Global gridded projections of household cooling energy demand to 2050

A global model and a new dataset to the benefit of the impacts community

Giacomo Falchetta[1,2], Enrica De Cian[1,3], Filippo Pavanello[4], Ian Sue Wing[5]

1 CMCC – Euro Mediterranean Center on Climate Change, Venice, Italy

2 International Institute for Applied Systems Analysis, Laxenburg, Austria

3 Ca' Foscari University of Venice, Department of Economics, Venice, Italy

4 University of Bologna, Bologna, Italy

5 Boston University, Boston, MA, USA

Cross-sectoral ISIMIP/PROCLIAS Workshop

Prague

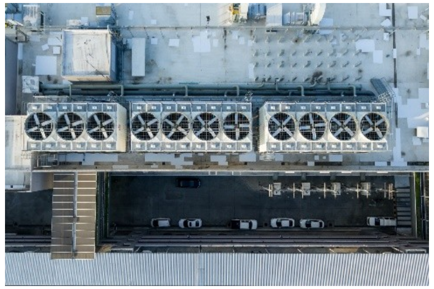
5th June 2023

Background and motivations

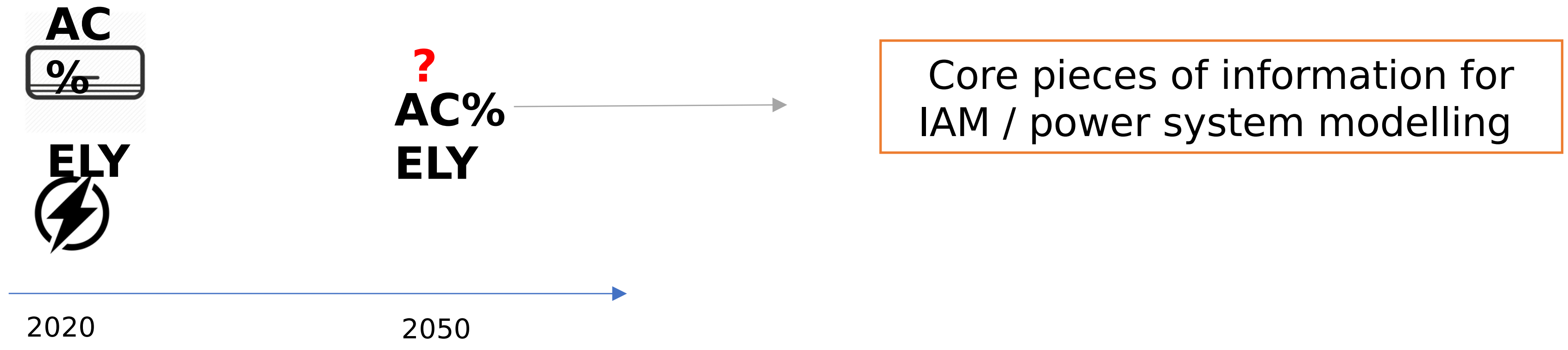
- **Energy demand for cooling and adaptation** -> increasingly crucial (IEA)
- **Climate change** -> increasing CDDs and acute heat **exposure**
- **Power system** stability and planning -> challenged by demand shocks and power supply variability/vulnerability
- **Feedback CO2 emissions** -> induced by electricity demand growth (until sector is decarbonised)

Necessary to understand **how cooling will be adopted and used worldwide.**

□ Challenge: cooling is context-specific (climate, environment), household specific (income, education) and influenced by social determinants



Research question and novelty



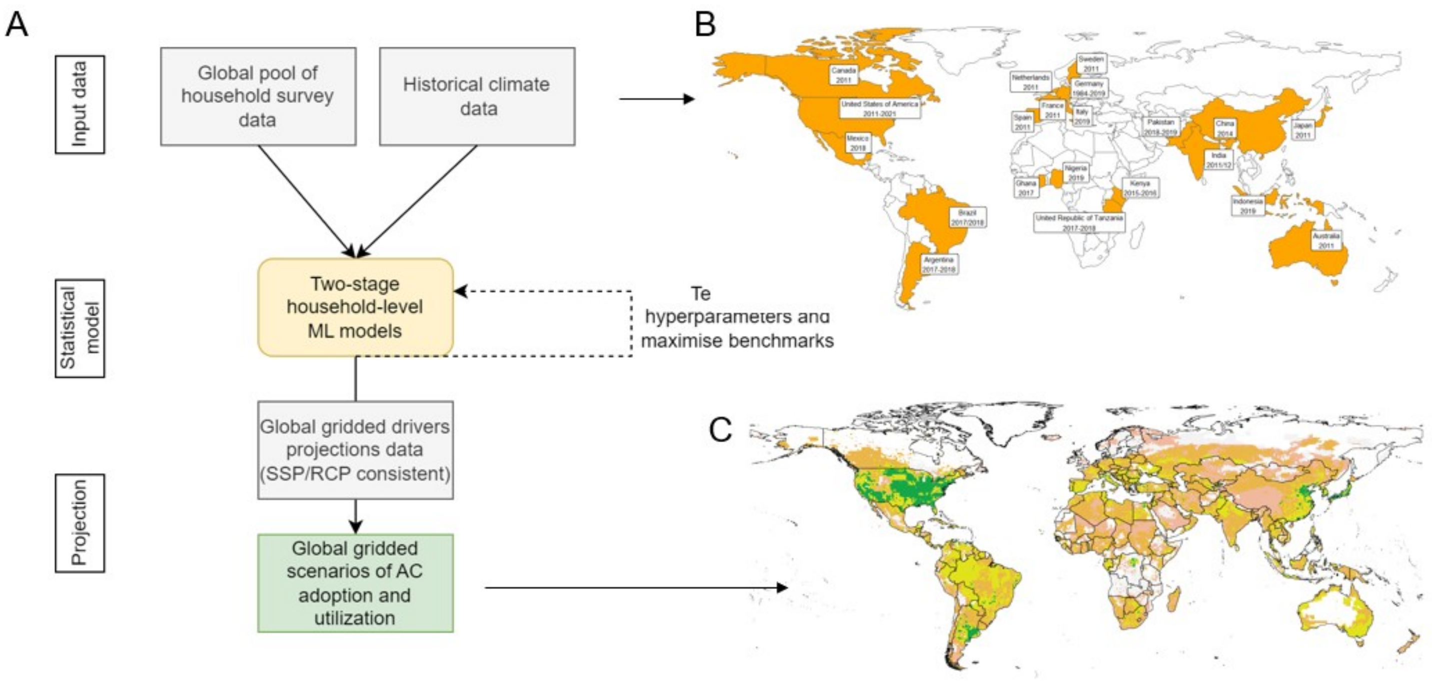
Given the projected transformation of drivers, what will happen to (local) AC adoption and the consequent electricity consumption?

