Daily load profiles clustering: a powerful tool for demand side management in medium-sized industries

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ABSTRACT

Customers' lack of detailed knowledge of their electrical load consumption was identified as a main barrier for demand side management in small and medium industries (SMIs). Visualization tools were developed to expand SMI customers' understanding of the relationship between their operations and electric load profile. Using interval meter data, a clustering algorithm groups daily load profiles based on shape and magnitude in order to produce a reduced set of typical profiles. A whole year's electric consumption can be visualized on a calendar featuring up to six typical daily profiles, all in a single page or screen. Examination of such graphical display was shown to help customers elaborate demand side management strategies or optimize production schedules.

Such one-pagers were used in demand response oriented surveys and walkthroughs targeting SMIs. It also shows the impact of seasonal weather on electricity consumption and points out daily peak. For a customer from the foundry sector, past unused production capacity and flexibility for demand response were quantified. For another from the plastics industry, the loads of each production line and, therefore, curtailment potential by line and energy saving estimates from replacing the less efficient one were clearly identified. In a meat processing plant, a high level of electricity consumption was found outside operating hours (weekend), resulting in a new lighting control strategy. Hydro-Quebec provided daily load profile clustering to 620 SMIs (200 kW to 5 MW) in a pilot project and considers using it as a tool to increases customer satisfaction and electricity usage awareness.

Introduction

Knowledge of their own detailed electrical load consumption patterns is the starting point of any electric utility customer's demand side management (DSM) efforts, including energy efficiency (EE), peak load management and demand response (DR). Many of the large industries have sub-metering of their larger loads, a team dedicated to energy management and the support of consultants to perform DSM efforts. In contrast, the small and medium industries (SMI) segment have limited resources devoted to energy management and, without sub-metering, have difficulty identifying their electrical loads - the main input to the economic evaluation of DR or EE opportunities. Since energy often accounts for only a marginal part of production costs, SMIs generally have higher priorities such as maintaining the quality of their products, increasing productivity, managing human resources, meeting the order book, etc. Nevertheless, given the proper tools, many SMIs are ready to capture opportunities for DSM.

Hydro-Québec (HQ), a Canadian publicly-owned electric utility, operates 36.9 GW of generation, with hydropower accounting for over 99 % of its output. To face winter peaking demand, it can count on about 850 MW of curtailment capacity coming mainly from large industrial customers (Hydro-Québec 2015).

For several years, an electricity consumption monitoring and analysis tool using15-minute interval data was offered to SMI customers through subscription, using standard phone line to transfer the data. With simpler access to such data, new approaches in the delivery of electric consumption pattern insights could be made available to the SMI market. Historically, HQ devoted much effort approaching the SMIs for energy efficiency programs. With the increasing need for power during winter peaks, a new DR program covering customers from the commercial, institutional and SMI markets has been launched in April 2016 (Hydro-Québec 2016). An incentive of $70CDN/kW-year is offered to customers able to curtail a minimum of 200 kW, representing at least 10% of their maximal demand registered in the winter period. DR events are three- or four-hour periods that can occur from 6:00 to 9:00 a.m. and from 4:00 to 8:00 p.m. between December 1st and March 31st, except weekends and holidays.

In preparation for this new program, DR oriented energy surveys and walkthroughs targeting SMIs were performed. The lack of knowledge of equipment consumption patterns was identified as one of the main barriers to DR program participation. Tools and indicators using 15-minute interval data were developed to support the surveys. This helped participants quantify DR strategies and evaluate financial benefits, facilitating customer engagement. One of the most appreciated tools was the daily load profiles clustering tool. Beyond the simple visualization of 15-minutes load profile data, a clustering algorithm groups daily load profiles based on shape and magnitude in order to propose a reduced set of typical profiles. The load profile of a whole year can be represented on a calendar featuring typical daily profiles. Four major industrial sectors took part in this project to gain deeper understanding of DR adoption triggers and barriers: sawmilling industry, foundry, food processing and plastic extrusion.

This paper presents this tool and three SMI case studies to illustrate the tool's ability to help customers capture insights into their own electrical load profiles, supporting the analysis and implementation of new DSM strategies or production schedule optimization.

Daily load profiles clustering

A one year long 15-minute sampled load profile contains over 35 000 readings, with fluctuations that occurs hourly, daily, weekly and on seasonal scales, all of which cannot be grasped from a single traditional time-series plot. To extract and synthesize meaningful information, a clear and user friendly way to render them is essential. The approach presented here uses an unsupervised clustering data mining technique. Load profile clustering has been proposed to group the load profiles of several customers at the utility level mainly for cost allocation and definition of rate structures (Chicco, Napoli, and Piglione 2006; Yamaguchi et al. 2009). Application of clustering to daily profiles of customers has various potential uses for pattern recognition related tasks such as inspection, comparison, load identification and day profiling (Poulin, Fournier, and Dostie 2010). For example, daily load profiles have already been proposed to analyze measured and simulated load profiles for buildings (Fournier and Lavigne, 2010), to identify electricity theft (Jokar, Arianpoo, and Leung 2016) or characterize household electricity consumption (Mc Loughlin, Duffy, and Conlon 2015).

