FONDAZIONE ENI ENRICO MATTEI

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A Spatially-Explicit Inquiry into the Dynamics of Access to Electricity in Sub-Saharan Africa

Working Paper

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FEEM Research Seminar

NB This presentation refers to a preliminay version of the working paper

Outline

1. **Background & literature**
2. **Estimation methodology and data**
3. **Estimation results**
4. **Post-estimation analysis**
   - Access to electricity inequality
   - Urban areas and proximity
   - O&G proximity and RE potential
5. **Modelling of the impacts of economic development on the electrification process**
   - Background
   - Models specification
   - Results
6. **Conclusions**

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1. Background

- **Electricity access rates:**
  - World's lowest in most countries of Sub-Saharan Africa
  - Average of 71% and 25% in urban and rural areas, respectively.
- People without access: paucity of detailed data
  - Where?
  - How many?
  - Why?
- Empirical strategy
  - Combine new generation satellite **night-time lights** imagery (from NASA's VIIRS satellite) and the CIESIN's GPW gridded **population** dataset

    → **high-resolution map of the unlit population for year 2015**
- Spatially explicit dataset used for:
  - Better understanding the relative significance of different factors in the **economics of access to electricity** and the key underlying **spatial trends**
  - **inform policy** for the power sector's development in the macro-region

1.

Literature

a) Covariates, drivers, and impacts of access

1. **Studies on electrification ←→ economic development**
   - e.g. Wolde-Rufael 2014; Apergis and Payne 2011
   - **Using panel bootstrap causality, dynamic panel, Granger causality…**
2. **Studies on socio-economic impacts of electrification**
   - e.g. Khandker et al. 2013; Lipscomb et al. 2013; Salmon and Tanguy 2016; Ahmad et al 2017; Barron and Torero 2017.
3. **Studies on the demand-side (drivers of the electrification process)**
   - Khennas 2012; Inglesi-Lotz and Pouris 2016; Westley 1984; Abosedra et al. 2009; Zachariadis and Pashourtidou 2007; Louw et al. 2008
4. **Studies on the covariates that statistically explain access levels**

Most studies are either country-level or very local (on the field)

1. Literature

a) Covariates, drivers, and impacts of access

b) Night lights in the social sciences

Inter alia

- Henderson et al. 2012; Chen and Nordhaus (2011)

  → econometric estimation of real income growth
- Shi et al. (2014) → modelling GDP and electric power consumption

... many other applicaitons in energy (CO2 emissions, gas flaring…), urban and regional economics and other disciplines

Literature

a) Covariates, drivers, and impacts of access

b) Night lights in the social sciences

c) Estimations of the number of people without access

- Doll and Pachauri (2010)

  → nighttime lights (old generation DMSP-OLS) to assess electrification between years 1990 and 2000.

- Min et al. (2013)

  → combines micro-level data from on-field analysis w/ n.l. data to provide counterfactual: find lights proxy well village electrification but weakly household consumption levels

- Burlig and Preonas (2016)

  → regression discontinuity design w/ n.l. data to evaluate the potential impact of RGGVY, an extensive electrification program in India

- Bertheau et al. (2017)

  → VIIRS lights data to estimate electricity access and subsequently to perform a simple electrification analysis

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2. Estimation methodology

1) Import **night lights and population** raster files

2) Create condition such that if a light layer pixel value is equal to 0 (denoting a dark area), then its value is set to 1; otherwise, if light is detected in that pixel, it is set it to 0;

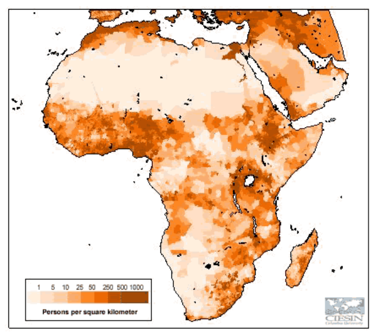
3) Multiply Boolean raster by the population raster, so that the newly created raster only includes population counts where the light is absent;

4) **Perform zonal statistics** into Global Administrative Unit Layers (GAUL) geographical units to calculate local electrification rates and absolute number of people without access;

5) **Compare** aggregated results with country-level data from IEA's *World Energy Outlook 2017* to check consistency;

6) Provide **descriptive statistics** and move to **post-estimation analysis**.

