OPPORTUNITIES FOR INDUSTRIAL DEMAND RESPONSE: A SURVEY OF GRID-RESPONSIVE SMART MANUFACTURING APPLICATIONS

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Abstract

Industrial demand response has struggled in implementation when compared to demand response in other sectors. Process complexity and a wide variety of process types make it difficult for catch-all solutions to industrial demand response. Case studies provide insight into how specific demand response measures can be implemented at facilities for effective demand response. This work analyzes ten different case studies in industrial demand response to understand their scope in the industrial process, the control mechanisms used, and the impact and applicability they have to other industrial facilities. The study finds that demand response measures that are integrated into the process seem to be simpler to control and cheaper to implement when compared to measures that are external to the process like generation or storage. Though this is the case, external demand response measures are more applicable across other types of facilities.

Keywords
demand response, load shifting, industrial, distributed generation

Introduction

In 2021, the U.S. Energy Information Administration (EIA) reported that the industrial sector accounted for about 35% of all energy use in the United States, second only to the transportation sector (Energy Information Administration EIA, 2022). As one of the largest consumers of energy, it is evident that the industrial sector is poised to be a key player in the ongoing energy transition in the U.S. Innovations with industrial heat sources, refrigeration, and advanced process control, among many others, are important research topics that are attracting many talented researchers across the world. Though there is one area where the industrial sector is significantly behind when compared to the other sectors: demand response. According to a 2021 publication by the EIA, the industrial sector accounted for less than 5% of all demand response energy savings in 2020 (Energy Information Administration EIA, 2021). The same report stated that the industrial sector has the highest potential peak demand reduction at over 15,000 MW, but only achieved about 32% of that reduction in 2020, a lower percentage than both the residential and commercial sectors.

The lack of demand response deployment in the industrial sector is most often attributed to the complexity and diversity of industrial systems compared to other sectors. Industrial processes are more complicated and take more effort to manipulate and utilize than simple heating and cooling systems found in residential and commercial facilities, almost without exception. An additional consideration is process diversity. Whereas the heating system of one office building could be very similar to the heating system of another office building, industrial facilities widely differ in product, process method, and technique based on company and market demand.

The purpose of this work is to analyze facility-specific demand response measures in published literature through case studies and to generalize the methods used to demonstrate applicability across similar types of manufacturing. The study focuses on specific case studies that may have originally been published with only one facility in mind, but that could have general applicability to other applications.

Relevant Previous Work

The generalization of industrial demand response potential is an open area of research that continues to grow as renewables achieve higher penetration on the grid and as industrial facilities look for new ways to electrify their systems and reduce emissions. Government entities including the Better Plants program and researchers at national labs have published articles, information sheets, and handbooks to help all different entities, including industrial facilities, participate in demand response. These publications have tended to be very general, pointing out generalized numbers of potential reduction and not giving specific instructions on how demand response would actually look. Researchers at

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Table 1: The list of published case studies used in this work. The number is a reference number for the case study used in this work for quick reference.

Case #	NAICS Code	Citation
1	311812	Machalek and Powell (2019a)
2	327410	Machalek and Powell (2019b)
3	212234	Machalek et al. (2020)
4	212392	Machalek et al. (2020)
5	336413	Machalek et al. (2020)
6	336413	Henning et al. (2019)
7	212234	Chen et al. (2022)
8	311812	Westberg et al. (2018)
9	336413	Brimley et al. (2019)
10	323111	Billings et al. (2022)

Oak Ridge National Laboratory released a study in 2013 on the potential of industrial demand response in the Western Interconnect region of the U.S. (Starke et al., 2013). The study generalized process elements across Standard Industrial Classification (SIC) codes to produce generalized load profiles for all different types of manufacturers and their potential for demand response. The study was novel in that it utilized geographic location, EIA and DOE energy use data, and dominating processes in each type of manufacturing system to build plausible load profiles and estimate the demand response potential in the Western Interconnect. The analysis is very general, grouping all manufacturers by the first two digits of the SIC code and completing the analysis for ten different groups.

