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Demand response during the peak load period in China: Potentials, benefits and implementation mechanism designs

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ABSTRACT

Demand response during the peak load period can not only enhance the security of power system operation under accelerated climate change, but also can reduce the unnecessary generation capacity and environmental externalities. However, the current capability of demand response lags far behind the expected goals in China, threatening the sustainable development of the electricity sector. The mechanism which allocates the national targets to different provinces is still lacked, making the DR implementation difficult to materialize in China. Moreover, stakeholders do not have a clear understanding of the magnitude of DR benefits, so they have insufficient motivations to participate. To bridge these gaps, five mechanisms are established to allocate national DR targets and three key elements are designed to implement DR. The major findings are that: (1) The duration of peak load time is very short in China, which represents for only 1.6% of the total hours within a year. (2) The annual total benefits from implementing demand response are 13 billion yuan, and the avoided capacity cost dominates in the potential benefits. (3) The average trigger point of starting demand response activities is 38 GW in China. (4) 19:00 pm is the most needed daily time for conducting demand response in most provinces.

1. Introduction

With the accelerating climate change and increasing electrification rates, the rising peak load is challenging the electricity system operation (Liu et al., 2020). Compared with building new electricity supply infrastructure for only a short balancing period, Demand Response (DR) is a more cost effective way to address the potential power shortages (Mueller and Moest, 2018; O'Connell et al., 2014). DR changes the electric usages from normal patterns in response to the variations of electricity prices or to the incentive payments (Guo et al., 2017; Paterakis et al., 2017). DR can smooth the load curve by cutting peak load and filling valley load, so the investment into electricity infrastructure will be reduced and costly generation from peaking units will be avoided (Bradley et al., 2013). Moreover, the DR has also been gaining interest as power systems become more congested, the share of renewable generation increases, the smart grids develop and the communication and automation technologies become less expensive and more sophisticated (Conchado et al., 2016). Many countries around the world have implemented DR through market mechanism or administrative measures, which have increased the flexibility and resilience of electricity system to a large extent (Keay et al., 2015). The current DR potential in developed countries can reach 9% of their peak loads, whose main sources come from industrial consumers (Pollitt et al., 2017). Demand Side Management (DSM) was proposed by the Chinese government in 2000 and has developed fast during the past twenty years (see Fig. 1). Currently, the government set a 'two 0.3%' target for the provincial grid companies, which mandates that both the saved peak load and the avoided electricity generation in the current year should not be lower than 0.3% of them in the previous year (Zhang et al., 2017). To ensure the electricity operational security, Chinese government also developed a long-term target to establish a DR capability of 3% of the national peak load.

Since the industrial consumption dominates in the demand side of electricity system, China can have a big potential of peak load reduction from implementing DR (Zhou and Yang, 2015). However, the shaved capacity (GW) by DR accounts for only 0.4% of the national peak load in 2018, which is far below the long-term national targets of 3%. There are several challenges in achieving the DR targets set by the government. On

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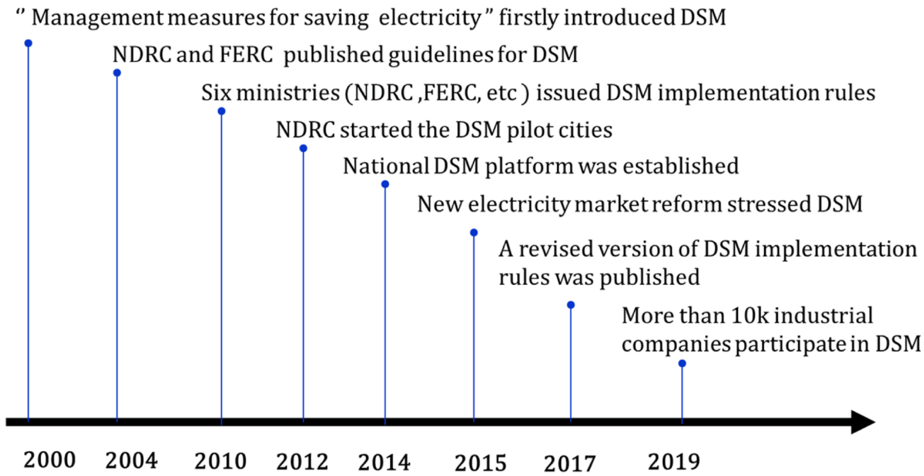

Fig. 1. the development history of DSM policies in China.

the one hand, stakeholders do not have a clear understanding of the magnitude of DR benefits, so they have insufficient motivations to participate (Zhou and Yang, 2015). Few studies have quantitatively estimated the benefits from DR in China, especially at the provincial levels (Keay et al., 2015). On the other hand, the mechanism which allocates the national targets to provincial targets is still lacked in China, making the DR implementation difficult to materialize. Moreover, the fairness of the target allocation mechanism is important considering the heterogeneity in the supply structure and economic status of different provinces. To provide guidance for the DR mechanism design, this study plans to conduct a target allocation and benefits estimation of DR in China, aiming at answering the following three questions:

(1) How to scientifically allocate the national DR targets to different provinces?
(2) How much economic benefits can be achieved from implementing DR in China?
(3) How to design the DR mechanism to incentivize its implementation?

With this motivation, this study firstly develops several mechanisms to allocate the national DR development targets to different provinces. Then, a framework is constructed to estimate the economic benefits in China. After that, three key elements of the DR mechanism are designed to support its implementation in China. At last, several suggestions are proposed to guide the DR implementation in China.

The remainder of this paper is organized as follows. The second section reviews the literature that focuses on costs and potentials of DR. The third section describes the methodologies and data used to estimate the DR potentials. The fourth section presents the results and discussions. The last section shows the conclusions and policy implications.

2. Literature review

DR is becoming a hot research topic with the increasing peak electricity load and the large scale integration of renewables (Bradley et al., 2013; Guo et al., 2017; Liu et al., 2020). A good mechanism design of DR is important for its successful implementation. Since the potential and benefit of DR are the two basic inputs for the mechanism design, this section plans to review the existing studies focused on these two topics.

