Horizon 2020 Societal challenge 5:
Climate action, environment, resource
efficiency and raw materials

CD-LINKS

Linking Climate and Development Policies – Leveraging International Networks and Knowledge Sharing

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No changes with respect to the DoA.

Dissemination and uptake

The project is currently in a fast track process to produce results for the IPCC 1.5 C Special Report, and within the model runs of the process, also sustainable development dimensions will be analysed, based on the methodologies presented in this deliverable. More specifically, this deliverable report will be used as input in a sustainable development dimension synthesis paper that the project is currently working on as part of the fast track process. In the synthesis paper, results of the methodologies presented in this deliverable will be further presented. Furthermore, Dr. Fujimori is currently working on a separate paper specifically on the food security methodology, for which this deliverable will also function as an input.

Short Summary of results (<250 words)

The integrated analysis of a broad portfolio of sustainable development objectives – as opposed to focussing on climate change mitigation in isolation – is important for informing the policy process, most notably guided by the United Nation's Sustainable Development Goals (SDGs). As an important step towards enabling analysis between sustainable development dimensions such as alleviating energy poverty, reducing income inequality, improving air quality and thereby human health, ensuring water availability and food and energy security, the CD-LINKS consortium applies a range of national and global Integrated Assessment Models (IAMs) that have different capabilities in terms of being able to contribute to the analysis of interactions between climate change and non-climate related SDGs. Further, by linking these tools and transferring the methodology applied by one model to other models, the scope of the SDG assessment is broadened. This deliverable report presents the work that has been undertaken with regards to the methodological advances and linkages between the models for broadening the scope of studying multiple objectives. The main sustainable development dimensions in which model development has taken place, and presented in this report, are: i) Food security, ii) Access to clean energy, iii) Air pollution and related health impacts, and iv) Lifecycle assessment impacts of electricity generation.

Evidence of accomplishment

Please see deliverable report for D4.1 (attached)

Linking Climate and Development Policies –
Leveraging International Networks and Knowledge Sharing

Deliverable 4.1:

Report on model harmonisation and development to represent multiple policy objectives

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Date: 13 March 2017

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Keywords: Sustainable Development Goals (SDGs); Climate policy; Model development

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Executive Summary

The integrated analysis of a broad portfolio of sustainable development objectives – as opposed to focussing on climate change mitigation in isolation – is important for informing the policy process, given that decision-making regularly involves balancing multiple objectives in a wide range of areas. At the political level, the United Nations' Sustainable Development Goals (SDGs) have been adopted as a framework to make progress in these multiple dimensions. Developing a better understanding of the synergies and trade-offs between the multiple policy objectives, such as alleviating energy poverty, reducing income inequality, improving air quality and thereby human health, ensuring water availability and food and energy security, is essential to inform the SDG-related policy process both globally as well as nationally.

As an important step towards enabling such analysis, on the one hand, the CD-LINKS consortium applies a range of national and global Integrated Assessment Models (IAMs) that have different capabilities in terms of being able to contribute to the analysis of interactions between climate change and non-climate related SDGs. On the other hand, by linking these tools and transferring the methodology applied by one model to other models, the scope of the SDG assessment is broadened. Therefore, the results from the range of models applied and linked in CD-LINKS are combined in order to arrive at an as broad assessment of SDG linkages as possible.

This deliverable report presents the work that has been undertaken with regards to the methodological advances and linkages between the models for broadening the scope of studying multiple objectives. The main sustainable development dimensions in which model development took place as well as the rationale to do so are listed below.

i. Food security
Different indicators related to food security, including food price indices and the change in average caloric intake of different populations can be directly derived from IAMs that include a representation of the agricultural sector. More directly speaking to the SDGs is the population at risk of hunger which cannot be provided by all IAMs represented in the CD-LINKS project. A method was established that allows deriving the number of people at risk of hunger based on output that IAMs with a representation of land use and in particular agriculture can generate.

ii. Access to clean energy
An indicator related to affordability of clean energy forms that can be produced by IAMs are consumer level (final energy) prices of energy. However, the impact of energy price changes on the affordability of different energy forms also depends on income level of different households which is not represented in most IAMs. The MESSAGE-Access model, a standalone residential cooking energy choice and demand fuel choice model, is used for quantifying the population relying on solid cooking fuels. In the model, population heterogeneity in affordability, access and availability of cooking fuels is accounted for by disaggregating households by income and urban/rural residence. This allows evaluating the distributional impacts of using solid cooking fuels and of climate and other policies on different segments of the population.

iii. Air pollution and related health impacts
While all IAMs are capable of tracking energy use in different energy conversion processes, only some IAMs also generate consistent air pollutant emissions and even fewer are able to

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translate these into health implications. The GAINS model, an integrated policy analysis tool that follows the pathways of atmospheric pollution from driving forces through the key emission sources to the most relevant health and environmental impacts, is used for the quantification of air pollution and related health impacts. In CD-LINKS, the drivers of pollutant emissions are derived from the scenarios by the national and global IAMs. The focus is placed on the pollutants that contribute directly or act as precursors of fine particles $PM_{2.5}$ and tropospheric ozone; these include primary particulate matter (predominately fine particles $PM_{2.5}$), secondary PM precursors (SO_2, NO_x, NH_3), and substances contributing to the ozone formation (NO_x and NMVOCs).

iv. Lifecycle assessment (LCA) impacts of electricity generation:
The transformation of the electricity generation sector is well characterized in IAMs, but the evaluation of environmental impacts is typically limited to emissions of different types and in some cases water. By contrast, LCA takes a much broader set of environmental impacts into account. To broader the scope of quantifying environmental co-benefits and adverse side-effects of the power sector decarbonization, so-called LCA midpoint impact indicators (not covered by the other methods employed in CD-LINKS) are used in CD-LINKS by linking the information on structural changes (in terms of new construction, operation, and decommissioning of power plants) from IAM scenarios to LCA indicators. This includes land occupation (of energy technologies excluding bioenergy supply), eutrophication, mineral resource depletion, release of ionizing radiation, human toxicity and ecotoxicity.

These model developments allow the quantification of indicators related to several SDGs. More specifically, the indicators derived from the model development described in this document can speak to SDGs #2 (zero hunger), #3 (good health and weel-being), #6 (clean water and sanitation), #7 (affordable and clean energy), #13 (climate change), #14 (life on land) and #15 (life below water).

The benefits of this model development will be used for assessing the implications of possible climate policies at the national and global scale along various sustainable development dimensions. A scenario set that explores global and national scenarios that follow implemented (and planned) policies through 2020 or implement the Intended Nationally Determined Contributions (INDCs) goals submitted by countries to the United Nations Framework Climate Change Convention (UNFCCC) under the Paris agreement and thereafter transition to emissions budgets that are consistent with the 2 and 1.5° C targets, is currently under development within CD-LINKS. The goal is therefore to explore the implications of short-term climate action, and in particular the "ratcheting up" of the ambition level embedded in the INDCs, for the achievability of the long-term temperature targets agreed upon in Paris. Within this set of scenarios, the development of non-climate sustainability objectives will be tracked as a consequence of climate policy with the idea to identify conditions under which synergies or trade-offs between climate change mitigation and other objectives may materialize.

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Abbreviations

CD-LINKS	"Linking Climate and Development Policies – Leveraging International Networks and Knowledge Sharing" research project
CTM	Atmospheric chemistry transport models
EMEP	European Monitoring and Evaluation Programme
FAO	the Food and Agriculture Organization
IAMC	the Integrated Assessment Modeling Consortium
IAMs	Integrated Assessment Models
INDCs	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
LCA	Lifecycle assessment
PM	Particulate matter
SDGs	United Nations' Sustainable Development Goals
SSP	Shared Socioeconomic Pathway
UNFCCC	United Nations Framework Climate Change Convention
WEO	World Energy Outlook

1. Introduction

The integrated analysis of a broad portfolio of sustainable development objectives – as opposed to focussing on climate change mitigation in isolation – is important for informing the policy process, given that decision-making regularly involves balancing a myriad of objectives in a wide variety of areas. At the political level, the United Nations' Sustainable Development Goals (SDGs) have been adopted as a framework to make progress in these multiple dimensions. To inform this process, it is therefore essential to develop an understanding of the synergies and trade-offs between the multiple policy objectives, including, for example, alleviating energy poverty, reducing income inequality, improving air quality and thereby human health, ensuring water availability and food and energy security, limiting and reducing GHG emissions, and increasing resilience to climate variability and change. Recent analyses have shown that significant synergies between at least a subset of these objectives exist and that these synergies may help to reconcile shorter-term national and regional objectives with the long-term objective to limit climate change (McCollum et al. 2011; McCollum et al. 2013; Shukla and Dhar 2011; van Vuuren et al. 2006). Going far beyond the limited state of the current literature on integrated, holistic sustainable development pathways requires that national and global modelling frameworks be enhanced in several key areas.

