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Booming Decentralized Solar Power in Africa's Cities

Satellite Imagery and Deep Learning Provide Cutting-Edge Data on Electrification

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In collaboration with:
CGEMP
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Key Takeaways

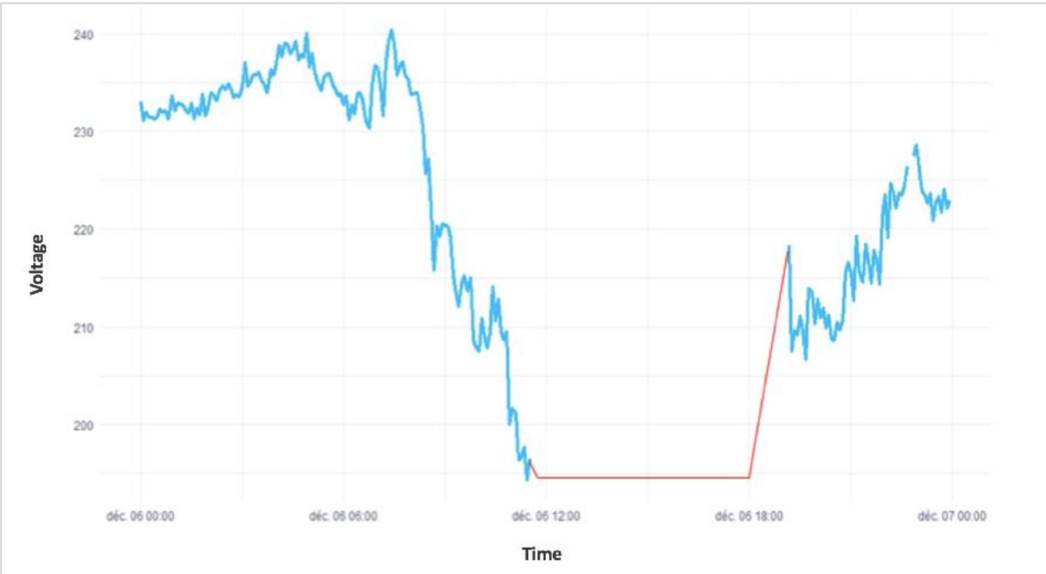
- The market for decentralized solar systems first developed in rural Africa, and today it is expanding to the continent's cities, though these areas are already covered by each country's central network.
- Analysis of millions of satellite images in 14 cities in Sub-Saharan Africa shows that the decentralized solar capacity installed there is between 184 MW and 231 MW. This represents nearly 10% of the centralized solar capacity installed in the region (excluding South Africa). Extending this analysis to other African cities would very likely increase this estimate.
- People in high-income households are the most likely to adopt decentralized solar systems, regardless of the reliability of their power supply from centralized grids.
- The gradual empowerment of customers vis-à-vis the national power grid for their electricity consumption is thus a fundamental trend, that will not simply be curbed by improving the management and reliability of electricity supplies. Sub-Saharan Africa's electricity sectors thus face an existential challenge as their most solvent customers adopt hybrid supply strategies.

Introduction[1]

Despite past progress in electrification, the number of Sub-Saharan Africans without access to electricity rose in 2020, owing to the Covid-19 crisis. This has made it even more difficult to achieve the 7th Sustainable Development Goal (SDG).

However, the electrification rate is not always a good indicator for judging actual access to electricity. Even in electrified areas, this rate should be qualified in terms of quality and stability of electricity supply. Power outages are common in many Sub-Saharan countries, and even when the grid is running, falls in voltage may limit the use of electrical appliances. Nigeria, for example, has an electrification rate of about 83.9%[2] in urban areas, but electricity is actually available only 50% of the time.[3] This weakness in Sub-Saharan power grids has a considerable negative effect on economies, representing an average cost across countries ranging from 1 to 5 percent of national GDP (Ouedraogo, 2017).[4]

Figure 1: A Typical Day on the Nigerian Power Grid (2019)



Source: A2EI data.