Estimating the potentials of DR is important for the electricity planning and operation. Survey is a frequently used method in quantifying the DR potentials (Diawuo et al., 2020; Gyamfi and Krumdieck, 2011). By dividing the consumers into different groups, surveys are designed and circulated to them to show their desire to participate in the DR activities. Then, a bottom-up approach is employed to forecast the DR potentials based on their participation willingness and electricity consumption behavior (Keay et al., 2015). Some studies also estimate the economic potentials of future demand response using optimization models (Derakhshan et al., 2016; Gils, 2016; Jordehi, 2019). For example, Feuerriegel and Neumann (2016) developed an optimization model to explore the potentials of three different types of DR in Germany. Moreover, most studies are conducted for the developed countries (Paterakis et al., 2017; Paulus and Borggrefe, 2011; Saele and Grande, 2011). The current DR potential is 3.2% in Texas, 3.6% in the United Kingdom and 9.1% in Pennsylvania-New Jersey-Maryland (PJM) (Khalid, 2016; Pollitt et al., 2017).

Quantifying the DR benefits is important for establishing incentive mechanisms to change the consumers' electricity usage habits. The benefits, in most studies, are defined as the cost differences between power operation results with DR and results without DR (Conchado et al., 2016). Understanding the cost components is the first step for the cost benefit analysis. Owing to the different research targets and the data availability, the components considered by different studies vary a lot (Shaw et al., 2009; Wang et al., 2017). The most frequent components considered by the existing studies are the avoided generation cost. Most studies value the DR benefits from two approaches. The first one uses power system optimization models to estimate the benefits by comparing the total cost with and without DR. This method is complex and has strict requirements for input data (Linares et al., 2008; Paterakis et al., 2015; Zareen et al., 2015). The second one is an easier bottom-up approach. It calculates the benefits based on ex-ante estimation of the demand reductions and shifts, and then estimate the economic benefits brought by the demand reductions and avoided generation capacity (Conchado et al., 2016; Liu et al., 2020). This approach is more transparent and easier to understand, but it does not account for the endogenous and dynamic processes involved in DR.

Compared with previous studies, this study makes two contributions to the existing studies. Firstly, most studies have neglected the temporal availability of DR applications and have not quantified the DR potential on an hourly basis. This study uses hourly electricity consumption data to estimate the benefits and potentials of DR in China at the provincial level, which can be served as a valuable supplement to the existing studies. Secondly, different criteria are designed to allocate the national DR targets to different provinces, so the comparison on different allocation results can provide good suggestions for the DR mechanism design in China.

Table 1
Definitions of the five allocation mechanisms.

Criteria	Definition	Theoretical Supports
Uniformity	Allocate the same share of peak load reductions as national targets	Hubei Energy Administration (2021)
Affordability	Allocate the targets according to the share of provincial GDP	Röpke (2013); Sovacool et al. (2016)
Equity	Allocate the targets based on the share of provincial electricity consumption	Rose et al. (1998)
Responsibility	Allocate the targets using the total share of the residential and tertiary sectors electricity consumption	Grandjean et al. (2011); Liu et al. (2020)
Profitability	Allocate the targets to maximize the economic profits	Feng et al. (2019)

Notes: In the Profitability criteria, the upper limit of DR potential is set as 10% according to the Pollitt et al. (2017).

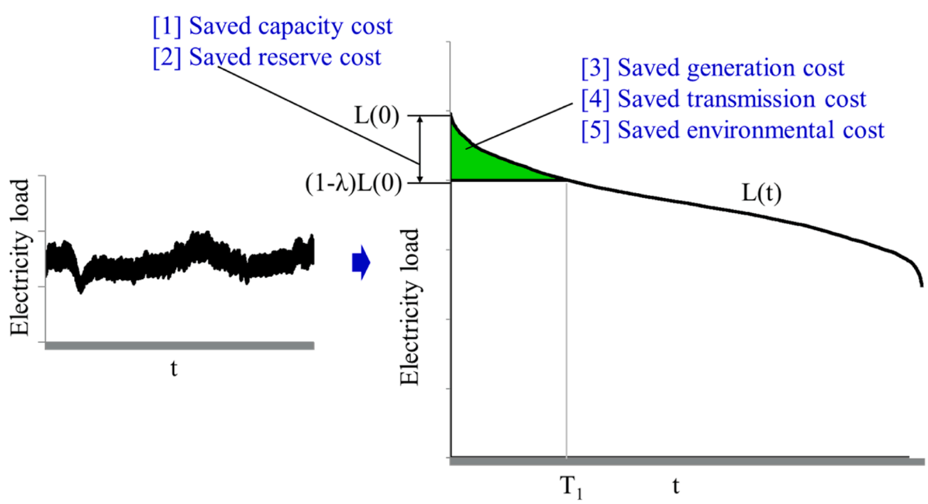

Fig. 2. Evaluation framework for the DR benefits.

