

Understanding long-term energy use in off-grid solar home systems in sub-Saharan Africa

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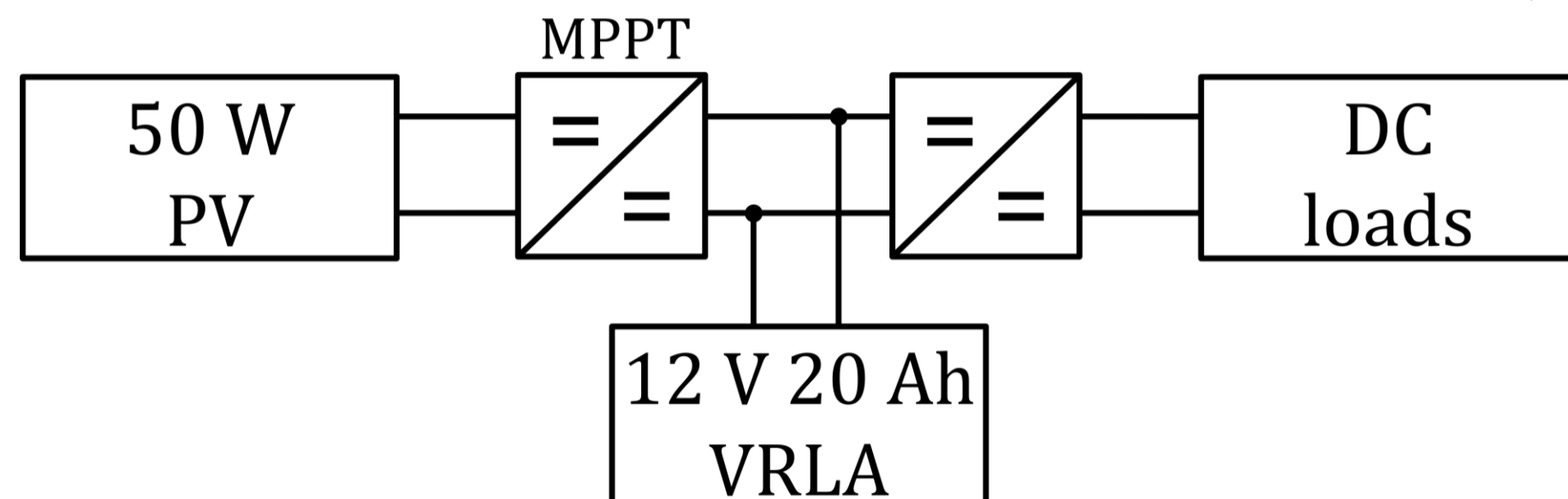
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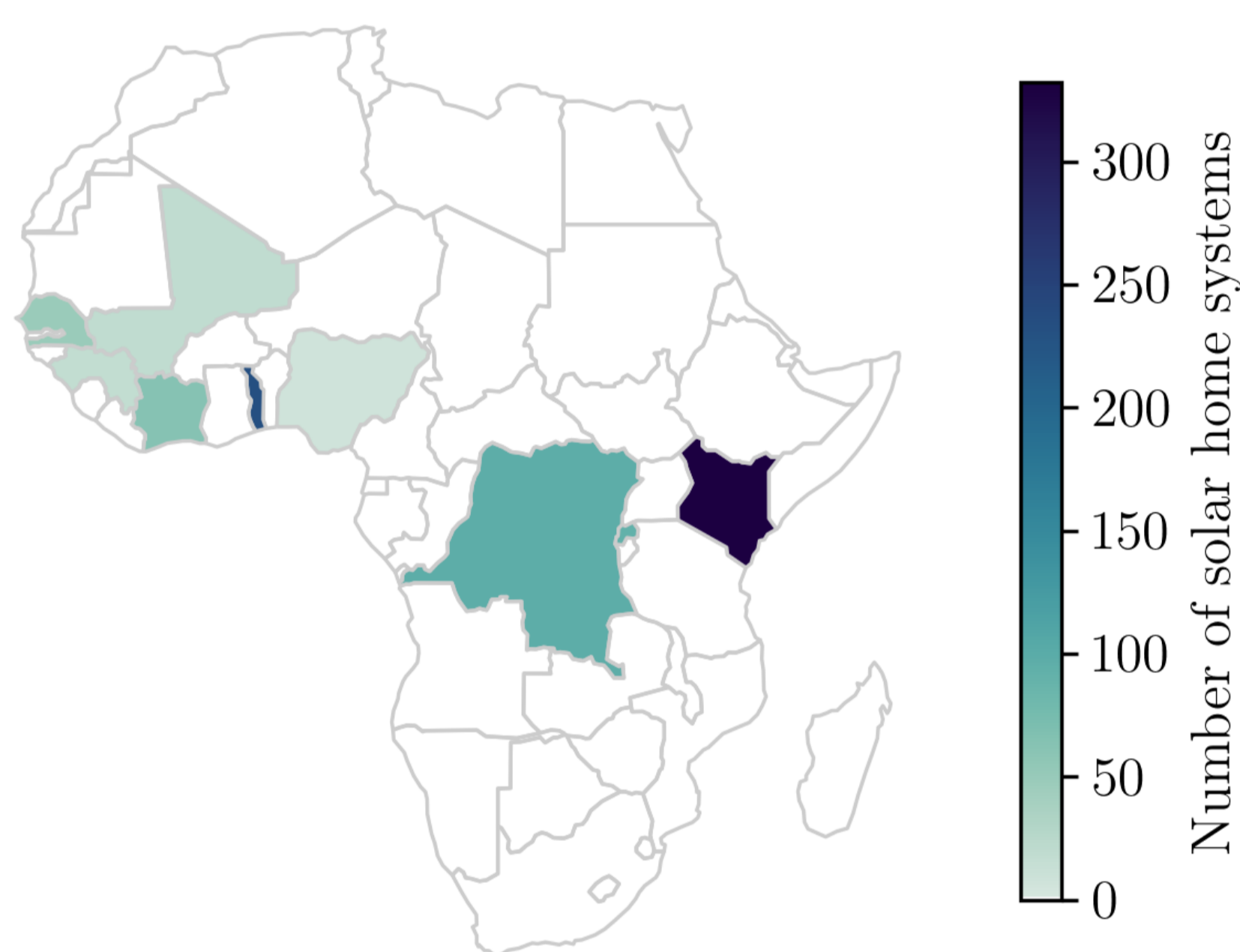
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1. Background