As an important step to enable such an analysis of synergies and trade-offs using multiple national and global energy-economy and integrated assessment models, the capabilities of models to quantify the relevant sustainable development dimensions had to be developed further. A second criterion in this context is the use of comparable indicators for quantifying various sustainable development objectives across different models. To allow for a broad quantification of sustainable development objectives of high quality, within CD-LINKS the approach was adopted to utilize models according to their strengths instead of trying to quantify each sustainable development objective in all models. At the same time, where possible more than one model is used for the analysis of synergies and trade-offs among the different objectives in order to quantify uncertainties and to assess the robustness of findings.

Against the background of the CD-LINKS consortium's decision to respond to the request by the European Commission to provide input to the IPCC Special Report on *the impacts of global warming of 1.5° C above pre-industrial levels and related global greenhouse gas emission pathways* (henceforth IPCC Special Report on 1.5° C), the model development plans to better represent non-climate sustainable development objectives were adjusted for compatibility with the revised timeline for scenario development.

A scenario set that explores global and national scenarios that follow implemented (and planned) policies through 2020 or implement the Intended Nationally Determined Contributions (INDCs) goals submitted by countries to the United Nations Framework Climate Change Convention (UNFCCC) under the Paris agreement and thereafter transition to emissions budgets that are consistent with the 2 and 1.5° C targets, is currently under development by the CD-LINKS consortium. The goals is therefore to explore the implications of short-term climate action, and in particular the "ratcheting up" of the ambition level embedded in the INDCs, for the achievability of the long-term temperature targets agreed upon in Paris. Within these CD-LINKS "fast-track" scenarios, the development of non-climate sustainability objectives will be tracked as a consequence of climate policy with the idea to identify conditions under which synergies or trade-offs between climate change mitigation and other objectives may materialize.

In order to allow developing this assessment on the timeline relevant for the IPCC Special Report on 1.5° C, the model development plans in CD-LINKS have been adjusted in the following way:

- To speed-up the model development in accordance with the timeline of the IPCC Special Report on 1.5° C and to allow for comparibility of indicators across different models, where possible centralized processes for assessing non-climate sustainable development objectives were developed and implemented.

- In general, proxy indicators that are produced by models endogenously are reported to a central database and then fed into specific add-on models that generate output that more directly speaks to sustainable goals. For example, energy models generally quantify energy prices which are in addition to socio-economic variables (e.g., income) important determinants of access to modern energy services (e.g., clean cooking fuels). However, a model that also takes into account infrastructure availability (which typically is different in urban and rural settings) and income hetereogeneity is needed to quantify the number of people depending on traditional fuels for cooking (Cameron et al. 2016).
- In addition, individual models have developed capabilities to quantify relevant sustainable development indicators such as water use in the energy systems (Fricko et al. 2016) that are reported in addition to the centralized assessment of non-climate sustainable development objectives. These individual model capacbilities will be utilized in the fast-track scenarios with the plan of continuing model development further by transferring the methods to other models that did not finish the development on the timeline relevant for the 1.5° C Special Report.

The main sustainable development dimensions in which model development was implemented in a centralized way are (i) food security, (ii) access to clean energy, (iii) air pollution and related health impacts, and (iv) lifecycle assessment impacts of electricity generation. In addition, given that covering multiple sustainable development dimension in parallel has tremendously expanded the requirements of the model reporting (see Annex, Section 9), the CD-LINKS project has undertaken a capacity building initiave on automated model result reporting to assisst modeling teams that have not yet build up such an automated mechanism in doing so. While driven to a good degree by the requirements of WP4, the benefits of this investment are equally relevant to WP3 within CD-LINKS as well as to other modeling projects.

2. Food security

Food security relates to Sustainable Development Goal (SDG) #2 on zero hunger and has multiple dimensions and as such cannot be addressed by a single quantitative indicator. In the CD-LINKS project, we take into account different indicators that relate to food security, including food price indices and the change in average caloric intake of different populations. However, one of the most policy-relevant indicators, in particular in the context of the SDGs, is the *number of people at risk of hunger* as highlighted as one of the central indicators related to SDG2. As not all Integrated Assessment Models (IAMs) represented in the CD-LINKS project can report this indicator directly, a method was established that allows deriving the *number of people at risk of hunger* based on output that IAMs with a representation of land use and in particular agriculture can generate.

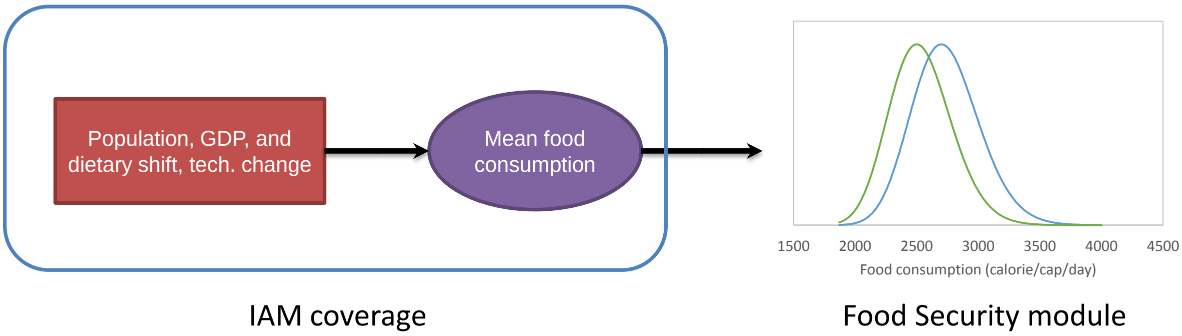

Figure 1: Illustration of linkage between IAMs and food security assessment module.

Figure 1 illustrates the linkage between IAMs and the food security assessment module schematically. Key inputs to the assessment include mean food consumption (in terms of caloric intake) derived from the IAMs along with input assumptions of demographic and economic development as well as measures of income equality. The method and its application within CD-LINKS are described in more detail in the following sections.

2.1 Methodology to estimate the people at risk of hunger

The methodology to estimate the people at risk of hunger is basically documented in Hasegawa et al.(Hasegawa et al. 2015a; Hasegawa et al. 2015b; Hasegawa et al. 2016).

The narrow definition of undernourishment or hunger is a state of energy (calorie) deprivation lasting over one year; this does not include the short-lived effects of temporary crises (EC-JRC/PBL 2012; FAO 2012). Furthermore, this does not include inadequate intake of other essential nutrients (FAO 2012).

The population at risk of hunger is a proportion of the total population and is calculated using Eq. 1.

$$Risk_t = POP_t \cdot PoU_t \qquad \text{(Eq. 1)}$$

where,

t : year

$Risk_t$: population at risk of hunger in year t [person]

POP_t : population in year t [person]

PoU_t : proportion of the population at risk of hunger in year t [−]

According to the Food and Agriculture Organization (FAO) methodology (FAO 2008), the proportion of the population at risk of hunger is defined using Eqs. 2 to 4. With the FAO methodology, the proportion is calculated using three parameters: the mean food calorie intake per person per day (*cal*), the mean minimum dietary energy requirement (*M*), and the coefficient of variation of the food distribution of the dietary energy consumption in a country (*CV*). The food distribution within a country is assumed to obey a standard normal cumulative distribution. The proportion of the population under the mean minimum dietary energy requirement (*M*) is defined as the proportion of the population at risk of hunger. The standard normal cumulative distribution has two parameters, the mean μ_t and the variance σ_t, as in Eq. 2. The parameters μ_t, and σ_t can be represented using the mean food calorie intake per person per day (*cal*) and the coefficient of variation of the domestic distribution of dietary energy consumption (*CV*) as Eqs. 3 and 4.

The weight-based consumption of food calculated by the IAMs is converted into the calorie-based consumption using conversion factors for each commodity, and this is used as the mean food calorie intake per person per day (*cal*). Calories per 100 g (FAO 2007) are weighted on the basis of production data in the base year and aggregated to the commodity classification to obtain the conversion factors. In this process, only the edible parts of commodities are considered for food consumption by using the edible parts ratios (FAO 2007). The *CV* is an indicator of food security observed in a household survey conducted by the FAO. It ranges from 0 to 1. FAO country data for CV are weighted on the basis of population data in the base year and aggregated to regional classification to obtain the CV of aggregated regions.

$$PoU_t = \Phi\left(\frac{\log M_t - \mu(cal_t, \sigma_t)}{\sigma_t}\right) \qquad \text{(Eq. 2)}$$

$$\mu\left(cal_t,\sigma_t\right)=\log_e cal_t-\sigma_t^2/2 \qquad \text{(Eq. 3)}$$

$$\sigma_t=\left[\log_e\left(CV^2+1\right)\right]^{0.5} \qquad \text{(Eq. 4)}$$

where,

M_t : mean minimum dietary energy requirement in year t

CV_t : coefficient of variation of the inter-national distribution of dietary energy consumption in year t

Φ : standard normal cumulative distribution

cal_t : mean food calorie intake per person per day in year t

The mean minimum dietary energy requirement (*M*) is calculated for each year and country using the mean minimum dietary energy requirement in the base year at the country level (FAO 2013), adjustment coefficient for the minimum energy requirements per person in different age and sex groups (FAO/WHO 1973) and the population of each age and sex group in each year (IIASA 2012), as in Eqs. 5 and 6.

$$M_t=Mbase\cdot\frac{MER_t}{MERbase} \qquad \text{(Eq. 5)}$$

$$MER_t=\frac{\sum_{i,j} RMER_{i,j}\cdot Pclass_{i,j,t}}{\sum_{i,j} Pclass_{i,j,t}} \qquad \text{(Eq. 6)}$$

where,

i: age group;

j: sex;

Mbase: mean minimum dietary energy requirement per person in the base year;

MER_t: Mean adjustment coefficient of minimum energy requirements per person in year *t*;

MER_{base}: Mean adjustment coefficient of the minimum energy requirements per person in the base year;

$RMER_{i,j}$: Adjustment coefficient for the minimum energy requirements per person of age *i* and sex *j*;

$Pclass_{i,j,t}$: population of age *i* and sex *j* in year *t*.

