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Evaluation of Demand Response Potential Flexibility in the Industry Based on a Data-Driven Approach

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Abstract: The rapid increase in renewable energy resources has resulted in the increasing need for a demand flexibility program (DFP) from industrial load resources as a solution to oversupply and peak load spikes. However, to reasonably estimate the DR potential flexibility, the load characteristics must be analyzed and potential assessment formulas must be validated. Thus, in this study, a novel method is proposed to evaluate the DR potential flexibility of industrial loads according to a process of related load-characteristic data analysis. The proposed potential-estimation model considers frequency, consistency, and DR event operation scores during designated ramp-up and ramp-down time intervals separately. A case study was conducted by considering typical cement industry process with actual power-consumption data analysis for demonstrating the test system. The results confirm that load reduction of more than half of the usual power consumption is possible if a potential score is about 0.27 in cement industry cases. Thus, the proposed method can be used as an indicator to determine how an industrial load is adequate for obtaining a DFP while suggesting meaningful implications through industrial load-resource data analysis.

Keywords: demand response; load flexibility; industrial load; data analysis

1. Introduction

Under the current energy and environmental conditions, researchers are intensively investigating the replacement of fossil fuels with renewable energy resources. In addition, studies of distributed energy resources (DERs) in microgrids are proceeding rapidly in accordance with the de-carbonation policy. Contrarily, renewable energy sources, such as solar and wind power, are characterized by the fluctuating power generation. The expansion of renewable energy in the distribution network causes a mismatch in power supply and demand, and as the size of the ancillary service market inevitably increases, the supply opportunities of economic and stable power sources are reduced. In addition, the demand for global energy is steadily increasing every year; however, the expansion of power-generation and power-transmission infrastructure cannot keep up with this pace. In general, the grid system is excessively designed to overcome peak demand consumption, which only requires a few hours during a one-year period [1]. For instance, 20% of the generator-rated capacity in the energy market is reserved with respect to spinning or non-spinning conditions to support the peak demand that occurs during 5% of the total one-year period [2]. Under uncertain and irregular energy production conditions of the renewable energy resources, the stability of the grid system must be secured and the peak load demand must be reduced; the realization of both these factors is important to achieve economic balance of supply and demand. As a solution, we propose a mechanism called the demand response (DR).

The DR is defined as the change in electricity usage patterns by end customers in response to the changes in the price of electricity over time or incentive payments designed to induce lower electricity use during high wholesale market prices or when system reliability is jeopardized [3]. Current DR programs can be classified into two types: incentive-and price-based. Customers participating in the incentive-based DR program either reduce energy directly in response to the request signal or adopt a contract that provides part of the control to the utility company [4]. In price-based DR programs, customers offer a DR bidding amount and price based on hourly changes in the electricity rates. They are encouraged to manage their loads by reducing power consumption or shifting consumption schedules to less-congested periods [5]. Based on the aforementioned DR operating categories, the customer's power demand may be adjusted according to electricity-price changes, incentives, or emergency situations in grid stability [6]. As a result, both utility companies and customers can benefit from the implementation of DR in terms of reduced energy use and costs, reduced investments in generators and network systems, and reduced power generation costs [7]. In recent years, with the rapid increase in the share of renewable energy, a new need for demand flexibility program (DFP) as a solution to rapid oversupply or peak load has been emphasized. For example, DFP can mitigate spikes in demand caused by a sharp drop in PV generation that usually occurs during the evening hours [8].

The types of resources involved in a DR can be largely divided into industrial, general, and residential uses. Industrial loads, which account for the largest proportion of capacity in a DR, are classified based on the mechanical characteristics of the process as follows [9]:

- Mechanical 1: An industrial load that includes the application of a mechanical force during a specified cycle, including cutting operations such as hydraulic units, press machines, and grinders. Although the load cannot be adjusted, if necessary, the power can be switched on or off over a long time.
- Mechanical 2: An industrial load that applies consistent forces to the mobile media, including the manufacturing process such as pumps, fans, blowers, and air compressors. The load can be adjusted through the control.
- Thermal: An industrial load that changes the phase, composition, or chemical characteristics of a raw material and is continuously running unless interrupted by maintenance or production schedule change, including smelter, metal heat treatment furnaces, electrolytic cells, and induction melting furnaces.

