Demand response potential of customer-side integrated energy system

Wei Zhao*, Jingtao Wang and Dongmei Jiang
NARI Technology Company Limited Beijing Energy Technology Branch, Beijing, China

*Corresponding author: zhaowei6@sgepri.sgcc.com.cn

Abstract. Fully utilizing the adjustable potential of integrated demand response (IDR) in customer-side multi-energy system is the effective way to improve energy efficiency, decrease energy cost during supply and use, and reduce the risk of default on the customer-side. In this paper, we propose an adjustable potential analysis method of customer-side IDR considering multi-energy coupling and conversion relationships. First, we classify the loads based on energy characteristics, establish the corresponding load response model. Then, construct an adjustable potential analysis model which is constrained by multi-energy output and energy balance before and after, aimed at lowest energy operation cost on the customer-side, using linear programming algorithm for model optimization. Finally, verify the correctness and effectiveness of the model by analyzing the impact of loads reduction on response in experimental case.

1. Introduction
IDR is an extension of traditional power demand response (DR) in integrated energy system (IES) [1]. The coupling relationship among multi-energy in IES is complex, also the operation characteristics of different energy devices, which pose great challenges to the analysis of the adjustable potential. The coupling and complementary relationship of multi-energy in IES provides the possibility to change energy consumption behaviour [2]. The premise of fully tapping IDR potential is not to affect the use of the customer-side. On this basis, it can maximize the complementary role of multi-energy, reduce the default risk on the customer-side, improve energy efficiency, and reduce energy supply and consumption costs effectively.

Some research studies have been carried out on IDR of IES. Authors in [3] establish a user-optimized aggregation model by analysing residents’ DR with the goal of minimum load aggregators’ cost. Authors in [4] construct an integrated price demand response model based on peak-valley electricity/heat prices and a transformational demand response model based on electricity-to-gas, electric refrigerators, and electric boilers with the economics and environmental protection of the IES as the target. Authors in [5] come up with a combined peak load adjustment strategy aimed building flexible loads where central air conditioning is the control object, and analyse the demand response potential of the flexible load. Authors in [6] conduct a research on the impact of the uncertainty of DR in the IES based on the combined cooling and heating power supply system. Authors in [7] establish a multi-time-scale optimal scheduling model for demand response and discuss the impact of multi-time-scale analysis in the IES.
The above literature demonstrates the importance to study the optimal configuration of multi-energy coupling and multi-system coupling in IDR, but there is little research on the analysis method of adjustable potential considering the coupling relationship of multi-energy such as electricity, gas, cold and heat on the customer-side. Therefore, this paper focuses on the analysis method of the adjustable potential of customer-side IDR considering multi-energy coupling and conversion relationships. An analysis model of maximum adjustable potential on the customer-side including adjustable loads, energy storage, distributed energy and energy conversion equipment was built. The model is solved with the target of the lowest operating cost on the customer-side to analysis the maximum adjustable potential of the customer-side IDR.

2. IES model of customer-side IDR

2.1. Composition of IES
The schematic diagram of IES system structure is shown in Figure 1. There are three parts in this IES: external energy supply, customer-side energy supply and storage, and energy conversion. The external energy supply consists of electric supply and the external gas supply, which is used as the external energy supply of customer-side IES. The customer-side energy supply and storage equipment is defined as customer-side energy supply and storage, including photovoltaic (PV), wind power plant (WPP), electricity storage device (ESD), cold energy storage (CES) and thermal energy storage (TES). WPP and PV maximize the use of natural conditions for power generation on the basis of meeting the system power generation constraints. Energy coupling device with energy conversion relationship is defined as energy conversion, which is used to realize the conversion of electricity, gas, cold and heat, including: gas-fired generator (GG), absorption chiller (AC), heat pump (HP), electric boiler (EB). GG and AC form a combined cooling and heating power system which can convert gas into electrical energy, cold and heat. HP can convert electrical energy into cold and heat to meet loads demand, and excess energy is stored in TES or CES.

![Figure 1. IES system structure](image)

2.2. Customer-side loads response model
According to the classification of the customer-side loads by the power DR, the customer-side demand response loads can be divided into reducible loads, shiftable loads and convertible loads. And the corresponding loads response model is established in the following.

