Quantifying Potential Power Savings from Household Appliance Consumption Data: A Methodological Approach and Estimated Results

Harriet Nyanchama Ocharo
Data Science Laboratory
Hitachi Central Research Lab
Tokyo, Japan
harriet.ocharo.wt@hitachi.com

2nd Daisuke Komaki
Data Science Laboratory
Hitachi Central Research Lab
Tokyo, Japan
daisuke.komaki.ht@hitachi.com

***Abstract*—The electricity grid becomes most stressed when there is high demand for electricity. Demand response programs are used as resource options for balancing supply and demand. Individual consumers can play a significant role in the operation of the electric grid by reducing or shifting their electricity usage during peak periods. However, it can be difficult to estimate how much power can be saved in a household at a particular time. To accomplish that, appliance consumption data recorded at 1-minute intervals was analyzed from 7 houses over a period of 3 days (August 1-3, 2022), when the grid in Tokyo experienced very low reserve margins. Three power saving approaches were considered: reducing the load, leveling the load or shifting the load. The amount of power that could be saved was estimated by generating simulation data and calculating the difference before and after performing the power saving action. The amount of power that could be saved relative to the total power consumed by all the houses ranged from 7% to 15.3%. The methodology applied in this research to quantify the power saving potential can be applied to smart meter data to estimate the amount of power that can be saved in a household at a particular time, which is important information for demand response programs.**

Keywords—demand response, household appliance data, load profiles, power saving actions

I. Introduction

Demand response (DR) programs are used by Transmission System Operators (TSO) or Distribution System Operators (DSO) as resource options for balancing supply and demand. In DR programs, consumers are asked to reduce or shift their electricity usage during peak demand hours. Previously, DR programs primarily targeted industrial customers, but more recently, there has been an increased recognition of the potential for demand reduction in residential buildings. DR programs incentivize individual consumers e.g., by paying them, to turn off their air conditioners, electric water heaters, pool pumps or other high energy consuming devices during peak demand.

With the increased adoption of Energy Management Systems (EMS), it is possible to understand power consumption of commercial buildings and factories. However, it is difficult to introduce Home Energy Management Systems (HEMS) to all the households. Non-Intrusive Load Monitoring of data from smart meters is acknowledged to be effective in estimating the consumption of specific appliances or devices.

Accurately estimating the amount of power that can be saved from households in DR programs is important for power generation, transmission and distribution companies to balance demand and supply for the stability of the grid, ensuring blackouts do not occur and reducing costs associated with turning on additional power generators during peak times. The report [1] on insights from smart meter data indicates that even a 2% reduction in power consumption could be significant. By examining appliance level data, the potential for power saving in each household can be more accurately estimated.

Therefore, this study analyzed appliance consumption data recorded at 1-minute intervals from 7 houses over a period of 3 days (August 1-3, 2022) when the grid in Tokyo experienced low reserve margins. The objective of this study was to assess and quantify the extent to which power could be saved by analyzing the appliances used in each household at the target time. By using actual appliance data, during actual peak times, and systematically checking which appliances and which power saving method (reduce, level, shift load) can be applied without inconveniencing the customer to a large extent, we are able to more accurately estimate the amount of power that can be saved. Direct demand response programs may have low responsiveness in achieving actual energy savings. By utilizing data obtained from smart meters, it is possible to increase the effectiveness of DR programs by targeted and personalized response programs.

II. Related Literature

Increase in the adoption of smart meters and non-intrusive electronic monitoring equipment has led to the generation of high-resolution time-series data which can be applied to mine consumption knowledge for various applications such as energy forecasting, smart meter analytics, asset management/analytics, grid operation, customer segmentation, energy trading, credit and collection, call center analytics, and energy efficiency and demand response program engagement and marketing [2].