Therefore, a clear analysis of the load characteristics (e.g., periodicity, patterns of loads that vary from process to process) must precede the use of DR resources for each type of industrial load. Despite the ability to collect data for the use of industrial loads by developing sensing and data-communication technologies, to the best of our knowledge, no studies have yet evaluated the potential of DFP based on the analysis results of industrial load data. Since data are not utilized due to industrial information security policies, experiments to create a virtual industrial process model based on statistical theory has conducted for replacing empirical data. For example, few studies have investigated the improvement in the DR operation by simply designing the process characteristics of cement, refinery, paper, and steel industries [10–14]. Therefore, a method must be developed to estimate and evaluate DR potential flexibility based on the data-analysis results of industrial-load resources.

Based on the aforementioned literature overview, the main objectives and contributions of this work are as follows.

- A novel method is proposed for evaluating the DR potential flexibility of industrial loads based on guaranteed DR potential estimation.
- A new data analysis framework is suggested for the industrial load data to verify the evaluation of DR potential flexibility.

The remainder of this paper is organized as follows. Section 2 presents a potential score-estimation method for evaluating the DR potential flexibility and the subsequent associated mathematical formulation. This is followed by a description of the test system and industrial load data information in Section 3. In Section 4, the results are presented to demonstrate and interpret the effectiveness of the proposed model. Conclusions are drawn in Section 5.

2. Potential Score Estimation

2.1. Determination of the Ramp-Up/Down Time Interval

Before presenting the methodology of evaluation of the DR potential flexibility for industrial demand resources, the ramp-up and ramp-down time intervals for the flexible operation of DR must be determined. In this study, the criteria for ramp-up and ramp-down time intervals are designed to mitigate the duck curve (i.e., flattening the net demand) through PV generation for reducing the renewable-energy generation limits. To alleviate the net demand fluctuations, DFP resources should be appropriately utilized, i.e., more load must be consumed during the event of a rapid decrease in net demand and the load must be reduced during a rise in net demand. The start and end times of the ramp-up interval are defined as the time points at which the gradient of the net demand is maximized and minimized, respectively. In the case of ramp-down intervals, the start time and end times are the time points at which the net-demand gradient is minimized and maximized, respectively. The ramp-up and ramp-down intervals for summer and winter, based on net demand in Jeju island, Korea, are shown in Figure 1, and they are accordingly defined as follows:

- Ramp-up interval: 12:00–17:59 (summer), 12:00–17:59 (winter).
- Ramp-down interval: 18:00–21:00 (summer), 18:00–20:00 (winter).

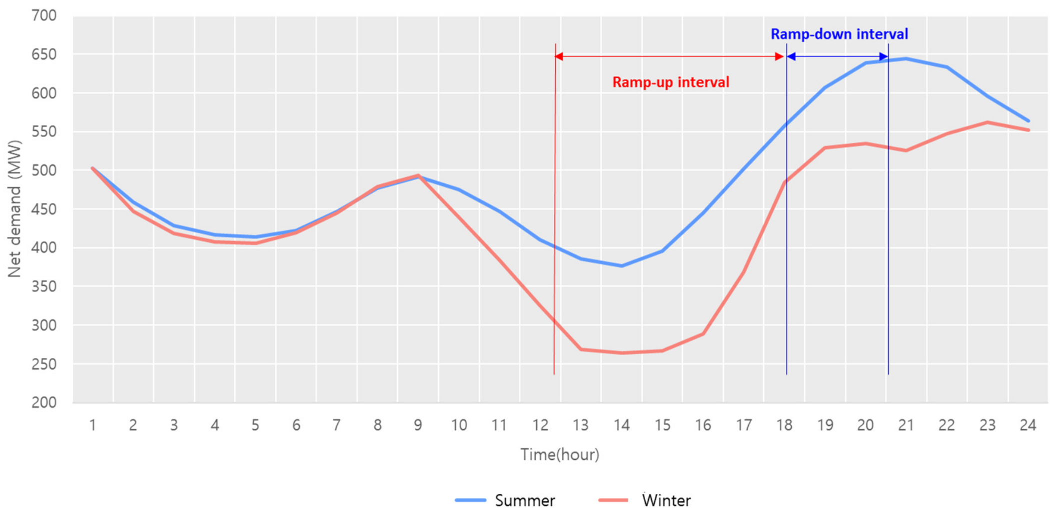


Figure 1. Ramp-up/down interval based on the net-demand profile of summer and winter.