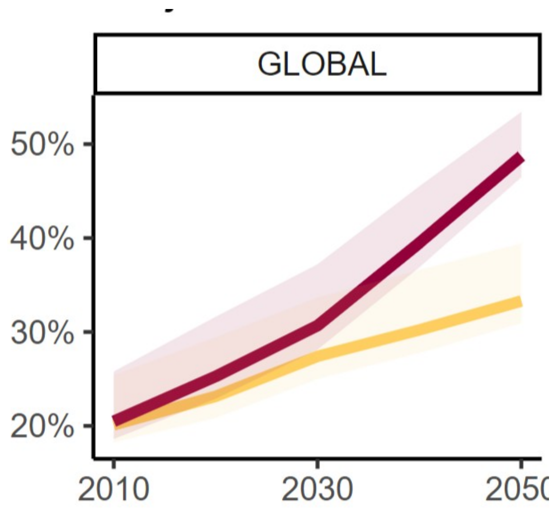
Objective: Generate the first global **gridded data product of scenarios of future residential air-conditioning adoption (extensive) and use (intensive).**

Based on CMIP6 RCP-SSP combinations with consistent trajectories of:

- Climate change (radiative forcing)
- Economic growth (income and expenditure)
- Population growth and urbanisation
- Social transformations (age, education)

Modelling framework



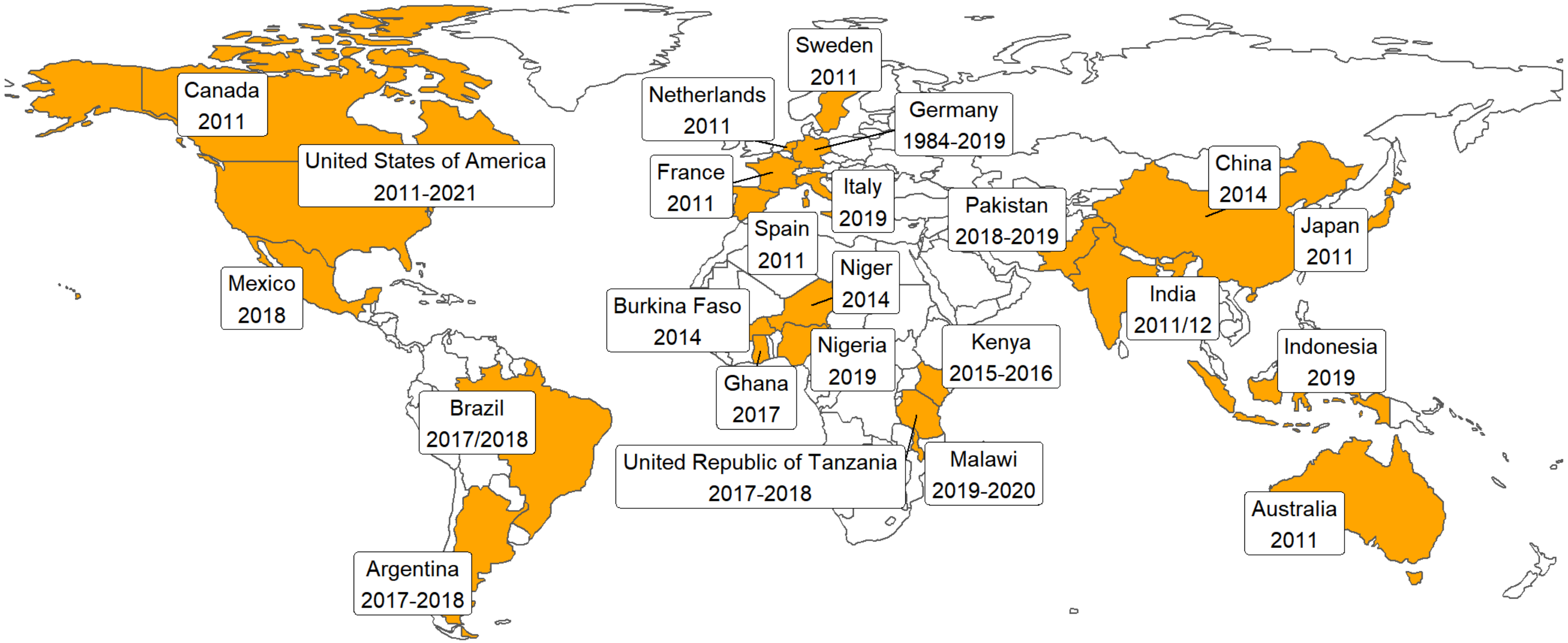


- Global pool of **household survey data**: n = 530,666 households in 25 countries together responsible for three quarters of global electricity consumption
- **Machine learning model** on HH survey data
- Grid-cell based upscaling and **projections** along SSP/RCP scenarios

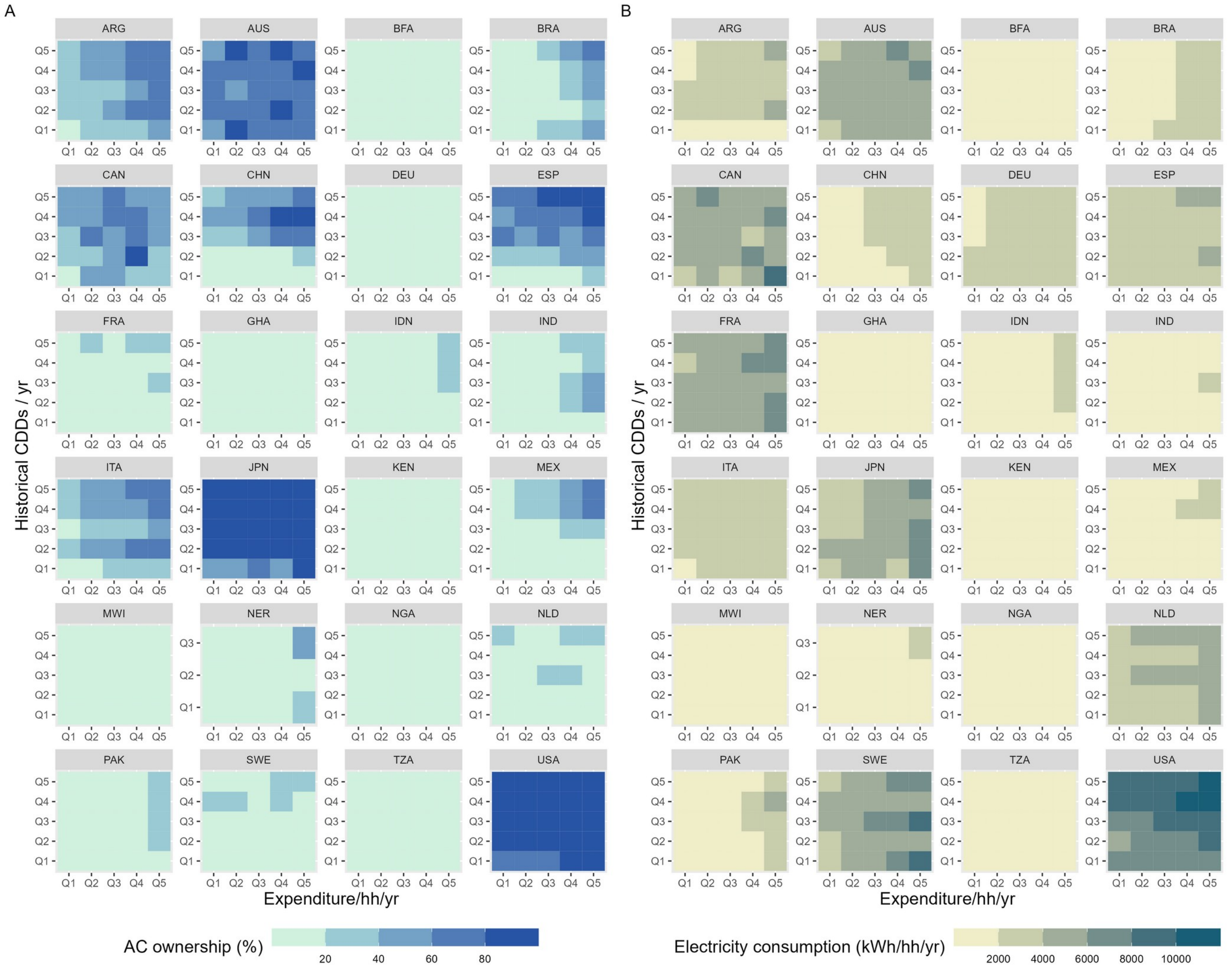
Figure: Falchetta et al. (in prep.)