Case studies are developed to combat generalization and provide specific examples of demand response. Some works have focused on specific equipment and how the equipment can be controlled as part of an industrial process for demand response (Seo et al., 2020; Tsay et al., 2019). Other works have examined a certain type of facility in a designated area and quantify the demand response potential across many facilities (Alcázar-Ortega et al., 2012; Goli et al., 2011; Kelley et al., 2022; Otashu and Baldea, 2019; Simkoff and Baldea, 2020). Case studies provide insight into what would actually work in specific processes and applications rather than general estimates or assumptions.

Case Studies Overview

This work focuses on published case studies concerning demand response methods and potential at industrial facilities. The list of case studies with a number for reference in the rest of this text, the NAICS code for the facility, and the citation are listed in Table 1. All of the case studies used in this work originated from energy assessments performed by the Intermountain Industrial Assessment Center housed at the University of Utah. With each case study, the affiliated assessment provides extended information concerning all utility usage and expenditures, production, sizing, and location.

The published case studies can be separated into three different categories, organized by the main tool in demand response: process storage, process shifting, and generation.

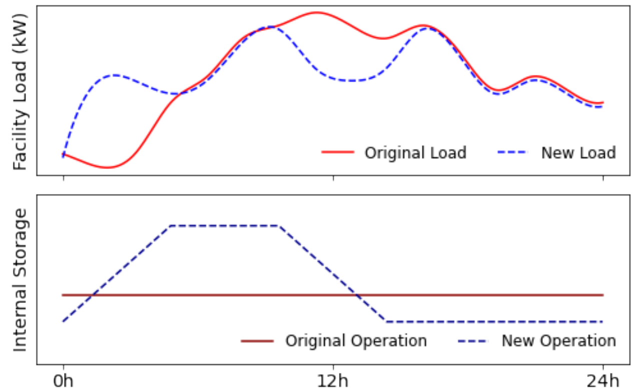

Figure 1: An illustration of how internal process storage can be used for demand response. The upper plot shows the original facility load, and the new load after demand response is implemented. The lower plot shows how the storage is originally used just to maintain the process and then it is filled during off-peak hours and emptied during on-peak hours.

Process Storage

Most processes in the industrial sector have a degree of built-in flexibility in their process. Flexibility is usually made possible through some form of storage within the process that allows production rates to vary both upstream and downstream from the storage. An illustration of this can be seen in Figure 1. Exploiting that storage for demand response is a method used by a few of the case studies included in this paper. One case study, case 1, utilized chilled glycol buffer storage tanks as a storage resource, chilling the buffer to lower temperatures than usual and utilizing sensible heat as the storage medium (Machalek and Powell, 2019a). The study charged the storage during off-peak hours using the designated pumping and chiller system and then utilized the storage during periods of high prices. Another case study, case 3, involving a mining facility utilized large water storage tanks used for storage during the dewatering process to level off demand to minimize demand peaks (Machalek et al., 2020). The same paper included a second case study, case 4, using large storage tanks and a very large pumping load as a means to charge the storage tanks during off-peak hours and reduce peak demand.

When process storage capacity is available, it tends to be the cheapest and least disruptive form of demand response compared to the other categories. The charging of storage takes place at times when the process can handle increased production and when electrical demand does not need to be reduced. The only capital expenses with process storage would be control schemes and mechanisms for implementing the storage and increasing the storage size during construction if increased demand response capabilities are desired.

Process Shifting

In processes where no significant storage capacity is available within the process, flexibility can sometimes be found

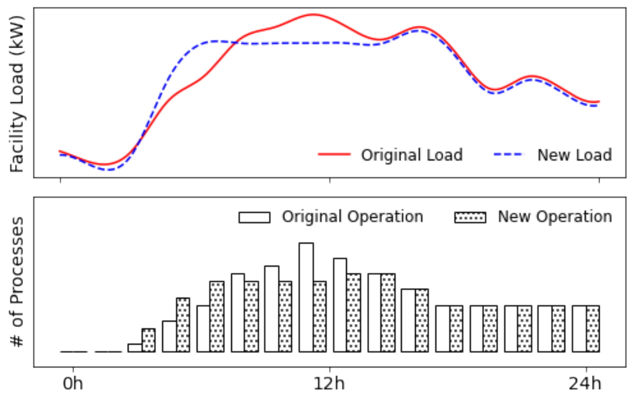

Figure 2: An illustration of how process shifting can be used for demand response. The upper plot shows the original facility load, and the new load after demand response is implemented. The lower plot shows the number of processes that are running at a given time for both the original and new operation. The new operation spreads out the processes to decrease the processes working simultaneously, bringing down the peak demand.