2.2. Potential Score Formulation

In this paper, a novel potential-score-estimation model is proposed as an indicator for quantitatively determining the amount of industrial demand resources that can be used as DFP resources to mitigate the restriction on renewable energy generation. The model considers data-driven power consumption characteristics that can affect DR participation by formulating assumptions based on industry process characteristics. The stability of demand reduction or increase in response to DR issuance and the amount of demand management for DR participation are regarded as the characteristics derived through the analysis of power-consumption data. In this study, three characteristic indexes were considered for potential-score estimation based on the evaluation method proposed in the preceding study [15]: frequency of power consumption, consistency of power consumption, and DR event operation. These attributes were scored between 0 and 1 and then multiplied to be penalized in terms of the degradation of the index scores.

The frequency of power consumption indicates how often industrial loads are operated during the ramp-up or ramp-down periods. In terms of DR resources, it is a factor that can reduce or increase demand when power-consuming devices are used during DR events. For example, industrial loads cannot respond flexibly if the power consumption equipment is not operated as a break during a DR event. Accordingly, the frequency score of power consumption (FS_i) is calculated as the ratio at which the resource operates at the time of the DR event over the entire period (D), as shown in Equation (1). Based on the threshold load (p_i^{th}), the operational state of the resource ($u_i(d)$) is estimated discretely during the DR event period, as formulated in Equation (2).

$$FS_i = \frac{1}{N_D} \cdot \sum_{d \in D} u_i(d), \tag{1}$$

$$u_i(d) = \begin{cases} 1 & \max_{t \in T}(p_i(d,t)) > p_i^{th} \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

The consistency of power consumption refers to the similarities between the patterns of power consumption and demand during DFP events. The demand resources with consistent power use could be determined to have the potential to perform well on contracted capacity when DR instructions are issued. The consistency score of power consumption (CS_i) is derived as shown in Equation (3) based on the root mean square percent error ($RMSP_i$), which is the ratio of the difference between normalized average power consumption over the historical period ($p_i^{n,\,avg}(t)$) and normalized power consumption per unit time ($p_i^n(d,t)$) as in Equations (4)–(6). $p_i^n(d,t)$ is estimated through min-max normalization over the entire period (D).

$$CS_i = 1 - RMSP_i, \tag{3}$$

$$RMSP_i = \sqrt{\frac{1}{N_D} \cdot \frac{1}{N_T} \cdot \sum\nolimits_{d \in D} \sum\nolimits_{t \in T} \left(\frac{p_i^{n,\,avg}(t) - p_i^n(d,t)}{p_i^{n,\,avg}(t)} \right)^2}, \tag{4}$$

$$p_i^n(d,t) = \frac{p_{i,}(d,t) - \min_{t \in T, d \in D}(p_{i,}(d,t))}{\max_{d \in D, t \in T}(p_{i,}(d,t)) - \min_{d \in D, t \in T}(p_{i,}(d,t))}, \tag{5}$$

$$p_i^{n,avg}(t) = \frac{1}{N_D} \cdot \sum_{d \in D} p_i^n(d,t). \tag{6}$$

The operation score (OS_i) of the DR event is considered for evaluating the valid demand management volume of the industrial load resource during the DR event period. As shown in Equation (7), OS_i is calculated based on the average power usage during the working period that matches the DR event. In the perspective of DR operations, the peak demand can be considered the maximum capacity that can be provided. Therefore, it is possible to score the capacity level that can increase or reduce demand based on average power consumption compared to peak demand during a DR event. Industrial load can reduce as much as the level of average power consumption during the ramp-down period, and can increase as much as the level excluding the average power consumption from peak demand during the ramp-up period. Since the peak demand is set to 1 by min-max normalization, it is expressed as Equation (7).

$$OS_i = \begin{cases} 1 - \frac{1}{N_D} \cdot \frac{1}{N_T} \cdot \sum\limits_{d \in D} \sum\limits_{t \in T} u_i(d) \cdot p_i^n(d,t) & \text{When ramp-up DR is issued} \\ \frac{1}{N_D} \cdot \frac{1}{N_T} \cdot \sum\limits_{d \in D} \sum\limits_{t \in T} u_i(d) \cdot p_i^n(d,t) & \text{When ramp-down DR is issued} \end{cases} \tag{7}$$

