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A methodology and implementation of automated emissions harmonization for use in Integrated Assessment Models

Matthew J. Gidden [a, *], Shinichiro Fujimori [b], Maarten van den Berg [c], David Klein [d], Steven J. Smith [e], Detlef P. van Vuuren [c], Keywan Riahi [a]

[a] International Institute for Applied Systems Analysis, Schlossplatz 1, A-2361 Laxenburg, Austria
[b] Center for Social and Environmental Systems Research, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan
[c] PBL Netherlands Environmental Assessment Agency, Postbus 30314, 2500 GH The Hague, The Netherlands
[d] Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, P.O. Box 60 12 03, D-14412 Potsdam, Germany
[e] Joint Global Change Research Institute, 5825 University Research Court, Suite 3500, College Park, MD 20740, USA

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A B S T R A C T

Emissions harmonization refers to the process used to match greenhouse gas (GHG) and air pollutant results from Integrated Assessment Models (IAMs) against a common source of historical emissions. To date, harmonization has been performed separately by individual modeling teams. For the hand-over of emission data for the Shared Socioeconomic Pathways (SSPs) to climate model groups, a new automated approach based on commonly agreed upon algorithms was developed. This work describes the novel methodology for determining such harmonization methods and an open-source Python software library implementing the methodology. A case study is presented for two example scenarios (with and without climate policy cases) using the IAM MESSAGE-GLOBIOM that satisfactorily harmonize over 96% of the total emissions trajectories while having a negligible effect on key long-term climate indicators. This new capability enhances the comparability across different models, increases transparency and robustness of results, and allows other teams to easily participate in intercomparison exercises by using the same, openly available harmonization mechanism.

Software availability

`aneris`, first made available in 2017, is available online at https://github.com/iiasa/aneris as a free and open-source Python software library (approximately 2000 lines of code). The `aneris` software was developed by the lead author whose contact information is shown on the title page of this manuscript. Documentation for the `aneris` Python package, including software requirements, is available online at http://software.ene.iiasa.ac.at/aneris/.

1. Introduction

Integrated Assessment Models (IAMs) are tools used to understand the complex interactions between energy, economy, land use, water, and climate systems. IAMs provide global projections of systemic change by dividing the world into a number of representative regions (typically 10 to 30), the definition of which is distinct for each model (Krey, 2014). Results from IAMs are integral in a number of international studies, which notably include projections of climate and energy futures. Recently, the IAM community has developed scenarios based on the Shared Socioeconomic Pathways (SSPs) (Riahi et al., 2017) which quantify a variety of potential global futures. The SSPs are designed to be used in research that include Earth System Model (ESM) simulations, climate impact, adaptation and climate mitigation studies (ONeill et al., 2013; Vuuren et al., 2013).

While IAMs are implemented in myriad ways,[1] including simulation and optimization, the core inputs and outputs are

* Corresponding author.
E-mail address: gidden@iiasa.ac.at (M.J. Gidden).

[1] IAM models are numerous and have a long history in the scientific literature. Various IAMs have collaborated to produce community IAM documentation (available online: http://themasites.pbl.nl/models/advance/index.php/ADVANCE_wiki) which readers can access for a full treatment of model implementation and features.

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similar across different models. Modeling teams incorporate data on energy systems, land use, economics, demographics and emissions sources and concentrations, among other data, in order to provide a consistent starting point for future projections. The models then provide estimates of future trajectories of these variables under various socio-economic and technological assumptions as well as proposed policy constraints, e.g., targets for future Greenhouse Gas (GHG) emissions.

The emissions trajectories calculated by IAMs are critical inputs for ongoing, worldwide scientific community efforts in the Coupled Model Intercomparison (Eyring et al., 2016), which is utilizing a number of marker SSP scenarios developed by the IAM community (Scenario Model Intercomparison Project (ScenarioMIP) (O'Neill et al., 2016), Aerosol Chemistry Model Intercomparison Project(-AerChemMIP) (Collins et al., 2017), among others). These trajectories are endogenously calculated by modeling the individual technologies and sectors that contribute towards the emissions of different air pollutants and GHGs as well as various mitigation technologies. However, the historical emissions starting points of models can differ by large amounts depending on the region, sector, and emissions species.

In practice, IAMs calculate the total source intensity of emitting technologies, for example the total activity of coal power plants in China, and incorporate emissions-intensity factors for individual gas species, for example the quantity of sulfur emissions from coal plants per megawatt-hour of production. Models are generally *calibrated* to historical data sources in one or more base years. Results in the historical period may differ between models as a result of the sometimes large uncertainties in historical data sets. Models can also differ in their choice of base-year, which may lag behind available inventory data. In addition, models have varying sectoral, regional, and fuel aggregations.

