



HOKKAIDO UNIVERSITY

Title	Energy Management for Demand Response in a Commercial Building with Chiller System and Energy Storage System
Author(s)	孫, 準浩
Degree Grantor	北海道大学
Degree Name	博士(情報科学)
Dissertation Number	甲第12486号
Issue Date	2016-12-26
DOI	https://doi.org/10.14943/doctoral.k12486
Doc URL	https://hdl.handle.net/2115/64464
Type	doctoral thesis
File Information	Joonho_Son.pdf



Doctoral Thesis

Energy Management for Demand Response in a Commercial Building
with Chiller System and Energy Storage System

Joonho Son

December, 2016

Division of Systems Science and Informatics
Graduate School of Information Science and Technology
Hokkaido University

Doctoral Thesis
submitted to Graduate School of Information Science and Technology,
Hokkaido University
in partial fulfillment of the requirements for the degree of
Doctor of Information Science.

Joonho Son

Thesis Committee: Professor Hiroyuki Kita
Professor Hajime Igarashi
Professor Satoshi Ogasawara
Associate Professor Ryoichi Hara

Energy Management for Demand Response in a Commercial Building with Chiller System and Energy Storage System*

Joonho Son

Abstract

The smart grid which is a modernized electrical grid for producing and distributing the electricity efficiently, reliably, economically and sustainably by information and communication technology between suppliers and consumers are globally emerging for resolving global anthropogenic CO₂ emissions, the fossil fuel crisis, generation capacity shortage, and so on while creating some new operation scheme and business opportunities. The smart grid technology would also provide opportunities for end-users such as commercial buildings (COBs), residences and industrial facilities to participate in deregulated power market. Especially, demand response (DR) that is used to shave the peak demand for securing the supply reliability of power system, is one of the attractive options for the end-users. The most popular adjustable demand response resource (DRR) in COB is a chiller system used in heating, ventilation and/or air conditioning loads (HVAC). It can be achieved by load reduction in a specified DR duration by thermal mass control (pre-cooling). On the other hand, installation of an energy storage system (ESS) have been accelerated in the world from the viewpoint of its high economic efficiency. A technique for charging and/or discharging ESS appropriately has been implemented for peak shifting operation to reduce the annual cost of electricity which is the sum of basic cost related annual peak load (KRW/kW) and the electricity usage cost (KRW/kWh) under the Time-Of-Use (TOU) tariff. However, ESS can be also achieved as an attractive DR resource because it can reduce the net load by discharging ESS in a specified DR duration. Based on this background, this paper proposes a new DR energy management algorithm which consists of the following two parts.

First, a day-ahead operation scheduling algorithm of chiller system and ESS is proposed to minimize the daily expected energy cost to ensure the benefit of a COB owner through Time-Of-Use (TOU) tariff and the Korean DR market. In the day-ahead operation, there are difficulties such that the owner does not know in advance when DR event happens. Therefore, this paper presents a scenario driven operation algorithm which makes it possible to vary the operation of chiller system and ESS depending on the DR event signal provided one hour prior to DR. Also, the proposed algorithm considers the uncertainties in the next day's ambient temperature; therefore, the day-ahead operation schedule which is robust for the assumed size of forecast temperature error can be obtained. From the simulation results, it was cleared that ESS can be charged as preparation for DR and discharged for maximum DR reward during DR duration, and comfort indoor temperature can be guaranteed regardless of DR event.

Second, a method for determining the optimal DR capacity in a COB with chiller system and ESS. In the proposed scheme, the optimal DR capacity (kW) can be determined so that the total expected cost of a COB becomes minimum by chiller system and ESS while avoiding DR penalty threat adopted in the Korean DR market. Here, since it is to reduce the long computer time needed to run the simulation based on the mathematical formulation, it is necessary to give some representative ambient temperatures. In order to give the desirable representative ambient temperatures, this paper presents a method for determining the representative ambient temperature by the k-means clustering algorithm which is popular for cluster analysis in data mining fields. Simulation results showed that the proposed scheme not only can simply find representative ambient temperatures based on big historical ambient temperature group but also can determine the optimal DR capacity using by chiller system and ESS for minimal energy cost associated with utility cost, DR reward, and DR penalty.

This paper is organized as follows. Chapter 1 describes the background of DR mechanism, type of proposed DR resources, uncertainty, and the objective of this thesis, and Chapter 2 introduces DR participation in the Korean regulation market, behavior for the DR participants, and technical issues for successful DR participation. Chapter 3 proposes the operation scheduling algorithm which divides into day-ahead operation scheduling and rescheduling on D-day in a COB with chiller system and ESS. Chapter 4 proposes a method for determining the optimal DR capacity using chiller system and ESS in a COB. Chapter 5 summarized the achieved results as the above chapter of this thesis.

Keywords: Energy management system (EMS), demand response (DR), energy storage system (ESS), chiller system

Contents

1. Introduction	1
1.1 Background	1
1.2 Demand Response (DR)	3
1.2.1 Demand response programs	5
1.2.2 Emergency demand response programs	6
1.3 Demand Response Resource (DRR)	7
1.3.1 Type of demand response resources	7
1.3.2 Type of demand response resources for end-users	7
1.3.3 HVAC for DR	8
1.3.4 Energy storage system (ESS) for DR	11
1.4 Uncertainty	13
1.4 Organization of Chapters	13
2. DR participation for end-user to the target DR market	15
2.1 Introduction	15
2.2 The Korean DR market	16
2.3 Behavior for the DR Participation	16
2.4 Technical issues for DR participation	17
2.4.1 Determination of the optimal DR capacity	17
2.4.2 Day-ahead operation scheduling	18
3. Operation scheduling in a Commercial Building with Chiller System and Energy Storage System	19
3.1 Introduction	19
3.2 Scenarios for Uncertainties	20
3.2.1 DR event	20
3.2.2 Ambient temperature	20
3.3 Mathematical Formulation	20
3.3.1 Concept of the proposed DR market	21
3.3.2 Day-ahead operation scheduling	21
3.3.3 Operation rescheduling on D-day	26
3.4 Simulation Results (Day-ahead operation scheduling)	28
3.4.1 Simulation conditions	29
3.4.2 Obtained simulation results (Conventional)	31

3.4.3	Obtained simulation results (Proposed)	33
3.4.4	The main advantages of the proposed method	34
3.5	Simulation Results (Operation rescheduling on D-day)	36
3.5.1	Simulation conditions	39
3.5.2	Obtained simulation results	39
3.7	Conclusion	43
4.	Determination of the optimal DR capacity in a Commercial Building with Chiller System and Energy Storage System	45
4.1	Introduction	45
4.2	Mathematical Formulation	46
4.2.1	Determination of the DR capacity	47
4.2.2	Dermination of representative ambient temperatures	50
4.2.3	Architecture for the proposed DR algorithm	52
4.3	Case Studies	54
4.3.1	Estimation for representative ambient temperatures	54
4.3.2	Economic evaluation of the proposed DR algorithm	61
4.4	Conclusions	70
5.	Conclusion	71
	Acknowledgment	73
	References	74
Appendix A	K-means clustering algorithm	79
Appendix B	The silhouettes analysis	81

List of Figures

1.1	Annual global anthropogenic carbon dioxide (CO ₂) emissions [1]	1
1.2	GHG emissions by economic sectors [2]	2
1.3	Observed annual and decadal global mean surface temperature anomalies [2]	2
1.4	The concept of demand response	4
1.5	Demand response event	4
1.6	Role of Demand Response in Electric System Planning and Operation	5
1.7	Schematic of HVAC system in a commercial building	9
1.8	The schematic of a typical building HVAC system	10
1.9	Market share of ESS applications	11
1.10	Schematic of ESS	11
1.11	ESS utilizations [20]	12
1.12	Entire structure of thesis	14
2.1	System configuration of a COB	17
3.1	Time chart DR operation used in the DR market	21
3.2	Signal driven DR operation used in the proposed method	22
3.3	Concept of the mathematical formulation for day-ahead scheduling	23
3.4	Concept of operation rescheduling on D-day	28
3.5	Daily load data of a COB excluding chiller system and ESS	29
3.6	Temperature profiles for day-ahead operation scheduling	30
3.7	Obtained optimal operations for day-ahead scheduling (Conventional)	31
3.8	Obtained optimal operations for day-ahead scheduling (Proposed)	31
3.9	Analyses of obtained power consumption by the proposed method	33
3.10	Other obtained day-ahead operation scheduling by the proposed method	36
3.11	Analysis of obtained power consumption of chiller system considering both of pre-cooling for DR and thermal comfort for the three temperature scenarios	39
3.12	Temperature profiles for operation rescheduling	40
3.13	Obtained optimal operations rescheduling on D-day (Applied with Actual T1)	41
3.14	Obtained optimal operations rescheduling on D-day (Applied with Actual T2)	41

3.15	Obtained operation rescheduling	42
3.16	Analysis of rescheduled power consumption of chiller system	43
3.17	Obtained optimal operation after rescheduling	43
4.1	Architecture for the proposed DR algorithm used to solve the optimal DR capacity problem	54
4.2	Input temperatures profiles for estimation	55
4.3	Silhouette value calculation to the various clustering	57
4.4	Determination of representative ambient temperatures	58
4.5	Obtained the DR capacity	59
4.6	Estimation for the optimal DR capacity	60
4.7	CBL for the optimal DR capacity	60
4.8	Input temperatures profiles for economic evaluation	62
4.9	Silhouette value calculation to the various clustering	64
4.10	Determination of representative ambient temperatures	66
4.11	Economic evaluation for every case	67
4.12	DR Penalty analysis for Case 2 and Case 3	69

List of Tables

1.1	Major EDRPs	6
3.1	Nomenclature for mathematical formulation	23
3.2	Simulation parameters	29
3.3	Assumed DR event scenarios	29
3.4	Simulation cases under DR resource category	37
3.5	Simulation results for ESS enhancing to day-ahead forecasting temperature forecasting error.	38
4.1	Nomenclature for mathematical formulation	46
4.2	DR event scenarios	56
4.3	Simulation parameters	56
4.4	Parameters of DR event scenarios for economic evaluation	63
4.5	Simulation cases under DR resource category	63
4.6	Assumed actual DR event scenarios for economic evaluation	64
4.7	Optimal DR capacity under simulation cases	64

Chapter 1. Introduction

1.1 Background

Greenhouse gases (GHG) emissions such as water vapor, carbon dioxide, methane, nitrous oxide, and ozone for a better life have been a global issue for last several decades. According to the report, global anthropogenic CO₂ emissions from fossil fuel combustion and industrial processes contributed about 78% to the total GHG emission increase between 1970 and 2010, with a contribution of similar percentage over the 2000–2010 period as shown in Fig. 1.1 [1]. More specifically, direct and indirect GHG emissions were analyzed in economic sectors as shown Fig. 1.2. Direct GHG emission are shares of five economic sectors in 2010. And indirect CO₂ emission shares from electricity and heat production are attributed to sectors of final energy use. Especially, building has occupied the highest rate of indirect CO₂ emissions [2].

As mentioned above, the GHG emissions make inversely people bad effects. More specifically, the GHG emissions have provided global warming, which is terms for the observed century-scale rise in the average temperature of the Earth's climate system and its related effects. The global warming affects oceans warming, which increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010 with only about 1% stored in the atmosphere as shown in Fig. 1.3 (a) and (b) [2]. Furthermore, the rate of sea level rise since the mid-19th century has been larger than the mean rate as shown in Fig. 1.3 (c) and (d). Consequently, the sea level rise should damage to human life such as hurricanes, tornadoes coastal erosion etc. Recently, many strategies for reducing GHG emission and managing the risks of climate change have been discussed in the world. One of the major promising strategies is to improve end-users' energy efficiency.

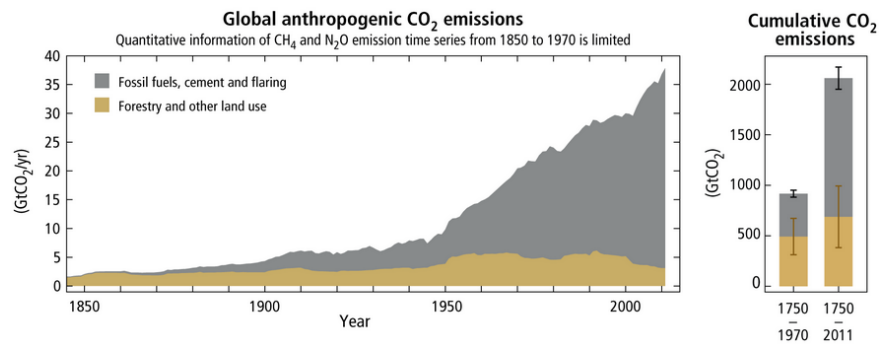


Figure 1.1: Annual global anthropogenic carbon dioxide (CO₂) emissions [1]

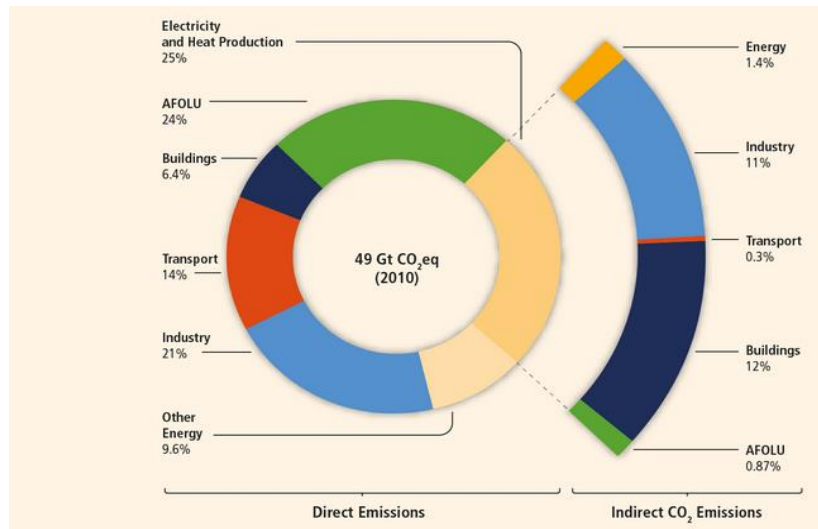


Figure 1.2: GHG emissions by economic sectors [2]

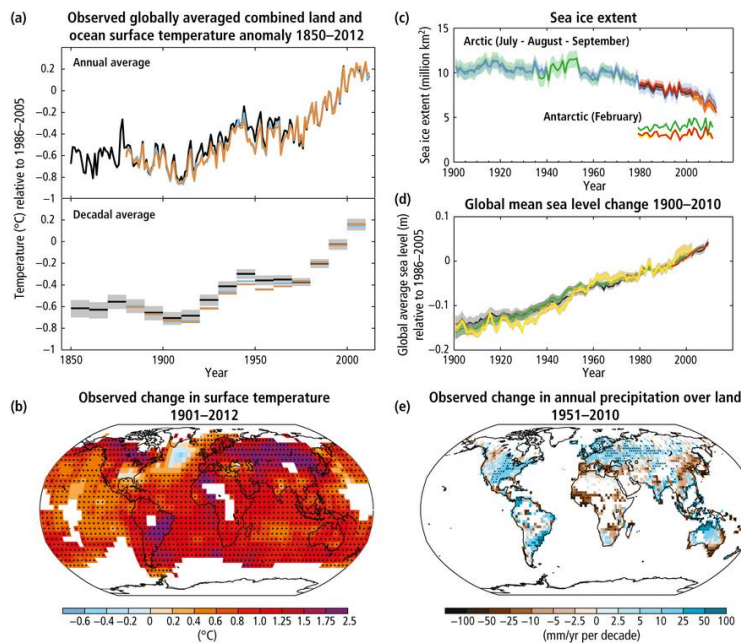


Figure 1.3: Observed annual and decadal global mean surface temperature anomalies [2]

Lower energy uses becomes an essential element of mitigation strategies for keeping temperature increase below 2 [°C]. The potential of end-use energy efficiency improvement in transport, buildings and industry is large: at least about 40-60%, 30-60%, and 30-50% respectively by 2050, compared to the baseline. Especially, human choices can be changed in transport modes, diet, and energy use in households for emission reduction. Buildings are big opportunities for emission reduction in new and renovated building by an energy management system (EMS), which can save electricity usage by changing lifestyle and behavior. Industry has also significant opportunities to improve energy efficiency, efficiency of material use, recycling and reuse in the short term,

allowing emissions to get below a fast growing baseline.

On the other hand, smart grid, which is a modernized electrical grid for the efficiency, reliability, economics, and sustainability of the production and distribution of electricity by information and communications technology between suppliers and consumers has been emerging to implement energy efficiency improvements.

1.2 Demand Response (DR)

Smart grid technology promotes deregulation policies in the electric power companies. It would provide business opportunities of market participation to end-users such as commercial buildings (COBs), residences, and industrial facilities. This is the key concept of demand response (DR). DR is defined by the U. S. Department of Energy (DOE) in its February 2006 report to Congress and subsequently adopted by the Federal Energy Regulatory Commission (FERC) is stated as [3]:

“Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.”

Fig. 1.4 shows the concept of demand response (DR). Customer baseline load (CBL) indicates load forecast, which would have used while there is no DR. It must be reasonably accurate for DR participation. Since load reductions can be quantified by accurate CBL, as well as it would be affected to calculate a reward for DR contribution. Accurate CBL has an RRMSE (relative root mean square error) less than or equal to 20%. Total amount of load reduction can be calculated that CBL minus actual load during specified DR event duration. Consumers as DR participants have the opportunity to manage their electricity use in response to conditions by means of reducing their electricity consumption when wholesale prices are high or the reliability of the grid is threatened, receiving payments for the reductions they make. Common examples of reduction strategies are turning up the temperature on the thermostat to reduce air conditioning or slowing down or stopping production at an industrial facility temporarily. Further, some industrial customers with backup generation and appropriate environmental permits might use their generators to meet a portion of their power needs during peak periods, enabling them to draw less from the system and reduce demand on the grid. DR programs offer customers the opportunity to reduce demand in response to a price signal or financial incentive. Typically, the request to reduce demand is made for a specific time period on a specific day, which is referred to as a Demand Response event (DR event). A DR event is defined as, the time periods, deadlines and transitions during which Demand Resources perform. It also describes points during the DR event where the customer receives notification of the beginning and end of the event and illustrates the point at which a customer should take action as shown in Fig. 1.5. [4].

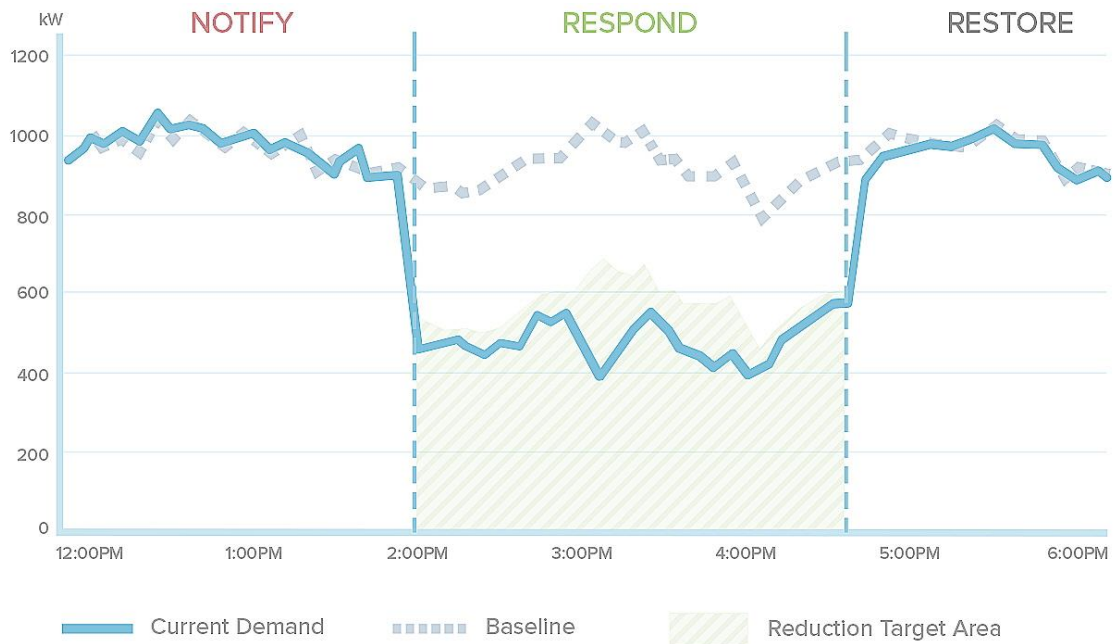


Figure 1.4: The concept of demand response

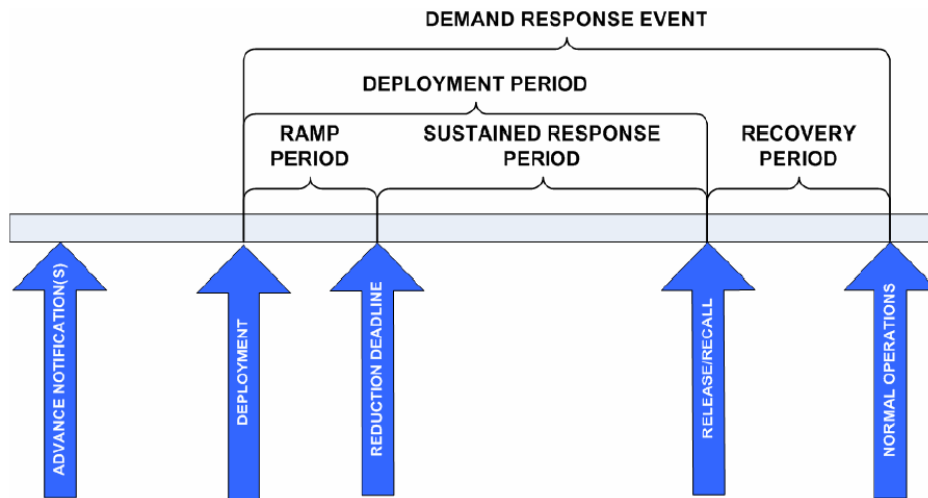


Figure 1.5: Demand response event

On the other hand, there are four major benefits of DR as utility companies' perspectives [5]. First, DR acts as a deterrent to the exercise of market power by generators. Second, utility companies have improved choice because customers can participate DR programs for reducing their electricity costs. Third, utility companies are provided with more flexible resources to meet contingencies. Finally, utility companies have reliability benefits by reductions in the likelihood and consequences of forced outages that impose financial costs and inconvenience on customers. In contrast, three major benefits of demand response are observed as end-users' perspectives. First, customer would save on their electric bills from using less energy when prices are high, or from

shifting usage to lower-priced hours, as well as any explicit financial payments the customer for agreeing to or actually curtailing usage in a demand response program. Second, lower wholesale market prices that result from demand response translate into reduced supply costs to retailers and eventually make their way to almost all retail customers as bill savings. Finally, customer are provide reliability by load reductions to the reduced risk of losing service in a blackout.

1.2.1 Demand response programs

Demand response options can be deployed at all timescales of electricity system management and can be coordinated with the pricing and commitment mechanisms appropriate for the timescale of their commitment or dispatch as shown in Fig. 1.6 [5]. As you can see, DR can be classified into two types; Time-based programs and Incentive-based programs. If utility resource planners and system operators have a good sense of how their customers respond to changes in the price of electricity, price-based demand response options may be incorporated into system planning at different time scales. Time-of-use (TOU) means a rate with different unit prices for usage during different blocks of time, usually defined for a 24 hour day. TOU rates reflect the average cost of generating and delivering power during those time periods. And Real-time pricing (RTP) is defined a rate in which the price for electricity typically fluctuates hourly reflecting changes in the wholesale price of electricity. Customers are typically notified of RTP prices on a day-ahead or hour-ahead basis. Critical Peak Pricing (CPP) is defined a hybrid of the TOU and RTP. That is, the basic rate structure is TOU. However, provision is made for replacing the normal peak price with a much higher CPP event price under specified trigger conditions (when system reliability is compromised or supply prices are very high).

On the other hand, incentive-based demand response programs may be introduced at virtually all timescales of electric system management. Capacity market programs mean customers offer load curtailments as system capacity to replace conventional generation or delivery resources.

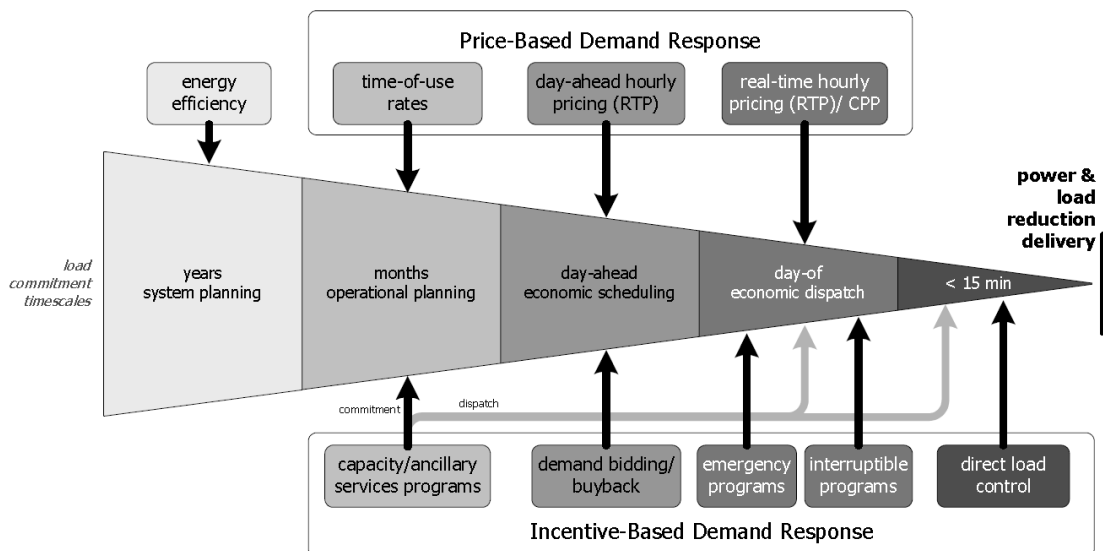


Figure 1.6: Role of Demand Response in Electric System Planning and Operation

Ancillary services market programs are defined that customers bid load curtailments in ISO/RTO markets as operating reserves. If their bids are accepted, they are paid the market price for committing to be on standby. If their load curtailments are needed, they are called by the ISO/RTO, and may be paid the spot market energy price. Demand Bidding/Buyback Programs is that customers offer bids to curtail based on wholesale electricity market prices or an equivalent. Mainly offered to large customers (e.g., one megawatt [MW] and over). Emergency Demand Response Programs (EDRP Interruptible/curtailable (I/C) service are integrated into retail tariffs that provide a rate discount or bill credit for agreeing to reduce load during system contingencies. Penalties maybe assessed for failure to curtail. Interruptible programs have traditionally been offered only to the largest industrial (or commercial) customers. Direct load control (DLC) is utilized that the program operator remotely shuts down or cycles a customer's electrical equipment (e.g. air conditioner, water heater) on short notice. Direct load control programs are primarily offered to residential or small commercial customers.

1.2.2 Emergency demand response programs (EDRPs)

EDRPs are reliability-based, and payments for load reductions are often linked to real-time energy market prices or values that reflect customer's outage cost or the value of lost load. Because when compromising reliability condition causes spike prices to the power system.

Table 1.1: Major EDRPs

	U. S			Korea
	PJM	NYISO	ISO-NE	Korea power exchange (KPX)
Name	Emergency Load Response Program	EDRP	Real-Time 2-hour Demand Response	demand response resource market
Advance notifications	day of 120 minutes	Day-ahead advisory and day of 120 minutes	day of 120 minutes	day of 120 minutes
Minimum Size	100kW	100kW	100kW	100 kW
Energy reward	The greater of LMP or minimum dispatch	The greater of hourly zonal LBMP or \$500/MWh	The greater of Real-Time LMP or \$350/MWh	Incentive price KRW/kWh
Capacity reward	Capacity credits	UCAP credits	ICAP Market price	Incentive price KRW/kW
Penalty	Yes	No	Yes	Yes

In order to recovery the compromised reliability conditions in the peak demand (summer or winter season), independent system operators (ISO) can operates EDRPs that support reliability. Customers can choose to allow the ISO to interrupt their service, for which the customer is paid a price determined through a bidding process. Major EDRPs are summarized in Table1.1 [6]-[9]. As you can see, DR events are usually declared within 30 minutes to 2 hours of power delivery. Customers who have over than 100 kW as demand response resources can participate the EDRPs for DR reward. In NYISO, EDRP pays customers an incentive which, for example, is more than 500 \$/MWh in New York power market or can be the prevailing real-time market price for curtailments of at least four hours long when called by the ISO. Energy reward for load reduction can be calculated that customer baseline load (CBL) minus real-time load curve during specified DR duration. However, when customers can't follow DR requests from utility company, capacity reward DR signal must be paid back to utility company.

1.3 Demand Response Resources (DRRs)

1.3.1 Type of demand response resources

FERC filing regarding Order No. 745 are defined three types of demand response resources (DRRs) such as DRR-Type I, DRR-Type II, and Demand Resource [10]. DRR-Type I is defined as a resource hosted by an energy consumer or load serving entity that is capable of supplying a specific quantity of energy or contingency reserve, at the choice of the market participant, to the energy and operating reserve market through physical load interruption. DRR-Type II is also defined as a resource hosted by an energy consumer or load serving entity that is capable of supplying a range of energy and/or operating reserve, at the choice of the market participant, to the energy and operating reserve market through behind the meter generation and/or controllable load. Finally, Demand Resource is used as interruptible load or direct control load management and other resources that can reduce demand during emergencies.

A DRR is same to generator in the power market and can be categorized as one of the following product such as energy, capacity, regulation and reserve. Energy is defined that a DRR are compensated based solely on demand reduction performance during a demand response event.

Capacity means a DRR are obligated over a defined period of time to be available to provide Demand Response (reduction) upon deployment by the system operator. Reserve is defined that a DRR is obligated to be available to provide demand reduction upon deployment by the system operator, based on reserve capacity requirements that are established to meet applicable reliability standards. Finally, regulation means a DRR increases and decreases load in response to real-time signals from the system operator. Demand resources providing regulation service are subject to dispatch continuously during a commitment period.

1.3.2 Type of DRRs for End-user

Customers participating in demand response options may respond to high prices or program

events in three possible ways [5]. Firstly, reducing usage at times of high prices or demand response program events without making it up later. For example, a residential customer might turn off lights or turn up the thermostat on an air conditioner during an event, or a commercial facility might turn off office equipment. In both cases, a temporary loss of amenity or comfort results. Second, rescheduling usage away from times of high prices or demand response program events to other times. More specifically, a residential customer might put off running a dishwasher until later in the day, or an industrial facility might reschedule a batch production process to the prior evening hours or the next day. Finally, some customers may respond by turning on an onsite (ESS, and cogeneration system (CGS), etc.) or backup emergency generator to supply some or all of their electricity needs. As mentioned above, although the customer may have little or no interruption to their electrical usage, their net load and requirements on the power system is reduced.

Meanwhile, a home energy management system (HEMS), a building energy management system (BEMS), and a factory energy management system (FEMS) have been recently studied for further energy efficacy, economics, and participating DR programs effectively as follows. In DR operation for residences applied with HEMS, they can potentially enable demand response applications for residential customers [11]-[12]. More specifically, HEMS can determine the status (turning on/off) of appliances such as clothes dryer, water heater, storage battery, and electric vehicle called schedulable loads based on the specified demand limit. Any violation in the demand limit will result in turning OFF selected appliances according to customers' priority by HEMS. Customer preference settings are usually allowed to be violated from the least important loads to the most important ones to guarantee the requested demand limit.