Finally, the potential score (S_i) is defined by the multiplication expressions of the aforementioned attributes of FS_i, CS_i, and OS_i as follows:

$$S_i = FS_i \times SC_i \times OS_i. \tag{8}$$

3. Test System

The electricity cost of a typical cement plant covers approximately 30% of its total cost [16]. Thus, the cement industry, one of the major consumers of energy, is highly advantageous for use as a DR resource. Figure 2 displays a simple diagram presenting different processes in a typical cement plant [17], which is mainly composed of four processes: (1) crushing and grinding of the raw materials, (2) blending of the materials in the correct proportions, (3) burning of the prepared mix in a kiln, and (4) grinding of the burned product, known as clinker, together with some gypsum of 5%. An overview of the cement process is as follows:

- In the first process, limestone obtained through quarrying is first crushed, often in two stages, and then ground in a raw mill.
- The fine powders of limestone and subsidiary materials such as iron and clay are blended to reinforce the deficiencies in terms of strength and viscosity.
- The blended materials are burned in the kiln to form a clinker, a half-finished cement product.
- The burned product (clinker) then passes from the kiln into the coolers.
- In the final process, cement products are made by grinding the clinker with addition of gypsum capable of controlling the rate of hardening of the cement.

Among these, quarrying and grinding (i.e., raw and cement mills, respectively) can be selected as the most electricity-intensive processes. In cement plants, a large potential of DR is found in large-scale grinding mills, especially in non-continuous processes such as quarrying operations, raw mills, clinker mills, and fuel mills. Therefore, cement plants can achieve DR potential by shifting the grinding process schedule. The suitability of DFP resource in cement plants can be verified through the analysis of operation characteristics based on high-time resolution of demand data.

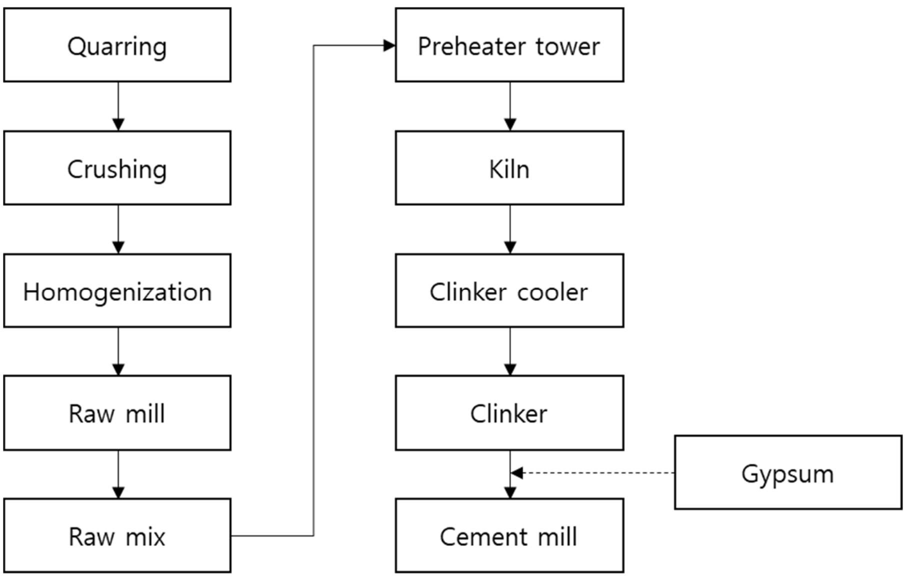


Figure 2. Supply chain of a typical cement plant.

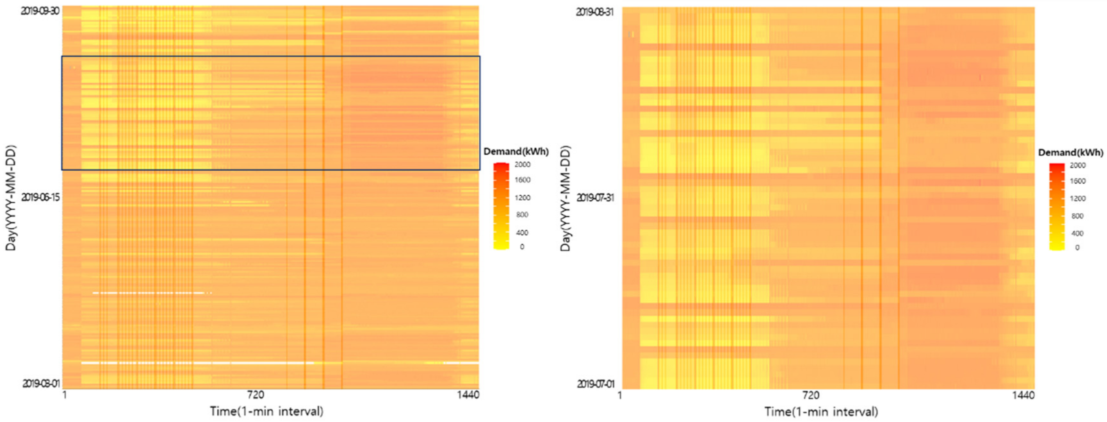
4. Results and Discussions

4.1. Results of Data Analysis

4.1.1. Data Description

This study utilized the data of two cement plants (i.e., cement #1 and #2) in Korea to evaluate the adequacy and potential level from the perspective of DFP resources utilization.