2.2 Parameterization of modelling approach

Future changes in the inequality of food distribution in a country were considered by changing the coefficient of variation (CV) of the distribution of dietary energy consumption among households within the country along with income growth. When the proportion of the population corresponding to different per-capita dietary energy consumption levels is assumed to be a lognormal function $LN\left(\mu,\sigma^2\right)$ (μ, mean; σ, standard deviation), the *CV* can be estimated as $CV=\sigma/\mu$ (FAO 2008). A higher CV means that the food consumption level varies more widely in the country and food is distributed more unequally. For the same mean consumption, the percentage of the population at risk of hunger would be higher in a country with a high CV. CV is one of the parameters used to calculate the percentage of the population at risk of hunger.

Future change in the CV was assumed based on observed data. A function between CV and income was estimated using nation-level observations for 2005 (FAO 2013) and best fitted coefficient is used for the intermediate scenario of the Shared Socioeconomic Pathways (SSP2). The function was shifted in elastic and inelastic directions of CV against income growth to express the range of the distribution of low-income level (less than US $10,000 per person). These functions were used to change the inequality of food distribution according to future income changes. They correspond to SSP1 and SSP3. CV was not allowed to fall below the lowest observed value of 0.15, 0.2, and 0.27 in SSP1, SSP2 and SSP3 respectively.

2.3 Reporting requirements from IAMs

The three variables listed below are the minimum requirement for future projection of risk of hunger.

1. Population
2. GDP
3. Mean food consumption (kcal per capita, per day)

As is discussed above, to assume CV and minimum energy requirement, we need further detailed information (e.g. demographic disaggregation). However, once each team indicates what SSPs are used for corresponding scenarios, the risk of hunger tool developed by the AIM/CGE model team can generate these assumptions automatically.

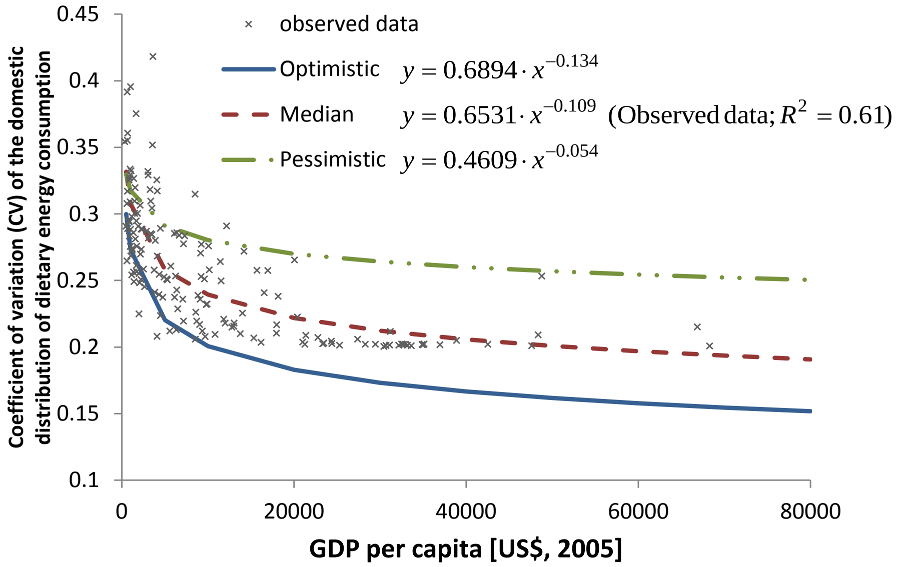

Figure 2: Observed and assumed relationships between income and the equality of food domestic distribution.

Table 1: Adjustment coefficients for the minimum energy requirements per person in different age and sex groups ($RMER_{i,j}$) (average = 1.0)

Age group (years)	Male	Female
0-4	0.46	0.59
5-9	0.75	0.97
10-14	0.97	1.13
15-19	1.02	1.05
20-39	1.00	1.00
40-40	0.95	0.95
50-59	0.90	0.90
60-69	0.80	0.80
70+	0.70	0.70

Note: this table is based on Table 26 in FAO/WHO(1973)

2.4 Illustration of results

The methodology to estimate the number of people at risk of hunger based on the CD-LINKS scenarios has been extensively tested with the AIM/CGE model (Fujimori et al. in preparation). Figure 3 shows preliminary results generated with the methodology described above based on CD-LINKS climate policy scenarios. As shown in the figure, single-minded climate policy that does take into account potential adverse impacts on food security may lead to significant adverse impacts by increasing the number of people at risk of hunger significantly. This increasing risk can be attributed to three different factors:

1. Competition over land between food and bioenergy production that leads to an increase of food prices,
2. increasing food prices due to GHG emission intensity of agricultural production, and
3. a reduction of household incomes due to climate policy which generally increases prices of consumption goods.

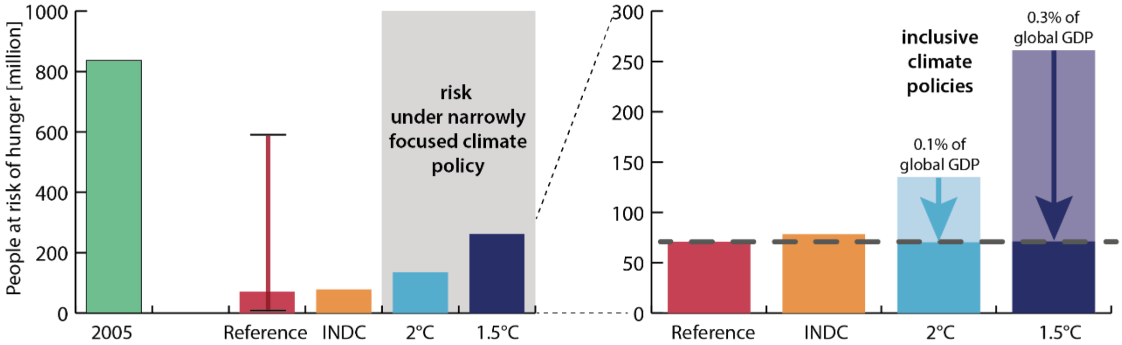

Figure 3: Number of people at risk of hunger in 2050 under different climate policy scenarios analysed with the AIM/CGE model in the CD-LINKS project (preliminary results). On the left panel the 2005 estimate from FAO is shown; the error bar on the Reference scenario indicates uncertainties due to different socio-economic developments based on SSPs is shown. On the right panel, for the 2°C and the 1.5°C scenarios, the costs (as fraction of global GDP) for supplementary policies to reduce the number of people at risk of hunger to the level observed in the Reference scenario have been estimated.

An important finding of this analysis is therefore that inclusive development and climate policies are key to reduce risk of hunger for simultaneous achievement of SDG 2 (hunger) and 13 (climate). Based on this assessment, additional analysis of supplementary (or smart) climate policies has been undertaken with the AIM/CGE model to reduce the adverse impacts of single-minded climate policy highlighted above (Fujimori et al. in preparation).

3. Access to clean energy

Universal access to clean, reliable and modern energy services is one of the three targets underlying SDG #7. Energy access has a strong distributional dimension as typically low income households in rural areas of developing countries (which often lack developed infrastructure to supply clean energy forms such as electricity or LPG) are mostly affected. In the modelling of energy access it is thus important to account for socio-economic and spatial heterogeneity that are key determinants of energy poverty and the reliance on traditional biomass or coal for cooking and heating. The tool used for the assessment of energy access in the CD-LINKS project is the MESSAGE-Access model (Cameron et al. 2016) that includes a representation of these critical factors and that is linked here to scenarios based on different models contributing to CD-LINKS.