FEMS shows the actual changes of power consumption compared with the targets of multiple levels planned in advanced [13]. But also, it will sound if the set point (in each level exceeds the restrain energy consumption. It can enhance DR operation for industrial facilities, in which it manages the power consumption of each electric power system, production line or each plant's area. More specifically, Schedulable tasks including feeds, intermediates, and final products are scheduled to operate on the operating point with low electricity consumption when the price is high and are scheduled to operate on the operating point with high electricity consumption when the price is low under the premise of satisfying the market demand.

BEMS effectively provides DR operation in commercial buildings through optimal controlling energy [14]-[17]. That is, it can be reduced by obtaining location information for individuals while ensuring building security, automatically controlling heating, ventilation, and air conditioning (HAVC), lighting, heat pump, ESS, electric vehicles (EV) and visually representing energy usage.

1.3.3 HVAC for DR

HVAC (Heating, Ventilation, and Air Conditioning) utilizes for humidity and temperature regulated whilst maintaining safe and healthy conditions in industrial and office buildings as shown in Fig. 1.7 [18]-[19]. It is designed to provide a relatively constant and comfortable temperature in buildings and provide fresh and filtered air with a comfortable humidity level. HVAC system in a commercial building typically accounts for 17-49% of the total building's energy use. A typical

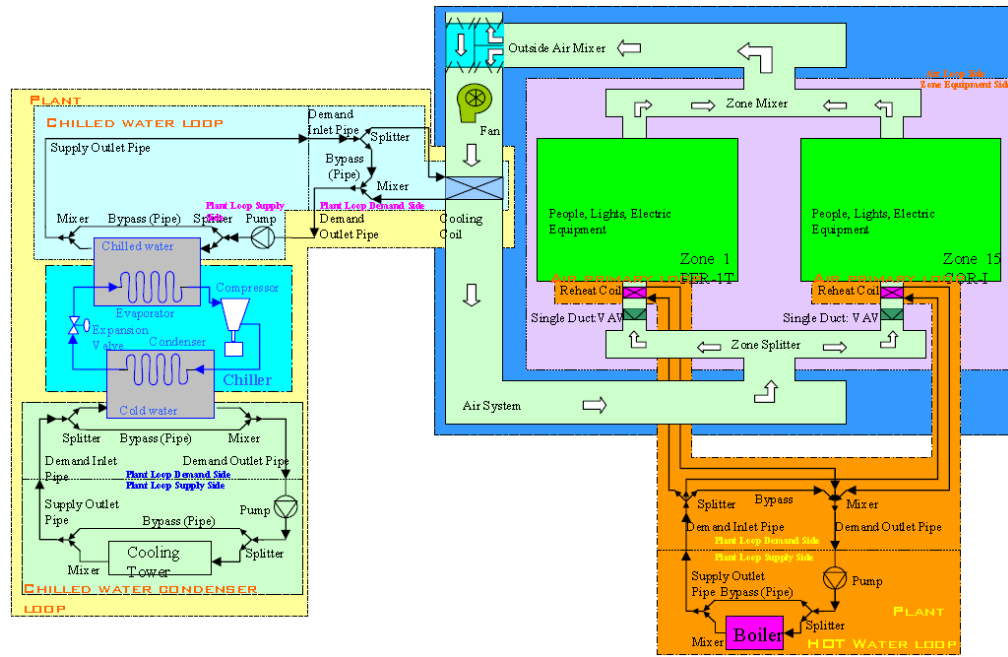


Figure 1.7: Schematic of HVAC system in a commercial building [19]

centralized HVAC system is comprised of a condenser water loop and chilled water loop that, together with chillers and indoor air loops provide a comfort environment for the conditioned space. The process of a condenser water loop consists of chiller condensers, pumps, cooling towers and fans. More specifically, operation mechanisms of HVAC are divided into five sections in the following process as shown in Fig. 1.8.

① Indoor air loop includes fans, cooling coils, terminal units, dampers, ducts, and controls. The air in the conditioned space is driven by fans through cooling coils and then distributed to terminal units. Dampers are used to control airflows to terminal units and fans are used to maintain a given air pressure in ducts. The cooling and ventilation loads are transferred from the conditioned space to chilled water.

② Chilled water loop includes pipes, pumps, cooling coils, chiller evaporators, valves, and controls. The chilled water in pipes is driven by pumps to circulate between cooling coils and chiller evaporators. Valves are used to control the water flow to cooling coils. The heat is transferred from air handling units (AHUs) to chiller evaporators.

③ Refrigerant loop includes evaporators, compressors, condensers, expansion valves and controls. The refrigerant absorbs heat in chiller evaporators by changing phase from liquid to gas. The working of compressors makes the refrigerant a high pressure and high temperature state. The refrigerant with high temperature is cooled in chiller condensers. The high pressure refrigerant in gas is released by expansion valves back to evaporators again with phase change. The heat is transferred from chiller evaporators to chiller condensers.

④ Condenser water loop includes cooling towers, chiller condensers, pumps and controls. The

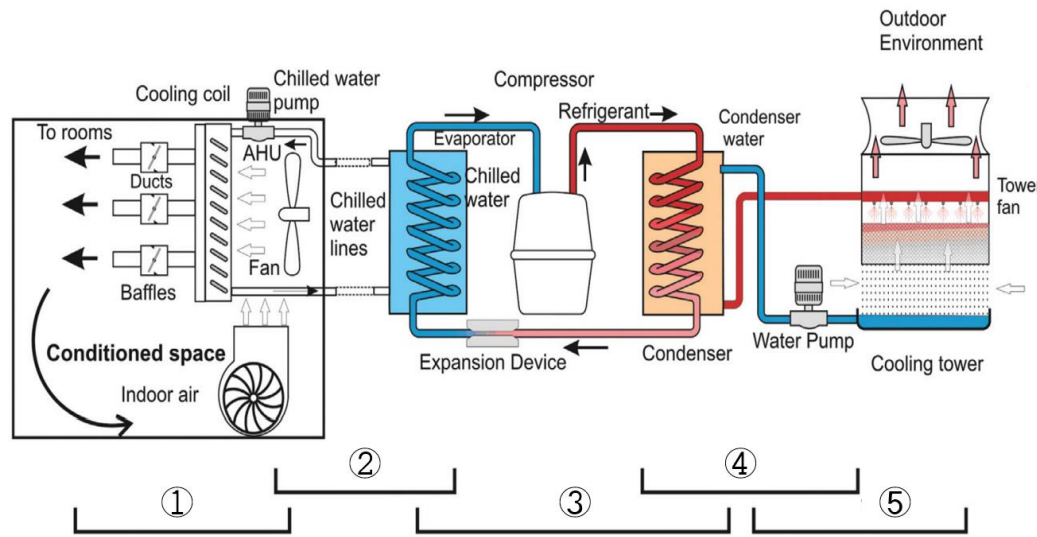


Figure 1.8: The schematic of a typical building HVAC system [20].

condenser water in chillers is delivered to cooling towers by pumps. The heat is transferred from chiller condensers to cooling towers.

⑤ Outdoor air loop includes fans, cooling towers, and controls. The outdoor air is driven by fans to go through cooling towers and to exchange heat with condenser water. The heat is transferred from cooling towers to ambient environment.

HVAC system is the most commonly adjusted to achieve demand response savings in commercial buildings. The goal of demand response strategies is to meet the electric shed savings targets while minimizing any negative impacts on the occupants of the buildings or the processes that they perform. Thermal flywheel (thermal storage) effect of indoor environments allows HVAC systems to be temporarily unloaded without immediate impact on the building occupants called pre-cooling strategy. HVAC system also has a strategy for reducing load evenly throughout all zones of a facility from certain area of normal temperature range to substantially deviated area. Then, thermal comfort is maintained in modern buildings through the use of closed loop control. Sensors are used to measure important parameters such as temperature and pressure. Controllers adjust actuators such as dampers or valves to maintain the desired set points for those parameters. Granularity of control using HVAC system can also allow building operators to create DR shed behaviors that are customized for their facility. An example of this would be to slightly increase all office zone temperature set points, but leave computer server room set points unchanged. Additionally, cycling constant air volume HVAC units or temporarily re-set static pressure in variable air volume HVAC, turning off ceiling fans and room fans, turning off or turn down chillers, reset chilled water temperature, adjusting variable speed drive controls to reduce load from fans, pumps and chillers. Apply ventilation control temporarily reducing outside air flow can help reduce cooling demand.

1.3.4 Energy Storage System (ESS) for DR

Energy storage system (ESS) will play a key role in enabling to develop a low-carbon electricity system, improving power quality and the reliable delivery of electricity to customers, proving high stability and reliability of transmission and distribution systems, enhancing use of existing equipment, thereby deferring or eliminating costly upgrades, and improving availability and increased market value of distributed generation sources as shown in Fig. 1.9 [21]-[24].

ESS is mainly composed of battery, battery management system (BMS), power conditioning system (PCS), power management system (PMS), energy management system (EMS)/SCADA, and other power distribution and communication facilities as shown in Fig. 1.10 [25]. Battery is charged or discharged to grid and renewable energy generation. BMS performs the whole monitoring function of battery system such as voltage, electric-current, state-of-charge (SOC), state-of-health (SOH), and temperature. PCS is inter-conversion control between grid or renewable energy generation (AC) and battery DC power. PMS performs overall ESS monitoring including collection and monitoring of battery and PCS operation information and environmental facilities.

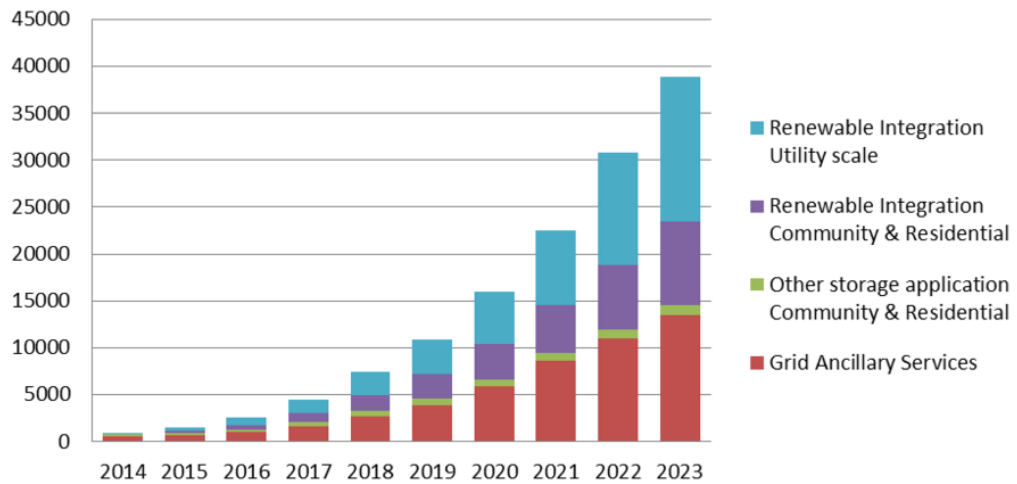


Figure 1.9: Market share of ESS application

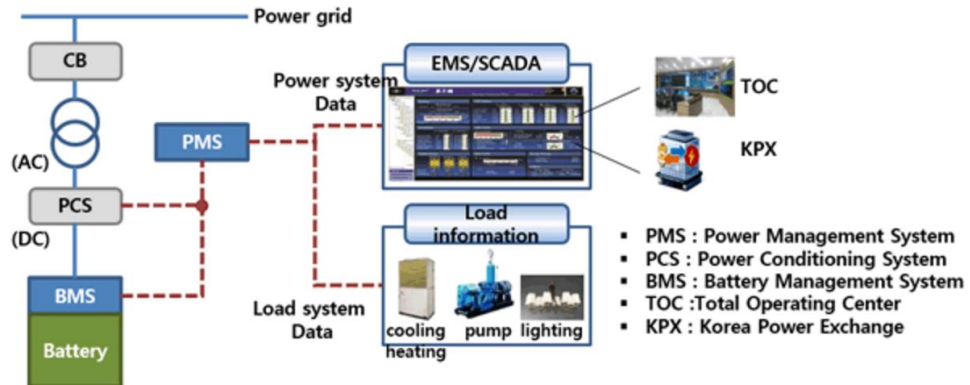
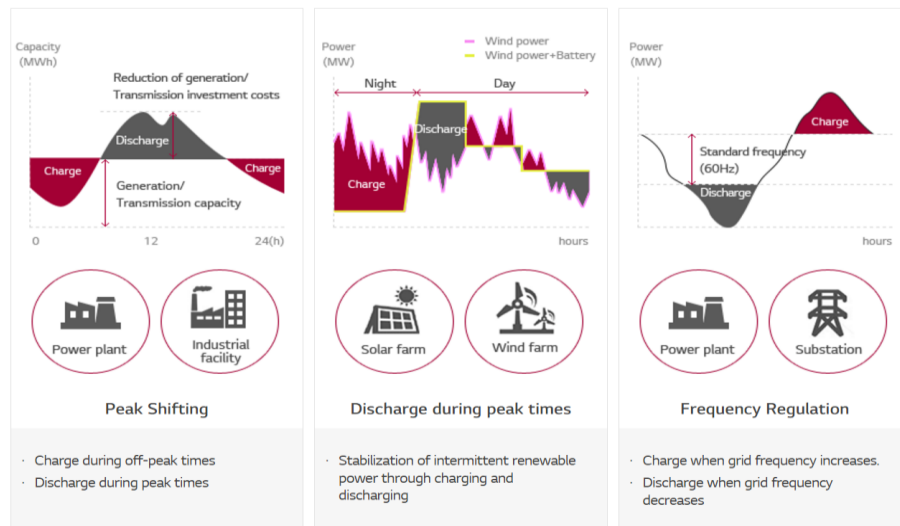


Figure 1.10: Schematic of ESS

EMS/SCADA execute overall energy management such as predictive operation, evaluation, and external system interlocking in buildings and plants. ESS is suitable for renewable and distributed generation and infrastructure/demand side energy management owing to their high efficiency rates, relatively lower cost, high energy densities, and longer range lifecycles. More specifically, there are three main advantages for ESS utilization to power system and end-users as shown in Fig. 1.11. ESS can be established to lower peak demands of the power plant and reduce electricity charge by charging with low-priced night time electricity and discharging for cutting electricity cost by lowering peak demands in home/commercial owners as shown in Fig. 1.11(a). ESS complements the intermittence of renewable energy produced by wind or solar power generation system. ESS stabilizes the output of renewable energy by charging & discharging irregular and intermittent power which is generated from wind and solar system as shown in Fig. 1.11(b). Further, frequency regulation is the means by which synchronism of the grid generators is maintained within acceptable limits and network stability is controlled. To avoid the possibility of damaging power imbalance scenarios adversely affecting the network, the network operator must maintain reserve generating capacity to cover imbalance with different magnitudes and duration to keep the generating capacity as close as possible in line the demand at all times. Because the magnitude of imbalance is reflected in the grid nominal system frequency. Here, ESS helps grid system operators maintain constant frequency, in which it operates for frequency regulation by means of charging when grid frequency increasing or discharging when decreasing grid frequency in power plant or substation as shown in Fig. 1.11(c).

However, the ESS would have potential as an attractive DR resource. More specifically, ESS can be contributed for DR by strategic discharging during peak demand events through demand response programs. That is, ESS would provide business opportunities of DR participation to earn incentives while enhancing system reliability during times when demand for electricity could outpace supply.



(a) Peak shaving (b) stabilization of renewable energy (c) Frequency regulation

Figure 1.11: ESS utilizations [20]

1.4 Uncertainty

DR resources as mentioned ESS and HVAC have to be operated not only based on the day-ahead hourly electricity prices (TOU tariff), but also DR event information with the amount and/or periods of load reduction. Thus, end-users have to determine the day-ahead optimal operation of DRRs for participation effectively in EDRP such as the Korean DR market considering both of TOU tariff and the Korean DR market. However, it is not easy for end-users to implement DR in EDRPs because of the following reasons.

First, the DR event signal including requested load reduction (called curtailment) and DR duration has an uncertainty. Namely, the end-users do not know in advance how much amount or how much time they should reduce the demand load. If end-users cannot follow DR requests, a penalty must be paid to utility company.

Second, ambient temperature also has an uncertainty. Forecasting error of the ambient temperature can cause insufficient DR contribution or deterioration in thermal comfort. For example, when end-users utilize chiller system used in HVAC as a DRR, the chiller system should be heavily operated to maintain thermal comfort for indoor temperature on a hot day. Namely, power consumption of chiller system strongly depends on the ambient temperature. The ambient temperature also affects the DR event. In fact, the DR events tend to happen in hot days. However, it's hard to accurately predict actual ambient temperature for optimal day-operation scheduling as DR participants' perspective.

Third, uncertain DR event and ambient temperature would affect the optimal DR capacity for obtaining maximum reward through the DR market. More specifically, end-users should determine their optimal DR capacity considering both of maximum DR reward and avoiding penalty threat before DR market participation. However, if end-users determine larger DR capacity than their capacity limit for DR participation, although DR reward with the waiting capacity (kW) and actual energy reduced (kWh) can be obtained as a high value, but a threat for penalty payment can be increased. When end-users determine small DR capacity than their possible capacity limit, they only obtain low DR reward for DR contribution without penalty threat. Therefore, it is very important to determine the optimal DR capacity as DR participants' perspective.

1.5 Organization of Chapters

This thesis consists of five chapters as illustrated in Fig. 1.12 and the contents are summarized as follows. Chapter 1 describes the background, business participation for demand response (DR), introduction of attractive demand response resources (DRRs) as chiller system used in HVAC system and ESS, optimization problems for participation considering both of TOU tariff and the Korean DR market in uncertain environments, and organization of chapters.

Chapter 2 shows DR participation for end-user to the DR market. The DR market regulation applied in the Korean introduces. And behavior for the DR participation from assumed end-user

discusses.

Chapter 3 focuses on operation scheduling considering demand response in a COB with chiller system and ESS. The operation scheduling consists of two parts; day-ahead operation scheduling and operation rescheduling on D-day. Their objective functions are to minimize a daily expected energy cost under uncertainties in ambient temperature and DR event as scenarios. Operation scheduling of chiller system and ESS as decision values are optimized by various constraints such as demand and supply balancing, characteristics of chiller system, dynamics of indoor temperature, operation for ESS, DR requirement and CBL, consistency before DR event notification, and capacity limit. The validity of the proposed operation scheduling is ascertained through case studies.

Chapter 4 deals with determination of the optimal DR capacity in a COB with chiller system and ESS. The optimal DR capacity (kW) can be determined so that the total daily expected costs of a COB becomes minimum by chiller system and ESS while avoiding DR penalty threat adopted in the Korean DR market. To solve the optimization problems, the proposed silhouette analysis and kmeans clustering algorithm were applied to determine representative ambient temperatures as input data. Estimation and economic evaluation of the proposed scheme are ascertained through case studies.

Chapter 5 summarizes the results of this research and presents the conclusions.

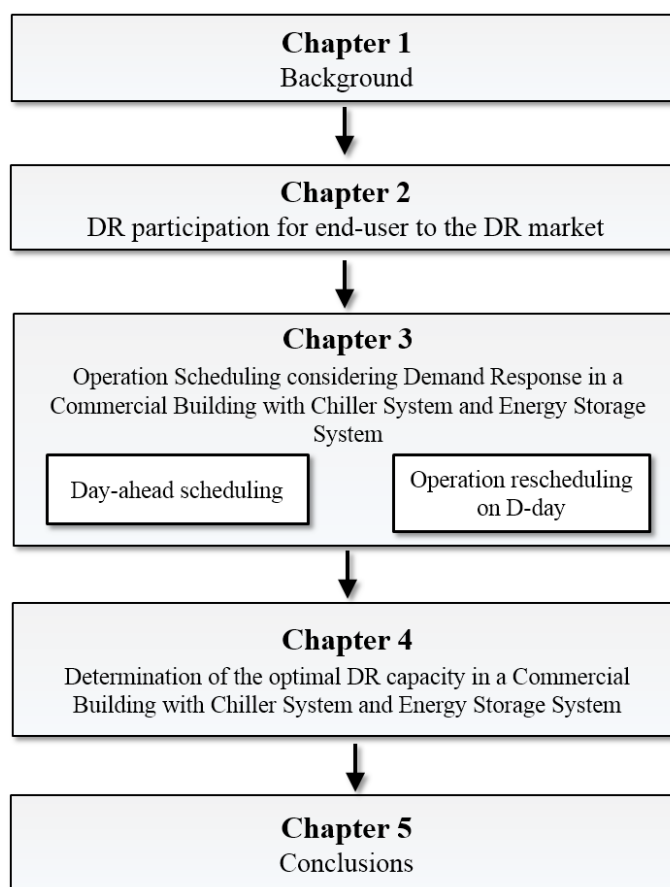


Figure 1.12. Entire structure of thesis

Chapter 2. DR participation for end-user to the DR market

2.1 Introduction

Challenges to realize the smart grid are globally emerging for resolving the global warming issue, the fossil fuels crisis, generation capacity shortage, and so on, while creating some new operation scheme and business opportunities. One of the new challenges is the demand response (DR) as mentioned in the previous section 1.2. In general, DR can be classified into two types; time-based programs and incentive-based programs [37]. One of the most promising incentive-based programs is emergency demand response program (EDRP) which was developed in the U.S. such as PJM, NYISO, ISO-NE, as well as the Korean DR market. For example, active end-users who have DR resources can participate and contribute by reducing their electricity consumption following the DR signal from the system operator. In the DR scheme, when reduction in the compromised reliability of power system was anticipated during peak demand periods, utility company notifies DR participants to reduce their electricity usage one or two hours ahead of the peak period.

EDRP can be divided into day-ahead and real-time (hourly-ahead) markets. In the day-ahead market, utility company should determine total amount of curtailment based on predicted peak demand before DR operation day. End-users participant to DR using their DR resources through given DR information of requested curtailment and specified DR duration one day before. However, it is very difficult to accurately predict peak demand from utility company the day before. If peak demand is incorrectly predicted on DR operation day, utility company would waste operation costs for power system reliability, in which a reward for the waiting DR capacity must be paid to end-users regardless of what DR event happens. However, utility company operating real-time market can correctly predict peak demand DR before 1-2 hours. Real time market not only has significant impact on DR operation due to higher accuracy for peak demand prediction than day-ahead market, but also it can be significantly reduced operating costs. We proposes DR through the Korean DR market.

This chapter introduces how to participate the proposed Korean DR market as end-users' perspective. First, the DR mechanism is briefly discussed in Korea. Second, system configuration of a COB including chiller system, ESS, energy management system (EMS) is introduced. Power consumption is reduced by fully or partially shutting down the chiller systems used in heating, ventilation and/or air conditioning (HVAC) loads. Furthermore, an energy storage system (ESS) which has been used for further improvements in energy and economic efficiencies and supply

reliability also has a potential as a contributor for DR.

Third, technical issues for DR participation to the end-user in the Korean DR market. More specifically, difficulties for determination of the optimal DR capacity are represented in order to achieve effectively DR operation from end-users. And then, strong reasons to execute day-ahead operation scheduling is described in the following sections.

2.2 The Korean DR market

We deal with the Korean DR market which has been constituted to shave peak demand and to recover compromised reliability in the Korean power systems. In this market, when the reduction in compromised reliability and/or occurrence of spike prices was anticipated, utility company notifies the market participants to reduce their electricity consumption by DR event signals [47].

The DR event signals consist of amount of reduction and specified DR duration. The amount of reduction is in kW less than or equal to the contracted DR capacity, which is determined based on DR participant's resources submitted in advance and is valid for one year. Also, the DR duration is applied for 2 hours. The market participants have to prepare their DR resources before 1 hour of DR, and execute load reduction during DR duration. DR participants can get DR reward which is divided into a reward for the contracted DR capacity (kW) and a reward for energy actually reduced (kWh). The reward for energy can be calculated by difference between customer baseline load (CBL) and actual load curve during DR duration. Here, CBL means average hourly energy consumption of end-user, and is calculated based on selected 4 recent non-event days (only weekdays). If DR participants cannot follow DR requirements, the DR reward for the contracted DR capacity must be paid back (called penalty). Therefore, to determine the optimal DR capacity for maximizing DR reward and avoiding penalty threat is very important for DR participants.

2.3 Behavior for a COB with chiller system and ESS

Fig. 2.1 shows a configuration of a COB which is composed of chiller system, ESS and EMS. The chiller system is the most popular adjustable demand in a COB which uses electricity to cool the water in HVAC for thermal comfort indoor temperature. The chiller system can achieve DR by means of pre-cooling since it can shift the power consumption from the specified DR periods to the other advancing periods without serious thermal comfort deterioration in a COB. ESS has been utilized for improvement in economic efficiency by peak-shift operation considering TOU tariff. The ESS would have also attractive potential as DR resources by discharging its energy in the specified DR duration. EMS can determine the optimal operation of chiller system and ESS for minimal energy cost through TOU tariff and the Korean DR market.

Utility company supplies electric power by power supply network and informs the TOU tariff or a DR event to end-users by using information technology (IT) network. When the price in the TOU tariff is low, the end-user would increase power consumption of chiller system to maintain within comfort temperature range and/or charge electric energy to ESS. When the price in TOU tariff is

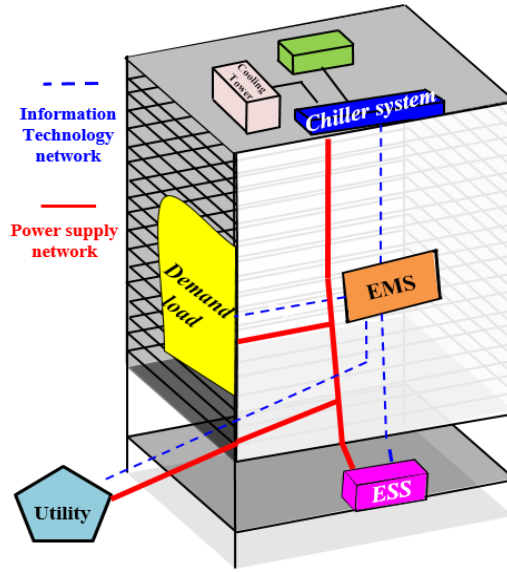


Fig. 2.1: System configuration of a COB

high, the end-user would decrease power consumption of chiller system and/or discharge electric energy from ESS. Furthermore, under the Korean DR market, operation of chiller system and ESS can be shifted from peak demand periods to off-peak periods with information about DR timing and amount of reduction. Thus, EMS is implemented for minimal energy cost and maximum DR reward through TOU tariff and the Korean DR market.

2.4 Technical issues for the DR participation to the COB's operator

2.4.1 Determination of the optimal DR capacity

The Korean DR market operates based on end-users' controllable DR resources (kW) as emergency reserves. The market adequacy constructs of the DR resources require DR to respond during power system emergencies. The number of DR calls per year are limited for 60 hours in the Korean DR market. A DR event dispatched by the system operator to support imports when capacity reserve margin for power system reliability are below 4,500 [MW], in which maximum power supply capacity is expected to exceed current power. DR resources are needed DR operation day starting at hh:mm and ending at hh:mm for reliability purposes. DR resources are subject to notice the DR information and requested load reduction level (kW) expected to be achieved on the each participant one hour before one hour DR execution.

Based on the above discussion, end-users can develop their controllable DRRs such as ESS and chiller system and should determine their annually amount of possible load reduction (curtailment) before participating the Korean DR market. However, uncertain notification of DR event and ambient temperature would affect the optimal DR capacity for obtaining maximum reward through the DR market. For example, when allocated DR capacity is larger than the optimal value, although

end-user will get a higher DR reward than the optimal value, DR penalty threat caused by insufficient DR contribution has to be increased on hot days, as well as the contract for participating DR program can be forcibly terminated from utility company. In contrast, when allocated DR capacity is smaller than an optimal value, end-user will obtain lower DR reward than the optimal value. Thus, it's very important to determine the optimal DR capacity for maximum DR reward and avoiding DR penalty before the targeted DR market participation as end-users' perspective.

2.4.2 Day-ahead operation scheduling

There are several important reasons to propose day-ahead operation scheduling considering DR resources such as ESS and chiller system from end-users as follows. First, a DR event signal has an uncertainty. That is, it's very difficult to predict the DR event by utility company one day before. End-users have to consider its' uncertainty for day-ahead operation scheduling. Second, ambient temperature also has an uncertainty. Some DR resources such as chiller system are affected by uncertain ambient temperature. On hot days, DR resources cannot be satisfied with the requested curtailment. Third, daily operation cost of an ESS is still expensive. It's very important to determine ESS charging or discharging time and rate of charging or discharging for energy efficiency and minimal energy cost. Fourth, end-users should make strategies for their minimal energy costs by reducing energy use and DR operation through TOU tariff and DR market. DR resources have to be operated not only based on the day-ahead hourly electricity prices (TOU tariff) but also DR event information such as the amount and/or periods of load reduction for DR. Thus, in order to effectively participate in EDRP such as the Korean DR market, end-users have to determine the day-ahead optimal operation of DR resources considering both of TOU tariff and the Korean DR market. We have mainly studied the day ahead operation scheduling for maximum DR reward and avoiding penalty threat under uncertain DR events and ambient temperatures as DR participants' perspective.

Chapter 3. Operation Scheduling in a Commercial Building with Chiller system and Energy Storage System

3.1 Introduction

The Korean DR market proposes suppression of peak demand under reliability crisis caused a natural disaster or unexpected power plant accidents as well as saving power plant construction costs and expanding amount of reserve as utility's perspective. As mentioned in the previous chapter 2, end-user is notified a DR event signal (central load dispatching) DR execution before one hour, and executes DR based on requested amount of load reduction. End-user has settlement for DRRs participating in the Korean DR market; reward for waiting capacity (kW) and reward for actually energy reduced (kWh). Reward for waiting capacity (kW) is annually contracted through a bedding system. Reward for actually energy reduced (kWh) are paid to end-user according to total executed load reduction. However, end-user cannot execute 80% of requested load reduction based on the contract capacity, DR penalty must be paid to utility company.

This chapter proposed a DR energy management algorithm that can be scheduled the optimal operations of chiller system and ESS in the next day considering the TOU tariff and DR scheme. In this DR algorithm is divided into two scheduling's; day-ahead operation scheduling with temperature forecasting error and operation rescheduling on DR operation. In day-ahead operation scheduling, the operations of DR resources are scheduled based on the finite number of ambient temperature scenarios, which have been generated based on the historical ambient temperature data. As well as, the uncertainties in DR event including requested amount of load reduction and specified DR duration are also considered as scenarios. Also, operation rescheduling on DR operation day is proposed to ensure thermal comfort and the benefit of a COB owner. The proposed method minimizes the expected energy cost by a mixed integer linear programming (MILP).

3.2 Scenarios for Uncertainties

The optimal operations of chiller system and ESS are scheduled for maximum DR reward and avoiding penalty considering uncertain environments through TOU tariff and the Korean DR market. The representative uncertainties for solving optimization problem in section 3.3 are DR event and ambient temperatures as follows.

3.2.1 DR Event

In the Korea DR scheme, occurrence of DR event is informed from the utility company only 1 hour before the execution with the information of DR duration and requested curtailment (in kW, less than or equal to the waiting DR capacity) [30]. It is very difficult to know when a DR event happens from end-user. Some DR resources such as chiller system and ESS can be achieved their energy reduction during DR events. End-user should schedule the optimal DR resources operation for minimal energy cost regardless of DR events. A variety of DR events including DR duration and requested curtailment with high occurrence probability are considered as scenarios to the mathematical formation.

3.2.2 Ambient temperature

On a hot day, the chiller system should be heavily operated to maintain thermal comfort for indoor temperature. Namely, power consumption of chiller system strongly depends on the ambient temperature. The ambient temperature also affects the DR event. In fact, the DR events tend to happen in hot days [31]. That is, error included in the ambient temperature forecast could cause deterioration in thermal comfort, or insufficient DR contribution. It is important that the DRR operation should be robust for the ambient temperature forecast errors. Ambient temperatures are considered as scenarios to mathematical formulation.