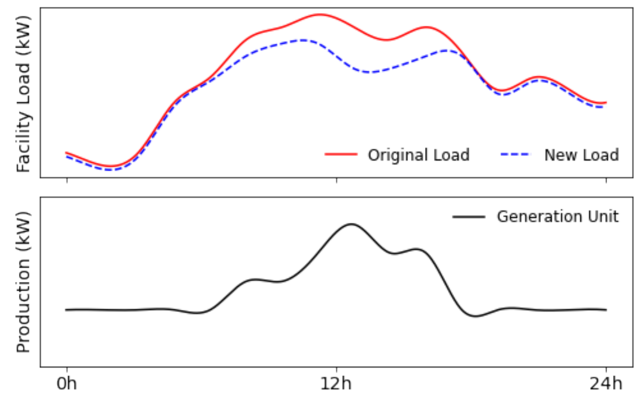

Figure 3: An illustration of how generation can be used for demand response. The upper plot shows the original facility load, and the new load after demand response is implemented. The lower plot shows the power produced by the generation unit, mimicking a profile that might be present with a solar installation.

in process scheduling. An illustration of this can be seen in Figure 2. This is most often found in batch manufacturing processes where steps of the process are performed sequentially with little to no continuous operation of any part of the process. Process scheduling can also be used to ramp continuous processes to perform demand response. This involves running this machinery at higher rates during off-peak times and reducing usage during on-peak times. Multiple case studies were identified as utilizing process shifting for demand response: a mineral processing facility ramping a rotary kiln based on peak demand periods but maintaining production levels (case 2) (Machalek and Powell, 2019b), a bakery with a batch-based process utilizing the scheduling of the large parts of the process to reduce demand during peak times (case 8) (Westberg et al., 2018), and an aeronautics manufacturer similarly using scheduling to minimize demand by improving the timing of large process systems like autoclaves, ovens, and mills (case 9) (Brimley et al., 2019).

Process shifting can provide quick, relatively easy, and cheap demand response for facilities with already flexible timing and production rates. Without that inherent flexibility, process shifting can sometimes become very complicated and costly when processes have problems or delays and cannot follow established schedules and sequences because of production quotas. During construction, process shifting can be built into the facility by means of redundant machinery or oversized machinery to accommodate different batch sizes, each of which can add significant capital costs to the facility.

Generation and External Storage

Generation involves part of the process that actively produces electricity to offset demand levels during production. An illustration of this can be seen in Figure 3. Specific case studies utilizing generation include a mining facility utilizing solar production (case 7) (Chen et al., 2022) and an aeronautics composites manufacturer using a non-traditional combined heat and power (CHP) system (cases 5 & 6) (Machalek et al., 2020; Henning et al., 2019). Generation resources, especially renewable sources, often are rendered most effective when coupled with storage. Storage allows the energy to be harvested and used when needed to reduce demand to the grid. This can also be done by using standalone storage, which is external to the process, and charging the storage directly from the grid during off-peak hours. This is illustrated in case study 10 involving an industrial printing facility utilizing standalone battery storage to minimize peak demand across all months of the year (Billings et al., 2022).

Generation and external storage systems for demand response tend to be the most expensive demand response options for industrial users. Combined heat and power systems are costly, typically replacing existing boiler systems, or they can require boiler systems as a supplement or backup to the CHP system. Renewable generation systems also necessitate a large capital investment and typically require storage installations to most effectively utilize the harvested energy for demand response. This is shown in case 7 with the mining facility (Chen et al., 2022).

Control Methodologies

As with all manufacturing processes, decision-making and control are paramount in effective and efficient operation. This is even more true when demand response performance is included in the decision process. The case studies explored in this work utilized various different methodologies to control the processes to maximize demand response. This section summarizes and analyzes the methods from the case studies.

