A unified modelling framework for projecting sectoral greenhouse gas emissions

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Motivation

- Greenhouse gas (GHG) emissions contribute to the looming threat of climate change, the biggest challenge of our time, but have many facets:
  - Sectoral composition of GHG emissions differs across countries
  - Dynamics of sectoral GHG emissions differ across but also within countries
- Thus, having projections of sectoral GHG emissions is important for:
  - Identification of focal points for climate policy within and across countries
  - Global stocktaking exercises and NDC formulation
- Currently, there is a lack of comprehensive, yet comparable projections of sectoral GHGs that allow for straightforward uncertainty quantification

Overview – Heterogeneities in Sector Composition

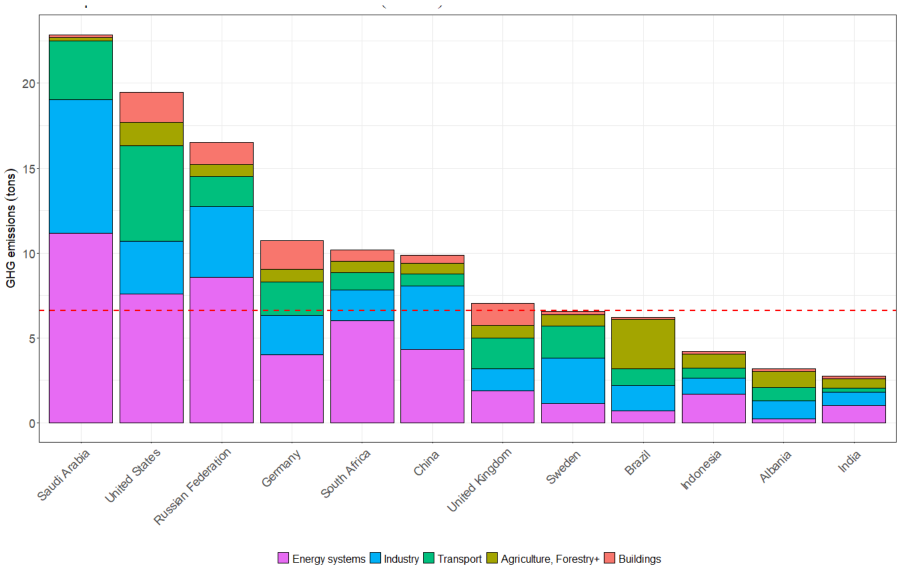


Chart: Per capita emissions in 2018 for selected countries. Source: Minx et al. 2021