In addition to their shortcomings in pushing further electrification and improving the reliability of centralized grids, Sub-Saharan power sectors face a daunting challenge: meeting the region's rapid population growth and urbanization. According to United Nations projections, the population of the Sub-Saharan region will almost double to

1. This project was carried out in collaboration with the Center for Geopolitics of Energy and Raw Materials (CGEMP) of Paris-Dauphine University.
2. "World Development Indicators", World Bank, available at: https://databank.worldbank.org.
3. "Enterprise Survey Indicators Data", World Bank, available at: www.enterprisesurveys.org.
4. N. Ouedraogo, "Modeling Sustainable Long-Term Electricity Supply-Demand in Africa", *Applied Energy*, Vol. 190, 2017, available at: www.sciencedirect.com.

2.1 billion by 2050. It will be concentrated mainly in cities, which will account for 60% of the population by the middle of the century (UNW, 2019).[5]

Given the increased electricity needs generated by economic and demographic growth, as well as the high cost of energy and low reliability of centralized power grids in most countries of the region, consumers have been encouraged to meet their electricity consumption needs on their own. Many autonomous electricity generation technologies are used by urban dwellers to overcome the weaknesses of the central grid. These include diesel generators and/or decentralized solar systems, which were originally dedicated to rural areas not covered by the grid, and are now increasingly used in urban areas (Jaglin, 2019).[6] In parallel, the market for decentralized solar systems has grown rapidly in recent years in rural Africa. Today, it is penetrating the continent's cities, despite the fact that they are covered by each country's central network.

Consumers are becoming more autonomous from networks

This *Briefing* shows that part of the market for decentralized solar systems in Sub-Saharan Africa is located in urban areas – even where the electricity supply is of good quality. This is an underlying trend that can present opportunities or threats for the sector, if not properly understood.

The research is based on an original methodology using deep learning methods to analyze satellite images. More than 4.7 billion m² of urban areas were scanned in search of solar panels in more than 14 Sub-Saharan cities.[7] The first section here reports on the development of the decentralized solar power market in recent years in Africa. The next section describes in a general way how the deep learning methodology has been used in the analysis.[8] The third section then discusses the results obtained with regard to the development of Sub-Saharan central networks.

The Uneven Rise of Solar Energy in Sub-Saharan Africa

So far, Africa is exploiting only a small share of its solar potential. According to statistics by the International Energy Agency, 10 TWh of electricity from solar energy were produced in the region in 2019:[9] i.e., less than 0.01% of its theoretical potential.[10] Even with regard to installed electricity generation capacity in Sub-Saharan Africa, solar power amounts to

5. "World Urbanization Prospects 2019", United Nations, Urbanization Division, available at: https://population.un.org.
6. S. Jaglin, "Off-Grid Electricity in Sub-Saharan Africa: From Rural Experiments to Urban Hybridisations", HAL, 2019.
7. Ouagadougou, Accra, Bamako, Cape Town, Dakar, Harare, Ibadan, Kampala, Khartoum, Lagos, Lusaka, Nairobi, Niamey and Windhoek.
8. It should be noted that the methodology used in this article is presented here in a summary manner. It will be set out in detail in a forthcoming academic publication.
9. Data & Statistics, IEA, available at: www.iea.org.
10. Z. Liu, *Global Energy Transition*, Academic Press, 2015.

1.7 GW[11] (7.7 GW including South Africa)[12]. This is just 2% of total installed electricity generation capacity (6% including South Africa).

While centralized solar capacities are only expanding gradually in Sub-Saharan Africa, because risks are high for private developers and the absorption capacity of central networks is low, the market for decentralized solar systems has grown strongly in recent years. The two leading companies to emerge in this market were founded in the last decade. Gradually, this market attracted private sector investors and developed rapidly in Sub-Saharan Africa, thanks in particular to the introduction of the pay-as-you-go (PAYG) system.

The Global Off-Grid Lighting Association (GOGLA) is the leading organization providing off-grid industry data and for gathering information, and today has more than 107 affiliated companies worldwide, including a large number of companies operating in Africa. The market is constantly growing. In 2019, global sales of decentralized solar systems of all sizes reached more than $1.75 billion, with an increase in industry revenues of more than 30% per year between 2017 and 2019.[13] Within a decade, more than 180 million solar products have been sold worldwide, including 150 million pico-solar products and about 30 million domestic solar systems[14] (GOGLA, 2020).[15] In 2018, 3.8 million units were sold in Africa, compared to 3.16 million in Asia, making the African continent the largest market for decentralized solar systems in the world.

