The Impact of Air-conditioning on Residential Electricity Consumption across World Countries

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Introduction

Motivation

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  - $\hookrightarrow$ 80% reduction in heat-related mortality in US
    (Barreca et al. 2016, JPE)
- Demand for air-conditioning is projected to skyrocket, particularly in the **developing world**
  (Davis et al. 2021, GEC; Pavanello et al. 2021, NC)

Research Question

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- Potential relevant repercussions on:
  1. Household expenditure
  2. Energy demand and electricity systems planning
  3. Feedback emission of greenhouse gases, and therefore climate policy, as well as other pollutants

What we do

1. Estimate of the impact of air-conditioning on residential electricity demand
    - Household survey data from 25 countries
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1. Estimate of the impact of air-conditioning on residential electricity demand
    - Household survey data from 25 countries
    - Modelling simultaneously intensive and extensive margin (discrete-continuous)
2. Projections of future electricity consumption for air-conditioning
    - Collecting projections data about several socio-economic and social drivers
3. Back-to-the envelope analysis of the implications of air-conditioning widespread
    - Impact on households' budget shares ⇒ energy poverty (historical)
    - Changes for peak capacity generation (future)
    - Social Cost of "Cooling" (future)

Data

Data

- Pool of **cross-sectional household survey data from 25 countries** (still expanding), with information about:
  - Electricity consumed (kWh/hh/yr)
  - Air-conditioning ownership
  - Households' economic characteristics (e.g. total expenditure, housing, home ownership)
  - Socio-demographic drivers (e.g. education, age, gender, household size)
- Population-weighted climate data from ECMWF ERA5 ($0.25° \times 0.25°$ cells):
  - Cooling and Heating Degree Days ($\overline{T} = 18$ °C)
- Urbanisation shares (Gao and Pesaresi, 2021)
- Electricity prices at sub-national and national level from various sources

Coverage

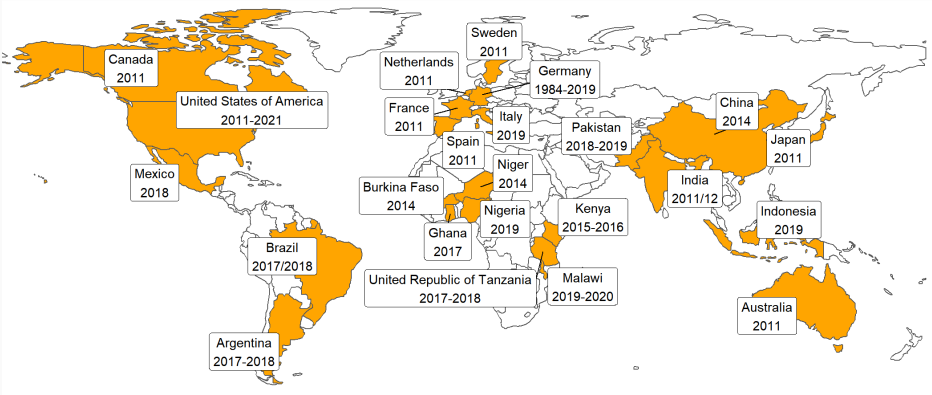


Figure 1: Countries covered in the data set (still expanding)

Theoretical Framework

Simple Adaptation Model 1/2

- Households derive a long-run utility, u, from the consumption of a generic good, x, and from being in a situation of thermal comfort, T:

$$u = u(T, x)$$

- Each household invests in thermal comfort according to a production function

$$T = f(c, q(c))$$

- Role of cooling:

$$\frac{dT}{dc} = \underbrace{\frac{\partial T}{\partial c}}_{\text{direct effect}} + \underbrace{\frac{\partial T}{\partial q}\frac{dq}{dc}}_{\text{role of cooling}}$$