Overview – Heterogeneities in Dynamics

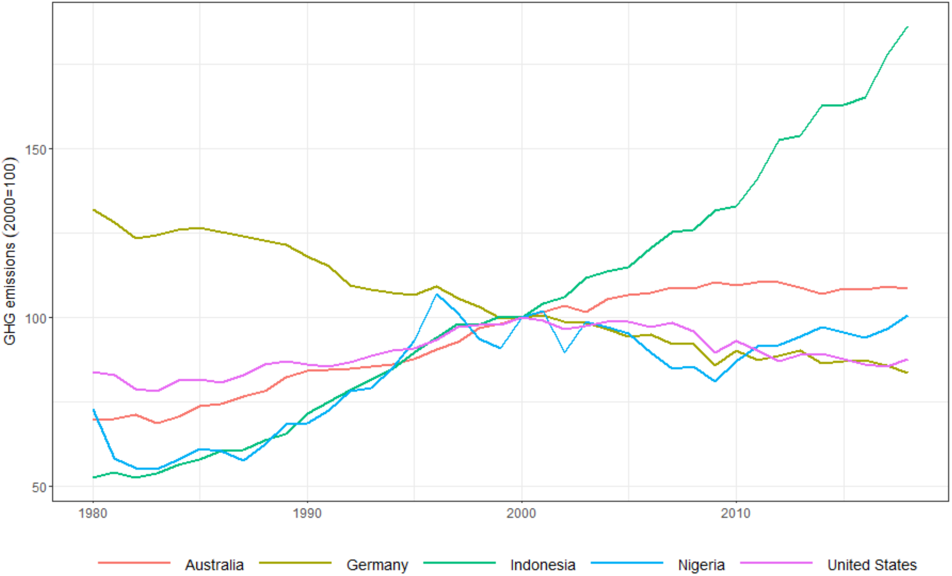


Chart: Aggregate GHG emissions evolution. Source: Minx et al. 2021

Overview – Heterogeneities of Sector Dynamics

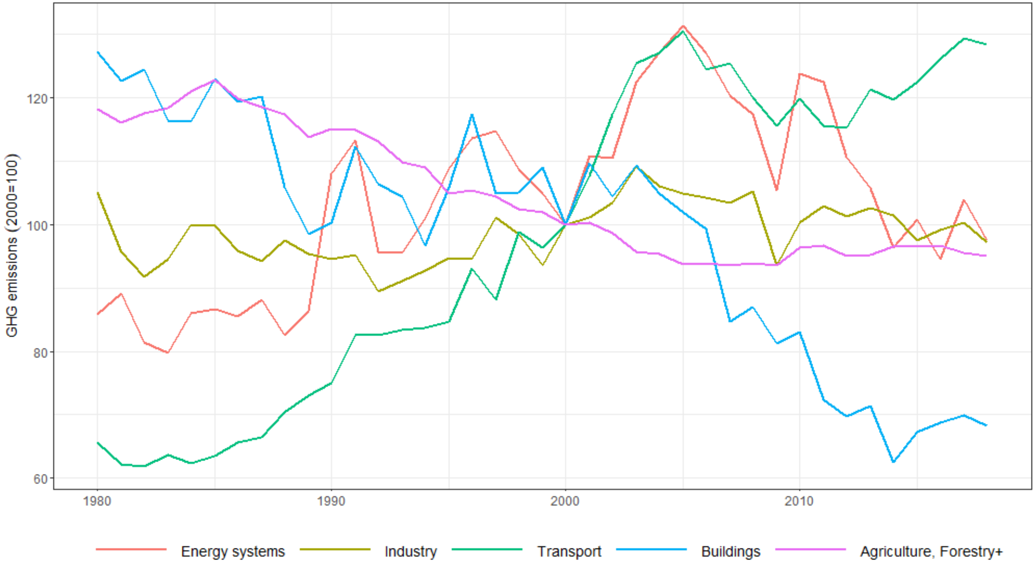


Chart: Sectoral emissions evolution in Austria. Source: Minx et al. 2021

Motivation

- (Global) Integrated Assessment Models (IAMs) models and downscaling methods have very rich model structure, making uncertainty quantification hard
- Country-specific studies feature wide variety of methodologies, assumptions, and sample periods; hindering comparability and aggregation
- Recent papers project aggregate CO_2 emissions (Raftery et al. 2017), neglecting sectoral differences and are detached from climate science community results
- Bridging these gaps equips policy-makers with information about most pertinent sectors but also provides an addition to the toolkit for scientific communities

Goal

Develop unified framework – conceptually and statistically – to project GHG emissions under "business-as-usual" on a sectoral basis for a global panel of countries

Methodology & Data

Modelling strategy – Conceptual framework

IPAT/Kaya decompositions as conceptual starting points:

$$E_s = L \times \frac{G}{L} \times \frac{E_s}{G}$$

- E_s: Emissions (per sector)
- L: Population
- G/L: GDP per capita
- E_s/G: Sectoral emission intensity

- Additional demographic covariates found to yield gains in predictive performance:
  - Age structure
  - Educational structure
  - Urbanization

Methodology – Panel VAR

$$\boldsymbol{y}_{i,s,t} = \sum_{j=1}^{p} \boldsymbol{A}_{i,s,j} \boldsymbol{y}_{i,s,t-j} + \boldsymbol{a}_{i,s} + \delta t + \varepsilon_{i,s,t} \,, \quad \varepsilon_{i,s,t} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\Sigma}_{i,s})$$

- $\boldsymbol{y}_{i,s,t} = [EMINT_{i,s,t}, GDPPC_{i,t}, POP_{i,t}, AGE_{i,t}, EDUC_{i,t}, URB_{i,t}]'$
- Models dynamic interdependencies between variables for country i in sector s
- Country/sector-specific deterministics based on whether emission intensity of a sector in a given country has peaked or not; estimation based on post-peak period
- VAR coefficients stem from common (global) distribution $\Rightarrow$ allows for different dynamic paths across countries/sectors but aids projections by pooling information

Methodology – Prior setup

Bayesian hierarchical prior structure inspired by Jarociński (2010) and Boeck et al. (2023). Let $\boldsymbol{\alpha}_{i,s} = vec([\boldsymbol{A}_{i,s,1}, \ldots, \boldsymbol{A}_{i,s,p}])$ for all i and s. Then:

$$\boldsymbol{\alpha}_{i,s} \sim \mathcal{N}(\bar{\boldsymbol{\alpha}}_s, \boldsymbol{\Omega}_{\alpha_{i,s}})$$

- $\bar{\boldsymbol{\alpha}}_s$ denotes a common (global) mean vector and $\Omega_{\alpha_{i,s}}$ effectively controls the deviations of individual country coefficients
- We specify a Normal-Gamma prior (Brown and Griffin 2010) on its elements:

$$[\Omega_{\alpha_{i,s}}]_j = \frac{2[\psi_{i,s}]_j}{\lambda_{i,s}^2}\,,\ \lambda_{i,s}^2 \sim \mathcal{G}(a_\lambda, b_\lambda)\,,\ [\psi_{i,s}]_j \sim \mathcal{G}(a_\psi, b_\psi),$$

- $\lambda_{i,s}$ imposes shrinkage towards common mean for all coefficients of country i, $[\psi_{i,s}]_j$ for $j = 1, \ldots, M^2 p$ governs strength of shrinkage for individual coefficients