Input data (model training and validation)

- Multi-country household survey dataset (n = 530,000 households) inclusive of 25 countries which together are responsible for three quarters of global electricity consumption.



Input data (model training and validation)



Model training data

Sub-national (varying spatial resolution, depending on country survey), **harmonised household-level dataset**:

- Electricity consumption
- Economic status (expenditures)
- Social characteristics (age, education, gender, household, housing…)
- Historical climate (CDDs/HDDs) (GLDAS)

Methods – two-stage modelling

$$AC_{ic} = f\left(CDD_{ic}, HHD_{ic}, lnEXP_{ic}, URB_{ic}, EDU_{ic}, AGE_{ic}\right) + \varepsilon_{ic}$$

AC

Classification probability model → predict AC ownership

Calculate seleciton term (Dubin and McFadden method) to correct for endogeneity

Endogeneity correction

$$\widehat{\zeta}_{ic} = \frac{\widehat{P}_{ic} \ln \widehat{P}_{ic}}{1 - \widehat{P}_{ic}} + \ln \widehat{P}_{ic}$$

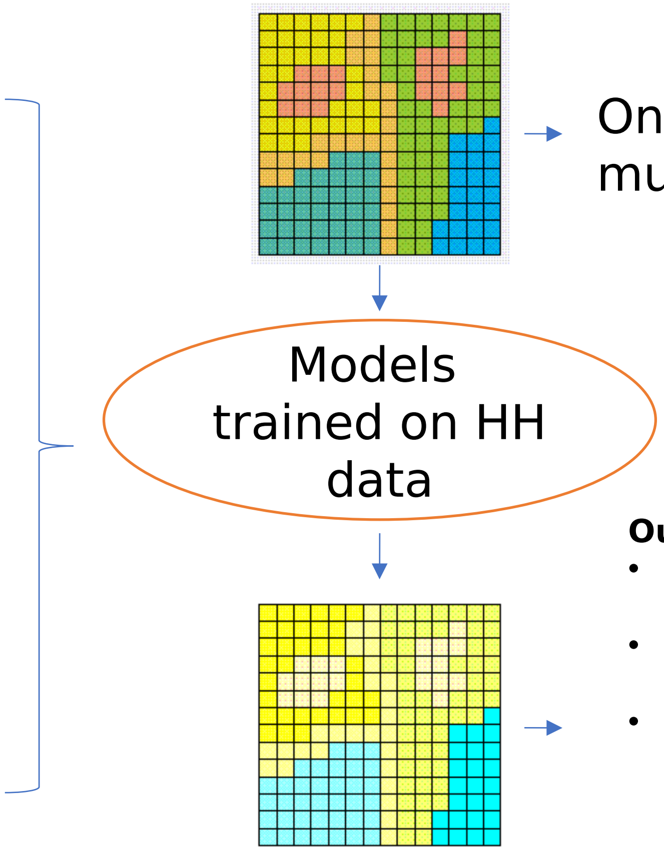
ELY

Regression model → predict electricity consumption

$$ELY_{ic} = f\left(\begin{array}{c} AC_{ic}, \widehat{\zeta}_{ic}, CDD_{ic}, HHD_{ic}, lnEXP_{ic}, \\ URB_{ic}, EDU_{ic}, AGE_{ic} \end{array}\right) + \varepsilon_{ic}$$

Methods – household to gridded scale scaling and projections

- **Time-varying drivers (SSP-RCP consistent):**
  - NASA NEXX CMIP6 multi-model median (SSPs 245 and 585 → CDDs and HDDs)
  - Gridded SSP-consistent GDP (Murakami et al. 2021) → expenditure (adjusted for savings rate [GTAP]
  - Gridded SSP-consistent population (Jones et al. 2016)
  - Gridded SSP-consistent urbanisation (Chen et al. 2022)
  - National SSP-consistent socio-demographic transformations (Education, gender, age of population) (Samir et al. (2017)
- **Static drivers:**
  - Macroregion fixed effects