Night lights layer → Boolean type x Population layer = **Estimation layer**



Data

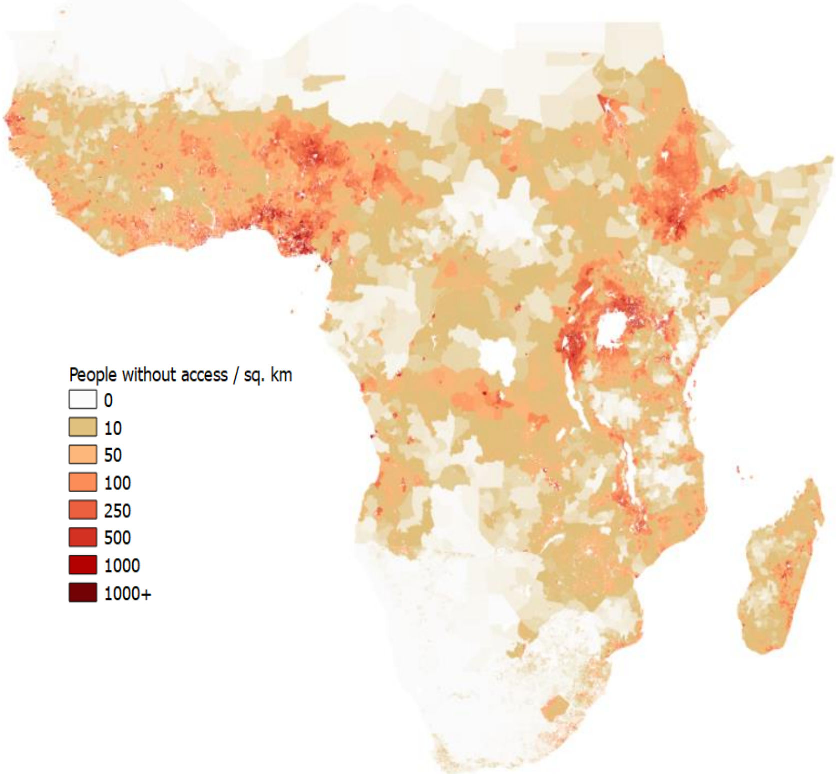
Data	Unit	Source
VIIRS 2015 night light DNB composite	nW · cm^{-2} · sr^{-1}	NOAA/NCEI (2017)
SEDAC gridded population of the world (GPW) v4	People · km^{-2}	CIESIN (2016)
IEA electrification rates	%	IEA (2017a)
Global Administrative Unit Layers (GAUL), levels 1-2	Regions boundaries	FAO (2015)
LANDSCAN World Urban Areas	Metropolitan areas boundaries	Patterson and Kelso (2012)
Africa - Electricity Transmission Grid	Position; volt (electric potential); length (km)	Arderne (2017)
Gridded GDP	Thousands of constant 2000 USD	Peduzzi and UNEP/DEWA/GRID-Geneva (2012)
Travel time to the nearest city of 50,000 or more people	hours	Nelson (2008)
ASTER Global Digital Elevation Map	meters	METI and NASA (2011)
CRU TS v4.01 historical precipitations and temperature	mm/year; degrees Celsius	Harris et al. (2014)
Potential Solar PV output	kWh/kWp	SolarGIS (2017)
Mean wind speed	m/s	Global Wind Atlas (2017)
Oil and gas fields	Position	Lujala et al. (2007)