Methodology

The methodology used to generate the daily load profiles calendar is similar to the one presented in (Poulin, Fournier, and Dostie 2010), where the profiles are grouped according to their similarity in shape and magnitude.

The yearlong load profile (Y) is first separated in a continuous sequence of n daily load profiles (D). Daily load profiles (D_n) are built from hourly load data ($H_{n,x}$) derived from the 15-minute interval meter.

$$Y = [D_1 \quad D_2 \quad \dots \quad D_n]; \qquad [1]$$

$$D_n = [H_{n,1} \quad H_{n,2} \quad \dots \quad H_{n,24}]. \qquad [2]$$

Feature vectors with 25 dimensions are then formed. The first 24 dimensions are the normalized components of the daily load profiles. The last dimension represents the ratio of the norm of the actual daily load profile vector to the greatest norm of all the daily load vectors of the year. This formulation of the feature vectors allows the grouping of similar daily profiles in terms of both shape and average load.

$$F_n = \left[\frac{D_n}{\|D_n\|} \quad \frac{\|D_n\|}{\max\|D_o\|} \right], \qquad D_o \in Y \, . \qquad [3]$$

The feature vectors (F) can then be fed to a clustering K-mean algorithm. The best results were found using the cosine similarity function to compare the feature vectors,

$$\cos(F_j, F_k) = \frac{F_j \cdot F_k}{\|F_j\| \|F_k\|} \, . \qquad [4]$$

Hence, the following objective function is maximized:

$$\sum_{i=1}^{p} \sqrt{\sum_{F_j, F_k \in S_i} \cos(F_j, F_k)} \qquad \text{for a given } p \, . \qquad [5]$$

The latter looks at the sum of the similarity function over the pairs of vectors belonging to the same cluster (S_i) in order to assign each vector a cluster. The result of this attribution is called a solution. The number (p) of clusters is set to six. A solution of six clusters is generally enough to capture the range of load profile shapes shown by the SMI operating modes and schedules and yet deliver a clear presentation of the results.

Solution display

Figure 1 illustrates the solution of daily load profile clustering. It is composed of two parts: the left one shows the temporal distribution of the clusters on a one year calendar while the second presents the six clusters of load profiles. Each calendar line corresponds to a week and each row corresponds to a day of the week, starting on Sunday. Days having a daily load profile belonging to a common cluster are represented by a unique color. The number of days in each cluster is indicated at the top of each cluster graph. All the daily load profiles are shown in gray. The colored line links the median of the cluster members for each hour of the day. Such representations were used in DR oriented energy surveys targeting SMIs. The following section shows three examples of application of this tool.