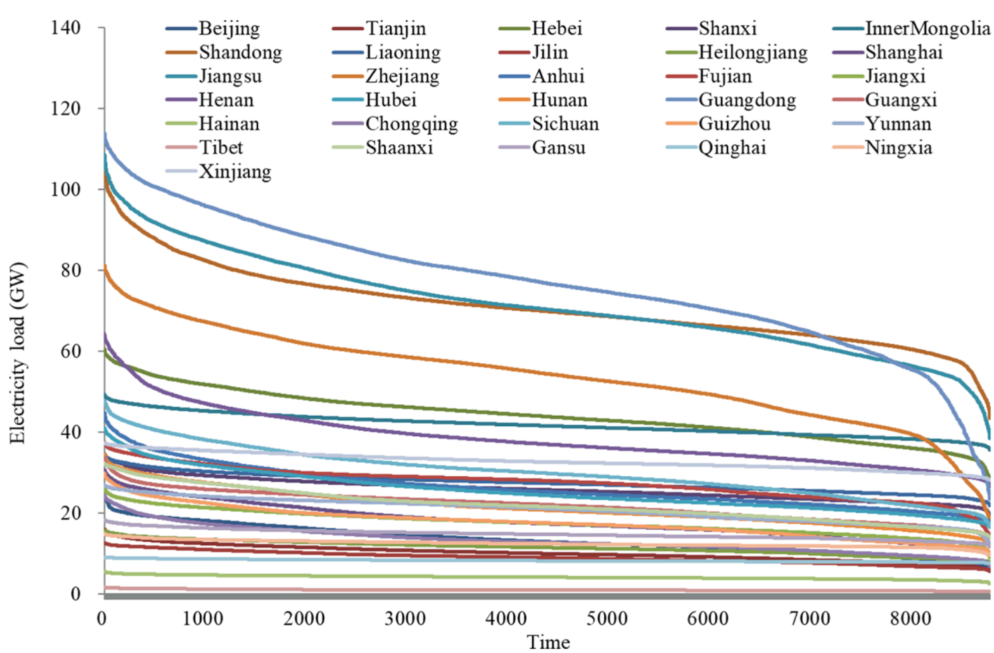

Fig. 3. Hourly load duration curves of 31 provinces in China.

3. Methodology

3.1. Target allocation model

Since the electricity supply structure, economic status and industrial structure differ a lot among different provinces, a fair and efficient allocation methodology is needed to incentivize stakeholders' (e.g. power plants, consumers and governments) participation to achieve the national DR targets.[1] The amount of DR potentials allocated to different provinces depends on the allocation criteria. Five mechanisms are designed to allocate the national DR targets to all the provinces, see Table 1.

[1] This study assumes that the cross-border electricity trading among different provinces are exogenous and predetermined, so as to focus on the pure DR benefits from the demand side.

Table 2
Statistical analysis of the major input parameters.

Parameters	Units	Mean	Std.	Min.	Max.	Sources
$L(0)$	GW	39.22	28.45	1.57	114.04	NDRC (2020)
CP_{coal}	yuan/kW	4011.00	0.00	4011.00	4011.00	EPPEI (2019)
CP_{gas}	yuan/kW	2380.00	0.00	2380.00	2380.00	EPPEI (2019)
CP_{hydro}	yuan/kW	10424.03	93.04	10221.00	10527.00	EPPEI (2019)
$CP_{nuclear}$	yuan/kW	16000.00	0.00	16000.00	16000.00	EPPEI (2019)
CP_{wind}	yuan/kW	7000.00	0.00	7000.00	7000.00	EPPEI (2019)
CP_{solar}	yuan/kW	4000.00	0.00	4000.00	4000.00	EPPEI (2019)
α	%	13.71	1.51	12.00	20.00	NEA (2017)
ω_k	%	16.67	22.91	1.23	81.02	NBS (2021)
θ_k	%	16.67	27.67	1.47	93.41	NBS (2021)
F_{coal}	yuan/kWh	0.22	0.04	0.11	0.31	NDRC (2021b)
F_{gas}	yuan/kWh	0.57	0.12	0.34	0.87	NDRC (2021a)
OM_k	yuan/kWh	0.03	0.02	0.02	0.08	Chen et al. (2020)
CE_{coal}	yuan/MWh	49.88	5.67	33.33	62.35	Chen et al. (2020)
CE_{gas}	yuan/MWh	18.84	0.00	18.84	18.84	Chen et al. (2020)
TP	yuan/kWh	0.17	0.05	0.08	0.24	NEA (2019)
GDP_k	Billion yuan	3168.78	2542.83	169.78	10798.69	NBS (2020)
E_k	TWh	233.82	167.30	7.80	669.60	NBS (2021)
RE_k	TWh	71.33	50.88	3.89	245.83	NBS (2021)

The Uniformity criterion is defined as assigning the national share of DR targets on every province as many pilots currently do (Hubei Energy Administration, 2021). Considering the economic shocks of energy policies to different people, the Affordability criterion assumes that the more economically developed regions are supposed to take more responsibility of the DR targets (Röpke, 2013; Sovacool et al., 2016). Inspired by the Grandfathering principle in allocating the carbon emission targets, the Equity criterion allocates the nation DR targets based on the latest electricity consumption of different provinces (Rose et al., 1998). Since the residential and the tertiary sectors contribute a lot to widening the peak-valley difference of the load curves, the Responsibility criterion is defined by allocating more targets to provinces with higher share of residential and tertiary electricity consumption (Grandjean et al., 2011; Liu et al., 2020). The Profitability criterion is set to maximize the benefits from the implementation of DR, which spurs the stakeholders' participation (Feng et al., 2019).

Based on the allocation criteria, the national targets of peak load shaving are allocated to different provinces, see equation (1).

$$PL_k = \begin{cases} \lambda \cdot L_k & \text{Uniformity} \\ NL \cdot GDP_k / \sum_{k=1}^{N} GDP_k & \text{Affordability} \\ NL \cdot E_k / \sum_{k=1}^{N} E_k & \text{Equity} \\ NL \cdot RE_k / \sum_{k=1}^{N} RE_k & \text{Responsibility} \\ max \sum_{k=1}^{N} TC_k \cdot PL_k,\ s.t.\ 0 \leqslant PL_k \leqslant MDR_k & \text{Profibility} \end{cases} \quad (1)$$

Where PL_k is the allocated DR target to province$k$; L_k is the annual maximum peak load in province$k$; λ is the national development target of DR; NL is the annual maximum peak load of China; GDP_k is the Gross Domestic Product in province$k$; E_k is the electricity consumption in province$k$; RE_k is the total electricity consumption of the residential and tertiary sectors; TC_k is the unit economic benefits from conducting DR in province$k$; MDR_k are the upper limit of DR potentials in province$k$.