3.3 Mathematical Formulation

This chapter deals with two operation scheduling's such as day-ahead scheduling with temperature forecast error and operation rescheduling on D-day. Day-ahead scheduling W/ forecast temperature error and rescheduling on D-day assume actual temperature has greater difference compared to day-ahead forecast temperature. The main purpose of two operation scheduling using chiller system and ESS are to minimize daily expected energy cost with maximum DR reward and avoiding penalty threat under thermal comfort constraints and scenarios for uncertain DR events and ambient temperatures.

3.3.1 Concept of the proposed DR scheme

If end-users are previously informed the specified DR information in the day ahead. The DR operation can be described in Fig. 3.1. The DR operation divides a whole day (24 hours, 48 intervals) into two sections; one is before DR event notification (h_{DRS-2}), specified by “*before DR*” and the other is after the notification at “ h_{DRS-2} ” specified by “*After DR*”. The DR event in the DR market is modeled to happen from “ h_{DRS} ” to “ h_{DRE} ” for the simplicity. The total load reduction to the requested DR is measured by difference between the actual electricity consumption after DR request and CBL. Therefore, if end-users know a specified DR event one day before. DR operation of DR resources can be optimized by certain DR event information in day ahead.

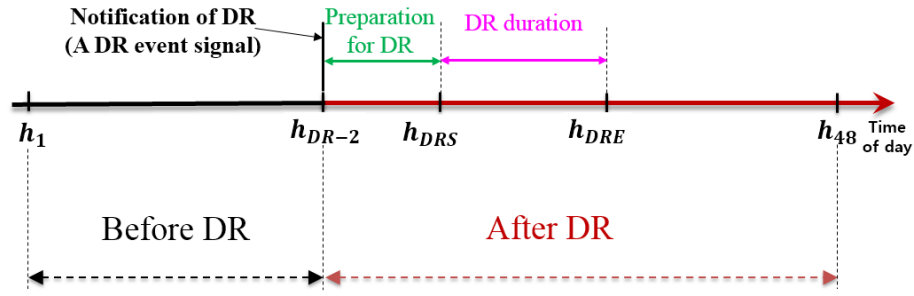
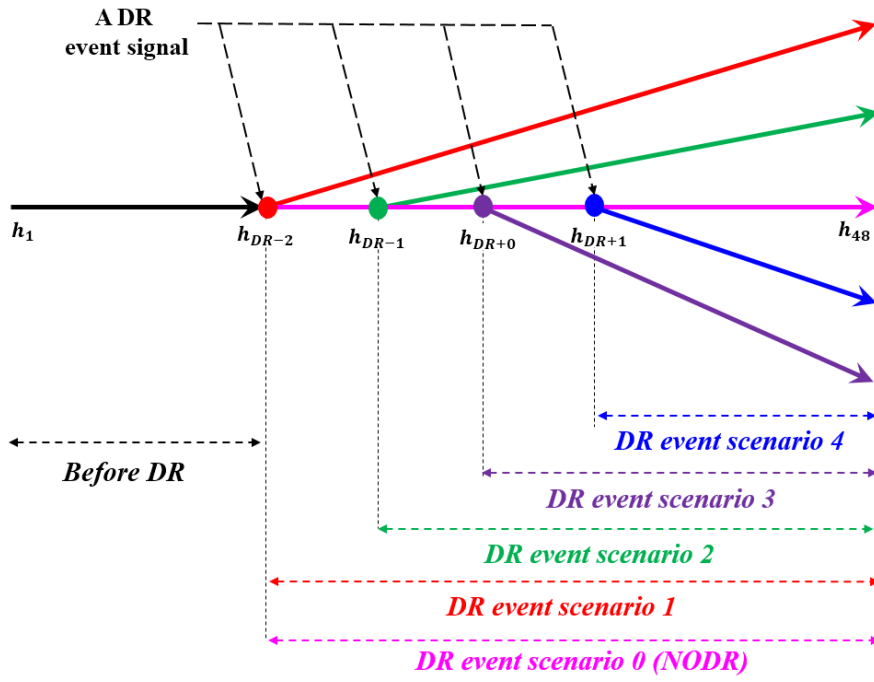


Figure 3.1: Time chart DR operation used in the DR market

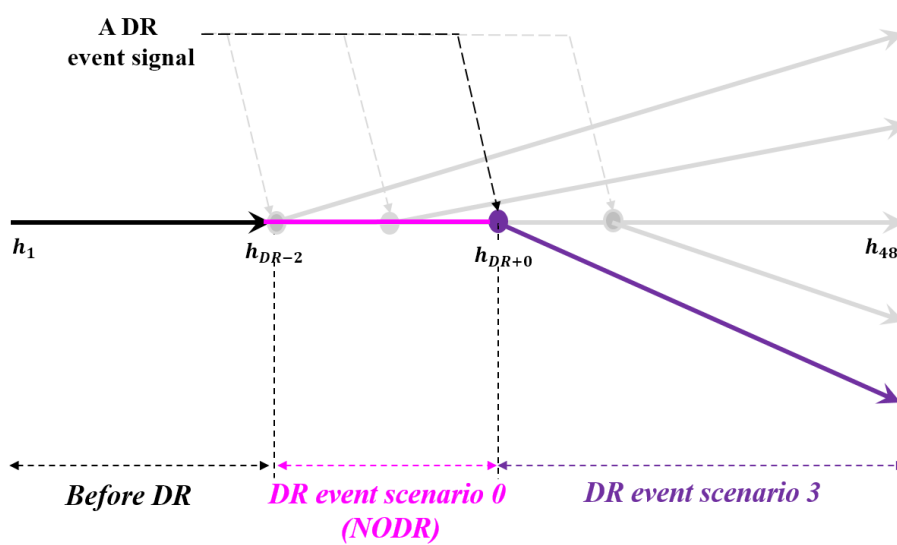
However, the day-ahead operation in the EDRP as the Korean DR market should be scheduled under uncertain DR event signal. In order to consider uncertain DR events, scenario planning is used in this thesis. The scenario planning is a strategic planning method that some organizations use to make flexible long-term plans. It focuses on learning about the future by understanding under the critical uncertainties specific to a given issue. We propose the signal driven operation with the scenario planning for uncertain DR events. The proposed day-ahead scheduling which divides the whole day into six scenarios specified by “Before DR”, “DR event scenario 0 (NODR)”, “DR event scenario 1”, “DR event scenario 2”, “DR event scenario 3”, and “DR event scenario 4” is described as shown in Fig. 3.2 (a). The proposed DR scheme is represented in the following procedures. First, the operation of DR resources as chiller system and ESS is optimized by the given TOU tariff before notification of the DR event from h_1 to h_{DR-2} , specified by “Before DR”. At this time, the DR operation must be same until informing the DR event signal. Second, determination of the operation scheduling out of five DR event scenarios from h_{DR-1} to h_{48} depends on driven a DR event signal from utility company. For example, a DR event signal is informed at h_{DR+0} , the operation scheduling for DR event scenario 3 which was optimized DR resources such as chiller system and ESS from h_{DR+0} to h_{48} can be effectively selected as shown in Fig. 3.2 (b). Here, the DR resource (chiller system and ESS) operations before the DR notification h_{DR-2} to h_{DR+2} must be same as the operation scheduling for DR event scenario 0 (NODR). As mentioned above background, each DR event scenario should be calculated an expected energy cost through unit energy price and given a price for DR contribution. Thus, objective function should be transformed to minimize the expected energy cost for all DR event scenarios.

3.3.2 Day-ahead operation scheduling

It is very important to effectively consider difference day-ahead temperature forecast from actual temperature loci for the day-ahead operation scheduling. Since temperature forecast error would provide deteriorated thermal comfort or insufficient DR. Furthermore, DR participants can pay back their reward for the contracted capacity (called penalty) or the contract termination can be happened by utility company. Therefore, the DR operation using by chiller system and ESS should be robust for the ambient temperature forecast error on D-day. Concept of the mathematical



(a) Concept of proposed signal driven operation to response DR event scenarios



(b) An example of the proposed driven DR operation.

Figure 3.2: Signal driven DR operation used in the proposed method

formulation for day-ahead scheduling is described in the following procedures as shown Fig. 3.3. Five representative DR event scenarios with high occurrence probability are considered for uncertain DR event signals from utility company, and each DR event scenario (d) has different notification of DR and DR duration. And three representative temperature scenarios (k) are applied with the each DR event scenario. More specifically, the operation of chiller system and ESS by the DR event scenario 0 (NODR) must be same as before DR happens given by the DR event

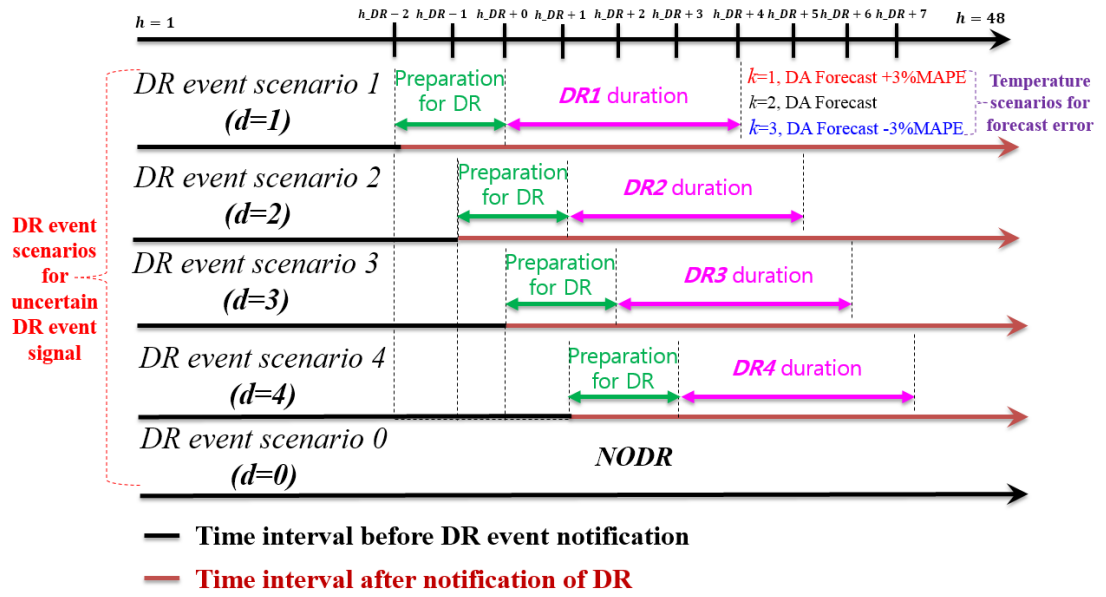


Figure 3.3: Concept of the mathematical formulation for day-ahead scheduling

scenarios (1, 2, 3, and 4) as shown in Fig. 3.3. And DR preparation by chiller system and ESS during preparation for four DR event scenarios are notified to the end-user. Then, power consumption of chiller system and ESS are reduced by the specified DR information. As mentioned, DR event scenarios for uncertain DR event signals are modeled same as the previous day-ahead scheduling without temperature forecast error. And three types of day-ahead forecasting temperature scenarios (k) proposed for robust day-ahead forecast error. Here, 1, 2, and 3 of index k indicate day-ahead forecasting temperature scenario with +3% mean absolute percentage error (MAPE), day-ahead forecasting temperature informed by the national weather service in the Korea, and day-ahead forecasting temperature scenario with -3% MAPE respectively. The forecast error

Table 3.1: Nomenclature for mathematical formulation

Parameter	Definition
$\frac{30}{60}$	0.5 hour (=30-minute)
h	Index for 30-minute interval in a day
k	Index for ambient temperature scenarios
d	Index for DR duration scenarios
$n_h, n_k, \text{ and } n_d$	Total number of time slot, ambient temperature scenarios, and DR duration scenarios ($d = 0$ means NODR)
$\min$ and $\max$	Minimum and maximum values

on D-day can be solved by ± 3 MAPE as the maximum allowable error range for optimal solution. That is, the DR operations by ESS and chiller system should be satisfied with three kinds of day-ahead forecasting temperature scenarios in each DR event scenario. The mathematical problem is to minimize the daily expected cost under forecasted ambient temperatures and DR event scenarios in the following formulation. Nomenclature for mathematical formulation is represented in Table 3.1.

Objective function

The objective function is to minimize total expected energy costs with DR event scenarios given by occurrence probability of DR event scenarios as follows:

$$\min \sum_{d=0}^{n_d} \sum_{h=1}^{n_h} p^{(d)} \cdot C_h^{(d)} \quad (3.1)$$

where $p^{(d)}$ and $C_h^{(d)}$ are occurrence probability of DR event and the total costs associated with DR events [KRW] respectively. The total costs associated with DR events are represented as follows:

$$C_h^{(d)} = \begin{cases} U_{T,h} \cdot P_{Utility,h}^{(d)} \cdot \frac{30}{60} - C_{E,h}^{(d)} & (h_{DRS}^{(d)} \leq h \leq h_{DRE}^{(d)}, d \neq 0) \\ U_{T,h} \cdot P_{Utility,h}^{(d)} \cdot \frac{30}{60} & (otherwise) \end{cases} \quad (3.2)$$

where $U_{T,h}$, $P_{Utility,h}^{(d)}$, $C_{E,h}^{(d)}$, $h_{DRS}^{(d)}$, and $h_{DRE}^{(d)}$ are price for electricity in Time Of Use tariff [KRW/kWh], power purchased from the utility [kW], a reward based on load reduced actually [KRW], starting time of DR, and ending time of DR respectively. A reward based on load reduced actually can be expressed in the following equation.

$$C_{E,h}^{(d)} = U_{E,h} \cdot (P_{CBL,h} - P_{Utility,h}^{(d)}) \cdot \frac{30}{60} \quad (3.3)$$

where $U_{E,h}$ is incentive price for DR contribution at time h [KRW/kWh] and $P_{CBL,h}$ is customer baseline load at time h [kW]

Demand and supply balancing constraints

The total power purchased from the grid is equal to the sum of demand load and power consumption of chiller system and ESS as follows:

$$P_{Utility,h}^{(d)} = P_{D,h} + P_{Chiller,h}^{(d)} + P_{ESS,h}^{(d)} \quad (3.4)$$

where $P_{D,h}$, $P_{Chiller,h}^{(d)}$, and $P_{ESS,h}^{(d)}$ are electricity demand excluding chiller system and ESS, power consumed by chiller system, and net charging or discharging power [kW] respectively

Operation constraints for ESS

Charging or discharging power of ESS and SOC constraints are represented in (3.5) and (3.6) respectively.

$$P_{ESS,h}^{(d)} = P_{ESS,h}^{+(d)} - P_{ESS,h}^{-(d)} \quad (3.5)$$

$$SOC_{h+1}^{(d)} = SOC_h^{(d)} + \frac{30}{60} \left\{ \eta \cdot P_{ESS,h}^{+(d)} - \frac{1}{\eta} \cdot P_{ESS,h}^{-(d)} \right\} \quad (3.6)$$

$(SOC_1 = SOC_{48})$

where $P_{ESS,h}^{+(d)}$, $P_{ESS,h}^{-(d)}$, $SOC_h^{(d)}$, and η are charging power of ESS [kW], discharging power of ESS [kW], state of charge, and the total efficiency of ESS (one-way) respectively.

Characteristics of chiller system

The power consumption of chiller system is simply formulated as the following linear function.

$$P_{Chiller,h}^{(d)} = A \cdot d_{c,h}^{(d)} \cdot \frac{30}{60} + B \quad (3.7)$$

where A , $d_{c,h}^{(d)}$, and B are power variation of chiller system according to a unit temperature variation [kW/deg-C], hourly temperature variation by chiller system [deg-C/h], and minimum chiller system operation power [kW] respectively.

Dynamics of indoor temperature

Indoor temperature in a COB is varied by a first order difference equation in (3.8) and (3.9). That is, the hourly temperature variation by chiller system is determined based on day-ahead forecasting temperatures under all DR event scenarios. Variation range of indoor temperature in (3.10) is set based on the thermal comfort of ASHRAE in summer season.

$$T_{in,h+1}^{(d,k)} = T_{in,h}^{(d,k)} + \frac{30}{60} \cdot (d_{u,h}^{(d,k)} - d_{c,h}^{(d)}) \quad (3.8)$$

$$d_{u,h}^{(d,k)} = \frac{(T_{o,h}^{(k)} - T_{in,h}^{(d,k)})}{\tau_T} \quad (3.9)$$

$$T_{in}^{min} \leq T_{in,h}^{(d,k)} \leq T_{in}^{max} \quad (3.10)$$

where k , $T_{in,h}^{(d,k)}$, $T_{o,h}^{(k)}$, $d_{u,h}^{(d,k)}$, and τ_T are index for day-ahead forecasting temperature scenarios, indoor temperature [deg-C/h], ambient temperature [deg-C/h], hourly temperature variation caused by heat-penetration through the building walls [deg-C/h], and thermal flywheel factor respectively.

Here, the day-ahead forecasting temperature provided by the national weather service in the

Korea is used as a medium temperature scenario. And then, a medium temperature scenario with $\pm 3\%$ mean absolute percentage errors (MAPE) are also applied in the day-ahead scheduling, called high and low temperature as scenarios.

DR requirement and CBL constraints

When a DR event happens, End-users should reduce their electricity consumptions as much as 100 [%] reduction of the contracted DR capacity based on upper and lower bound constraints in (3.11).

$$0.8 \cdot P_{DR} \leq P_{CBL,h} - P_{Utility,h}^{(d)} \leq 1.2 \cdot P_{DR} \quad (3.11)$$

$$\left(h_{DRS}^{(d)} \leq h \leq h_{DRE}^{(d)}, d \neq 0 \right)$$

where P_{DR} is requested load reduction [kW].

Consistency before DR event notification

The end-user only changes the DR resource (chiller system and ESS) operations after the DR event notification comes; that is, the DR resource operations before the DR notification must be same as follows.

$$P_{Chiller,h}^{(d)} = P_{Chiller,h}^{(5)} \quad (h < h_{DRS}^{(d)}, d \neq 0) \quad (3.12)$$

$$P_{ESS,h}^{(d)} = P_{ESS,h}^{(5)} \quad (h < h_{DRS}^{(d)}, d \neq 0) \quad (3.13)$$

Capacity limit constraints

The capacity constraints for utility company and chiller system are represented in (3.14) and (3.15) respectively. The maximum charging or discharging power of ESS are limited by the maximum ESS power as shown in (3.16) and (3.17) respectively. Battery energy stored cannot exceed the maximum storage capacity in (3.18).

$$0 \leq P_{Utility,h}^{(d)} \leq P_{Utility}^{max} \quad (3.14)$$

$$P_{Chiller}^{min} \leq P_{Chiller,h}^{(d)} \leq P_{Chiller}^{max} \quad (3.15)$$

$$P_{ESS,h}^{-(d)} \leq P_{ESS}^{max} \cdot \mu_h^{(d)} \quad (3.16)$$

$$P_{ESS,h}^{+(d)} \leq P_{ESS}^{max} \cdot (1 - \mu_h^{(d)}) \quad (3.17)$$

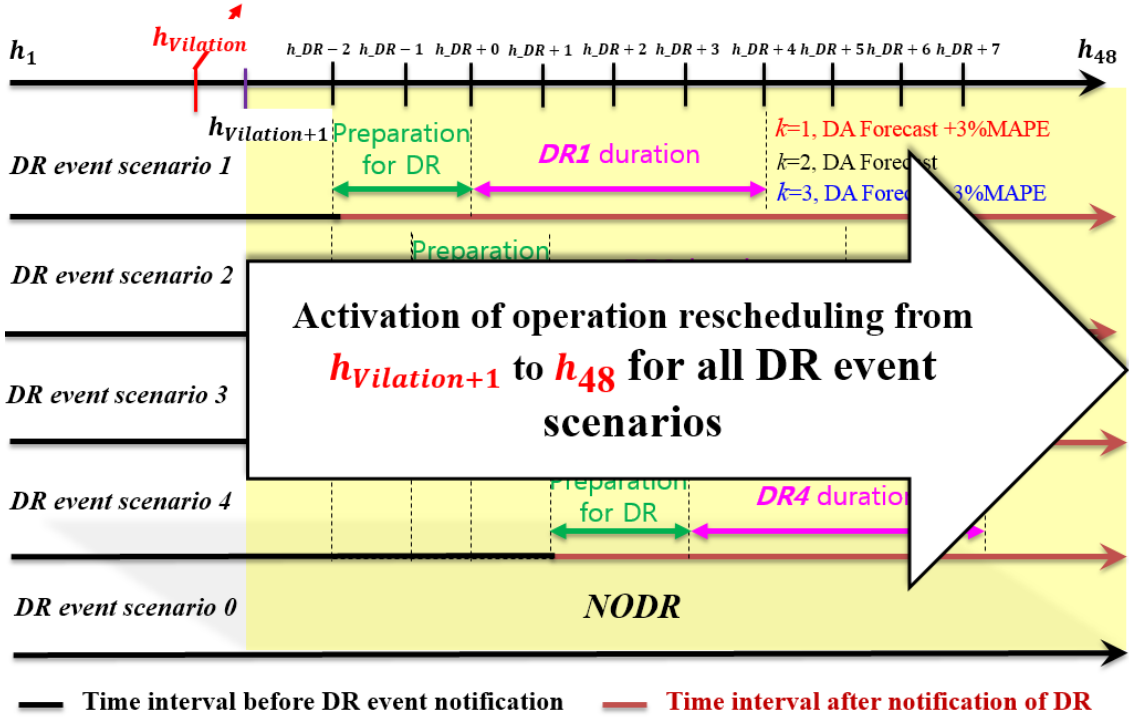
$$SOC^{min} \leq SOC_h^{(d)} \leq SOC^{max} \quad (3.18)$$

where $\mu_h^{(d)}$ is binary variables specifying ESS operation mode (charge = 0 or discharge = 1).

3.3.3 Operation rescheduling on D-day

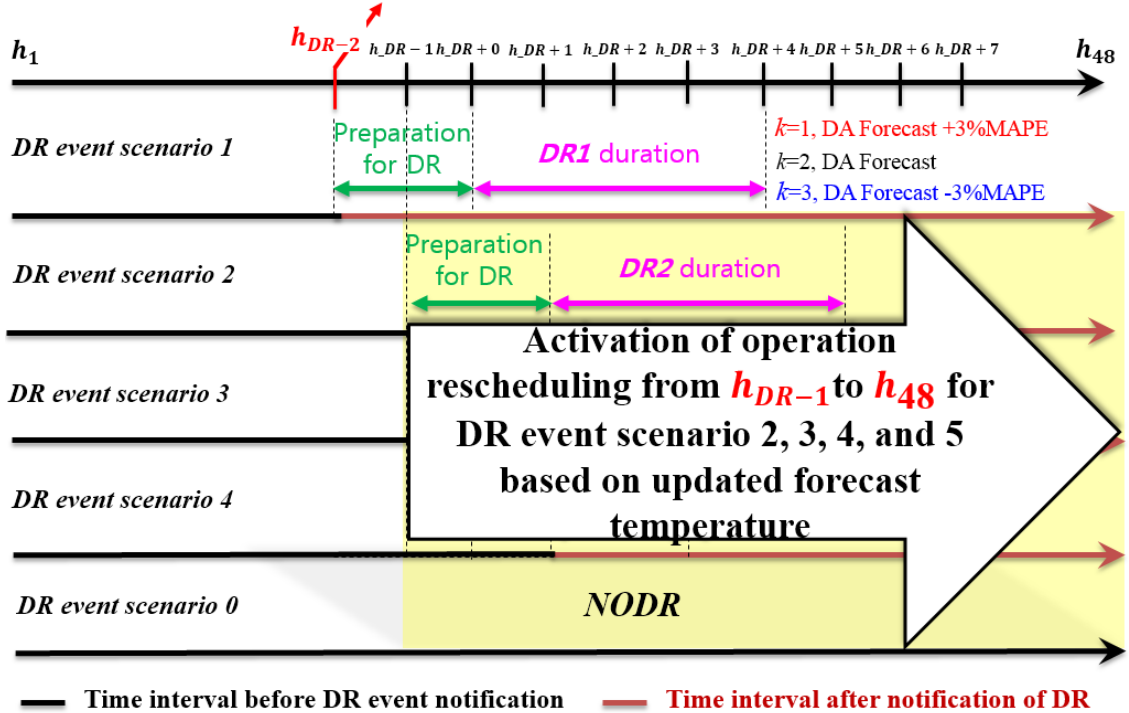
When the indoor temperature violates and is leaving from the thermal comfortable range, the rescheduling process is activated and the DR resource operations defined by the day-ahead

The time occurred to violation of thermal indoor temperature on D-day

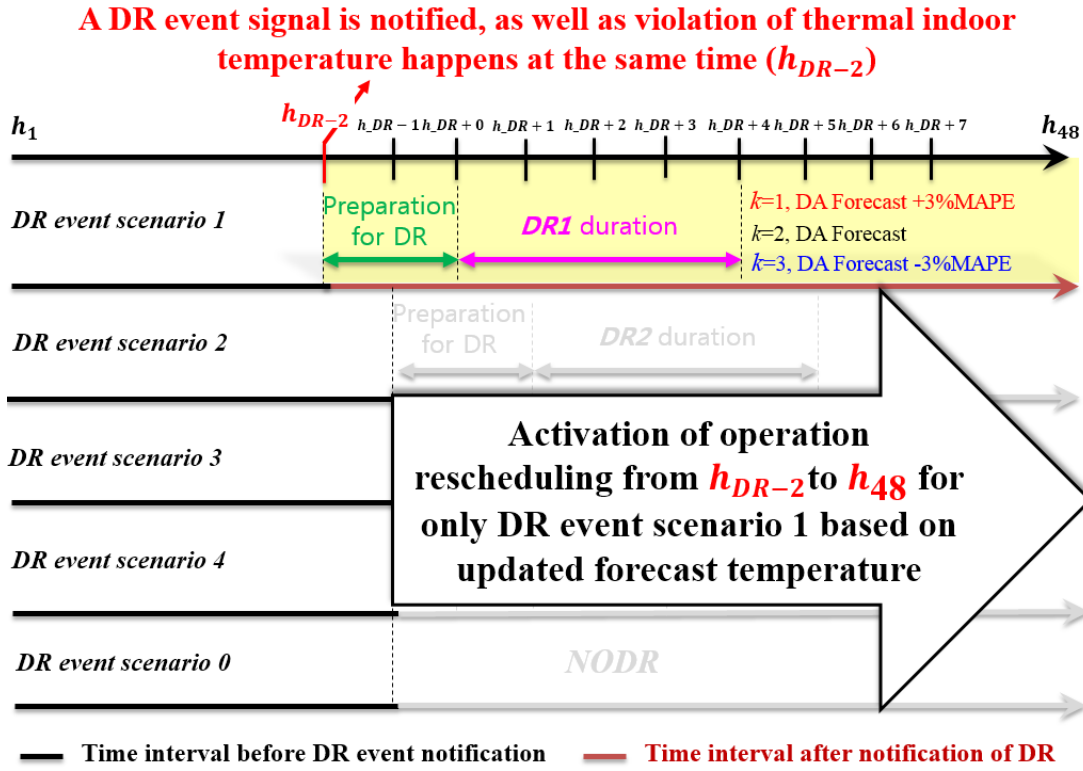


(a) Violation of thermal comfortable before DR event scenarios

The time occurred to violation of thermal indoor temperature on D-day



(b) Violation of thermal comfortable after DR event scenario



(a) Violation of thermal comfortable after DR event scanrio

Figure 3.4: Concept of operation rescheduling on D-day

scheduling is revised based on the updated ambient temperature forecast on D-day. The proposed rescheduling process is almost same as the day-ahead scheduling with temperature forecast error, except the targeted time intervals; in the rescheduling process just focuses on the intervals from the current one to the end of the D-day. More specifically, the proposed operation rescheduling on D-day deals with three main probabilistic cases as shown in Fig. 3.4 (a), (b), and (c). First, if deterioration in thermal comfort occurs at $h_{vilation}$ as shown in Fig. 3.4 (a), the operation on D-day is rescheduled for the all DR event scenarios from $h_{vilation+1}$ to h_{48} based on recent temperature forecast. Second, if uncomfortable indoor temperature happen at h_{DR-2} as shown in Fig. 3.4 (b), the rescheduling is only activated for DR event scenario 2, 3, 4, and 5. Finally, if a DR event signal is notified, as well as violation of thermal indoor temperature happens at the same time (h_{DR-2}) as shown in Fig. 3.4 (c), the operation of DR event scenario 1 scheduled in the day ahead is only activated and rescheduled considering both of maximum DR reward and thermal comfortable indoor temperature.

3.4 Simulation Results (Day-ahead operation scheduling)

This section presents review for day-ahead operation scheduling that ascertain through case studies. By employing the proposed operation scheduling, a problem for temperature forecast error was effectively overcome under uncertain DR environments and there are verified in the following

3.4.1 Simulation conditions

The proposed DR management algorithm for day-ahead operation scheduling with temperature forecast error is applied to a COB model with 500 [kW] chiller system and 1,000 [kW]/2,000 [kWh] ESS (Lithium-ion battery). Single daily load pattern is assumed for the electricity demand in a COB except ESS and chiller system as shown in Fig. 3.5. Other assumptions for simulation are almost same as Table 3.2. Assumed DR event scenarios are same as Table 3.3. Fig. 3.6 shows the forecasted ambient temperature profiles for the day-ahead operation scheduling as scenarios. That is, day-ahead forecast temperature becomes a medium temperature scenario. And then, two temperature scenarios generated by a medium temperature scenario with $\pm 3\%$ mean absolute percent error (MAPE) was applied to overcome day-ahead forecast error on D-day. The thermal comfort is originally specified as 22.0 - 24.0 [deg-C] by the American Society of Heating, Refrigerating and Air Conditioning Engineers [16]. In this paper, narrower thermal comfort is applied as 22.4 - 23.6 [deg-C] considering 0.4 [deg-C] margins, which is set as maximum possible margins for chiller system operation to be robust the thermal comfort.

Table 3.2: Simulation parameters

$U_{T,h}$	10:30 ~ 12:00, 13:30 ~ 17:00	293.8 KRW/kWh
	23:00 ~ 9:00	56.2 KRW/kWh
	Otherwise	108.5 KRW/kWh
A, B	290 kW/deg-C, 110 kW	
τ_T	11.2	
η	80 %	
$P_{Utility}^{max}$	3,000 kW	
SOC^{min}, SOC^{max}	200 kWh, 1800 kWh	
$P_{Chiller}^{min}, P_{Chiller}^{max}$	139, 500 kW	
$T_{in}^{min}, T_{in}^{max}$	22, 24 deg-C	
$U_{E,h}$	550 KRW/kWh	
P_{DR}	200 kW	

Table 3.3: Assumed DR event scenarios

DR scenario	Duration	Requested curtailment	Occurrence probability
1	13:30-15:30	100%	0.1
2	14:00-16:00	100%	0.1
3	14:30-16:30	100%	0.1
4	15:00-17:00	100%	0.1
5	N/A	0%	0.6

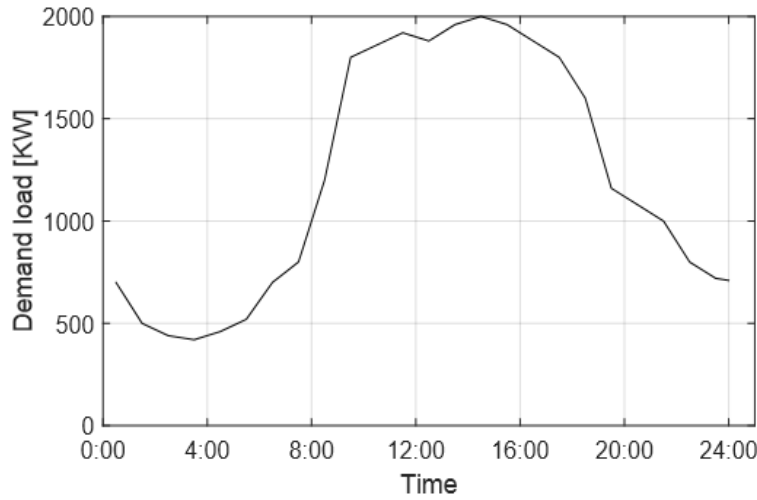


Figure 3.5: Daily load data of a COB excluding chiller system and ESS

3.4.2 Obtained simulation results (W/O proposed)

We ascertained the validity of the proposed operation scheduling through case studies. The simulation result consists of two parts: day-ahead temperature forecast as shown in Fig. 3.6 (a) only considered for operation scheduling and assumed actual temperature loci as a day-ahead forecast +3% MAPE was applied to the previous simulation result. Fig. 3.7 (a) shows simulation results for day-ahead operation scheduling applied with DR scenario 1 ($d = 1$) and a day-ahead temperature forecast ($k = 2$). Obtained optimal operations of electricity demand excluding chiller system and ESS (gray bar), power consumed by chiller system (orange bar), net charging or discharging power (red or blue bar), state of charge (purple solid line), and customer baseline load (pink line), and indoor temperature (black dotted line) were summarized respectively.