A new market segment in decentralized solar power is emerging

The market for domestic solar systems has developed in different ways across the regions of Africa. Taking all systems and means of sale together, East Africa accounts for nearly 78% of the market, compared with 15% for West Africa and 5% and 1% respectively for Central and South Africa. Similarly, PAYG sales have grown faster in East Africa than in West Africa, which accounted for only 12% of PAYG sales in Africa, between 2013 and 2017 (Barry and Creti, 2020).[16] This is due in part to the slower penetration of mobile money in West Africa compared to East Africa.

Until now, decentralized solar-power companies have focused primarily on rural areas not covered by the network, giving consumers first-time access to electricity. A new market segment is now emerging in areas covered by the grid but where it is unreliable and where decentralized solar systems are used to overcome power outages. GOGLA (2020)[17] estimates there are a potential 153 million customers who have access to electricity grids,

11. This figure includes photovoltaic and thermal solar capacities.
12. IRENA, *Renewable Energy Statistics*, 2021, disponible sur : www.irena.org.
13. Decentralized solar systems belong to different categories of products in terms of capacity, ranging from 0 WC to 100+WC. The smallest solar appliances provide basic lightning, while larger ones can provide enough electricity to power a refrigerator or a television, for example.
14. For more information on the different definitions of decentralized solar systems, see www.gogla.org.
15. Gogla, « 2020 Off-Grid Solar Market Trends Report », mars 2020, available at: www.gogla.org.
16. M. Barry and A. Creti, "Pay-As-You-Go Contracts for Electricity Access: Bridging the "Last Mile" Gap? A Case Study in Benin, Energy Economics", August 2020, available at: www.sciencedirect.com.
17. Gogla, "2020 Off-Grid Solar Market Trends Report", *op. cit.*

but who face an unreliable network in Sub-Saharan Africa.[18] Yet the decentralized solar market could also develop in areas where the grid is reliable. Understanding the choices for adopting decentralized technologies in the urban areas covered by the network is essential to better identifying the evolution of electricity systems in Sub-Saharan Africa.

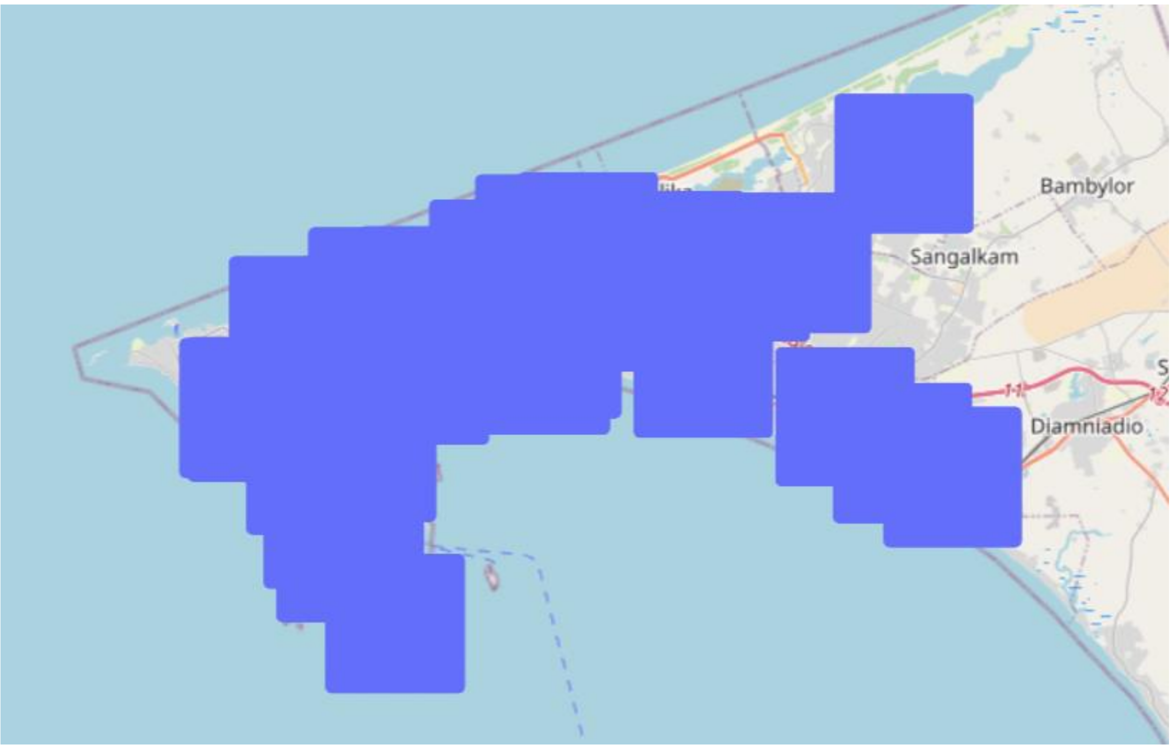
The Use of Deep Learning and Spatial Econometrics for Satellite Imaging Analysis