3.2. Benefits estimation model

The benefits from DR implementation are defined as the cost reductions from DR. An evaluation framework is developed to quantify both the economic and environmental benefits from conducting DR, see Fig. 2. Firstly, the original hourly load curves are transformed to Load Duration Curves in descending order based on pairwise comparison of the electricity load data on each of the 8760 time steps. The detailed transformation process can be seen from Vos (2012) and Wiskich (2014). Then, the amount of avoided installed capacity and electricity generation are estimated based on allocations of the national DR target. At last, cost savings of DR are assessed based on the saved capacity and generation.

In the load duration curves ($L(t)$), the annual peak electricity load is $L(0)$ at$t = 0$. If we set the national development target of peak load shaving share asλ, then the new peak load after DR will be$L(T_1) = (1-\lambda) \cdot L(0)$. The reduced electricity generation (ΔE) can be calculated by equation (2).

$$\Delta E = \int_0^{T_1} L(t)\, dt - L(T_1) \cdot T_1 \quad (2)$$

This study considers five major benefit components from implementing DR, including the saved installed capacity cost, the avoided reserve cost, the reduced generation cost, the saved transmission cost and the saved environmental cost. The total benefits from DR can be estimated by equation (3).

$$TC = CC + RC + GC + TC + RCC \quad (3)$$

The saved capacity cost (CC) is calculated by equation (4) and (5).

Table 3
The durations of different peak load definitions.

Provinces (short name)	Time lengths of electricity load over the threshold value (h)				
	≥99% *L	≥98% *L	≥97% *L	≥96% *L	≥95% *L
Beijing (BJ)	5	10	15	23	27
Tianjin (TJ)	8	12	18	29	37
Hebei (HEB)	3	13	33	64	94
Shanxi (SX)	2	11	33	58	82
Inner Mongolia (IMG)	11	41	86	187	329
Shandong (SD)	7	12	22	29	46
Liaoning (LN)	5	24	53	88	149
Jilin (JL)	8	27	48	87	131
Heilongjiang (HLJ)	5	14	40	59	101
Shanghai (SH)	5	11	18	29	40
Jiangsu (JS)	5	9	14	19	40
Zhejiang (ZJ)	7	21	31	45	70
Anhui (AH)	3	8	10	12	27
Fujian (FJ)	5	10	22	49	81
Jiangxi (JX)	3	5	9	9	18
Henan (HEN)	3	8	16	33	44
Hubei (HUB)	6	14	25	43	60
Hunan (HUN)	2	6	10	17	25
Guangdong (GD)	4	18	34	60	94
Guangxi (GX)	2	7	12	18	29
Hainan (HAN)	2	6	10	17	21
Chongqing (CQ)	2	3	6	13	24
Sichuan (SC)	5	14	21	32	40
Guizhou (GZ)	1	5	8	15	25
Yunnan (YN)	4	26	54	101	190
Tibet (TB)	2	2	6	8	16
Shaanxi (SHX)	7	32	66	111	155
Gansu (GS)	10	23	60	92	152
Qinghai (QH)	30	108	277	581	1010
Ningxia (NX)	3	18	51	116	205
Xinjiang (XJ)	30	150	347	652	958
Average	6	22	47	87	139

Notes:L indicates the highest annual electricity load.

The characteristics of provincial electricity supply structure are integrated into the cost estimations, which can be seen from the capacity-weighted capital cost of different technologies ($\sum_{k=1}^{N}\omega_k \cdot ACP_k$).$\omega_k$ is the capacity share of the k th generation technology; CP_k is the capital cost of the k th generation technology; ACP_k is the annualized capital cost of the k th generation technology; r is the discount rate; Len_k is the life length of the k th generation technology.

$$CC = \lambda \cdot L(0) \cdot \sum_{k=1}^{N} \omega_k \cdot ACP_k \tag{4}$$

$$ACP_k = \frac{r/(1+r)}{1-(1+r)^{-Len_k}} CP_k \tag{5}$$

Power system operation requires a certain amount of reserves to safeguard against fluctuations in the electricity load and intermittent renewable generation. The conserved generation capacity can also reduce the cost of providing additional operating reserves. The reserve cost savings (RC) are estimated by equation (6). α is the reserve share of the dispatch region.

$$RC = \alpha \cdot \lambda \cdot L(0) \cdot \sum_{k=1}^{N} \omega_k \cdot ACP_k \tag{6}$$

The avoided electricity generation cost (GC) is estimated by equation (7), which multiplies the reduced generation by its unit cost. The generation cost of one kWh is calculated as the generation-weighted (θ_k) cost of different technologies within a dispatch region. Two components are considered in the generation cost, including the fuel cost (F_k), the operations and maintenance cost (OM_k).

$$GC = \Delta E \cdot \sum_{k=1}^{N} \theta_k \cdot (F_k + OM_k) \tag{7}$$

The saved electricity generation can also reduce the electricity transmission cost (TC), see equation (8). TP is the electricity transmission cost.

$$TC = \Delta E \cdot TP \tag{8}$$

In addition to the economic benefits, we also considered the environmental benefits represented by the saved carbon emission cost (RCC) using equation (9). EF_k is the CO_2 emission factor of the power generation from the energy resource$k$, CE is the unit cost of carbon emissions.

$$RCC = \Delta E \cdot CE \cdot \sum_{k=1}^{N} \theta_k \cdot EF_k \tag{9}$$

3.3. Data

This study uses the 2019 data of China to conduct the empirical study at the provincial level. There are three types of data used in this study.