Methodology – Conditional forecasts

- Using estimated model, conditional forecasts for emissions intensity are derived from established methods (Bańbura, Giannone, and Lenza 2015)
- Condition on short-term forecasts of GDP combined with projections from the Shared Socioeconomic Pathways (SSPs) to derive emission intensity predictions
- Based on projected emission intensity and GDP trajectories under SSP2, create projections of emissions for country-sector pairs until 2050
- Conditioning on SSPs enhances comparability to results from climate science community but uncertainty reduces to a lower bound estimate

Modelling strategy – Data

- Large panel dataset of GHG emissions for 173 countries
- Yearly data spanning 1980 to 2018 with some variations
- Covering 5 main sectors for GHG emissions–excluding LULUCF–with data from novel database based on EDGAR (Minx et al. 2021)
- Other covariates and SSP-consistent paths to condition on taken from:
  - World Bank, IMF, Maddisson Project for historical GDP data
  - Wittgenstein Centre for Demography and Global Human Capital
  - Crespo Cuaresma (2017) for GDP per capita projections
  - Chen et al. (2022) for urbanization patterns and projections

Results

Key Results

- Global GHG emissions (excl. LULUCF) increase almost unhindered until 2050
- Transport emissions rise the strongest (often also in countries with otherwise falling emissions) but energy-producing sector remains largest
- Africa and SE-Asia experience strongest increases; Eastern Asia remains largest emitter; Europe (ex Turkey) and North America decrease emissions
- Variations across countries and sectors but only few peak and reduce before 2050
- Geographical and sectoral distribution of GHG emissions changes until 2050, both on aggregate and individual level

Projection Examples – Individual country-sector pairs

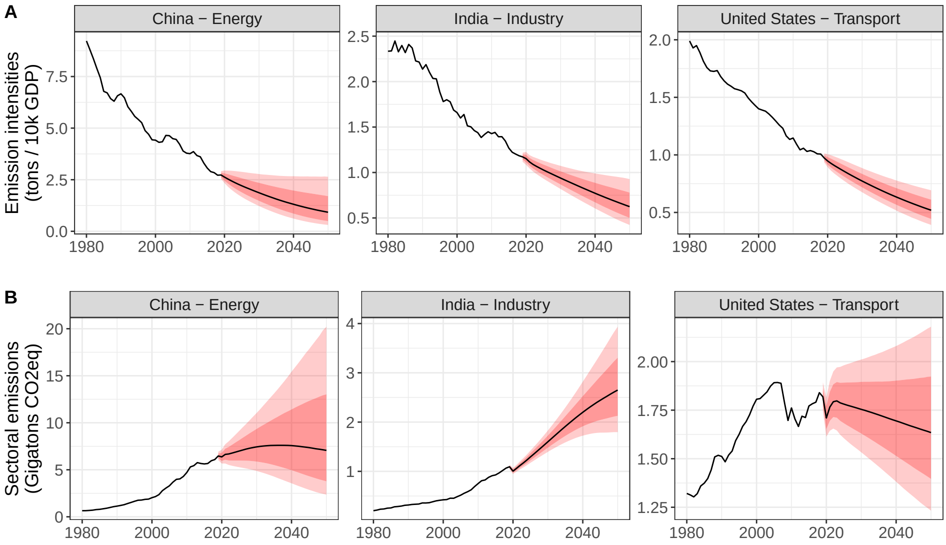


Chart: Selected country-sector projections

Projections – Regional Emission Intensities

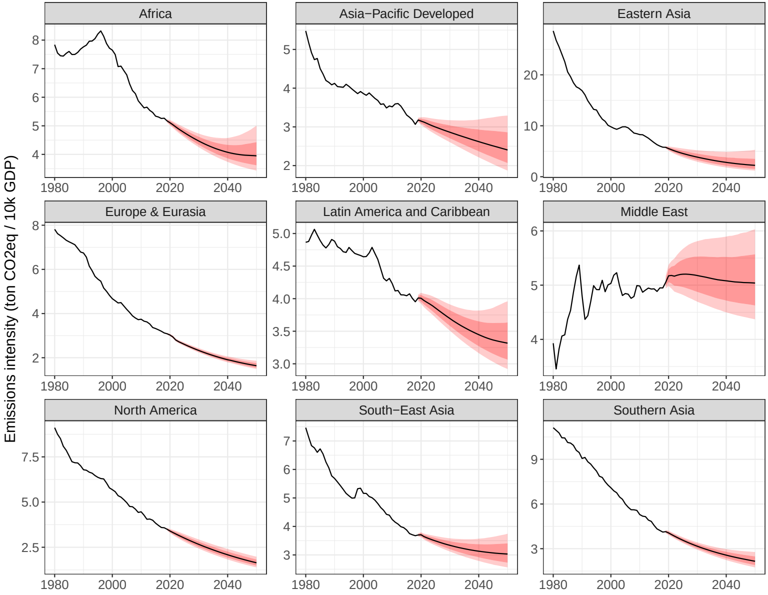


Chart: Regional GHG emission intensity projections.