To assess market penetration of decentralized solar systems in African cities, deep leaning methods were used to analyze 2.4 million satellite images. This makes it possible to determine the presence of solar panels and assess their surface area in a selection of African capital cities. An original and geolocated database of solar panels present in Sub-Saharan cities, including both their location and their surface area, was therefore set up. This database was then linked to the latest geo-localized socio-economic database of Afrobarometer (Round 7).[19] Crossing these two databases allows a detailed analysis of the socio-economic determinants to be carried out, which explains the development of the market for decentralized solar systems in urban areas of the region, thanks in particular to spatial econometrics models. Above all, the analysis tests the hypothesis that household wealth levels are essential to the adoption of such decentralized systems in African urban areas, while controlling for the reliability of the electricity provided by the main grid.

The Google Maps Static API was used to collect satellite images as it enables geo-located satellite images with a satisfactory resolution to be collected for Africa's territory. To avoid collecting information that could not be used later, only square areas with a radius of 2.5 km around the geolocated points of the Afrobarometer socio-economic database were downloaded. The analysis was limited to 14 cities for which resolution was sufficient. In the future, access to better resolution images could allow the analysis to be extended to new cities not covered by this article. Figure 2 below shows an example of an area download for the city of Dakar, Senegal. Three typical images of Google Static Maps API are shown for illustration purposes in Figure 3. Over 2.4 million images, representing a total area of approximately 4.7 billion m2 were downloaded.

18. In comparison, the market for consumers with no access to electricity is estimated at around 588 million customers.
19. For more information on Afrobarometer surveys and methodologies, see: https://afrobarometer.org.

Figure 2: Area Downloaded for the City of Dakar



Source: Authors.