3.1 Methodology to estimate people relying on solid cooking fuels

The MESSAGE-Access is an extension of the widely used integrated assessment model MESSAGE. The "Access" model is a separate standalone residential cooking energy choice and demand model that is typically iterated with the MESSAGE integrated assessment model to account for macro-economic price feedbacks. In the model, population heterogeneity in affordability, access and availability of cooking fuels is accounted for by disaggregating households by income and urban/rural residence. This also allows for evaluating the distributional impacts of policies on different segments of the population. Cooking demands, expenditures, and household characteristics in the base year are calibrated using data derived from nationally representative household surveys.

To estimate cooking fuel demand in future years, fuel-specific demand curves are estimated for each household group by regressing the quantity of fuel purchased on the cost to cook with that fuel. Demand curves are estimated applying a best-fit power function that assumes price elasticities are constant. Future fuel prices are determined by iterating the Access model with MESSAGE (see below). Cooking cost in the Access model is determined as a function of not only the fuel price, but also the price of stoves. To incorporate stove costs into the overall cooking cost, stove prices are amortized over the total useful energy delivered, accounting for differences in the efficiencies of different stove-fuel combinations. The stove cost is amortized using an implicit discount rate unique to each household group, which is calculated as a function of household income.

Observed cooking patterns determined from representative household surveys are utilized to also define fuel "tiers", with fuels that are predominantly chosen and used by more affluent household groups assumed to be the most convenient and assigned to the top tier. The defined tiers then determine the sequence in which the estimated demand curves are deployed to estimate cooking energy demand. The demand curve for the most convenient fuel (e.g. gas) that is in the top tier is used first to meet cooking energy demand. If the quantity of top tier fuel that can be afforded at the scenario-specific price is inadequate to meet total cooking energy needs (given income and budget constraints), the next most convenient fuel (e.g. kerosene), assigned to the next tier, is used to fill demand. If after this process, cooking energy demand is still not fully met, the unfulfilled cooking energy demand is assumed to be met by collected firewood, which is included in the lowest fuel "tier".

A full documentation of the model and methods is provided in Cameron et al. (2016). A public version of the model is available at http://data.ene.iiasa.ac.at/MESSAGE-Access/.

3.2 Parameterization of modelling approach

Data to calibrate the model in the base year are derived from analysis of large nationally representative household surveys (in the current version of the case included here, a survey from the year 2004-05 for India is used). A set of .txt files in the constraints, inputs, and settings directories of the public version of the model, include all the input data required to calibrate the model in the base year as well as data on future population and income projections by household group that are used as inputs in the model for future scenario analysis. Future population and income projections are drawn from Global Energy Assessment (Gea 2012) and the Shared Socioeconomic Pathways (SSP) database (IIASA 2012). Projections of Gini coefficients that measure income inequality within nations are from Rao et al. (2016), and downscaling methods are applied from Gidden et al. (forthcoming).

In addition, the file entitled "Example MESSAGE fuel price inputs.RData" provides an example of the price inputs required to run the model. Table 2 below summarizes the key inputs used in the model and the data sources used to derive these.

Table 2: Summary of key input parameters used in the MESSAGE-Access model and the primary data sources for these.

Data	Source
Household sector (rural or urban)	Nationally representative household survey
Household income	
Household weighting factor	
Number of people per household	
Quantity of each fuel used for cooking	
Price of each fuel used for cooking	
Stove prices	Industry Literature, Peer-Reviewed Literature
Stove efficiency	
Stove lifetime	
Current and projected future population	Scenario projections from the SSP database
Current and projected future GDP	
Projected future shadow prices for fuels	MESSAGE and other IAMs

3.3 Reporting requirements from IAMs

Shadow prices for each cooking fuel derived from IAMs are used in the Access model. Generally speaking, fuel prices reported by IAMs reflect marginal costs of producing an additional unit of fuel. These are a proxy for the cost to supply the fuel, but usually do not capture market and distribution costs such as retail profits that determine the market price residential consumers face. To account for these differences, a fixed-margin adjustment is applied to the IAM prices. Given that for optimization-based IAMs such as MESSAGE, the base year calibration typically distorts estimates of prices in the calibrated model periods (e.g., 2005 and 2010), fuel prices reported by models in 2015 or 2020 are used for calculating the adjustment factor. Here, the residential market prices per fuel which are derived from the representative household surveys are compared with the 2015 or 2020 price reported by IAMs for the respective fuel and applied to fuel prices in each subsequent time period. In the case where policy scenarios are also being run, an additional fixed-margin adjustment estimated as the difference between the IAM prices from baseline and policy scenario runs is calculated for 2020 and applied to the 2020 price and price in each subsequent time period.

3.4 Illustration of results

Running the model produces computed fuel consumption for cooking by fuel type and time period for each household group. See for instance Figure 4 below as an example of output from the MESSAGE-Access model.

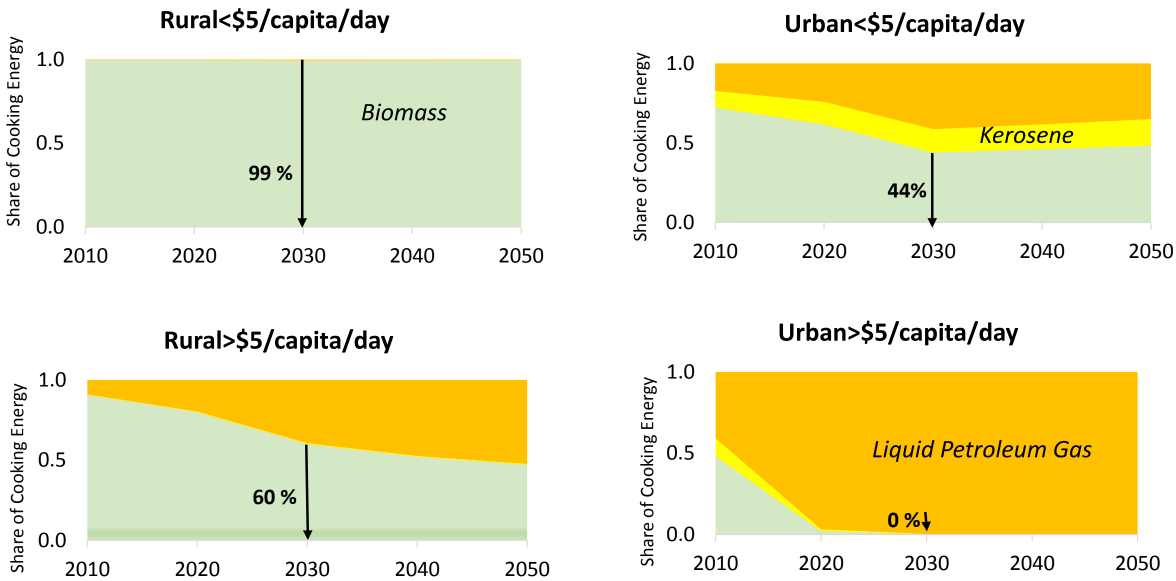

Figure 4: Share of solid biomass in total residential cooking final energy in India between 2010 and 2050 for the Shared Socioeconomic Pathway 2 (SSP2) baseline scenario.

4. Air pollution and health impacts

The main objective of the CD-LINKS WP4 is a comprehensive assessment of the multiple aspects of sustainability within the climate mitigation strategies as modelled by the project participants. Air quality related health impacts are an important concern under SDG #3 on health. In addition, air quality also has environmental impacts such as acidification and eutrophication which can be associated with SDGs #14 and #15 related to life on land and below water, respectively. Finally, air pollutants as so-called short-lived climate forcers also contribute to climate change (SDG #13).

The platform used for the quantification of air pollution and related health impacts, including evaluation of potential synergies and trade-offs within emission scenarios, is the IIASA's GAINS model (Greenhouse gas and Air pollution INteractions and Synergies). GAINS is an integrated policy analysis tool that follows the pathways of atmospheric pollution from driving forces through the key emission sources to the most relevant health and environmental impacts (Amann et al. 2011). Within the CD-LINKS project, the focus is placed on the pollutants that contribute directly or act as precursors of fine particles $PM_{2.5}$ and tropospheric ozone; these include primary particulate matter (predominately fine particles $PM_{2.5}$), secondary PM precursors (SO_2, NO_x, NH_3), and substances contributing to the ozone formation (NO_x and NMVOCs).

4.1 Methodology for quantification of air quality and health impacts and linkage of IAMs to GAINS

4.1.1 Methodology for quantifying air pollutant emissions

In GAINS emissions *E* of the pollutants under examination are calculated as the product of the activity levels *A*, the "uncontrolled" emission factor *ef* in absence of any emission control measures *t*, a factor adjusting for the removal efficiency of emission control measures *reff* and the application rate *x* of such measures across fuels *f* and sectors *s*.

$$E = \sum_{f,s} A_{f,s} ef_{f,s} (1 - reff_t) x_{f,s,t}$$

The penetration of specific control technologies *t* defines a "control strategy", which reflects the level of implementation of emission abatement techniques in order to comply with the legislation and adoption of environmental standards. It is noted that the GAINS database contains information about hundreds of abatement technologies (or measures) in numerous sectors, applicable to a range of activities or energy carriers.

