Research Article

Effect of Demand Response Programs on Industrial Specific Energy Consumption: Study at Three Cement Plants

Somayeh Siahchehre Kholerdi¹ and Ali Ghasemi-Marzbali²

¹Mazandaran Regional Electric Company (MAZREC), Sari, Iran
²Department of Electrical and Biomedical Engineering, Mazandaran University of Science and Technology, Babol, Iran

Correspondence should be addressed to Ali Ghasemi-Marzbali; ghasemi.agm@gmail.com

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Demand-side management (DSM) is the modification of consumer utilization manner for energy through various methods to smooth their power consumption curve and increase their energy efficiency. Although the DSM improves the electricity grid stability and protects the environment, it allows customers to reduce their costs. The available literature classifies DSM into two different areas: (i) energy efficiency (EE) and (ii) demand response (DR). In other words, cement plants are the largest customers of electricity, so the implementation of DSM programs in these heavy industries is very important for electricity companies. Past studies have often examined the impact of DR programs in cement factories on solving peak problems and changing load profiles but have not studied the effects of DR implementation on the energy efficiency index in the short and long term in these industries. In this paper, while examining the effect of implementing three types of common DR programs in smart grids including demand bidding (DB), ancillary services (A/S), and time of use (TOU) on the load profile of cement plants, based on the mathematical model of the load and the real data of the case study, it is shown that the implementation of the TOU program has created the highest energy efficiency by reducing specific energy consumption (SEC) in cement plants.

1. Introduction

Energy policymakers have always faced several major challenges to supply electricity: limited primary sources of convertible energy to electricity, low efficiency of the conversion process in power plants, high cost of generation, transmission and distribution of electricity, and the impossibility of storing electricity. This has led them to optimize power consumption. Therefore, energy consumption management is very vital and any action to optimize energy consumption is precisely in line with the maintenance of public capital, development of social welfare and reducing the cost of manufactured goods, and reducing environmental pollution and increasing the quality of life. The term “demand-side management” (DSM) refers to concepts such as load management, energy efficiency, energy saving, and activities related to this field [1]. DSM programs are classified into energy efficiency and demand response. Figure 1 shows the main categories of demand-side management.

1.1. Energy Efficiency (EE) Programs. Energy efficiency (EE) is the reduction of the amount of energy consumed to provide the same amount of products and services [2]. The vital aspects of energy efficiency are public budgets, local air pollution, total price, security, saving, and poverty alleviation. Specific energy consumption (SEC) is an indicator of energy efficiency improvement that shows the ratio of primary energy consumed to produce a product [3].

1.2. Demand Response (DR). The US Department of Energy (DOE) has stated that demand response (DR) is empowering consumers in various sectors including residential,
agricultural, industrial, and commercial, for smoothing their load curve in order to obtain reasonable prices and increase the reliability of the electricity grid [4]. Figure 2 shows the effect of DSM on customer load profile.

DR programs are classified into two main branches, including the incentive-based demand response (IBDR) and the time-based demand response (TBDR) programs. The incentive-based programs consist of Direct Load Control (DLC), Emergency Demand Response (EDR), Interruptible/ Curtailable (I/C), Demand Bidding (DB), Capacity Market (CAP), Ancillary Service (A/S), and Reduction Bidding (RB). The time-based programs consist of others options such as Time of Use (TOU), Critical Peak Pricing (CPP), and Real Time Pricing (RTP) [4]. Figure 3 shows the various categories of demand response programs.

The following is a brief description of DR programs [4].

1.3. Types of Demand Response Programs

1.3.1. Direct Load Control (DLC). This program is a remote control switch to manage the compensation directly.

1.3.2. Emergency Demand Response (EDR). In this program, customers receive a reward for stopping at the start of an emergency. Of course, power outages are optional and will not be penalized if the customer does not do so. The amount of the bonus or prize is predetermined.

1.3.3. Interruptible/Curtailable Service (I/C). Customers who participate in this program will receive a discount on their electricity bills or, due to the reduction in their consumption, will have a higher credit rating (bill credit) and will be penalized if they do not reduce their consumption on arranged time.