- 759 million people globally lack access to electricity, 75% of whom live in sub-Saharan Africa.
- Solar home systems are a key technology for rural electrification: low-cost, scalable, and widely deployed. They comprise a solar panel, valve-regulated lead-acid battery (VRLA) and DC loads (lights, phone chargers, radios, shavers and TVs).



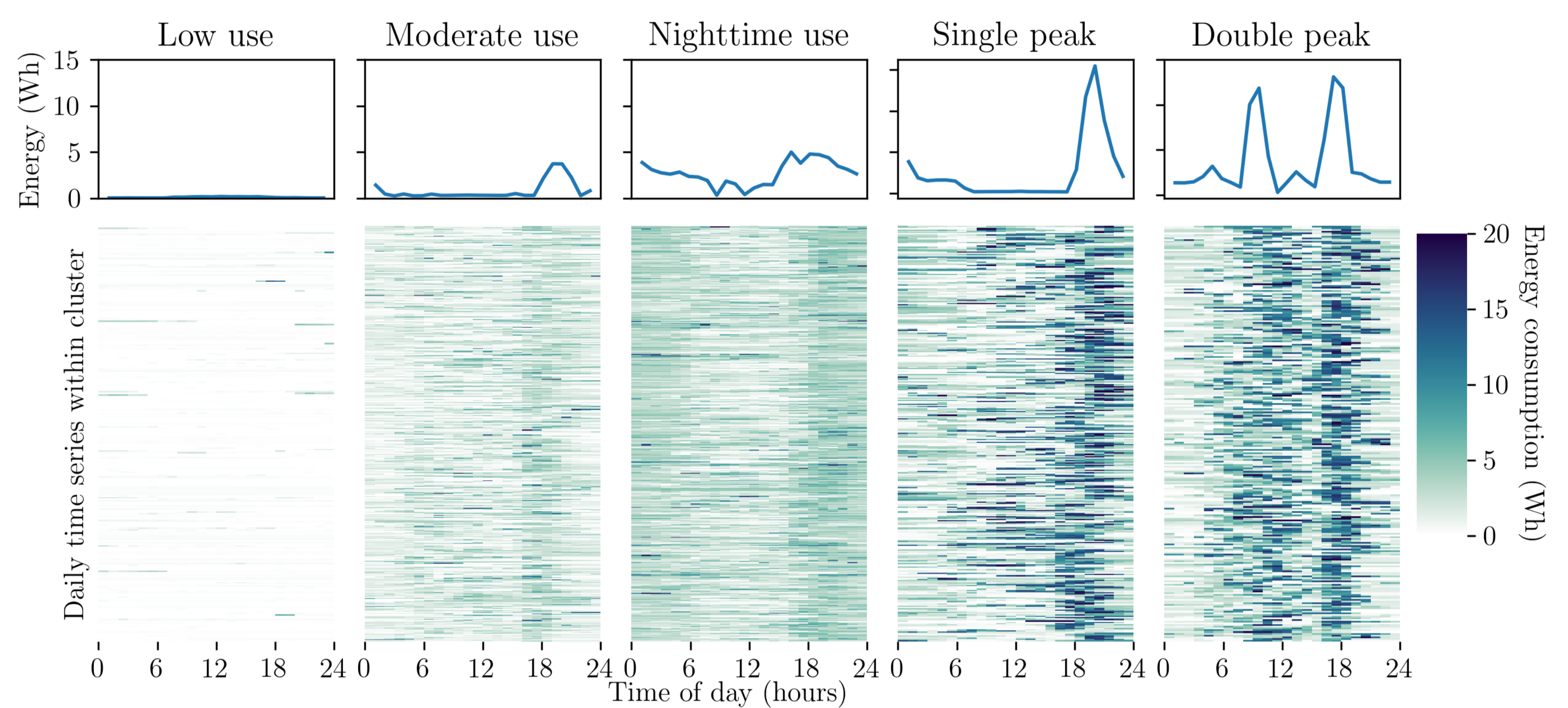
- Often households previously had no access to electricity, so little is known about how households use electricity once solar home systems are adopted.
- Understanding demand is essential to improve solar home system design, reduce costs, improve system longevity and ensure sustainable energy access.
- We analysed 1,000 solar home systems from BBOXX customers across sub-Saharan Africa.



