Reaching SDG 7: Shedding a light on the causal effect of mini-grids on rural electrification

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In a nutshell

- We investigate the causal impact of mini-grid projects on electrification rate at the village level.
- How ?
  - We rely on geo-localized mini-grid dataset and Nighttime Lights (NTL) to proxy electrification rate.
  - We combine a range of remote sensing data with matching to build a sample comparable to a quasi-experimental study.
  - We estimate the ATT on the NTL using difference in differences.
- Results:
  - We find evidence of a significant and positive effect of mini-grids on the NTL during the first 3 years after implementation.
  - It suggests mini-grids, based on renewable energies, are a viable solution to reach SDG 7.

The big picture: electricity access in Africa

- African countries are aiming to reach the Sustainable Development Goal (SDG) 7, "Ensure access to affordable, reliable, sustainable and modern energy for all".
- In 2020 only 48% of the Sub-Saharan Africa population have access to electricity (WDI, World Bank)
- Important disparities between urban and rural access rates, only 28% in rural areas (WDI, World Bank).
- Existing infrastructures usually struggles to provide sufficient power to the grid leading to outages (blackouts).
  - 77% of African firms experienced outages in 2021 (Enterprise surveys, World Bank).
  - Even leading countries in the electric sector like South Africa are now struggling with 92% of firms affected in 2020.

Technical constraints and solutions for rural electrification

- Current national electric infrastructures have reliability issues.
- Environmental constraints push for reducing the use of fossil fuels.
- Rural areas are difficult to reach by grid extension.
- $\rightarrow$ New technical solution: Mini-grids
  - A mini-grid is an autonomous electrical network, usually at a village scale, that allows to generate and consume electricity on-site. Usually off-grid but can also be connected to regular grid infrastructure.

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Motivation

- The impact of mini-grids in Africa has not been studied with an experimental setting.
- Only anecdotal evidence from NGO reports.
- No proof that NTL can track performance of mini-grids.
- Mini-grids, as any technological solutions, is subject to technical failures.
- → Research questions: Is there a measurable impact of mini-grid projects on the NTL ? If so what is the dynamic ? Are mini-grids a viable solutions to reach SDG 7 ?

Literature: NTL and electrification

- NTL from DMSP satellite has been used as a tool to estimate electrification of rural villages from the grid in different developing countries such as India (Dugoua et al., 2018), Senegal, Mali (Min et al., 2013) and Vietnam (Min and Gaba, 2014).
- NTL have also been found to be a good predictor of power consumption at the national level (Falchetta and Noussan, 2019) and sub-national level (Chand et al., 2009; Shi et al., 2014) down to city level (Ma et al., 2014).
- Meta-analysis on Decentralized Electrification: Mini-grids, of larger size, especially with hybrid renewable sources of energy, have more positive impacts on Lifestyle, Technology use and Household agenda (Berthelemy and Millien, 2018).

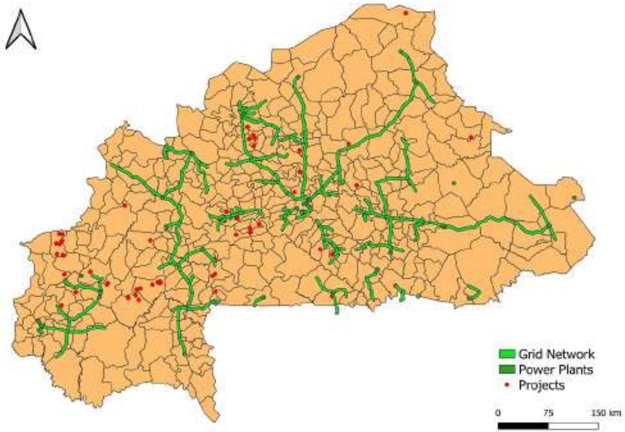
Literature: NTL and electrification

- Authors also mobilized NTL data to estimate electrification rate with either DMSP data (Doll and Pachauri, 2010) or more recent VIIRS data (Falchetta et al., 2019).
- More generally remote sensing literature links NTL to economic activity at sub-national level (Beyer et al., 2022; Hu and Yao, 2021).