1.3.4. Demand Bidding (DB)/Buyback. In DB, large consumers offer a reduced amount of demand along with the price to utility; if the price offered by the electricity company is accepted, customers have to execute their contract. Figure 4 shows the effect of the DB implementation on the energy price in the electricity market [4, 5]. In Iran, a heavy industry (like cement plant) buys its required demand from the utility under a fixed contract. During peak times (hours/days) of the power grid, the factory temporarily transfers (resells) part of the purchased demand to the electricity company. If the power company accepts the factory’s offer, the customer must reduce his/her load and instead the utility allows the customer to consume electricity at a reduced rate at other times. Customers who participate in this program often transfer their annual overhaul to the requested period of the electricity company.
1.3.5. Capacity Market Programs (CAPs). In this method, customers are committed to reducing a certain amount of load and will be penalized if they do not. This procedure is usually performed for loads greater than 100 kW, and the reduction time is extended to four hours, and the subscriber is notified 2 hours in advance.

1.3.6. Ancillary Service Market (A/S) and Reduction Bidding (RB). In this program, large consumers offer utility to keep their shipping cut off like the reservation market. If their offer is accepted by the electricity company, they will receive the market clearing price, and whenever they are called by ISO/utility and reduce their energy consumption, they may receive the point (spot) price of market [4, 6]. In Iran, utility offers its discount to the factory. If it is accepted by the customer, it will provide a part of its demand to the electricity company as a reservation in a certain period and will receive a reservation reward for it. In addition, at the request of the power company and also by the reduction of energy consumption by the factory, the cooperation reward is given to the industry. Figure 5 shows the daily load reduction under the ancillary service program in Iran power grid (June-July 2018) [7].

1.3.7. Time of Use (TOU). In TOU, the energy price is received in peak, mid-peak, and off-peak load consumption. Accordingly, the price of energy will have the highest value in the peak and the lowest value in the off-peak [8]. Figure 6 shows the effect of implementing the TOU program in one of the provinces of Iran [7].

1.3.8. Critical Peak Pricing (CPP). The CPP program is obtained by combining the TOU and flat rate programs and uses the real-time values during peak jumps. However, these mutations may not be more than a few hours a year. Obviously, the price of CPP is higher than the price of regular couriers. But it is not clear when the courier will arrive, so the power industry cannot tell the customer in advance.

1.3.9. Real-Time Pricing (RTP). In the RTP program, the price is related to the hourly cost of energy. This connection takes place in the real-time market or in the market the day before (day ahead or D-ahead). This program runs in two ways (one-part RTP and two-part RTP). In the two-part price method, a consumption ceiling is set for major customers. If the customer consumes below the set ceiling, it is calculated at a lower price, and if the customer consumes above a certain ceiling, it is calculated at a higher price.

In Iran, the electricity industry is managed by the central government and DR-related rules are set by the government. Since DB, TOU, and A/S programs are the most common demand response programs in Iran that are implemented by the government, in this paper, the effect of the implementation of these three programs in cement plants on their consumption profile is examined, and then what effect the implementation of these DR programs in the cement factories will have on their specific energy consumption will be analyzed.
2. Brief Literature Review

There are many research studies about the demand response program and specific energy consumption. Researchers in [9] have stated that demand response program is one of the most practical smart grid applications that leads to active participation of consumers in balancing energy supply and consumption, and in the meantime, industrial customers are important because of their intense power consumption as well as their advanced metering and monitoring infrastructure. Cement factories can quickly adjust their load consumption rate by turning their crushers on/off. However, in the cement plant as well as other industrial loads, turning on/off the loading units only achieves discrete energy changes, which restricts the power from offering valuable ancillary services. The researchers in this paper have proposed methods that enable cement plants to supply these loads with the support of an on-site energy saving system.

