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Clustering of load profiles and RAMP model calibration applied to productive uses of electricity in rural Benin

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Introduction

Productive Uses of Electricity (PUEs) are vital for the socio-economic development of rural communities, as they enable income-generating activities and improve livelihoods. They are also a key driver of the viability of solar mini-grids in rural areas. However, the diversity and seasonality of PUE demand remain largely unexplored. Most of the previous studies have applied clustering methods such as k-means, which are less robust when dealing with noisy or atypical data.

This research proposes a methodological framework that combines Density-Based Spatial Clustering of Applications with Noise (DBSCAN), applied to daily features and survey-driven stochastic generated load profiles, to create representative seasonal demand profiles of PUEs in rural mini-grids in Benin.

Methodology

Load data are collected from different PUEs (shops, incubators, mills, workshops, and an inn). Clustering focuses on maize mills, which have dedicated meters, while for some of the other PUEs the metering setup may include household loads, making their profiles less directly exploitable.

Maize mills daily profiles are segmented and normalized to capture shape dynamics independently of consumption levels, then described by a set of features including peak power, average power, time of peak, and day/night ratio. Clustering is performed using DBSCAN based on these features, which automatically detects the number of clusters, handles varied shapes, and isolates atypical days. The seasonal distribution of clusters is then analyzed to assign a representative profile to each season. Finally, the representative profiles identified with DBSCAN are used to calibrate the stochastic demand profile generation model RAMP through an automated process that adjusts appliance parameters. The accuracy of the calibrated model is then assessed using validation criteria such as relative error, normalized root mean square error (NRMSE), and load factor.

Results

The application of DBSCAN distinguishes relevant daily patterns, revealing both regular routines and atypical days. In the case of a maize mill in Gbowele, the algorithm is applied from October 2024 to May 2025, covering 243 days of data, of which 207 are retained after filtering (≈15%). One dominant cluster emerges, representing 191 days (≈92%) of regular milling activity, while 16 days (≈8%) are classified as outliers. Seasonal analysis confirms this stability: during the dry season (November–April), 154 days are regular and 12 are outliers, whereas in the transition months (October and May), 37 of 41 days are regular and 4 are outliers, reflecting slightly higher variability.

The representative profiles identified with DBSCAN are used to calibrate the RAMP model, ensuring that the stochastic demand profiles generated reproduce the observed seasonal consumption patterns.

Conclusions and perspectives

This work represents one of the first applications of feature-based clustering methods to PUE load profiles in rural Sub-Saharan Africa. Combining DBSCAN and RAMP provides an innovative, replicable framework for seasonal demand forecasting in mini-grids. Representative seasonal profiles calibrated on field data improve mini-grid sizing and enhance understanding of demand variability.

An important strength of the framework is its stochastic dimension, which captures inherent variability in PUE demand and increases the robustness of forecasts for planning. These results offer practical insights for operators and policymakers to strengthen the techno-economic sustainability of rural mini-grids.

Future work should extend the methodology to other PUEs such as shops, workshops, refrigeration units, and carpentry machines, whose characterization will deepen the understanding of productive demand and support their integration into energy planning models.

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