are described by a linear expenditure system function. The saving ratio is endogenously determined to balance saving and investment, and capital formation for each good is determined by a fixed coefficient. CO2, CH4, N2O, and F-gases are treated as GHGs. BC, CO, NH3, NMVOC, NOX, OC and sulfur are treated as air pollutant gases. Basically, the emissions factors are changed over time according to the implementation of air pollutant removal technologies and relevant legislation. The implementation of mitigation actions is represented by assuming either a global total emissions constraint. Once the emission constraint is implemented, the carbon price becomes a complementary variable to that constraint and determines marginal mitigation cost.

GCAM (Global Change Assessment Model) explores the complex relationship between economic activity, energy systems, land use systems, ecosystems, emissions and resulting impact on climate change. The main focus of this model is technology analysis and implications of various technology pathways for climate policies in a national and global context. The model includes 16 emissions tracked (e.g. CO2, CH4, N2O, and SO2), is divided into 14 regions and runs from 1990 to 2095 in time steps of 5 years. The model assumes that regional population and labor productivity growth assumptions are the main drivers for energy and land-use systems. The end-use energy service demands associated with time path of economic activity have been aggregated as three energy services- industrial energy services, building energy services, and transportation energy services. MAGICC is an embedded reduced form model of the carbon cycle, atmospheric chemistry and climate change that provides GHG concentrations, radiative forcing, and climate change. This is the only non-European model participating in the LIMITS project and further information on its specifications can be found in Calvin et al. (2011).

IMAGE (Integrated Assessment Modelling Framework) is in fact a complex modelling framework, i.e. several linked and integrated models describing long-term dynamics of global environmental variations, such as air pollution, climate change, and land-use change. The TIMER is the global energy model that describes the demand and production of primary and secondary energy and the related emissions of GHGs and regional air pollutants. The Land-Use Emissions Model (LUEM) computes the emissions of atmospheric pollutants (GHGs and air pollutants) from both natural and land-use related sources. The model provides results for 16 global regions. A detailed description of IMAGE can be found at Bouwman et al. (2006).

The MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) model, version V, is a linear programming system engineering optimization model used for medium- to long-term energy system planning and policy analysis. The model minimizes total discounted energy system costs, and provides information on the utilization not only of several energy and technology related variables (from use to trade) but also on pollutant emissions. The model also includes generic representations of agriculture and
forestry, including emissions and mitigation options for the GHGs and other radiatively active substances. The model includes 11 regions across the globe and provides results for the time period of 2100. Further information can be found at [1, 2]

REMIND (Regionalized Model of Investments and Development) is a global multi-region model that represents an inter-temporal energy-economy-environment. It incorporates the economy, the climate system and a detailed representation of the energy sector, maximizing global welfare based on nested regional macro-economic production functions. This model allows for unrestricted inter-temporal trade relations and capital movements between 11 world regions, providing information regarding technology options and policy proposals for climate mitigation. Mitigation costs estimates are based on technological opportunities and constraints in the development of new energy technologies. Further information can be found at Leimbach et al. (2009, 2010).

The WITCH (World Induced Technical Change Hybrid model) regional model allows for the analysis of the socio-economic dimensions of climate change. It provides figures of the economic consequences of climate policies and helps to devise optimal strategy planning for climate change mitigation. In this model the non-cooperative nature of international relationships is explicitly accounted for and climate policies across the 13 regions included and over time can be differentiated allowing considering several policy scenarios. The model most interesting features regard the endogenous treatment of technological innovation in the mitigation sector, and the modelling of multiple externalities, both climatic and technological, in a game-theoretic setup. The climate module provides information on climate change impact and optimal adaptation response. Further details on the model can be found at Bosetti et al. (2006, 2009).
2. Scenario Description
The reference scenario is a counterfactual scenario with no climate policies included and is based on median GDP and population projections.

The climate policy case includes both emissions reduction targets for the year 2020 as laid down in the Copenhagen pledges with inclusion of some plausibility considerations of the pledges and a long-term 450 ppm CO2e target (defined in terms of limits on the combined radiative forcing from all anthropogenic radiative agents assessed in the IPCC 4th assessment report, except nitrate aerosols, mineral dust aerosols, and land use albedo changes). Full where (region) and what (sector) flexibility of emissions reduction was assumed ensuring the selection of the cheapest globally available mitigation option at the margin.