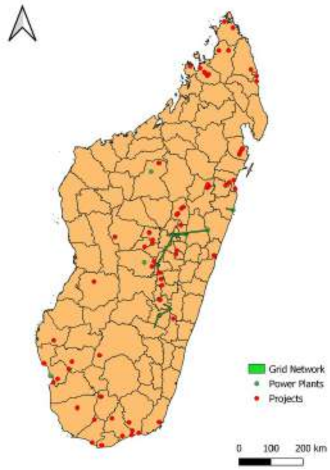
Mini-grids data - Club ER

- Club ER (Association of African rural electrification agencies) worked on a mapping of mini-grid projects in Africa.
- 144 mini-grids projects since 2015, 75 in Burkina Faso and 69 in Madagascar.
- 70% of the projects in our sample were launched after 2018.
- Renewable energy: 62% of the projects rely on solar energy as a renewable source. Second most used renewable source is hydro with 18%.

Burkina Faso's mini-grids



Madagascar's mini-grids



Remote sensing data

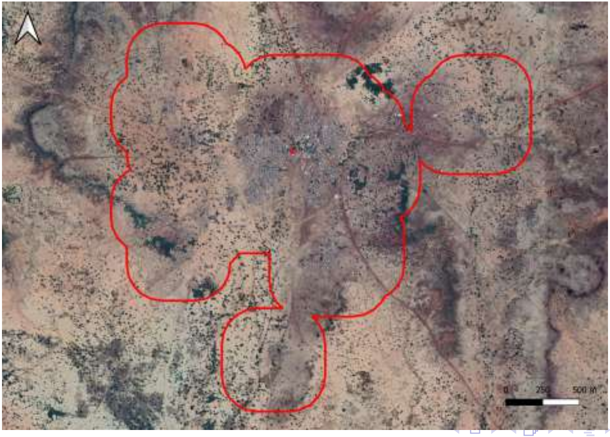
- Nighttime Lights (NTL) from 2013 to 2021 (monthly), resolution of 500m, by the Earth Observation Group (EOG), Colorado School of Mines.
- Land cover from the Copernicus Global Land Service, Built-up layer to identify villages at a resolution of 100m.
- Population density GPWv4 2015, resolution of 1km, from NASA's SEDAC.
- Altitude and terrain gradient from SRTM 90m of CGIAR-CSI.
- Potential photovoltaic electric production in kWh/kWp, resolution of 250m, from Energydata.info.
- Distance to major cities (pop. $>$ 50k.), resolution of 1km, by Nelson et al. (Nelson et al., 2019).

Sample building

- Identification of treated villages with Land cover from Copernicus
- Identification of potential control villages between a 3km and 50km radius.
- Sample filtering with the exclusion of :
  - villages within a 3km of a power-plants installation, grid network, or other energy project.
  - villages 2x bigger than largest treated village.