The global climate change community has recently developed a new global historical emissions data set for both anthropogenic emissions (i.e., the Community Emissions Data System (CEDS) (Hoesly et al., 2018) and open-burning Land-use and Land-use Change (LULUC) emissions (van Marle et al., 2017)) which, in conjunction with the SSP IAM trajectories, will be used for climate-related modeling exercises of CMIP6.

When participating in intercomparison exercises in which a consistent historical starting point is required (e.g., in CMIP6), model teams incorporate a single, common historical data set through *harmonization*. Harmonization refers to the process of adjusting model results to match a selected historical time series such that the resulting future trajectories are consistent with the original modeled results and provide a smooth transition from the common historical data. In the emissions context, this means that each individual combination of model region, model sector, and emissions species must be harmonized. Depending on the total number of model regions, sectors, and emissions species, this can require the selection of thousands to tens-of-thousands of harmonization methods.

Harmonization has been addressed in previous studies as it is a common practice in the IAM and climate change communities. For example (Meinshausen et al., 2011a), describes the use of scaling routines for the 5 regions used in the IPCC Special Report on Emissions Scenarios (SRES) (Nakićenović et al., 2000); however, only total emissions were harmonized in the exercise, thus there is no sectoral dimension. Further (Rogelj et al., 2011), describes the impacts of choosing various harmonization routines on future trajectories. During the evaluation of the Representative Concentration Pathways (RCPs), IAM results have been harmonized by sector and the 5 RCP global regions (Vuuren et al., 2011). Importantly, the choice of harmonization method to date has been determined by individual experts and has generally been applied to all trajectories for a given class of emissions species.

Climate modeling efforts have continued to progress, demanding increased spatial and sectoral resolution from IAMs. Furthermore, a new generation of climate scenarios which combines aspects of both the RCPs and SSPs have been developed in order to incorporate both physical and socio-economic detail. In order to address the growing dimensionality of model outputs and support ongoing scenario generation and analysis efforts while still providing a consistent and scientifically rigorous harmonization procedure, an automated process for determining harmonization methods is preferred. The use of an automated, documented, and openly available harmonization mechanism additionally allows for full procedural reproducibility and for direct participation by additional modeling teams not involved in the original exercise.

The remainder of this paper describes the methodology and implementation of the harmonization software `aneris` (Gidden, 2017), written in the Python programming language (detailed documentation is available online at http://software.ene.iiasa.ac.at/aneris/). Section 2 provides a detailed description of the underlying mathematical components of `aneris` as well as the procedural workflow. A case study of applying the automated harmonization mechanism on two example IAM scenarios, one with emissions growth and another with emissions mitigation, is presented in Section 3. Finally, the general effectiveness and potential future improvements on the automated methodology is discussed in Section 4.

2. Methodology & implementation

2.1. The conceptual basis for choosing harmonization methods

The goals of any scenario harmonization exercise are threefold: aligning model results in the harmonization year to a common historical data source, faithfully representing the original IAMs internal consistency between the driver of emissions (e.g. energy use) and emissions, and maintaining critical parameters from the original scenario design. Any harmonization method achieves the first goal by design. If the difference between the model base year and historical values are small, considering the second and third goals leads to a method choice that matches modeled drivers (e.g., a `ratio` method discussed in Section 2.2) and converges prior to the final model year. It preserves the relationship between IAM output and emissions inventory in the base year while also matching the original model output at some point in the modeled time period. It furthermore maintains the consistency of the model's usage of energy technology, volume of agricultural activities, and abatement options with harmonized emissions trajectory.

However, other concerns may lead to a better-informed choice than using a blanket method for all emissions trajectories. For example, emissions from LULUC are known to have high year-to-year variation, and therefore historical data may change drastically depending on the base year considered. In such a situation, a method that converges at a year past the modeled time period is a better choice in order to smooth out discrepancies between the historical data used to develop model and the new data source being used for harmonization.

Separately, if there are large discrepancies between the model results in the base year and the historic data used for harmonization, convergence methods can result in harmonized trajectories that do not faithfully represent the underlying drivers of emissions. Furthermore, if models report negative emissions, as is possible in scenarios designed to depict the deployment of climate mitigation policies with large CO_2 reductions and storage, then end-of-century emissions characteristics should be considered in order to faithfully match the design parameters of the original scenarios, such as