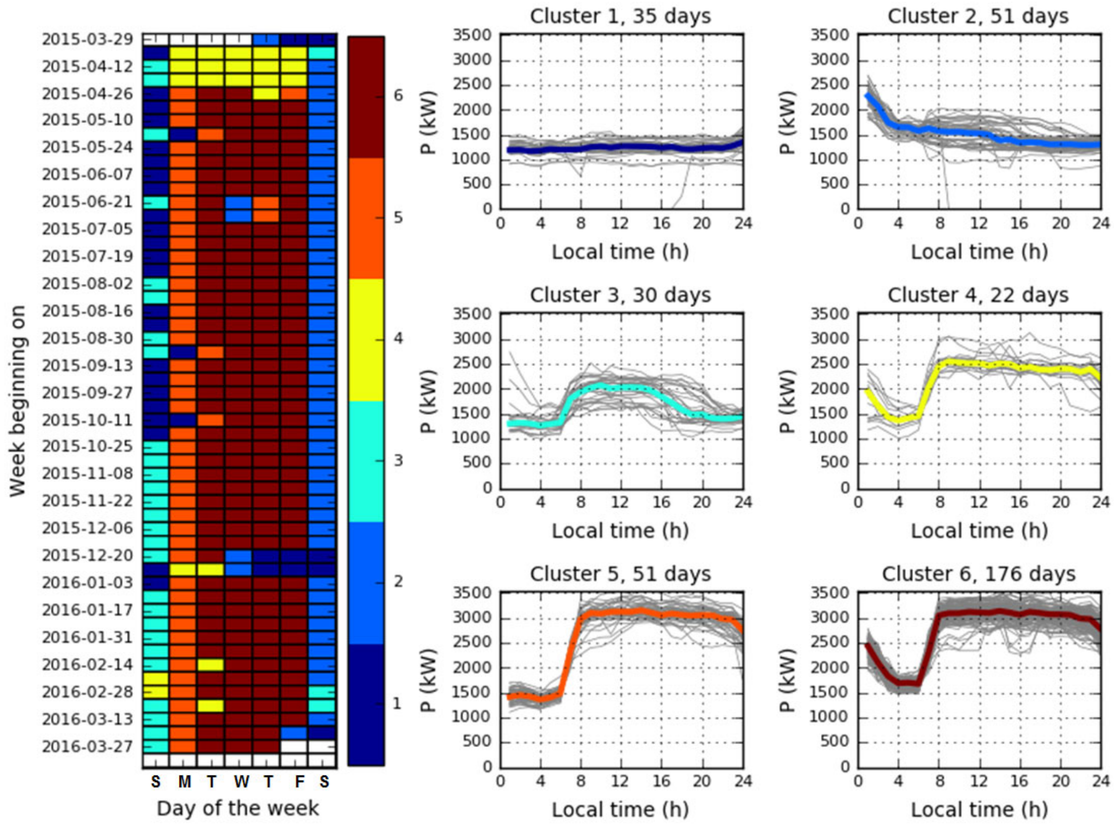

Figure 1. Load profile clustering featuring a whole year calendar (left) and six daily profiles clusters (right).

Medium-sized industries case studies

Foundry sector

According to the DR oriented energy survey performed with the manager, the plant's electricity consumption is dominated by an iron melting furnace. The demand of this energy intensive equipment varies up and down over three hour cycles. Other major contributors to the electricity consumption include other furnaces, various small motors, HVAC systems, compressed air and lighting. The plant normally operates sixteen hours a day (occasionally, 24 hours), five days a week. The visualization of this plant's 15-minute interval data profiles for a year, a winter week and two days are shown in Figure 2. The time-series plot featuring two days of electrical demand shows the typical demand cycles of the melting furnace.

Figure 3 presents the resulting daily load profile clustering solution for this particular customer. The first two clusters (# 1 in dark blue and # 2 in light blue) correspond to days where the melting furnace does not operate (or barely does), mainly weekend and holiday periods. What differentiates the other four clusters is the melting process schedule, more specifically, the time of the last casting operations. Given that the typical melting cycles are three hours, Cluster # 3 (cyan) would most likely represent a day where four melting cycles took place, Cluster # 4 days (yellow) five cycles, Cluster # 5 days (orange) six cycles and Cluster # 6 days (red) seven or eight cycles. Since eight is the maximum number of melting cycle that can be achieved during a day, the patchwork-like colour arrangement of working days is indeed an indicator of the "unused production capacity" throughout the past year. The number of cluster members corresponds to the number of days where each "unused production capacity" level occurred. The magnitude of the colored profile and the variation of the profiles in gray also give indications of the electric demand related to the melting process and other uses (both the median demand and variations).

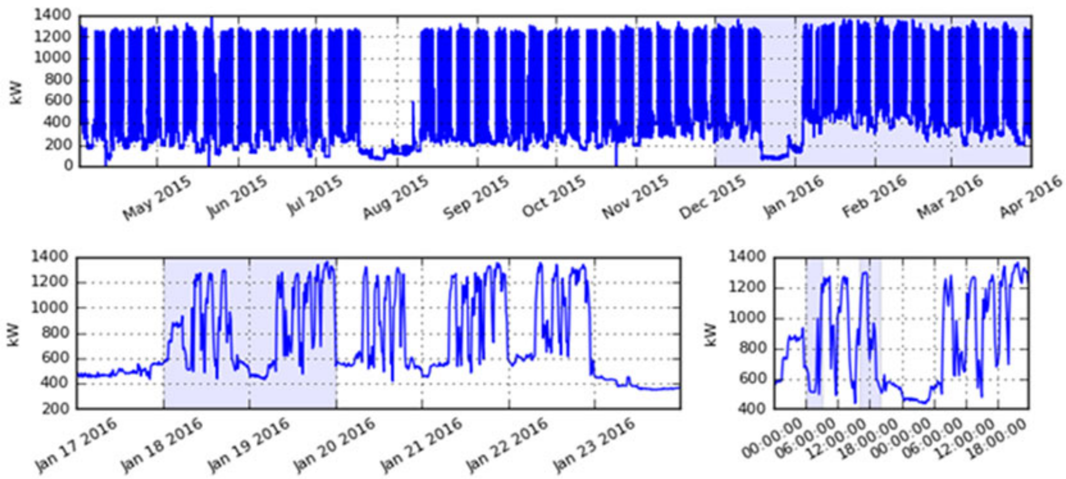

Figure 2. Visualization of interval meter data (i 15-minute intervals) for a year (top), a winter week (bottom-left) and two days (bottom-right) for customer in the foundry sector