Outline

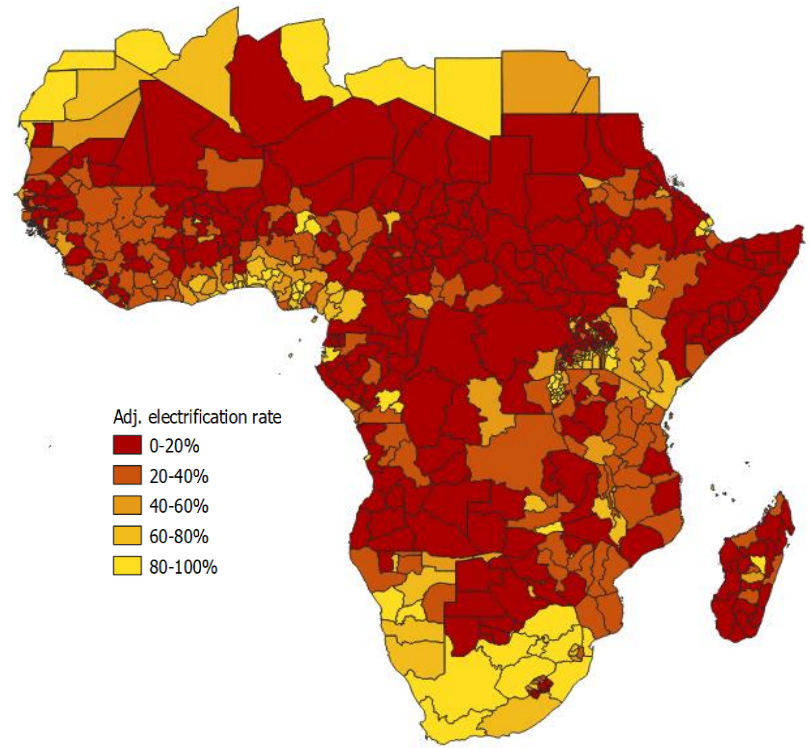
3. Estimation results

732.65 million → **22%** above of 600 million reported as **people living without access to electricity** by the IEA (2017)

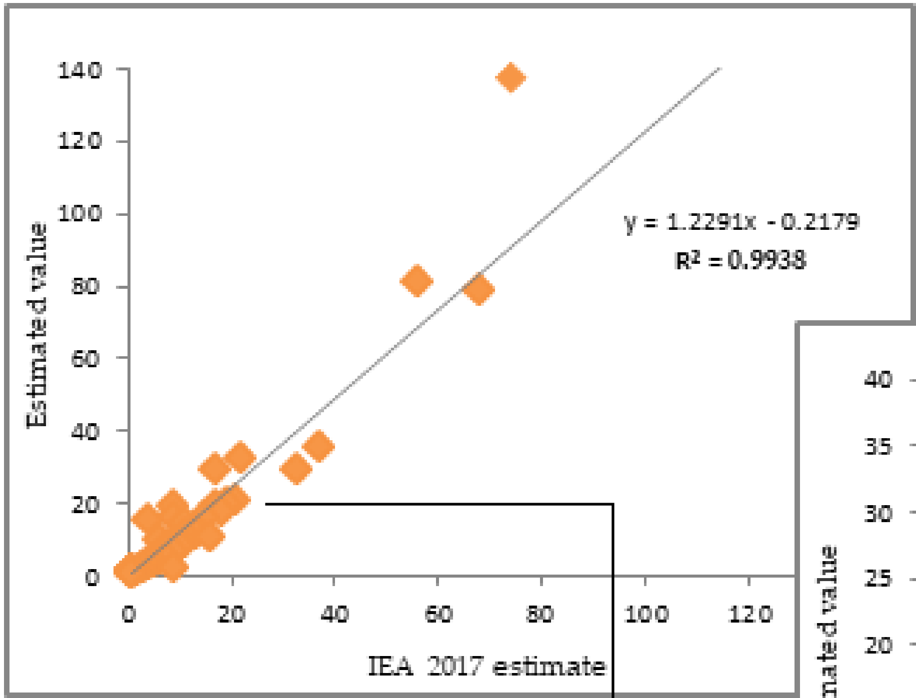
Absolute number of people without access (density)