In [10], the authors have addressed the problem of a small group of customers when they enter the energy market and face it. In this paper, a case study of 1000 small prosumers from the Iberian market has been used to compare four day-ahead bidding strategies and two real-time control strategies, as well as the performance of combined day-ahead and real-time strategies. The results have shown that the proposed strategies allow the ISO to reduce the net cost by 14%. In [11], the authors have designed a quantitative analytical framework to calculate and analyze the effect of household characteristics under the TOU price on peak demand reduction (PDR). The results of a case study containing smart metering data and survey data in this article have shown that peak demand reduction level cannot be obtained simply based on the appliance’s ownership and its usage habits. In [12], the authors have presented an enhanced TOU (ETOU) which was introduced for industrial customers in Malaysia. ETOU was the advanced version of classical TOU where the daily time was divided into six period blocks. Case studies using different data from various industries were presented and discussed in this paper. Based on obtained results, an industrial customer can change into ETOU scheme if it can shift its load consumption. In [3], the authors stated that SEC is the ratio of energy consumed to the product amount and recommended to consider these factors for calculating SEC: specifications of equipment and production rate, environmental conditions, quality of data, system ranges, primary energy, and so on. Cantini et al. [13] studied the improving energy efficiency in the cement plant. Researchers have stated that using high-efficiency technology in the production process is an appropriate strategy to reduce the energy required by the cement factory. The purpose of this article is to explain the use of high-efficiency technology in the Italian cement industry and the future prospects of its related technologies. The results of a real case study in this paper have proved that solutions to reduce the energy consumption of auxiliary systems like engines, pumps, and compressors are currently the best opportunities. In [14], the authors have stated that cement factories are heavy consumers of energy. Energy management in these factories is essential in both financial and environmental aspects. It accounts for approximately 15% of the total energy consumed by these industries. In this article, an integrated three-phase model has been presented to help the cement plant managers for achieving their energy saving targets. The tool has shown its applicability in the ranked list of opportunities for three real cases.

Summerbell et al. [15] described a method of DSM that minimizes either electrical energy costs or CO₂ emissions from electricity. The proposed model reschedules production process to reduce cost or carbon periods, without reducing overall production, within the available constraints. A case study has shown the potential to decrease electricity costs by 4.2% and carbon emissions by 4%.

In light of the revised EU Energy Efficiency Directive, Malinauskaitė et al. [16] discussed new developments brought by the EU together with the national case studies of Slovenia and Spain. Both countries analyzed in this paper have high domestic dependence on imported energy sources, thus showing a great potential for energy efficiency. This paper has explored the newly issued integrated national energy and climate plans together with national measures and policies that support energy efficiency in industry, including the quantification of achieved and forecast energy savings in these two EU member states.

Goh and Ang [17] stated that there are many debates on the appropriate way to measure energy efficiency performance for energy policy development in the literature. There is also a fair share of confusion over how different energy efficiency performance estimates should be interpreted. So, this article has studied the sources of contention by examining different definitions, methods, measures, and policy objectives that are used to evaluate energy efficiency and concluded that differences in results at different levels of analysis should be studied in detail to understand the challenges faced in translating efficiency improvements at the device, process, and sub-sector levels to national level improvements.

Article [18] has addressed the issue that to date, more research has focused on the impact of energy efficiency on overall electricity demand, but not on electricity demand profiles. To study this gap, the paper has estimated the impact of energy efficiency measures and policies such as minimum energy performance standards on peak load by developing a bottom-up model that generates Swiss household hourly electricity demand profiles based on production time data. In this paper, it has shown that changing the bulbs to light leads to the same reduction peak as moving the cookware to off-peak consumption periods throughout the year. It also has shown that the evening appliance peak demand could reduce in 2035 by 24% thanks to the improvement of the energy performance of the stock. Results have shown that policymakers should pay due attention to energy efficiency improvement not only for reducing electricity demand but also in order to reduce peak load.

According to the best review of knowledge, demand response programs concentrate on shifting loads in response to particular conditions within the electricity system.
Demand response programs aim to change the time patterns of the load in the grid, e.g., by demand load shifting. On the other hand, energy efficiency generally aims to reduce overall energy consumption and therefore focuses on the magnitude of the load rather than on the time pattern. Actions taken under this strategy include increasing energy efficiency and energy conservation that aims to decrease the total load on the grid. Therefore, the implementation of energy efficiency (EE) measures is considered a key strategy for reducing non-renewable energy consumption and CO2 emissions globally.

There is an extensive amount of work in literature on demand response trials, demand response modelling, and consumer acceptability and willingness to participate in demand response programs. There are also many articles on energy efficiency and improving its indicators. To date, it seems that the analysis of the impacts of demand shifting and energy efficiency measures have been presented mostly separately. In other words, the effect of demand response has been studied only on the electricity demand profile but not on the energy efficiency measures. Several studies have also shown that energy efficiency programs and demand response programs are rarely coordinated [19, 20]. Given this background, a question can be posed as follows. If demand response program is implemented to reduce peak load, could we achieve an improvement in the energy efficiency index? This article examines the answer to this question. For this purpose, three common DR programs in Iran have been implemented as a real case study for three cement factories in three consecutive years to study their numerical results on the specific energy consumption (SEC) index.