Table 2-1: Summary of Durban Platform climate change policies in 2020

<table>
<thead>
<tr>
<th>Region</th>
<th>GHG emissions reduction in 2020(1)</th>
<th>GHG intensity reduction in 2020(2)</th>
<th>Modern Renewable share in electricity(3)</th>
<th>Installed renewable capacity in 2020 (Wind, solar)</th>
<th>Installed nuclear power capacity (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EU27</td>
<td>-15% (2005)</td>
<td>-</td>
<td>20% (2020)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>China</td>
<td>-</td>
<td>-40%</td>
<td>25% (2020)</td>
<td>200 GW; 50GW</td>
<td>41 GW (2020)</td>
</tr>
<tr>
<td>India</td>
<td>-</td>
<td>-20%</td>
<td>13% (2020)</td>
<td>20 GW; 10GW</td>
<td>20 GW (2020)</td>
</tr>
<tr>
<td>Japan</td>
<td>-1% (2005)</td>
<td>-</td>
<td>4.5% (2020)</td>
<td>5 GW; 28GW</td>
<td>-</td>
</tr>
<tr>
<td>USA</td>
<td>-5% (2005)</td>
<td>-</td>
<td>10% (2020)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Russia</td>
<td>+27% (2005)</td>
<td>-</td>
<td>7.5% (2025)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>AUNZ</td>
<td>-13% (2005)</td>
<td>-</td>
<td>7.5% (2025)</td>
<td>34GW (2030)</td>
<td>-</td>
</tr>
<tr>
<td>Brazil</td>
<td>-18% (BAU)</td>
<td>-</td>
<td>17% (2020)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mexico</td>
<td>-15% (BAU)</td>
<td>-</td>
<td>17% (2020)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>LAM</td>
<td>-15% (BAU)</td>
<td>-</td>
<td>10% (2020)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CAS</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>KOR</td>
<td>-15% (BAU)</td>
<td>-</td>
<td>8 GW; -</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>IDN</td>
<td>-13% (BAU)</td>
<td>-</td>
<td>7.5% (2025)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SSA</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CAN</td>
<td>-5% (2005)</td>
<td>-</td>
<td>13% (2020)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EEU</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
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<tr>
<td>EFTA</td>
<td>-</td>
<td>-</td>
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<td>-</td>
</tr>
<tr>
<td>MEA</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NAF</td>
<td>-</td>
<td>-20%</td>
<td>15% (2020)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PAK</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SAF</td>
<td>-17% (BAU)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SAS</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SEA</td>
<td>-</td>
<td>15% (2020)</td>
<td>20 GW; -</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TWN</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Abbreviations:
AUNZ = Australia and New Zealand, LAM = Latin America
CAS = Central Asia
KOR = South Korea
IDN = Indonesia
SSA = Sub-Saharan Africa
CAN = Canada
EEU = Eastern Europe excl. EU27 and Russia
3. Assumptions on Pollution Control

In order to quantify the levels of AP control stringency, a global dataset of emission factors derived from the GAINS model [3] is provided. This dataset reflects recent developments in the air pollution legislation across the world and draws on data collection, model evaluation, and discussion with air quality policy, measurement and modeling communities; in particular work on the revision of the European Union National Emission Ceiling Directive, the UNECE LRTAP Task Force on Hemispheric Transport of Air Pollution (TF HTAP), UNEP Black Carbon and Tropospheric Ozone assessment, as well as various ongoing EU funded initiatives.

The projections of emission factor trajectories up to 2030 have been derived based on the World Energy Outlook (WEO) 2011 baseline scenario [4] implemented in the GAINS model. While the documentation of these recent emission scenarios is under preparation, the data has been made available to the modeling community via GEIA/ECCAD (www.geiacenter.org) and ECLIPSE (http://eclipse.nilu.no/) web portals. Furthermore, the similar dataset (based on the WEO 2009 ([5]) developed with GAINS has been documented in the past, e.g., [6-11] and subsequently applied to a number of studies [12-14].