The data of the aforementioned industrial loads were measured at 1-min intervals for a total of seven months from 1 March to 30 September, 2019. During the data-acquisition periods, a DR event was organized on 13 June, and the cement plants implemented their demand reduction in accordance with the instructions. Heat maps for the electricity-demand data of the cement plants are illustrated as Figure 3. The proportion of missing data (NA) in cement #1 and #2 was measured as 0.4% (NA observations: 1219) and 0.22% (NA observations: 685), respectively, owing to the omission of specific days. Out of seven months, the number of days of omission for cement #1 and #2 was 3 days (15 March, 17 April, and 23 April), and 2 days (9 September and 10 September), respectively.



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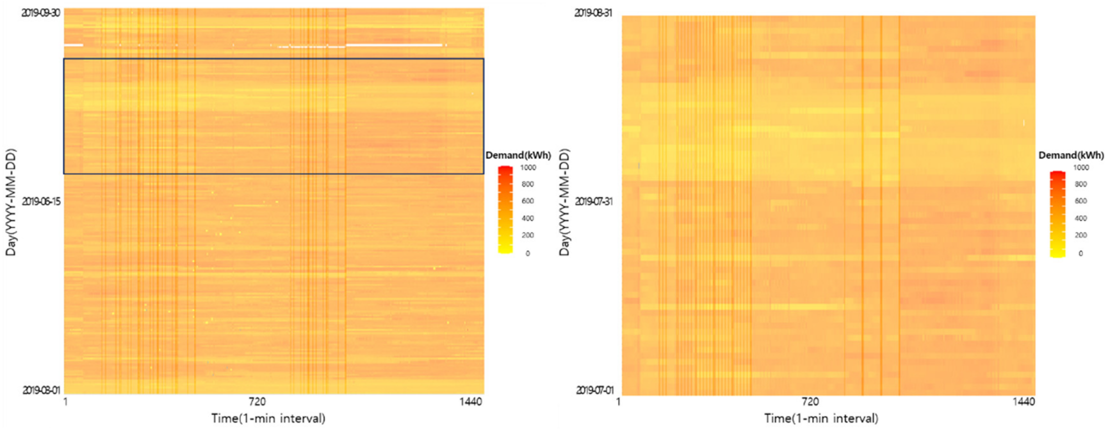

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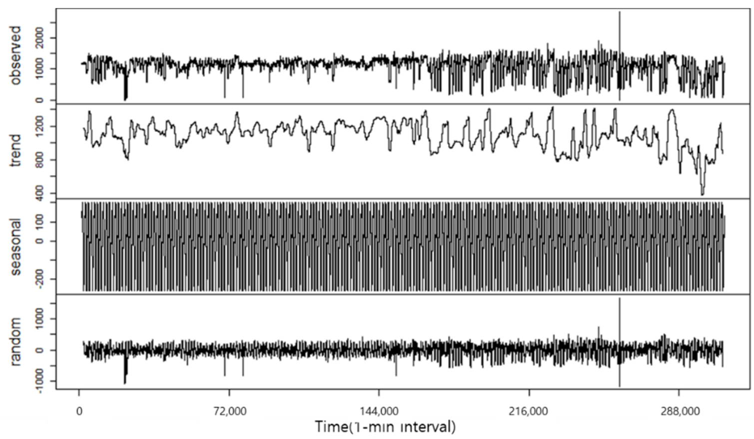
Figure 3. Electricity demand heat map (1 March–30 September 2019, 1 July–31 August 2019): (**a**) Cement #1, (**b**) Cement #2.

4.1.2. Analysis of Data Characteristics

Characteristic analysis of electricity-demand data, including trend, seasonality, demand pattern, and daily demand variance, was conducted to determine the suitability of cement plants as a DFP resource.