- Each household maximizes the utility under the following budget constraint

$$x + k(q(c)) \leq y$$

Simple Adaptation Model 2/2

- We assume that households can effectively increase their thermal comfort through air-conditioning
- Households maximise their utility with respect to a conditional electricity demand:

$$q = q(c) \rightarrow q = q(c|a)$$

where a indicates whether household owns at least an air-conditioner:

$$a = a(\bar{c}, e)$$

- Solving the model we so get in equilibrium:

$$\underbrace{\frac{\partial k(q^*(c|a))}{\partial q(c|a)}}_{\text{marginal cost of adaptation}} = \underbrace{MRS_{T,x}\frac{\partial f(c, q^*(c|a))}{\partial q(c|a)}}_{\text{marginal benefit of adaptation}}$$

- Final conditional demand for electricity quantity q is:

$$q^* = q(c, p_e, y|a(\bar{c}, e)))$$

Empirical Framework

Discrete-Continuous Framework 1/3

Households simultaneously decide both the change in electricity use for a given level of air-conditioning stock (intensive margin), and the adjustment of the air-conditioning stock (extensive margin):

$$Q_{ic} = \beta_0 + \beta_1 AC_{ic} + \beta_2 AC_{ic} \times f(CDD_{d(i)c}) + \beta_3 f(CDD_{d(i)c}) + \\ + \beta_4 Y_{ic} + \beta_5 P_{ic} + \beta_6 \mathbf{Z}_{ic} + \mu_c + \epsilon_{ic}$$

- Q_{ic}: log of annual electricity demand (in kWh) of household i in country c
- AC_{ic}: dummy variable taking value 1 if household i has an air conditioning installed in its dwelling, 0 otherwise
- $f(CDD_{d(i)c})$: second-degree polynomial of dry-bulb Cooling Degree Days (CDD) experienced in administrative area d in country c during the survey year
- Z_{ic}: vector of household and housing characteristics
- Fixed-effects: country FE (μ_c)

Discrete-Continuous Framework 2/3

- The coefficients of air-conditioning β_1 and β_2 are likely to be endogenous
- Two-stage approach: we introduce a correction term
  (Dubin and McFadden 1984, EC; Davis and Killian 2011, JPE; Barreca et al. 2016, JPE)
- First, we estimate the following logit regression:

$$AC_{ic} = \gamma_0 + \gamma_1 f(\overline{CDD}_{d(i)c}) + \gamma_2 Y_{ic} + \gamma_3 f(\overline{CDD}_{d(i)c}) \times Y_{ic} + \gamma_4 f(CDD_{d(i)c}) + \\ + \gamma_5 P_{ic} + \gamma_6 \mathbf{X}_{ic} + \gamma_7 \mathbf{Z}_{ic} + \mu_c + \eta_{ic}$$

  - $f(\overline{CDD})$: second-degree polynomial of the average of annual dry-bulb Cooling Degree Days (CDD) experienced in administrative area d in country c during the period 1970-(survey year - 1)
  - X_{ic}: vector of price interactions with household size, home ownership and $f(\overline{CDD})$

Discrete-Continuous Framework 3/3

- Second, we then modify the demand equation as follows:

$$Q_{ic} = \beta_0 + \beta_1 AC_{ic} + \beta_2 AC_{ic} \times f(CDD_{d(i)c}) + \beta_3 f(CDD_{d(i)c}) + \\ + \beta_4 Y_{ic} + \beta_5 P_{ic} + \beta_6 \mathbf{Z}_{ic} + \hat{\zeta}_{ic} + \mu_c + \epsilon_{ic}$$