Of course, there are several ways that can improve the effectiveness of DR programs that have been studied and researched by various researchers in the past. For example, the battery energy storage system (BESS) and the dynamic thermal rating (DTR) system can supply peak demands and reduce the frequency of load interruptions. However, the combined efficacy of BESS, DR, and DTR have also never been studied because their simultaneous deployment has never been considered [21]. One of the most interesting topics studied in recent years to increase the efficiency of power systems is the combination of demand response programs and the use of renewable energy technology. Demand response is effective in relieving the load demands and reducing the number of peaks, but rescheduling energy usage incurs cost to utilities, which should be considered when it is used to aid the integrations of renewable energy technology like wind power [22]. On the other hand, as electricity systems integrate increasing penetrations of variable renewable energy, system operators are seeking technologies and strategies that increase their system’s flexibility. Despite obstacles around hardware and market structure and lack of experience, demand response is an important source of flexibility that complements more conventional supply-side flexibility resources [23]. However, in this paper, the interactions between the use of DR programs and renewable energy technologies or BESS and DTR, etc. are not discussed, which is a gap that can be considered in future studies. As mentioned, this article merely examines the effect of selected DR programs (commonly performed in Iran) on the SEC index based on a real case study.

The rest of this paper is organized as follows. In Section 3, the mathematical model of load changes with energy prices is presented, and based on it, customer behavior in DR and EE programs is predicted. In Section 4, implementation analysis of the intended method among selected cement plants in the sub-transmission level in Iran is presented so that the impact of implementing triple DR programs (DB, A/S, and TOU) on seasonal and annual SEC can be studied with real numbers. Then, the obtained results are summarized and analyzed in Section 5. Finally, future work is suggested in Section 6.

3. Energy Consumption and Economic Model for Cement Industries’ Load Consumption

3.1. SEC Index. According to the energy audit report in one of the cement industries, different parts and equipment consuming electrical energy in the cement industry are shown in Figure 7 [24]. In cement factories, in addition to the technology used in energy equipment such as furnace system, material grinding, preheater, cooling, etc., the raw material can also affect energy consumption. But in general, the numbers in Figure 8 show the share of different parts of a cement plant in electrical demand consumption [24]. Generally, specific energy consumption (SEC) index is calculated by the following equation (kwh/ton):

$$\text{SEC} = \frac{\text{energy used}}{\text{product’s amount}}$$  \hspace{1cm} (1)

where the meaning of “energy used” is total electrical energy consumed (kwh) and “product’s amount” is final amount of cement produced (tone) in a specific period (seasonal or annual).

3.2. Economic Model for Cement Plants’ Load Consumption. In economic terms, an alternative (linear) utility function is a concept that measures preferences concerning a set of goods or services for consumer. Often, utility is correlated with concepts like satisfaction, welfare, and happiness for which there is no specific method for formulating them and they are often obtained through empirical methods. In fact, the utility function is an economic term that represents the interest in gaining greater returns. The constant elasticity of substitution (CES) is one of the most well-known standard utility functions developed for microeconomic analyses. The CES is widely famous among economists working on...
microeconomic issues and is commonly used in cases where there are several different goods to consume. The alternative utility function for $n$ goods or commodities is obtained from the following equation [25]:

$$f(x_1, x_2, \ldots, x_n) = \left( \sum_{i=1}^{n} a_i^{(1-\mu)} \cdot x_i^{\mu} \right)^{\frac{1}{\mu}}, \quad \mu < 1, \mu \neq 0, \quad \sum_{i=1}^{n} a_i = 1, a_i > 0,$$

where $\alpha_i$ shows the share factors and $(\mu - 1)^{-1}$ denotes the elasticity of substitution. For expanding the CES to the electricity market, the electrical energy with price $P_1$ is considered as commodity $x_1$ and electrical energy at price of $P_2$ is considered as commodity $x_2$ and so on. So, assuming $n$ electricity price levels for 24 hours round the clock, we will have $n$ commodities. The $\mu$ parameter specifies the customer’s desire to participate in the DR program. Accordingly, the greater the value of $\mu$ is, the more the desire of the consumer will be to participate in DR plan. Also, the $\alpha_i$ parameter calculates for adjustment of consumption ratio over the time according to the consumer’s request. Thus, changing the $\alpha_i$ parameter introduces a new order of the consumption per hour.