Projections – Regional Emissions

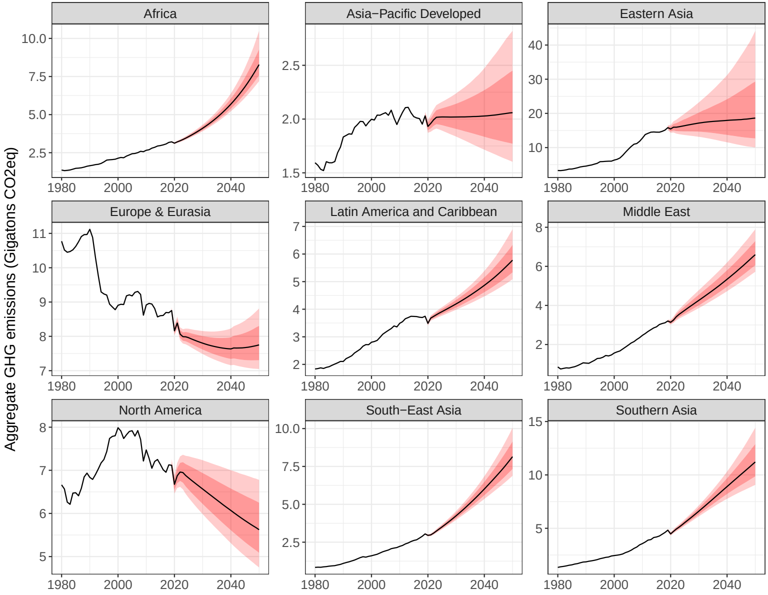


Chart: Regional GHG emission projections.

Projections – Global sectoral Emissions

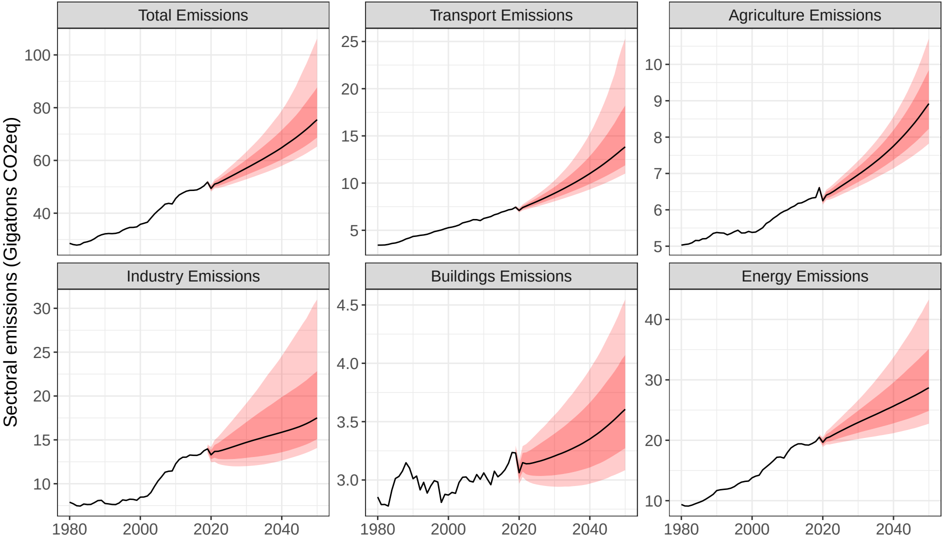


Chart: (Global) sectoral GHG emissions projections

Transport Sector Emissions Rise

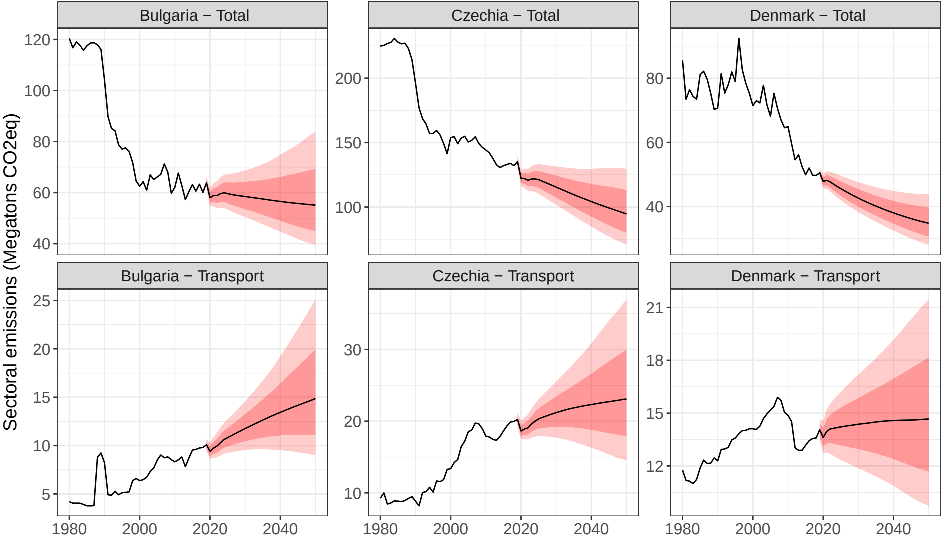


Chart: Selected countries with decreasing overall GHG emissions but rising transport emissions.