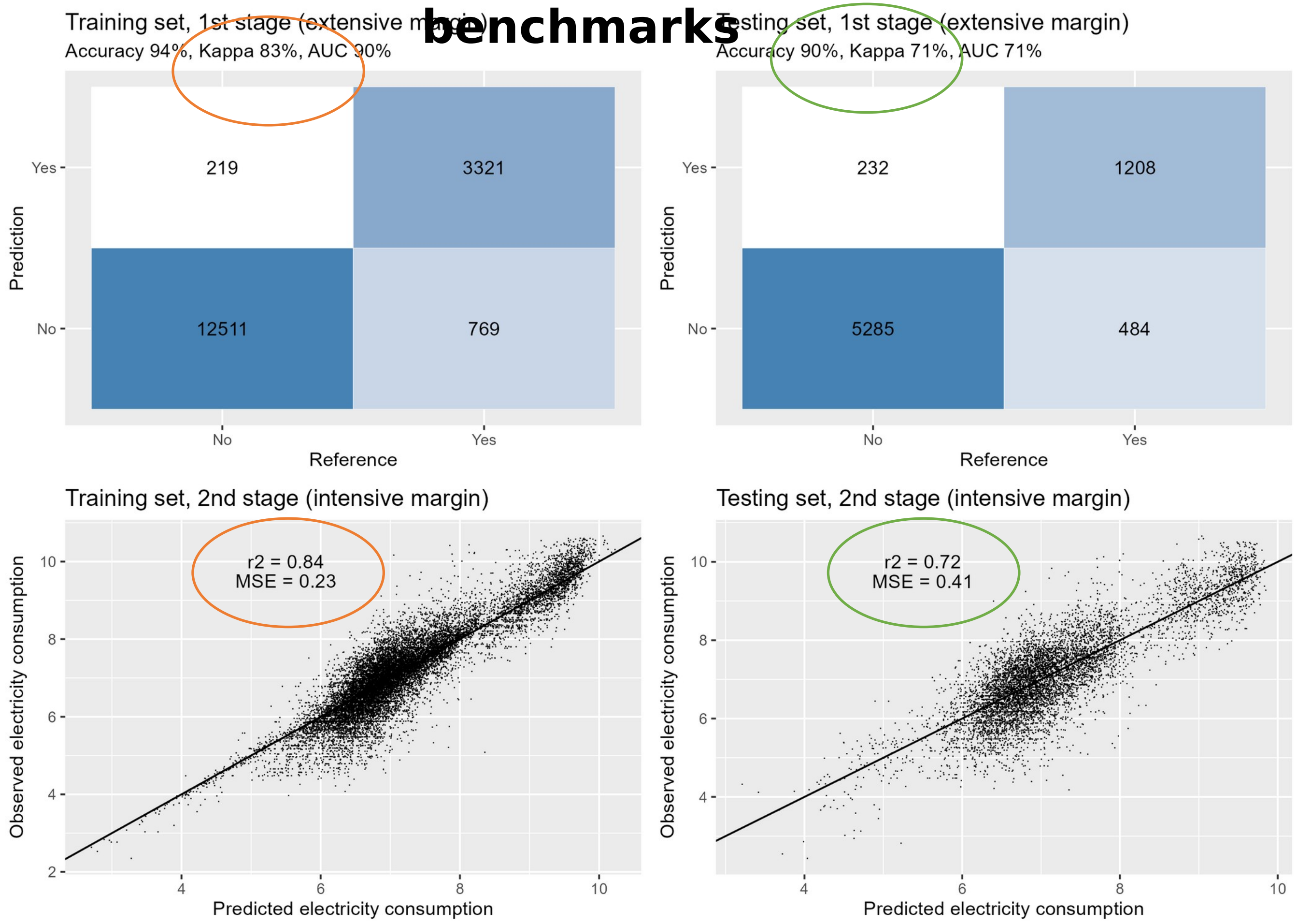
One grid cell = multiple HHs

Output data

- **Scenarios:** SSPs 2(45) and 5(85)
- **Resolution:** 0.25° regular grid
- **Output variables:** AC penetration rate; average (per HH) AC-induced electricity consumption; total (GWh/yr) consumption

Results - model benchmarks

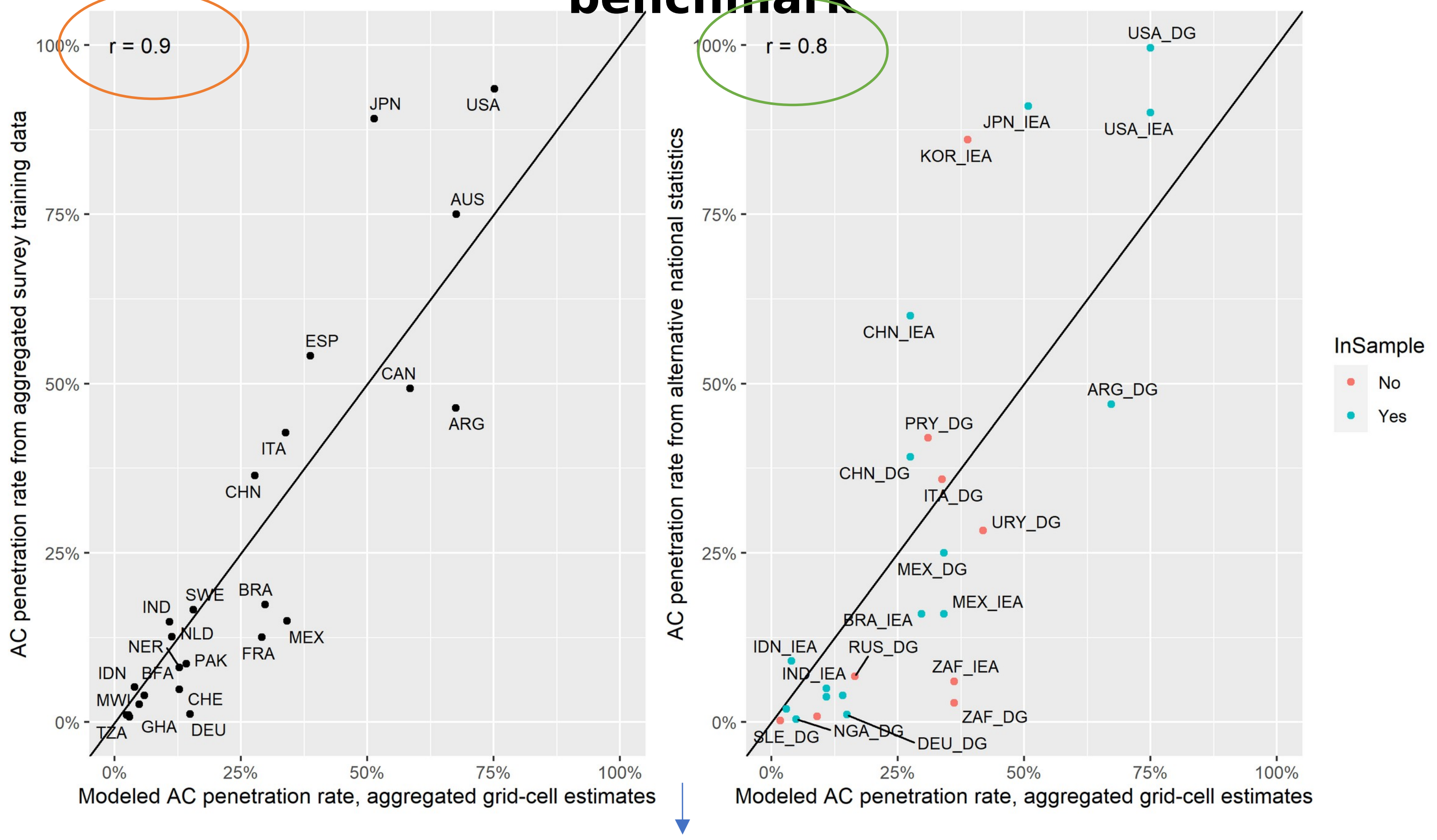
Household-level benchmarks



- Different models tested: ML largely outperforms OLS/GLM and semi-parametric spline models
- Repeated (10-fold) cross-validation ensures that the model is able to generalise well
- Testing set to ultimately assess the predictive capacity of the model on unseen data
- **Cohen's Kappa [range: 0-1]** (metric of reference for 1st stage) effectively deals with class unbalance (more HHs without AC than AC -> accuracy metric would be biased)
- R-squared **[range: 0-1]** (metric of reference for 2nd stage) assesses the % of explained variation in HH electricity consumption.
- **Bottom line:** the two models show satisfactory results in predicting AC extensive and intensive margin in unseen data.