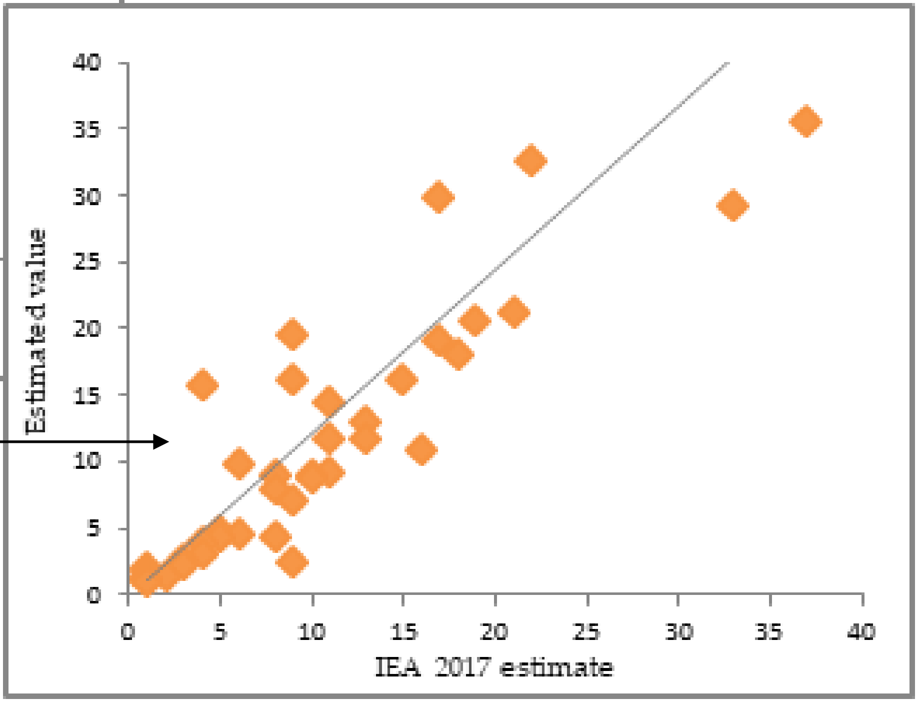
Sub-national electrification rates



Correlation of estimates with IEA values



Zoom



3.

Zoom (against electricity transmission and distribution grid)

Analysis enables :

- spatial electrification studies
- least-cost electrification modelling

e.g. in every cell

min cost (tech_i, electr_tier)

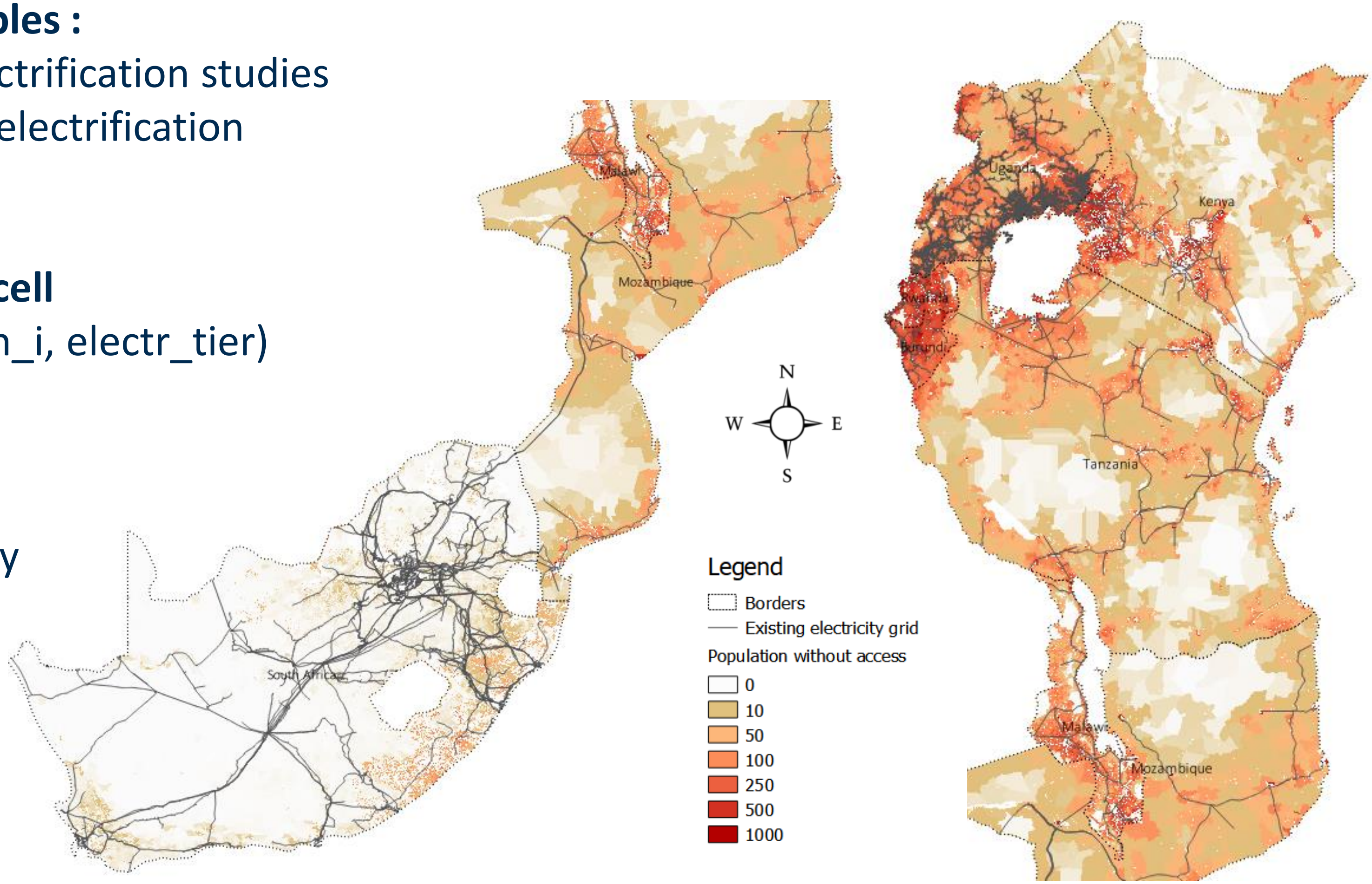
s.t.