Overview – Aggregate Emissions I

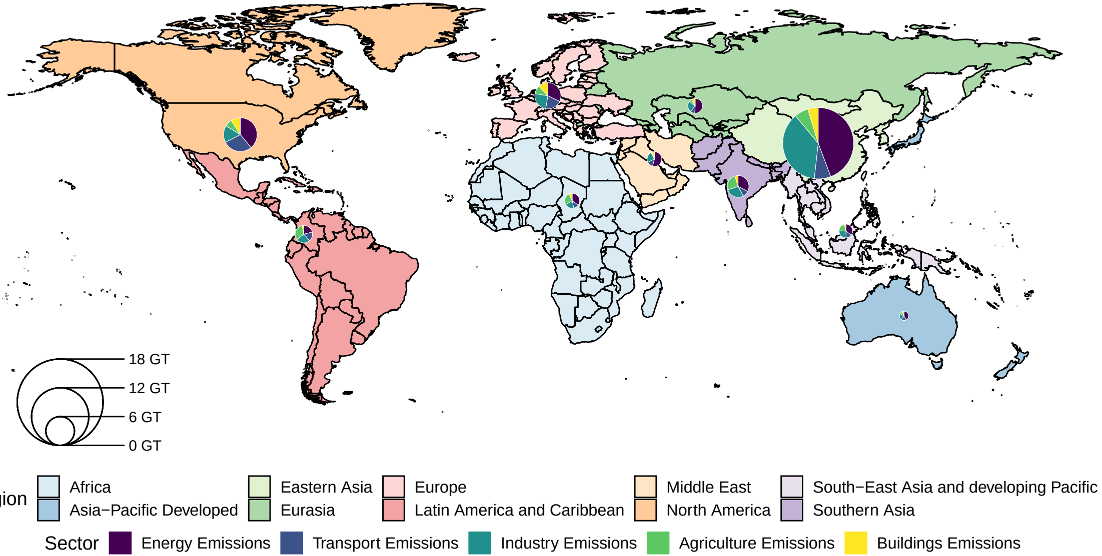


Chart: Aggregate GHG emissions in 2018.

Overview – Aggregate Emissions II

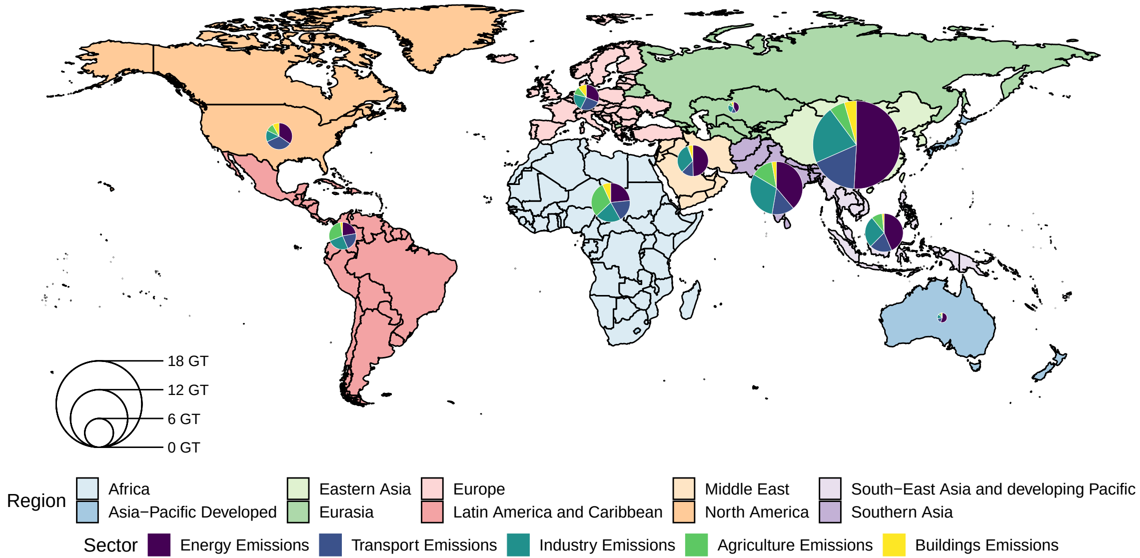


Chart: Aggregate GHG emissions in 2050.