For demand response programs, load profiling and load clustering [3] are important data mining techniques. Load profiling plays a vital role in the design of profitable demand programs by providing necessary information about individual customers, such as their electrical consumption patterns. Information about the number of household occupants; the number of appliances; and daytime occupancy of the home is important as it is closely related to the consumption patterns [4]. This can influence the design of measures to shift residential loads away from peak periods. In addition, information regarding the external environment such as the effects of the weather, and the lifestyle of the consumer are important information for successful DR programs. In one such study, a cluster-based approach is proposed to analyze usage patterns of an individual customer throughout the year while implicitly incorporating the impact of the weather and holidays [5].

While load profiling provides useful insights into overall energy consumption patterns, it may not be efficient for demand response programs due to a lack of granularity as load profiling provides a high-level view of consumption patterns. In addition, there is limited flexibility. DR programs require the ability to adjust energy consumption in response to changing demand conditions in a timely and effective manner.

Detailed appliance-level consumption data is essential for DR programs. Using realistic load profiles of individual appliances for such studies will lead to more effective DR programs [6]. Appliance-level data enables DR programs to identify specific appliances that consume more energy and develop targeted interventions to reduce their usage at peak demand periods [7]. Furthermore, appliance-level data can improve load forecasting accuracy so that DR programs can better predict energy usage during peak periods and adjust interventions as required. Customers are also more likely to participate in DR programs when they are provided with personalized insights into their energy usage patterns [8]. Finally, the effectiveness of DR programs can easily be verified by measuring the actual energy savings achieved from appliance level consumption data.

There are several DR studies utilizing appliance-level consumption data. These studies identify suitable appliances to focus on for DR programs. In the paper [6], load profiles of major appliances from two U.S. households and their demand response opportunities were studied, by considering whether the loads were interruptible (reducing consumption) or deferrable (shifting the load). The DR potential of the clothes dryers was found to be high (interruptible for up to 30 minutes and deferrable entirely), water heaters high (reducing consumption), the air conditioners medium (reducing consumption), and the rest of the appliances low. In a related study with European data [9], clothes washing machines, dryers and dishwashers were considered as shiftable loads that can be used to forecast or estimate the flexibility potential (in kW) which they can get from group of households at different times of the day.

In general, there are two ways to quantify the amount of power that can be saved: by actual measurement or simulation [10]. Simulation studies estimate the amount by reducing appliance power consumption (total energy consumption falls) or shifting the appliance load to an off-peak period. This study considers a third approach: appliance load leveling, in which the amount of power consumed by an appliance at peak duration is spread out more evenly.

To summarize the literature review, it has been established that analyzing appliance-level consumption data is crucial for effective demand response programs. The appliances and the factors that relate to peak periods were identified, and some of the methods for estimating the power saving potential of the appliances were stated. It is also evident that power saving potential of an appliance is highly contextual to the local environment and can vary depending on the region.

By analyzing appliance-level consumption data during summer months in Japan, this study provides a valuable contribution to demand response literature. The estimated amount of power that could be saved is then quantified using simulation techniques. Specifically, the study identifies which appliances would be most effective to target for demand response (DR) programs and proposes appropriate power-saving methods for each appliance.

III. METHODOLOGY

The power consumption data of the appliances recorded in 1-minute intervals were obtained from 7 houses over a period of 3 days (August 1-3, 2022). The appliances include *clothes washing machines, clothes dryers, microwaves, refrigerators, rice cookers, air conditioners* and *IH cooking heaters*. Each appliance was analyzed to select the appropriate power saving method as either reducing consumption, leveling the load or shifting the load, as illustrated in Fig 1. The amount of power that could be saved was estimated by generating simulation data and calculating the difference before and after performing the power saving action.

A. Reducing the load

Applicable appliances for this method of power saving are air conditioners and clothes dryers. The reason is that the air conditioner temperature settings can be easily modified to decrease energy consumption, whereas the use of clothes dryers can be completely avoided on hot, sunny days.