In consumer choice theory, consumer decisions are under budget constraints [25]. This theory views customer behavior as a maximization problem in which the aim is to maximize profit from limited resources. Therefore, the linear utility function subject to budget constraint is

$$f(E_1, E_2, \ldots, E_{24}),$$

s.t. $B = \sum_{i=1}^{24} E_i \cdot P_i.$

It is assumed that the customer adjusts their load consumptions ($E_i$) in accordance to the electricity market.
Based on the Lagrange multiplier method, we will have

\[ L = \left( \sum_{i=1}^{24} \alpha_i \cdot E_i^{(1-\mu)} \right)^{1/\mu} \cdot \left( \sum_{i=1}^{24} \alpha_i \cdot E_i^{(1-\mu)} \right)^{(1-\mu)/\mu} - \lambda P_i = 0, \]  
(6)

\[ \frac{dL}{d\lambda} = B - \sum_{i=1}^{24} E_i \cdot P_i = 0. \]  
(7)

Considering (6) and (7), it can be concluded that

\[ B = E_1 \cdot P_1 + \frac{\alpha_2}{\alpha_1} \left( \frac{P_2}{P_1} \right)^{1/(\mu-1)} \cdot E_1 \cdot P_2 + \frac{\alpha_3}{\alpha_1} \left( \frac{P_3}{P_1} \right)^{1/(\mu-1)} \cdot E_1 \cdot P_3 + \ldots + \frac{\alpha_{24}}{\alpha_1} \left( \frac{P_{24}}{P_1} \right)^{1/(\mu-1)} \cdot E_1 \cdot P_{24}, \]  
(9)

\[ E_1 = \frac{B}{P_1 + (\alpha_2/\alpha_1) \left( P_2/P_1 \right)^{1/(\mu-1)} \cdot P_2 + (\alpha_3/\alpha_1) \left( P_3/P_1 \right)^{1/(\mu-1)} \cdot P_3 + \ldots + (\alpha_{24}/\alpha_1) \left( P_{24}/P_1 \right)^{1/(\mu-1)} \cdot P_{24}}. \]

The denominator of formula (9) is called \( \pi \), so we will have

\[ \pi = P_1 + \frac{\alpha_2}{\alpha_1} \left( \frac{P_2}{P_1} \right)^{1/(\mu-1)} \cdot P_2 + \frac{\alpha_3}{\alpha_1} \left( \frac{P_3}{P_1} \right)^{1/(\mu-1)} \cdot P_3 + \ldots + \frac{\alpha_{24}}{\alpha_1} \left( \frac{P_{24}}{P_1} \right)^{1/(\mu-1)} \cdot P_{24}. \]  
(10)

Thus, the load economic model for 24 hours a day in the presence of a time pricing-based DR program is obtained with
Since the industrial production in each industrial customer including cement plant is directly related to their electricity consumption, there is no difference between the total electricity consumption in a 24-hour period before and after the implementation of the DR program. In other words, the change will be in the hourly power pattern of customer consumption, not in the total load consumed, which means the change will be in the hourly power pattern of customer consumption.

\[
E_{\text{essential}} = \sum_{h=1}^{24} E_h = \sum_{h=1}^{24} \frac{\alpha_h}{\alpha_1} \left( \frac{P_h}{P_1} \right)^{1/\left(\mu - 1\right)} \cdot \frac{B}{\pi} \quad (12)
\]

where \( E_{\text{essential}} \) is the total electrical energy consumed by the cement industry before the implementation of the DR program.

\[
B = \frac{\pi \cdot E_{\text{essential}}}{\sum_{h=1}^{24} \left( \frac{\alpha_h}{\alpha_1} \right) \left( \frac{P_h}{P_1} \right)^{1/\left(\mu - 1\right)}} \quad (13)
\]

By substituting (13) into (11), it can be concluded that

\[
E_h = \frac{\alpha_h}{\alpha_1} \left( \frac{P_h}{P_1} \right)^{1/\left(\mu - 1\right)} \cdot \frac{E_{\text{essential}}}{\sum_{h=1}^{24} \left( \frac{\alpha_h}{\alpha_1} \right) \left( \frac{P_h}{P_1} \right)^{1/\left(\mu - 1\right)}}. \quad (14)
\]

As shown in equation (14), the load consumption for each hour \( E_h \) is a function of \( B, P_h, \alpha_h, \) and \( \mu \). The budget of consumers is limited. So, \( P_h, \alpha_h, \) and \( \mu \) are parameters that determine the extent of customer participation in the DR program. In other words, changes in energy prices per hour change the amount of load consumption by customer and vary his/her participation in DR programs.