Overview – Per Capita Emissions I

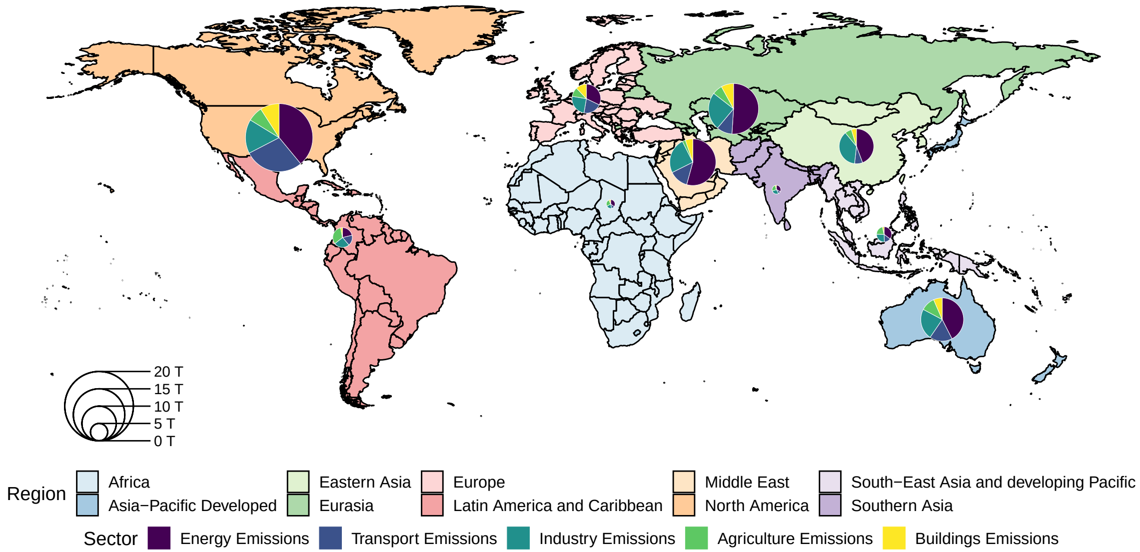


Chart: Per capita GHG emissions in 2018.

Overview – Per Capita Emissions II

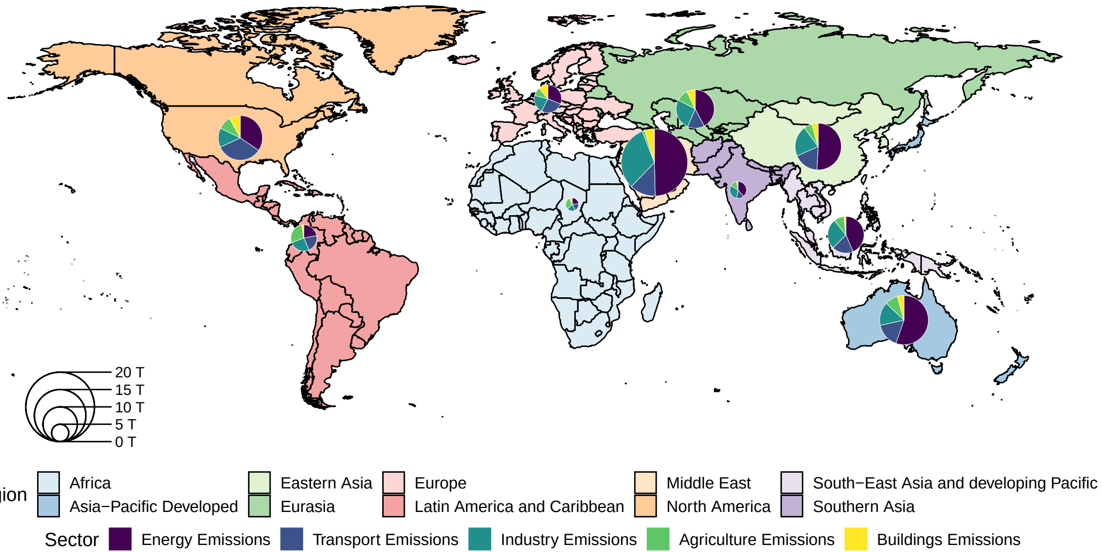


Chart: Per capita GHG emissions in 2050.