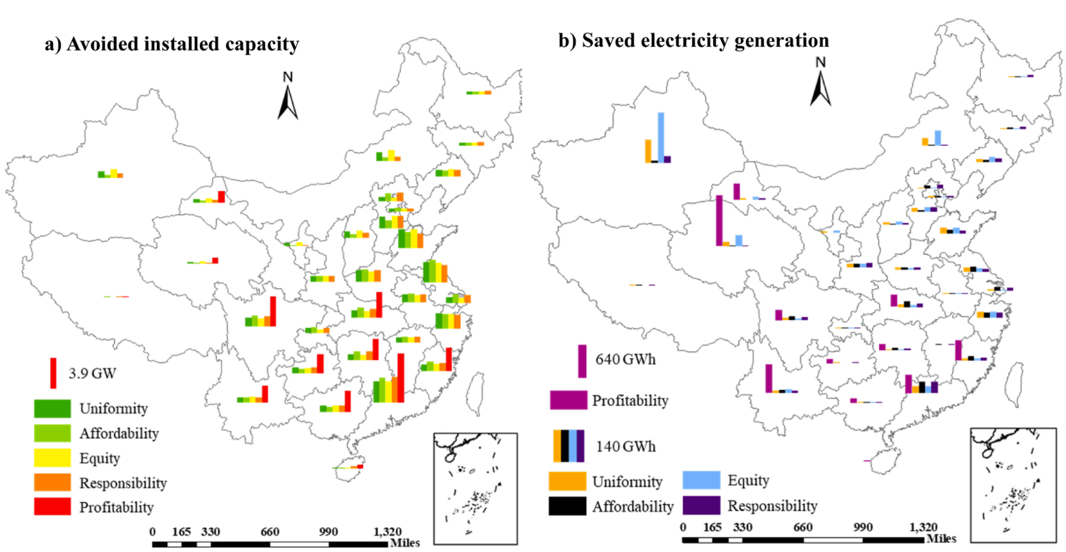

Fig. 4. the results comparison of national DR target allocations Notes: the left figure **a** shows the avoided installed capacity under different criteria, while the right figure **b** shows the saved electricity generation under different criteria.

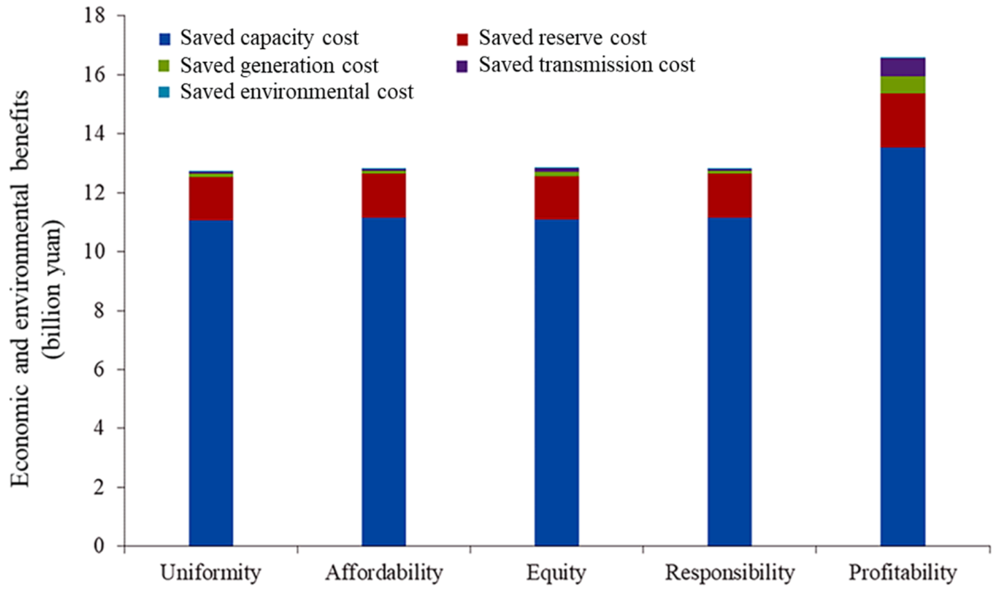

Fig. 5. The economic and environmental benefits of DR under different mechanisms.

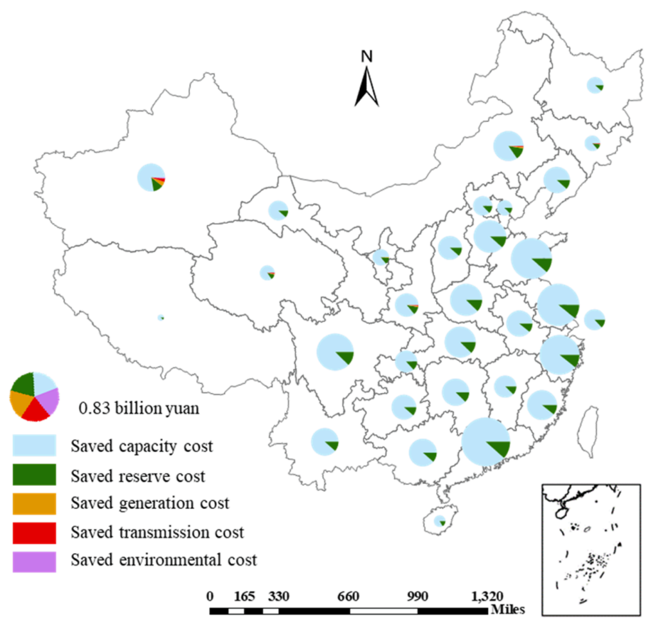

Fig. 6. the spatial distribution of DR benefits under the Uniformity allocation mechanism.

The first one is the hourly electricity load data of different provinces, based on which we can transform the original load data to load duration curves (see Fig. 3). We can see that Guangdong has the biggest peak load, while Tibet has the smallest peak load. The second one is the technical data of electricity system, including the installed capacity, the electricity generation and the share of operational reserves. Six types of generation technologies are considered in this study, namely the coal-fired generators, gas-fired generators, hydro generators, nuclear generators, wind generators and solar generators. The third one is the economic data of electricity system, which contains the investment cost, the generation cost, the O&M cost and the carbon emission cost. The discount rate is chosen as 5% according to Chen et al. (2016). A statistical analysis of these data and their sources are summarized in Table 2.

