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The Formulation of a Reference Load Curve to Measure Energy Flexibility

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Key Innovations

- Reference load curve for each residential consumer based on historical consumption data.

Practical Implications

For the days when energy flexibility is activated, the difference of reference load curve (RLC) and measured load curve (MLC) gives a measure of energy flexibility.

Introduction

An indirect feedback of energy flexibility is given to the consumer after the period of energy consumption. It is either historic (comparing the energy consumption with the past consumption of the same household), or normative (comparing household energy consumption with that of a group of similar households) (Wang et al. 2018). Graphically, it is presented in the form of clustered baseline load curve of identical households (Abreu, Câmara Pereira, and Ferrão 2012) or average load curve of same household (Ozawa, Furusato, and Yoshida 2016).

This extended abstract presents a statistical comparison of methods to formulate RLC of residential consumer. An RLC (superposed on MLC) is helpful in measuring energy flexibility of a residential consumer during a flexibility activated day ‘D’. An example of RLC for load curtailment between 6 PM and 8 PM is given in figure 1.

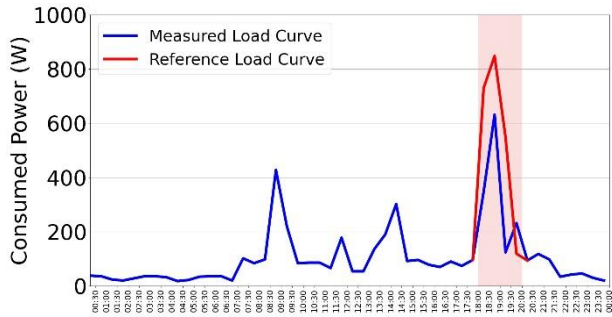


Figure 1: Superposition of RLC over MLC to visualize load curtailment of a residential consumer on day ‘D’

Methods

The consumption data of 96 French households (spanning over a year) is taken. These households participated in an experiment of energy flexibility and indirect feedback is given in the form of images as illustrated in figure 1. Subjecting to the intended type of flexibility, RLC is used to measure flexibility on activation day ‘D’ for individual household to measure:

- Load curtailment between 6 PM and 8 PM.
- Load shifting from evening to ‘noon and 3 PM’.

Kernel Density Estimation (KDE)

For each timestamp of alert period, KDE is implemented on the historical power consumption to choose the value with highest density (i.e. most probable value).

Mean [P_{D-1} & {Max or Min (P_{D-2} : P_{D-5})}]

For an alert day ‘D’, an RLC is created by taking average of measured load curve of previous day ‘D-1’ and the measured load curve having highest or lowest energy consumption between day ‘D-2’ and ‘D-5’, for load curtailment and load shifting respectively.

Max or Min (P_{D-1} : P_{D-5})

For an alert day ‘D’, the measured load curve having highest or lowest energy consumption between day ‘D-1’ and day ‘D-5’ is taken as reference load curve, for load curtailment and load shifting respectively.

Random Forest (Sequence to Sequence)

A sliding window of 5 alert periods between ‘D-1’ and ‘D-5’ is used to train a random forest regression model. This model predicts the RLC of alert day ‘D’.

Random Forest (Point to Point)

For each timestamp of alert period, a sliding window of 5 same timestamps between ‘D-1’ and ‘D-5’ is used to train a random forest regression model. This model predicts the RLC of alert day ‘D’.

Energy Difference Indicator

Using the historical data of 1 year, RLC is calculated for all the methods. An energy difference indicator is used to compare the methods using equations below.

$$EDI_{load\ curtailment}^{20:00}_{18:00} = \sum_{18:00}^{20:00} RLC - \sum_{18:00}^{20:00} MLC \quad (1)$$

$$EDI_{load\ shifting}^{15:00}_{12:00} = \sum_{12:00}^{15:00} RLC - \sum_{12:00}^{15:00} MLC \quad (2)$$

Discussion

An RLC is in fact an expected MLC if no flexibility activation is put in place. The difference of RLC (i.e. expected MLC) with flexibility driven MLC measures achieved energy flexibility on activation day ‘D’. Hence, the difference between an ideal RLC and MLC is zero for non-activated days, and vice versa.