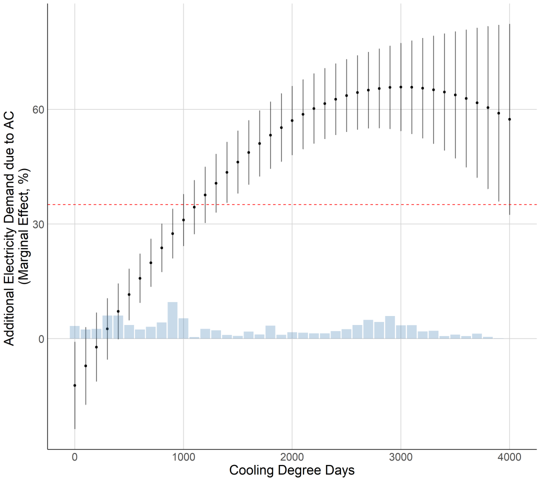
where $\hat{\zeta}_{ic}$ is the correction term and is equal to:

$$\hat{\zeta}_{ic} = \frac{\hat{\pi}_{ic}\, ln(\hat{\pi}_{ic})}{1 - \hat{\pi}_{ic}} + ln(\hat{\pi}_{ic})$$

- Identification: exclusion of the prices interactions $\mathbf{X}_{ic}$ and $f(\overline{CDD})$
- Survey weights are applied in both first and second stage
- Standard errors are clusterised at the ADM1-level

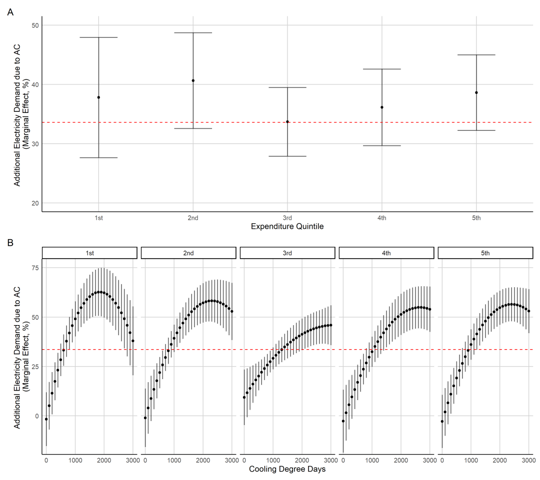
Results

Air-conditioning use and Temperature



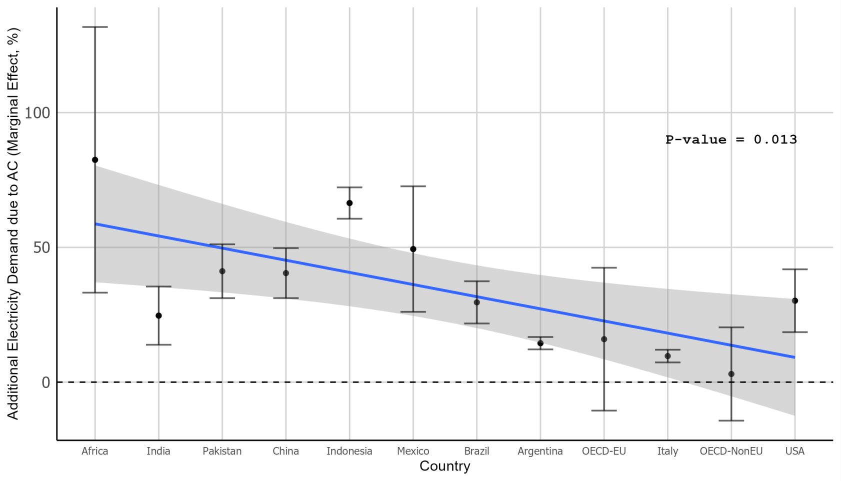
Marginal effects of air-conditioning ownership on household electricity consumption for different level of contemporaneous cooling degree days (CDD). Background shaded in grey: distribution of CDD in the sample. Confidence intervals depict statistical significance level at 95%. Red dashed line corresponds to the average marginal effect (AME).