4. Results and discussions

4.1. The potentials of capacity and generation savings under different allocation mechanisms

Although the peak load can have different definitions, they all last for a very short time in China, see Table 3. The duration of electricity load over 95% of the highest load, on average, only lasts for less than 140 h annually. Tibet and Jiangxi have the smallest time duration of peak load, while Qinghai and Xinjiang have the biggest time length of peak load. Considering the fact that the break-even annual operating time is 5500 h for coal generators in China, it is not cost-effective to build additional generation capacity to meet the short time of peak load (Wei et al., 2018).

Based on the established five allocation mechanisms, the potentials of avoided installed capacity and saved electricity generation from different allocation mechanisms are shown in Fig. 4. We can see that provinces located in the east coast have larger benefits from peak load shifting from DR. These provinces are also more economic developed and have higher electricity retail prices, so this can make the DR implementation more promising in these provinces. Furthermore, the allocation results under different mechanisms vary a lot, indicating that a fair and well-accepted allocation mechanism is necessary to achieve the planned targets.

4.2. Benefits evaluation of the demand response implementation

Using the established benefits estimation model, economic gains are assessed for the five allocation mechanisms, see Fig. 5. We can see that the benefits under the Profitability allocation mechanism are the biggest, whose total benefits are about 1.5 times than that of the others. Moreover, the monetary value of avoided installed capacity represents the largest share in the total amount of benefits. This is because the amount of electricity generation during the peak load period is relatively small, which is also consistent with the conclusions from Keay et al. (2015). In addition, 581 kt CO_2 emission could be reduced under the Uniformity criteria, see Fig. 5.

Apart from the national total benefits, we have also compared the regional distributions of the attained benefits from DR. Taking the Uniformity allocation mechanism as an example, the total benefits of different provinces are shown in Fig. 6. The national total potential benefits from DR implementation are 13 billion yuan. Guangdong has

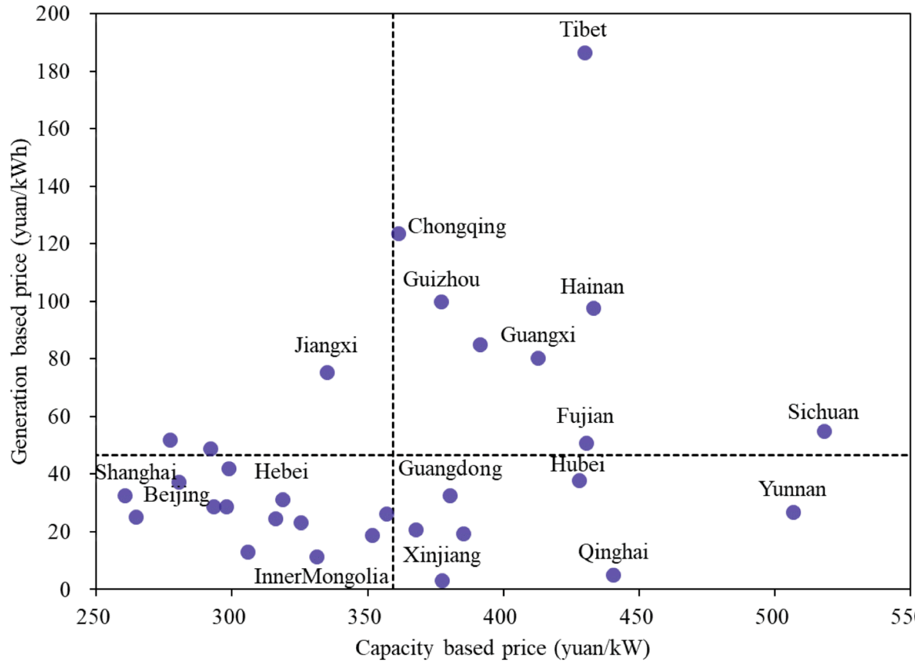

Fig. 7. Price settings for the provincial DR mechanism.

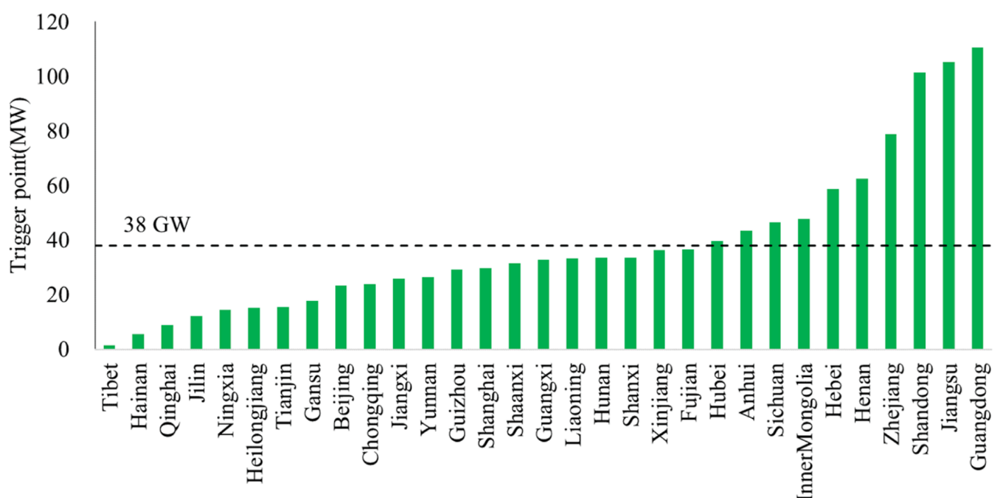

Fig. 8. The trigger points of DR in different provinces.

the largest amount of benefits (1.30 billion yuan), while Tibet has the smallest amount of benefits (0.02 billion yuan). Moreover, the avoided capacity cost is the major cost component, accounting for more than 80% of the total cost in most provinces.