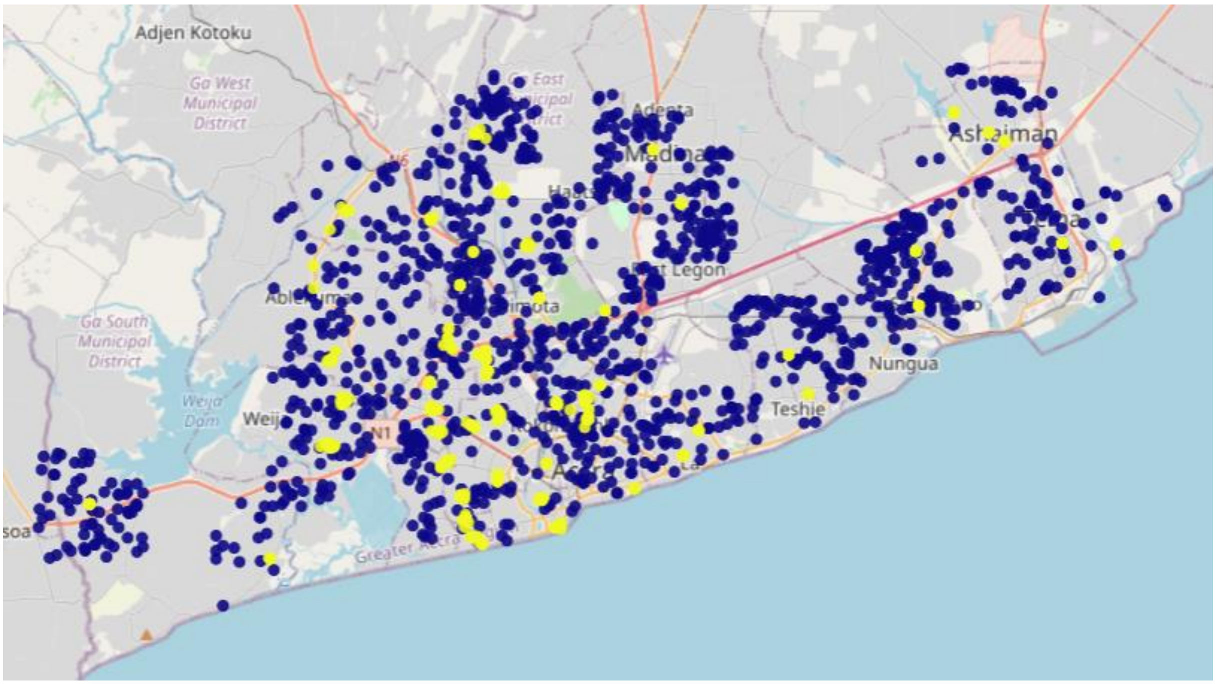
Figure 3: Example of Downloaded Images - Cities of: Dakar, Bamako, and Accra (from left to right)

Source: Google Static Maps API.

To analyze satellite images, a "pipeline" built around two different models was established to determine first the geolocation of solar panels, and then extract the surface area. First, a classification model was used which gives the probability that a panel is present in an image. Then, a segmentation model was applied to determine the panel surface. In both cases, convolutional neural networks were used, which are common in deep learning.

Figure 4 below shows the location of the panels detected by the classification model in one of the 14 Sub-Saharan cities covered. The yellow dots represent the locations of the socio-economic data points in the Afrobarometer survey.[20] Figure 5 shows an example of an image classified as having a solar panel and its segmentation mask which is used to determine the surface area of the panels.[21]

Figure 4: Solar Panels Detected in Accra (Ghana)



Source: Authors.

20. The model used for classification is a Resnet50. See K. He, X Zhang, *et al.*, "Deep Residual Learning for Image Recognition." ArXiv:1512.03385 [Cs], December 2015, http://arxiv.org. Transfer learning using a pre-trained network was used to improve the performance of the model while increasing the training speed. A pre-trained Dino Resnet50, recently published by Facebook's research teams, was used (see https://github.com). This has improved the performance of the model compared to a pre-trained resnet on *Imagenet*. The training database has over 23,957 images, of which 12,131 are positively annotated and 18,925 are negatively annotated. The model was trained on Google Cloud virtual machines for several hours. At the end of training, the classification model recorded an accuracy, precision and recall of 92.6.