Method of generating simulation data:

- For the air conditioner, we calculated the average consumption during the day (Watts) when the air conditioner is on, and at the target time, reduced the power consumption data to that average. This study makes the assumption is that the average consumption value (W) for each is that it could offer a balance of energy savings and comfort for that particular user. If the power usage was below average at the specified time or if the air conditioner was not in use, then there was no opportunity for conserving energy.
- To generate simulation data for the dryer, the power waveform data for the dryer is excluded by deletion (dryer not utilized). In many cases, the washer-dryer was the same machine. In such cases, the dryer function was deleted, which is approximately 45 minutes after the washing machine cycle starts. This study makes the assumption that with the hot weather, dryer use could be avoided without inconveniencing the customer. However, in cases where it could not be avoided, then shift operation was considered.

B. Leveling the load

To level the load of an appliance, the power consumption should be distributed more evenly over time, such as illustrated in Fig. 2. Out of the targeted devices, only *air conditioners* were considered applicable. The reason is upon switching on the air conditioners, there was often a

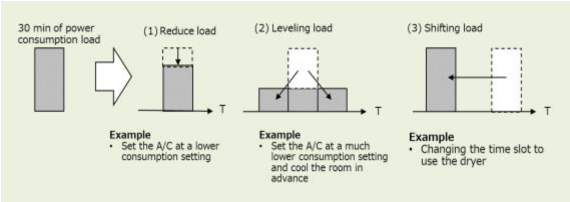

Fig. 1. Power saving methods

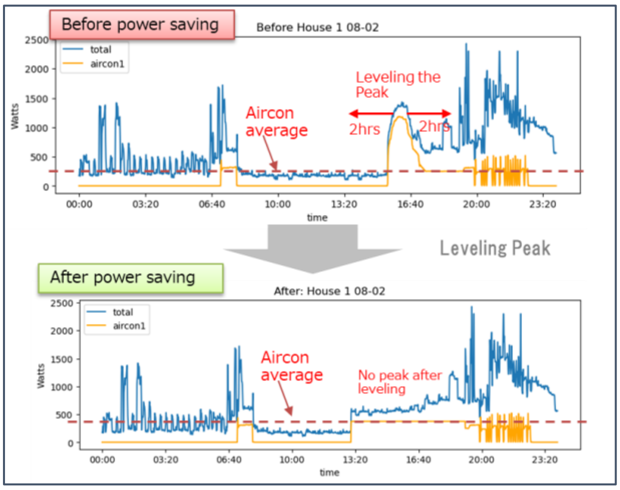

Fig. 2. An example of leveling the load

noticeable surge in energy usage that leveled off as the room temperature reached a more comfortable level. This initial peak in consumption can be leveled by turning on the air conditioner at an earlier time but at a lower power consumption setting. The general advice is to turn on the air conditioner in the morning while the house is still moderately cool and keep it at a constant temperature all day.

- Method for generating simulation data: similar to reducing the load, for the air conditioner, we calculated the average consumption during the day (Watts) when the air conditioner is on, and leveled the usage to that average some duration before and after the target time.

- To ensure that the total consumption (kWh) did not increase, the method of flattening considered was to calculate the amount of power consumed at the peak duration, and then to spread out the consumption to an appropriate duration before and after the peak.

peak consumption (W) × *peak duration (min)* = *average consumption on the day (W)* × *new duration (min).* (1)

- Since we have the peak value and duration, and we can calculate the average consumption on that day, then we can solve equation (1) for the new duration. This duration varies depending on the consumption of the air conditioners.

- In Fig. 2, an example of leveling the peak of an air conditioner of a particular house is shown. By turning on the air conditioner 2 hours before but at the average consumption (W), the peak at 16:00-17:00 can be avoided.

- It is important to note that the total consumption per day in kilowatt hour (kWh) does not reduce or increase. However, leveling the peak results in reduced consumption at the time the peak occurs.

C. *Shifting the load*

Applicable appliances include those with flexibility in the usage and where consumption is not continuous. Air conditioners are not applicable as they are critical for cooling the room in summer and shifting the load would inconvenience the customer, putting them at risk of heat stroke. Applicable devices for shifting the load are: *IH cooking heater*, *clothes dryer*, *rice cooker* and *microwave*. However, the power saving potential offered by rice cookers and microwaves is so low as to be insignificant. Although refrigerators consume a large amount of power (kWh), they are constantly on so their loads cannot be shifted.