Projections – Country BAU comparison

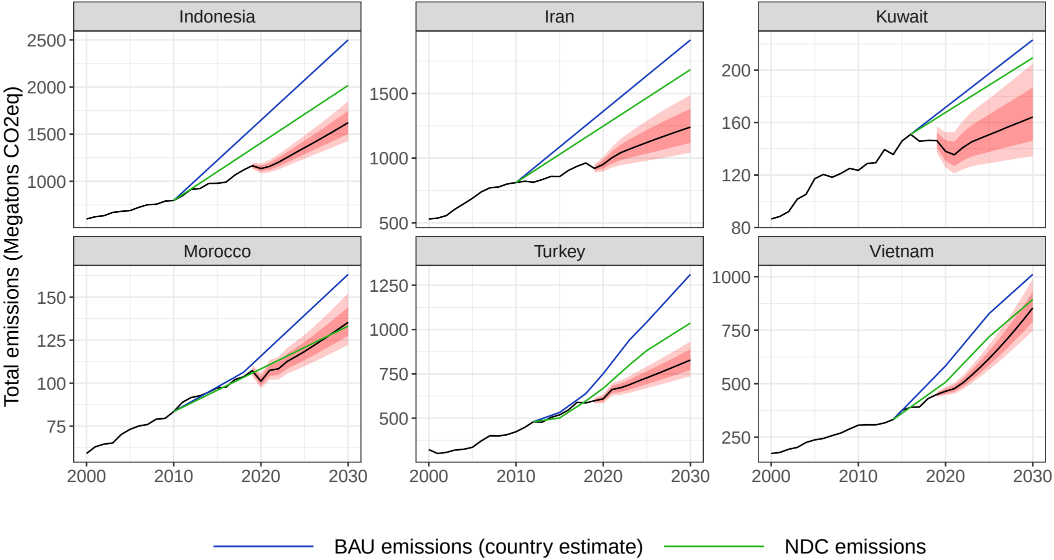
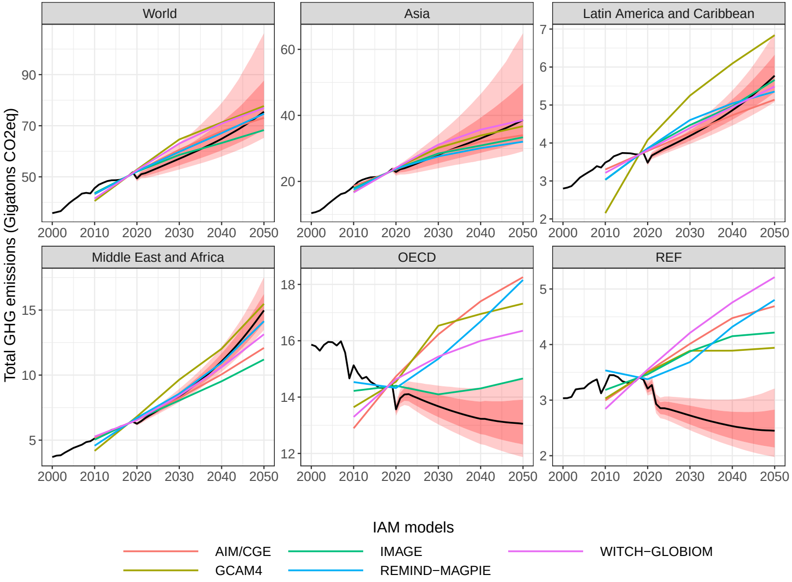


Chart: Comparison to country's own BAU trajectories.

Projections – IAM comparison



Summary & Conclusion

- Extensive forecasting exercise results in "business-as-usual" projections of GHG emissions for five main sectors and 173 economies
- Bayesian time series methods used to overcome estimation difficulties, pool information across countries and allow for uncertainty quantification
- Results point towards almost unchecked emissions growth globally — with variation across countries and sectors
- Country BAU estimates often inflated, raising questions about ambition of NDCs
- Simulations from IAMs fall well within the range of our predictions globally but deviate for some regions $\Rightarrow$ revisit some of the underlying assumptions

Utilization of Results: The World Emissions Clock

- Comparison of BAU projections with ones from IAMs depicting full implementation of NDCs and 1.5°-compatible scenario from IAMs
- Covers 5 main sectors, 24 subsectors for 180 countries up to year 2050
- Uncovers implementation and ambition gaps for various countries and sectors

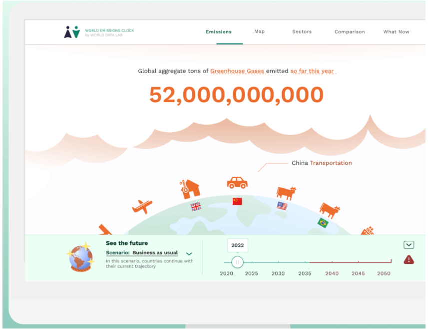


Chart: The World Emissions Clock (https://worldemissions.io/)

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Appendix

Forecasting Methodology – (Remaining) prior setup

- Similar to the setup for the VAR coefficients of individual countries, we impose a Normal-Gamma prior setup the common mean vector
  - Shrinks coefficients towards zero
  - Shown to aid predictive performance in VAR models (Huber and Feldkircher 2019)
- For variances, a setup closely related to standard inverse-Wishart prior is used
  - $\Sigma_{i,s}$ decomposed into $\boldsymbol{HSH}^\intercal$; triangularization for computational gains
  - Normal Gamma prior imposed on free off-diagonal elements of H
  - For elements of diagonal matrix $\boldsymbol{S}$, inverse-Gamma priors are used
- Large parts of prior setup follow Huber and Feldkircher (2019); also allows for straightforward extensions (heteroskedastic errors, lag-specific shrinkage,...)