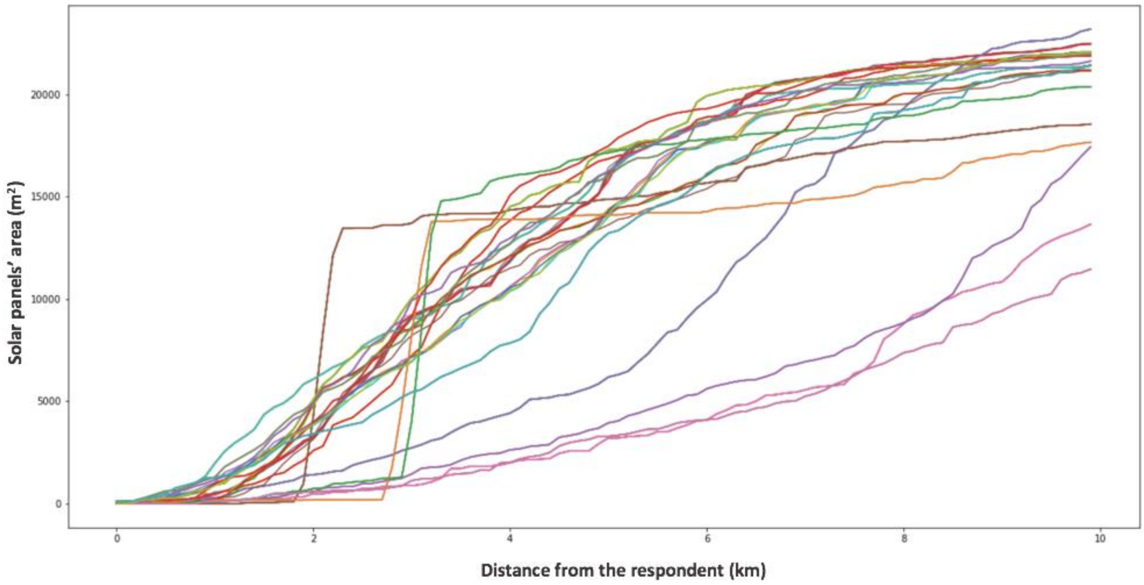
21. For segmentation, a U-Net (see O. Ronneberger, P. Fischer and T. Brox, "U-Net: Convolutional Networks for Biomedical Image Segmentation" *in* N. Navab, J. Hornegger, W. Wells and A. Frangi (eds.), *International Conference on Medical Image Computing and Computer-Assisted Intervention*, Springer, Cham, 2015, pp. 234-241, https://doi.org) was trained on more than a thousand manually annotated images. This is a commonly used model in computer vision as it is particularly effective for segmentation tasks, even with restricted training databases. At the end of training, the model attained a Dice score of 0.97. The model was then applied several times to the same image that was put through four rotations in order to improve segmentation performance. Again, the computing power required to train this type of model required the use of Google's virtual machines.

Figure 5: An Example of the Model's Segmentation Results for Two Positive Images

Source: Images: Google Static Maps API; segmentation masks: Authors.

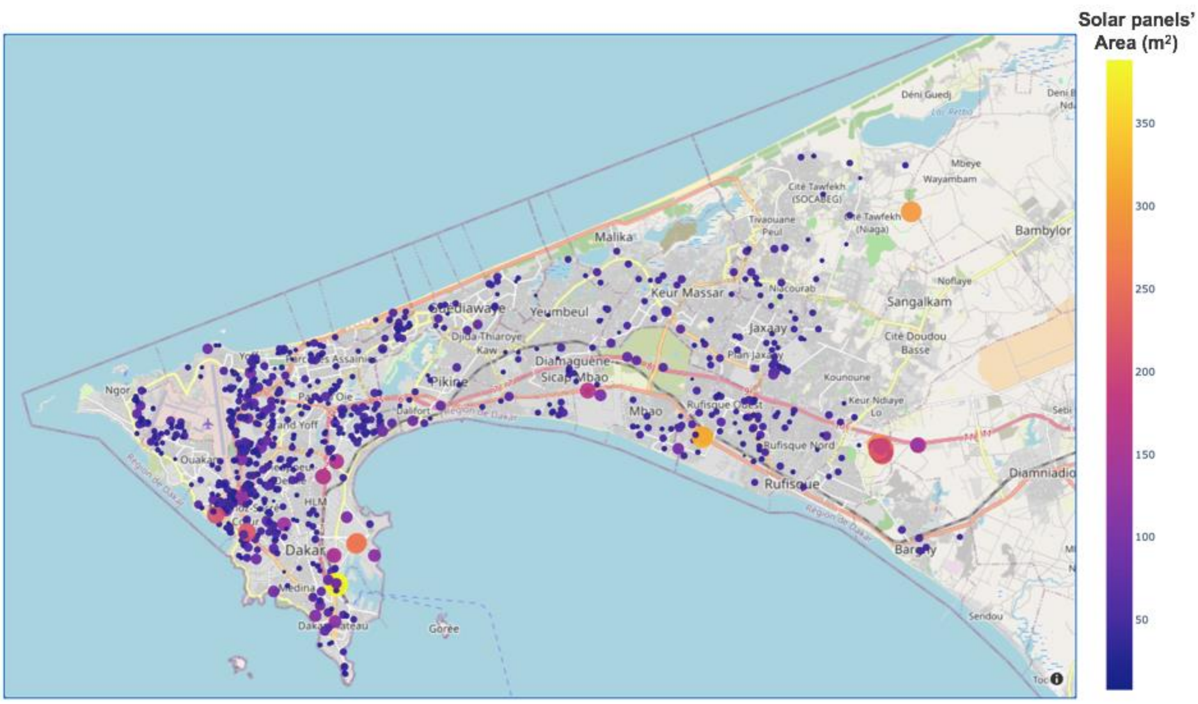
The main problem with the data collected from satellite imagery is that the model cannot differentiate between residential solar panels and commercial solar panels. This may subsequently introduce a bias in the econometric analysis because the socio-economic data of the study relate only to surveys of residential households. Failure to take this into account may result in inaccurate subsequent econometric analysis. Indeed, a household living near commercial premises with several mini-solar power installations would seem to have a large area of installed solar panels around it, without these necessarily being residential solar panels. Figure 6 below shows the example of the area of solar panels installed in Dakar, Senegal, for a selection of persons surveyed. The X-axis shows the distance from the respondent's location, and the Y-axis shows the area of the installed solar panels. The above-mentioned phenomenon can be seen in this graph with a "step" effect that corresponds to a mini-solar plant installed in the city of Dakar. Figure 7 below shows the location of solar panels in the city of Dakar, and their relative surfaces. To separate residential solar panels from commercial solar panels, a machine-learning method was used, namely a Gaussian Mixture Model (GMM).