### 3.3. Time of Use (TOU) Program in Cement Plant

As mentioned, in TOU, the price of electric energy per hour is dependent on generation costs at that time round the clock. Thus, the energy cost is low in the off-peak hours, medium in the mid-peak hours, and high in the peak hours. According to the final mathematical model of the load shown in equation (14), implementation of this program causes the cement plants to transfer their transferable loads such as crushers and grinders to off-peak period according to energy price [26].

### 3.4. Demand Bidding (DB) in Cement Industry

The cement factories offer their plan to reduce the consumption load to the utility by releasing the contracted demand. In Iran, participants in the DB program usually adjust their main repair and overhaul program for the period that the region’s electricity consumption is at its highest level and offer it to the electricity company. If the electricity company accepts, it will buy the reduced load of the cement factory at the offered price. During the period when the cement factories implement the DB program, the consumption load of the factories is reduced during 24 hours. The economic and mathematical model of load in equation (14) predicts that if the reduced price of demand purchased by the electricity company is appropriate, the cement plant will want to reduce its load and participate in the DB program [4].

### 3.5. Ancillary Services (A/S) in Cement Industry

The electricity company announces to the cement plant the forecast of days and weeks when electricity consumption will reach an alarming level. The cement plant announces that it will participate in the A/S program according to the amount of incentives offered by the electricity company and concludes a contract with the electricity company, in which it determines how much will be the load reduction. The cement plant will receive a reservation or readiness reward throughout the contract period and will also receive a load reduction bonus on days when the electricity company requests a reduction in consumption [4]. The changes in the power profile of the cement plant with the implementation of the DR program are shown schematically in Figure 9.
among the three demand response programs DB, A/S, and TOU, the mathematical model of load predicts that TOU will conduct more EE for the system because it will affect energy prices more. For evaluating the model results, 3 large cement factories are selected and triple DR programs (DB, A/S, and TOU) are implemented for them and their effect on the SEC is analyzed with real data.

4. Implementing the DR Program for the Selected Cement Factories

The proposed DR program (DB, A/S, and TOU) was implemented for 3 cement industries that were covered by the Mazandaran Regional Electric Company (MAZREC) at the sub-transmission level in Iran. According to Table 1, the total demand consumption for these industries was 53 MW.

The yearly peak of electrical load consumption in Iran happens during July and August months, and the daily peak period in these months is 12–18. Figures 10 and 11 show the hourly and annual load curves of Iran, respectively.

According to these curves, three DR programs (DB, A/S, and TOU) for selected cement plants were proposed and implemented within 3 years. Because the DB and A/S programs focus on the peak season (summer in Iran), the factories’ SEC index was calculated on an annual and seasonal (summer) basis prior to the implementation of the DR programs. Table 2 shows the SEC (kwh/ton) values for the base year (before the implementation of DR programs). As the figures in Table 2 show, the energy efficiency index of the cement industry was improved in the summer, because of the warm weather in this season.

In the first year of this research project, the factories entered into the DB contract, and thus the power company, according to the curve shown in Figure 11, requested the cement factories within 33 days (from July 3 to August 25) to resell their contracted demand to the electricity company in the amount of around 30 MW, or in other words, to reduce their consumption by 30 MW. Figure 12 shows the effect of the DB implementation on the load curve of factories.

During the implementation of the DB program, cement factories have removed all major equipment such as furnaces, crushers, and material mills from the electricity grid and reduced production to zero. The actual amount of load reduction that occurred during the 33 days of the program was about 27 MW. The SEC index calculated in summer as well as at the end of the year under the influence of the DB program is shown in Table 3.

As the figures in Table 3 show, the energy efficiency index of the cement industries, with the implementation of the DB program in summer, has increased significantly (between +7.5% and +9%) compared to the same period in base year because it drastically reduced the production of the factory during this period, while some departments, such as office equipment, building, lighting, and electrical equipment needed for overhaul, were still consuming electricity. However, the implementation of DB leads to small change (less than ±1%) on the annual SEC index, because all cement plants maintenance, repair, overhaul throughout the year, the difference is that the implementation of DB determines the time of overhaul with the agreement of the electricity company. In the second year of this research project, the A/S program was implemented. According to the curve shown in

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Figure 9, the power company asked the cement plants to keep ready some of their demand consumption (approximately 15 MW in total) for reduction during 93 days. Within 71 days of this period, the load was reduced from 12:00 to 18:00, according to the electricity company announcement. Figure 13 shows the average 24-hour load consumption of cement plants during the 71 days of the A/S implementation load reduction (the days when the factories were only in a state of readiness and did not have a request to reduce the demand consumption are not included in these curves).