2.2.1. Reducible loads. Reducible loads refer to the loads that the user can partially reduce or increase according to their own demand and price. The loads type can be divided into electrical loads and cold loads. Typical representatives of reducible loads are lightings, air-conditioning terminal controllers, etc. The model is shown as follows:
Where, \( P_{\text{cut}} \) and \( P_{\text{cut}} \) are continuous variables which represent the reduction of electrical loads and cold/heat loads that can be reduced. \( b_{\text{cut}} \) and \( b_{\text{cut}} \) are Boolean variables which represent the reduction state of customer-side electrical loads and the cold/heat loads. Superscript \( i \) is the time index of the demand response period, and \( i \in \{0,1,\ldots,n,n+1,\ldots,n+m,\ldots,l-1\} \). \( n \) is the serial number of the demand response start time in the total control time, and \( m \) is the number of time periods during which the demand response continues, and \( l \) is the number of unit time periods within the control time. \( P_{\text{cut}}^{\min}, P_{\text{cut}}^{\max} \) and \( P_{\text{cut}}^{\max} \) are the minimum and maximum reductions for reducible loads.

2.2.2. Shiftable loads. The shiftable loads are also divided into electrical device and cooling/heating device. Generally, there are two working modes including charging and discharging. In a certain time range, the loads and working time of these device are adjustable, and the total energy consumption is approximately unchanged. Typical device includes: V2G electric vehicles, ESD, CES, etc. When modelling the shiftable loads, we consider the overall operating characteristics of the device such as storage status, charging and discharging power.

1) Electric storage loads model. There are two continuous variables \( P_{\text{ch}} \) and \( P_{\text{ch}} \) that are charging power and discharging power, respectively. Also, Boolean variables \( b_{\text{ch}} \) and \( b_{\text{ch}} \) representing the state of charging and discharging which exist in the model where 0 means not working and 1 means working. The electric storage loads model is as follows:

\[
\begin{align*}
\underline{P}_{\text{ch}}^{\min} b_{\text{ch}}^i & \leq P_{\text{ch}}^i \leq \overline{P}_{\text{ch}}^{\max} b_{\text{ch}}^i \\
\underline{P}_{\text{dis}}^{\min} b_{\text{dis}}^i & \leq P_{\text{dis}}^i \leq \overline{P}_{\text{dis}}^{\max} b_{\text{dis}}^i \\
\overline{P}_{\text{ch}}^{\min} + \overline{P}_{\text{dis}}^{\min} & \leq 1 \\

P_{\text{ch,net}} & = -P_{\text{dis}}^i + P_{\text{ch}}^i \\
SOC_{\text{ch}} & = SOC_{\text{ch}}^{\min} + (t \times \eta_{\text{ch}} \times P_{\text{ch}}^i - t \times P_{\text{dis}}^i / \eta_{\text{dis}}) / E_{\text{ch,net}} \\
SOC_{\text{ch}}^{\min} & \leq SOC_{\text{ch}} \leq SOC_{\text{ch}}^{\max}
\end{align*}
\]

Where, \( t \) is the length of the unit time. \( P_{\text{ch}}^{\min} \) and \( P_{\text{ch}}^{\max} \) are minimum and maximum of charging power. \( P_{\text{dis}}^{\min} \) and \( P_{\text{dis}}^{\max} \) are minimum and maximum of discharging power. \( P_{\text{ch,net}} \) is the charging and discharging power of the ESD where the charge is positive and the discharge is negative. \( SOC_{\text{ch}} \) is the state of the ESD. \( SOC_{\text{ch}}^{\min} \) and \( SOC_{\text{ch}}^{\max} \) are the minimum and maximum state of charge. \( \eta_{\text{ch}} \) and \( \eta_{\text{dis}} \) are the charging efficiency and discharging efficiency of the ESD.
2) Cold/heat storage loads model. There are two continuous variables \( P_{\text{ch}} \) and \( P_{\text{dis}} \) that are charging and discharging power of cooling/heating respectively. Also, we set two Boolean variables \( b_{\text{ch}} \) and \( b_{\text{dis}} \) that are the state of charging and discharging. The cold/heat storage loads model is as follows:

\[
\begin{align*}
  b_{i,\text{ch}}^i P_{\text{min}} & \leq P_{i,\text{ch}}^i \leq b_{i,\text{ch}}^i P_{\text{max}}^i \quad (9) \\
  b_{i,\text{dis}}^i P_{\text{min}} & \leq P_{i,\text{dis}}^i \leq b_{i,\text{dis}}^i P_{\text{max}}^i \\
  b_{i,\text{ch}}^i + b_{i,\text{dis}}^i & \leq 1 \\
  P_{i,\text{con}} & = -P_{i,\text{ch}}^i + P_{i,\text{dis}}^i \\
  P_{i,\text{con}} & = \beta \left( P_{i,\text{ch}}^i + P_{i,\text{dis}}^i \right) \\
 \end{align*}
\]

\[
SOC_i^j = SOC_i^{j-1} + \left( t \times \eta_{i,\text{ch}}^j \times P_{i,\text{ch}}^j - t \times P_{i,\text{dis}}^j / \eta_{i,\text{dis}}^j \right) / E_{i,\text{max}} 
\]

\[
SOC_{i,\text{min}} \leq SOC_i^j \leq SOC_{i,\text{max}} 
\]

Where, \( P_{\text{ch}}^\text{min} \) and \( P_{\text{ch}}^\text{max} \) are the minimum and maximum charging power of cooling/heating, \( P_{\text{dis}}^\text{min} \) and \( P_{\text{dis}}^\text{max} \) are the minimum and maximum discharging power of cooling/heating, \( P_i \) is the power consumption of the CES and TES. \( \beta \) is the ratio of the electric power to the charging and discharging cold power. \( SOC \) is the energy state of CES and TES. And \( SOC_{\text{ch}}^\text{min} \) and \( SOC_{\text{ch}}^\text{max} \) are the minimum and maximum of \( SOC_i^j \). \( \eta_{i,\text{ch}}^j \) and \( \eta_{i,\text{dis}}^j \) are the charging and discharging efficiency of CES and TES.

2.2.3. Convertible loads. Convertible loads are the device with energy conversion capability between multi-energy. Reasonable configuration and use of customer-side energy conversion devices can improve demand response ability and user comfort. Typical energy conversion devices include gas-fired generators and electricity cooling device, etc. When modelling the convertible loads, we consider the conversion capacity of multi-energy.

1) Gas-fired generators loads model. Set a continuous variable \( P_{\text{gg}} \) to represent the power of GG. Also, set a Boolean variable \( b_{\text{gg}} \) to represent operation state. The GG loads model is as follows:

\[
\begin{align*}
  b_{i,\text{gg}}^i P_{\text{min}} & \leq P_{i,\text{gg}}^i \leq b_{i,\text{gg}}^i P_{\text{max}}^i \\
  P_{i,\text{con}} & = \eta_{i,\text{gg}}^j \times P_{i,\text{gg}}^i \\
\end{align*}
\]

Where, \( P_{\text{gg}}^\text{min} \) and \( P_{\text{gg}}^\text{max} \) are the minimum and maximum power of GG. \( \eta_{i,\text{gg}}^j \) is the conversion coefficient of gas consumption rate and generating power, which is determined by the gas calorific value and generation efficiency. \( P_{i,\text{con}} \) is the speed of gas consumption for GG.
2) Load model of electricity cooling device. From the perspective of electricity consumption, the electricity cooling device belongs to the load-side device. While, from the perspective of cooling and heating, it belongs to the source device. Therefore, the model should include electricity power and cooling/heating power. We set a continuous variable $P_{i,c}$ to represent cooling/heating power, and a Boolean variable $b_{i,c}$ to represent the state of starting and stopping. The load model of electricity cooling device is as follows:

$$b_{i,c}^j P_{i,c}^{\min} \leq P_{i,c} \leq b_{i,c}^j P_{i,c}^{\max}$$  \hspace{1cm} (18)

$$P_{i,c} = P_{i,c} / COP_{ac}$$  \hspace{1cm} (19)

Where $P_{i,c}^{\min}$ and $P_{i,c}^{\max}$ are the min and max cooling power of electricity cooling device. $COP_{ac}$ is the energy efficiency coefficient of electric cooling device, and $P_{i,c}$ is the power consumption of electric cooling device.