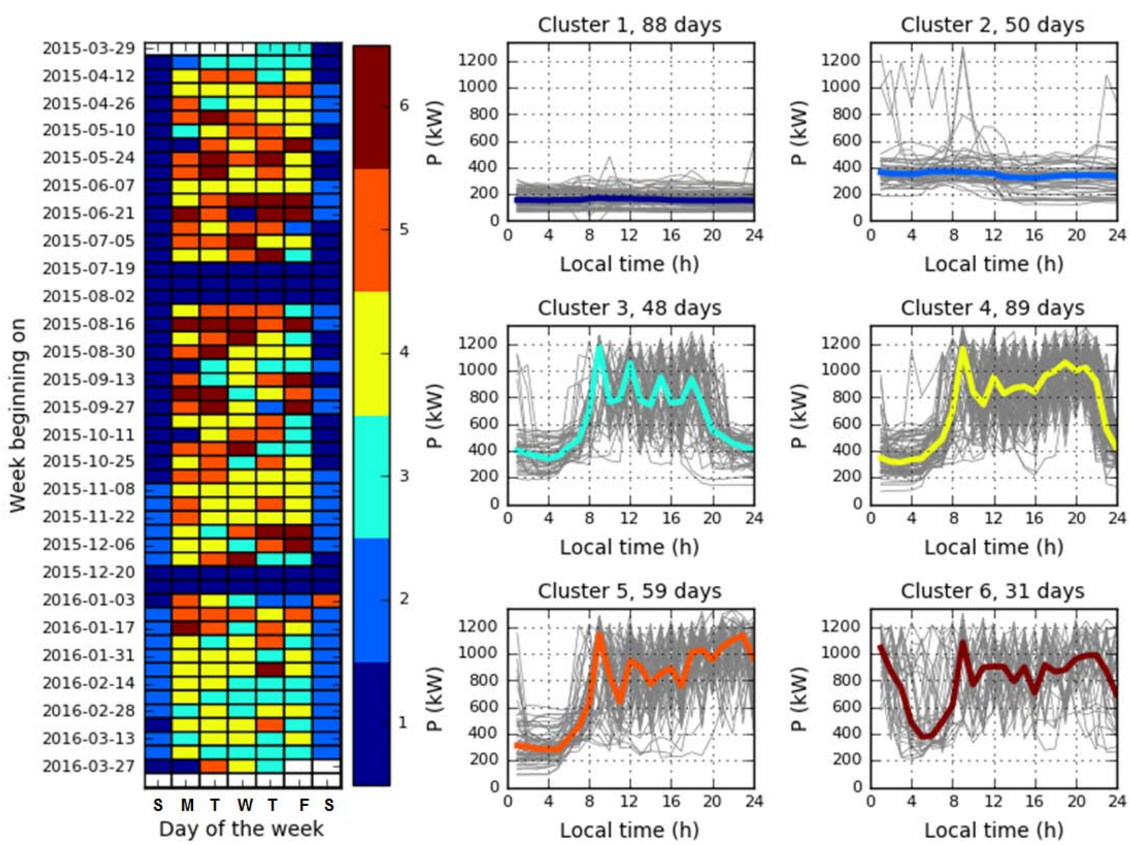

Figure 3. Iron foundry daily load profile clustering for a year

For this customer, the DR potential primarily lies in temporarily shutting down the melting furnace during the DR events. However, meeting the order book being the top priority, production delays should ideally be recovered within a day. The daily load profile clustering allows a quick analysis of past production flexibility and also helps evaluate the economics of a possible DR program enrollment. The plant manager confirmed that the daily load profile clustering yielded new and valuable information to him; it goes beyond what he gets from his load controller data.

Plastic industry

The DR oriented energy survey filled out by the plant manager showed that the electrical consumption of the plant is driven by the operation of three production lines associated with two recent extruders (line #1 and line #2) and a less productive one (line #3). In addition to the extrusion process itself, each line has its own shredder and a couple of small electrical motors driving a conveyor belt. The overall load of each line was unknown prior to the survey. Auxiliary loads include compressed air, HVAC systems and lighting. The plant operates on weekdays, having three shifts of eight hours a day. The 15-minutes load profile for a year illustrated on Figure 4 shows the production level fluctuations throughout the year, as indicated by the red lines.