Two sets of emission factors are available (with a third derived from these).

**CLE**: ‘current legislation’ – These emission factors assume efficient implementation of existing environmental legislation. It thus describes a scenario of pollution control where countries implement all planned legislation until 2030 with adequate institutional support. The CLE emission factors are “fleet average” values that are the aggregate emission factor of all ages of equipment operating in the given year.

**MTFR**: ‘maximum technically feasible reduction’ – These emission factors assume implementation of ‘best available technology’ as it exists today independent of their costs but considering economic lifetime of technologies and selected other constraints that could limit applicability of certain measures in specific regions. While, the full penetration of MTFR measures in the near-term is not a feasible scenario, these values serve rather as ultimately achievable air pollutant emission factors for conventional technologies considered being available at the present time.

**SLE**: Stringent policies, where emissions factors close up to 75% of the difference between CLE and MTFR (derived from two datasets above). Because the MTFR emission factors do not represent the impacts of vintaging or super-emitters, the derived SLE emission factors can be considered, in many cases, to be quite ambitious.

Emission factor estimates are provided for:

- All energy-related combustion (supply and demand), conversion, and transformation sectors.
- 26 world regions;
Sulfur dioxide (SO$_2$), nitrogen oxides (NO$_x$), organic carbon (OC), black carbon (BC), carbon monoxide (CO), and non-methane volatile organic carbons (NMVOC).

Note that the base-year 2000 emissions factors in this dataset may differ from other datasets that may be used for IAM calibration (e.g. [15]). For some substances, such as BC and OC, these differences may be substantial and this is a reflection of the large uncertainty in current emissions for these species. It is important to note that these differences in current emission factors, in general, do not translate to similar differences in MFR (or, for the most part, SLE) emissions factors, as these represent emission factors for technologies with strong emission controls. There are uncertainties here as well, but these are largely independent of uncertainties in current-day emissions.

Table 3-1: Details of assumed pollution Controls

<table>
<thead>
<tr>
<th></th>
<th>Transport</th>
<th>Industry and power plants</th>
<th>International shipping</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current legislation (CLE)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfur dioxide (SO$_2$)</td>
<td>OECD: EU fuel quality directive</td>
<td>OECD: For EU, emission</td>
<td>MARPOL Annex VI</td>
<td>Limiting open burning of</td>
</tr>
<tr>
<td></td>
<td>(2009/30/EC) and national legislation</td>
<td>standards from the</td>
<td>revisions from</td>
<td>agricultural waste (if</td>
</tr>
<tr>
<td></td>
<td>on the sulfur content in liquid</td>
<td>LCPD (2001), IED (2010),</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Non-OECD: National legislation on</td>
<td>National legislation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>the sulfur content in liquid fuels</td>
<td>elsewhere.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>and coal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Non-OECD: Increased use of low-</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>sulfur coal, increasing penetration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>of flue gas desulfurization (FGD)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>after 2005 in new and existing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>plants according to national</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>legislation.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen oxides (NO$_x$)</td>
<td>OECD: Emission controls for vehicles</td>
<td>OECD: For EU, emission</td>
<td>MARPOL Annex VI</td>
<td>Limiting open burning of</td>
</tr>
<tr>
<td></td>
<td>and off-road sources up to the</td>
<td>standards from the</td>
<td>revisions from</td>
<td>agricultural waste (if</td>
</tr>
<tr>
<td></td>
<td>EURO-IV/ EURO-V standard (vary by</td>
<td>LCPD (2001), IEC (2010),</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Non-OECD: National emission</td>
<td>National emission</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>standards equivalent to approximately</td>
<td>standards on stationary</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>EURO III-IV standards (vary by</td>
<td>sources– if stricter than</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>region)</td>
<td>in the LCPD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>As above for NO$_x$</td>
<td></td>
<td></td>
<td>Limiting open burning of</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>agricultural waste (if</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>legislation exists)</td>
</tr>
<tr>
<td>Volatile organic</td>
<td>Measures as described above for</td>
<td>A number of directives for</td>
<td></td>
<td></td>
</tr>
<tr>
<td>compounds</td>
<td>NO$_x$; legislation on fuel</td>
<td>the EU; e.g., Solvent</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>quality and evaporative</td>
<td>Directive of the EU</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1999), stage I directive</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1995), stage II directive</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2001), stage III directive</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2004), stage IV directive</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pollutant</td>
<td>As for NOx (including BC and OC)</td>
<td>Additional Measures in Stringent legislation (SLE): Corresponding to 70% of Maximum Technologically Feasible Reduction Levels</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>---------------------------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SO(_2)</td>
<td>As in CLE</td>
<td>High-efficiency flue gases desulfurization (FGD) on existing and new large boilers Use of low-sulfur fuels and simple FGD techniques for smaller combustion sectors High-efficiency controls on process emission sources</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO(_x)</td>
<td>OECD and Non-OECD: EURO-5 and EURO-6 for light duty vehicles</td>
<td>Selective catalytic reduction at large plants in industry and in the power sector Combustion modifications for smaller sources in industry and in the residential and commercial sectors High-efficiency controls on process emission sources</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>As in CLE</td>
<td>Reduction in agricultural waste burning</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VOC</td>
<td>As in CLE</td>
<td>Reduction in agricultural waste burning</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ammonia (NH\(_3\))