First of all, load data were decomposed into trends, seasonality and white noise through additive decomposition. The additive decomposition method is one of the time series analysis methods for estimating the seasonal effect and trend of a time series, and allows the time series data to be composed of the sum of trend, seasonal, and random values (white noise). As a result of the additive decomposition of cement plants data, we can identify the daily seasonality and no trends over the measured time. The results of the additive decomposition are shown in Figure 4, confirming the absence of a trend and daily seasonality. The comparison between the demand profile and actual demand shows the variances based on the profile to be 159.56 and 23.64 kWh, respectively, showing that the actual demand does not significantly deviate from the demand profile. Accordingly, the power consumption of the cement plants showed a consistent daily pattern. Weekly seasonality was not observed owing to the operation of the industrial characteristics regardless of the weekdays or weekends, as confirmed by the similar profiles for all days. As observed, cement plant #2 showed little difference in terms of power consumption on weekdays and weekends, and power consumption during daytime on weekends is higher than on weekdays. It was also confirmed that the cement #1 plant of the power consumption gap during daytime between weekdays and weekends was wider compared to the cement #2 plant.



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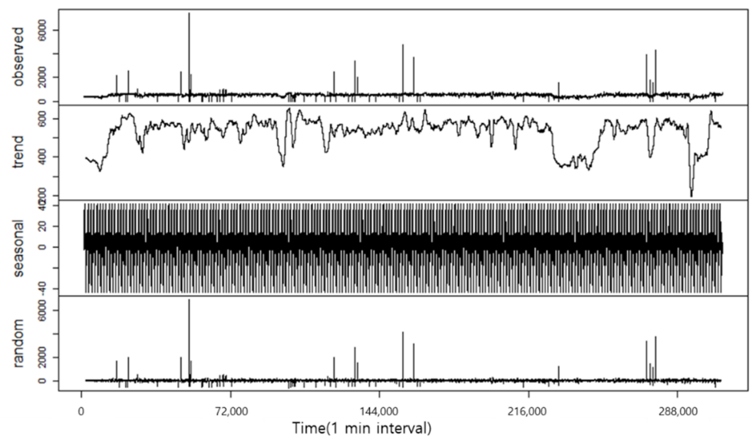

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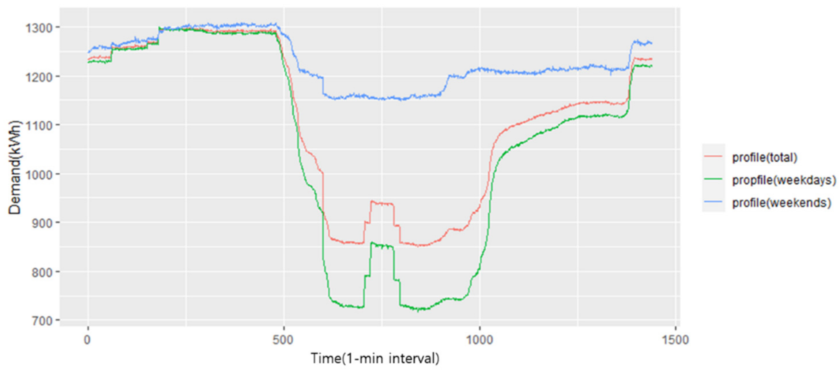
Figure 4. Decomposition of electricity demand data: (**a**) cement #1 and (**b**) cement #2.

In addition, an analysis was conducted on the reasons why the demand pattern was shown, as in Figure 5, and it was confirmed that this was closely related to industrial electricity rates. Therefore, both cement plants identified a significant reduction in power consumption during the morning and daytime, which is due to the electricity rate plan paid by cement factories. The electricity rate plan of industrial customers (i.e., cement plants) is termed as Time-of-use (TOU) pricing, in which the unit price of electricity changes according to the time of day and rate level that vary depending on the off-peak load, mid-load, and peak load time. As cement plants operate properly in response to the TOU rate, they reduce their electricity consumption during the peak time (between 10:00 and

12:00) and activate the equipment mainly during the off-peak time (between 13:00 and 23:00). The load profiles of the total number of days, weekdays, and weekends for the two cement plants are shown in Figure 5. The comparison of the ramp-up period (between 12:00 and 17:59) and ramp-down period (between 18:00 and 21:00) of the designed flexible DR program shows that the cement plants have sufficient DR potential to be utilized as a resource through shifting operation schedules.