Heterogeneity - Income Level



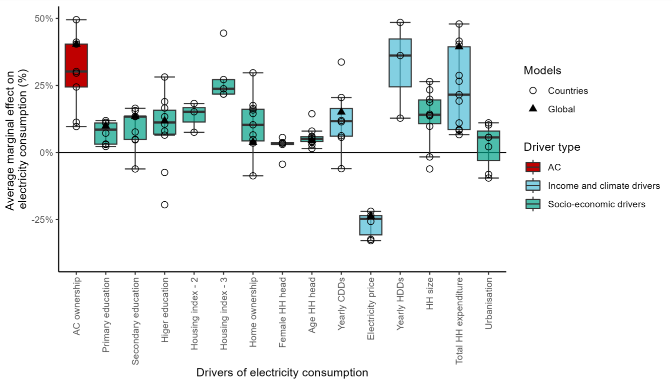
Marginal effects of air-conditioning ownership on household electricity consumption, by country-specific expenditure quintile: (A) Total effects; (B) Effects at different CDD levels. Confidence intervals depict statistical significance level at 95%. Red dashed line corresponds to the pooled estimate.

Heterogeneity - Country Level



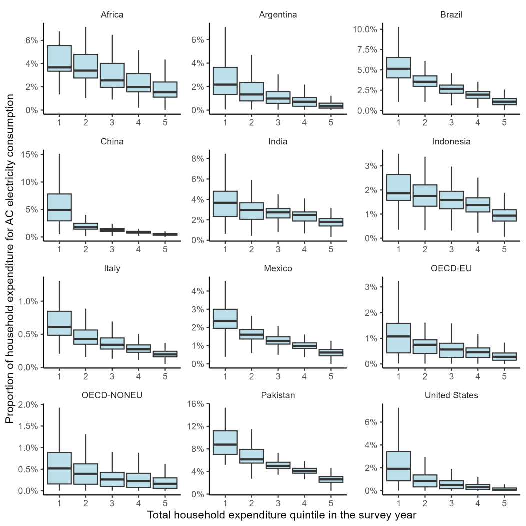
Marginal effects of air-conditioning ownership on household electricity consumption by country. Confidence intervals depict statistical significance level at 95%. Blue line represents the linear regression of country-specific air-conditioning coefficients on countries. Countries are sorted by total expenditure per capita.

Air-conditioning and other Drivers



Boxplot of the marginal effects of the drivers of household electricity consumption. Estimates are based on country-specific average marginal effects from standardised regression coefficients.

Implications: Households’ Budget



Distribution of estimated household (air-conditioning) electricity consumption, stratified by quintile of total household consumption.

Projections

Projections of Air-conditioning Adoption and Use

	AC penetration rate (%)			AC electricity (kWh/hh/yr)			Total AC electricity (TWh)		
	2020	SSP245 (2050)	SSP585 (2050)	2020	SSP245 (2050)	SSP585 (2050)	2020	SSP245 (2050)	SSP585 (2050)
Country	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean
Pool	25.9	**40.3**	**52.7**	1979.3	2100.4	2293.8	532.1	1007.7	1381.5
Africa	3.50	7.6	14.9	332.2	403.6	399.5	0.7	3.5	5.7
Argentina	68.0	85.1	90.6	350.6	495.1	592.7	3.0	6.1	7.0
Brazil	34.3	53.9	71.6	1694.4	1754.8	1967.0	36.9	66.6	91.0
China	57.5	81.8	89.7	959.1	1362.3	1779.5	195.4	363.0	504.0
Indonesia	15.4	45.8	72.7	1404.9	1646.8	1989.2	11.7	45.0	80.7
India	16.1	48.5	65.1	1384.2	1614.8	1838.7	72.6	323.0	439.5
Italy	69.3	86.2	91.2	284.8	499.5	648.1	4.3	9.2	14.6
Mexico	27.9	45.0	57.7	629.8	780.5	800.9	5.7	13.6	15.1
OECD-EU	35.7	50.1	57.5	888.0	1158.0	1149.6	14.6	29.7	39.4
OECD-NonEU	94.0	97.7	98.7	986.3	1371.4	1837.7	52.3	76.9	122.4
Pakistan	14.8	24.0	33.7	1708.0	1839.2	1909.2	8.1	20.0	24.4
United States	94.9	97.8	98.6	2506.5	3215.6	3580.6	293.1	458.9	609.30