PM2.5

For the OECD like for SO\(_2\), NO\(_x\) for the Non-OECD, improving enforcement of PM control with end of pipe measures required by national legislation; often linked to FGD requirements Limiting open burning of agricultural waste (if legislation exists)

Additional Measures in Stringent legislation (SLE): Corresponding to 70% of Maximum Technologically Feasible Reduction Levels

SO\(_2\) As in CLE High-efficiency flue gases desulfurization (FGD) on existing and new large boilers Use of low-sulfur fuels and simple FGD techniques for smaller combustion sectors High-efficiency controls on process emission sources Reduction in agricultural waste burning

NO\(_x\) OECD and Non-OECD: EURO-5 and EURO-6 for light duty vehicles Selective catalytic reduction at large plants in industry and in the power sector Combustion modifications for smaller sources in industry and in the residential and commercial sectors High-efficiency controls on process emission sources Reduction in agricultural waste burning

CO As in CLE Regular monitoring, flaring, as well as control of the evaporative loses from storage Reduction in agricultural waste burning

VOC As in CLE Solvent use: full use of potential for substitution with low-solvent products in both “do it yourself” and industrial applications, modification of application methods and introduction of Reduction in agricultural waste burning
solvent management plans

NH₃
End-of-pipe controls in industry
(fertilizer manufacturing)
Substitution of urea fertilizers, rapid incorporation of solid manure, low nitrogen feed and bio-filtration

PM2.5
As in CLE
High-efficiency electrostatic precipitators, fabric filters, new boiler types, filters, good practices
Revised MARPOL Annex VI (2005) regulations
Reduction in agricultural waste burning

4. Sector Definitions

**Table 4-1: Definition of Sectors**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Supply</td>
<td>Emissions from Extraction and Distribution of Fossil Fuels (including fugitive Emissions, IPCC category 1B); Electricity production and distribution, district heating and other energy conversion (e.g. refineries, synthetic fuel production)</td>
</tr>
<tr>
<td>Energy Demand</td>
<td>Emissions from all energy end-use sectors, including industry emissions. Includes International Shipping.</td>
</tr>
<tr>
<td>Land Use</td>
<td>Total anthropogenic emissions from land use (Burning of Agricultural waste (IPCC category 4F), Emissions from Deforestation, Emissions from Fertilizer use, Enteric Fermentation, manure management, Use of pesticides (IPCC categories 4A, 4B, 4C, 4D), Emissions from agricultural rice production, Emissions from agricultural livestock, including manure management, Emissions from fertilizer use)</td>
</tr>
<tr>
<td>Solvents</td>
<td>Emissions from Solvent and other Product Use (IPCC Category 3)</td>
</tr>
<tr>
<td>Waste</td>
<td>Emissions from Landfills, wastewater treatment, human wastewater disposal and waste incineration (non-energy) (IPCC category 6)</td>
</tr>
</tbody>
</table>
5. Regional Definitions