In this case, day-ahead operation scheduling for chiller system and ESS was optimized for minimal energy cost until 12:30 (before DR happen). When an event DR signal was notified to the DR participant at 12:30, chiller system consumed the maximum power consumption as 500 [kW] for acquiring a DR resource as pre-cooling during preparation for DR (12:30-13:30). ESS was also charged as the maximum power output until SOC is charged up 100% in the same time. Then, chiller system consumed at 139 [kW] as the minimum power output for DR contribution during the DR duration. Moreover, ESS was concentrated to discharge up to 630 [kW] during the specified DR duration. Total amount of load reduction was calculated that customer baseline load (CBL) minus power purchased from utility company during DR duration. As a result, average load reduction was obtained 240 [kW] as the maximum value constrained maximum fulfillment rate as 120% in (3.11). Since the cooperation between chiller system as pre-cooling and ESS as discharge affected to make higher DR reward. It was found that resultant indoor temperatures was maintained within thermal comfort range regardless of the DR event.

On the other hand, we applied an actual temperature loci as a day-ahead forecast +3% MAPE ($k = 1$) on D-day and applied to the previous simulation results in Fig. 3. 7 (a). Obtained operation

scheduling of chiller system and ESS was same as the previous simulation results as shown in Fig. 3. 7 (b). However, the resultant indoor temperature was exceeded the set thermal comfort range (22.4 [deg-C] - 23.6[deg-C]) from 0:00-7:00 and 14:30-24:00. This is because the forecast error on D-day affected to the day-ahead operation scheduling. Therefore, power consumption of chiller system and ESS should be considered the forecast error on-Day for the constrained thermal comfort range, minimal energy cost, and maximum DR reward.

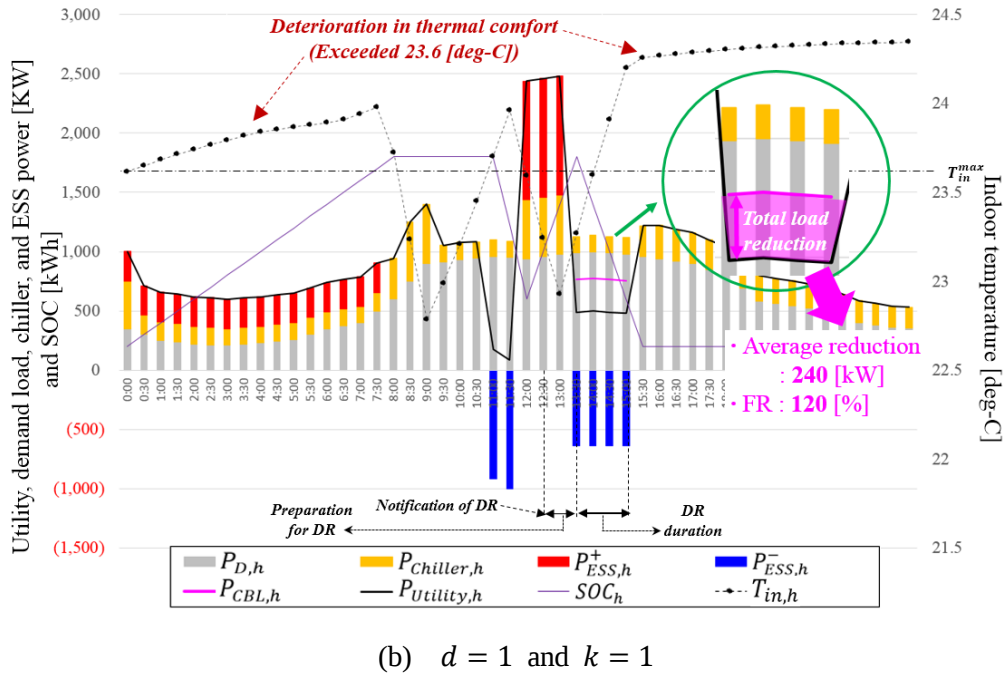
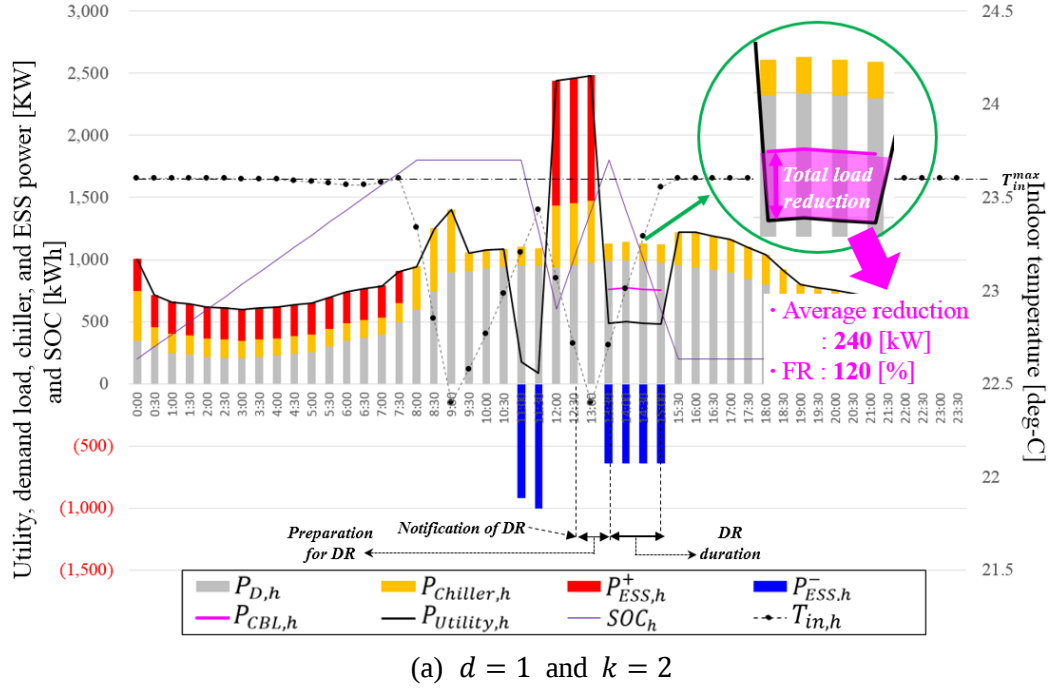


Figure 3.7: Obtained optimal operations for day-ahead scheduling (Conventional)

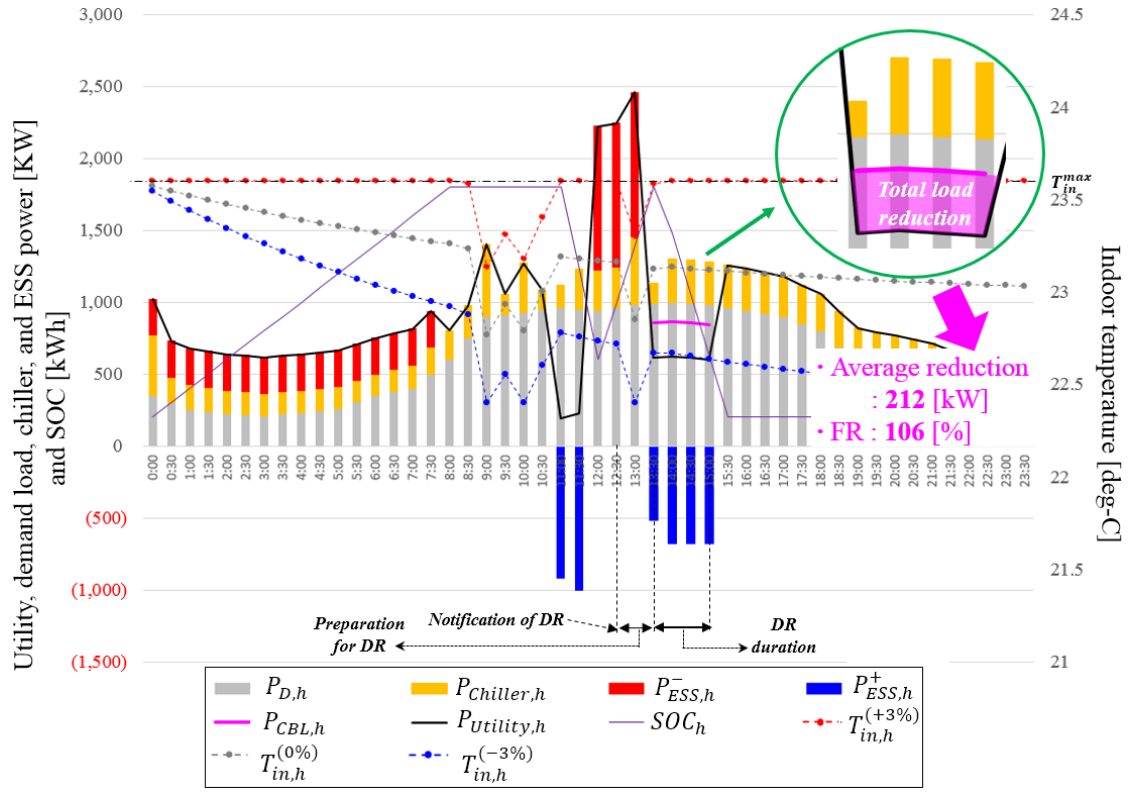
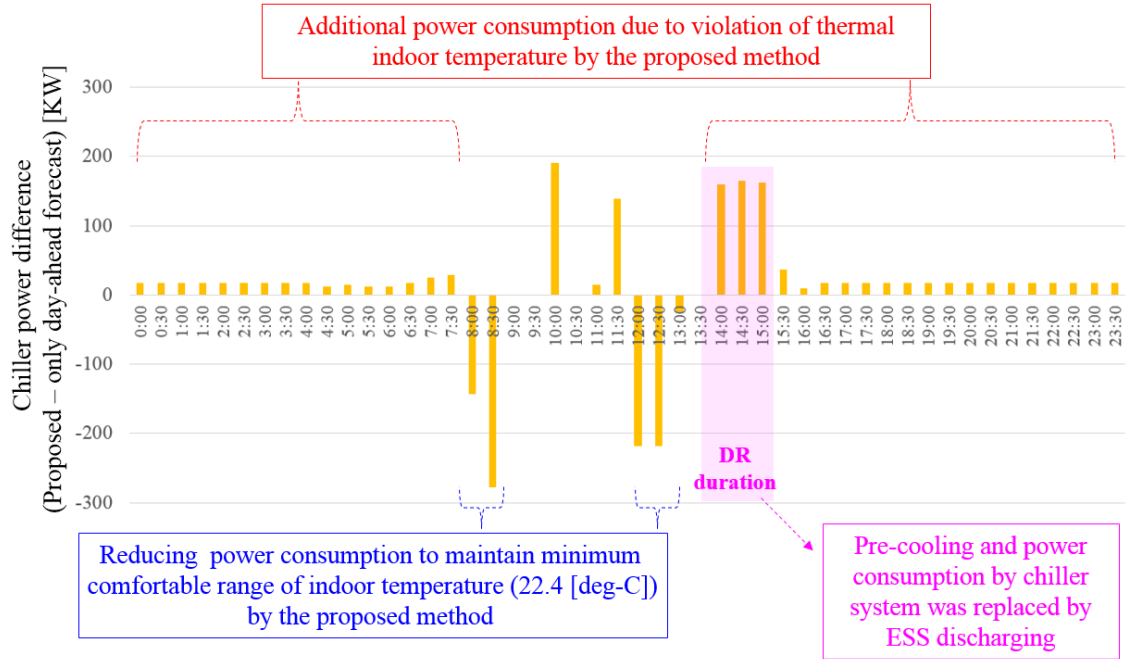


Figure 3.8: Obtained optimal operations for day-ahead scheduling (Proposed)

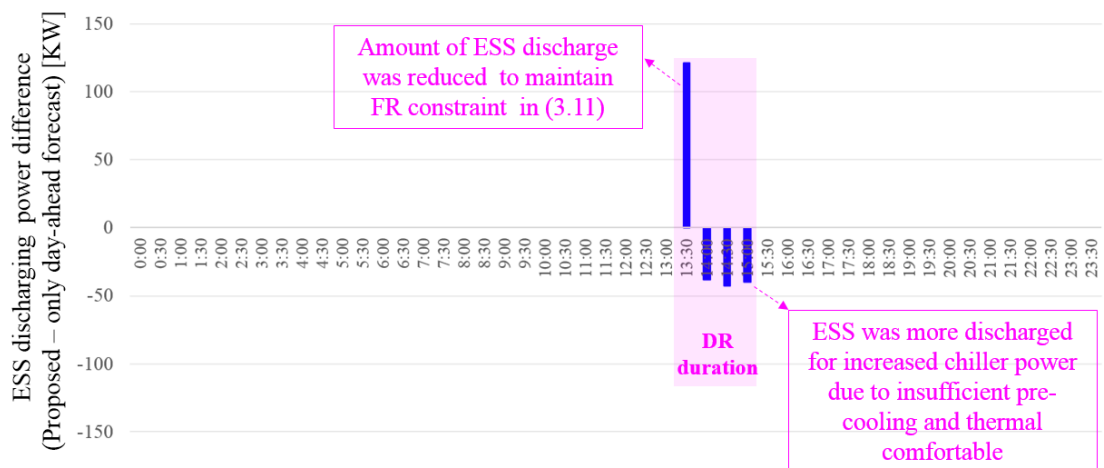
3.4.3 Obtained simulation results (W/ proposed)

Fig. 3.8 shows simulation results for day-ahead operation scheduling by the proposed method. As shown in this Figure, three optimized resultant indoor temperature (red, gray, and blue dotted lines) under the three ambient temperature scenarios specified by “DA forecast” and “DA forecast $\pm 3\%$ MAPE” shown in Fig. 3.6 were represented. The proposed DR operation scheduling using by chiller system and ESS in day-ahead was obtained for the DR event scenario 1 to compare with the simulation results in Fig. 3.7 (b). In proposed operation scheduling, the operations of chiller system were optimized considering both of TOU tariff and three day-ahead forecast temperature scenarios before a DR event happened until 12:30. In this period, three resultant indoor temperatures were maintained with the set thermal comfort range. Since amount of power consumption by chiller system was optimized by the three day-ahead forecast temperature scenarios. ESS charge or discharge rate and time interval was optimized for minimal energy cost under TOU tariff until a DR event is notified. When the DR event signal was notified at 12:30, ESS was charged up to 100% of SOC during preparing for DR and discharged for maximum DR reward during the DR duration. Average load reduction was obtained 212 [kW], in which the value is smaller than the result in Fig. 3.7 by 28 [kW]. Because chiller system was more consumed to maintain comfortable indoor temperature during 0:00-7:00 and 14:00-23:00, As well as the DR duration as shown in Fig. 3.9 (a). Meanwhile, power consumed by chiller system was increased

during DR duration. This is because Pre-cooling and power consumption by chiller system was replaced by ESS discharging during DR duration as shown in Fig. 3.9 (b). That is, ESS was more discharged to obtain as possible as maximum DR reward due to reduced amount of chiller power caused by insufficient pre-cooling and thermal comfortable during DR duration. As a result, the proposed operation scheduling not only can obtain as possible as maximum DR reward by cooperation between chiller system and ESS regardless of DR event, but also can enhance the robustness and effectiveness of the temperature forecast error on D-day



(a) Chiller power difference

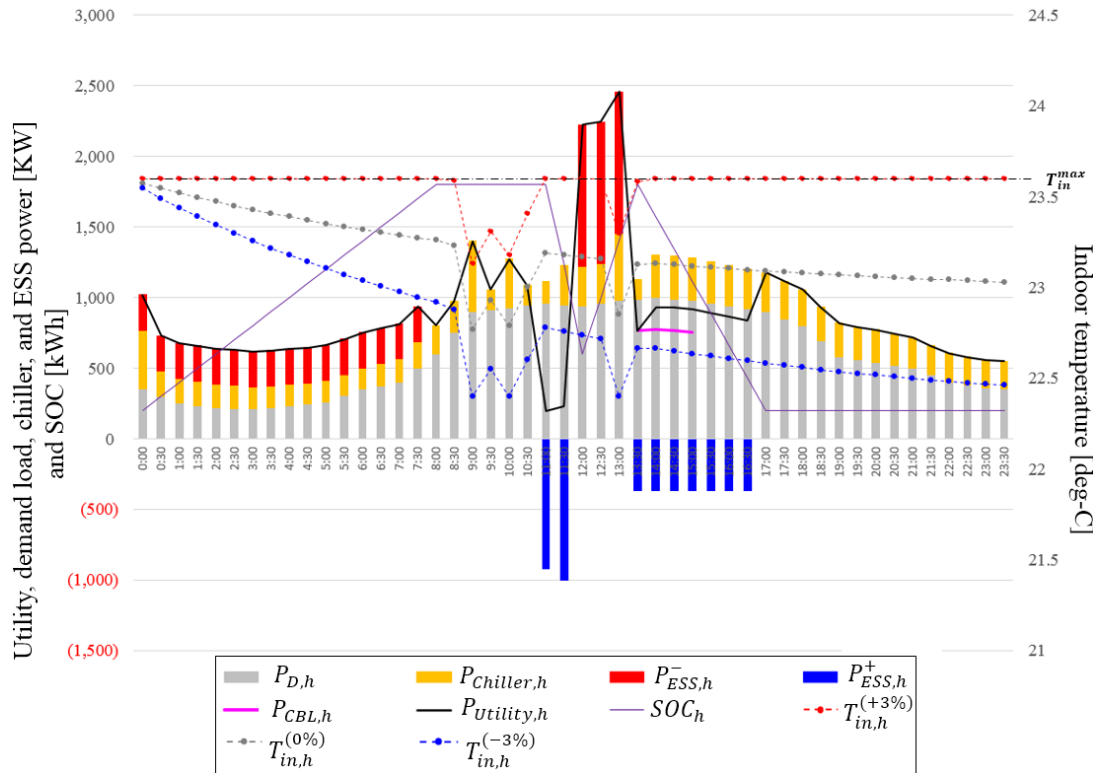


(b) ESS discharging difference

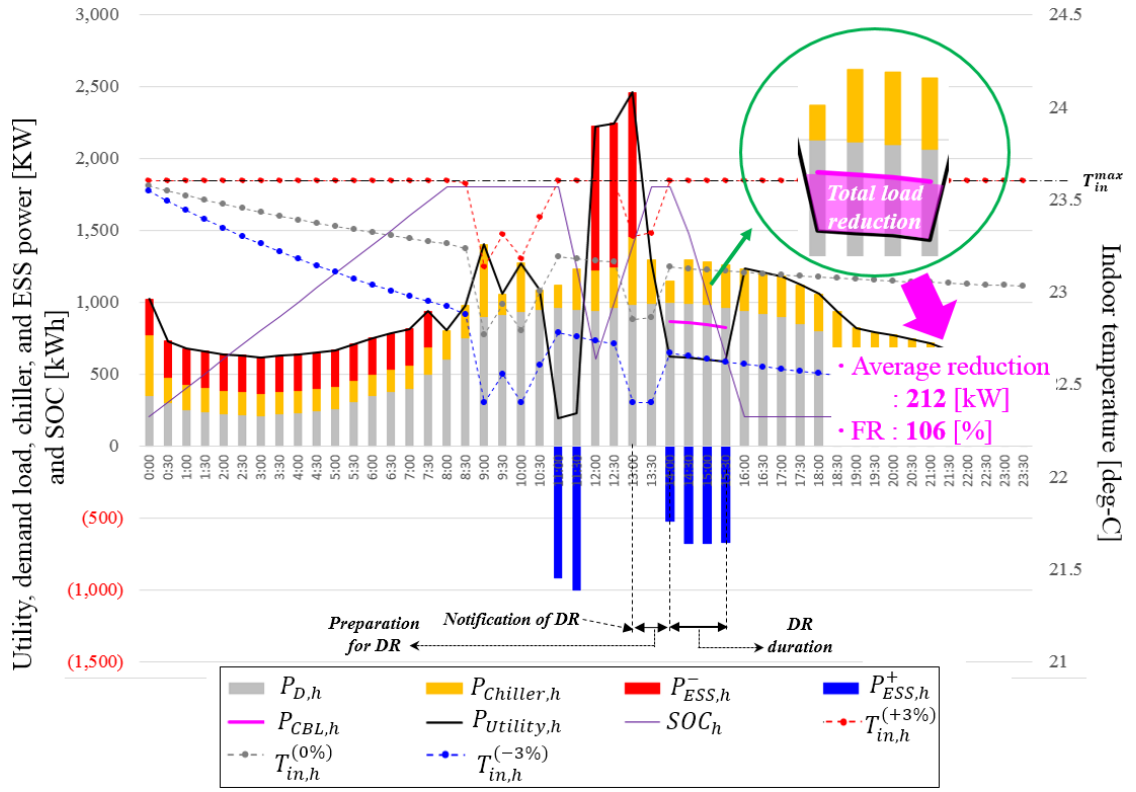
Figure 3.9: Analyses of obtained power consumption by the proposed method
(Proposed - Conventional)

Other proposed optimal operations were scheduled for the DR event scenario 0 (W/O DR), 2, 3, and 4 (W/ DR) as shown in Fig. 3.10 (a), (b), (c), and (d) respectively. In DR scenario 0 (W/O DR), ESS was discharged (blue bar) during 11:00 - 12:00 and 13:30 - 17:00 since the highest TOU tariff was applied in this period. The operation of chiller system (orange bar) was scheduled based on TOU tariff, as well as the day-ahead forecast scenario and the forecast scenario with $\pm 3\%$ MAPE. Pre-cooling by chiller system was not happened in the scenario case. Three resultant indoor temperatures were maintained within the thermal comfort range (between 22.4 [deg-C] and 23.6 [deg-C]) as shown in Fig. 3.10 (a).

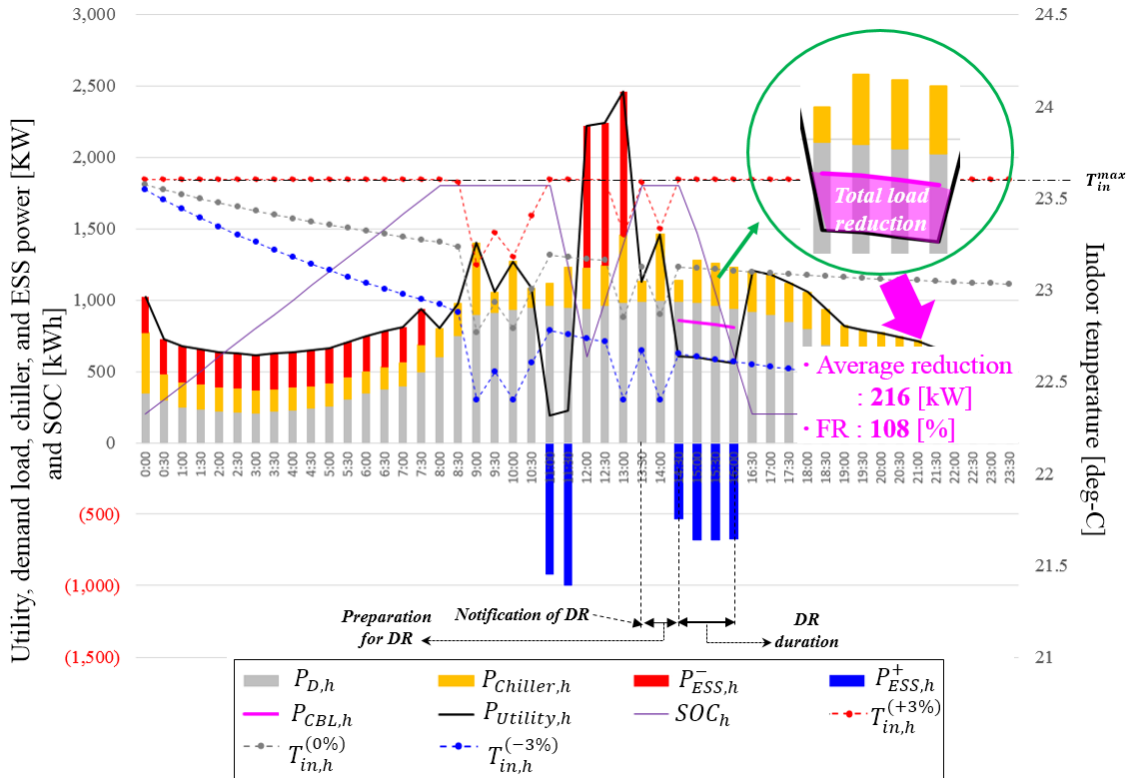
In DR scenario 2, operation of chiller system was different among the above two scenarios; pre-cooling was achieved from 13:00 to 14:00 in which the chiller more consumed by 290 [kW] (increased from 139 [kW] to 429 [kW]). This is because the incentive price for the energy actually reduced (kWh) is higher than the highest TOU tariff. This is, the pre-cooling by chiller system was achieved considering both of minimal energy cost and DR during preparation for DR. Three resultant indoor temperatures were still sustained within the comfort range regardless of pre-cooling and the DR event. Thus, chiller system consumed minimal power consumption from 14:00 to 16:00. Then, ESS was intensively discharged for maximum DR reward based on requested curtailment during DR duration. Average load reduction for two hours was obtained as 212 [kW] by cooperation between pre-cooling of chiller system and discharging of ESS. In DR scenario 3 and 4, the optimal operation features obtained by the proposed method were same as DR scenario 2 as shown in Fig. 3.10 (c) and (d).



(a) In DR scenario 0



(a) In DR scenarios 2



(c) In DR scenarios 3



Fig. 3.10: Other obtained day-ahead operation scheduling by the proposed method

3.4.4 The main advantages of the proposed method

Three simulation cases shown in Table 3.4 were modeled to evaluate the proposed method. More specifically, optimal operations of chiller system and ESS were only executed by TOU tariff in Case 1. (A comparison group). In Case 2, chiller system was optimally scheduled considering both of TOU tariff and the Korean DR market. However, operation of ESS was only calculated considering TOU tariff. More specifically, first the optimal operation of ESS was calculated, in which a daily energy cost purchased from the utility becomes minimum considering TOU prices. Next, on fixing the operation of ESS, the optimal operation of chiller system was calculated considering both of the DR market and TOU prices. In Case 3, operations of chiller system and ESS were scheduled considering TOU tariff and the Korean DR market by the proposed day-ahead method.

The existence of a feasible solution by the waiting DR capacity

Optimal solution for maximum possible waiting DR capacity is determined by the previous section 3.3.3. We confirmed the existence of feasible solution using by a verify waiting DR capacity. When 40 [kW] of the waiting DR capacity is applied to Case 2 (Conventional) and 3 (proposed). In case 2, the feasible solution was not found in the formulation 3.3.2. Since 40 [kW] of the waiting

Table 3.4: Simulation cases under DR resource category

DRR Category		Simulation Case		
		1	2	3
Chiller system	TOU tariff	○	○	○
	DR market	X	○	○
ESS	TOU tariff	○	○	○
	DR market	X	X	○

DR capacity was allocated more than proper DR capacity in Case 2 as shown in Fig. 3.11 (a). In other words, there wasn't existed the feasible solution to satisfy the DR requirement constraint in (3.11). However, in Case 3, the feasible solution is obtained and then optimal operation scheduling of chiller system and ESS was determined. This is because enough amount of ESS discharge was contributed to satisfy the constraint in (3.11) and to replace insufficient DR contribution in Case 2 as shown in Fig. 3.12 (c). As obtained the simulation results, we can know that determination of optimal waiting DR capacity is very important directly impact on DR reward and DR penalty. This reasonable DR capacity should be determined in the chapter 4.

The existence of a feasible solution by the day-ahead forecast error margin

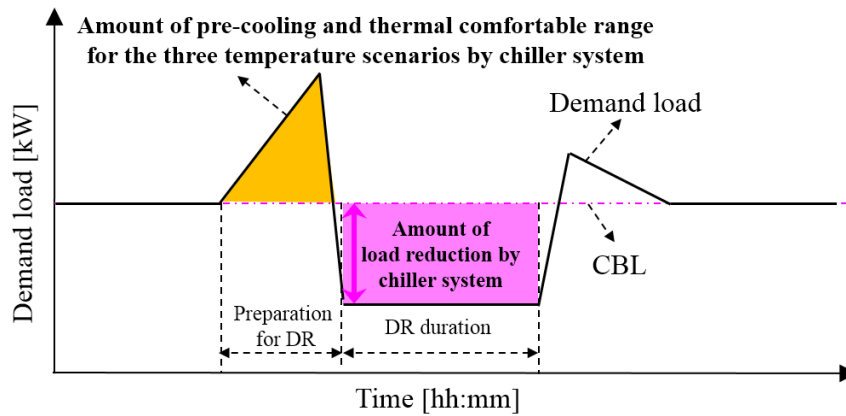
We estimated the day-ahead forecast error margin using the proposed method. More specifically, the waiting DR capacity as 40 [kW] in the previous section was fixed, and the day-ahead forecast error margin was increased up to $\pm 4\%$ MAPE based on the day-ahead forecast. Simulation result whether the feasible solution exists were Table 3.5. As a result, the feasible solution existed until $\pm 2\%$ of the forecast error margin in Case 2 and 3. Because temperature forecast error range impacts on amount of power consumption of chiller system. For example, chiller consumes little power when the forecast error range is narrow or otherwise. That is, the reduced amount of chiller's consumption for thermal comfortable range less than $\pm 2\%$ of the forecast error margin case, can be contributed by DR means of pre-cooling as shown in Fig. 3.11 (a) and (c). However, reduced of pre-cooling by chiller system caused by wide forecast error margin ($\pm 3\%$ MAPE) happened during preparation for DR. Then, amount of load reduction by chiller system was not sufficient for DR contribution and couldn't find a feasible solution which satisfied the DR requirement and CBL constraints in (3.11).

On the other hands, when ESS is applied for DR operation in Case 3 (Proposed), chiller only consumed for thermal comfortable range by wide forecast error margin ($\pm 3\%$ MAPE) during preparation for DR. Then, insufficient load reduction in wide forecast error margin ($\pm 3\%$ MAPE) was fully replaced by ESS discharging. This is because ESS has enough amount of discharging over than 40 [kW] of the waiting DR capacity. That is, ESS would enhance the possibilities for uncertain forecasting error on D-day using the proposed scenarios planning.

