Empirical CO$_2$ Emission Projections Point to the Likelihood of a High-Warming Future: A Decomposition Approach to Assessing the SSPs and RCPs

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2015 PIAMDDI Workshop
Motivation

- IAMs are the principal tool for constructing projections of future economic activity, energy use, GHG emissions and the costs of their abatement at global and regional scales.

- To do this, IAMs rely on assumptions about the future trajectories of exogenous variables, and for this reason scenario development has always been at the core of integrated assessment modeling.

- Recent research has seen scenario development in the form of the representative concentration pathways (RCPs) and shared socioeconomic pathways (SSPs).

- A key feature of these scenarios is that their development follows a process of storylines which articulate different future states of the world. However, a key limitation of this approach is the complete absence of information about the likelihood of these alternative futures, which complicates our ability to analyze either their plausibility or quantify in precise terms the changes in the trajectories of emission precursors that are necessary for the world to end up in these states.

- Question we address here is: If the next 40 years are like the prior 40 years, how plausible are the combinations of RCPs and SSPs currently simulated by IAMs?

- Corollary: What characteristics of the long-run interrelationships among the drivers of CO₂ emissions would need to change to enable the future to be consistent with different RCPs/SSPs?
Decomposition Analysis

A target variable $q$, is a function of explanatory variables, $x$ and $y$, that evolve in time ($t$):

$$q_t = h[x_t, y_t]$$

We attribute the change in $q$ over some horizon $t = [0, T]$ to changes in its drivers through index number decomposition

1. Express the instantaneous growth of the target variable as the sum of components, each corresponding to the weighted growth rate of the individual drivers:

$$\frac{d \log q}{dt} = \frac{1}{u} \frac{du}{dt} = \frac{\partial h}{\partial x} \cdot \frac{1}{x} \frac{dx}{dt} + \frac{\partial h}{\partial y} \cdot \frac{1}{y} \frac{dy}{dt} = w^x_t \frac{d \log x}{dt} + w^y_t \frac{d \log y}{dt} = z^x_t + z^y_t$$

Data are generally recorded at discrete time intervals (e.g., annually). We implement the continuous log differential using the centered difference approximation

$$\hat{v}_t \approx \frac{d \log v}{dt} \approx 2 \frac{v_t - v_{t-1}}{v_t + v_{t-1}}$$

2. Express each component’s cumulative effect as a chained index, using our approximation

$$Z^v_0 = 1, \quad Z^v_t = \prod_{\tau=0}^{t} \frac{2 + z^v_{\tau}}{2 - z^v_{\tau}} \quad (2)$$
Decomposing Historical Fossil Fuel CO$_2$ Emissions

Our analysis begins with an extension of the Kaya Identity. Emissions are the product of 5 drivers: the CO$_2$ intensity of sectoral energy use ($\xi$), the sectoral final energy intensity of output ($\phi$), the sectoral composition of GDP ($\theta$), GDP per person ($I$), and population.

We use statistics on aggregate CO$_2$ ($C$), GDP ($Y$) and population ($N$) for $r = 106$ countries over $t = 39$ years overing 80% of global emissions, and data on emissions ($c$), final energy consumption ($e$) and value added ($y$) in $j$ sectors within these countries:

$$C_t = \sum_r C_{r,t} = \sum_r \left\{ \sum_j \left( \frac{c_{j,r,t}}{e_{j,r,t}} \times \frac{e_{j,r,t}}{y_{j,r,t}} \times \frac{y_{j,r,t}}{Y_{r,t}} \times \frac{Y_{r,t}}{N_{r,t}} \times N_{r,t} \right) \right\}$$

Using (1) we perform decomposition at two levels, individual countries

$$C_{r,t} = \sum_j \lambda^\Xi_{j,r,t} \hat{\xi}_{j,r,t} + \sum_j \lambda^\Phi_{j,r,t} \hat{\phi}_{j,r,t} + \sum_j \lambda^\Theta_{j,r,t} \hat{\theta}_{j,r,t} + \lambda^I_{r,t} \hat{I}_{r,t} + \lambda^N_{r,t} \hat{N}_{r,t}$$

and regions or the world

$$C_t = \sum_r \sum_j \omega^\Xi_{j,r,t} \hat{\xi}_{j,r,t} + \sum_r \sum_j \omega^\Phi_{j,r,t} \hat{\phi}_{j,r,t} + \sum_r \sum_j \omega^\Theta_{j,r,t} \hat{\theta}_{j,r,t} + \sum_r \omega^I_{r,t} \hat{I}_{r,t} + \sum_r \omega^N_{r,t} \hat{N}_{r,t}$$

and express the results as chained country and regional index numbers using (2).
Future Projections of Decomposed Factors

Estimation
Over the period of our sample (1972-2010), each of the driving forces is related to its own past values, past values of the other drivers, as well as exogenous time-varying factors which may or may not be observed. Moreover, the web of interrelationships will likely be unique in each country.

To capture this heterogeneity we statistically model the historical time-evolution of the drivers by estimating a vector autoregression (VAR) on our chained index numbers at the country level. Stacking the index numbers derived from (4), \( Z_{r,t} = \text{vec} \left[ Z^\Xi_{r,t}, Z^\Phi_{r,t}, Z^\Theta_{r,t}, Z^I_{r,t}, Z^N_{r,t} \right] \), we estimate the following VAR in levels

\[
\log Z_{r,t} = A_r + \sum_\ell B_{\ell,r} \log Z_{r,t-\ell} + G_{r,t} + u_{r,t} \tag{6}
\]

Lag lengths \( \ell \) are selected to achieve eigenvalue stability of the system. All the action is in the \( 106 \times \ell \) matrices of coefficients \( B_{\ell,r} \), which provide a parsimonious, self-contained representation of the drivers of CO\(_2\) emissions growth at the country level.

Projection
Assuming that the interrelationships \( B_{\ell,r} \) reflects \( r \)'s stable long-run economic equilibrium, we use the fitted eqs. (6) to construct dynamic country-level forecasts \( \log Z_r \) for the period 2011-2050. First differencing the forecast series yields an approximation for the interannual growth of the five drivers over the projection horizon, which eq. (4) implies we can simply sum to obtain the instantaneous growth rates of countries’ future emissions!

Most importantly, we can exploit the autoregressive structure in conjunction with the standard errors of the predictions to construct country, regional and global emission confidence intervals against which IAM simulations can be compared.
CO₂ Emission Drivers: Past and Future Projections

World

Latin America

Asia

OECD

Middle East & Africa

Reforming Economies

- CO₂ Intensity
- Energy Intensity
- Structural Change
- GDP per capita
- Population
- Sum of Effects
Forecast CO$_2$ Emissions and SSP/RCP Comparison (MT)
Emission Drivers Comparison (Cumulative GT, 2011-2050)