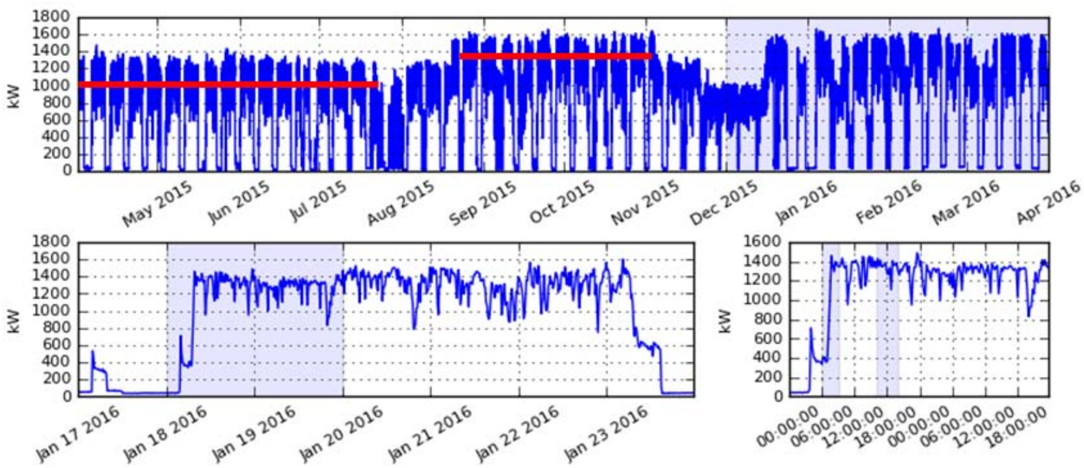

Figure 4. Visualization of interval meter data (15 minutes intervals) for a year (top), a winter week (bottom-left) and two days (bottom-right) for a customer in the plastic industry sector

Figure 5 presents the daily load profile clustering solution for the same year. Cluster #1 (dark blue) corresponds to Sundays and holidays, when none of the extrusion line is in operation. Cluster #2 (light blue) corresponds to eight-hour overtime shifts between 8 a.m. to 4 p.m. scheduled on Sundays and on the second week of a summer normally scheduled shutdown used to catch up with the production target. Cluster # 3 (cyan) and Cluster #4 (yellow) correspond to Saturdays and to holidays following a workday. Cluster # 4 is differentiable from Cluster # 3 because of the presence of an eight-hour overtime shift from 8 a.m. to 4 p.m. As for Cluster # 5 (orange), it is related to Mondays or days following a holiday. Finally, Cluster # 6 (red) groups normal production days. Working days have highly fluctuating loads (800 kW - 1500 kW) caused by the varying number of production lines in operation.