elrate=1

LCOE_solar=x

LCOE_diesel=y

…



3. Overestimation: potential expainations and sensitivity check

- **Why do we overestimate vs. IEA?**

a) Peri-urban (slum) populations

→ masking a 25-km radius buffer around largest cities away from the estimate makes the discrepancy almost vanish

Country	IEA (2017a)	Est. with cities	Est. without cities
Nigeria	74	137.60	76.60
Ethiopia	56	81.10	58.49
DR Congo	68	78.80	62.94
Cameroon	9	19.36	12.62
Ivory Coast	9	15.98	13.35
Kenya	17	29.70	16.40
Ghana	4	15.72	12.84
Sudan	22	32.57	30.10
Total SSA	**588-600**	**732.65**	**598.89**

b) Weak proxying of low consumption (e.g. absent streetlights in rural areas)

Potential solution (work in progress):

→ use **mobile phone coverage +** spatially-explicit big data on **internet services usage** to proxy areas where there is at least some access to **charge a mobile phone**

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SEDAC gridded population of the world (GPW) v4	$People \cdot km^{-2}$	CIESIN (2016)
Electrification rates and number of people without access	%, people	Author's elaboration
IEA electrification rates	%	IEA (2017a)
Global Administrative Unit Layers (GAUL), levels 1-2	Regions boundaries	FAO (2015)
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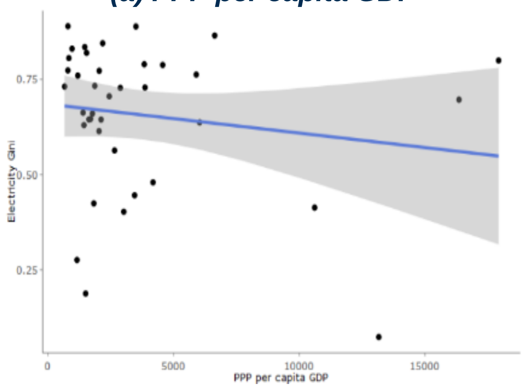
Oil and gas fields	Position	Lujala et al. (2007)

Access to electricity inequality - relative correlations

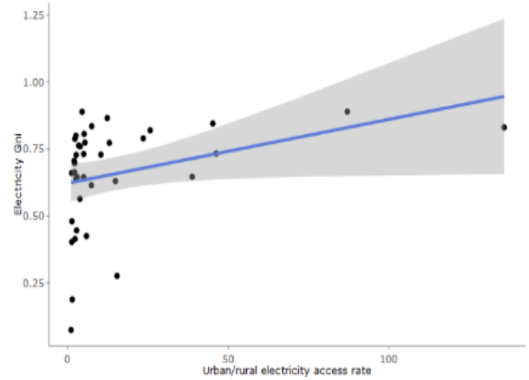
Gini coefficients of electricity access inequality in (a) standard and (b, c) spatial formulations
(calcuated in R following Kalogirou 2017)

Country	Gini elect. coefficient	Gini neighb. fract.	Gini non-neighb. fract
Congo	0.89	0.11	0.89
C.Af.Rep	0.89	0.14	0.86
Angola	0.86	0.05	0.94
Chad	0.84	0.03	0.97
Eritrea	0.84	0.19	0.81
South Africa	0.07	0.17	0.83
Malawi	0.28	0.39	0.61
Kenya	0.40	0.13	0.87
Namibia	0.41	0.07	0.93
Rwanda	0.42	0.42	0.58