Results - external validity

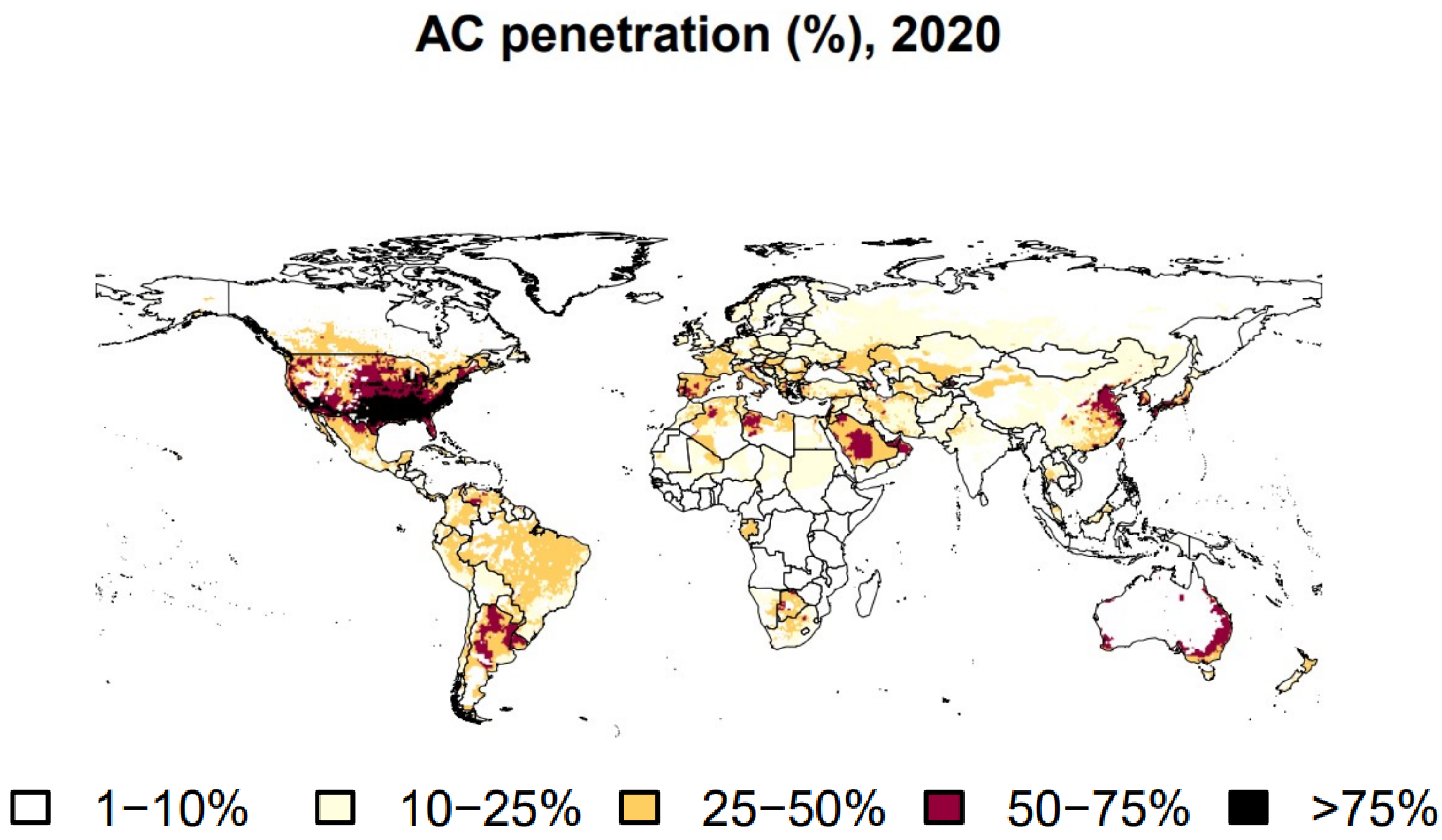
Country-level, general benchmark



2010 estimate, grid-cells aggregated to national boundaries

- To evaluate the **external validity** of the model, it is relevant to check how well the grid cell-level AC model predictions upscaled at the country level match with national statistics available online.
- Points include both countries that are present and absent from the training set.
- **Correlation of 90%** suggests very strong consistency of gridded estimates with derived statistics from survey data (in-sample training countries)
- **Correlation of 80%** suggests general good external validity of the grid cell-level model estimates

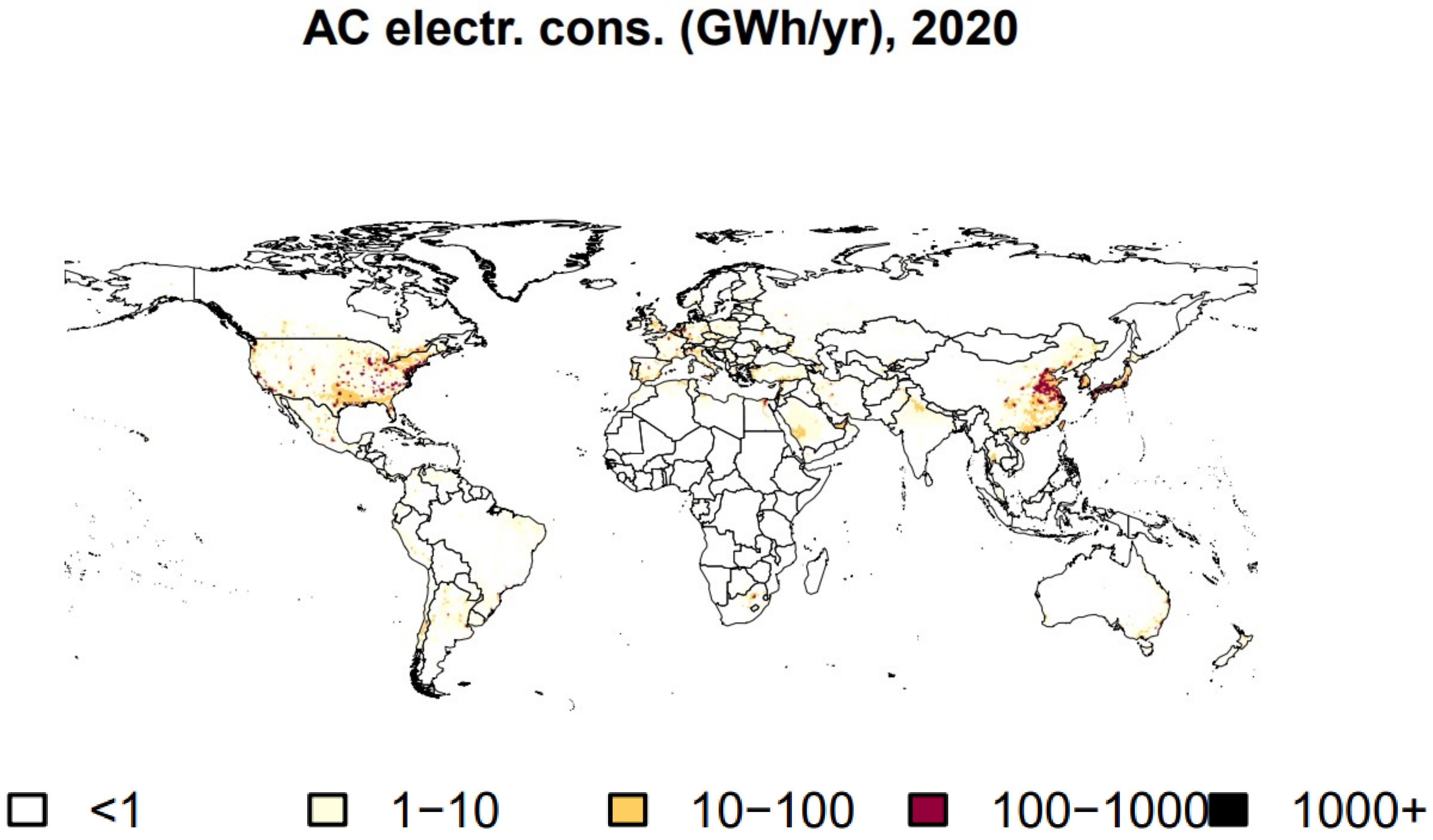
Results – gridded projections (AC)