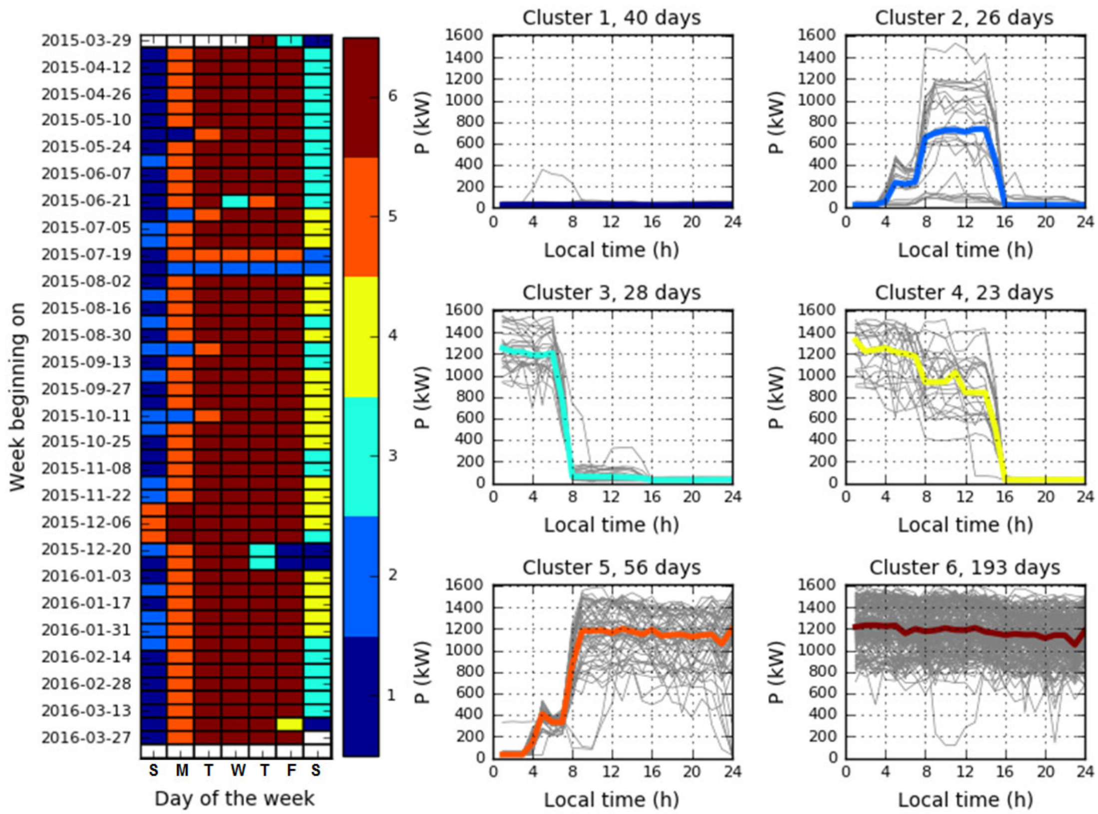

Figure 5. Plastic extrusion plant daily load profile clustering for a year

For this plastic production plant, the DR potential lies for the most part in shifting the production of one extrusion line off-peak. To evaluate the economic potential of DR, the loads associated with each production line during DR events has to be determined. To quickly address this issue, a second clustering was performed on working days with outdoor temperature under 10 °C (50 °F) as shown on Figure 6. Three Clusters were associated with different production levels. According to the plant manager, Cluster # 3 (cyan) groups days where only production line #2 and #3 were in operation. Cluster # 5 (orange) groups days where production line #1 and #2 were in operation. Finally, Cluster # 6 days (red) groups days where all the three extrusion lines operated simultaneously. By deduction, the average load of the production line #1, #2 and #3 was estimated to 500, 500 and 200 kW, respectively. This second clustering underlined the additional benefits of interactive features that allow a deeper analysis of specific days or clusters.

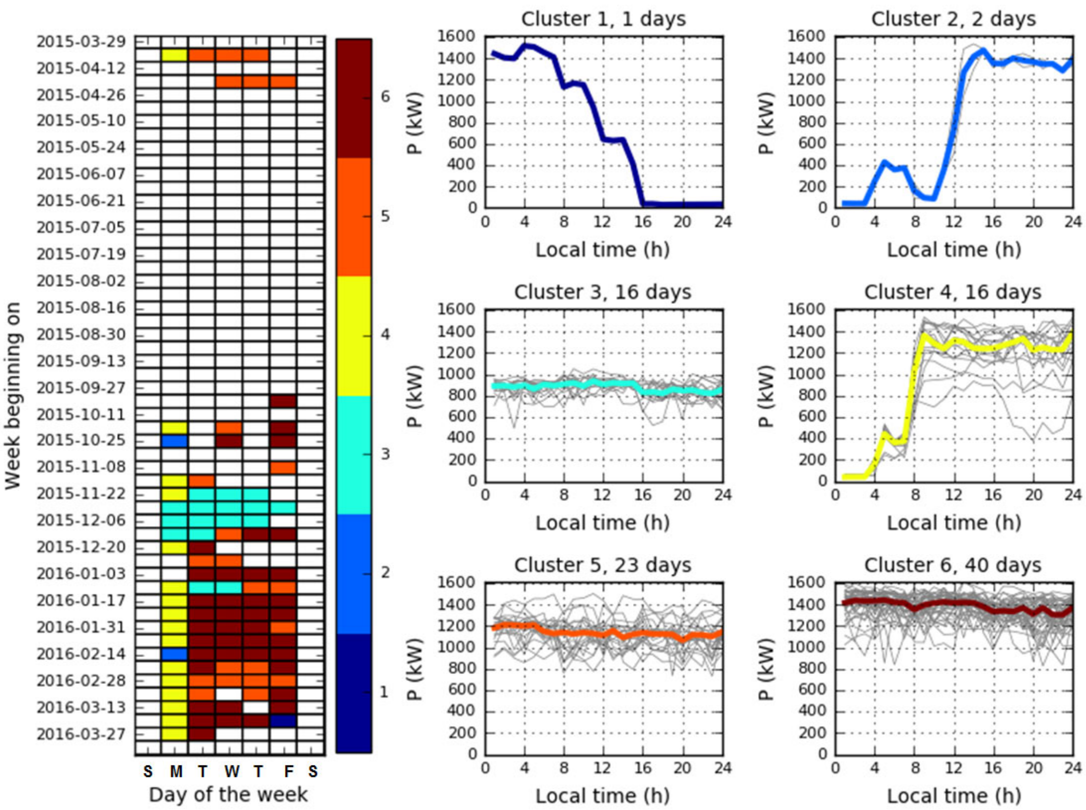

Figure 6. Plastic extrusion plant daily load profile clustering for a year using only working days when external temperature was below 10 °C (50 °F)

With this information, the plant manager evaluated that the DR program was economically attractive for his plant and subscribed to it. He confirmed that the daily load profile clustering was valuable to him as he didn't have to add sub-metering nor to ask his electric technician to manually measure the load of each production line. Also, the plant manager used the information to evaluate the impact on energy costs of upgrading the least efficient line (#3) while respecting the plant power electrical supply limitations.