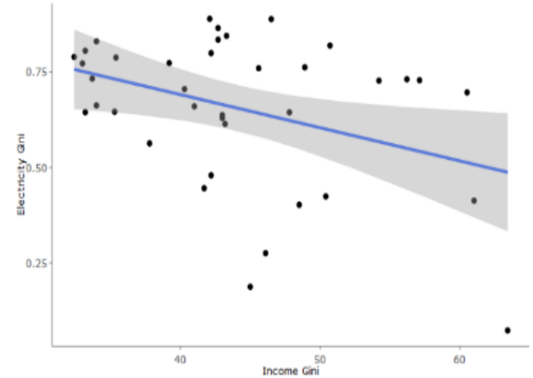
(a) PPP per capita GDP



(b) Urban/rural electricity access rate

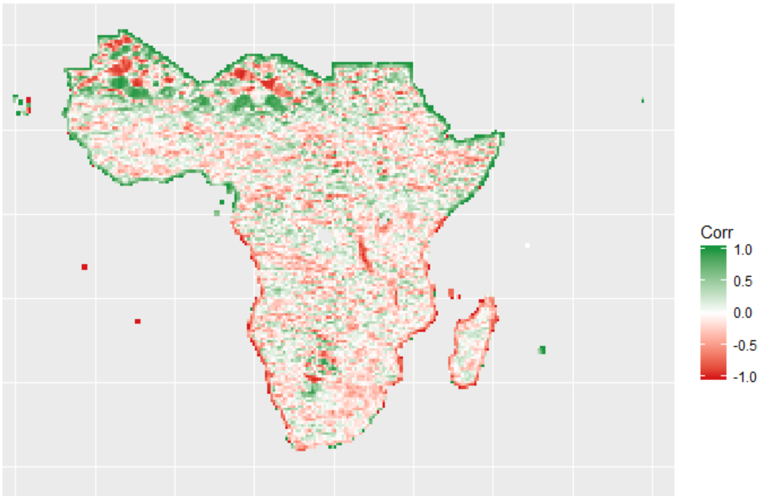


(c) Income Gini



4. Urban areas and proximity

	(1)	(2)	(3)
VARIABLES	**Elrate (all GAUL)**	**elrate (rural)**	**elrate (urban/peri-urban)**
urbtimemea	-0.0453***	-0.0121***	-0.212***
	(0.00308)	(0.00160)	(0.0141)
urbtimemea^2	0.00122***	0.000284***	0.0158***
	(0.000148)	(5.33e-05)	(0.00190)
Constant	0.338***	0.141***	0.682***
	(0.0115)	(0.00888)	(0.0207)
Observations	4,270	2,950	1,320
R-squared	0.184	0.031	0.363



- Simple fractional probit regressions to assess correlation → **evidence of a negative quadratic relationship**
- **Focal correlation map of el. rate and effective urban distance**

O&G proximity and RE potential

VARIABLES	(1) elrate	(2) elrate	(3) elrate	(4) elrate	(5) elrate	(6) elrate
ogfielddis	0.000425***	-0.000147**				
	(3.73e-05)	(7.23e-05)				
pvpotmean			0.0969***	-0.0177		
			(0.0140)	(0.0233)		
windspmean					0.211***	-0.0490
					(0.0226)	(0.0431)
Country fixed effects (F-test of joint sig.)	-	2950.57***	-	3056.06***	-	3188.01***
Constant	-1.794***	-2.101***	-3.008***	-1.910***	-2.434***	-1.989***
	(0.0352)	(0.109)	(0.227)	(0.407)	(0.109)	(0.206)
Observations	2,950	2,950	2,950	2,950	2,950	2,950

- Substantial impact of adding country fixed effects
- O&G distance negatively correlated with rural access
- Solar and wind potential not systematically correlated with access in rural areas

→ Countries with higher level of access are those with higher PV potential and wind speed, but this **does not apply at the sub-national scale** for rural provinces