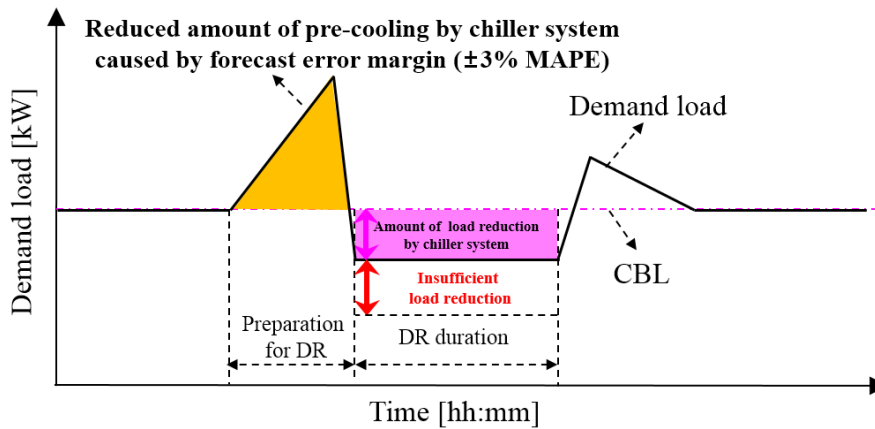
In case of $\pm 4\%$ MAPE of forecast error margin, there are not existence of feasible solutions both of Case 2 and Case 3. Since the power consumption of chiller system was not insufficient for thermal indoor comfort. Then, the constraint of upper and lower bounds for indoor temperature in (3.8) was not satisfied during the DR duration. Therefore, the proposed ESS utilization for DR would support scalable and flexible solutions to uncertain forecast error on D-day. Accuracy to determine forecast error margin can be set by historical analysis of weather forecasting data.

Table 3.5: Simulation results for ESS enhancing to day-ahead forecasting temperature forecasting error.

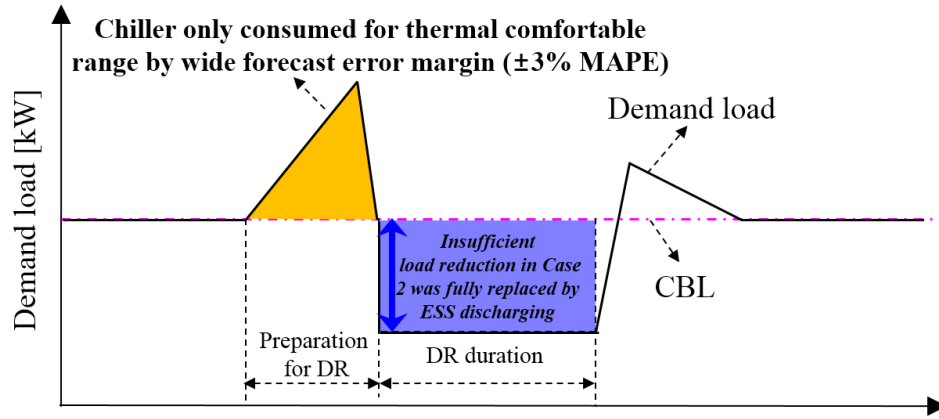
DRR Category	Simulation Case (Day-ahead forecasting temperature with MAPE)			
	$\pm 1\%$	$\pm 2\%$	$\pm 3\%$	$\pm 4\%$
Only chiller system (Case 2)	O	O	X	X
Chiller system and ESS (Case 3)	O	O	O	X



(a) Analysis of the existence of a feasible solution in Case 2



(b) Analysis of infeasible solution in Case



(a) Analysis of feasible solution in Case 3

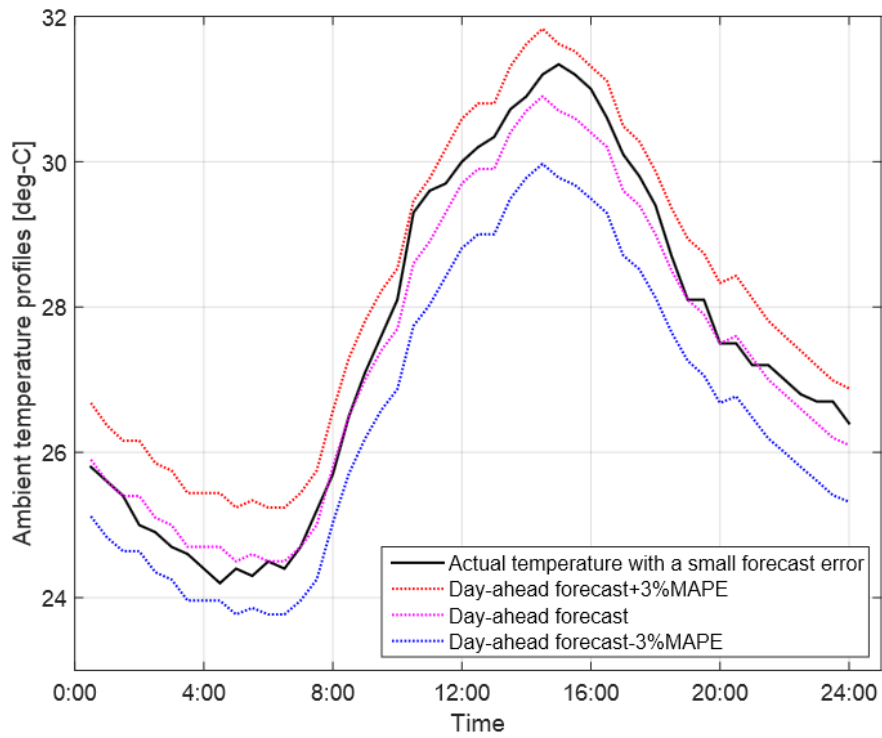
Fig. 3.11: Analysis of obtained power consumption of chiller system considering both of pre-cooling for DR and thermal comfort for the three temperature scenarios

3.5 Simulation Results (Operation rescheduling on D-day)

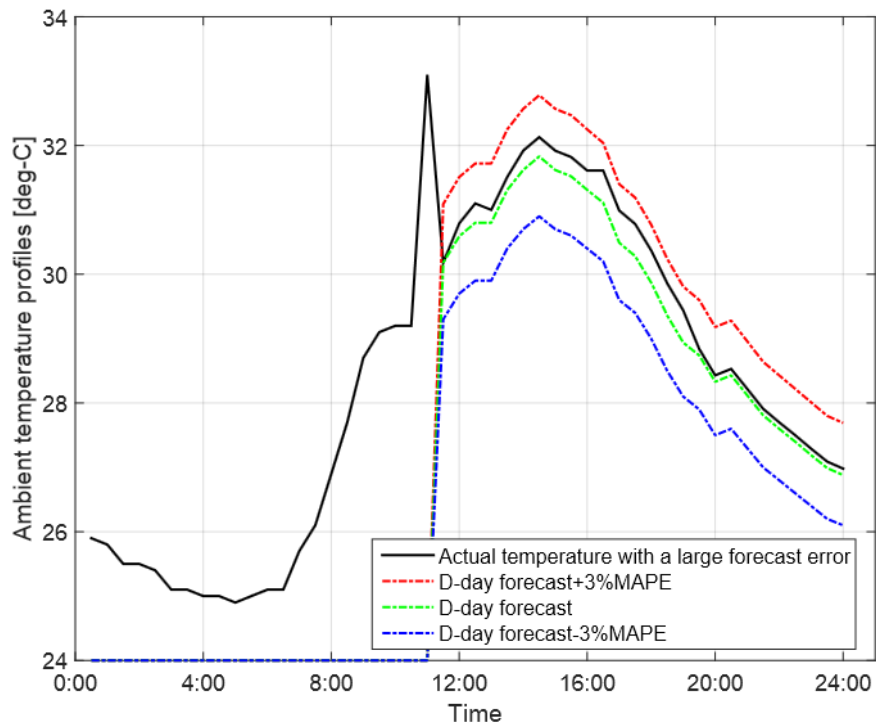
This section concerned with the effectiveness of the development operation rescheduling on D-day itself. The proposed method helps the DR participant to find the point of uncomfortable indoor temperature for the process. Specifically, it aids in maintaining thermal comfort for occupants of buildings by updated ambient temperature forecast on D-day.

3.5.1 Simulation conditions

Two types of the actual ambient temperature shown in Fig. 3.12 are prepared for evaluation the D-day operation rescheduling. Actual ambient temperature with a small forecast error was included within day-ahead forecasting temperature scenarios with $\pm 3\%$ MAPE (Actual T1) as shown in Fig. 3.12 (a). Other actual temperature with a large forecast error was exceeded the set forecast error range (Actual T2) as shown in Fig. 3.12 (b). More specifically, the actual ambient temperature on D-day was rapidly increased at 10:30 and then, exceeded the day-ahead forecasting ambient temperature with $+3\%$ MAPE at 11:00. The proposed rescheduling process was evaluated with the updated three ambient temperatures specified by “D-day forecast” and “D-day forecast $\pm 3\%$ MAPE” from 11:30 on D-day. Simulation results of chiller system and ESS were obtained under mentioned above two type of actual ambient temperatures in the following.



(a) In case of actual temperature with a small forecast error



(b) In case of actual temperature with a large forecast error

Fig. 3.12: Temperature profiles for operation rescheduling

3.5.2 Obtained optimal operation rescheduling on D-day

When applying the actual temperature with a small forecast error (Actual T1) shown in Fig. 3.12 (b), rescheduling process was not happened on D-day. Because a resultant indoor temperature (a black dotted line) was maintained within the comfort range as shown in Fig. 3.13. That is, the actual ambient temperature can be covered by the temperature scenarios assumed in the day-ahead scheduling. In other words, power consumption of chiller system was only scheduled based on the three temperature scenarios and its consumption was enough to cover the actual temperature (Actual T1) in the scenario 0 (NODR). Then ESS operation with the time and rate of charging or discharging was not depend on the actual temperature, the operation was charged or discharged by the TOU tariff.

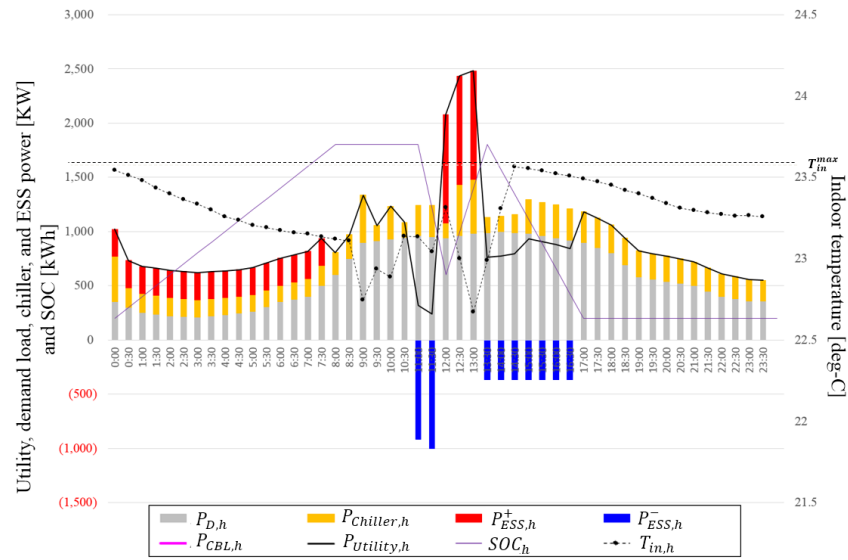


Fig. 3.13. Obtained optimal operations rescheduling on D-day (Applied with Actual T1)

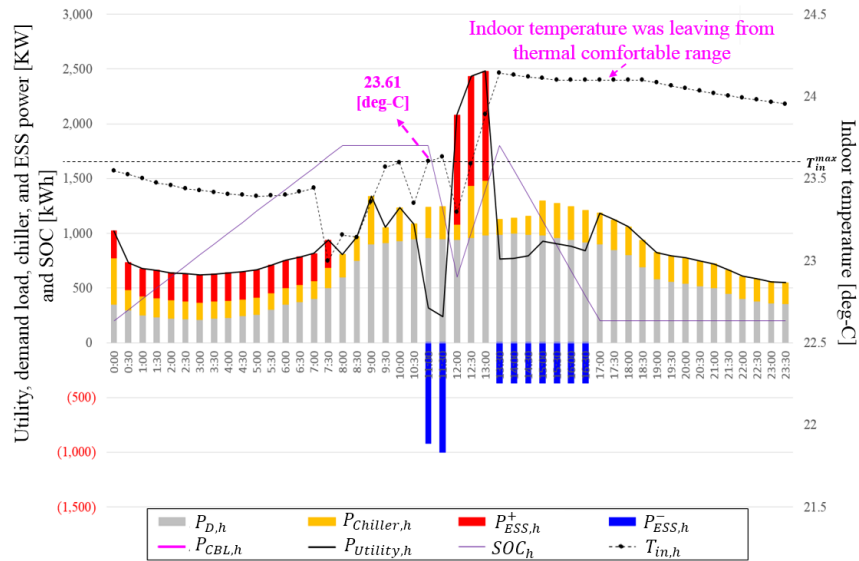


Fig. 3.14: Obtained optimal operations rescheduling on D-day (Applied with Actual T2)

On the other hand, when the other actual temperature (Actual T_2) is largely different from the forecasted scenarios, the resultant indoor temperature was violated the upper narrower comfort range (23.6 [deg-C]) at 11:00 as shown in Fig. 3.14. Further, it was over than 24 [deg-C] from 13:00. This would be disadvantaged to DR market participants such as losing work efficiency, decreasing reward for DR, and increasing DR penalty threat. Therefore, the rescheduling should be activated and the DR schedules should be revised by the proposed method. Fig. 3.15 shows obtained simulation results applied with the actual temperature (Actual T_2). The operation of chiller system and ESS was not changed before the set comfortable temperature range is exceeded until 11:00. Resultant indoor temperature was increased up 23.61 [deg-C] at 11:00. Therefore, the operation rescheduling was activated and power consumption of chiller system was increased based on the mentioned three temperature scenarios (“D-day forecast” and “D-day forecast $\pm 3\%$ MAPE”) as shown in Fig. 3.13 (b). As a result, chiller system was concentrically more consumed for comfortable temperature range from 11:30 - 12:30 as shown Fig. 3.16. Finally, resultant indoor temperature was effectively maintained within the comfortable range. As a result, the anticipated temperature loci can be maintained within the thermal comfort. On the other hand, DR contribution using by chiller system and ESS was stably obtained after rescheduling as shown in Fig. 3. 17. Average load reduction was 208 [kW]. Insufficient pre-cooling by chiller power was replaced by ESS discharge during DR duration. Therefore, the proposed operation rescheduling can be robust for thermal comfortable indoor temperature and maximum DR reward regardless of DR events.

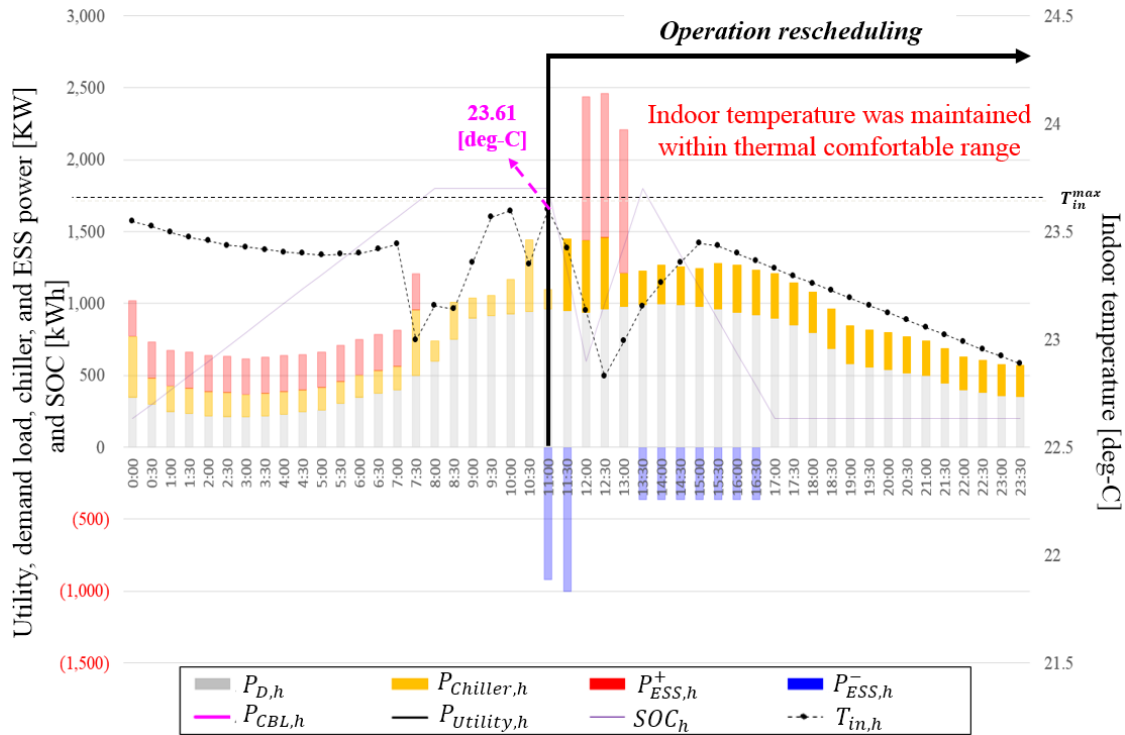


Fig. 3.15: Obtained operation rescheduling

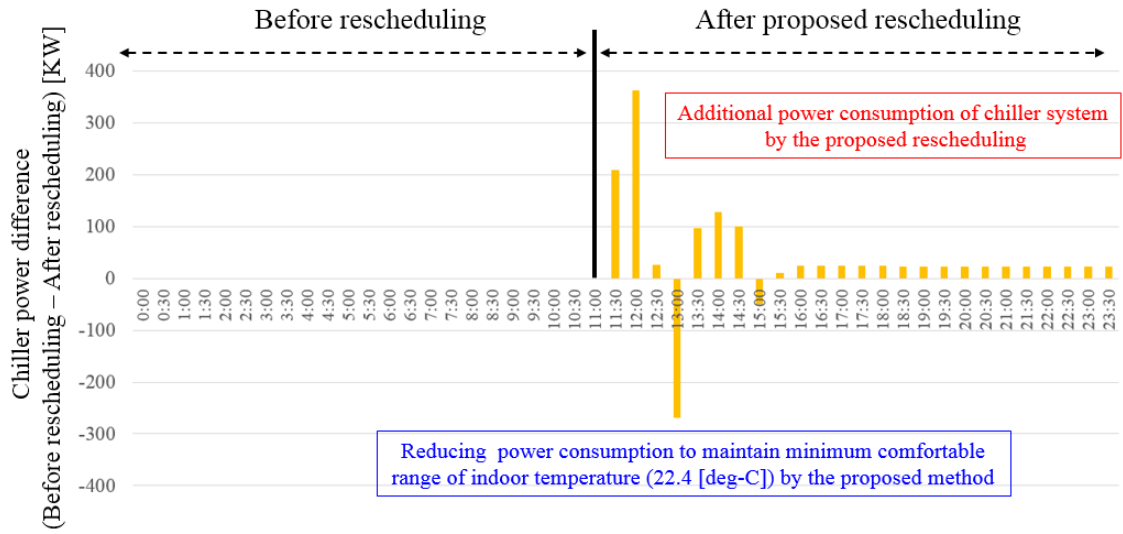


Figure 3.16: Analysis of rescheduled power consumption of chiller system

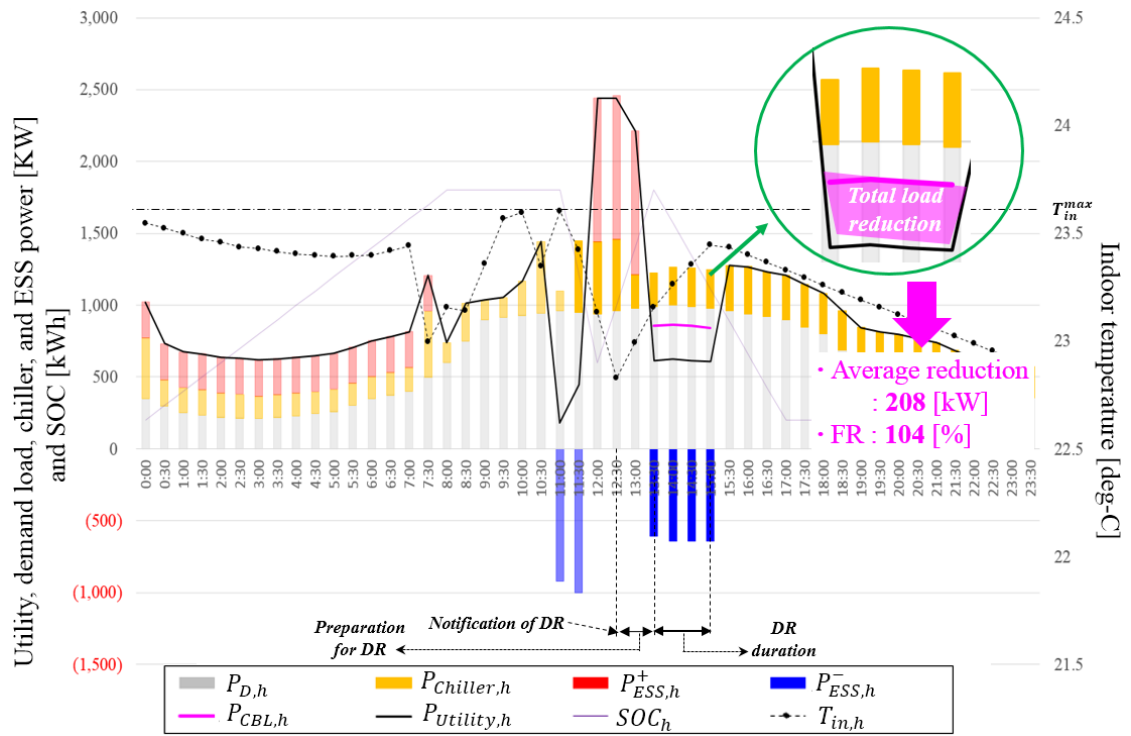


Figure 3.17: Obtained optimal operation after rescheduling

3.6 Conclusion

The proposed DR energy management supports additional utilization of chiller system and ESS as a DR resource for the Korean DR market. It proposes an optimal day-ahead operation scheduling whether temperature forecast error or not, and operation rescheduling on D-day for chiller system

and ESS in a COB under the DR scheme. Uncertainties in variety DR events applied with specified DR duration and amount of curtailment, and forecast error of ambient temperatures are considered for day-ahead operation scheduling and operation rescheduling on D-day compared with the no temperature forecasting error method. Simulation results showed that chiller system and ESS were cooperated for under maximum DR profit under DR events and minimum energy cost under TOU tariff. The proposed method not only can make higher DR profit, but also can protect penalty threat. Major advantages of the proposed algorithm are as follows.

- a. DR request can be met under the uncertainty of temperature.
- b. Comfort indoor temperature are guaranteed regardless of DR event.
- c. The proposed day-ahead schedule is robust for the assumed size of forecast error.
- d. The rescheduling process assures that the indoor temperature can be maintained within the thermal comfort.

Chapter 4. Determination of the Optimal DR Capacity in a Commercial Building with Chiller System and Energy Storage System

4.1 Introduction

Demand response (DR) which is used to shave the peak demand, is one of the most promising manners from end-users for securing supply reliability in power system. In particular, commercial buildings (COBs) which consume over 70% of the total electricity in the U.S. are the most effective end-users for DR. Lighting, heat pump, heating, ventilation, and air conditioning (HAVC) in COBs can be used as demand response resources (DRRs) for load reduction and load shifting during the specified DR duration. Furthermore, ESS which is an on-site generation installed at COBs can be used to ensure the reliability of power system through DR programs. Recently, EMS for DR has become a key technology for participation in effective and economical DR. Some management methods for changing electricity consumption patterns using a mixed-integer linear programming (MILP), fuzzy and genetic algorithm (GA) have been presented in [38]-[41]. In addition, an intelligent building management system for minimizing occupant inconvenience and reducing energy cost has been developed in [42]-[46]. DR resources have to be operated not only based on the day-ahead hourly electricity prices (TOU tariff) but also DR event information such as the amount and/or periods of load reduction for DR. Thus, in order to effectively participate in EDRP such as the Korean DR market, end-users have to determine the day-ahead optimal operation of DRRs considering both of TOU tariff and the Korean DR market. In Chapter 2, the day ahead operation scheduling/rescheduling on D-day have been mainly studied for maximum DR reward and avoiding penalty threat under uncertain DR events and ambient temperatures as DR participants' perspective. However, uncertain DR event and ambient temperature would affect the optimal DR capacity for obtaining maximum reward through the DR market. When allocated DR capacity is larger than an optimal value, although end-user will obtain high DR reward, DR penalty threat will be gradually increased in hot days, as well as contract for participating DR program can be forcibly terminated from utility company. When allocated DR capacity is smaller than an optimal value, end-user will obtain low DR reward. Thus, it's very important to determine the optimal DR capacity before the targeted DR market participation as end-users' perspective. This chapter presents a DR energy management algorithm for determining the optimal DR capacity considering a COB with chiller system and ESS through the TOU tariff and the Korean DR market.

The problem for determining the optimal DR capacity is formulated by a mixed integer linear programming (MILP). The objective function minimizes an expected value of daily energy cost. Uncertainties in large scale ambient temperatures and DR requirements are considered as several scenarios. The performance of the optimal DR capacity is evaluated through some case studies. The simulation results show that the proposed DR algorithm effectively can determine the optimal DR capacity, shift demand from peak periods to off-peak periods and reduce the energy costs in a COB.

4.2 Mathematical Formulation

It presents a DR management algorithm for determining the optimal DR capacity for end- user with chiller system and ESS. The objective function to be minimized is an expected value of energy cost based on TOU tariff and the Korean DR market under uncertain environments in ambient temperatures and DR events. This problem can be formulated as a MILP, in which the decision variables can be both discrete and continuous as well as the objective function and the constraint are linear. This algorithm is implemented in MATLAB and computed with the CPLEX solver. Nomenclatures for mathematical formulation are described in Table 4.1.

Table 4.1: Nomenclature for mathematical formulation

Parameter	Definition
$\frac{30}{60}$	0.5 hour (=30-minute)
h	Index for 30-minute interval in a day
k	Index for ambient temperature scenarios (1: representative 1, 2: representative 2, number of k and its occurrence probabilities are determined by subsection 3.2.2)
j	Index for amount of reduction scenarios (0: 0% reduction, 1: 25% reduction, 2: 50% reduction, 3: 75% reduction, and 4: 100% reduction)
d	Index for DR duration scenarios (1: DR1 event (13:30-15:30), 2: DR2 event (14:00-16:00), 3: DR3 event (14:30-16:30), and 4: DR4 event (15:00-17:00) durations)
n_h, n_k, n_j and n_d	Total number of time slot, ambient temperature scenarios, amount of reduction scenarios, and DR duration scenarios.
min and max	Minimum and maximum values

4.2.1 Determination of the optimal DR capacity

Objective function

The objective function to be minimized is an expected value of daily cost for end-user under the uncertain environment which can be defined as follows.

$$\min \sum_{k=1}^{n_k} \sum_{j=0}^{n_j} \sum_{d=1}^{n_d} \sum_{h=1}^{n_h} p^{(k,j,d)} \cdot C_h^{(k,j,d)} - C_C \quad (4.1)$$

where $p^{(k,j,d)}$, $C_h^{(k,j,d)}$, and C_C are occurrence probability associated with ambient temperature (k), amount of reduction (j), and DR duration (d) scenarios, the total costs associated with DR events [KRW], and a reward for the contracted DR capacity [KRW] respectively. The total costs associated with DR events are represented as follows:

$$C_h^{(k,j,d)} = \begin{cases} U_{T,h} \cdot P_{Utility,h}^{(k,j,d)} \cdot \frac{30}{60} - C_{E,h}^{(k,j,d)} \left(h_{DRS}^{(k,j,d)} \leq h \leq h_{DRE}^{(k,j,d)}, j \neq 0 \right) \\ U_{T,h} \cdot P_{Utility,h}^{(k,j,d)} \cdot \frac{30}{60} & (otherwise) \end{cases} \quad (4.2)$$

where $U_{T,h}$, $P_{Utility,h}^{(k,j,d)}$, $C_{E,h}^{(k,j,d)}$, $h_{DRS}^{(k,j,d)}$, and $h_{DRE}^{(k,j,d)}$ are price for electricity in TOU tariff [KRW/kWh], power purchased from the utility [kW], a reward based on load reduced actually [KRW], starting time of DR, and ending time of DR respectively. A reward based on load reduced actually can be expressed in the following equation.

$$C_{E,h}^{(k,j,d)} = U_{E,h} \cdot (P_{CBL,h}^{(k)} - P_{Utility,h}^{(k,j,d)}) \cdot \frac{30}{60} \quad (4.3)$$

where $U_{E,h}$ is price for DR contribution [KRW/kWh], $P_{CBL,h}^{(k)}$ is a customer baseline load (CBL) for temperature scenario k [kW] which is also one of decision variables in this problem. Also, a reward for the contracted DR capacity can be calculated by

$$C_C = U_C \cdot P_{DR} \quad (4.4)$$

where U_C and P_{DR} are price for contracted DR capacity [KRW/kW] and the contacted DR capacity [kW] respectively.

Demand and supply balancing constraints

Equal constraints for demand and supply balancing are represented as follows:

$$P_{Utility,h}^{(k,j,d)} = P_{D,h} + P_{Chiller,h}^{(k,j,d)} - P_{ESS,h}^{(k,j,d)} \quad (4.5)$$

where $P_{D,h}$, $P_{Chiller,h}^{(k,j,d)}$, and $P_{ESS,h}^{(k,j,d)}$ are electricity demand excluding chiller system and ESS, power consumed by chiller system, and net charging/discharging power [kW] respectively.

Characteristics of chiller system

The chiller system's electrical consumption is simply described in the following equation.

$$P_{Chiller,h}^{(k,j,d)} = A \cdot d_{c,h}^{(k,j,d)} \cdot \frac{30}{60} + B \quad (4.6)$$

where A , $d_{c,h}^{(k,j,d)}$, and B are power variation of chiller system according to a unit temperature variation [kW/deg-C], hourly temperature variation by chiller system [deg-C/h], and minimum chiller system operation power [kW] respectively.

Dynamics of indoor temperature

Equality constraints for indoor temperature dynamics in a COB can be formulated by a first order difference equation shown in (4.7) and (4.8). Indoor temperature in (4.9) should be maintained within the thermal comfort of ASHRAE in summer season.

$$T_{in,h+1}^{(k,j,d)} = T_{in,h}^{(k,j,d)} + (d_{u,h}^{(k,j,d)} - d_{c,h}^{(k,j,d)}) \cdot \frac{30}{60} \quad (4.7)$$

$$d_{u,h}^{(k,j,d)} = \frac{(T_{o,h}^{(k)} - T_{in,h}^{(k,j,d)})}{\tau_T} \quad (4.8)$$

$$T_i^{min} \leq T_{in,h}^{(k,j,d)} \leq T_i^{max} \quad (4.9)$$

where $T_{in,h}^{(k,j,d)}$, $T_{o,h}^{(k)}$, $d_{u,h}^{(k,j,d)}$, and τ_T are indoor temperature [deg-C/h], ambient temperature [deg-C/h], hourly temperature variation caused by heat-penetration through the building walls [deg-C/h], and thermal flywheel factor respectively.