- Method for generating simulation data for the dryer and IH cooking heater: the power waveform data is deleted at the target time and inserted at a different time slot outside of the peak hours (target time for power saving).

D. *Device and Power Saving Action Summary*

The power saving actions that are applicable for each appliance are summarized in Table 1.

IV. FINDINGS FROM 2022 AUGUST 1-3 ANALYSIS

The power saving approaches described in section III were applied to the appliance power consumption data obtained from the 7 houses between August 1-3, 2022. Table II shows the applicable appliances for power saving for each house, the power saving method and the amount of power saved. The target time was when the power reserve margins were low, below 10%. The power reserve margins data was obtained from the Japan Organization for Cross-regional Coordination of Transmission Operators [11].

On 2022/08/01, there were low reservation margins in the Tokyo area between 15:30-17:00. In 3 out of the 7 houses, there was no apparent room for power saving in this period. Air conditioners were off or operating at the average consumption load (W) or below. Other appliances like dryers, IH cooking heaters, were not in use at this period. In 4 out of the 7 houses, by reducing the consumption of air conditioners, the amount of power saved in the entire period in each household ranged from 0.1 kWh to 1.5kWh, with an average of 0.5kWh. This represents an average of 0.33kWh per hour per household with potential savings. The total power saved is 2kWh, which is 15.3% of the total power consumed by all the 7 houses in this period.

On 2022/08/02, there were low reservation margins in the Tokyo area between 15:30-19:00. In 4 out of the 7 houses, there was likely no room for power saving in this period. In 3 out of the 7 houses, by reducing the consumption of air conditioners and leveling the load in one case, the amount of power saved ranged from 1.2 kWh to 1.85kWh, with an average of 1.6kWh. This represents an average of 0.46kWh per hour per household with potential savings. The total power saved is 4.8kWh, which is 14.6% of the total power consumed by all the 7 houses in this period.

TABLE I. SUMMARY OF APPLICABLE POWER SAVING ACTIONS

Appliance	Power Saving Method		
	(1)Reduce load	*(2) Leveling load*	*(3) Shifting load*
Air conditioner	✓	✓	X
Dryer	✓	X	✓
IH cooking heater	X	X	✓
Rice cooker	X	X	✓
Microwave	X	X	✓
Refrigerator	X	X	X

TABLE II. FINDINGS ON AUG 1-3

House	Day/Time Appliance/Method/Estimated Amount		
	Aug 1 (Mon) 15:30-17:00	*Aug 2 (Tue) 15:30-19:00*	*Aug 3 (Wed) 9:00 -17:00*
1	Aircon1 Reduce load Save 0.2kWh	-	(13:00-14:00) Aircon1 Reduce load Save 0.2kWh
2	Aircon1 Reduce load Save 0.1kWh	Aircon1 Reduce load Save 1.2kWh	-
3	Aircon 2 & 4 Reduce load Save 0.2 kWh in total	-	-
4	-	-	-
5	-	Aircon4 Reduce load Save 1.05kWh	(12:00-17:00) Aircon4 Reduce load Save 1kWh
6	Aircon1 Reduce load Save 1.5kWh	Aircon 2 Level the load at 16:00-17:00 Save 0.8 kWh Aircon4 Reduce load Save 1.05kWh	(13:20-16:00) Aircon4 Reduce load Save 1.067kWh
7	-	-	(10:00-11:00) Aircon2 Reduce load Save 0.4kWh

On 2022/08/03, there were low reservation margins in the Tokyo area between 9:00-17:00. In the morning, between 10:00-11:00, about 0.4kWh of power could be saved in house number 7 (Hs7) by reducing the consumption of the air conditioner. It appears that there is not much room for power saving in the morning. In the afternoon, **13:00-17:00**, there are three houses a total of 2.27kWh can be saved, with an average of 0.75kWh per household. This represents an average of 0.19kWh per hour per household with potential savings. The total power saved is 2.27kWh, which is 7% of the total power consumed by all the 7 houses in this period.