Table 5-1: Definition of Regions

<table>
<thead>
<tr>
<th>Macro region</th>
<th>Acronym</th>
<th>Countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asia</td>
<td>ASIA</td>
<td>China, China Hong Kong SAR, Republic of Korea, Indonesia, Dem. People's Republic of Korea, Mongolia, Brunei Darussalam, Malaysia, Singapore, India, Sri Lanka, Papua New Guinea, Vanuatu, Samoa, Tonga, Philippines, Afghanistan, Bangladesh, Bhutan, Nepal, Pakistan, Cambodia, Lao People's Democratic Republic, Myanmar, Taiwan, Thailand, Viet Nam</td>
</tr>
<tr>
<td>Middle East + Africa</td>
<td>MAF</td>
<td>Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Mauritius, Reunion, Rwanda, Somalia, Uganda, United Republic of Tanzania, Central African Republic, Chad, Democratic Republic of the Congo, Sudan, Egypt, Iran, Bahrain, Iraq, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates, Yemen, Israel, Jordan, Lebanon, Syrian Arab Republic, Algeria, Libyan Arab Jamahiriya, Morocco, Tunisia, Lesotho, South Africa, Swaziland, Malawi, Mozambique, Zambia, Zimbabwe, Angola, Botswana, Namibia, Cameroon, Congo, Equatorial Guinea, Gabon, Sao Tome and Principe, Benin, Burkina Faso, Cape Verde, Cote d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Togo</td>
</tr>
<tr>
<td>OECD</td>
<td>OECD90</td>
<td>Australia, Austria, Belgium, Luxembourg, Netherlands, Canada, Switzerland, Portugal, Spain, Finland, France, Ireland, United Kingdom, Greece, Italy, Japan, Iceland, Norway, New Zealand, Fiji, Solomon Islands, Germany, Denmark, Sweden, Turkey, United States of America</td>
</tr>
<tr>
<td>Latin America + Caribbean</td>
<td>LAM</td>
<td>Argentina, Uruguay, Brazil, Chile, Mexico, Aruba, Bahamas, Barbados, Cuba, Dominican Republic, Grenada, Guadeloupe, Haiti, Jamaica, Martinique, Netherlands Antilles, Puerto Rico, Saint Lucia, Saint Vincent and the Grenadines, Trinidad and Tobago, Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, Panama, Bolivia, Colombia, Ecuador, French Guiana, Guyana, Paraguay, Peru, Suriname</td>
</tr>
<tr>
<td>Reforming Economies</td>
<td>REF</td>
<td>Slovenia, Bulgaria, Cyprus, Hungary, Malta, Kazakhstan, Poland, Estonia, Latvia, Lithuania, Albania, Bosnia and Herzegovina, Croatia, The Former Yugoslav Republic of Macedonia, Czech Republic, Slovakia, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, Romania, Armenia, Azerbaijan, Georgia, Russian Federation, Belarus, Republic of Moldova, Ukraine</td>
</tr>
</tbody>
</table>
6. Air Quality Modeling

For atmospheric analysis, the TM5-FASST model [16], a reduced-form global air quality source-receptor model (AQ-SRM) was used, allowing for computation of PM2.5 concentrations for several scenarios developed by all six IAMs. In this simplified model the relation between the emissions of compound $i$ from source $x$ and resulting pollutant $j$ concentration (where $j = i$ in case of a primary component) at receptor $y$ is expressed by a simple linear relation which mimics the underlying meteorological and chemical processes:

$$C_{ij}(x, y) = C_0^j(y) + A_{ij}(x, y)E_i(x)$$

where $C_{ij}(x, y)$ is the concentration of species $j$ at receptor $y$ formed from precursor $i$ emitted at source $x$, $E_i(x)$ is the emission rate (kg/yr) of precursor $i$ at source $x$, $A_{ij}(x, y)$ is the so-called source-receptor coefficient between source location $x$ and receptor location $y$ for emitted precursor $i$ leading to end product $j$, and $C_0^j(y)$ is a constant for pollutant $j$ and location $y$. The source-receptor coefficients are stored as matrices with dimension $[x,y]$. There is a single matrix for each precursor $i$ and for each resulting component $j$ from that precursor.