Operation constraints for ESS

ESS charging and discharging power and SOC constraints are represented in (4.10) and (4.11) respectively.

$$P_{ESS,h}^{(k,j,d)} = P_{ESS,h}^{+(k,j,d)} - P_{ESS,h}^{-(k,j,d)} \quad (4.10)$$

$$SOC_h^{(k,j,d)} + \frac{30}{60} \cdot \left\{ \eta \cdot P_{ESS,h}^{+(k,j,d)} - \frac{1}{\eta} \cdot P_{ESS,h}^{-(k,j,d)} \right\} = \begin{cases} SOC_{h+1}^{(k,j,d)} & (1 \leq h < n_h) \\ SOC_1 & (h = n_h) \end{cases} \quad (4.11)$$

where $P_{ESS,h}^{+(k,j,d)}$, $P_{ESS,h}^{-(k,j,d)}$, $SOC_h^{(k,j,d)}$, and η are charging power of ESS [kW], discharging power of ESS [kW], state of charge, and the total efficiency of ESS (one-way) respectively..

DR requirement and CBL constraints

CBL must be same as power purchased from the utility while a DR event is not happens, and is formulated in (4.12). It assumes that DR participants are requested to reduce their consumptions as much as 25 [%], 50 [%], 75 [%], and 100 [%] reduction of the contracted DR capacity considering between 80 [%] as minimum DR fulfillment rate for no DR penalty and 120 [%] as maximum DR fulfillment rate for reward based on load reduced actually as shown in (4.13)-(4.16).

$$P_{CBL,h}^{(k)} = P_{Utility,h}^{(k,0,d)} \quad (4.12)$$

$$(0.8 \cdot 0.25) \cdot P_{DR} \leq P_{CBL,h}^{(k)} - P_{Utility,h}^{(k,1,d)} \leq (1.2 \cdot 0.25) \cdot P_{DR} \quad (4.13)$$

$$0.8 \cdot 0.5 \cdot P_{DR} \leq P_{CBL,h}^{(k)} - P_{Utility,h}^{(k,2,d)} \leq (1.2 \cdot 0.5) \cdot P_{DR} \quad (4.14)$$

$$(0.8 \cdot 0.75) \cdot P_{DR} \leq P_{CBL,h}^{(k)} - P_{Utility,h}^{(k,3,d)} \leq (1.2 \cdot 0.75) \cdot P_{DR} \quad (4.15)$$

$$0.8 \cdot P_{DR} \leq P_{CBL,h}^{(k)} - P_{Utility,h}^{(k,4,d)} \leq 1.2 \cdot P_{DR} \quad (4.16)$$

Consistency before DR event notification

The DR participants only change their DRR (chiller system and ESS) operations after the DR event notification comes; the DRR operations before the DR notification must be same. That is,

$$P_{Chiller,h}^{(k,j,d)} = P_{Chiller,h}^{(k,0,d)} \quad (h < h_{DRS}^{(k,j,d)}, j \neq 0) \quad (4.17)$$

$$P_{ESS,h}^{(k,j,d)} = P_{ESS,h}^{(k,0,d)} \quad (h < h_{DRS}^{(k,j,d)}, j \neq 0) \quad (4.18)$$

Capacity limit constraints

Power purchased from the grid and chiller power must be below the maximum contracted capacity from the utility company and the maximum chiller power given by (4.19) and (4.20) respectively. Charging and discharging powers of ESS, which are determined by the binary values (when a binary value is 0, ESS is charging mode and when a binary value is 1, ESS is discharging mode), should be less than or equal to the maximum ESS power in (4.21) and (4.22) respectively. The quantity of stored ESS energy at any time cannot exceed the maximum storage capacity described in (4.23).

$$0 \leq P_{Utility,h}^{(k,j,d)} \leq P_{Utility}^{max} \quad (4.19)$$

$$P_{Chiller}^{min} \leq P_{Chiller,h}^{(k,j,d)} \leq P_{Chiller}^{max} \quad (4.20)$$

$$P_{ESS,h}^{-(k,j,d)} \leq P_{ESS}^{max} \cdot \mu_h^{(k,j,d)} \quad (4.21)$$

$$P_{ESS,h}^{+(k,j,d)} \leq P_{ESS}^{max} \cdot (1 - \mu_h^{(k,j,d)}) \quad (4.22)$$

$$SOC^{min} \leq SOC_h^{(k,j,d)} \leq SOC^{max} \quad (4.23)$$

where $\mu_h^{(k,j,d)}$ is binary variables specifying ESS operation mode (charge = 0 or discharge = 1)

4.2.2 Determination of the representative ambient temperatures

To solve the problems formulated in the subsection 4.2.1, it is necessary to give some representative ambient temperatures as input data. More specifically, the DR scale has to be determined considering possible various ambient temperatures as shown in (4.8). However, the number of temperature to be considered would be exponentially increased. Unfortunately, this phenomenon may cause increasing the dimension of the mathematical problem, lacking of computer memory, and making the simulation very much consuming.

Thus, a reduction of the total simulation time can be expected by determining representative ambient temperatures. In order to give the desirable representative ambient temperatures, this paper presents a method for determining the representative ambient temperature by the following three procedures. First, this paper evaluates the values of all ambient temperature scenarios from the viewpoint of daily costs given by (4.24)-(4.36). Second, this paper applies the k-means clustering algorithm which is popular for cluster analysis in data mining fields for finding centroid of each of the k clusters from among observations on obtained daily costs in (4.37) and (4.38) [48]. The concrete algorithm is shown in Appendix A. Finally, the ambient temperature which is the closest to centroid becomes the representative ambient temperature given by (4.39). It formulates the following problems for a given ambient temperature.

$$\min \sum_{h=1}^{n_h} C_h \quad (4.24)$$

$$C_h = \begin{cases} U_{T,h} \cdot P_{Utility,h} \cdot \frac{30}{60} - C_{E,h} + C_{P,h} & (h_{DRS} \leq h \leq h_{DRE}) \\ U_{T,h} \cdot P_{Utility,h} \cdot \frac{30}{60} & (otherwise) \end{cases} \quad (4.25)$$

Other constraints for minimizing objective function are described as follows:

$$C_{E,h} = U_{E,h} \cdot (P_{CBL,h} - P_{Utility,h}) \cdot \frac{30}{60} \quad (4.26)$$

Here, $P_{CBL,h}$ is used for calculating a reward based on load reduced actually before the DR market participation as end-user perspective in this section. $P_{CBL,h}$ differs in a CBL defined by the DR market.

$$C_{P,h} = C_C \cdot \tau_{P,h} \quad (4.27)$$

where $C_{P,h}$ is DR penalty [KRW] and $\tau_{P,h}$ is penalty coefficient and can be expressed in the

following equation.

$$\tau_{p,h} = \begin{cases} 0 & (80 \leq FR_h \leq 120), \\ 0.2 & (70 \leq FR_h \leq 79), \\ 0.4 & (60 \leq FR_h \leq 69), \\ 0.6 & (50 \leq FR_h \leq 59), \\ 1 & (1 \leq FR_h \leq 49) \end{cases} \quad (4.28)$$

Here, FR_h is DR fulfillment rate and can be calculated by

$$FR_h = \frac{(P_{CBL,h} - P_{Utility,h})}{P_{DR}} \times 100 \quad (4.29)$$

$$P_{Utility,h} = P_{D,h} + P_{Chiller,h} \quad (4.30)$$

$$0 \leq P_{Utility,h} \leq P_{Utility}^{max} \quad (4.31)$$

$$P_{Chiller,h} = A \cdot d_{c,h} \cdot \frac{30}{60} + B \quad (4.32)$$

$$P_{Chiller}^{min} \leq P_{Chiller,h} \leq P_{Chiller}^{max} \quad (4.33)$$

$$T_{in,h+1} = T_{in,h} + (d_{u,h} - d_{c,h}) \cdot \frac{30}{60} \quad (4.34)$$

$$d_{u,h} = \frac{(T_{o,h} - T_{in,h})}{\tau_T} \quad (4.35)$$

$$T_i^{min} \leq T_{in,h} \leq T_i^{max} \quad (4.36)$$

$\sum_{h=1}^{n_h} C_h$ means the daily cost for a given ambient temperature. Here, the decision variables in this problem are power consumptions of chiller system at every time. This optimization problem is solved for every scenario on DR given in advance because the value of daily cost is different for every scenario. It defines cost in time period h for scenario j on DR duration as $C_h^{(j)}$. Here, scenario on the amount of DR is fixed to be 100% for consideration of the severest case. And then, the obtained n_d daily energy costs for the same ambient temperature are combined into a single cluster data as follows.

$$C_{Combine,i} = \begin{cases} C_i^{(1)}, & i = 1 \sim n_h \\ C_{i-n_h}^{(2)}, & i = n_h + 1 \sim 2 \cdot n_h \\ \vdots \\ C_{i-n_h \cdot (n_d-1)}^{(n_d)}, & i = n_h \cdot (n_d - 1) + 1 \sim n_d \cdot n_h \end{cases} \quad (4.37)$$

where $C_{Combine,i}$ and $C_i^{(n_d)}$ are a sequential combined energy cost at i observation, and the obtained daily energy cost for the same ambient temperature during DR duration scenarios at i observation respectively.

Next, it classifies past several days' ambient temperatures into n clusters by the following steps. Here, the number of cluster, n can be determined by the silhouette value in Appendix B [49].

Step 1: Every ambient temperature is assigned into n clusters randomly.

Step 2: A centroid of every cluster is computed as follows:

$$C_{Centroid,i}^{(\alpha)} = \frac{C_{Combine,i}^{(\alpha,1)} + C_{Combine,i}^{(\alpha,2)} \cdots C_{Combine,i}^{(\alpha,\alpha^N)}}{\alpha^N} \quad (4.38)$$

where $C_{Centroid,i}^{(\alpha)}$ is a centroid at i observation of the α th cluster, $C_{Combine,i}^{(\alpha,i)}$ is sequential combined energy cost obtained for ambient temperatures belonging in the α th cluster and can be calculated in (4.37), and α^N means the number of elements which belongs in the α th cluster.

Step 3: A distance of every ambient temperature to the centroids obtained in step 2 are calculated by the following equation.

$$D = \sum_{i=1}^{n_i} w_i \cdot \left\| C_{Combine,i} - C_{Centroid,i}^{(\alpha)} \right\|^2 \quad (4.39)$$

where D , n_i and w_i are a distance of every ambient temperature to the centroids, total number of i observation, and weighted factor by DR occurrence probability at i observation respectively.

Step 4: Every ambient temperature is re-assigned into the cluster with the nearest centroid, and go to Step 2.

The above steps are iterated until convergence. The representative temperature in every cluster can be founded as the ambient temperature that the distance to the centroid becomes minimum. Then, number of sequential combined energy costs assigned to the clustering group divided by the total number sequential combined energy costs makes occurrence probability for the representative ambient temperature of the clustering group.

4.2.3 Architecture for the proposed DR algorithm

The problems in the subsection 4.2.1 for determining the optimal DR capacity are needed some ambient temperatures as input data. On the other hand, the problems in the subsection 4.2.2 for determining the representative ambient temperatures are needed the optimal DR capacity as input data. Therefore, those two problems are solved iteratively until the convergence as shown in Fig. 4.1.

1) Set parameters and initial variables

Input data include TOU Tariff, the Korean DR market information (incentive price for DR load reduction and contracted DR capacity, penalty price and coefficient), actual daily temperature loci, DR event information (including DR event scenarios and occurrence probabilities), a COB information (including demand load, initial indoor temperature and thermal comfort range), operating information of ESS (including energy storage capacity, initial state of charge, maximum charging and discharging rate, and charging and discharging efficiency) and operating information about chiller system (including power variation of chiller system according to a unit temperature variation, minimum chiller system operation power and thermal flywheel factor). All the inputs are formulated using MILP, which includes an objective function and a series of constraints.

2) (A) Arrange sequential combined utility cost for past N days by Eq. (4.24)-(4.39)

Sequential combined utility cost with DR event scenarios are calculated and collected for past N days ambient temperature loci.

3) Decide how many k cluster from the cluster in (A) by the silhouette value

The optimal k cluster number in sequential combined utility costs (A) is determined by the proposed silhouette value analysis.

4) Find centroid of each of the k clusters by K-means clustering algorithm

Centroid of each of the k clusters is found by K-means clustering algorithm applied to the proposed squared Euclidean distance with DR occurrence probability.

5) Find representative ambient temperatures

Representative ambient temperatures and its occurrence probabilities are determined by Eq. (4.38)-(4.39) and used for initial variables.

6) Minimizing expected energy cost considering DR scenarios by MILP in Eq. (4.1)-(4.23)

The optimal DR capacity using chiller system and ESS is calculated by Eq. (4.1) and (4.23).

CBL and DR capacity without DR scenarios are used as initial values. The proposed DR algorithm is implemented feedback loop, which is re-calculated based on updated DR capacity under the determination procedure of representative ambient temperatures until obtained optimal DR capacity is same as previous one because validity of the obtained DR capacity should be confirmed by iteration.

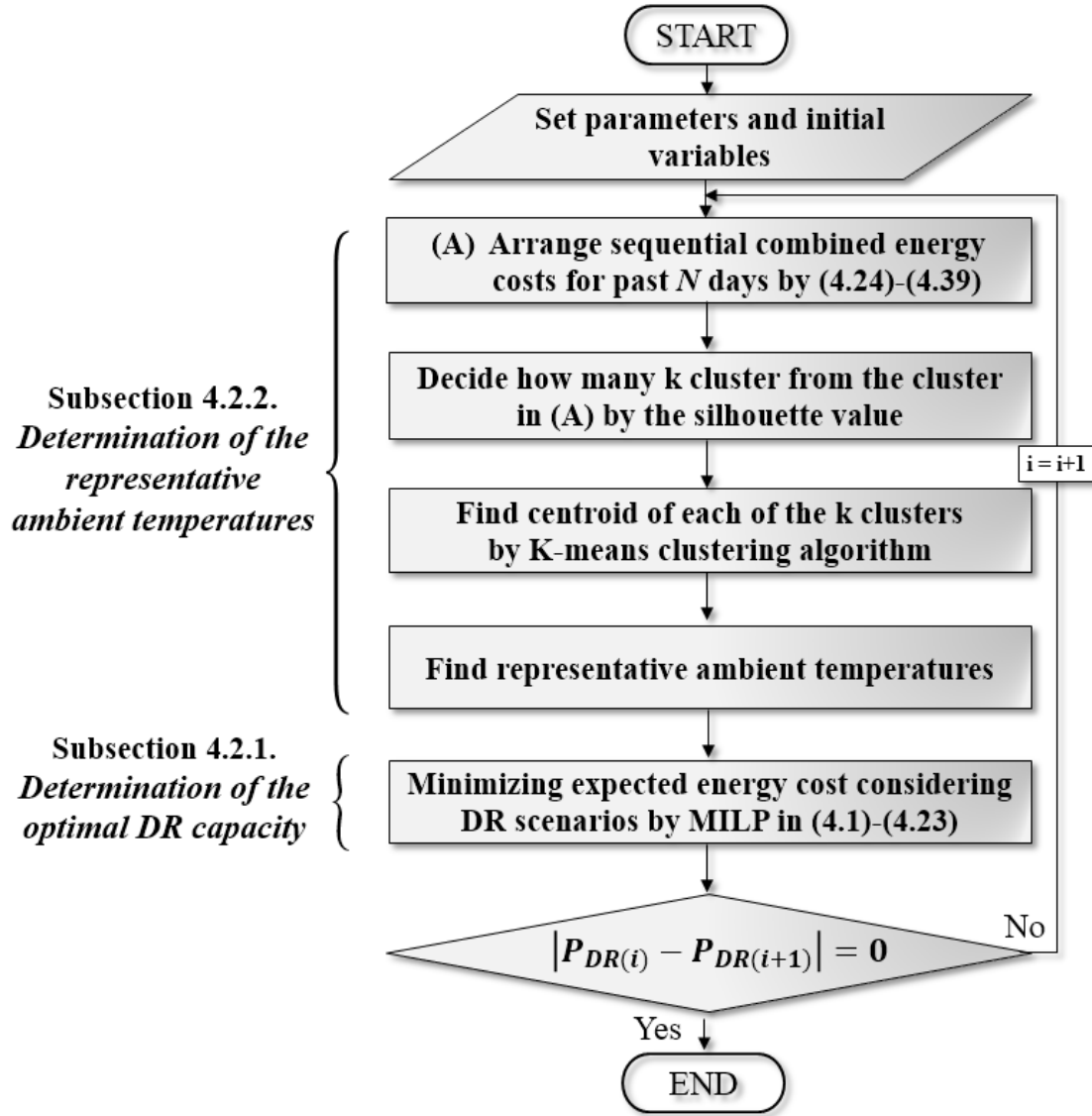


Fig. 4.1: Architecture for the proposed DR algorithm used to solve the optimal DR capacity problem

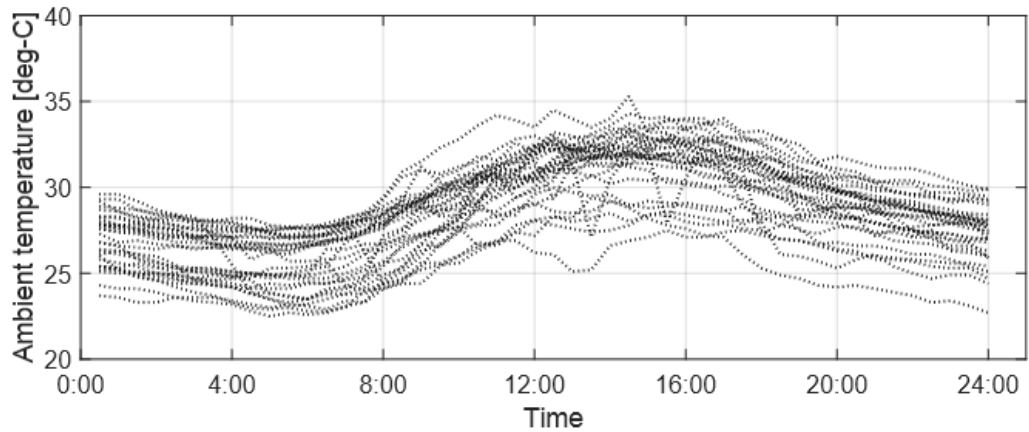
4.3 Case Studies

In this section, the effectiveness of the proposed method for determining some representative ambient temperatures and the optimal DR capacity are shown in the subsection 4.3.1. Next, in the subsection 4.3.2, an expected value of daily energy cost based on the cooperation between chiller system and ESS is analyzed.

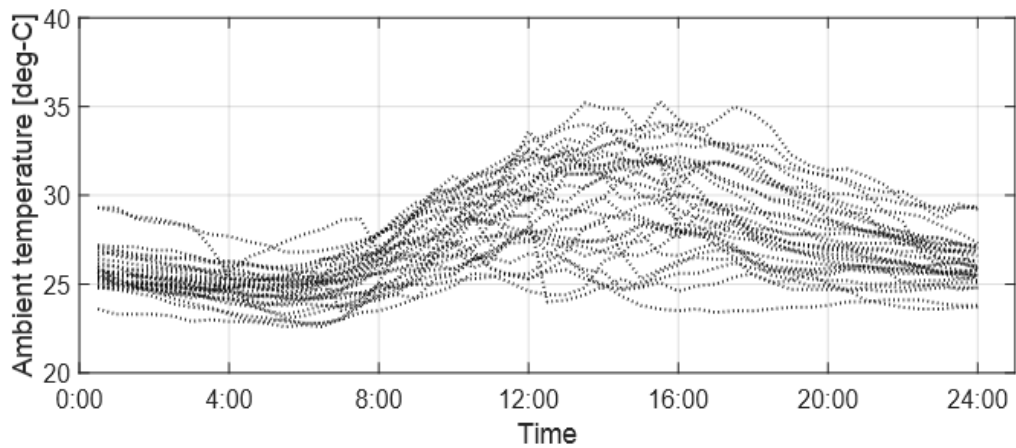
4.3.1 Estimation for representative ambient temperatures

Simulation Conditions

The proposed energy management algorithm for DR was applied to a COB with 500 [kW] chiller system and 1,000 [kW] / 2,000 [kWh] ESS (Lithium-ion battery). The daily load data of the COB excluding chiller system and ESS is shown in Fig. 4.5. Total 60 days of ambient temperature profiles were selected based on actual daily temperature loci in Aug. 2011 and 2012 [50]-[51], and were divided into two sets as shown in Fig. 4.3 (a) and (b). A set of temperature shown in Fig. 4.3 (a) are utilized for designing the desirable representative ambient temperatures and optimal DR capacity. A set of temperature in Fig. 4.3 (b) are used to evaluate the effectiveness of the designed results. For simplicity, only two DR events shown in Table 4-2 were assumed as scenarios. The other assumptions regarding simulation parameters are summarized in Table 4.3. Here, the thermal comfort about the indoor temperature was specified as 22.0-24.0 [deg-C] by the American Society of Heating, Refrigerating and Air Conditioning Engineers [33]. The maximum and minimum DR fulfillment rate (FR) were defined as 80 [%] and 120 [%] by the Korean DR market role [47]. And price for DR contribution and price for the contracted DR capacity were applied as 550 [KRW/kWh] and 64,000 [KRW/kW] based on the Korean power exchange respectively.



(a) Temperature profiles for obtaining DR capacity (30 days/Aug. 2011)



(b) Temperature profiles for estimation (30 days/Aug. 2012)

Fig. 4.2: Input temperatures profiles for estimation

Table 4.2: DR event scenarios

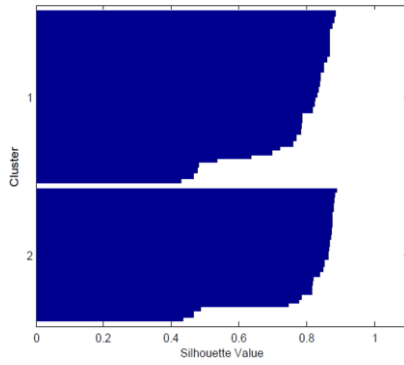
DR scenario	DR duration	Power reduced by DR (Rate with respect to the contracted power)	Occurrence probability of DR
1	N/A	0%	0.5
2	14:30-16:30 (DR3)	100%	0.5

Table 4.3: Simulation parameters

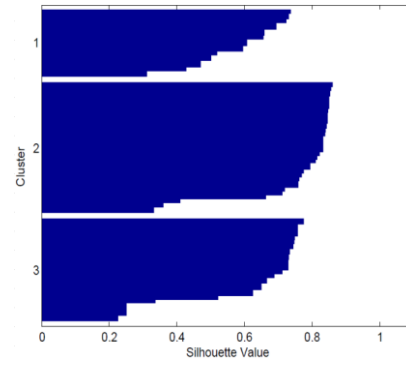
Parameter	Value		Unit
U_T	10:30~12:00, 13:30~17:00	293.8	KRW/kWh
	23:00~9:00	56.2	
	Otherwise	108.5	
A	290		kW/deg-C
B	110		kW
τ_T	11		.
η	80		.
$SOC^{\min}, SOC^{\max}$	200, 1800		kWh
$P_{ESS}^{\min}, P_{ESS}^{\max}$	-1000, 1000		kW
$P_{Chiller}^{\min}, P_{Chiller}^{\max}$	139, 500		kW
$T_{in}^{\min}, T_{in}^{\max}$	22, 24		deg-C
$FR^{\min}, FR^{\max}$	80, 120		%
$U_{E,h}$	550		KRW/kWh
U_c	64,000		KRW/kW

Selecting the number of k clusters with silhouette analysis on kmeans clustering

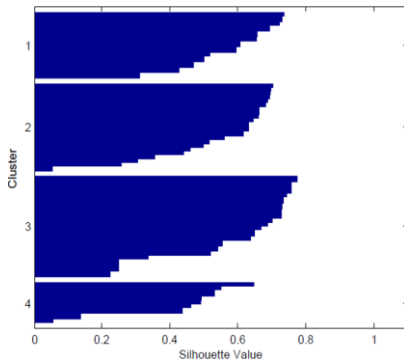
Silhouette analysis can be used to study the separation distance between the resulting clusters in the Appendix B. That is, the silhouette estimates how close each point in one cluster is to points in the neighboring clusters. Consequently, silhouette analysis was performed for number of k clusters based on combined energy costs given by (3.24) - (3.37). The silhouette coefficient values for 4 kinds clustering were analyzed as shown in Fig. 4.3 (a), (b), (c), and (d) respectively. As a result, the silhouette coefficient with 2 clustering shown in Fig. 4.3 (a) was obtained the highest value as 0.792 than other cases. It means 2 clustering is well classified the given combined energy costs with reasonable clustering, and 2 clusters was applied to the following process.



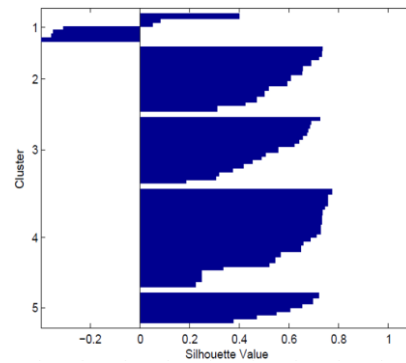
(a) The silhouette values with 2 clustering
(The silhouette coefficient: 0.792)



(b) The silhouette values with 3 clustering
(The silhouette coefficient: 0.653)



(a) The silhouette values with 3 clustering
(The silhouette coefficient: 0.536)

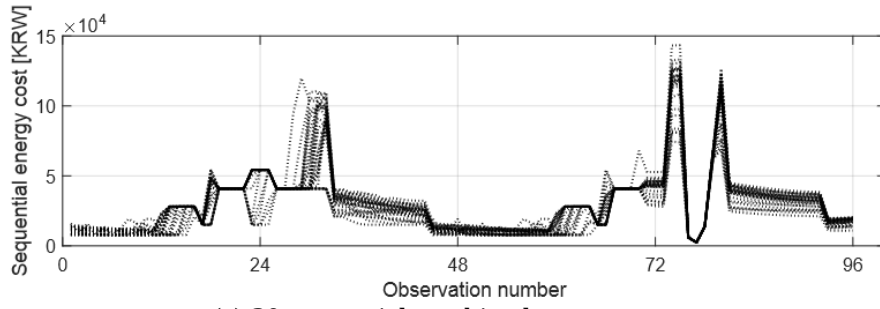


(b) The silhouette values with 4 clustering
(The silhouette coefficient: 0.444)

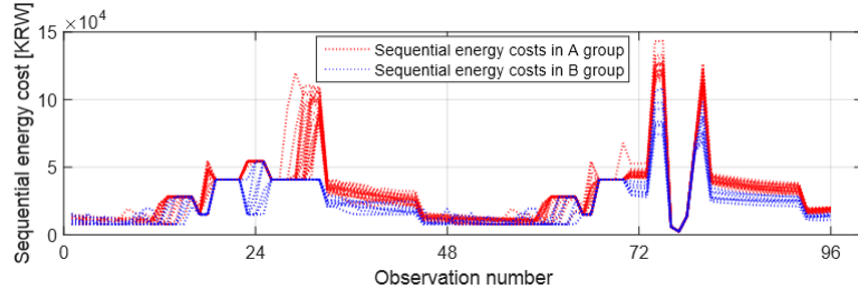
Fig. 4.3: Silhouette value calculation to the various clustering

Determination of representative ambient temperature

Fig. 4.4 (a) illustrates 30 sequential combined energy costs which were determined for two DR scenarios given in Table 4.2. Every sequential combined energy cost was calculated by (4.24)-(4.37) based on ambient temperature profiles (30 days) shown in Fig. 4.4 (a). Since the optimal number of clusters was two in this simulation, those sequential energy costs were categorized into two groups as shown in Fig. 4.4 (b). Occurrence probabilities of the A and B groups were calculated 0.53(16/30) and 0.47(14/30) respectively, and were used for parameters of representative ambient temperatures in A and B groups. Then the centroids for every group were obtained based on eq. (4.38). And then, the sequential combined energy costs closest to their centroids were founded by eq. (39) as shown in Fig. 4.4 (c). Those days were 14th day (A group) and 30th day (B group), and ambient temperatures of those days were selected as representative ambient temperatures as shown in Fig. 4.4 (d).

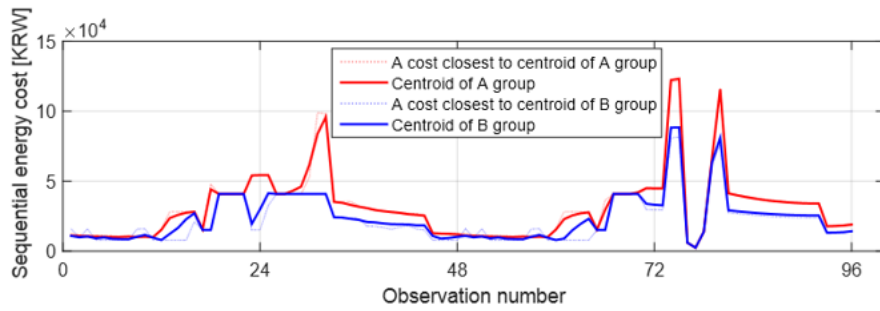


(a) 30 sequential combined energy costs

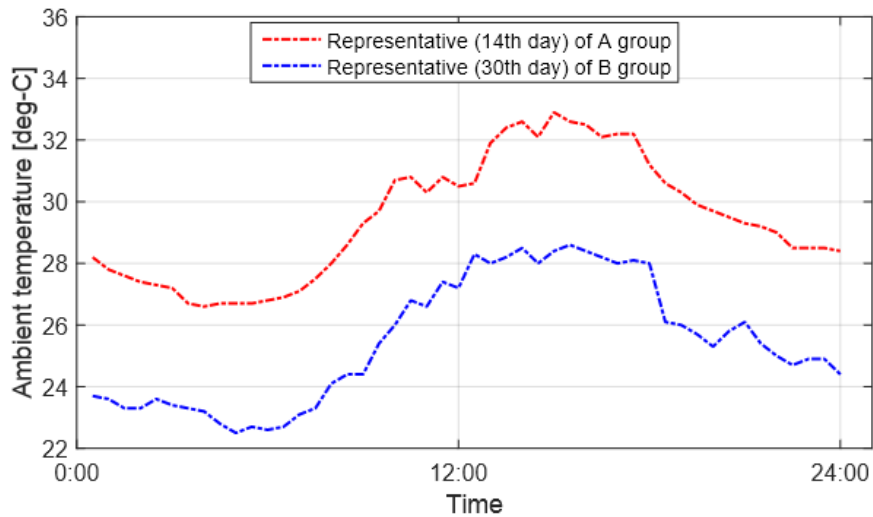


(b) Two clustering groups for 30 sequential energy costs

(Occurrence probabilities for A and B groups: 0.53 and 0.47 respectively)



(c) The centroids and the combined energy costs closest to centroids



(d) Representative ambient temperatures

Fig. 4.4: Determination of representative ambient temperatures

Determination of the optimal DR capacity and simulation results

Two representative temperatures obtained in the previous section and their occurrence probabilities were used as scenarios for determining the optimal DR capacity. The obtained optimal DR capacity was 48 [kW]. The validity of the representative ambient temperatures was ascertained by comparing with the different ambient temperatures. More specifically, the value of DR capacity was determined for any of two data selected from 30 pieces of temperature data in Fig. 4.2 (a). Fig. 4.5 shows DR capacities obtained for any two temperatures.

Fig. 4.6 shows expected values of daily reward, penalty and total cost calculated for every DR capacity. Here, these values were calculated considering DR event scenarios of Table 4.2 for total 30 days of ambient temperatures shown in Fig. 4.6 (b). In case of lower DR capacity (1-29 [kW]) in Fig. 4.7, we can find that the expected value of total cost decreases with the increase in the DR capacity because the expected value of reward of DR increases. In this case the reduction in load demand during DR duration was achieved easily without violating the constraints on indoor temperature even on hot days because the power to be reduced was small. Therefore, there were no penalties in this case. However, in case of the middle DR capacity (30-35 [kW]), the penalty for DR occurred on hot days because it was harder to reduce the power consumption of chiller system for DR without violating comfortable indoor temperature. Further, in case that DR capacity became larger (36-48 [kW]), there were no penalties again. This is because that the CBL in this case was higher than the other cases as shown in Fig. 4.7 and power consumption of chiller system before executing DR was larger. Then, the minimum expected value of daily energy cost is obtained at a temperature pair including 14th and 30th days of temperatures in Fig. 4.4 (a), which provides the DR capacity of 48 [kW] same as the optimal DR capacity by the proposed DR algorithm. That is, we can see that the optimal DR capacity was determined by the proposed method for determining a pair of effective representative ambient temperatures.