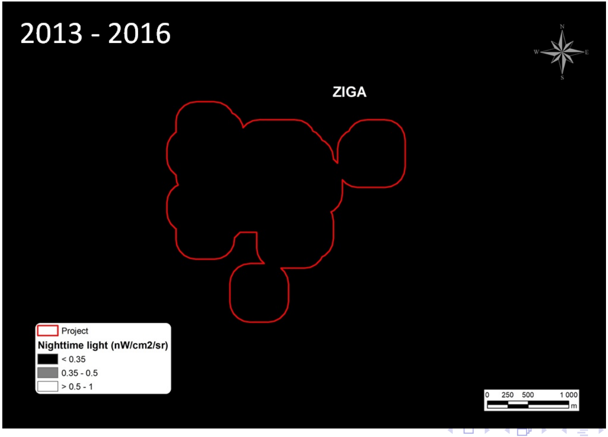
Ziga, Yatenga, Burkina Faso

Figure: Ziga delimitation from Copernicus Land cover



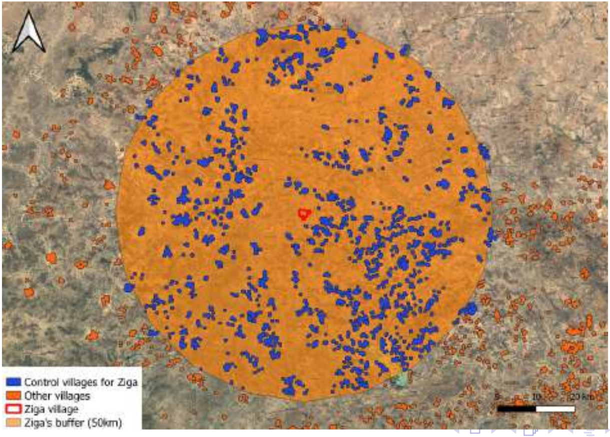
NTL in Ziga, Yatenga, Burkina Faso

Figure: Ziga NTL evolution from 2014 to 2021



Ziga, Yatenga, Burkina Faso and its surroundings

Figure: Ziga and potential controls cluster



Matching

- We use distance metrics as it should be preferred to PSM for matching observations to simulate a fully blocked randomized experiment (King and Nielsen, 2019).
- For each cluster we match using the Mahalanobis distance on the following variables :
  - Village surface area;
  - Altitude;
  - Land gradient;
  - Population density;
  - Distance to cities;
  - Potential photovoltaic production;
  - Pre-project NTL average.
- As robustness we use Euclidean distance and geographical distance (closest villages).

Matching with 3 controls per treated

Table: Burkina Faso matching

Characteristic	**Overall**, N = 300[1]	**Projects**, N = 75[1]	**Controls**, N = 225[1]	**p-value**[2]
Surface area (km²)	2.75 (1.51)	2.92 (1.71)	2.69 (1.45)	0.3
Altitude (meters)	310 (36)	309 (39)	311 (34)	0.7
Land gradient	1.61 (0.49)	1.61 (0.52)	1.61 (0.49)	>0.9
Population (hab/km²)	70 (60)	70 (60)	70 (60)	>0.9
Distance to cities (min.)	71 (48)	69 (49)	71 (48)	0.7
Potential photovoltaic production (kWh/kWp)	4.59 (0.06)	4.58 (0.06)	4.59 (0.06)	0.9
NTL pre-project avg.	1.67 (2.85)	2.38 (5.35)	1.44 (1.09)	0.13

[1] Mean (SD)
[2] Welch Two Sample t-test

Matching with 3 controls per treated

Table: Madagascar matching

Characteristic	Overall, N = 276[1]	Projects, N = 69[1]	Controls, N = 207[1]	p-value[2]
Surface area (km²)	1.31 (1.42)	1.82 (1.73)	1.15 (1.26)	0.004
Altitude (meters)	530 (556)	528 (548)	531 (560)	>0.9
Land gradient	6.4 (4.0)	6.6 (4.6)	6.3 (3.8)	0.6
Population (hab/km²)	58 (51)	60 (48)	58 (52)	0.8
Distance to cities (min.)	302 (294)	294 (291)	305 (295)	0.8
Potential photovoltaic production (kWh/kWp)	4.70 (0.35)	4.69 (0.37)	4.71 (0.34)	0.8
NTL pre-project avg.	0.64 (0.77)	0.87 (0.90)	0.56 (0.70)	0.012

[1]Mean (SD)
[2]Welch Two Sample t-test

Model

- Two Way Fixed Effects is the standard model to estimate Diff-in-diff in a panel set-up.