Smart Scheduling

Processes that utilize batch manufacturing typically utilize scheduling when implementing demand response. Proper process scheduling is performed continuously by all facilities to maintain production and capacity levels. Including demand in scheduling decisions is sometimes called smart scheduling. Scheduling can be as simple as making sure a piece of equipment is off before starting another one. Many of the case studies used in this work used scheduling to integrate demand response. Case 9, involving batch manufacturing of composite aeronautical components, utilized a genetic algorithm to improve the process scheduling in the facility with the objective of decreasing peak demand (Brimley et al., 2019). The genetic algorithm was chosen because of its ability to handle changing loads, production goals, and operation hours. Other batch manufacturers, like case 8 with the bakery facility, utilized an understanding of the process to test various different scheduling schemes involving the major process equipment (Westberg et al., 2018). The scheduling schemes used machine staggering and pre-charging of storage capacity to reduce electricity usage during peak demand periods. Similar scheduling schemes were used in the CHP case study, case 6, utilizing stacked schedules and staggered schedules to either place higher demand during off-peak hours or limit demand during on-peak hours (Henning et al., 2019).

Active Control Methods

One step up from smart scheduling of process elements are simple control algorithms that can be implemented as logic controllers to utilize untapped storage capabilities for demand management. Case 1, involving dough processing, utilized a simple short-term load shifting algorithm to utilize chilled glycol storage as a means to shift production to off-peak times (Machalek and Powell, 2019a). The algorithm utilized logic and setpoints with only a few measurements from the process to effectively shift demand. A similar method was used in case 3 with logic determining when dewatering pumps should decrease power to a setpoint or increased to required levels based on production requirements, on/off-peak timing, and storage capacity (Machalek et al., 2020).

Some industrial processes and equipment require controllers that can account for many unknown elements in a process. The mineral processing case study, case 2, utilized a continuous process with a large rotary kiln that could ramp up and down depending on process needs (Machalek and Powell, 2019b). The proposed control algorithm used model predictive control (MPC) with a sophisticated energy and mass transfer model of the rotary kiln as the model for the controller. The controller was then used to maintain product quality while performing ancillary services to the grid through demand modulation. Case 10 created a Gaussian process regression from historical load data that was then used to make battery dispatch decisions to bring down overall process demand (Billings et al., 2022). The method utilized Bayesian decision theory to quantify risk aversion and load uncertainty and then make decisions on battery discharge rates. Demand response systems can become less complicated when the facility includes a generation source. The CHP case study, case 5, utilized PI controllers to maintain process setpoints while utilizing a smart scheduling baseline to decrease demand during peak hours (Machalek et al., 2020). This case study differs from most of the other case studies cited in this work because CHP includes maintaining heat loads through simple control while producing power to decrease electric demand. Similar control methods were used in case 7 with the well pumps in a mining application which compared the demand response potential of the system with solar generation and battery storage (Chen et al., 2022).

Table 2: Table indicating the applicability of each case study to other facilities. The table shows the case number and then indicates whether the case study would apply to facilities with the same NAICS code (Same NAICS), facilities with a similar process but a different NAICS code (Similar Process), and facilities with different NAICS codes and different processes (Different Process).

Case #	Same NAICS	Similar Process	Different Process
1	✓	✓	
2	✓		
3	✓	✓	
4			
5	✓	✓	✓
6	✓	✓	✓
7	✓	✓	
8	✓		
9	✓		
10	✓	✓	✓

Control methods in the industrial sector have increasingly become more sophisticated with academic research integrating detailed models, machine learning, and large amounts of historical data to facilitate effective control. Fundamentally at the facility level, these case studies indicate that simple control and scheduling could be sufficient for many facilities to reduce demand. Many facilities lack in-house staff and expertise in new and innovative control methods and would benefit from simple, proven methods that have never been implemented.

Expanded Application of Case Studies

Each case study can be examined on the applicability of the demand response measure to other facilities with the same NAICS code, facilities with different NAICS codes that may have similar processes, and facilities with different NAICS codes with no process similarities. The indications of applicability for each of these criteria are shown in Table 2.