2. Daily load demand profile clustering

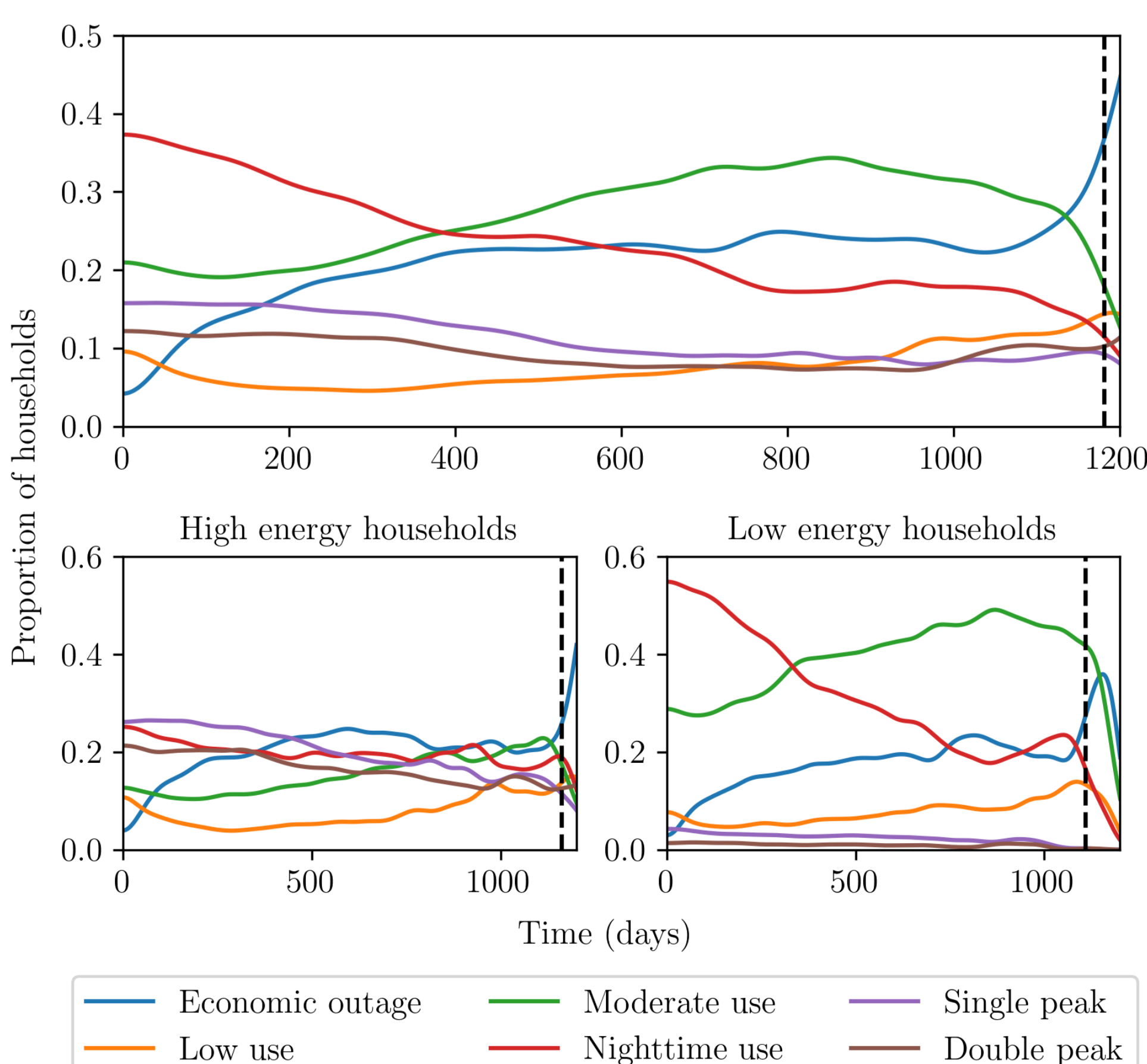
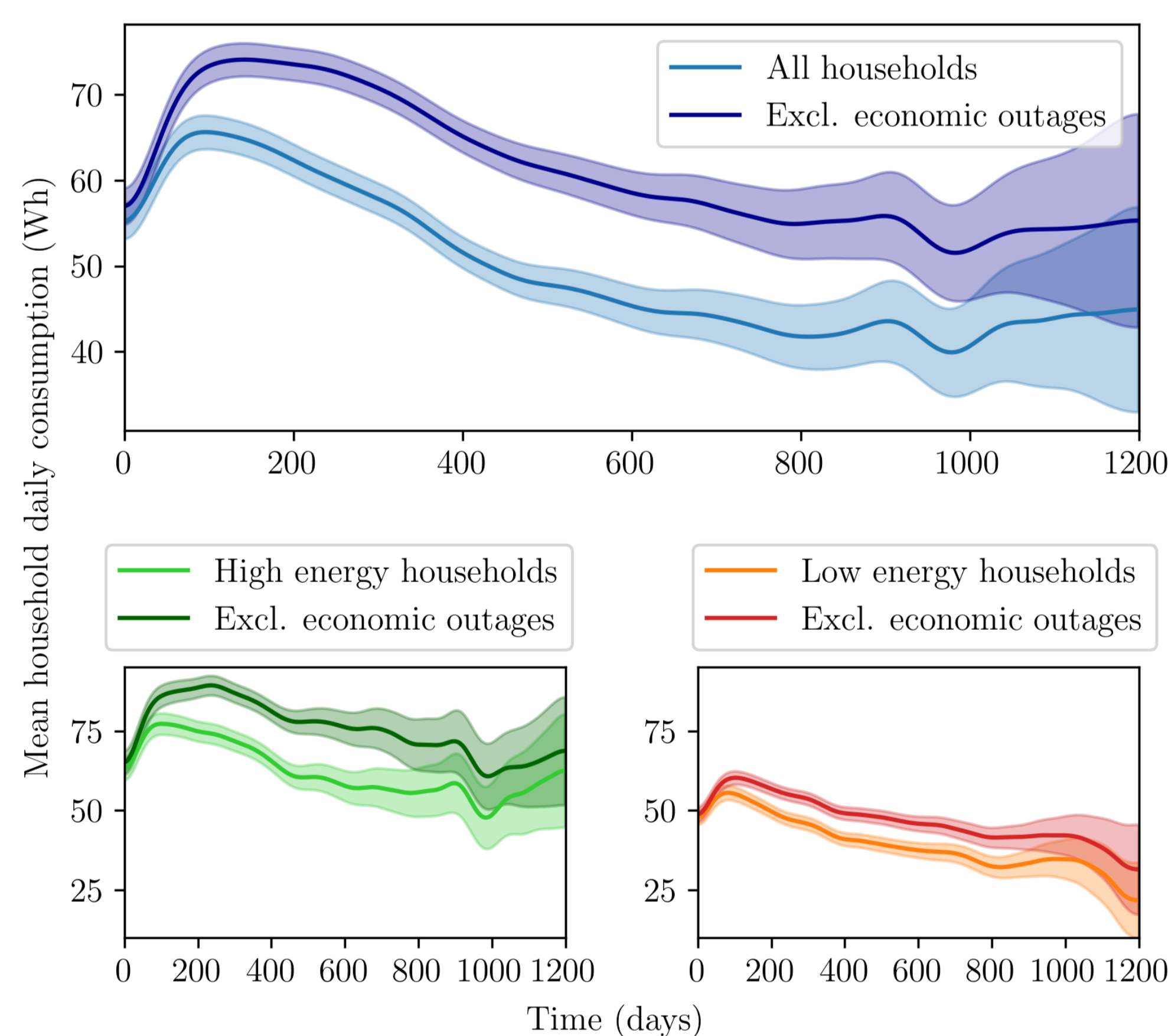
- From the 1,000 customers, there are 647,021 daily load demand profiles. Stratified sampling was essential to form a viable clustering problem, of 2,000 time series.
- Clustering method:** a k-medoids inspired mixed integer programming, focusing on minimising intra-cluster distance.
- Similarity measure:** dynamic time warping, which aligns time series by stretching and compressing along the time axis.
- We used our homebrew open-source software for fast dynamic time warping and clustering, DTW-C++ [2].
- BBOXX solar home systems are pay-as-you-go, hence the *low use* cluster has a subsection of economic outages, where the system hasn't been paid for that day.