4.3. Mechanism designs of the demand response

The estimated potentials and benefits can be used to support the DR mechanism design. On the one hand, they can be used to check whether the DR mechanisms in the current pilot markets are providing good economic signals. On the other hand, they can be used to design DR mechanisms for the non-pilot provinces. There are many elements in the DR implementation mechanism, such as the price settings, the trigger points, the implementation time, the notification time, etc (Wang et al., 2017). This section only focuses on three key elements based on the results from the Uniformity allocation mechanism.

4.3.1. Price settings

A proper price setting is important for the successful implementation of DR. A DR mechanism with extremely high prices will attract too many consumers' participation and will lead to a waste of public finances, while a DR mechanism with extremely low prices will not provide enough incentives for consumers to achieve the planned targets. This section designs DR prices from a break-even perspective, which means that all the estimated benefits are used to compensate the consumers for their contributions in offering DR services. In the existing pilot DR markets in China, consumers are compensated for either the saved installed capacity or the conserved electricity generation, so we have also calculated the compensation prices based on these two physical indicators for every province, see Fig. 7. The average prices are 359 yuan/kW for capacity-based scheme and 47 yuan/kWh for the generation-based scheme. Sichuan has the highest compensation price for the saved capacity (518 yuan/kW), while Tibet has the biggest price for the avoided electricity generation (186 yuan/kWh). However, they are all much higher than the prices set in the existing pilot DSM markets.

a) Duration length

Monthly DR (hours)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
BJ	0	0	0	0	0	0	0	15	0	0	0	0	15
TJ	0	0	0	0	0	0	2	16	0	0	0	0	18
HEB	0	0	0	0	0	0	6	26	0	0	0	1	33
SX	0	0	0	0	0	0	0	0	0	0	0	33	33
IMG	0	0	0	0	0	0	0	0	0	0	8	78	86
SD	0	0	0	0	0	0	0	22	0	0	0	0	22
LN	0	0	0	0	0	0	11	13	0	0	0	29	53
JL	17	0	0	0	0	0	0	0	0	0	0	31	48
HLJ	3	0	0	0	0	0	0	0	0	0	2	35	40
SH	0	0	0	0	0	0	11	7	0	0	0	0	18
JS	0	0	0	0	0	0	0	14	0	0	0	0	14
ZJ	0	0	0	0	0	0	15	16	0	0	0	0	31
AH	0	0	0	0	0	0	4	6	0	0	0	0	10
FJ	0	0	0	0	0	0	9	13	0	0	0	0	22
JX	0	0	0	0	0	0	0	0	0	0	0	9	9
HEN	0	0	0	0	0	0	9	7	0	0	0	0	16
HUB	0	0	0	0	0	0	25	0	0	0	0	0	25
HUN	0	0	0	0	0	0	0	0	0	0	0	10	10
GD	0	0	0	0	14	0	8	12	0	0	0	0	34
GX	0	0	0	0	0	0	0	0	0	0	0	12	12
HAN	0	0	0	0	0	0	10	0	0	0	0	0	10
CQ	0	0	0	0	0	0	1	0	5	0	0	0	6
SC	0	0	0	0	0	0	0	14	7	0	0	0	21
GZ	0	0	0	0	0	0	0	0	0	0	0	8	8
YN	11	10	0	0	0	0	0	0	0	5	4	24	54
TB	0	0	0	0	0	0	0	0	0	0	0	6	6
SHX	0	0	0	0	0	0	30	17	0	0	0	19	66
GS	0	0	0	0	0	0	0	0	0	0	35	25	60
QH	105	0	0	0	0	0	0	0	0	10	147	15	277
NX	0	0	0	0	0	0	0	0	0	0	17	34	51
XJ	0	0	0	0	0	0	33	31	0	0	66	217	347
	136	10	0	0	14	0	174	229	12	15	279	586	

b) Implementation frequencies

Monthly DR (times)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
BJ	0	0	0	0	0	0	0	5	0	0	0	0	5
TJ	0	0	0	0	0	0	1	6	0	0	0	0	7
HEB	0	0	0	0	0	0	5	14	0	0	0	0	19
SX	0	0	0	0	0	0	0	0	0	0	0	25	25
IMG	0	0	0	0	0	0	0	0	0	0	5	23	28
SD	0	0	0	0	0	0	0	7	0	0	0	0	7
LN	0	0	0	0	0	0	9	7	0	0	0	23	39
JL	13	0	0	0	0	0	0	0	0	0	0	21	34
HLJ	3	0	0	0	0	0	0	0	0	0	2	29	34
SH	0	0	0	0	0	0	4	3	0	0	0	0	7
JS	0	0	0	0	0	0	0	7	0	0	0	0	7
ZJ	0	0	0	0	0	0	7	6	0	0	0	0	13
AH	0	0	0	0	0	0	3	4	0	0	0	0	7
FJ	0	0	0	0	0	0	8	12	0	0	0	0	20
JX	0	0	0	0	0	0	0	0	0	0	0	4	4
HEN	0	0	0	0	0	0	4	3	0	0	0	0	7
HUB	0	0	0	0	0	0	9	0	0	0	0	0	9
HUN	0	0	0	0	0	0	0	0	0	0	0	7	7
GD	0	0	0	0	8	0	4	6	0	0	0	0	18
GX	0	0	0	0	0	0	0	0	0	0	0	5	5
HAN	0	0	0	0	0	0	8	0	0	0	0	0	8
CQ	0	0	0	0	0	0	1	0	2	0	0	0	3
SC	0	0	0	0	0	0	0	6	4	0	0	0	10
GZ	0	0	0	0	0	0	0	0	0	0	0	8	8
YN	10	10	0	0	0	0	0	0	0	5	4	24	53
TB	0	0	0	0	0	0	0	0	0	0	0	4	4
SHX	0	0	0	0	0	0	12	8	0	0	0	9	29
GS	0	0	0	0	0	0	0	0	0	0	23	17	40
QH	65	0	0	0	0	0	0	0	0	9	68	12	154
NX	0	0	0	0	0	0	0	0	0	0	15	22	37
XJ	0	0	0	0	0	0	10	12	0	0	21	47	90
	91	10	0	0	8	0	85	106	6	14	138	280	

Fig. 9. The distributions of total time length and frequencies of DR in different provinces Notes: the left figure **a** shows the duration time of DR in different provinces, while the right figure **b** shows the frequencies of DR in different provinces. The first column of two figures shows the short names of provinces, which have already been shown in Table 3. A cell with darker color indicates a bigger number. The bottom and the right of the figure show the summed values.