Across and within-country variations in AC penetration rates

- 2020 (modelled baseline)
- SSP2(45), 2050
- SSP5(85), 2050

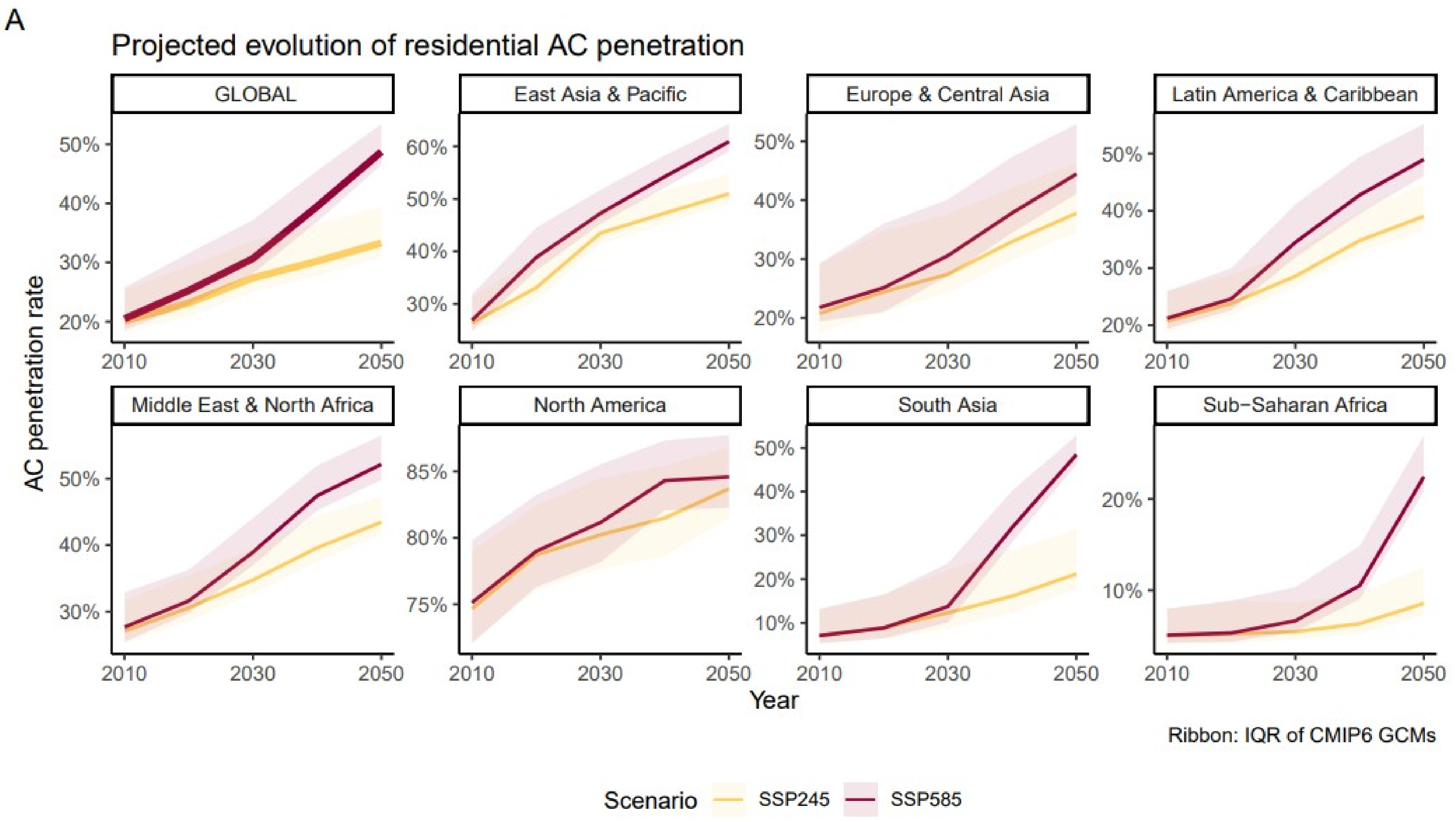
Results – gridded projections (electricity)