	Proportion in data set (%)	Mean consumption (Wh/day)	No. of daily peaks	Use between 6am and 6pm (%)	Mean appliance rating (W)	TV ownership (%)
Economic outage	18	0	0	N/A	73	49
Low use	6	12	0	50	71	48
Moderate use	24	39	0.2	50	50	17
Nighttime use	28	73	0.1	41	55	22
Single peak	14	102	1.1	46	96	84
Double peak	10	122	1.9	59	97	92



3. Long term energy consumption trends

- Average daily consumption initially rises, peaking at day 96. Beyond this, consumption steadily declines.
- By the end of the first year, 77% of households have decreased their daily consumption.
- Over the first 2 years of ownership, there is a 33% reduction in mean household consumption from the peak (66 Wh/day) to the 2-year mark (44 Wh/day).
- When economic outages are removed, the decrease in daily consumption is still present, showing households are decreasing their energy consumption even on days when they are paying.



- Decrease in energy consumption is consistent across both high (> 50 W appliances) and low energy (≤ 50 W appliances) households.
- Over the first year there is a significant increase in *economic outages*.
- Beyond the first year, the decrease in energy consumption is driven by an increase in the *low use* and *moderate use* clusters, while *nighttime use*, *single peak* and *double peak* decrease.
- In high energy households there is more variation in clusters because more appliances means more flexible loads.

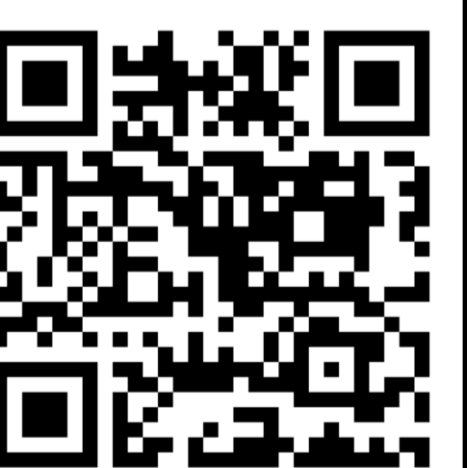
4. Conclusions

- ✓ Dynamic time warping clustering effectively finds archetypal load profiles, easing long-term load demand analysis.
- ✓ Household solar home system demand is not stable – energy use generally decreases over time.
- ✓ Declines are driven by both economic outages and a shift towards lower-use clusters.
- ✓ This creates a mismatch between system size and long-term use, increasing costs and stressing batteries.

References

[1] Perriment, R., Mergulhao, V., Kumtepelı, V., Parikh, P., McCulloch, M. and Howey, D., 2025. Understanding long-term energy use in off-grid solar home systems in sub-Saharan Africa. arXiv preprint arXiv:2502.14630.

[2] Kumtepelı, V., Perriment, R. and Howey, D.A., 2024. DTW-C++: Fast dynamic time warping and clustering of time series data. Journal of Open Source Software, 9(101), p.6881. (github.com/Battery-Intelligence-Lab/dtw-cpp).



Acknowledgements

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