V. CONCLUSION

This study contributes to the existing research in demand-response programs by systematically considering three methods for power saving: reducing the load, shifting the load or flattening the load. The power saving methods were applied to appliance level consumption data in 7 households in the Tokyo area. There was room for power saving in 3 or 4 of the 7 houses during the periods of low reserve margins. This suggests that about half of the households may have the potential for power saving. It was found that air conditioners are appliances with the most power saving potential during the day. The average amount of power saved per household per hour was 0.33kWh on Aug 1, 0.46kWh on Aug 2 and 0.19kWh on Aug 3. The amount of power that could be saved relative to the total power consumed by all the houses ranged from 7% to 15.3%. The power reserve margins in Tokyo on Aug 1-3, 2022, were quite low, as low as 5% at certain times. By targeting households with potential for power saving and instructing them to reduce, shift or level their appliance consumption as appropriate, it may be possible for the households to lower their power consumption by 7-15%, which can significantly reduce the stress on the grid and potentially increase the reserve margins. To extrapolate the amount of power that can be saved in the entire Tokyo area, more data is needed in terms of the number of households as 7 households may not be an adequate sample size. The methodology applied in this study can be used to design targeted and personalized DR programs which can increase the effectiveness of DR programs.

VI. REFERENCES

[1] A. Todd, M. Perry, B. Smith, M. Sullivan, P. Cappers and C. Goldman, "Insights from Smart Meters: The Potential for Peak-Hour Savings from Behavior-Based Programs," State and Local Energy Efficiency Action Network., 2014.

[2] SAS, "Utility analytics in 2017: Aligning data and analytics with business strategy," Tech Republic, 2017.

[3] F. M. Dahunsi, A. E. Olawumi, D. T. Ale and O. A. Sarumi, "A systematic review of data pre-processing methods and unsupervised mining methods used in profiling smart meter data," *AIMS Electronics and Electrical Engineering, 5(4)*, p. 284–314, 2021.

[4] J. Curtis, "Household attributes associated with peak period domestic appliance loads," *Heliyon*, 2021.

[5] T. Song, Y. L, X.-P. Z. J. Li, C. Wu, Q. Wu and B. Wang, "A Cluster-Based Baseline Load Calculation Approach for Individual Industrial and Commercial Customer," *Energies*, vol. 12, no. 1, p. 64, 2019.

[6] M. Pipattanasomporn, M. Kuzlu, . S. Rahman and Y. Teklu, "Load Profiles of Selected Major Household Appliances and Their Demand Response Opportunities," *IEEE Transactions on Smart Grid, Vol.5, No.2*, pp. 742-750, 2014.

[7] M. Afzalan and F. Jazizadeh, "Residential loads flexibility potential for demand response using energy consumption patterns and user segments," *Applied Energy*, vol. Volume 254, p. 113693, 2019.

[8] J. Torriti, G. M. Hassan and M. Leach, "Demand response experience in Europe: Policies,

programmes and implementation," *Energy*, vol. Volume 35, no. Issue 4, pp. 1575-1583, 2010.

[9] M. Z. Degefa, S. Hanne, P. Idar and A. Peter, "Data-driven household load flexibility modelling: shiftable atomic load.," in *IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, 2018.

[10] X. Yu and S. Ergan, "A Data-driven Framework to Estimate Saving Potential of Buildings in Demand Response Events," in *35th International Symposium on Automation and Robotics in Construction*, Berlin, Germany, 2018.

[11] Organization for Cross-regional Coordination of Transmission Operators, Japan, "Regional Reserve Margin Information," [Online]. Available: https://web-kohyo.occto.or.jp/kks-web-public/.

[12] Y. Wang, Q. Chen, C. Kang, M. Zhang, K. Wang and Y. Zhao, "Load Profiling and Its Application to Demand Response: A Review," *Tsinghua Science and Technology 20.2*, pp. 117-129, 2015.