Across and within-country variations in AC-induced electricity consumption

- 2020 (modelled baseline)
- SSP2(45), 2050
- SSP5(85), 2050

Results – upscaled projections, AC



Huge boost in **global AC penetration** (from 25% in 2020 to 34-47% in 2050

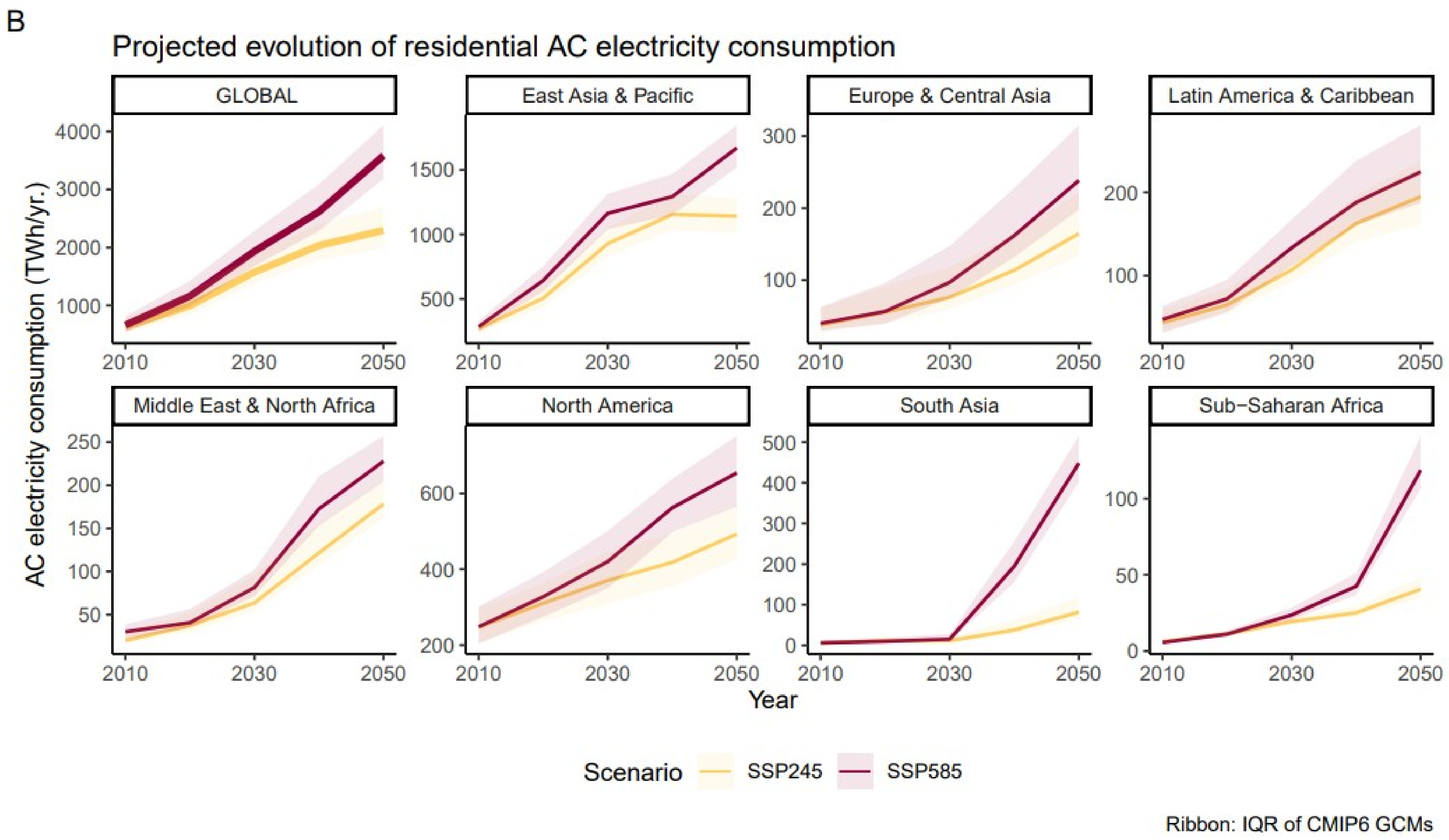
From 1.7 billion **people with AC access** to 3-3.7 billion people in 2050

Strong implications for:

- Policy & energy planning

Results – upscaled projections, electricity

B



Even larger **impact on electricity demand** (from 795 TWh/yr in 2020 to 1,930-3,260 TWh/yr in 2050)

Major implications for:

- Power capacity requirement
- Grid stability
- Power-sector emissions if not decarbonised fast enough

Results – upscaled projections, emissions

Table 1. Estimated CO_2 emissions from AC electriciy consumption in 2020 and 2050, by region. Note: the main numbers refer to projections calculated with the CMIP6 GCMs enemble median (exluding 'hot models'[27]), whilst the number in parentheses describe the IQR of CMIP6 GCMs.

Region	2020	SSP245 (2050)	SSP585 (2050)
East Asia & Pacific	133.4 (114.3 - 156.5)	253.5 (225.1 - 283)	310.4 (282.1 - 342.6)
Europe & Central Asia	10.8 (7.5 - 18.1)	32.6 (26.1 - 44.6)	53.8 (42.9 - 70.7)
Latin America & Caribbean	9.1 (7.7 - 11.7)	27.9 (23.1 - 34)	34.2 (28.5 - 42.6)
Middle East & North Africa	4.8 (3.8 - 6.6)	23.4 (21.3 - 27)	30.1 (26.9 - 34)
North America	73.1 (61.8 - 85.3)	107.8 (92.6 - 124.3)	131.9 (113.6 - 151)
South Asia	2 (1.3 - 3.9)	14.5 (11.5 - 20.9)	69.9 (62.5 - 80)
Sub-Saharan Africa	3.4 (2.9 - 4)	10.4 (8.7 - 12.2)	21 (18.7 - 25)
Total	374.1 (316.9 - 447.5)	470 (408.4 - 546)	651.4 (575.2 - 745.8)

- **Emission factors** based on IPCC AR6 Database scenarios
- Residential cooling emissions: **374 Mt in 2020 470-651 Mt in 2050**
- Future global residential AC electricity might emit almost **half of the current total electricity emissions by the US (1,551 Mt)**

Future use of gridded projections

Ultimate goal: stimulate the **explicit consideration of AC** use and its implications **in global models**, e.g. IAMs but also power system models (e.g. grid reliability and peak loads) and CGE models.

Integration in IAMs -> heterogeneous impact of climate change on cooling energy demand -> adaptation impacts into climate change mitigation assessments

---

Ongoing / future work:

- Link to health outcomes and mortality impacts
- Role of alternative cooling solutions: e.g. urban green space

Data availability

Variables:

- Projected AC penetration rate (share of population in grid cell with AC)
- # of projected households with AC in grid cell
- Average projected AC-induced electricity consumption per household in grid cell
- Total projected AC-induced electricity consumption in grid cell

Scenarios:

- SSP 2(45)
- SSP 5(85)

Spatial resolution:

- 0.25° regular grid

Time resolution:

- 10-year time step (2020-2050)

Soon available open-access and open-source on:

zenodo

GitHub

Thank you!

- Falchetta, G., De Cian, E., Pavanello, F., & Wing, I. S. (<u>in preparation</u>). Global gridded scenarios of residential cooling energy demand to 2050
- Falchetta, G., Pavanello, F., De Cian, E., Wing, I. S. & Romitti, Y. (<u>in preparation</u>). The Impact of Air-conditioning on Residential Electricity Consumption across World Countries

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme under grant agreement No 756194.

Supplementary slides

Previous (selected) studies

- *Dubin and McFadden (1984)* -> two-stage model of extensive and intensive margin with endogeneity correction
- *McNeil and Letschert (2008)* -> country-level two stage model, no endogeneity correction
- *Isaac and van Vuuren (2011)* -> future projections based on McNeil and Letschert (2008)
- *Barreca et al. (2016)* -> health benefits of AC using Dubin & McFadden (1984) model
- *De Cian, Sue Wing, van Rujiven (2019)* -> amplification of total demand due to climate change
- *Mastrucci et al. (2019) -> Residential cooling needs in the Global South*
- *Davis & Gertler (2021)* -> inequality and AC using microdata; extensive margin only: electricity consumption not analysed
- *Pavanello et al. (2021)* -> household-level projections based for four developing countries, both extensive and intensive margin
- *Colelli et al. (2022)* -> role of energy for adaptation in mitigation pathways