4.2. Comparison of DR Potential Score

To estimate the DR potential flexibility score of cement industrial loads, the seasonal load characteristics of summer and winter were reviewed, and the potential score was calculated separately based on the ramp-up and ramp-down of the DR interval. In this study, the potential scores of cement #1 and #2 were evaluated and compared only for the summer season based on the data obtained for the limited experimental period. The calculation of potential score was performed using the proposed method in Section 2. As shown in Table 1, the potential score for both loads averaged at approximately 0.2662. The *FS* for the ramp-down DR was significantly higher than that for the ramp-up DR, and this served as the most significant factor in determining the difference between the potential scores, *S*, of ramp-up DR and ramp-down DR. The aforementioned result was derived from the fact that both cement #1 and #2 responded well to the time of use (TOU) rate plan and lowered the power consumption during the ramp-down DR period with high rate.



(**a**)

(**b**)

Figure 5. Electricity demand profile for (**a**) Cement plant #1, and (**b**) Cement plant #2.

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The potential score is a value between 0 and 1, and a score estimated close to 1 indicates that the potential amount available to participate in DFP is large. However, the evaluation of the potential scores showed that the estimation of the practical capacity level of load resources or the ratio of the potential amount to total capacity is impossible. To verify this, an experiment should be conducted on the actual ramp-up or ramp-down of the DR for the resources.

Table 1. Potential score result (season: summer; industrial DR resources: cement #1 and cement #2).

Industrial DR Resource	Score	Ramp Up	Ramp Down
Cement #1	*FS*	0.4103	0.8718
	CS	0.6935	0.8805
	OS	0.7066	0.4641
	S	0.2011	0.3563
Cement #2	*FS*	0.4103	0.6291
	CS	0.8904	0.8816
	OS	0.6269	0.5017
	S	0.2290	0.2783

4.3. Discussion of Actual DR Performance

To identify the significance of the potential scores, the level of demand reduction was analyzed from the data collected on the days of ramp-down of the DR issuance for cement #1 and #2. The issuance of DR lasted for 1 h from 18:00 to 19:00 on 13 June 2019. The power-consumption profiles of the cement load and customer baseline load (CBL) calculated as Max 4/5 are described in Figure 6.

During the DR period, demand reduction of 45,000 and 13,000 kWh was requested for cement #1 and #2, respectively, and their corresponding reduction performances were calculated as 51,198 and 18,540 kWh, respectively. Similar to the results in which the potential score of cement #1 for ramp-down DR was higher than that for cement #2, the load-reduction rate of cement #1 in this case was higher. The load-reduction ratios of the two resources were measured as 68.81% and 53.27%, respectively, based on the CBL, confirming that both have the ability to reduce load by more than half.

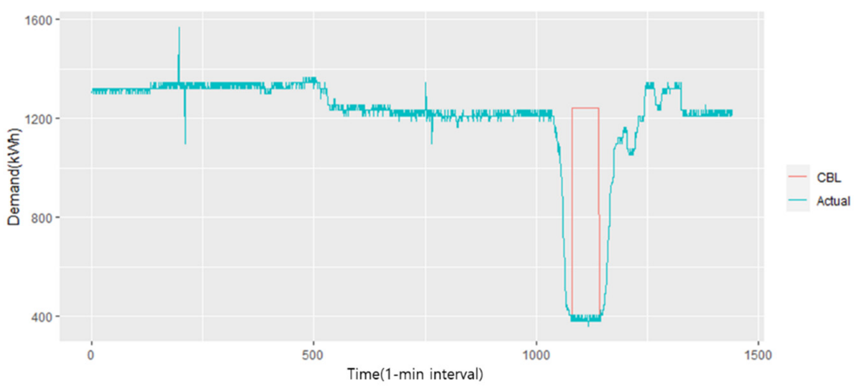

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Figure 6. *Cont.*

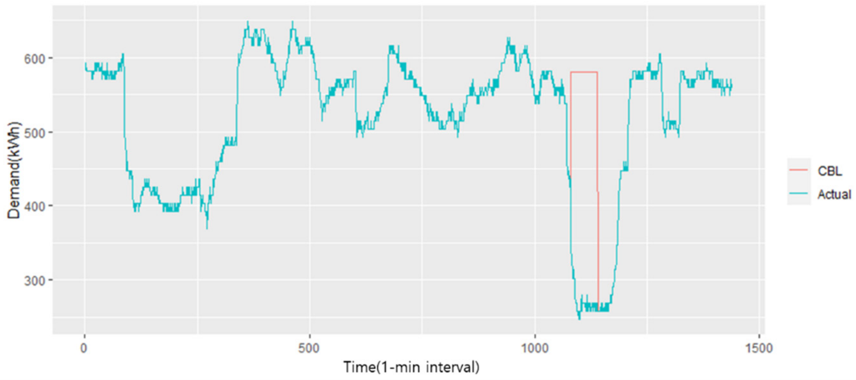

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Figure 6. Industrial DR performance profiles for (**a**) cement plant #1 and (**b**) cement plant #2.