The SRCs have been derived from a set of runs with the full chemical transport model TM5-CTM [17] by applying emission perturbations for each of a defined set of source regions and precursor components. TM5-CTM explicitly solves the mass balance equations of the species using detailed meteorological fields and sophisticated physical and chemical process schemes. TM5-CTM covers the global domain with a resolution of $1^\circ \times 1^\circ$. The reduced form TM5-FASST model produces $1^\circ \times 1^\circ$ resolution grid maps of PM2.5 surface concentrations taking as input annual emission rates of pollutants for each of 56 TM5-FASST regions. For population exposure calculations, the resulting PM$_{2.5}$ grid maps are interpolated to $7.5^\prime \times 7.5^\prime$ to match high resolution population grid maps [12, 18].

The SRCs are stored as matrices for each precursor and for each corresponding resulting component. These have been derived from a set of runs with the full chemical transport model TM5-CTM (Tracer Model, version 5, Krol et al. (2005)) where the base emission value was changed by 20% for a defined set of 56 source regions (see Figure 1) and major air pollutant precursors, like SO$_2$, NO$_x$, BC, OC, NMVOC, and NH$_3$. In practice this means that for each region the change in concentration of all affected pollutant species was calculated by reducing by 20% the emissions of a precursor over a source region. The base run had as a reference emission dataset the AR5 RCP year 2000$^1$. The resulting concentrations were obtained for a global domain at $1^\circ \times 1^\circ$ resolution. Having established and stored all relevant source-receptor matrices, those are subsequently used to calculate the resulting concentration change from any emission by scaling them with actual emission changes. An overview of all considered precursor-pollutant combinations are given in Table 2. This set of linear equations for all components and all source and receptor regions emulates the full-fledged TM5-CTM, and constitutes the ‘kernel’ of TM5-FASST.

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$^1$ Representative Concentration Pathways (trntcat.iiasa.ac.at:8787/RcpDb) from the Fifth Assessment Report of IPCC (https://www.ipcc.unibe.ch/AR5/)
**Figure 2** Definition of the 56 source regions within TM5-FASST. EU27 is represented by 16 regions.

**Table 6-1** Relevant emitted precursor-pollutant pairs. The number of x’s gives a qualitative indication of the most influential precursors (xxx: highest influence). Influences indicated by one x are due to feedback mechanisms affecting the level of oxidants, and hence the lifetime of OH radicals, in the atmosphere, which in turn affects the oxidation rate of the precursors.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>SO₂</th>
<th>NOx</th>
<th>NH₃</th>
<th>O₃</th>
<th>CH₄</th>
<th>SO₄</th>
<th>NO₃</th>
<th>NH₄</th>
<th>BC</th>
<th>POM</th>
<th>SOx</th>
<th>NOy</th>
<th>BC</th>
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<tr>
<td>SO₂ (g)</td>
<td>xxx</td>
<td>x</td>
<td>xx</td>
<td>x</td>
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<td>xxx</td>
<td>xx</td>
<td>xx</td>
<td>x</td>
<td>xxx</td>
<td>xxx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO₂ (g)</td>
<td>x</td>
<td>xxx</td>
<td>xx</td>
<td>xxx</td>
<td>xx</td>
<td>xxx</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
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<tr>
<td>NH₃ (g)</td>
<td>x</td>
<td>x</td>
<td>xxx</td>
<td>x</td>
<td>x</td>
<td>xx</td>
<td>xx</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BC (pm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>xxx</td>
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<td></td>
<td>x</td>
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<td>NMVOC (g)</td>
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<td>x</td>
<td>xxx</td>
<td>xx</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
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<tr>
<td>CO (g)*</td>
<td></td>
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<td></td>
<td></td>
<td>xxx</td>
<td></td>
<td></td>
<td>xx</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>CH₄ (g)*</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>xxx</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
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</tr>
</tbody>
</table>

* From HTAP, 2011

The resulting air pollutant concentrations, and their specific spatial distribution, are then further processed into impacts, such as the effect of particulate matter on human health (mortalities, reduction of statistical life expectancy), the impact of O₃ on vegetation and crop damage, the deposition of eutrophying or acidifying components to sensitive ecosystems. Mostly these calculations are based on simple empirical dose-response functions from literature, making use of additional data to be overlaid with the pollutant concentration (or derived metric) in order to
properly calculate the exposure (population maps, crops and vegetation maps, sensitive ecosystem maps, etc.).