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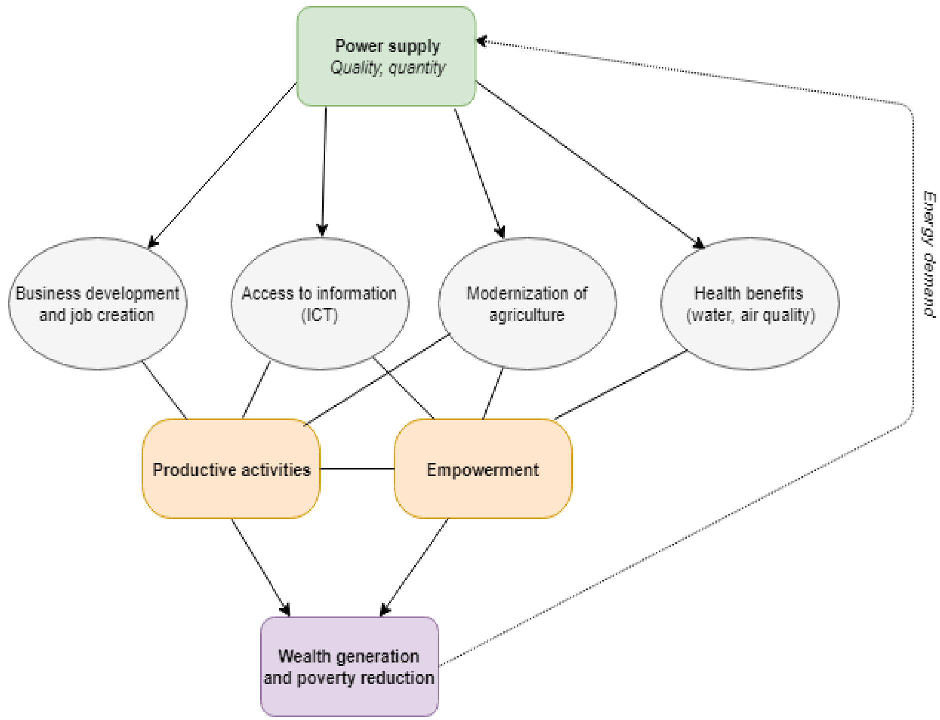
How does economic growth drive the electrification process?



Is there an im**pact of economic development on the process of rural electrification** at the *within-country* level, after controlling for other drivers?

5. Econometric modelling challenges

➢ **Country fixed effects**

To **control** for national economic development level, institutions, electrification policy and efforts...

➢ **Omitted variable bias**

Many potential variables correlated with GDP that are **omitted** from the specification $Cov(GDP_{ic}, u_{ic}) \neq 0$

➢ **Endogeneity (simultaneous causality)**

Causality direction between GDP and el. rate highly debated in the literature → need to break likely simultaneous causality to **separate** direction of effects

➢ **Spatial autocorrelation**

Represents a violation of GM4 $Cov(\varepsilon_i, \varepsilon_j) = 0, (i \neq j)$ → implies **serial correlaiton over space**, needs to be controlled for, otherwise wrong SEs and inference

5. Model specifications

$$Y_{ic} = \alpha_0 + GDP_{ic}\beta_1 + X_{N_{ic}}\beta_N + \varepsilon_{ic}$$

1- Fractional probit

$$Y_{ic} = \alpha_0 + \widehat{GDP}_{ic}\theta_1 + X_{N_{ic}}\beta_N + \varepsilon_{ic}$$

2- 2SLS fractional probit

$$Y_{ic} = \alpha_0 + WY_{-1\,ic}\zeta_1 + \widehat{GDP}_{ic}\theta_2 + X_{N_{ic}}\beta_N + \varepsilon_{ic}$$

3- Spatial autoregressive IV model (SAR-spatial lag model)

$Y_{ic} = \alpha_0 + \widehat{GDP}_{ic}\theta_1 + X_{N_{ic}}\beta_N + u_{ic}$ **with** $u_{ic} = Wu_{-1\,ic}\lambda_1 + \varepsilon_{ic}$

4- Spatial error model (SEM)

$$Y_{ic} = \alpha_0 + WY_{-1\,ic}\zeta_1 + \widehat{GDP}_{ic}\theta_2 + X_{N_{ic}}\beta_N + u_{ic}$$

5- Spatial autoregressive combined model (SARAR)

$$Y_{ic} = \alpha_0 + WY_{-1\,ic}\zeta_1 + \widehat{GDP}_{ic}\theta_2 + X_{N_{ic}}\beta_N + WX_{-1\,ic}\mu_N + u_{ic}$$

5- General nesting spatial model (GNS)

5. Preliminary regression results (baseline + 1st stage IV)

VARIABLES	(1) Fractional Probit	(2) 2nd stage frac. Prob. IV	(2*) 1st stage
gdpdensity	0.000986*** (0.000365)	0.0105*** (0.00224)	-
popsum	-5.55e-08 (1.05e-07)	-8.41e-08 (7.83e-08)	5.14e-06* (3.08e-06)
elevmean	-0.0200*** (0.00761)	0.00200 (0.00708)	-5.869*** (1.218)
precmeanme	-	-	1.038*** (0.391)
tempmeanme	-	-	-8.897*** (1.882)
Country fixed effects (Chi-squared/F-test)	2635.69***	1296.84***	13.89***
Constant	-2.016*** (0.122)	-1.837*** (0.180)	261.2*** (52.34)
Rho	-	-0.815*** (0.155)	-
Sigma	-	4.223*** (0.229)	-
AMEs (elasticity)	0.0032*** (.0012)	0.1978*** (.0423)	-
Observations	2,950	2,950	2,950