Total air-conditioning electricity use increases by 2 to 2.6 times

Social Drivers

Implications: Power System

Take **India** as example $\longrightarrow$ peak generation capacity of **230 GW** in 2023

- Assume that about half of the projected AC electricity consumption growth is concentrated in the summer season (March to May) (Ramapragada et al. 2022)
- An average run time of about six hours
- Homogeneous distribution of use in this period and in each hour of the day

$\hookrightarrow$ An increase of at least 150-200 GW in peak generation capacity would be necessary to satisfy the increased hourly electricity demand from air-conditioning

Implications: Emissions and Social Cost of Cooling

- In the 25 countries:
  - **Current CO_2 emissions** due to AC electricity: 365 $MtCO_2$
  - **Future CO_2 emissions** due to AC electricity: 692-948 $MtCO_2$
- Central value of the social cost of carbon of 185 USD/tCO_2 (Rennert et al. 2022)

  ↪ Social Cost of Cooling: **128-175 billion USD** in 2050
- Note that:
  - Rode et al. (2021): decreases in global heating energy use should counterbalance the surge in cooling energy use
  - Yet, high spatial and social unbalance in the source of emissions and who bears them

Conclusions

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- On average, owning air-conditioning increases household electricity consumption by nearly 34%
- The impact on residential electricity is heterogeneous and varies:
    1. across temperature levels
    2. across income levels
    3. across countries
- Poor households in some countries already spend 5% of their budget on electricity for air-conditioning → new dimension of **energy poverty**
- Without technological improvements, the increasing adoption and use of air-conditioning would have important repercussions

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Appendix

Impact of Air-conditioning on Electricity Consumption

	OLS (1)	OLS (2)	DMF (3)	DMF (4)
AC	0.601***	0.363***	0.336***	-0.122**
	(0.033)	(0.031)	(0.037)	(0.058)
AC $\times$ CDD				0.052***
				(0.008)
AC $\times$ CDD^2				-0.001***
				(0.000)
Controls	NO	YES	YES	YES
Correction Term	NO	NO	YES	YES
Country FE	YES	YES	YES	YES
R^2	0.695	0.721	0.721	0.725
Countries	25	25	25	25
Observations	673219	673219	673219	673219

Notes: (1), (2), (3) and (4) standard errors at the ADM1-level in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Regressions are conducted using survey weights. ”Controls” include natural logarithm of electricity price, and weather and socio-economic and demographic variables.

Full Robustness

Impact of Air-conditioning on Electricity Demand

	OLS (1)	OLS (2)	DMF (3)	DMF (4)
AC	0.601***	0.363***	0.336***	-0.122**
	(0.033)	(0.031)	(0.037)	(0.058)
AC $\times$ CDD				0.052***
				(0.008)
AC $\times$ CDD^2				-0.001***
				(0.000)
CDD		0.025**	0.024**	0.017
		(0.010)	(0.011)	(0.011)
CDD^2		-0.000*	-0.000*	-0.000
		(0.000)	(0.000)	(0.000)
HDD		0.001	0.000	0.006
		(0.008)	(0.008)	(0.007)
HDD^2		-0.000	-0.000	-0.000
		(0.000)	(0.000)	(0.000)
Log(Exp)		0.372***	0.371***	0.368***
		(0.031)	(0.031)	(0.031)
Log(P)		-0.388***	-0.391***	-0.392***
		(0.084)	(0.085)	(0.085)
Urbanisation (%)		-0.182	-0.177	-0.134
		(0.152)	(0.149)	(0.140)
House Ownership (Yes = 1)		0.033**	0.034**	0.038***
		(0.014)	(0.015)	(0.014)
Household Size		0.024*	0.024*	0.025*
		(0.013)	(0.013)	(0.013)
Primary Edu.		0.111***	0.106***	0.098***
		(0.015)	(0.015)	(0.014)
Secondary Edu.		0.153***	0.147***	0.134***
		(0.020)	(0.020)	(0.020)
Post Edu.		0.155***	0.147***	0.117***
		(0.028)	(0.028)	(0.027)
Age (Head)		0.002***	0.002***	0.002***
		(0.001)	(0.001)	(0.001)
Female (Yes = 1)		0.015*	0.015*	0.016*
		(0.009)	(0.009)	(0.008)
ζ			-0.036**	-0.022*
			(0.014)	(0.012)
Country FE	YES	YES	YES	YES
Adj. R^2	0.695	0.721	0.721	0.725
Countries	25	25	25	25
Observations	673215	673215	673215	673215