The available 3D aerosol fields in the 20% emission perturbation runs with TM5-CTM are used to derive the change in global forcing for each of the perturbed emitted precursors. Applying the methodology described by Fuglestvedt et al., 2010, the resulting forcing responses [W/m²]/[kg/yr] are then further used to calculate the global warming potential (GWP) and global temperature potential (GTP) for a set of time horizons H. In this way, a set of climate metrics is obtained which is consistent with the air quality metrics, health and ecosystem impacts calculated from the concentration and deposition fields.

TM5-FASST is currently implemented as an interactive Excel application (56x56 SR matrices) and as an IDL (Interactive Data Language) programme (56-to-1°x1° grid SR matrices).

The pollutant emissions determined by each of the IAMs for their native regions were redistributed according to the TM5-FASST regions and used as input to determine concentration maps and impacts on health and vegetation (not discussed in this study). This was achieved by using available sector-specific 1°x1° gridded emission inventories from previous assessments (GEA, 2011) to derive the relative contribution of each country to the emission of each IAM native region, which leads to an estimated disaggregation of IAM regional emissions to country level, after which the country emissions are aggregated to 56 TM5 source regions, needed for the application of SRC. By aggregating the final concentration and population exposure results again at the level of the 5 IAM regions, errors in the emission redistribution between individual countries are deemed to be largely cancelled out. This procedure was done for each scenario and for the years 2030 and 2050. The PM2.5 values were then aggregated into 10 global regions and

Figure 6-1 Overview of the major components in the TM5-FASST tool. The traditional process-modelling is replaced by simple matrix calculations.
for each model and different years it was possible to determine the changes across scenarios to evaluate the effectiveness and co-benefits of policy implementation.
7. Additional Results

Figure 7-1: Primary Energy by Sector across IAMs
Figure 7-2: Emissions of CO, VOC and OC
Figure 7-3: Cumulative Reductions in MIT scenarios CO₂ and air pollutants (2010-2050)
Figure 7-4: Emissions by sector, REF scenario (above), MIT scenario (below)
Table 7-1: Regional population-weighted change in man-made PM2.5 (µg/m³) in 2050 relative to 2010 for 4 scenarios, obtained with the TM5-FASST model. Mean and standard deviation resulting from input emissions provided by 6 IAMs.

<table>
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<th>Region</th>
<th>REF CLE2050-2010</th>
<th>REF SLE2050-2010</th>
<th>MIT CLE2050-2010</th>
<th>MIT SLE2050-2010</th>
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<tr>
<td></td>
<td>mean</td>
<td>σ</td>
<td>mean</td>
<td>σ</td>
</tr>
<tr>
<td>NAM</td>
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<td>0.8</td>
<td>-3.1</td>
<td>0.7</td>
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<tr>
<td>EUR</td>
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<td>1.0</td>
<td>-5.0</td>
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<tr>
<td>CHINA+</td>
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<td>-13.5</td>
<td>3.6</td>
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<tr>
<td>INDIA</td>
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<td>4.7</td>
<td>-6.2</td>
<td>4.0</td>
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<tr>
<td>REST_ASNIA</td>
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<td>1.2</td>
<td>-4.1</td>
<td>1.1</td>
</tr>
<tr>
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<td>1.3</td>
<td>-1.3</td>
<td>1.5</td>
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<tr>
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<td>1.6</td>
<td>-1.8</td>
<td>1.8</td>
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<tr>
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<td>1.9</td>
<td>-3.3</td>
<td>1.8</td>
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<tr>
<td>PAC_OECD</td>
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<td>REF_ECON</td>
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8. References