All but one of the case studies was seen as able to be applied to other facilities with the same NAICS code. Case study 4 is a very specific project regarding a facility with a uniquely long pipeline to pump its intermediate product. Most other facilities of this type would not have the same setup, hence the lack of applicability to facilities with the same NAICS code. Case studies 1, 3, 5, 6, 7, and 10 all have applicability to facilities with different NAICS codes but with similar processes. Case 1 could apply to any facility with glycol storage that is used for process cooling since those sys-

Table 3: The associated utility usage and charges for each facility affiliated with each published case study. The table shows the case study reference number for this work, the annual usage in GWh, the average monthly demand peak in MW, the percent share by NAICS code, and the percent demand reduction of the total facility demand for each case study. Cases 3, 4, and 7 have no percent share because their NAICS codes are not included in MECS.

Case #	Usage (GWh)	Peak (MW)	% Share	% Reduced
1	6.15	1.04	0.007	7.3
2	45.4	3.90	3.28	-
3	214	28.7	-	6
4	75.2	10.5	-	14
5	3.48	1.09	0.036	73
6	3.48	1.09	0.036	70
7	294	37.1	-	5.6
8	6.15	1.04	0.007	36
9	1.15	4.36	0.012	21
10	11.6	2.50	0.730	7.5

tems are widely used in manufacturing. Case 3 could apply to almost any mining or drilling operation where water needs to be removed from the process. Cases 5 and 6 have wide applicability to any process where there is a significant process heat load that can be met in part by a CHP system. This is why processes with no similarities are also checked for both cases. Case 7 has applicability similar to case 3 in that there are many mining applications where smart pumping and renewables could be incorporated together for demand response. Case 10 is applicable across all different types of manufacturers. Facilities would need peaks in their electrical use that could be leveled by a local battery installation. It is interesting to note that the cases with higher applicability also tend to have higher capital implementation costs. Generation and external storage applications have a high degree of applicability to all different types of industrial applications, though in many cases these systems are prohibitively expensive for industrial facilities.

The savings of each case study can be quantified annually by comparing the savings of the demand response study to the total annual electrical usage of the facility. The total energy usage of the facility was taken from DOE's Industrial Assessment Center Database and can be seen in Table 3. Included in the table is a value for the percent share the facility has compared to other facilities in the U.S. with the same NAICS code, according to the most recent Energy Information Administration's Manufacturing Energy Consumption Survey (MECS). MECS reports the total electricity consumption according to the NAICS code with the last report being released in 2018.

All of the case studies conclude with the ability of the new measure to reduce peak demand for the facility. The last column in Table 3 shows the demand reduction calculated for each case study. The case studies with the highest percentages are 5 and 6 which use generation in the form of CHP to reduce demand. Some of the case studies utilizing storage saw an increase in overall energy use even though there was a decrease in peak demand. This is indicative of overall efficiencies of storage that must be taken into account when considering the overall impact of the applications from these case studies.

Consideration must be taken as to decide whether it is worth the time, resources, and effort to find and utilize facility-specific demand response measures. The same consideration must be taken to analyze whether generalized solutions like battery installations and solar generation are worth the large capital investment for industrial facilities. Future work could focus on the economic comparison of facility-specific measures and generalized plug-and-play options that would be applicable to almost every industrial facility. There could exist some synergy between using facility-specific measures to more effectively utilizing the generalized solutions for maximum benefit. A possible innovation to help improve the comparison of demand response measures across different industrial entities would be the establishment of metrics for better comparison. These metrics would need to account for cost, magnitude, and interruption caused to the process, among other factors.

Conclusion

Industrial demand response is an untapped resource for the changing grid. Though generalized solutions for demand response have been proven effective in the residential and commercial sectors, the complexity and plethora of different types of facilities in the industrial sector necessitate specificity. Case studies in industrial demand response provide insight into the realistic applications in the industrial sector. The case studies investigated in this work were categorized into three different groups: process storage, process shifting, and generation and external storage. The control of the demand response in the case studies was relatively simple with most relying on scheduling to shift demand and others relying on simple controllers and predictive control to provide demand reduction. The most applicable case studies to other applications were the ones that would require higher capital investment to implement. Facility-specific measures for demand response utilize knowledge and understanding of the process itself to provide demand response. The case studies indicate that demand response measures that utilize the process as a resource tend to be cheaper but require extensive knowledge of the process and facility operations. On the other side, general solutions that would apply to many different facilities tend to bring higher capital costs and are not integrated into the process. The case studies illustrate that both process integrated and external demand response measures require different resources but both are effective in industrial demand response.

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