4.1.2 Linkage of IAMs to GAINS

Projections of economic activities of different types – e.g., energy supply and demand, industrial production, transport, agriculture – are exogenous inputs into the GAINS database and constitute a basis for the emission and impact computation. Since the activity data provided by the various CD-LINKS models have in many cases different level of technological detail or geographical resolution than those of GAINS, it is necessary to perform some form of aggregation in order to relate the inputs and GAINS structures to each other.

The energy projections and economic activity pathways are implemented directly in GAINS in order to develop emission scenarios, while conversion of the input data requires the relationships between variables in the reporting templates and GAINS. The data linkage is determined in terms of a) regional structure, and b) activities and sectors. Mapping of equivalent regions provides the consistency in the regional representation in models involved, as well as a downscaling procedure is used to further disaggregate the regional energy balances into the corresponding countries or subregions. The example of mapping the IMAGE to GAINS model regions is provided in

Table 3 below.

Table 3 Mapping of IMAGE and GAINS model regions.

IMAGE 3.0 Country/ Group	GAINS regions
WEU	Austria, Belgium, Cyprus, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Malta, Netherlands, Portugal, Spain, Sweden, United Kingdom, Iceland, Norway, Switzerland
CEU	Bulgaria, Czech Rep, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, Slovenia, Albania, Bosnia and Herzegovina, Croatia, Macedonia, Serbia, Montenegro, Kosovo, Belarus, Moldova
TUR	Turkey
UKR	Ukraine
RUS	Russia European, Russia Asian
STAN	Armenia, Azerbaijan, Geogia, Kazakstan, Kyrgyzstan, Rest of FSU
CAN	Canada
USA	United States
MEX	Mexico
BRA	Brazil
RSAM	Argentina, Chile, Bolivia, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela
RCAM	Carribeans, Rest of Central America
KOR	South Korea (4 subregions)
JAP	Japan (6 subregions)
CHN	China (32 subregions incl. Hong Kong)
INDIA	India (23 subregions)
INDO	Indonesia (4 subregions)
RSAS	Afghanistan, Bangladesh (2 subregions), Bhutan, Mongolia, Nepal, North Korea, Sri Lanka, Pakistan (4 subregions)
SEAS	Brunei, Cambodia, Lao, Malaysia (3 subregions), Myanmar, Philippines (3 subregions), Singapore, Thailand (6 subregions), Taiwan, Vietnam (2 subregions)
OCE	Australia, New Zealand
NAF	Egypt, North Africa
WAF *EAF* *RSAF*	Other Africa
SAF	South Africa
ME	Middle East, Israel, Iran, Saudi Arabia

Mapping between the activity and sector combinations used in the CD-LINKS stocktaking templates and GAINS is shown Table 4. Essentially, this indicates which GAINS activity-sector combinations had to be aggregated in order to translate the input activity levels into the GAINS structure. The resulting ratio between the input-activity and the corresponding aggregated GAINS activity is then used to scale the existing GAINS activities, providing the converted 'input' activity levels for all relevant GAINS activities and sectors (Rafaj et al. 2013):

$$A'_y = A_y \cdot f$$

where

A'_y is the 'input' activity in GAINS structure in year y

A_y is the GAINS activity in year y

and the factor f is taken to be the minimum of:

$$f = \frac{M_y}{G_y}$$

and

$$f = \frac{M_y}{G_y} \cdot \frac{G_{2005}}{M_{2005}}$$

where

M_y is the activity from a given energy model in year y

G_y is the aggregated GAINS activity in the input structure in year y

The scaling algorithm also assures that the resulting energy projections adopted in GAINS correspond to overall primary energy consumption of the main energy carriers as provided by the energy models. The model interface is implemented as a set of database queries that provide a consistent and efficient means of repeating the model linkage whenever required.

Table 4: Mapping of CD-LINKS and GAINS variables. Note: Only major combustible fuels are displayed: brown coal grades 1, 2 (BC1, BC2), hard coal grades 1, 2, 3 (HC1, HC2, HC3), coke (DC), natural gas (GAS), medium distillates (MD), gasoline (GSL), liquefied petroleum gas (LPG), fuel oil (HF), solid biofuels (OS1), wastes (OS2). Detailed definition of the GAINS fuels and sectors is provided at http://gains.iiasa.ac.at.

CD-LINKS sector		CD-LINKS fuel	←	GAINS fuel	GAINS sector				
Final Energy	Residential and Commercial	Biomass	←	OS1 OS2	Residential (DOM_RES)				
		Coal	←	HC1 HC2 HC3 BC1 BC2 DC	Services (DOM_COM)				
		Gases	←	GAS	Domestic others (DOM_OTH)				
		Liquids	←	MD GSL LPG HF					
		Electricity	←	ELE					
		Heat	←	HT					
		Geothermal	←	GTH					
		Solar	←	STH					
Final Energy	Industry	Biomass	←	OS1 OS2	Paper & Pulp (IN_PAP_OC)	Iron & Steel (IN_ISTE_OC)	Chemical industry (IN_CHEM_OC)	Non-Ferrous Metals (IN_NFME_OC)	Other Industry (IN_OTH_OC)
		Coal	←	HC1 HC2 HC3 BC1 BC2 DC	Paper & Pulp Boilers (IN_PAP_BO)	Non-Metalic Minerals (IN_NMM_OC)	Chemical industry boilers (IN_CHEM_BO)	Conversion Sector Boilers (IN_CON_BO)	Other Industry Boilers (IN_OTH_BO)
		Gases	←	GAS					
		Liquids	←	MD GSL LPG HF					
		Electricity	←	ELE					
		Heat	←	HT					
		Other	←	GTH					
		Other	←	STH					
Primary Energy	Input to Power sector incl. CCS	Biomass	←	OS1 OS2	Existing power plants (PP_EX_OTH)	New plants (PP_NEW)	Advanced plants (PP_MOD)	IGCCplants (PP_IGCC)	Engines/DG-sets (PP_ENG)
		Coal	←	HC1 HC2 HC3 BC1 BC2 DC					
		Gas	←	GAS					
		Oil	←	MD GSL LPG HF					
		Nuclear	←	NUC					
		Hydro	←	HYD					
		Geothermal	←	GTH					
		Solar	←	SPV STH					
		Wind	←	WND					
Final energy	Transport	Biomass	←	(included in mineral oil products)	Off-road 2-&4-stroke sources (TRA_OT_LD, TRA_OT_LB)	Off-road machinery and construction (TRA_OT_CNS)	Agriculture (TRA_OT_AGR)	Inland navigation (TRA_OT_INW)	Maritime (TRA_OTS)
		Coal	←	HC1 HC2 HC3 BC1 BC2 DC	Domestic aviation (TRA_OT_AIR)	Rail (TRA_OT_RAI)			
		Gases	←	GAS	Two-wheelers 2-&4-stroke (TRA_RD_LD2, TRA_RD_M4)	Cars (TRA_RD_LD4C)	Light-duty cars (TRA_RD_LD4T)	Buses (TRA_RD_HDB)	Heavy-duty trucks (TRA_RD_HDT)
		Oil	←	MD GSL LPG HF					
		Electricity	←	ELE					
		Hydrogen	←	H2					

Although the data inputs from the energy models provide typically information on the time evolution of the energy sector until 2050, there is a set of emission sources (non-combustion related) not always covered directly by the energy models. Missing information are therefore completed based on scenarios already available in GAINS or are derived from relevant drivers, for example, gross domestic product (GDP) and population projections. In particular, this includes derivation of sector-specific data for transport (vehicle-kilometres, vehicle numbers) and estimation of activities causing process emissions (production of energy-intensive products, agricultural activities, storage and handling of materials, waste treatment, etc.). Projections of activities for the process sector are based on national statistics and reflect assumptions about future changes in production structure of energy-intensive commodities and potential shift from industrialised countries to the developing world.

4.1.3 Evaluation of health impacts

A starting point for the health impact assessment in GAINS is ambient $PM_{2.5}$ concentrations that are calculated on a grid basis from the emissions of PM and precursor gases from all regions. Atmospheric transport and chemistry is represented through linear source receptor coefficients based on sensitivity simulations with atmospheric chemistry transport models (CTMs). Within the CD-LINKS assessment, output of perturbation runs with the European Monitoring and Evaluation Programme (EMEP) global CTM on 0.5∘× 0.5∘ grid is applied for a set of region groups containing Europe, Latin America (Mexico, Brazil, Argentina), East Asia (China, Korea, Japan), India and South-East Asia (Thailand, Indonesia, Vietnam, others), and five source pollutants (NH_3, NO_x, PM, SO_2, NMVOC). Model simulations use gridded emissions from the previous GAINS assessments, and meteorological fields for 2015 (2010 for regions outside Asia). In each of the simulations, emissions of one pollutant are reduced by 15% in one region, and the transfer coefficients are calculated as the linear response from this perturbation. To reflect local concentration gradients related to dispersion of emissions below the 0.5° grid resolution, an urban concentration increment is calculated based on emission densities of primary PM from low level sources for all cities >100,000 inhabitants. The population exposure takes into consideration the evolution of the share of urban versus rural population in the respective regions (Kiesewetter et al. 2016).