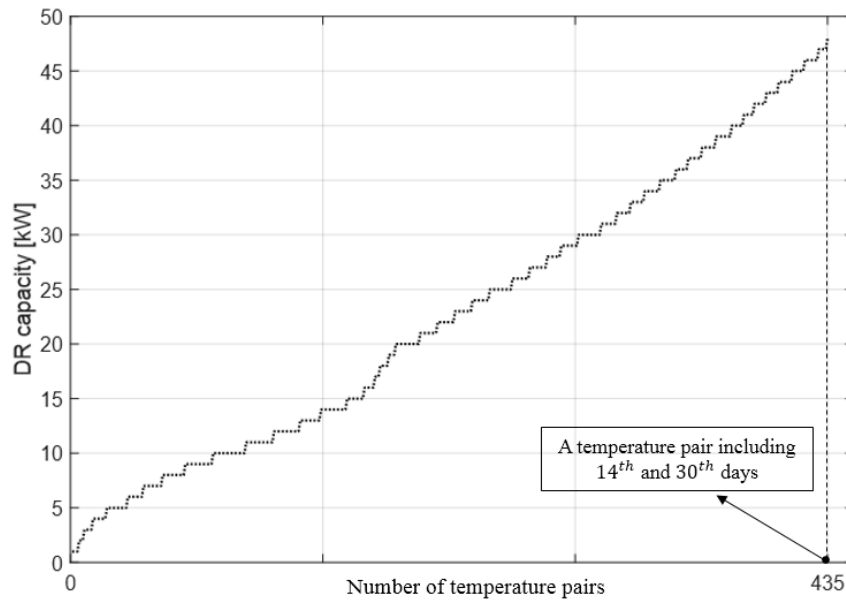
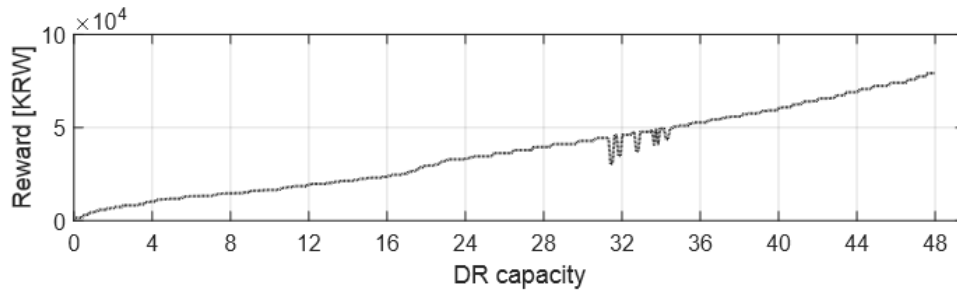
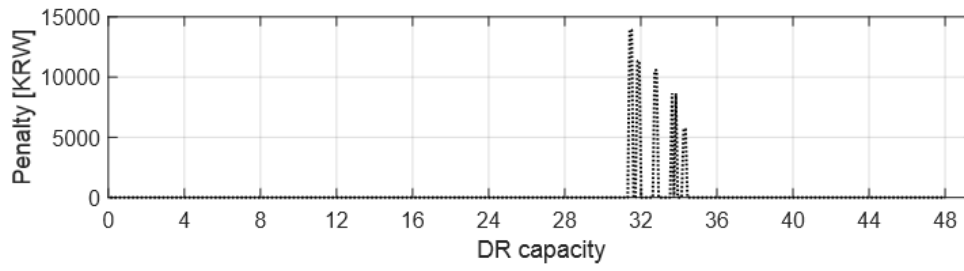


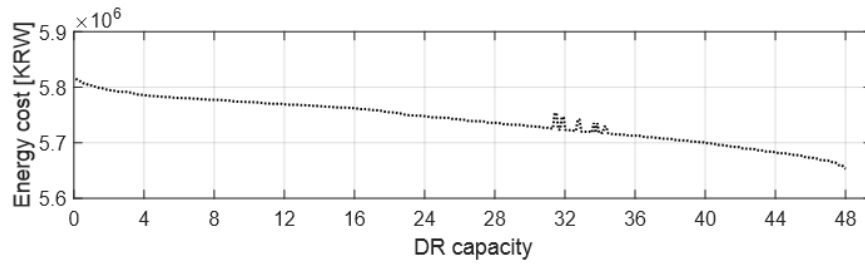
Fig. 4.5: Obtained the DR capacity



(a) An expected value of daily DR reward



(b) An expected value of daily penalty



(c) An expected value of daily energy cost

Fig. 4.6: Estimation for the optimal DR capacity

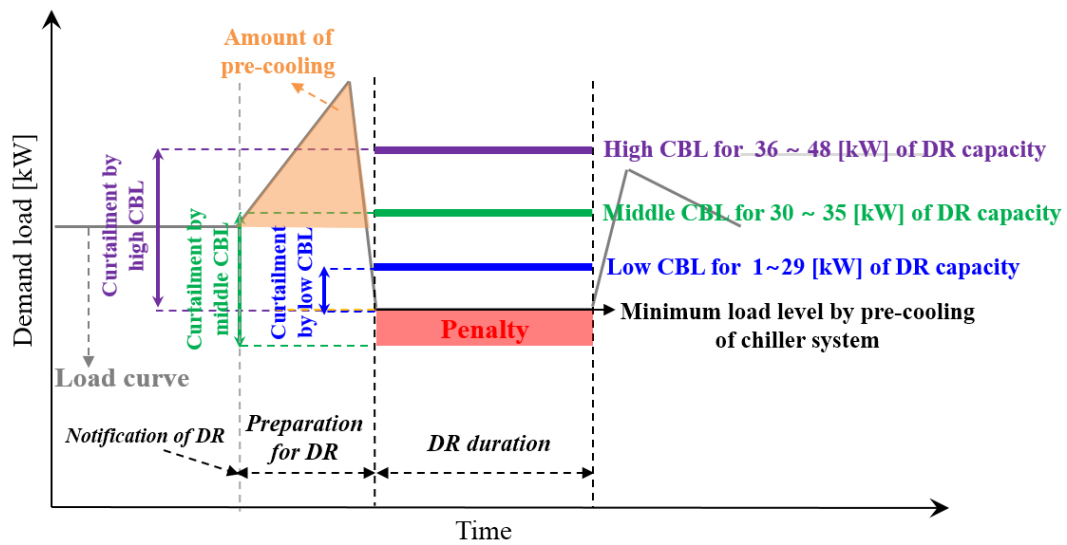


Fig. 4.7: CBL for the optimal DR capacity

4.4.2 Economic evaluation of the proposed DR algorithm

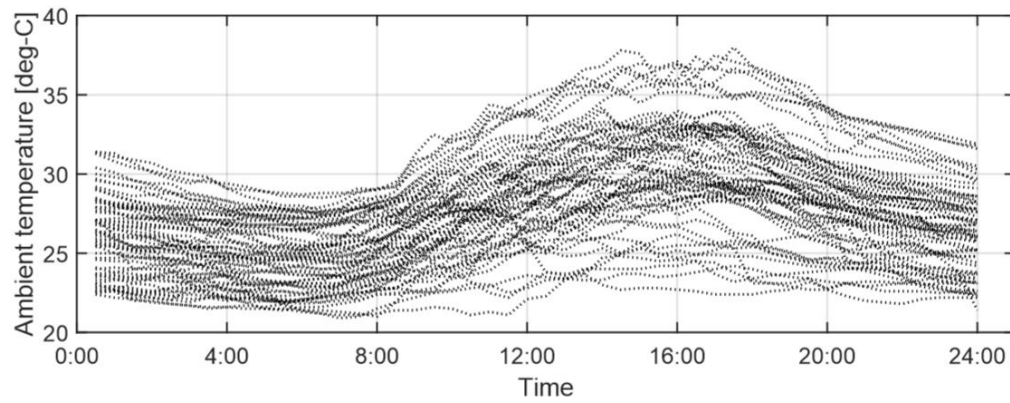
Simulation Conditions

Total 124 of ambient temperatures (in July and August of 2012 and 2013) were divided into two sets which are used for determination of the optimal DR capacity and economic evaluation as shown in Fig. 4.9 (a) and (b) respectively. Parameters on DR event scenarios were determined by probabilistic analysis given by historical data of DR event (in July and August of 2012, 2013, and 2014), and were summarized in Table 4.4. More specifically, Analysis of number of times and specified time of real DR executed in July/August 2012, 2013, and 2014 was employed to determine number and occurrence probability of index “*d*” and “*j*” based on references [34]-[35]. DR events were mainly happened in July/August as a specified summer season. As a result, 4 kinds of index “*d*”, in which there are higher daily occurrence probabilities of DR event in summer season were determined. The DR durations are highly dependent on ambient temperature. Then, occurrence probabilities of four DR duration scenarios (*d*) were calculated as 0.11(13:30-15:30), 0.32(14:00-16:00), 0.37(14:30-16:30), and 0.21(15:00-17:00) based on the mentioned above probabilistic analysis given by DR statistics in July/August 2012, 2013, and 2014 respectively. Furthermore, 5 kinds of index “*j*” such as 0%, 25%, 50%, 75% and 100% set up amount of reduction scenarios. More specifically, occurrence probability of 0% amount of reduction scenario was previously calculated by eq. (4.39), it was approximately 0.9.

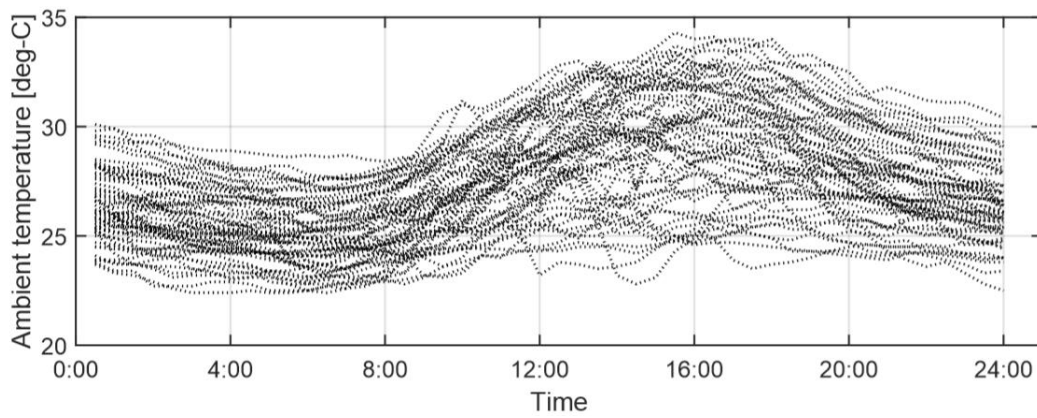
$$1 - \frac{DR\ event\ days}{Total\ days} \quad (4.39)$$

Then, the other value (0.1) of occurrence probability was divided into 25% (0.025), 50% (0.025), 75% (0.025) and 100% (0.025) amount of reduction scenarios. The other parameters were set to the same values as Table 4.5. Three cases shown in Table 4.6 were investigated.

More specifically, in Case 1, optimal operations of chiller system and ESS were calculated based on only TOU tariff. In Case 2, optimal operation of chiller system was calculated considering both of TOU tariff and the Korean DR market. However, the operation of ESS was scheduled considering only TOU tariff. More specifically, first the optimal operation of ESS was calculated so that the cost of electricity purchased from the utility becomes minimum considering TOU prices. Next, on fixing the operation of ESS, the optimal operation of chiller system was calculated considering both of DR market and TOU prices based on the proposed method. In Case 3, operations of chiller system and ESS were scheduled considering TOU tariff and the Korean DR market by the proposed method.



(a) Temperature profiles for the optimal DR capacity
(62 days in July and August of 2012)



(b) Temperature profiles for economic evaluation
(62 days in July and August of 2013)

Fig. 4.8. Input temperatures profiles for economic evaluation

In cases 2 and 3 representative temperatures were selected in the same manner as the previous subsection from data of temperatures in Fig. 4.8 (a). In every case, the expected value of daily cost based on multiple DR scenarios shown in Table 4.4 was calculated for each of 62 temperatures in Fig. 4.8 (b).

Table 4.4. Parameters of DR event scenarios for economic evaluation

DR duration (<i>prob. : d</i>)	Amount of reduction (<i>prob. : j</i>)	Occurrence probability (<i>d * j</i>)
13:30-15:30 (0.11)	100% (0.025)	0.11 * 0.025
	75% (0.025)	0.11 * 0.025
	50% (0.025)	0.11 * 0.025
	25% (0.025)	0.11 * 0.025
	0% (0.9)	0.11 * 0.9
14:00-16:00 (0.32)	100% (0.025)	0.32 * 0.025
	75% (0.025)	0.32 * 0.025
	50% (0.025)	0.32 * 0.025
	25% (0.025)	0.32 * 0.025
	0% (0.9)	0.32 * 0.9
14:30-16:30 (0.37)	100% (0.025)	0.37 * 0.025
	75% (0.025)	0.37 * 0.025
	50% (0.025)	0.37 * 0.025
	25% (0.025)	0.37 * 0.025
	0% (0.9)	0.37 * 0.9
15:00-17:00 (0.21)	100% (0.025)	0.21 * 0.025
	75% (0.025)	0.21 * 0.025
	50% (0.025)	0.21 * 0.025
	25% (0.025)	0.21 * 0.025
	0% (0.9)	0.21 * 0.9

Table 4.5: Simulation cases under DR resource category

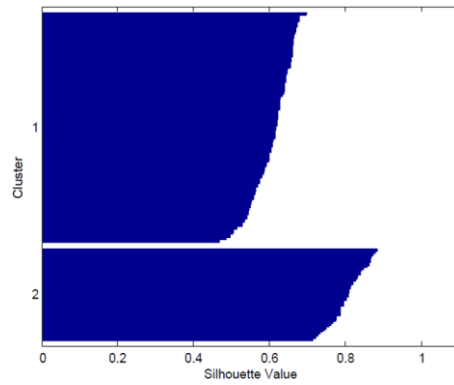
DRR Category		Simulation Case		
		1	2	3
Chiller system	TOU tariff	○	○	○
	DR market	X	○	○
ESS	TOU tariff	○	○	○
	DR market	X	X	○

Table 4.6: Assumed actual DR event scenarios for economic evaluation

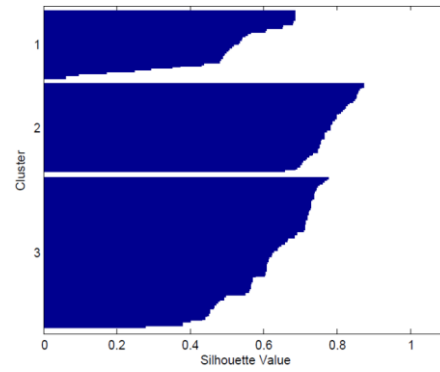
DR scenario	DR duration	Amount of reduction	Occurrence probability
1	13:30-15:30	100%	0.025
2	14:00-16:00	100%	0.025
3	14:30-16:30	100%	0.025
4	15:00-17:00	100%	0.025
5	N/A	0%	0.9

Selecting the number of k clusters with silhouette analysis on kmeans clustering

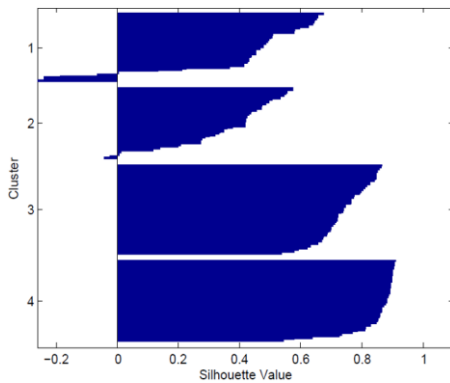
Fig. 4.9 shows obtained silhouette values for optimal number of clusters applied with DR event scenarios for economic evaluation. As a result, Number of k clusters was chosen as two clustering. Since silhouette coefficient (0.707) of 2 clustering as shown in Fig. 4.9 (a) was the higher than other 3 cases.



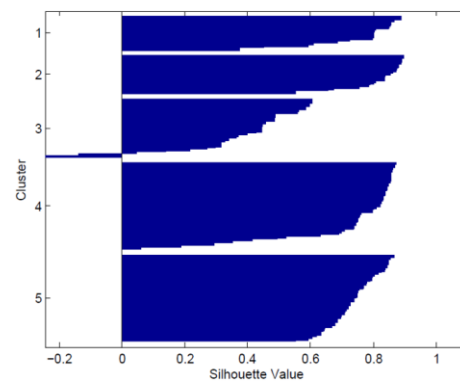
(a) The silhouette values with 2 clustering
(The silhouette coefficient: 0.707)



(b) The silhouette values with 3 clustering
(The silhouette coefficient: 0.634)



(a) The silhouette values with 3 clustering
(The silhouette coefficient: 0.590)

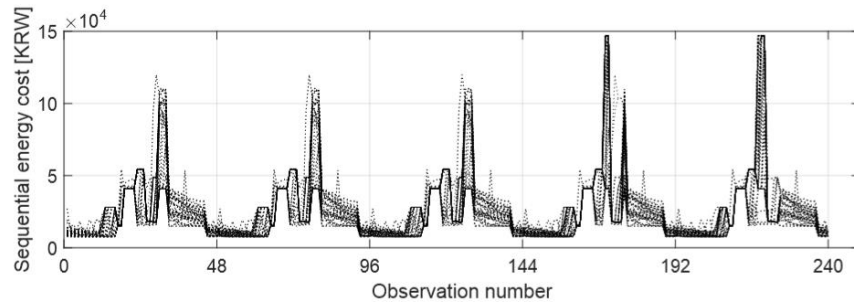


(b) The silhouette values with 4 clustering
(The silhouette coefficient: 0.691)

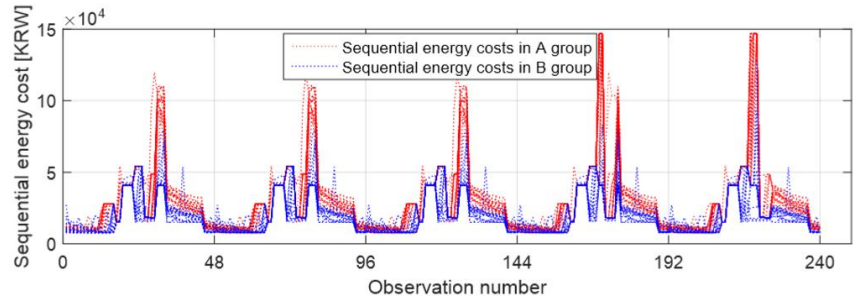
Fig. 4.9: Silhouette value calculation to the various clustering

Determination of representative ambient temperature

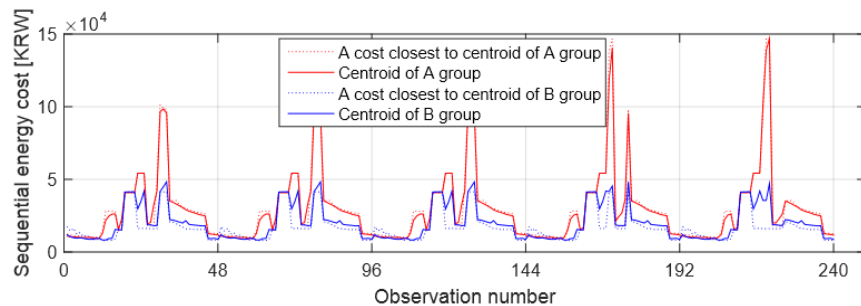
Two representative ambient temperatures for economic evaluation were selected on temperature profiles shown Fig. 4.9 (a) in the following process as shown in Fig. 4.10 (a), (b), (c), and (d) respectively. Fig. 4.10 (a) illustrates sequential combined energy costs which were calculated for four DR scenarios (including NODR) in Table 4.3. The sequential energy costs were divided into two clustering groups as shown in Fig. 4.10 (b) because number of clusters was chosen in the previous section. The A and B groups' occurrence probabilities were calculated 0.56 and 0.44 respectively. These are used for parameters as occurrence probabilities associated with ambient temperature in the mathematical formulation. And the sequential combined energy costs closest to their centroids were founded by eq. (4-39) as shown in Fig. 4.10 (c). Those days were 7th day (A group) and 27th day (B group). This is, ambient temperatures of those days were selected as representative ambient temperatures as shown in Fig. 4.10 (d).



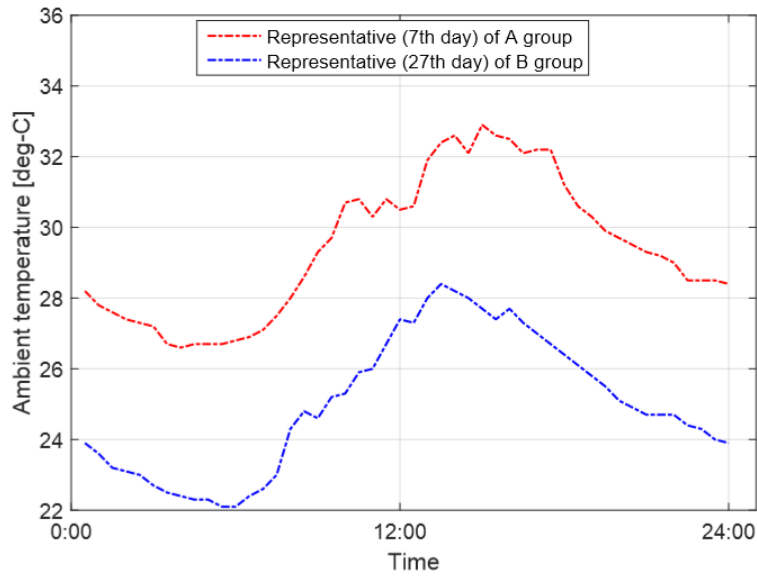
(a) 30 sequential combined energy costs



(b) Two clustering groups for 30 sequential energy costs
(Occurrence probabilities for A and B groups: 0.56 and 0.44 respectively)



(c) The centroids and the combined energy costs closest to centroids



(d) Representative ambient temperatures

Fig. 4.10: Determination of representative ambient temperatures

Determination of the optimal DR capacity and simulation results

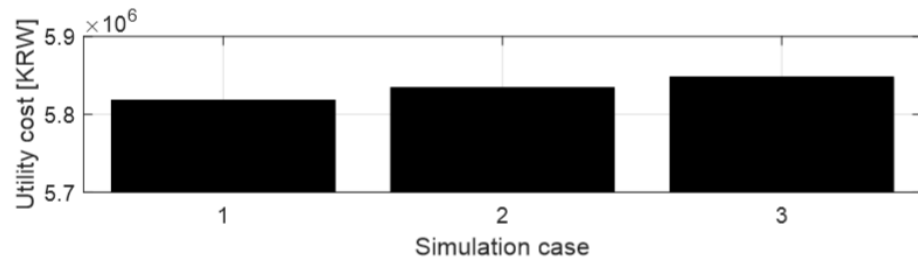
Two representative temperatures obtained in the previous section and their occurrence probabilities were used as scenarios for determining the optimal DR capacity. The optimal DR capacities were determined using the representative temperatures as shown in Table 4.7.

Table 4.7: Optimal DR capacity under simulation cases

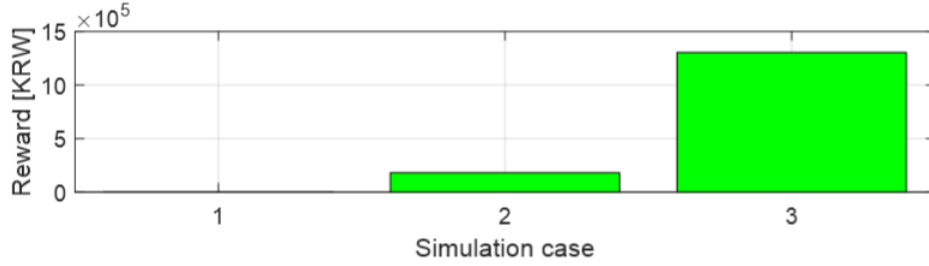
1	Simulation Case		
	1	2	3
Optimal DR capacity [kW]	·	28	200

Simulation Results

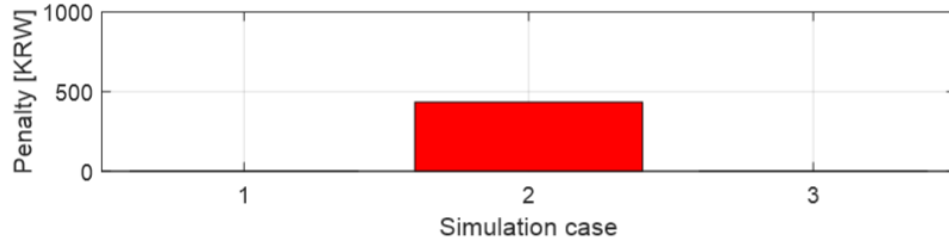
A daily expected value, which is the sum of all average of the obtained 62 expected values based on the DR scenarios was represented in Fig. 4.12. Here, an expected value of daily cost for the electricity purchased from the utility, expected values of daily DR reward, daily DR penalty, and daily energy cost were summarized in Fig. 4.12 (a), (b), (c), and (d) respectively.



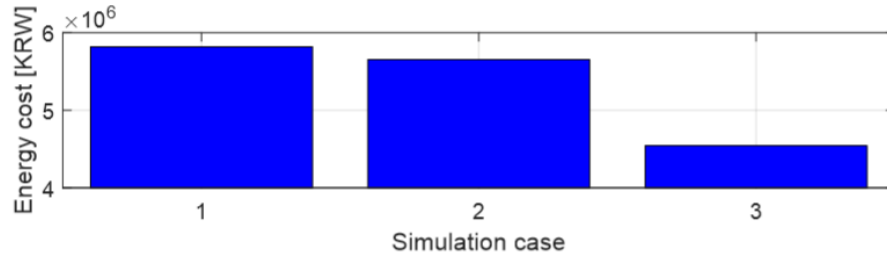
(a) An expected value of daily cost for the electricity purchased from the utility



(b) An expected value of daily DR reward



(c) An expected value of daily DR penalty



(d) An expected value of daily energy cost

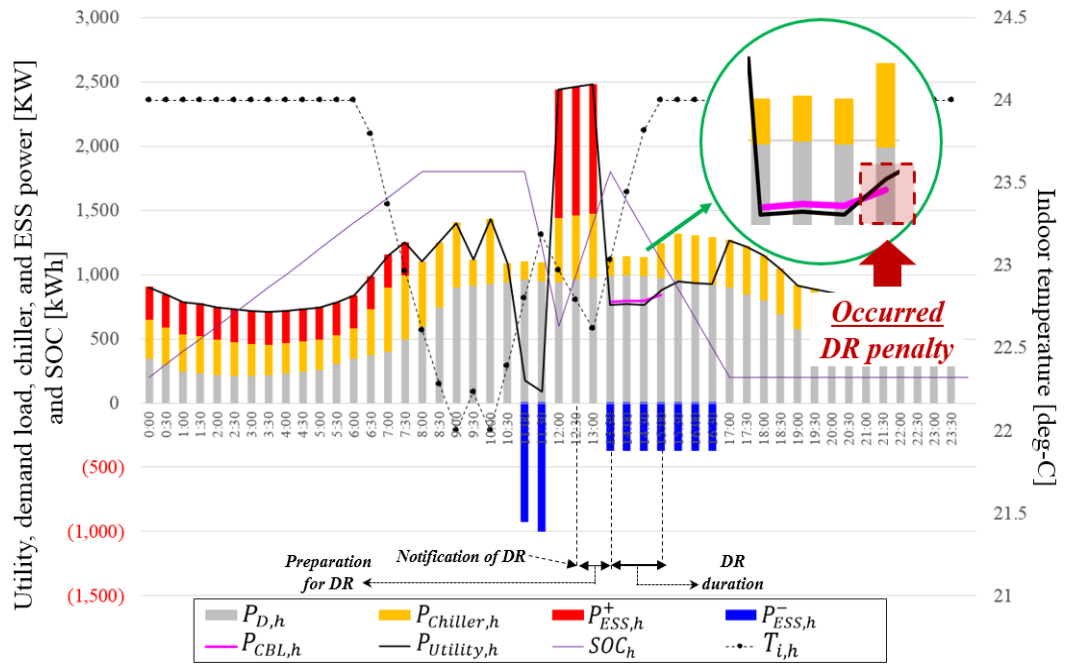
Fig. 4.11: Economic evaluation for every case

An expected value of daily energy cost in Case 1 was 5,818,191 [KRW] as shown in Fig. 4.11 (d). In this case, DR reward and penalty were zero because of not participating DR market. Thus, the expected value of daily cost was same as an expected value of daily cost for electricity purchased from utility as shown in Fig. 4.11 (a). On the other hand, an expected value of daily cost in Case 2 was 5,715,337 [KRW] as shown in Fig. 4.11 (d). More specifically, although, an expected value of daily cost for electricity purchased from the utility in Case 2 as 5,834,163 [KRW] was higher by 15,972 [KRW] than Case 1, an expected value of daily DR reward of Case 2 was 181,546 [KRW]. And an expected value of daily DR penalty was 434 [KRW]. More specifically, the penalty was observed as shown in Fig. 4.11 (c). Since, on a hot day, chiller system consumed its electric energy considering both of minimal energy cost and the specified comfortable temperature range

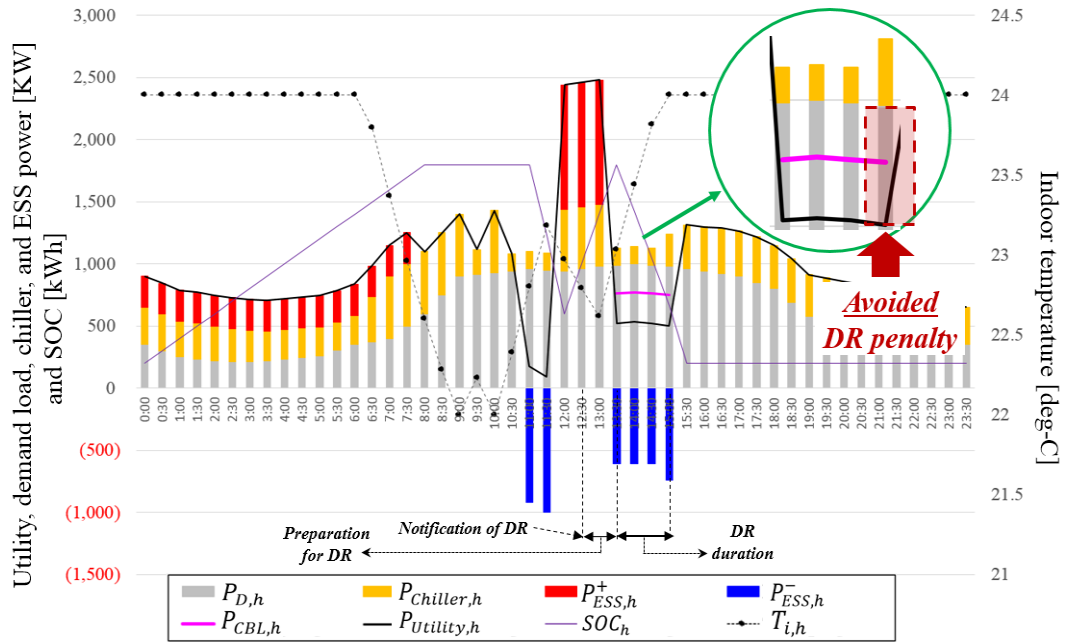
before a DR event notification. When a DR event occurred at 12:30, chiller system heavily operated as maximum power output for DR during preparation for DR. However, finally DR penalty happened from 14:30 to 15:30 because chiller system needed to consume its electric energy for holding indoor temperature between 22 [deg-C] and 24 [deg-C] by eq. (4.36) during DR duration. At this time, ESS is only charged or discharged for minimal energy cost based on TOU tariff regardless of the DR event. As a result, the end-user could not utilize the chiller system as a DRR.