Practically, RLC can be formulated by using naïve methods or regression. An indirect feedback with an RLC that underestimates energy flexibility may discourage the consumer. On the other hand, an extreme overestimation

is not helpful for distribution system operator (DSO) or energy aggregator to measure energy flexibility. Since an ideal RLC does not exist, therefore it is required to select an RLC that slightly overestimates energy consumption. For the purpose of study, the difference between RLC and MLC of 96 households is calculated using EDI during non-activation days. EDI is calculated between 6 PM and 8 PM in the case of load curtailment. Ideally, the difference should be zero, however practically the difference should be small and positive for non-activated days. The statistical distribution of EDI is visualised in figure 2 for each method of RLC formulation.

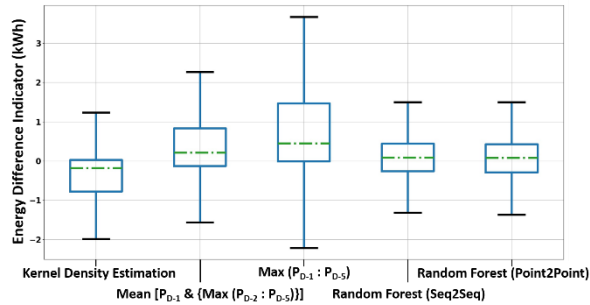


Figure 2: Comparison of RLC formulation methods w.r.t energy difference indicator for load curtailment

It can be observed by figure 2, that KDE method will mostly underestimate the prospective load curtailment on activated day. This is due to the fact that it takes historical consumption and therefore a most probable value is calculated for gross variation in energy consumption. The other 4 methods fulfil the criteria, however the method $\text{Max}(P_{D-1} : P_{D-5})$ is widely dispersed and may extremely overestimates the prospective load curtailment on activated day, therefore it is not suitable. The random forest regression methods are less dispersed and the median value is closer to zero, therefore they create suitable RLC for load curtailment.

In the case of load shifting, EDI is calculated between noon and 3 PM. Since it is expected that the consumer consumes more than usual during this time period, therefore the difference should be small and negative for non-activated days. Similar to figure 2, the statistical distribution of EDI is visualised in figure 3 in the case of load shifting.

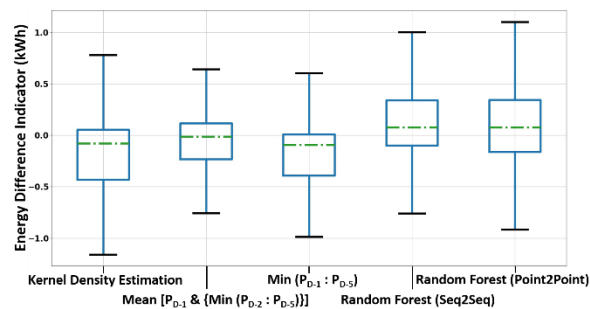


Figure 3: Comparison of RLC formulation methods w.r.t energy difference indicator for load shifting

The random forest regression methods are not suitable for assessment of load shifting as they are widely dispersed

and have positive EDI (i.e. underestimation). Among the other 3 methods, $\text{Mean}[P_{D-1} \& \{\text{Min}(P_{D-2} : P_{D-5})\}]$ is most suitable as the median of EDI population is close to zero and the population is not widely dispersed.

Conclusion

Indirect feedback is given to the energy consumers in numerical form, as a clustered load curve of identical households or as average daily load curve. However a customized reference load curve for each consumer is required to measure individual energy flexibility. A simulated load curve can serve as a reference load curve. This simulated load curve is an expected MLC if no flexibility activation is put in place. The difference of this expected MLC with flexibility driven MLC measures energy flexibility on activation day 'D'. Ideally, the difference of reference load curve and measured load curve is zero. Practically, a good RLC should not underestimate or extremely overestimate the prospective energy flexibility and also it should nudge the consumer to carry on their efforts for energy flexibility.

Random forest regression gives good formulation of RLC for load curtailment however it is not found effective for load shifting. Therefore, the naïve method with less dispersed EDI population and median close to zero is most suitable for load shifting. The visualization of RLC superposed on MLC gives the DSO or energy aggregator a measure of energy flexibility whereas on the other hand it may nudge the consumer through indirect feedback to continue practicing energy flexibility.

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Nomenclature

- RLC : Reference Load Curve
- MLC : Measured Load Curve
- EDI : Energy Difference Indicator

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