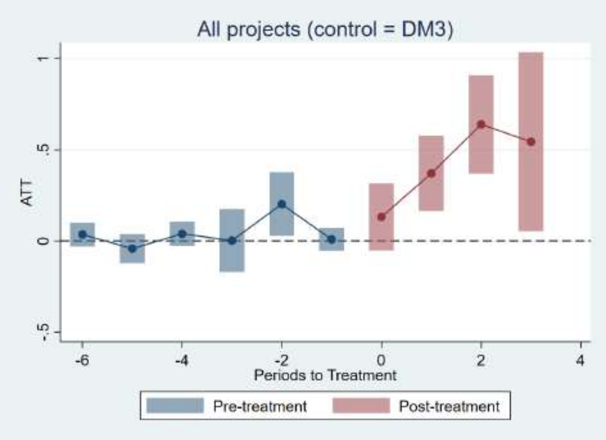
$$NTL_{i,t} = \alpha + \sum_{e=-9}^{-2} \beta_e^{lead} D_{i,t}^e + \sum_{e=0}^{9} \beta_e^{lag} D_{i,t}^e + V_i + Y_t + \gamma X_{i,t} + \epsilon_{i,t} \quad (1)$$

- where, i is a village, t a time period and e the event study time. $NTL_{i,t}$ is the night time light level of village i at time t. $D_{i,t}^e$ is an "event-study" dummy variable that takes value one if a unit i is e periods away from initial treatment at time t and zero otherwise.

Estimation

- TWFE models estimated by OLS are biased absent strong restrictions on treatment effect homogeneity and sample structure (Borusyak et al., 2022; Goodman-Bacon, 2021).
- Multiple solutions to estimates TWFE to avoid bias have been developed (Callaway and Sant'Anna, 2021; de Chaisemartin and D'Haultfœuille, 2020; Sun and Abraham, 2021).
- We use Callaway and Sant'Anna as we have a staggered binary treatment and a stable control group over time.

Main results with all projects - Graph



Main results with all projects - Table

VARIABLES	(1) MD1	(2) MD3	(3) MD5	(4) MD10	(5) GD3
Post_average	0.406***	0.428***	0.442***	0.504***	1.099***
	(0.103)	(0.106)	(0.109)	(0.110)	(0.134)
T 0	0.125	0.126	0.129	0.156	0.406***
	(0.0977)	(0.102)	(0.103)	(0.104)	(0.119)
T+1 year	0.342***	0.370***	0.390***	0.442***	0.950***
	(0.110)	(0.115)	(0.118)	(0.119)	(0.136)
T+2 years	0.618***	0.647***	0.672***	0.733***	1.277***
	(0.139)	(0.125)	(0.125)	(0.125)	(0.147)
T+3 years	0.540**	0.567**	0.575**	0.685***	1.764***
	(0.215)	(0.226)	(0.228)	(0.233)	(0.279)
Observations	1732	3464	5196	9526	3464

Notes: Standard errors in parentheses; *** $p<0.01$, ** $p<0.05$, * $p<0.1$; MD#: Mahalanobis distance ; GD#: Geographical distance ; # refers to the number of controls per treated retained.

Results heterogeneity

- By country: Similar results in both countries.
- By project characteristics: No difference between solar and not solar. Mini-grid connected to national grid perform similarly to other mini-grids. Power of mini-grid impact the magnitude of the effect but not the significance.
- By likelihood of success of the project: we compute a likelihood of success based on the temporal break in trend of the NTL of treated villages. Projects classified as successful yield a larger ATT (almost double). One classified as failed only significant at 10% level with low magnitude.

Robustness checks

- Add village size as a control variable. Results are still significant and positive but magnitude is reduced for Madagascar.
- Use Euclidean distance for matching. Almost no change in ATTs estimated.
- Use de Chaisemartin and D'Haultfoeuille as estimator. Results remain significant the first 3 years, magnitude of the ATT is slightly lower.
- Explore potential spill-over effect based on the geographical distance. We use villages at 10km away as controls instead of 3km. No spill-over seems to appear in close villages in the short-term as results are similar.

Conclusion

- We can see a significant increase in the NTL of villages that received mini-grids both in Madagascar and Burkina Faso.
- After two years, the NTL increased in average by 80% in Madagascar and by 25% in Burknia Faso.
- The dynamic of the effects suggest an increase in electrification rate during the first 2 years.
- Mini-grids seems to be a viable technological solution to reach SDG 7 as they rely heavily on renewable energy and provide proper electrification.
- Failure rates of mini-grids seems quite high and might call for more robust or better designs.