The performance rates, namely the ratio of reduction amount to the contracted capacity, of the resources both exceeded 100%, which was attributed to conservatively contracting capacity, to avoid penalties arising from failure to reduce. The performance results of the actual DR compared to the DR requests are shown in Table 2.

Table 2. Actual DR performance result (DR event: 2016.06.13 18:00–19:00).

Industrial DR Resource	Cement #1	Cement #2
CBL (kWh)	74,404	34,802
Metered load (kWh)	23,206	16,262
DR Reduction (kWh)	51,198	18,540
Reduction rate (%)	68.81	53.27
DR capacity issued	45,000	13,000
Performance rate (%)	113.77	142.62

The actual performance level of ramp-up DR is expected to be lower than that of ramp-down DR with the same potential score, as additional costs are required for the demand increase. As discussed in the aforementioned data-analysis results, as the peak power consumption of the cement-production process occurred during the nonpeak period at night, a low potential score, *S*, was calculated because of the small *OS* value with low DR responsiveness. Accordingly, although the linearity of the relationship between the potential score and DR reduction rate of both cement #1 and #2 could not be determined, a similar score could be derived from the same industrial process. In addition, this relationship is expected to converge at a specific point based on sufficiently extended data. To ensure the validity of the aforementioned discussions, the following conditions and experiments should be supplemented:

- Large amounts of heterogeneous data investigations with multidimensional industry, period, season, and time resolution.
- Demonstration results of large DR events.

5. Conclusions

This paper proposed a DR potential flexibility evaluation model for industrial loads. The proposed methodology derives results with scores between 0 and 1, and it is designed such that the closer the score is to 1, the higher is the potential. The value of an industrial resource was quantified from the perspective of data analysis, reflecting the frequency of power consumption, consistency of power consumption, and DR operation. Prior to the DR potential flexibility evaluation, demand characteristic analysis was performed for two cement plants, which are industrial demands. As a result, daily seasonality was confirmed, but weekly seasonality was not identified as they worked regardless of weekdays and weekends. There was also no trend in the demand load of the two cement plants because average power consumption does not increase unless additional processes or equipment are increased. In addition, the daily patterns of the two cement plants were closely related to the industrial electricity rate they have been paying for. The potential scores were calculated for two cement plants, cement #1 and #2, and were compared with the demand-reduction performance result. The results confirmed that a load reduction of more than half of the usual power consumption is possible if the potential score on ramping down the demand for cement loads is 0.27. The proposed method can be used as an indicator to determine whether an industrial load is adequate to participate in DFP. However, this study has certain limitations: the level of resource capacity was not considered, although the rates load reductions and increases in the power consumption for a single industrial load were reflected as a potential flexibility evaluation indicator. For both the cement plants, similar scores were shown through a case study despite a difference of almost two times in the amount of load reduction. Thus, in the future, further research is needed to apply an additional indicator of resource capacity in the estimation of the potential score.

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Nomenclature

Indices	
i	Index of industrial demand resources
t	Index of time slots of when DR was issued
d	Index of date slots
Sets	
T	Set of all time slots t
D	Set of all date slots d
Parameters and Variables	
FS_i	Frequency score of industrial demand resource i
CS_i	Consistency score of industrial demand resource i
OS_i	Operation score of industrial demand resource i
S_i	Potential score of industrial demand resource i
$RMSP_i$	Root mean square percentage of i
N_D	Total number of date slots d
N_T	Total number of time slots t
$p_i(d,t)$	Power consumption of industrial demand resource i at date d and time t
$p_i^n(d,t)$	Normalized power consumption of industrial demand resource i at date d and time t
$p_i^{n,avg}(t)$	Normalized average power consumption of industrial demand resource i at time t over the span of D
p_i^{th}	Power consumption threshold that determines whether industrial demand resource i is operating
$u_i(d)$	Binary variable indicating whether industrial demand resource i is available for DR participation at date d

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