Preliminary regression results (spatial models)

VARIABLES	(3) SAR	(4) SEM	(5) SARAR	(6) GNS
gdpdensity	0.000393***	0.000481***	0.000330***	0.000264***
	(0.000122)	(0.000185)	(0.000115)	(7.07e-05)
popsum	-7.51e-09	-7.63e-09	-7.50e-09	-7.99e-09
	(1.38e-08)	(1.40e-08)	(1.38e-08)	(8.63e-09)
elevmean	-0.00149	-0.00111	-0.00143	-0.000474
	(0.00101)	(0.00112)	(0.00104)	(0.000803)
SAR term	1.228**		1.439***	2.198***
	(0.489)		(0.547)	(0.305)
SE term	-	3.444***	1.872***	1.607***
		(0.719)	(0.323)	(0.278)
sp.l.elevmean	-	-	-	-0.0153***
				(0.00359)
sp.lag.popsum	-	-	-	-4.86e-07
				(3.97e-07)
Wald test of spatial terms	6.31***	22.91***	44.78***	164.13***
Country fixed-effects (chi2)	3266.45***	3266.45***	3990.71***	1847.50***
Constant	-0.0169	0.0311**	-0.0164	0.0304
	(0.0195)	(0.0135)	(0.0219)	(0.0287)
AMEs (elasticity)	0.012	0.009	0.020	≈0
Observations	2,950	2,950	2,950	2,950

5.

Average marginal effects

Model	(1) Fractional Probit	(2) 2SLS IV Probit	(3) SAR	(4) SEM	(5) SARAR	(6) GNS
AMEs (*dyex*) inverse-distance weight matrix	0.003%	0.198%	0.012%	0.009%	0.02%	-0.002%
AMEs (*dyex*) contiguity weight matrix			0.018%	0.02%	0.013%	0.012%

- **AMEs →** obtained by calculating marginal effects in elasticity terms (*ey/dx*) at every observed value of each variable X_i and **averaging across the resulting effect estimates**
- Small but positive and statistically significant **impact of economic development on electrification** (after controlling for geographic and institutional factors)
- Representative rural GUAL-2 region w/ mean GDP density (output/km^2) of 1,889 constant 2000 USD (the median value in the dataset). *Ceteris paribus* mean **1% increase in the region's GDP density →** expected **0.009-0.02%** increase in the electrification rate.

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6. Scheduled improvements

- **New data sources to be added (to post-estimation correlation analysis and regression specifications):**
    - Replace wind speed with wind capacity factor (modelled)
    - Try to replace temp/prec with number/intensity of hydrological droughts in the last 50 yrs
    - Distance from electiricity substations (OSM data)
    - Small/mini hydro potential (KTH data)
    - Road network density (CIESIN)
    - Power plants (Energydata.info)
    - Coal plants and coal bearing areas distance (EndCoal's Global Coal Plant Tracker)
    - Pipelines distance
    - Cost of diesel to power genset (Travel-time based GIS computation)
    - Distance from coast (degree of landlock)
    - Terrain ruggedness index (Nunn and Puga 2012)
- **Try different spatial scales** for post-estimation analysis (points vs. level 1 vs. level 2) to cope with *modifiable areal unit problem* (Yang 2005)
- **More proximity/distance-to-nearest-hub GIS analysis**

6. Conclusions

- Nighttime lights-based estimate **consistent** with IEA data (R^2 = 99.38% country-level).
- **732 million** people living in the dark in Sub-Saharan Africa in 2015 (+22%) over IEA threshold.
- Peri-urban population and population with very low levels of access **largely explain the discrepancy .**
- Republic of Congo, Central African Republic, Angola, Chad, and Eritrea are identified as the countries with the greatest ***within*** **access inequality**, while South Africa, Malawi and Kenya figure among the **least inequal**.

6. Conclusions cont'd

- Evidence of **quadratic negative link between travel time** to the closest mid-sized centre (50,000+ inhabitants) and **access** to electricity
- In GAUL-2 provinces, long-run averages of **climate variables** (mean temperature and precipitation levels) are **predictors of local GDP density.**
- When controlling for state fixed effects and other exogenous control variables, **rural economic growth has a small but positive impact on electrification**
- Ceteris paribus mean 1% increase in the region's GDP density → expected 0.009-0.02% increase in the electrification rate.

Thank you very much for your attention!

Questions & suggestions?