Figure 6: Surface of Solar Panels Installed by Household in Dakar



Source: Authors.

Figure 7: Surface of Solar Panels Installed in Dakar



Source: Authors.

The Urban Deployment of Decentralized Solar Power

The table below summarizes the installed capacity estimated in various Sub-Saharan cities, based on two hypothetical panel yield values. The table shows that the richest cities – especially Windhoek, Nairobi, and Cape Town – have the largest aggregated decentralized solar panel capacity of 23.7 MW, 21.7 MW, and 55.7 MW, respectively, with a yield of 16%; and 29.6 MW, 27.1 MW and 69.6 MW with a yield of 20%. The poorest cities such as Khartoum or Harare have much smaller installed capacities, 0.8 MW and 3.6 MW respectively and 1 MW and 4.5 MW, assuming yields of 16% and 20%. The total estimate for all these cities lies between 184 MW and 231 MW.

While this may seem marginal by European standards, it should be remembered that throughout Sub-Saharan Africa (excluding South Africa), there are only about 1.7 GW of installed centralized solar capacity. Decentralized capacity therefore accounts for nearly 10 percent of this figure. Moreover, this analysis only covers 14 Sub-Saharan cities representing 32 million inhabitants. However, there are more than 80 cities with more than 500,000 inhabitants in Sub-Saharan Africa, with a total population of 115 million inhabitants. Therefore, had all other African cities been covered, this estimate would most likely have been much higher.

Table: Estimated Decentralized Solar Capacity by City (MW)

Yield / City	16%	20%
Ouagadougou	17.177	21.472
Accra	8.671	10.839
Bamako	17.624	22.052
Cape Town	55.715	69.644
Dakar	6.928	8.660
Harare	3.578	4.472
Ibadan	1.957	2.446
Kampala	3.171	3.963
Khartoum	0.836	1.045
Lagos	14.353	17.941
Lusaka	4.626	5.783
Nairobi	21.684	27.105
Niamey	4.888	6.110
Windhoek	23.696	29.620
Total	**184.927**	**231.159**

Econometric analysis on socio-econometric data from Afrobarometer crossed with the data collected on solar panels makes it possible to determine what factors explain the differences in market development that can be observed between cities and between different neighborhoods. This analysis takes into account, for example, living standards, educational level, the modernity of the neighborhood, the reliability of access to electricity, etc. The results of the econometric model show that people in the upper classes of society, with a high standard of living, are the most likely to adopt decentralized solar systems. Yet, when considering living standards, the reliability of power supply no longer seems to be a determining factor in the choice of installing a decentralized solar system. In other words, wealthy households especially will be more likely to have a decentralized solar system, regardless of the quality of electricity supplied from the central grid.