Forecast Examples - Trend Reversals I

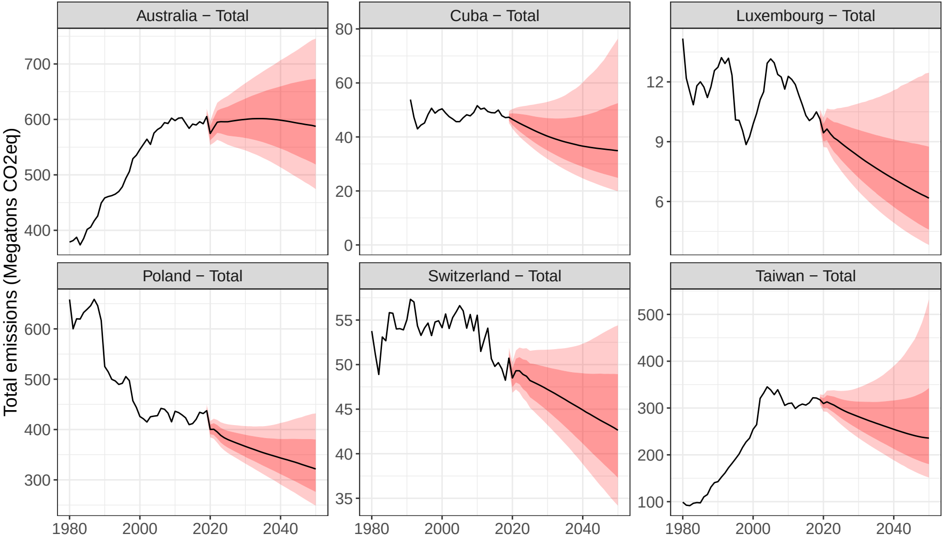

Chart: Selected countries not identified as sustainably reducing GHG emissions by Lamb et al. 2022 whose overall GHG emissions are predicted to peak and decline until 2050.

Forecast Examples - Trend Reversals II

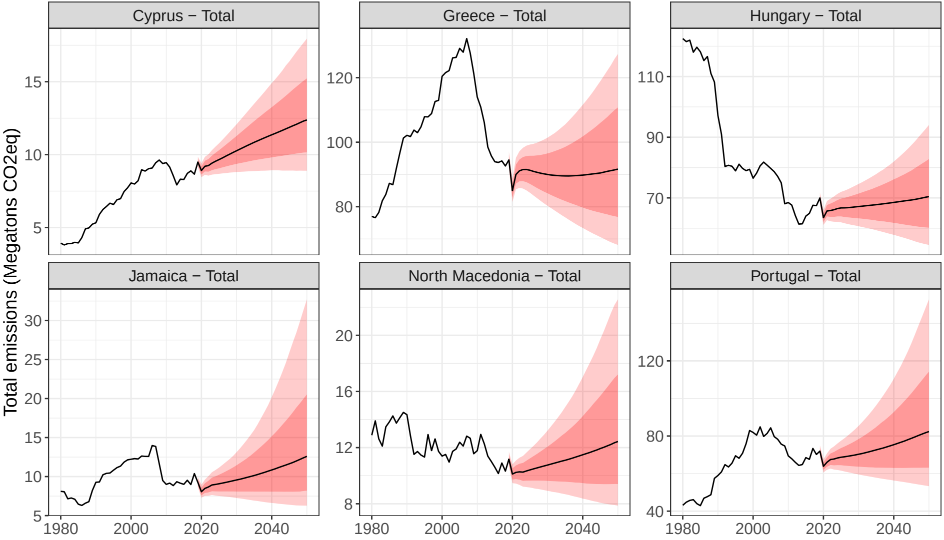

Chart: Selected countries found as being sustainably reducing GHG emissions by Lamb et al. 2022, who are set to increase emissions again.

Forecast Examples - Energy Sector

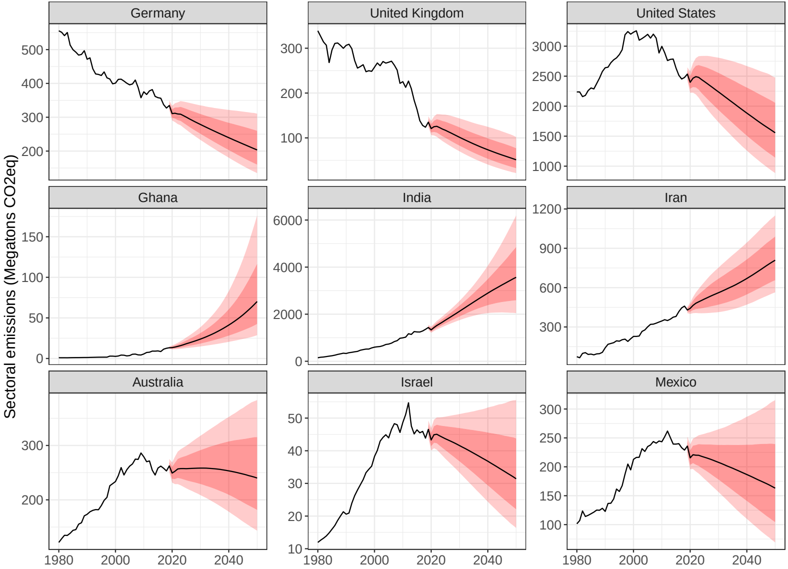

Chart: Energy sector emissions for selected countries.