As shown by epidemiological studies, exposure to elevated concentrations of $PM_{2.5}$ is associated with an increased probability to die from cardiovascular and pulmonary diseases. We follow here the methodology developed in the framework of the Global Burden of Disease (GBD) studies (Forouzanfar et al. 2015; Lim et al. 2013), which assumes an integrated exposure response curve relating PM exposure to mortality. This approach specifies premature mortality with respect to disease and age, using non-linear disease and age-specific integrated exposure response functions (IERs) developed by Burnett et al. (2015) and further updated recently. At this stage of the project, the health impact computation covers the exposure to the ambient air pollution while the impacts from indoor $PM_{2.5}$ are not quantified.

4.2 Illustration of results

Following the methodology described above, a preliminary set of results is presented in this section in order to illustrate implications of a selected CD-LINKS scenario for the future air pollution exposure and health impacts in China, India and Brazil. The inputs from three national models have been converted into GAINS: TIMES_China, MARKAL_India and MESSAGE_Brazil. The activity projections take into consideration the Intended Nationally Determined Contributions (INDCs) towards climate mitigation and the resulting impacts on the evolution of energy systems in the respective countries. As shown in Figure 5, the current emission levels of $PM_{2.5}$ are dominated by the combustion of solid fuels in all regions. Until 2050, changes in the fuel mix as well the assumed adoption of end-of-pipe measures lead to a stabilisation or declining emissions from the energy sector. On the other hand, a rapid growth in some industrial processes (cement, iron&steel production) might results in an overall emission increase (India – middle panel of Figure 5).

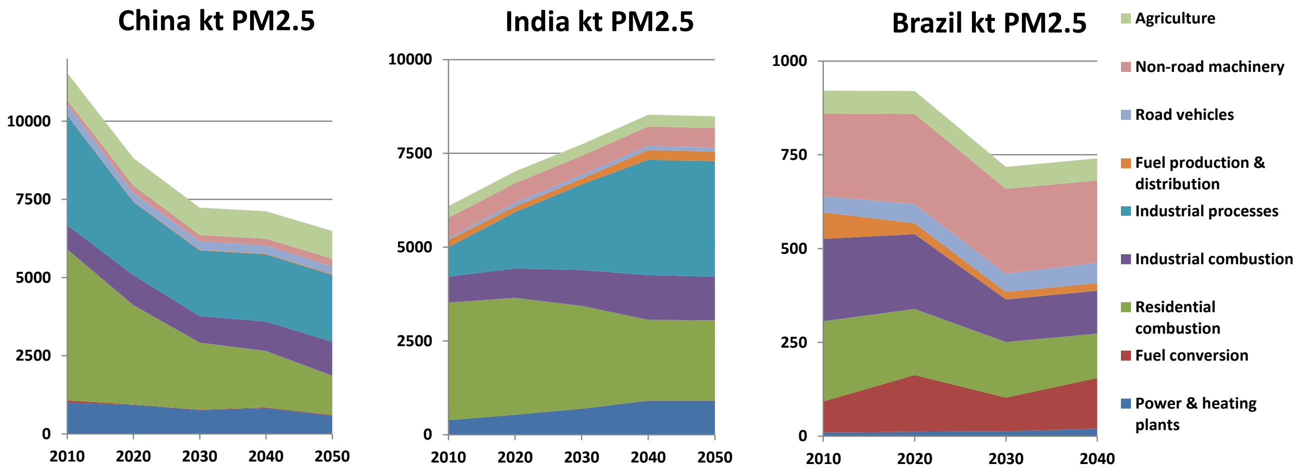

Figure 5: Preliminary projections of $PM_{2.5}$ emissions estimated by GAINS for the CD-LINKS INDC scenario for China, India and Brazil.

For the same scenario, an air quality indicator – the average concentration of fine particles, as well as a number of premature deaths attributable to air pollution, are estimated and summarised in Table 3. Except Brazil, the current and future concentration levels (annual mean) do not attain the World Energy Outlook (WEO) air quality guideline of 10 µg/m^3. An interesting observation can be made in the case of China: in spite of declining emission levels and lower PM concentration in the year 2050 when compared to 2010, the number of premature deaths increases over time. This is explained by the evolution of the population structure, which assumes the growing rate of urbanisation in China (resulting in more people close to the emission sources) and the population ageing (enlarging the share of population more vulnerable to the health impacts of air pollution).

Table 5: Annual mean population weighted concentrations of $PM_{2.5}$ and health impacts due to $PM_{2.5}$ estimated by GAINS for the CD-LINKS INDC scenario for China, India and Brazil.

	Average concentration (µgPM2.5/m3)		
	2010	*2050*	*change*
China	43	37	-20%
India	42	70	+65%
Brazil	10	9	-10%
	Premature deaths (thousands)		
	2010	*2050*	*change*
China	864	1568	+80%
India	480	1135	+140%
Brazil	25	40	+65%

5. Lifecycle assessment impacts of electricity generation

The main objective of the CD-LINKS WP4 is a comprehensive assessment of the multiple aspects of sustainability within the climate mitigation strategies as modelled by the project participants. To quantify environmental co-benefits and adverse side-effects of the power sector decarbonization, we build on earlier work on the integration of lifecycle assessment methodologies within IAMs developed during the ADVANCE project[1]. This approach focuses on so-called midpoint impact indicators (Goedkoop et al. 2009) not covered by the other methods employed in CD-LINKS, such as land occupation (of energy technologies excluding bioenergy supply), eutrophication, mineral resource depletion, release of ionizing radiation, human toxicity and ecotoxicity. These indicators relate to a number of SDGs, including SDG #14 and #15 on life on land and life below water, SDG #3 on good health and well-being and SDG #6 on water.

5.1 Methodology for assessing life cycle impacts of energy technology deployment

The integration of life cycle assessment (LCA) methods into integrated energy scenarios in a forward-looking framework allows to explore the role of embodied energy demand, indirect emissions and a diverse set of environmental impacts of the energy transformation sector in the coming decades.

In this analysis, the CD-LINKS consortium relies on tool development as part of the FP7 project ADVANCE[2]. Through collaborative research between IAM teams and LCA researchers, a dataset of embodied energy use for the electricity sector, breaking down energy demand by energy carrier, energy service/material demand and electricity technology across regions and future time steps, was developed.

5.2 Parameterization of modelling approach

The life-cycle impact coefficients used for this method were derived from the integrated Life-Cycle-Assessment-Model THEMIS. THEMIS was originally introduced in (Gibon et al. 2015; Hertwich et al. 2015). The THEMIS version used for the life-cycle impact coefficients is documented in Arvesen et al. (submitted). THEMIS integrates process-detailed life-cycle assessment data (largely based on the Ecoinvent database (Ecoinvent 2010; Frischknecht et al. 2000)) and multi-regional input-output tables (EXIOBASE) with forecasts of future changes in the technology performances (e.g., solar photovoltaic panels) or upstream processes (e.g., steel manufacturing). This approach allows establishing consistent, prospective life-cycle inventories of all major power sector technologies. Beyond the technologies assessed in Hertwich et al. (2015), the dataset used here also includes nuclear power (Dones et al. 2000; Ecoinvent 2010) and biomass-based power generation. Two types of biomass feedstocks are modelled. While boreal forest residues are represented based on Singh et al. (2014), life-cycle inventories of purpose-grown lingo-cellulosic biomass was informed from a set of scenarios produced with the global landuse model MAgPIE (Bodirsky et al. 2012; Klein et al. 2014; Lotze-Campen et al. 2008; Popp et al. 2014), as described in Arvesen et al. (submitted).

In accordance with common practice in life-cycle assessment, life-cycle inventory data (i.e., substance flows such as life-cycle copper requirements, emissions of specific chemicals, etc.) are translated to environmental impacts using linear coefficients, so-called characterization factors. The characterization factors used here are based on the well-established ReCiPe methodology in its updated version 1.08 (Goedkoop et al. 2014; Goedkoop et al. 2009). Some environmental impacts occur during construction of power generation capacities, while others are others are related to operation of power systems or their end-of-life (decommissioning). The relative importance of these stages differs across power technologies and environmental impact categories. To adequately reflect the timing of impacts incurred the life-cycle impact coefficients are broken down by these three phases. This approach also allows accounting for power plant operation (i.e., deployment in terms of electricity produced per unit of nameplate capacity) evaluating scenarios of the future.