3) Load model of gas cooling device. Gas cooling device consumes gas to generate cold and heat, so the model should include gas consumption speed and cooling/heating power. We set a continuous variable $P_{i,gb}$ to represent cooling/heating power, and a Boolean variable $b_{i,gb}$ to represent the state of starting and stopping. The load model of gas cooling device is as follows:

$$b_{i,gb}^j P_{i,gb}^{\min} \leq P_{i,gb} \leq b_{i,gb}^j P_{i,gb}^{\max}$$  \hspace{1cm} (20)

$$P_{i,gb} = P_{i,gb} / \eta_{gb}$$  \hspace{1cm} (21)

Where $P_{i,gb}^{\min}$, $P_{i,gb}^{\max}$ are the min and max cooling power of the gas cooling device, $\eta_{gb}$ is the energy efficiency coefficient of the gas cooling device, and $P_{i,gb}$ is the gas consumption rate.

2.2.4. Renewable energy output. Renewable energy output $P_{i,e}$ can replace the power grid partly and increase the customer-side demand response. This part of the contribution is affected by uncertain factors such as the weather. Therefore, we get $P_{i,e}$ by the means of forecasting.

3. Adjustable potential analysis model of customer-side IDR

We analyze the combination of various loads and devices and construct an adjustable potential analysis model of customer-side IDR.

3.1. Customer-side IES energy balance constraint

Constraints of electric balance means that the production and consumption of electric in the system must be kept in balance at all times. Constraints are as follows:

$$P_{i,load} = \sum_{i=1}^n P_{i,load} - \sum_{i=1}^n P_{i,ac} = \sum_{i=1}^n P_{i,grid} + \sum_{i=1}^n P_{i,gb} + \sum_{i=1}^n P_{i,grid}$$  \hspace{1cm} (22)

$$P_{i,load} = \sum_{i=1}^n P_{i,load} - \sum_{i=1}^n P_{i,ac} = \sum_{i=1}^n P_{i,grid} + \sum_{i=1}^n P_{i,gb} + \sum_{i=1}^n P_{i,load}$$  \hspace{1cm} (23)

Where, $n_{load}$, $n_{ac}$, $n_{gb}$, $n_{grid}$ are the number of reducible loads, cooling and heating devices, electric storage devices, gas-fired generations, respectively.
3.2. Objective function
The purpose of demand response is to minimize operating cost. The cost includes three parts: electricity purchase cost, gas purchase cost, response incentives. The objective function is as follows:

\[
f(x) = \sum_{i=1}^{l} p_{e_{ip}}(x) + p_g P_g(x) + \varepsilon_{es} p_{es} \sum_{i=1}^{m} P_{is}(x) / m
\]

Where, \(x\) is the decision variable. \(p_e\) is the time-of-use electricity price and \(P_{e_{ip}}(x)\) is the amount of electricity purchased. \(p_g\) is the price of gas and \(P_g(x)\) is the amount of gas purchased. \(\varepsilon_{es}\) is the coefficient of demand response speed. \(p_{es}\) is the incentive price of demand response. \(P_{es}(x)\) is the load reduction under demand response. \(n\) is the order number of demand response start time. \(m\) is the amount of demand response periods, and \(f(x)\) is the operating cost within the control time.

3.3. Problem building
Based on the model in Section 3.1, we set the constraints of the problem. Based on the objective function constructed in Section 3.2, a mixed integer programming problem is established and can be solved using a linear programming algorithm solver. According to this model we get the output plan of each device and adjustable potential results when the operating cost is the lowest.