By implementing the A/S program, the cement plants turned off some of their removable loads, such as crushers and cement grinders, between 12 and 18 hours. The actual amount of load reduction that occurred during the 71 days of the program was about 17.47 MW. The SEC index calculated in summer as well as at the end of the year under the influence of the A/S program is shown in Table 4.

Based on Table 4, the SEC index of the cement industry, with the implementation of the A/S program in the summer, has increased (between +4.1% and +5.5%) compared to the same period in base year. Investigations into the performance of cement plants show that turning off some electrical equipment such as crushers at 12 o’clock and turning them on again at 18 o’clock due to the consumption of starting current to reach the nominal working point increased amount of electricity consumption to produce a unit of product. Also, the energy efficiency of heating units such as preheaters reaches its highest level at 18 pm. Thus, the seasonal SEC has increased. However, the implementation of A/S has had little change (between −0/2% and +0/5%) on the annual SEC index, and these slight changes in the annual SEC index were often related to changes in the product sales market, which affected production amount in a fiscal year. In the third year of this research project, the TOU program was implemented. According to the curve shown in Figures 14 and 15, the electricity company prepared the TOU program during the year in the form of Table 5 and announced it to the cement plants. Accordingly, the price of electricity during peak hours was set twice as high as during mid-peak hours and four times as high as during off-peak hours.

Figure 14 shows the average 24-hour load consumption of cement plants in spring and summer, and Figure 15 shows the average 24-hour load consumption in autumn and winter during the TOU implementation.

The implementation of the TOU program dictates the cement factories to shift their portable loads, such as crushers and cement grinders, from peak period to off-peak or mid-peak period to manage their energy costs. The load reduction during peak hours in a year of TOU programming was approximately 13.84 MW. The SEC index calculated in the end of the year under the influence of the TOU program is shown in Table 6. Since the TOU has been running during a year, the SEC calculations have been done only annually.

From the results in Table 6, the SEC index of the cement industry, with the implementation of the TOU program in a year, has decreased (between −5.9% and −3.7%) compared to the same period in base year. Analysis of the cement plants operation has shown that when the customers are in the TOU program and have to pay the price of electricity in proportion to the hours of the day in different months of a year, they change consumption behavior (according to equation (14) presented in Section 3 of this article). Therefore, to manage their energy costs, the industries under this study have implemented energy audit program. The studies of this energy audit were conducted in the first half of the year, and for this reason, the curves in Figure 14 only show the displacement of the load from peak hours to off-peak hours. However, due to the implementation of the results of energy audit studies and optimization of energy consumption in the second half of the year, the curves in Figure 15 not only show the load shifting from peak period to off-peak period but also show that the base load for industries has also decreased because even during off-peak hours, the curves have not gone higher than the base year load, while the peak load has been transferred to this sector. The most important strategies proposed to increase energy efficiency and improve the SEC index in energy audit studies and implemented by cement plants are shown in Table 7.
Figure 12: (a) Load curve of A factory (base load and DB load). (b) Load curve of B factory (base load and DB load). (c) Load curve of C factory (base load and DB load). (d) Three factories’ load curve (base load and DB load).

Table 3: The SEC of cement plants under the influence of DB program (kwh/ton).

<table>
<thead>
<tr>
<th>Cement plant</th>
<th>In the base year (without DR)</th>
<th>In the year with DB</th>
<th>Percentage of changes compared to the base year (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annual SEC</td>
<td>Seasonal SEC</td>
<td>Annual SEC</td>
</tr>
<tr>
<td>A</td>
<td>105.4</td>
<td>102.7</td>
<td>106.1</td>
</tr>
<tr>
<td>B</td>
<td>101.7</td>
<td>99.4</td>
<td>101.1</td>
</tr>
<tr>
<td>C</td>
<td>102.1</td>
<td>99.6</td>
<td>101.9</td>
</tr>
</tbody>
</table>

Figure 13: Continued.
Figure 13: (a) Load curve of A factory (base load and A/S load). (b) Load curve of B factory (base load and A/S load). (c) Load curve of C factory (base load and A/S load). (d) Three factories’ load curve (base load and A/S load).