[1] http://www.fp7-advance.eu
[2] http://www.fp7-advance.eu/content/environmental-impacts-module

Table 6 Impact indicators

List of environmental impact indicators considered
Human toxicity
Ionizing radiation
Freshwater ecotoxicity
Marine ecotoxicity
Land occupation
Freshwater eutrophication
Marine eutrophication
Mineral resource depletion

Table 7 Power technologies

List of environmental impact indicators considered
Coal without and with carbon capture and storage (CCS)
Gas without and with carbon capture and storage (CCS)
Biomass without and with carbon capture and storage (CCS)
Hydropower
Nuclear Power
Solar photovoltaics (PV)
Concentrating solar power (CSP)
Wind power

5.3 Reporting requirements from IAMs

In order to calculate midpoint impacts per year, LCA midpoint coefficients are linked to IAM scenario data via the determining quantities (e.g., capacity additions of power plants, generation of electricity). Specific impacts from the "Construction" and "End-of-life" phases (per MW) are added up (since end-of-live impacts are typically minor in comparison, the error of shifting them to the beginning of capacity lifetime is quite small) and multiplied by the amount of new capacity additions (in MW), yielding absolute impacts for a given year. Specific impacts from the "Operation" phase are likewise multiplied either by installed capacity (in MW) or electricity generation (in GJ) of the given year. As wind, concentrating solar power and solar photovoltaics do not use any bulk materials (such as coal or oil) during the "Operation" phase, their impacts depend mainly on the maintenance of present installations. Consequently, absolute impacts are calculated by multiplying per-MW coefficients with installed capacity. Coal, gas, biomass and nuclear power generation depend on the transport and use of large quantities of fuel, ash and other materials, or technically sophisticated nuclear fuel cycles. Therefore absolute impacts are calculated based on per-GJ coefficients and power generation in a given year. The LCA coefficients for the "Operation" phase of hydropower are set to zero. Table 9 gives an overview of the reported IAM variables that are used for computing impacts from lifecycle phases.

Table 8: Reported IAM variables and units used to calculate lifecycle impacts

Reported Variable	Unit	Calculated Lifecycle Impacts
Capacity Additions|Electricity|Coal|w/o CCS	GW/yr	Construction and End-of-Life
Capacity Additions|Electricity|Coal|w/ CCS	GW/yr	Construction and End-of-Life
Capacity Additions|Electricity|Gas|w/o CCS	GW/yr	Construction and End-of-Life
Capacity Additions|Electricity|Gas|w/ CCS	GW/yr	Construction and End-of-Life
Capacity Additions|Electricity|Biomass|w/o CCS	GW/yr	Construction and End-of-Life
Capacity Additions|Electricity|Biomass|w/ CCS	GW/yr	Construction and End-of-Life
Capacity Additions|Electricity|Hydro	GW/yr	Construction and End-of-Life
Capacity Additions|Electricity|Nuclear	GW/yr	Construction and End-of-Life
Capacity Additions|Electricity|Wind|Onshore	GW/yr	Construction and End-of-Life
Capacity Additions|Electricity|Wind|Offshore	GW/yr	Construction and End-of-Life
Capacity Additions|Electricity|Solar|CSP	GW/yr	Construction and End-of-Life
Capacity Additions|Electricity|Solar|PV	GW/yr	Construction and End-of-Life
Secondary Energy|Electricity|Coal|w/o CCS	EJ/yr	Operation
Secondary Energy|Electricity|Coal|w/ CCS	EJ/yr	Operation
Secondary Energy|Electricity|Gas|w/o CCS	EJ/yr	Operation
Secondary Energy|Electricity|Gas|w/ CCS	EJ/yr	Operation
Secondary Energy|Electricity|Biomass|w/o CCS	EJ/yr	Operation
Secondary Energy|Electricity|Biomass|w/ CCS	EJ/yr	Operation
Secondary Energy|Electricity|Nuclear	EJ/yr	Operation
Capacity|Electricity|Wind|Onshore	GW	Operation

Capacity|Electricity|Wind|Offshore	GW	Operation
Capacity|Electricity|Solar|CSP	GW	Operation
Capacity|Electricity|Solar|PV	GW	Operation

The LCA impact coefficients are differentiated by scenario based on the IEA scenarios from the "Energy Technology Perspectives 2010: Scenarios & Strategies to 2050 "Baseline" and "BLUE Map" scenarios (IEA 2010), indicating either general or strong improvements in material and energy intensity of industrial processes, and region. These are matched to the IAM scenarios and regions on a simple one-to-one basis. The "BLUE Map" scenario coefficients are used for all scenarios with stringent climate change mitigation policies, whereas the "Baseline" scenario coefficients are used for IAM scenarios with no or insufficient mitigation efforts (including NDC scenarios). IAM regions are simply matched to the THEMIS (IEA) region with the best regional fit, as exemplified for two IAM models in Table 9.

Table 9: Exemplary matching between THEMIS and IAM regions.

THEMIS	REMIND 1.7	MESSAGE-GLOBIOM 1.0
AME	AFR	AFR
AME	MEA	MEA
AS	OAS	PAS
CN	CHN	CPA
EIT	RUS	EEU
EIT	—	FSU
IN	IND	SAS
LA	LAM	LAM
PAC	JPN	PAO
PAC	ROW	—
RER	EUR	WEU
US	USA	NAM

Since the LCA midpoint coefficients are available only for the years 2010, 2030 and 2050, they are interpolated linearly in between and kept constant before and afterwards. This assumes no further improvements in material and energy efficiency after 2050 and therefore may tend to overestimate impacts from that point on.

The tool for calculating LCA-based impacts of deploying and operating electricity generation technologies that was developed as part of the ADVANCE project is written in R[3], a language for statistical computing and visualization and for the purpose of CD-LINKS was connected to the scenario database system that processes all scenario results. Technically speaking, the R-code was

[3] http://www.r-project.org

implemented as a web service is called from the Java backend of the scenarios database system once a new scenario is submitted. This integration with the scenario database infrastructure allows automatically running the LCA once a new scenario is submitted and thus streamlines the application of the newly developed methodology. The results of the LCA are then added to the scenario database to enable researchers to easily include this dimension into their assessment of multiple sustainable development objectives of the transformation scenarios developed in the CD-LINKS project.

5.4 Illustration of results

In the ADVANCE context, the integration of IAM scenario data has been applied to (i) estimate indirect energy requirements and greenhouse gas emissions from power supply (Pehl et al. submitted), and (ii) to analyse how the sector's environmental co-benefits and adverse side-effects depend on technology choice in decarbonization pathways (Luderer et al. in preparation). As an illustrative example, Figure 6 shows human toxicity impacts calculated for the three models GCAM, IMAGE and REMIND in baseline (no climate policy) and policy (2°C-consistent decarbonization) scenarios.

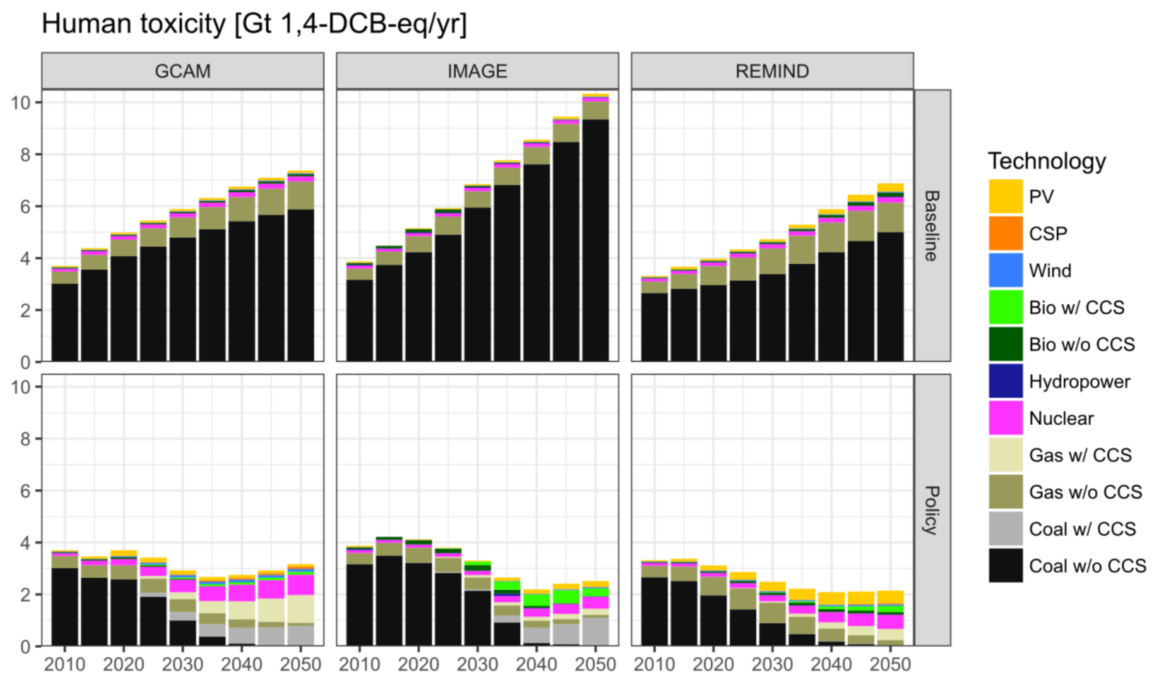

Figure 6: Emissions toxic to humans from the power sector across two scenarios without and with climate protection policy and based on results from three IAMs.