On the other hand, an expected value of daily cost for electricity purchased from utility in Case 3 was 5,847,825 [KRW]. It was the highest value compared to Case 1 and Case 2. This is because disturbance of DR operation affected to TOU optimal operation. An expected value of daily DR reward was 1,303,422 [KRW] in Case 3, but also DR penalty did not appear compared to Case 2 shown in Fig. 4.13 (a) and (b). More specifically, obtained optimal operations of chiller system and ESS were same as the results of Fig. 4.12 (a) before notification of DR. By employing the proposed method, when notifying the DR event, ESS was significantly discharged to avoid DR penalty from 14:30 to 15:30 including DR duration, as much as replacement for holding comfortable temperature range of chiller system. In other words, most of the energy usage of chiller system for comfortable indoor temperature was consumed by ESS discharging instead of the utility for satisfying no penalty. From this results, we found that the co-operation between chiller system and ESS can be effectively avoided DR penalty threat.

Furthermore, ESS was charged as preparation for DR and was discharged for maximum DR reward during DR duration when a DR signal is informed. This co-operation between chiller system and ESS for DR is the main advantage in this paper. The average of the expected values of daily cost for each of 62 temperatures was calculated at 4,544,403 [KRW] and was lower than Cases 1 and 2. Especially, when ESS had enough discharging energy as a DRR, as much as replacement for pre-cooling of chiller system, it was only discharged for DR in specified DR duration to prevent excessive power consumption as pre-cooling of chiller system during preparation for DR.



(a) When DR scenario 1, obtained optimal operations on a hot day in Case 2
(DR penalty: 358,400 [KRW])



(b) When DR scenario 1, obtained optimal operations on a hot day in Case 3
(DR penalty: 0 [KRW])

Fig. 4.12: DR Penalty analysis for Case 2 and Case 3

4.4 Conclusion

This chapter proposed a method for determining the optimal DR capacity using chiller system and ESS in a COB. The proposed DR scheme optimizes the operation of chiller system and ESS in terms of minimum expected energy cost considering TOU tariff and the Korean DR market as DR participants' perspective. Uncertainties in ambient temperature and the DR timing and amount of reduction are considered as scenarios. The proposed scheme is particularly recommended in a COB with chiller system and ESS, which can be economically or variously used because the ESS introduction cost is still expensive. Through simulated case studies, the authors verified the effectiveness of the proposed scheme. The major advantages of the proposed DR scheme are summarized as follows:

- e. Operation of chiller system and ESS is scheduled by an EMS in a COB and it provides more economically efficient use of electricity.
- f. Proposed CBL can be realized day-ahead operation/ rescheduling in the DR day for a minimum energy cost
- g. Maximum DR profit can be obtained regardless of DR event and ambient temperature.
- h. Reducing penalty threat
- i. Comfort indoor temperature are guaranteed regardless of DR event

Chapter 5. Conclusion

The major findings and conclusions of this thesis are summarized as follows.

In Chapter 1, we reviewed global warming issue due to greenhouse emissions generated by exhaust gases from fossil fuel combustion and industrial processes etc. Opportunities for improving energy efficiency in residences, buildings, and industrial facilities were explained in order to reduce greenhouse emissions. Also, Market participation for emergency DR programs in U.S and Korea were introduced as end-user's perspectives. Major promising demand response resources such chiller system as thermal mass control (pre-cooling) and energy storage system as specified discharging in a commercial building were discussed. And then, this study stated optimization problems associated with uncertain DR event signal and ambient temperature for operation scheduling through emergency DR program.

In Chapter 3, the reasons for the optimal operation scheduling while end-users participant to the Korean DR market were referred; uncertain DR event and ambient temperature would affect DR low reward and high penalty through the DR market. The proposed DR energy management consists of day-ahead scheduling without temperature forecast error, day-ahead scheduling with temperature forecast error and rescheduling on operation day. Day-ahead scheduling without temperature forecast error can be applied to no difference case between day-ahead forecast value and actual value. If day-ahead temperature forecast value has large difference with actual value, the proposed method for day-ahead scheduling with temperature forecast error can be used. Then, if the actual temperature variation control range for day-ahead temperature, the proposed rescheduling was executed on operation day. As a result, the optimal operation scheduling was achieved for obtaining maximum DR reward and avoiding penalty under scenarios in DR event and ambient temperatures through TOU tariff and the Korean DR market. Additionally, Pre-cooling of chiller system was achieved considering both of minimal energy cost and DR during preparation for DR. Resultant indoor temperatures were still sustained within the comfort range regardless of pre-cooling and the DR event. ESS was intensively discharged for maximum DR reward based on requested curtailment during DR duration. Furthermore, co-operation between chiller system and ESS was contributed for minimal energy cost.

In Chapter 4, it proposed a method for determining the optimal DR capacity considering a COB with chiller system and ESS through the TOU tariff and the Korean DR market. The proposed DR method is composed of two main procedures; determination of the optimal DR capacity and determination of the representative ambient temperature. The optimization problem for determining the optimal DR capacity is formulated by a mixed integer linear programming (MILP). The objective function minimizes an expected value of daily energy cost with scenarios applied

representative ambient temperatures and DR requirements. A determination problem for the representative ambient temperatures was determined by the k-means clustering algorithm, in which daily minimal energy cost depending on an assumed DR event under a given ambient temperature was used as mining data. As a result, we found the optimal DR capacity was effectively determined by the proposed method for determining a pair of effective representative ambient temperatures. The proposed DR algorithm determined the optimal DR capacity, shift demand from peak periods to off-peak periods and reduce the energy costs in a COB. The proposed co-operation between chiller system and ESS was effectively avoided DR penalty threat. Furthermore, ESS was charged as preparation for DR and was discharged for maximum DR reward during DR duration when a DR signal is informed.

Acknowledgment

Completion of this doctoral dissertation was possible with the support of several people. I would like to extend thanks to the many people who so generously contributed to the work presented in this thesis.

Firstly, I would like to express my sincere gratitude to my enthusiastic supervisor Prof. Hiroyuki Kita for the continuous support of my Ph.D study and related research, for his tremendous academic support, patience, and motivation. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my Ph.D study. I am also hugely appreciative to Associate Prof. Ryoichi Hara, who has been a truly dedicated to his role as my secondary supervisor for his critical or scientific advice, extensive knowledge and many insightful discussions for my Ph.D study. I thank Assistant Prof. Eiichi Tanaka for his tremendous academic support and the facilities provided to carry out the research work.

Besides my advisor, I would like to thank the rest of my PhD committee: Prof. Hagime Igarashi, Prof. Satoshi Ogasawara for their insightful comments and encouragement, but also for the hard question which incited me to widen my research from various perspectives.

Specially, I would like to appreciate Prof. Daeseok Rho who was my supervisor during the master's course, not only for providing me with a fantastic lab training, but also nurturing my enthusiasm for upcoming new electric power systems. I also have to thank Dr. Miyoung Kim for her warm encouragement.

I would like to acknowledge the whole staff of graduate school of information science and technology at Hokkaido University in providing an economic support through a research assistant (RA) program.

Finally, but by no means least, thanks go to my parents and younger sister for almost unbelievable support. They are the most important people in my world and I dedicate this doctoral dissertation to them.

References

- [1] Intergovernmental Panel on Climate Change (IPCC), The Intranet Architecture: Summary for policymakers of the IPCC's Fifth Assessment Report (AR5) [Online]. Available: http://ar5-syr.ipcc.ch/topic_summary.php
- [2] Intergovernmental Panel on Climate Change (IPCC), The Intranet Architecture: Observed changes of the IPCC's Fifth Assessment Report (AR5) [Online]. Available: http://ar5-syr.ipcc.ch/topic_observedchanges.php
- [3] Federal Energy Regulatory Commission (FERC), The Intranet Architecture: 2007 Assessment of Demand Response and Advanced Metering (Staff Report) [Online]. Available: <http://www.ferc.gov/legal/staff-reports/09-07-demand-response.pdf>
- [4] AEIC Load Research Committee The Intranet Architecture: Demand Response Measurement & Verification [Online]. Available: https://www.smartgrid.gov/files/demand_response.pdf
- [5] U.S. Department of Energy, a report to the united states congress pursuant to section 1252 of the energy policy act of 2005, The Intranet Architecture Benefits of demand response in electricity markets and recommendations for achieving them [Online]. Available: http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/DOE_Benefits_of_Demand_Response_in_Electricity_Markets_and_Recommendations_for_Achieving_The_m_Report_to_Congress.pdf
- [6] PJM Interconnection LLC (PJM), The Intranet Architecture: PJM emergency load response program [Online]. Available: <https://www.pjm-eis.com/~media/committees-groups/committees/mc/20111020/20111020-item-09-emergency-load-response-cost-allocation-tariff-and-oa-revisions.ashx>
- [7] New York independent system operator (NYISO), The Intranet Architecture: Emergency Demand Response Program Manual [Online]. Available: http://www.nyiso.com/public/webdocs/markets_operations/documents/Manuals_and_Guides/Manuals/Operations/edrp_mnl.pdf
- [8] ISO New England (ISO-NE), The Intranet Architecture: ISO New England Load Response Program [Online]. Available: https://www.google.co.jp/url?sa=t&rct=j&q=&esrc=s&source=web&cd=5&cad=rja&uact=8&ved=0ahUKEwin7ZzpxbjNAhUEF5QKHQuyD4QQFgg7MAQ&url=https%3A%2F%2Fwww.mwcog.org%2Fuploads%2Fcommitteedocuments%2FIV5fX1hd20071218115823.doc&usq=AFQjCNFe3yQSzyj_LkT00FaQQyEtZVitQ&sig2=O0BZo5NlsgQGKX6Dk0hGw&bvm=bv.124817099,d.dGo
- [9] Korea power exchange (KPX), The Intranet Architecture: Market role for demand response market [Online]. Available: www.kpx.or.kr/www/downloadBbsFile.do?atchmfnlNo=23426

- [10] Federal Energy Regulatory Commission (FERC), The Intranet Architecture: Order No. 745 [Online]. Available: <http://www.ferc.gov/EventCalendar/Files/20110315105757-RM10-17-000.pdf>
- [11] Manisa Pipattanasomporn., Murat Kuzlu; Saifur Rahman " An Algorithm for Intelligent Home Energy Management and Demand Response Analysis", IEEE Trans. Smart Grid, vol. 3, no. 4, pp. 2166 - 2173, Dec. 2014
- [12] Sereen Althaher., Pierluigi Mancarella., Joseph Mutale" Automated Demand Response from Home Energy Management System Under Dynamic Pricing and Power and Comfort Constraints", IEEE Trans. Smart Grid, vol. 6, no. 4, pp. 1874 - 1883, July. 2015
- [13] Yue Min Ding., Seung Ho Hong., Xiao Hui Li" A Demand Response Energy Management Scheme for Industrial Facilities in Smart Grid", IEEE Trans. Industrial Informatics, vol. 10, no. 4, pp. 2257 - 2269, Nov. 2015
- [14] D. Murayama., K. Mitsumoto., Y. Takagi; Y. Iino., S. Yamamori" Smart grid ready BEMS adopting model-based HVAC control for energy saving", in Proc. 2012 IEEE
- [15] Transmission and Distribution Conference and Exposition (T&D). pp. 1-6.
- [16] Jonson controls, The Intranet Architecture: Demand Response in Commercial Buildings [Online]. Available: http://www.buildingefficiencyinitiative.org/sites/default/files/legacy/InstituteBE/media/Library/Resources/Smart-Grid_Smart-Building/CommercialBuildingsDR.pdf
- [17] Pacific Northwest national laboratory, The Intranet Architecture: The Role of Energy Storage in Commercial Building [Online]. Available: http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-19853.pdf
- [18] Hara Akihiro., Kitamura Mitsuhiro (NEC), The Intranet Architecture: "Smart Buildings" (BEMS) to Optimize the Energy Supply and Demand Control of Buildings [Online]. Available: <http://www.nec.com/en/global/techrep/journal/g12/n01/pdf/120117.pdf>
- [19] EnergyConservation.sg, The Intranet Architecture: "HVAC System Description [Online]. Available: http://www.energyconservation.sg/index.php/hvac-system-description-en#condenser_water_pump_unit
- [20] Alan Richardson (NEC), the Intranet Architecture: HVAC Energy Efficiency in Commercial Buildings [Online]. Available: <http://www.slideshare.net/AlanRichardson/hvac-energy-efficiency-in-commercial-buildings>
- [21] Baojie Mu., Yaoyu Li., John E., Seem Bin Hu " A Multivariable Newton-Based Extremum Seeking Control for Condenser Water Loop Optimization of Chilled-Water Plant ", The American society of mechanical engineers (ASME), Journal of Dynamic Systems, Measurement, and Control, vol. 137, no. 11, pp. 1 - 10, Nov. 2013
- [22] Jim Eyer, Garth Corey "Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide", Report, Sandia National Laboratories, Feb 2010.
- [23] The International Renewable Energy Agency (IRENA), the Intranet Architecture: Battery storage for renewables: Market status and technology outlook [Online]. Available: http://www.irena.org/documentdownloads/publications/irena_battery_storage_report_2015

.pdf

- [24] Steve Blume (Energy storage council), the Intranet Architecture: 2015 Battery storage for renewables: Market status and technology outlook [Online]. Available: http://neca.asn.au/sites/default/files/media/state_nsw/News%20&%20Views/ESC%20Global%20Energy%20Storage%20Report_2015.pdf
- [25] Green energy storage, the Intranet Architecture: Market trends for ESS [Online]. Available: <http://www.greenenergystorage.eu/en/market-overview/>
- [26] GS Neotek, the Intranet Architecture: ESS system configuration [Online]. Available: <http://www.gsneotek.co.kr/en/business/env/ess.jsp>
- [27] John Soden, Robin Aldina, Dalia Patiño-Echeverri, "Guide to Inform Institutions about Participation in PJM's Demand Response Programs", " Master. D. dissertation, Nicholas School of the Environment, Duke Univ., Durham, 2013.
- [28] NYISO Auxiliary Market Operations. (2013, October). The Intranet Architecture: Emergency Demand Response Program Manual, NYISO, NY. [Online]. Available: http://www.nyiso.com/public/webdocs/markets_operations/documents/Manuals_and_Guides/Manuals/Operations/edrp_mnl.pdf
- [29] AEIC Load Research Committee (2014, June). The Intranet Architecture: Measurement and Verification of Demand Reduction Value from Demand Resources, ISO-NE, MA. [Online]. Available: https://www.smartgrid.gov/files/demand_response.pdf
- [30] R. Walawalkara, S. Fernandsa, N. Thakura, K. and R. Chevva, "Evolution and current status of demand response (DR) in electricity markets: Insights from PJM and NYISO ", The International Journal ENERGY., vol. 35, pp. 1515–1866, April 2010.
- [31] Korea power exchange, The Intranet Architecture: Market Operation Regulation.[Online].Available:https://www.kpx.or.kr/KOREAN/servlet/BOController?cmd=download&url=/freeboard/&filename=%C1%F6%B4%C9%C7%FC%20%BC%F6%BF%E4%C0%DA%BF%F8%BD%C3%C0%E5%20%BF%EE%BF%B5%B1%D4%C4%A2%20%B0%B3%C1%A4_2013_7_4.pdf
- [32] Local observations of Korea Meteorological Agency, The Intranet Architecture: Automatic Weather System [Online]. Available:<http://www.kma.go.kr/weather/observation/currentweather.jsp>
- [33] S. Taylor, P. Dupont, B. Jones, T. Hartman, M. Hydeman, "Cool Tools Chilled Water Plant Design and Specification Guide", PG&E Cool Tools Report CT-016, May 2000
- [34] "Thermal Environmental Conditions for Human Occupancy", The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard: ANSI/ASHRAE 55-1992
- [35] Local observations of Korea Meteorological Agency: <http://www.kma.go.kr/weather/observation/currentweather.jsp>
- [36] Y. Linde, A. Buzo, and R.M. Gray. "An algorithm for vector quantizer design. IEEE Transactions on Communications", 1:84–95, 1980.
- [37] Aghaei, J., Alizadeh, M.-I. "Critical peak pricing with load control demand response

- program in unit commitment problem", IET Trans. Generation, Transmission & Distribution., vol. 7, no. 7, pp. 681-690, Jan. 2013
- [38] U.S. Department of Energy, Intranets: benefits of demand response in electricity markets and recommendations for achieving them[Online].Available:http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/DOE_Benefits_of_Demand_Response_in_Electricity_Markets_and_Recommendations_for_Achieving_Them_Report_to_Congress.pdf
- [39] Joonho, S., Ryoichi, H., Hiroyuki, K., Eiichi T." Energy Management considering Demand Response Resource in Commercial Building with Chiller System and Energy Storage Systems", in Proc. 2014 IEEE Power Engineering and Renewable Energy. pp. 96-101.
- [40] Joonho, S., Ryoichi, H., Hiroyuki, K., Eiichi T." Operation Scheduling considering Demand Response in a Commercial Building with Chiller System and Energy Storage System", in Proc. 2015 IEEE PES Asia-Pacific Power and Energy Engineering (APPEEC). pp. 1-5.
- [41] Jayadev, V., Swarup, K.S. "Optimization of microgrid with demand side management using Genetic Algorithm," in Proc. 2013 IET Power in Unity: a Whole System Approach, Conf., pp. 1-6.
- [42] Sankur, M. ; Arnold, D. ; Auslander, D. "An architecture for integrated commercial building demand response," in Proc. 2013 IEEE Power and Energy Society General Meeting Conf., pp. 1-5.
- [43] Puradbhat, S. ; Banerjee, R. "Estimating demand side management impacts on buildings in smart grid," in Proc. 2014 IEEE Innovative Smart Grid Technologies – Asia Conf., pp. 635-640.
- [44] Asano, H., Takahashi, M., Yamaguchi, N., Bando, S. "Demand participation in the power market by load curtailment of building energy use and distributed generation of commercial customers in Japan," in Proc. 2009 Clean Electrical Power Conf., pp. 520-525.
- [45] Lau, R., Ayyorgun, S., Siun Chuon Mau, Eswaran, S., Misra, A., Bushby, S., Holmberg, D. "Strategy and modeling for building DR optimization", in Proc. 2014 IEEE Smart Grid Communications., pp. 381-386.
- [46] Aldina, Robin and Soden, John (2013, May). The Intranet Architecture: Guide to Inform Institutions about Participation in PJM's Demand Response Programs. Duke University, Durham, NC. [Online]. Available: <http://dukespace.lib.duke.edu/dspace/handle/10161/6674>
- [47] Mohagheghi, S." Communication services and data model for demand response", in Proc. 2012 IEEE Online Conference on Green Communications., pp. 80-85.
- [48] Korea power exchange, The Intranet Architecture: Trading results of intelligent DR market [Online]. Available: <https://www.kpx.or.kr/KOREAN/servlet/MICController>
- [49] Kaufman L., and P. J. Rousseeuw. "Finding Groups in Data: An Introduction to Cluster Analysis" Hoboken, NJ: John Wiley & Sons, Inc., 1990.
- [50] Y. Linde, A. Buzo, and R.M. Gray. "An algorithm for vector quantizer design," IEEE Trans. Power Delivery Communications, vol. 28, pp. 84-95, Apr. 1980.
- [51] Local observations of Korea Meteorological Agency, The Intranet Architecture:

- Automatic Weather System [Online]. Available:
<http://www.kma.go.kr/weather/observation/currentweather.jsp>
- [52] Local observations of Korea Meteorological Agency, The Intranet Architecture: Short-range Forecast, [Online]. Available: <http://www.kma.go.kr/index.jsp>
- [53] Korea power exchange (KPX), The Intranet Architecture: Power Market Statistics in 2014 [Online]. Available:
https://epsis.kpx.or.kr/epsis/ekkn/board/n/list.do?bbs_id=100245&cd_upper=100200&left_pos=100245
- [54] Korea power exchange (KPX), The Intranet Architecture: Electricity-trading system of demand response resources [Online]. Available: http://dr.kmos.kr/main/system_01.html

Appendix A K-means clustering algorithm

K-means clustering algorithm is one of the simplest unsupervised learning algorithms and is the simplest partitioning method for clustering analysis and widely used in data mining applications. It aims to partition in observations into k clusters in which each observation belongs to the cluster with the nearest mean, serving as a prototype of the cluster.

That is, the centroid of each of the k clusters and its occurrence probability to the each centroid can be obtained by in following procedures [29]-[33].

Given k , the k-means clustering algorithm consists of four steps.

- Step 1. Select initial centroids at random as shown in Fig. A-1
- Step 2. Assign each object to the cluster with the nearest centroid as shown in Fig. A-2
- Step 3. Compute each centroid as the mean of the objects assigned as shown in Fig. A-3 to it. That is, it calculates point-to-cluster-centroid distances of all observations to each centroid in eq. (A.1). That is, K-means minimizes within-cluster point scatter.

$$C(i) = \arg \min \|x_i - m_k\|^2, i = 1, \dots, N \quad (\text{A.1})$$

where $C(i)$, x_i and m_k are cluster number for the i th observation, cluster number for the i th observation, data points and the mean vector of the k th cluster respectively.

Here, m_k can be represented by

$$m_k = \frac{\sum_{i:C(i)=k} x_i}{N_k}, k = 1, \dots, K \quad (\text{A.2})$$

where N_k is the number of observations in k th cluster.

- Step 4. Iterate above previous two steps until convergence, which means cluster assignments do not change, or the maximum number of iterations is reached as shown in Fig. A-4~A-8

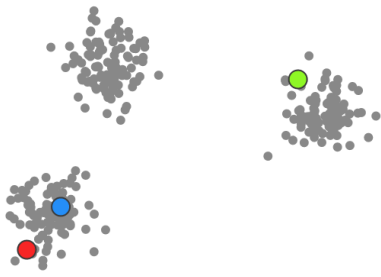


Fig. A-1 randomly generate K initial

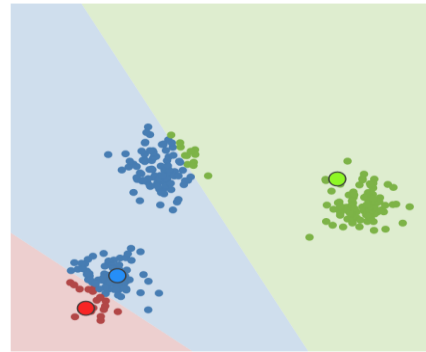


Fig. A-2 associate every observation with the nearest means

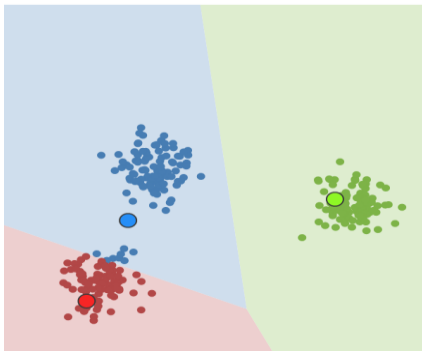


Fig. A-4 iterate above previous step 2

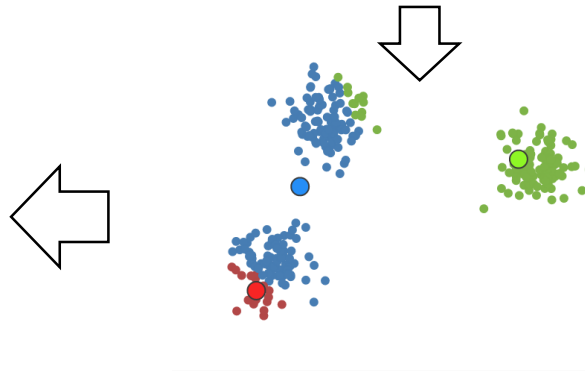


Fig. A-3 the centroid of each of the k becomes the new clusters becomes the new mean.

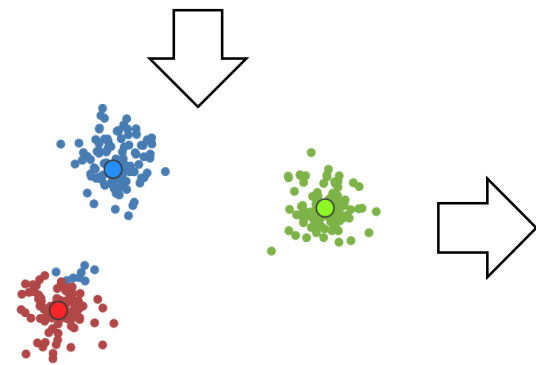


Fig. A-5 iterate above previous step 3

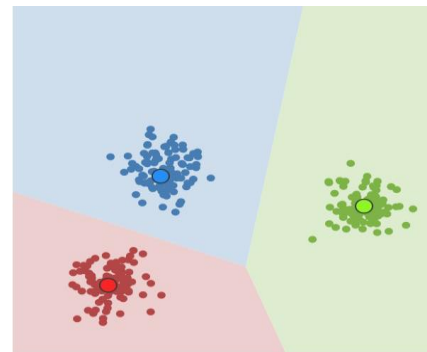


Fig. A-6 iterate above previous step 2

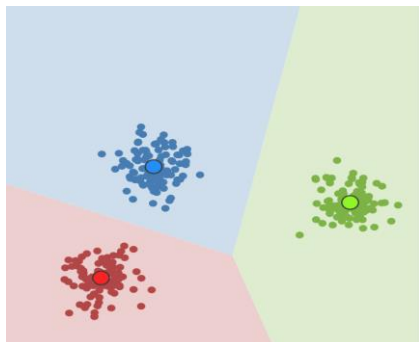


Fig. A-8 end when convergence has been reached

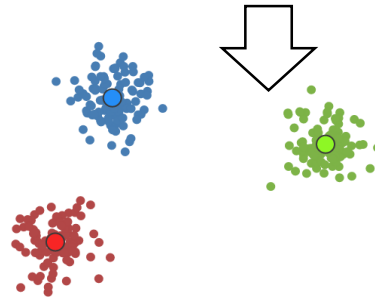


Fig. A-7 iterate above previous step 3

Appendix B The silhouettes analysis

The silhouettes constructed below are useful when the proximities are on a ratio scale (as in the case of Squared Euclidean distances) and when one is seeking compact and clearly separated clusters. Indeed, the definition makes use of average proximities as in the case of group average linkage, which is known to work best in a situation with roughly k clusters. In order to construct silhouettes, we only need two things: the partition we have obtained (by the application of some clustering technique) and the collection of all proximities between points. The silhouette value of a point shown in Fig. B-1 is a measure of how similar a point is to points in its own cluster compared to points in other clusters in the following three steps

Step 1. For the point i , calculate its average distance to all other points in its cluster A. Call this value $a(i)$.

Step 2. For the point i and cluster B not containing the point i , calculate the point's average distance to all the points in the cluster B, Find the minimum such value with respect to all clusters; call this value $b(i)$

Step 3. For the point i , the silhouette value is calculated by eq. (B.1)

$$s(i) = \frac{b(i) - a(i)}{\max\{a(i), b(i)\}} \quad (\text{B.1})$$

The number $s(i)$ is obtained by combining $a(i)$ and $b(i)$ as follows:

$$s(i) = \begin{cases} 1 - \frac{a(i)}{b(i)}, & \text{if } a(i) < b(i) \\ 0, & \text{if } a(i) = b(i) \\ \frac{b(i)}{a(i)} - 1, & \text{if } a(i) > b(i) \end{cases} \quad (\text{B.2})$$

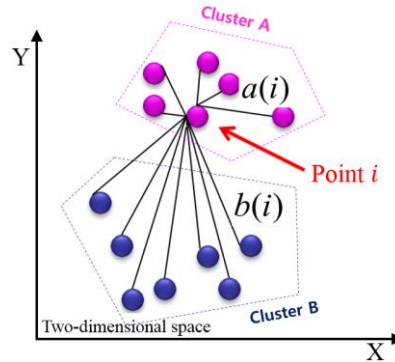
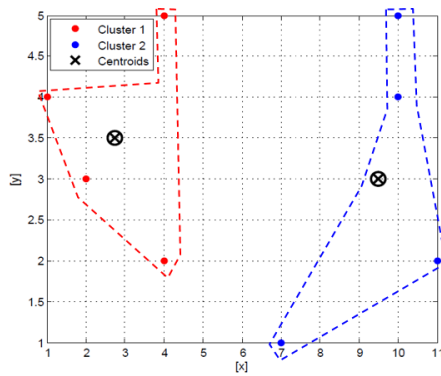


Fig. B-1 Concept of calculating the silhouette value

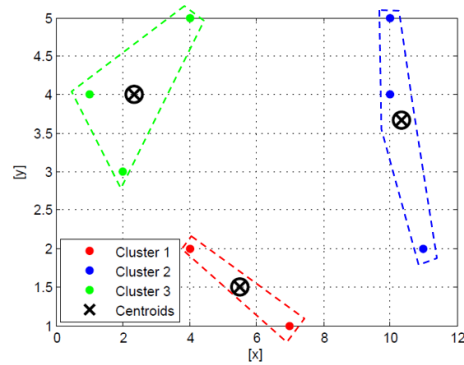
The silhouette coefficient, which is the average silhouette value over all points is estimated for a quantitative measure that can assess the quality of a clustering. The silhouette coefficient, can vary between -1 and 1 in (B.3). When the silhouette coefficient is negative, it means classified wrong or undesirable because this corresponds to a case in which $a(i)$, the average distance to points in the cluster, is greater than $b(i)$, the minimum average distance to points in another cluster. The silhouette coefficient classified well should be positive ($a(i) < b(i)$), and for $a(i)$ to be as close to 0 as possible, since the coefficient assumes its maximum value of 1 when $a(i) = 0$.

$$-1 \leq s(i) \leq 1 \quad (\text{B.3})$$

For example, 8 points scattered in the two-dimensional space can be divided into 2 or 3 clusters as shown in Fig. B-2 (a) and (b) respectively. Each silhouette value given by in (B.1) is calculated for 2 or 3 clusters as shown in Fig. B-3 (a) and (b). 2 cluster is well-matched to its own cluster, and poorly-matched to neighboring clusters. Since the silhouette coefficient (0.552) at 2 cluster was higher than 3 cluster (0.416).

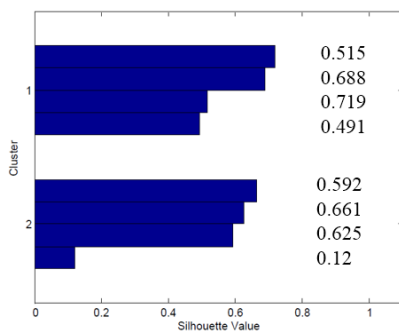


(a) 8 points divided into 2 clusters

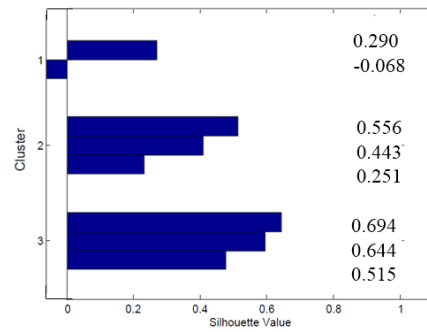


(b) 8 points divided into 3 clusters

Fig. B-2 a example for kmeans clustering algorithm



(a) Silhouette values of the points in Fig. B-2 (a) (b) Silhouette values of the points in Fig. B-2 (b)
(The silhouette coefficient: **0.552**)



(The silhouette coefficient: **0.416**)

Fig. B-3 Silhouette values based on the clustering data in Fig. B-2