Aging and air-conditioning - projections

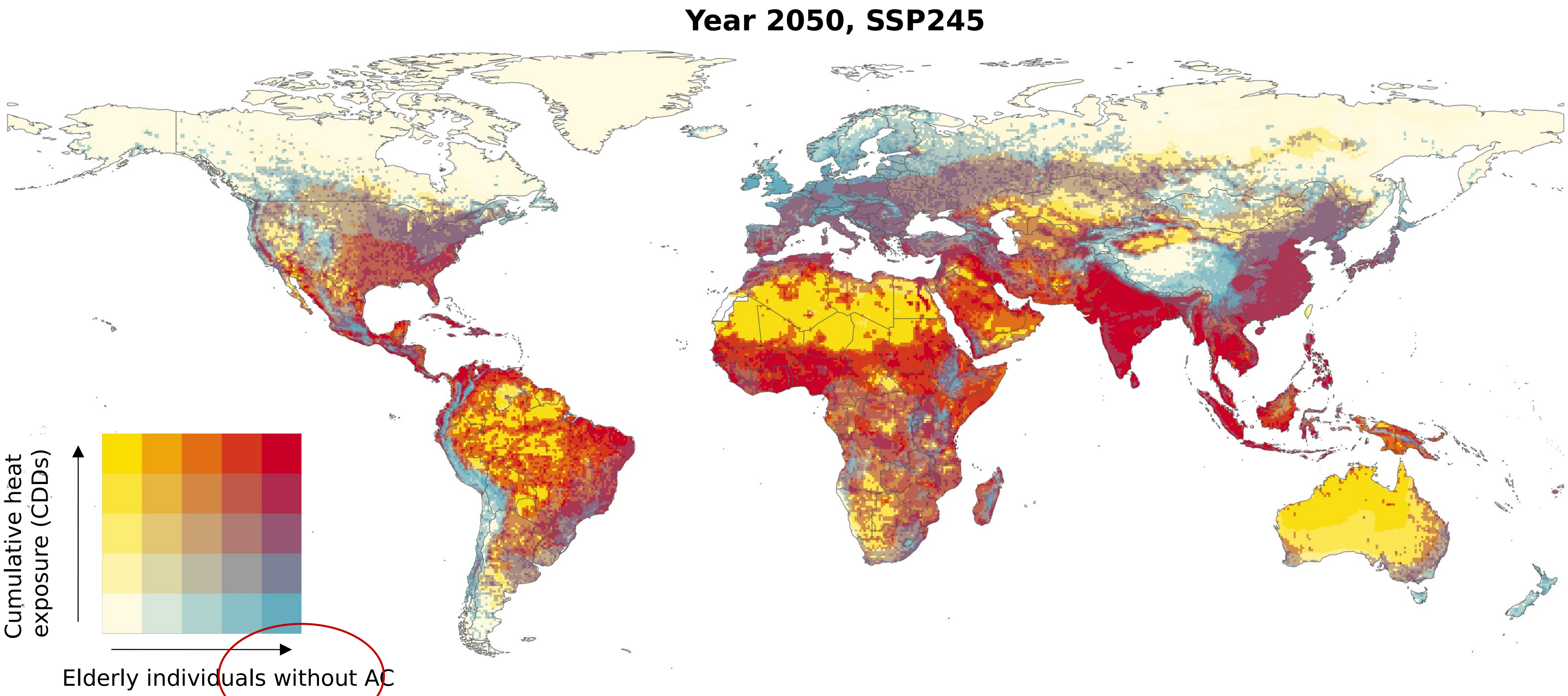


Figure: Falchetta et al. (in preparation), **example for SSP245, year 2050**

Aging and air-conditioning – cooling adaptation deficit

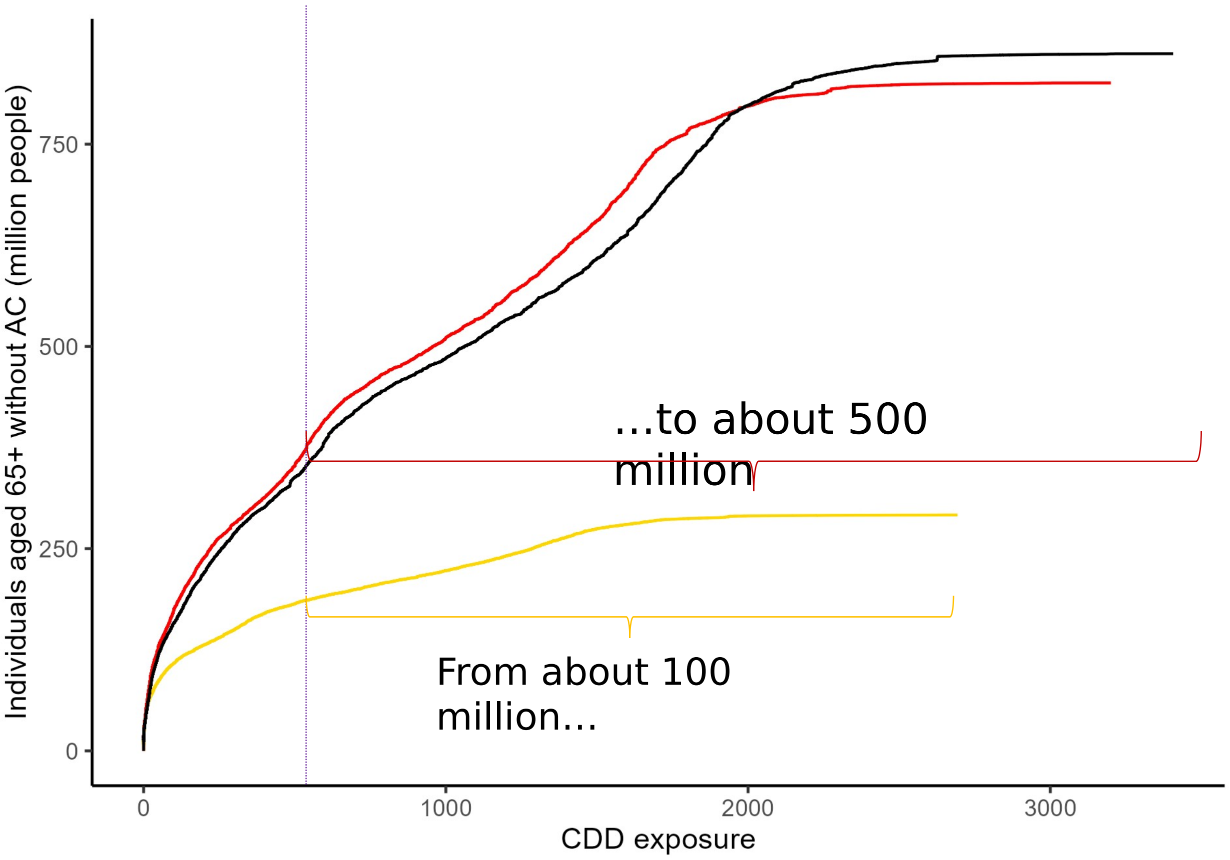


Figure: Falchetta et al. (in preparation)

The global elderly cooling gap (**GECG**) is defined as the number of elderly individuals without cooling in year *t* as a function of their cumulative heat exposure

It is a **function** of: population aging, population growth, AC penetration change, climate change

GECG in 2020:

- 180 million >0 & <500 CDD/yr
- 40 million > 500 & < 1000 CDD/yr
- 70 million >1000 CDD/yr

GECG in 2050 (SSP245-585 ranges):

- 350 million >0 & <500 CDD/yr
- 150 million > 500 & < 1000 CDD/yr
- 350 million >1000 CDD/yr