Notes: (1), (2), (3) and (4) clustered std. errors at the first subnational (ADM1) level in parentheses in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Regressions are conducted using survey weights.

Air-conditioning Ownership

	LPM		Logit	
			Coefficients	M. Effects
	(1)	(2)	(3)	(4)
$\overline{\text{CDD}}$	0.096**	0.033	0.596*	0.057*
	(0.039)	(0.040)	(0.334)	(0.032)
$\overline{\text{CDD}}^2$	-0.002**	-0.000	-0.021**	-0.002**
	(0.001)	(0.001)	(0.009)	(0.001)
$\overline{\text{CDD}}$ × Log(Exp)		0.008***	0.038	0.004
		(0.003)	(0.024)	(0.001)
$\overline{\text{CDD}}^2$ × Log(Exp)		-0.000**	0.001	0.000
		(0.000)	(0.001)	(0.000)
CDD	-0.058*	-0.067*	-0.461*	-0.044*
	(0.035)	(0.035)	(0.251)	(0.024)
CDD^2	0.001	0.001	0.002	0.000
	(0.001)	(0.001)	(0.005)	(0.001)
$\overline{\text{CDD}}$ × Log(P)	-0.005	-0.005	0.034	-0.003
	(0.006)	(0.006)	(0.059)	(0.006)
$\overline{\text{CDD}}^2$ × Log(P)	0.000	0.000	-0.002	-0.000
	(0.000)	(0.000)	(0.002)	(0.000)
Log(Exp)	0.090***	0.032**	0.225*	0.022*
	(0.007)	(0.016)	(0.132)	(0.013)
Log(P)	0.062	0.056	-0.040	-0.004
	(0.057)	(0.056)	(0.431)	(0.041)
Log(P) × Household Size	0.000	0.000	-0.049	-0.005
	(0.004)	(0.004)	(0.045)	(0.004)
Log(P) × House Ownership	0.039***	0.036***	0.152	0.015
	(0.014)	(0.014)	(0.117)	(0.011)
Urbanisation (%)	0.328***	0.341***	2.902***	0.280***
	(0.100)	(0.099)	(0.640)	(0.060)
House Ownership (Yes = 1)	0.105***	0.101***	0.663***	0.059***
	(0.020)	(0.019)	(0.177)	(0.015)
Household Size	-0.004	-0.004	-0.146**	-0.014**
	(0.005)	(0.005)	(0.065)	(0.006)
Primary Edu.	0.048***	0.045***	0.670***	0.058***
	(0.009)	(0.009)	(0.064)	(0.006)
Secondary Edu.	0.118***	0.114***	1.156***	0.110***
	(0.014)	(0.014)	(0.088)	(0.008)
Post Edu.	0.196***	0.193***	1.795***	0.180***
	(0.016)	(0.016)	(0.107)	(0.012)
Age (Head)	0.000**	0.000**	0.007***	0.001***
	(0.000)	(0.000)	(0.001)	(0.00)
Female (Yes = 1)	-0.005	-0.004	-0.134***	-0.013***
	(0.004)	(0.004)	(0.036)	(0.004)
Country FE	YES	YES	YES	YES