Table 4: The SEC of cement plants under the influence of A/S program (kwh/ton).

<table>
<thead>
<tr>
<th>Cement plant</th>
<th>In the base year (without DR)</th>
<th>In the year with A/S</th>
<th>Percentage of changes compared to the base year (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annual SEC</td>
<td>Seasonal SEC</td>
<td>Annual SEC</td>
</tr>
<tr>
<td>A</td>
<td>105.4</td>
<td>102.7</td>
<td>104.9</td>
</tr>
<tr>
<td>B</td>
<td>101.7</td>
<td>99.4</td>
<td>101.6</td>
</tr>
<tr>
<td>C</td>
<td>102.1</td>
<td>99.6</td>
<td>102.5</td>
</tr>
</tbody>
</table>

Figure 14: (a) Load curve of A factory (base load and TOU load in spring and summer). (b) Load curve of B factory (base load and TOU load in spring and summer). (c) Load curve of C factory (base load and TOU load in spring and summer). (d) Three factories’ load curve (base load and TOU load in spring and summer).
Figure 15: (a) Load curve of A factory (base load and TOU load in autumn and winter). (b) Load curve of B factory (base load and TOU load in autumn and winter). (c) Load curve of C factory (base load and TOU load in autumn and winter). (d) Three factories’ load curve (base load and TOU load in autumn and winter).

Table 5: Peak, mid-peak, and off-peak hours in TOU program.

<table>
<thead>
<tr>
<th>Seasons</th>
<th>Off-peak hours</th>
<th>Peak hours</th>
<th>Mid-peak hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring and summer</td>
<td>24–8</td>
<td>13–17</td>
<td>9–12 and 18–23</td>
</tr>
<tr>
<td>Autumn and winter</td>
<td>24–8</td>
<td>20–24</td>
<td>8–20</td>
</tr>
</tbody>
</table>

Table 6: The SEC of cement plants under the influence of TOU program (kwh/ton).

<table>
<thead>
<tr>
<th>Cement plant</th>
<th>In the base year (without DR)</th>
<th>In the year with TOU</th>
<th>Percentage of changes compared to the base year (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>105.4</td>
<td>99.2</td>
<td>−5.9</td>
</tr>
<tr>
<td>B</td>
<td>101.7</td>
<td>97.5</td>
<td>−4.1</td>
</tr>
<tr>
<td>C</td>
<td>102.1</td>
<td>98.3</td>
<td>−3.7</td>
</tr>
</tbody>
</table>
5. Conclusion

There are many benefits to implementing DSM programs, both for the electricity companies and large-scale customers such as cement plants. Demand response and energy efficiency are two essential strategies in this regard. DR is considered to reduce the load profile at peak consumption times and increased the load factor, and energy efficiency. Based on the economic load model in Section 3, the cement plants adjust their load profile according to energy prices and incentives offered by the power company. According to the real data and presented case study from Tables 3 and 4, it can be seen that the implementation of DB and A/S programs increased the seasonal specific energy consumption index (between +7.5% and +9% for DB and between +4.1% and +5.5% for A/S), because that it does not have much effect on the annual energy efficiency index (less than ±1% for DB and between -0.2% and +0.5% for A/S). Also, the changes in the consumption load curve of the industries under the influence of DB and A/S programs are shown in Figures 12 and 13, respectively. The changes for the DB program were a reduction of 30 MW during 33 days of the year and a reduction of 17.47 MW for A/S program during 71 days a year.

Since the TOU program affects on the energy prices over a longer period of time and increases the energy prices during mid-peak and peak hours up to 2 and 4 times, it motivates cement industries to pursue and implement energy efficiency (EE) improvement programs. For this purpose, they have performed energy audits and according to Table 7 have reduced their base load by 4.8 MW, which has led to the improvement of the annual SEC index according to Table 6, between 3.7% and 5.9%. In addition, as shown in Figures 14 and 15, the TOU program changed the load profile of the cement plants present in this program in all seasons of the year and shifted their consumption load by 13.84 MW from peak hours to other hours of the day during the year.

6. Future Work

Since the results of this study can help the electricity companies and heavy industries in choosing the DR program with the highest energy efficiency, the researchers of this study in the next step will study and examine the effects of other DR programs on energy efficiency in large factories. Also, the effect of implementing demand response programs in the presence of renewable energy or the use of BESS and DTR technologies will be included in the future work plan.

Data Availability

All data generated or analyzed during this study are included in this published article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References