6. Automated variable reporting

In order to improve efficiency of comparing and synthesising results from multiple models, for example as part of model intercomparison projects, the IAM community several years ago has established a process to standardize data reporting templates. Through this process which is coordinated by the Integrated Assessment Modeling Consortium (IAMC), the overhead of collecting information has been greatly reduced and many of global IAM teams have developed automated reporting algorithms that significantly lower the burden of data processing when participating in model intercomparisons. However, many national modelling like those that are contributing to the CD-LINKS project have not been participating in such activities in the past and therefore lack automated algorithm for data processing and submission. This, on the one hand increases the effort for submitting additional scenarios and variables and therefore takes time away from working on the scenarios itself, and on the other hand also increases the risk of introducing errors when submitting a new scenario. Given the multiple sustainable development dimensions that are modelled and analysed in WP4, the number of reporting variables in CD-LINKs is higher than in other projects that compare scenario results across different models which provides an additional incentive for investing into automated data reporting (see the Annex, Section 9, for the full CD-LINKS data template).

Figure 7 below provides an overview of the technical model specifications for input data handling, model implementation and post-processing of global and national IAMs used in the CD-LINKS consortium. This compilation allows modelling teams in CD-LINKS that do not have automated reporting algorithms in place to identify other teams that utilize similar reporting infrastructure and thus able to provide support.

Model	Input data		Implementation		Model results	IAMC reporting
GCAM ★	R	data translated to xml tables	C++		basex (db)	via xml queries to csv, then using R
WITCH ★	txt/xls, gdx	using R to write gdx	GAMS		gdx	post-processing in GAMS, then using R to write csv
IMAGE ★	txt/xls		MyM		txt/xls	extract data using "mapping" Excel table
REMIND ★	R		GAMS	using readgdx	R	use open-source class "magclass"
MESSAGE ★	txt		mxg	using Java via MS Excel	ORACLE (db)	Java/SQL db2db transfer
DNE21+	MS Access		C++/GUROBI		txt, xls	
TIMES-Russia	R		GAMS		R, xls	
MARKAL-India	xls		GAMS		xls	no automation yet
IPAC-AIM	MS Access		GAMS		MS Access	
TIMES-China	xls		GAMS		xls	extract data using "mapping" Excel table

★ Explicit use of version control system (Git, Github, Tortoise, SVN, etc.)

Figure 7: Stocktaking of technical model specifications for input data handling, model implementation and post-processing for models used by the CD-LINKS consortium.

To go beyond an informal exchange of information among modelling teams within CD-LINKS and to acknowledge the fact that automated data reporting is relevant also in many other model intercomparisons projects, a shared resource was created by means of a GitHub repository[4]. This publically accessible repository provides a number of template workflows and illustrative examples to automate the processing of model results to the standardized Microsoft Excel results template used by the Integrated Assessment Modeling Consortium (IAMC). The aim is to provide best-practice code snippets for output data processing to the modelling community, to make the reporting less error-prone and more efficient and thus allow more time to be spent on developing models and analysing the results. Given that other model intercomparison projects face similar challenges as CD-LINKS when it comes to ensuring high quality data collection, the CD-LINKS consortium partnered with the IAMC to make this repository useful to the wider IAM research community.

[4] https://github.com/IAMconsortium/reporting_workflows

7. Summary and conclusions

The integrated analysis of a broad portfolio of sustainable development objectives – as opposed to focussing on climate change mitigation in isolation – is important for informing the policy process, given that decision-making regularly involves balancing multiple objectives in a wide range of areas. At the political level, the United Nations' Sustainable Development Goals (SDGs) have been adopted as a framework to make progress in these multiple dimensions.

As an important step towards enabling such analysis, on the one hand, the CD-LINKS consortium applies a range of national and global Integrated Assessment Models (IAMs) that have different capabilities in terms of being able to contribute to the analysis of interactions between climate change and non-climate related SDGs. On the other hand, by linking these tools and transferring the methodology applied by one model to other models, the scope of the SDG assessment is broadened. Therefore, the results from the range of models applied and linked in CD-LINKS are combined in order to arrive at an as broad assessment of SDG linkages as possible.

The main sustainable development dimensions in which model development took place as well as the rationale to do so are listed below.

i. Food security
Different indicators related to food security, including food price indices and the change in average caloric intake of different populations can be directly derived from IAMs that include a representation of the agricultural sector. More directly speaking to the SDGs is the population at risk of hunger which cannot be provided by all IAMs represented in the CD-LINKS project. A method was established that allows deriving the *number of people at risk of hunger* based on output that IAMs with a representation of land use and in particular agriculture can generate.

ii. Access to clean energy
An indicator related to affordability of clean energy forms that can be produced by IAMs are consumer level (final energy) prices of energy. However, the impact of energy price changes on the affordability of different energy forms also depends on income level of different households which is not represented in most IAMs. The MESSAGE-Access model, a standalone residential cooking energy choice and demand fuel choice model, is used for quantifying the population relying on solid cooking fuels. In the model, population heterogeneity in affordability, access and availability of cooking fuels is accounted for by disaggregating households by income and urban/rural residence. This allows evaluating the distributional impacts of using solid cooking fuels and climate and other policies on different segments of the population.

iii. Air pollution and related health impacts
While all IAMs are capable of tracking energy use in different energy conversion processes, only some IAMs also generate consistent air pollutant emissions and even fewer are able to translate these into health implications. The GAINS model, an integrated policy analysis tool that follows the pathways of atmospheric pollution from driving forces through the key emission sources to the most relevant health and environmental impacts, is used for the quantification of air pollution and related health impacts. In CD-LINKS, the drivers of pollutant emissions are derived from the scenarios by the national and global IAMs. The focus is placed on the pollutants that contribute directly or act as precursors of fine particles $PM_{2.5}$ and tropospheric ozone; these include primary particulate matter (predominately fine particles $PM_{2.5}$), secondary PM precursors (SO_2, NO_x, NH_3), and substances contributing to the ozone formation (NO_x and NMVOCs).

iv. Lifecycle assessment (LCA) impacts of electricity generation:
The transformation of the electricity generation sector is well characterized in IAMs, but the evaluation of environmental impacts is typically limited to emissions of different types and in some cases water. By contrast, LCA takes a much broader set of environmental impacts into account. To broaden the scope of quantifying environmental co-benefits and adverse side-effects of the power sector decarbonization, so-called LCA midpoint impact indicators (not covered by the other methods employed in CD-LINKS) are used in CD-LINKS by linking the information on structural changes (in terms of new construction, operation, and decommissioning of power plants) from IAM scenarios to LCA indicators. This includes land occupation (of energy technologies excluding bioenergy supply), eutrophication, mineral resource depletion, release of ionizing radiation, human toxicity and ecotoxicity.

These model developments allow the quantification of indicators related to several SDGs. More specifically, the indicators derived from the model development described in this document can speak to SDGs #2 (zero hunger), #3 (good health and weel-being), #6 (clean water and sanitation), #7 (affordable and clean energy), #13 (climate change), #14 (life on land) and #15 (life below water).

The benefits of this model development will be used for assessing the implications of possible climate policies at the national and global scale along various sustainable development dimensions. A scenario set that explores global and national scenarios that follow implemented (and planned) policies through 2020 or implement the Intended Nationally Determined Contributions (INDCs) goals submitted by countries to the United Nations Framework Climate Change Convention (UNFCCC) under the Paris agreement and thereafter transition to emissions budgets that are consistent with the 2 and 1.5° C targets, is currently under development within CD-LINKS. The goal is therefore to explore the implications of short-term climate action, and in particular the "ratcheting up" of the ambition level embedded in the INDCs, for the achievability of the long-term temperature targets agreed upon in Paris. Within this set of scenarios, the development of non-climate sustainability objectives will be tracked as a consequence of climate policy with the idea to identify conditions under which synergies or trade-offs between climate change mitigation and other objectives may materialize.

In addition, given that covering multiple sustainable development dimensions in parallel has tremendously expanded the requirements of the model reporting, the CD-LINKS project has undertaken a capacity building initiave on automated model result reporting to assisst modeling teams that have not yet build up such an automated mechanism in doing so. Here, CD-LINKS has partnered with the Integrated Assessment Modeling Consortium (IAMC) to make the resources developed for automated model reporting available to the wider IAM modeling community.

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9. Annex

The complete data reporting template used in CD-LINKS, including all standard as well as sustainable development related variables and their definitions, can be obtained via the following web-link http://db1.ene.iiasa.ac.at/CDLINKSstocktakingDB/dsd?Action=htmlpage&page=about.

Additional documentation on the IAMC data template is available at http://data.ene.iiasa.ac.at/database/.