Robustness Checks

	Sub-national FE		CDD 24 - HDD 15		No Elec. Price		Price Interactions		Unweighted	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
AC	0.305***	0.003	0.392***	0.200***	0.361***	0.011	0.362***	0.034	0.444***	-0.145***
	(0.024)	(0.041)	(0.011)	(0.017)	(0.012)	(0.027)	(0.012)	(0.027)	(0.004)	(0.009)
AC × CDD		0.036***		0.079***		0.041***		0.038***		0.045***
		(0.007)		(0.005)		(0.004)		(0.004)		(0.001)
AC × CDD^2		-0.001***		-0.003***		-0.001***		-0.001***		-0.001***
		(0.000)		(0.000)		(0.000)		(0.000)		(0.000)
Controls	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Correction Term	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Sub-national FE	YES	YES	NO	NO	NO	NO	NO	NO	NO	NO
Country FE	NO	NO	YES	YES	YES	YES	YES	YES	YES	YES
Adj. R^2	0.729	0.728	0.730	0.732	0.720	0.722	0.732	0.734	0.701	0.705
Countries	25	25	25	25	25	25	25	25	25	25
Observations	534892	534892	673215	673215	673215	673215	673215	673215	673215	673215

Notes: (1)-(10) std. errors clustered at the first subnational (ADM1) level in parentheses in parentheses. $***p < 0.01$; $**p < 0.05$; $*p < 0.1$. Regressions (1)-(8) are conducted using survey weights. "Controls" include natural logarithm of electricity price, and weather and socio-economic and demographic variables.

Main

Projections: Data

- Grid-cell level SSP-RCP-consistent projections:
  - Gross Domestic Product and population (Murakami et al. 2017)
  - Climate (NEX-GDDP-CMIP6)
  - Urbanisation (Gao and Pesaresi, 2021)
- National-level projections:
  - Socio-demographic drivers (Samir and Lutz, 2017)
- Two scenarios:
  - RCP4.5-SSP2
  - RCP8.5-SSP5

A Household-level Approach

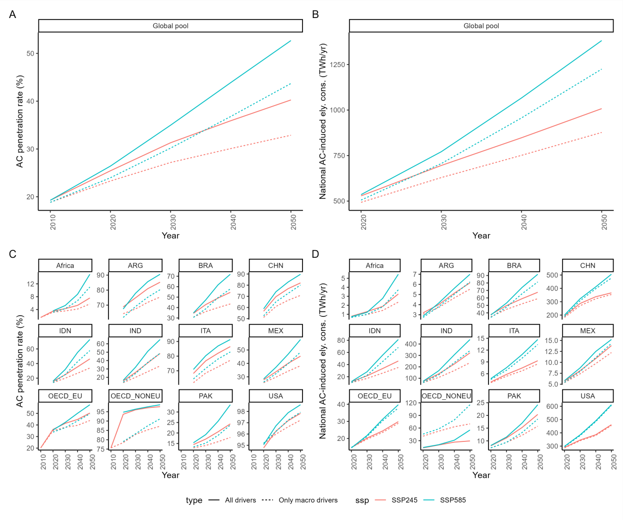
- We use our pool regressions to get:

  1. Future air-conditioning ownership
  2. Future household electricity demand for cooling

- Bottom-up approach:

  1. Update both the first and second stage covariates with future values
  2. Re-fit the first-stage logit regression to calculate the future adoption probability for each household
  3. Update air-conditioning ownership, and predict future household-level electricity demand using the coefficients from the second-stage
  4. Multiply future household total electricity consumption by the air-conditioning's coefficients to get household future electricity for cooling

The Relevance of Social Drivers



Comparison of future (A) air-conditioning penetration and (B) total electricity consumption for cooling (TWh/yr) when projecting all drivers (bold line) or only climate and income (dashed line)

Back