4. Case Study
Paper analyses potential in typical daily demand response of an office park in the north in summer.

4.1. Basic situation
In the park, there are reducible loads, shiftable loads, convertible loads and distributed energy. The typical daily load is predicted based on the local natural conditions, actual electricity consumption and gas consumption. The load is shown in Figure 2(a) and 2(b). Besides, the time we set for customer-side to participate in demand response is 15:00~16:30.
In this study, we take the cold load reduction as the control constraint. In summer, the cold load reduction is equivalent to customer-side comfort. The cold load reduction is set to 0%, 5%, 10%, 15%, 20%, 25%, and 30%, respectively. By the analysis model, we get eight maximum of comprehensive demand response potential under the corresponding conditions. And the maximum is the reduced electricity from power grid. The corresponding relationship between cold load reduction and power grid purchases is shown in Figures 3(a) and 3(b). As shown in Figure 3, when the cold load reduction increases gradually, the power grid purchase decreases gradually. When the cold load reduction reaches a certain percentage, power grid purchase may be reduced to zero. There is a correlation between the two amounts. Moreover, when the cold load reduction increases from 0% to 5%, the downtrend of power grid purchase is the most obvious. When the cold load reduction reaches 35%, the power grid purchase drops to zero.

The operation state of reducible loads, shiftable loads, convertible loads and distributed energy is shown in Figure 4. We set four cold load reduction for analyzing, including 0%, 5%, 20% and 35%. In the customer-side IES, based on the optimal optimization goal of economic efficiency, ESD, CES, GG, and PV can participate in IDR at the same time. The ESD fully exerts the adjustment function of reducible loads, and changes the state from energy storage to energy release during demand response time. As the reducible load, the CES reduces the cooling power of electric load by ground source heat pumps and air source heat pumps. As the convertible load, the GG supplies power by consuming gas to reduce the power grid purchases. Through the integrated control of all kinds of flexible loads, we get the different maximum adjustable potential of customer-side IES under different cold load reduction. Besides, customer-side reduces the power grid purchase and the operating cost of the park effectively.
(a) Electric load reduction is 0                    (b) Electric load reduction is 5

(c) Electric load reduction is 20                     (d) Electric load reduction is 35

(e) Cold load reduction is 0                      (f) Cold load reduction is 5

(g) Cold load reduction is 20                      (h) Cold load reduction is 35

Figure 4. Composition of electric load and composition of cold load
5. Conclusion
In this study, an IDR potential model of customer-side is established, which considers the coupling and conversion of multi-energy in IES. Through calculations and analysis, the conclusions are as follows:

1) An evaluation method of customer-side IDR potential is defined, which can provide users guidance on the adjustable potential of the comprehensive demand response of each flexible device.
2) Using the customer-side IDR potential model, the trend of power load with cold load reduction is fitted. Furthermore, the optimal cold load reduction is found.
3) Energy storage devices have a great role in IDR and have a strong demand response capability.

Acknowledgments
This work was financially supported by the fund of NARI Technology Co., Ltd. (No. 524608200058)

References
[1] X. Zhen, S. Hongbin, G. Qinglai, et al. Review and Prospect of comprehensive demand response research [J]. Proceedings of the CSEE, 2018, 38 (24): 7194-7205+7446.
[2] S. Hongbin, P. Zhaoguang, G. Qinglai, et al. Research on multi energy flow energy management: challenges and Prospects [J]. Automation of Electric Power Systems, 2016, 40 (15): 1-8+16.
[3] S. Yanpin, L. Hong, Y. Wenhai, et al. Optimization aggregation model of residential users based on SOM demand response potential [J]. Electric Engineering, 2017, 38 (07): 25-33.
[4] L. Peiyun, D. Tao, et al. Optimal market transaction strategy of load aggregator based on comprehensive demand response [J]. Electric Power Automation Device, 2019, 39 (08): 224-231.
[5] L. Peng, Y. Zibo, et al. An optimal scheduling model of park integrated energy system considering multi energy and multi demand response [J]. Electric Engineering, 2020, 41 (05): 45-57.
[6] C. Shuqin, et al. Characteristic index system and case study of air conditioning power load in regional buildings [J]. Journal of Harbin Institute of Technology, 2019, 51 (04): 187-193.
[7] L. Wenxia, et al. Coordinated optimal allocation of integrated energy system considering the uncertainty of demand response [J]. Automation of Electric Power Systems, 2020, 44 (10): 41-53.