Living standards are important to acquisition

The effects of other socio-economic factors are close to initial expectations. University-educated respondents are more likely to live in an area where the penetration of decentralized solar systems is high. Similarly, a neighborhood's modernity is important: Living in a modern neighborhood, well-served by public services, tends to increase the likelihood of having a decentralized solar system. This confirms that the penetration of this technology in urban areas of Sub-Saharan Africa is not necessarily directly related to a deficiency in public services. Qualitative interviews with professionals and residents in Sub-Saharan Africa tend to confirm the results presented above.

An additional idea emerges from these interviews and the model's results, namely that there is a "U-shaped" penetration of decentralized solar systems of all sizes in the urban areas of the continent, depending on populations' standards of living. For the poorest people living in areas covered by the network, the connection to the central grid may be inaccessible due to their meager incomes; the only way to consume electricity would be to use pico-solar systems such as solar lamps or systems that allow only the charging of mobile phones. As revenue increases, these systems are abandoned by consumers in favor of connection to the central network, which becomes more accessible. At this stage, the use of decentralized solar systems becomes marginal. Finally, solar technologies then re-emerge as large decentralized solar systems among the most affluent layers of the population.

Conclusion: Consumer Autonomy Issues Matter

This analysis shows that the gradual increase in consumer autonomy vis-à-vis the central network is a fundamental trend and cannot be countered simply by improving the management and reliability of electricity supply. The progressive decentralization of electricity systems in Sub-Saharan Africa is underway and is being reinforced by rapid urbanization in the continent. In addition, it is less and less correlated with the reliability of the grid.

If these new uses are analyzed and integrated into policies for developing electrical systems, they could represent opportunities. Greater power autonomy for consumers through decentralized solar systems could lower their electricity costs and increase the penetration of solar technology across the continent, while reducing pollution from diesel generators, for example. The decentralization of production capacity could also increase the resilience of networks in the face of extreme natural events that could damage each country's national grid, making consumers less dependent on centralized infrastructures and help pass peak demand periods. The autonomy of some consumers may even have beneficial, if marginal, effects on utilities' finances. Indeed, many consumers do not pay for their electricity bills in Sub-Saharan Africa, so their greater autonomy could help to reduce the loss of income from these consumers' unpaid bills. Finally, in the longer term, if electricity is produced primarily where it is consumed, it does not need to pass through transmission lines. This would help to prevent electricity losses in power lines, which are high in many countries of the region, and could reduce network investment needs. Thus, these new uses could be fostered with tax instruments, such as a reduction in VAT or a reduction in import tariffs on solar products. These tax instruments are already in place in several East African countries, and partly explain differences in prices, which are lower, and market penetration rates, which are higher, than in other parts of the continent.[22] In other African countries, such measures would lower the threshold for adopting large-scale solar systems from households in the wealthiest social class through to the middle classes, and using small systems for the poorest consumers.

Power autonomy is less and less correlated with grid reliability

Yet such greater consumer autonomy from national grids could also have adverse consequences for the centralized power sectors of the region. Given the difficult financial situation in which almost all African electricity utilities find themselves, the partial loss of their best customers (residential, but also commercial, or small-scale industrial) could be a severe blow to their finances. Moreover, the financial sustainability of strategies to extend central networks to the poorest consumers in adjacent peri-urban and rural areas is based on cross-subsidization. The largest consumers pay higher tariffs than the poorest, who consume less and who thus benefit from subsidized electricity tariffs. This system may reach its limits even more quickly if the most profitable customers in cities turn away from the network. Consumer autonomy could therefore contribute to fragmenting centralized grids in Sub-Saharan Africa.

As a result, the new trend will have far-reaching implications both for essential access to power for Africa's populations and for the financial health of the region's centralized networks. While these are still difficult to assess, the phenomenon of consumers becoming autonomous from central networks offers new avenues for research, with regard to the formulation of future public policies aimed at developing reliable and sustainable electricity systems in Africa.

22. In Benin and Niger, however, these tax incentives have been in place for several years.

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