Meat processing plant

The electricity consumption of the plant is dominated by both cold storage and cooling/freezing processes such as blast freezers, according to its managers interviewed in the DR oriented energy survey. Other electricity uses include various small motors, HVAC systems (with some electric heating), and lighting. It normally operates sixteen hours a day, five days a week. The sanitation process takes place at the night. Figure 7 presents the 15-minute interval meter data and Figure 8 presents the daily load profile clustering solution for a year.

Cluster #1 (dark blue) corresponds to mostly Sundays and holidays. Cluster#2 (light blue) corresponds to mostly Saturdays and the first day of holidays following a working day and, therefore, including a night sanitation period. Cluster # 3 (cyan) and Cluster # 5 (orange) group Mondays or the day after a holidays. Cluster # 4 (yellow) and Cluster # 6 (red) group the rest of the working days. Working day profiles were also automatically separated based on amplitude of electric demand. Warmer days with higher refrigeration process demand are represented in

Cluster # 4 and # 6. Colder working days with lower electric demand are included in Cluster # 3 and #5. The profiles are regular and the schedule appears quite clearly. Even the impact of lunchtime shows on electric demand. When there is no production nor sanitation (Cluster #1), electric demand is about 600 kW, which is about 30 % of the demand during production hours.

The customer commented that the daily load profile clustering was useful either to set a reference case for measurement and verification purposes following energy efficiency measure implementation or continuous fault detection. Upon viewing high electric demand outside operating hours (weekend), the superintendent in charge of the plant suggested a new lighting control strategy and the possibility of modifying the refrigeration compressors part-load operation. Since the number of days in each cluster is shown, the figure helps to provide a quick estimation of the annual saving of energy efficiency measures.

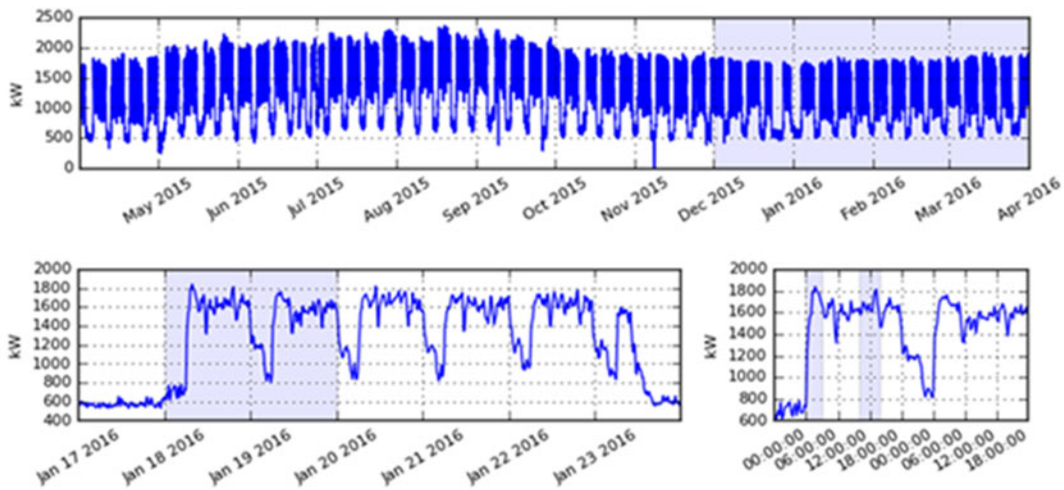

Figure 7. Visualization of interval meter data (15 minute intervals) for a year (top), a winter week (bottom-left) and two days (bottom-right) for a customer in the meat processing sector

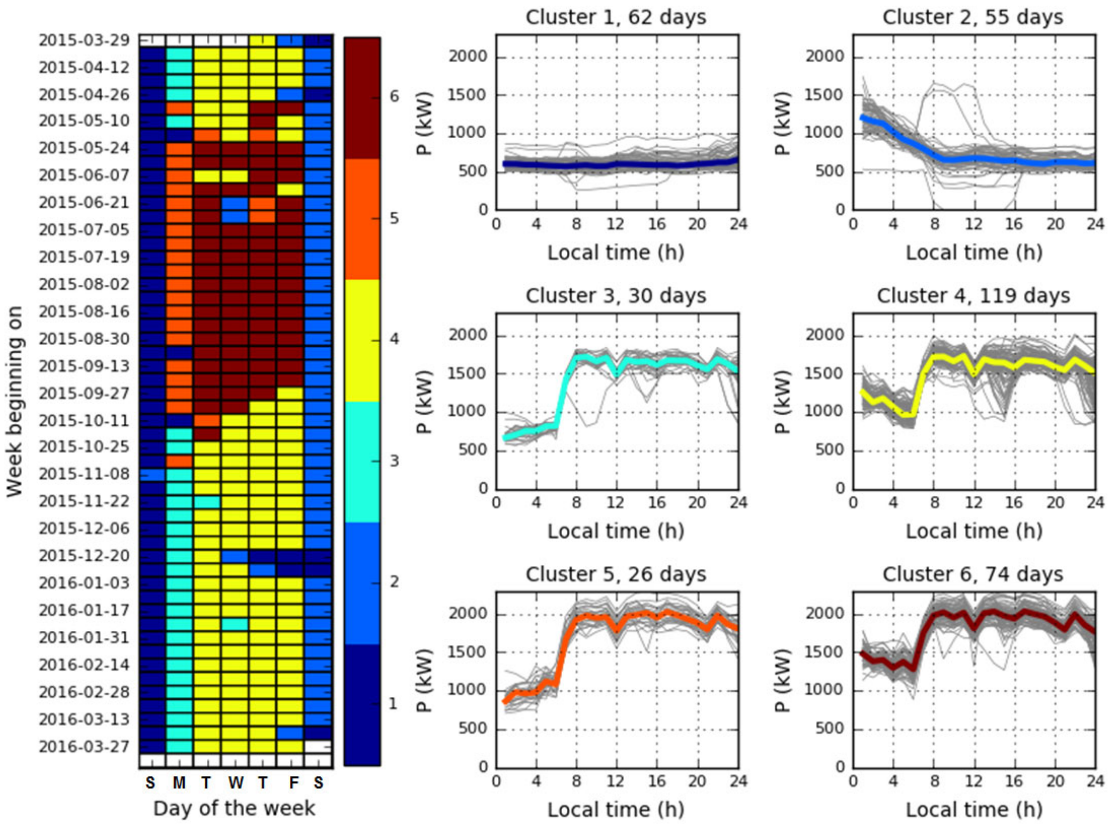

Figure 8. Meat processing plant daily load profile clustering for a year

Conclusions

Amongst a series of tools and indicators using 15-minute interval data developed to support DR oriented energy surveys for SMI customers, daily load profile clustering appeared to provide the most insight and meaningful information to customers. Although some valuable information can be extracted by the simple visualization of 15-minutes load profile data (time-series plot), a clustering algorithm that groups daily load profiles into typical clusters provides the following additional benefits:

- It presents a clear view of the electrical consumption patterns, and indirectly the plant operation, of a whole year in a single representation.
- It provides typical profiles with the median electric demand at every hour, beyond the anecdotal data of single day observations that can fluctuate day-by-day.
- It illustrates the impact of seasonal weather on electric demand when the facility's consumption is weather sensitive.
- Outlier consumption events can reliably be spotted in relation to a reference profile determined from the clusters, even where multiple operation modes are present.
- Plant managers can instinctively use the display to interpret the relationships between energy demand, production schedule and equipment loads.

- The number of days in each cluster being known, the clustering helps to quickly estimate the annual savings provided by energy efficiency measures that are sometimes specific to working days, nights, holidays, etc.
- The typical profiles provide a reference for DR strategy evaluations, daily power peak management and may illustrate operational flexibility.

The case studies demonstrated that this tool helped plant managers to quickly identify or analyze new strategies for DSM in their plant, like operational flexibility for DR participation, new EE opportunities and production schedule optimization. Also, without sub-metering, loads associated with different production line have been estimated.

For the utility, this tool has the potential to increase participation and engagement of SMIs in the DR and EE programs, but also enhance customer satisfaction. Following the DR oriented energy survey in spring 2016, Hydro-Quebec provided a one-pager presenting daily load profile clustering to 620 SMIs (200 kW to 5 MW) in a pilot project. HQ is now evaluating the opportunity to provide this new tool on a self-service web page to their customer. Beyond paper reports, an application could allow interactive features such as underlining a specific day profile in its cluster, restricting the clustering on a set of specific days or changing the number of clusters.

Acknowledgements

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