For example, the current prices of generation-based scheme in pilot provinces range from 0.80 yuan/kWh to 4.00 yuan/kWh,[2] and the current prices of capacity-based scheme in pilot provinces change from 10 yuan/kW to 130 yuan/kW.[3] In addition, there are significant price variations among different provinces, so the provincial heterogeneity needs to be well integrated into DR market design.

4.3.2. *Trigger points*

Trigger points are the threshold conditions to initiate the DR, which are typically taken in the forms of either threshold electricity loads or threshold temperatures. Since the peak electricity load is highly correlated with the temperature, this study designs trigger points based on the share (3%) the national DR development target, see Fig. 8. We can see that the average trigger point of starting DR activities is 38 GW. Guangdong has the highest trigger point (111 GW), while Tibet has the lowest trigger point (2 GW).

4.3.3. *Implementation time and frequencies*

It is necessary to correctly understand the implementation time in conducting the mechanism design, because committed electricity consumers need to be informed before the peak load come. Using the hourly electricity load of all the provinces, we firstly analyze the seasonal distributions of the duration lengths and frequencies under the Uniformity allocation mechanism, see Fig. 9. In most provinces, DR is mainly needed in four months (July, August, November and December), no matter from the durations or the frequencies. The most intensive activities will occur in December. Furthermore, there is an uneven distribution of the needed DR activities in China's 31 provinces, so more attention needs to be focused on the provinces that have more requirements for DR activities. Xinjiang has the longest duration of DR activities (347 h annually), while Qinghai has the highest frequency of DR activities (154 times annually).

Then, we have also analyzed the distributions of DR frequencies at the hourly level, see Fig. 10. We can see that 19:00 is the most frequent time for conducting DR in most provinces. This is in line with the typical load curves of different regions in China and other countries (EIA, 2011; NDRC, 2020). Besides, summarizing the released time-of-use (TOU) electricity price policies of 26 provinces in China, we also found that 19:00 is included in the peak-load period of every province without exception.[4] Most of the DR activities will occur from 11:00 to 21:00. However, there is no need of DR services from 1:00 to 6:00. With the distribution information of DR activities at the hourly level, notifications can be more accurately send to the consumers who agreed to participate in the DR activities.

5. Conclusions and policy implications

5.1. *Conclusions*

With the accelerating climate change and increasing electrification rates, the increasing peak load is challenging the electricity system

[2] The current prices of generation-based scheme in some pilot provinces are 0.80 yuan/kWh in Jiangxi, 2.00 yuan/kWh in Shanghai, 2.50 yuan/kWh in Guangdong, 2.83 yuan/kWh in Jiangsu, and 4.00 yuan/kWh in Zhejiang. The data are drawn from the provincial Economic and Information Commissions (EICs) and Development and Reform Commissions (DRCs).

[3] The current prices of capacity-based scheme in some pilot provinces are 10 yuan/kW in Chongqing, 130 yuan/kW in Foshan, 30 yuan/kW in Shandong, 100 yuan/kW in Jiangsu, and 80–120 yuan/KW in Beijing. The data are drawn from the provincial Economic and Information Commissions (EICs) and Development and Reform Commissions (DRCs).

[4] TOU electricity prices are set according to the local characteristics of load curves, which provide policy evidence on the peak-load periods in different provinces. The collection of 26 provincial TOU electricity price policies is available at: https://mp.weixin.qq.com/s/Yq_KquYz2aHB_CjAh-kSSQ.

Hourly DR (hours)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
BJ	0	0	0	0	0	0	0	0	0	0	2	2	2	2	1	2	2	0	2	0	0	0	0	0	15
TJ	0	0	0	0	0	0	0	0	0	0	2	0	0	2	2	2	3	3	3	1	0	0	0	0	18
HEB	0	0	0	0	0	0	0	0	0	0	3	5	0	0	5	3	6	9	0	0	2	0	0	0	33
SX	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	2	3	5	9	6	0	0	0	33
IMG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	25	28	17	5	1	0	0	86
SD	0	0	0	0	0	0	0	0	0	0	4	2	2	4	4	3	2	1	0	0	0	0	0	0	22
LN	0	0	0	0	0	0	0	0	0	13	10	0	0	7	2	7	0	0	0	0	0	14	0	0	53
JL	0	0	0	0	0	0	0	0	0	7	18	0	0	0	0	7	11	5	0	0	0	0	0	0	48
HLJ	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	0	26	6	0	0	0	0	0	0	40
SH	0	0	0	0	0	0	0	0	0	0	3	2	4	4	1	2	0	1	1	0	0	0	0	0	18
JS	0	0	0	0	0	0	0	0	0	0	2	0	2	3	2	2	0	1	1	0	1	0	0	0	14
ZJ	0	0	0	0	0	0	0	0	0	2	3	0	3	8	6	3	2	2	2	0	0	0	0	0	31
AH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	3	5	0	0	0	10
FJ	0	0	0	0	0	0	0	0	0	0	14	0	0	2	0	1	0	3	2	0	0	0	0	0	22
JX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	1	2	2	0	0	9
HEN	0	0	0	0	0	0	0	0	0	0	0	1	4	4	4	1	0	0	2	0	0	0	0	0	16
HUB	0	0	0	0	0	0	0	0	0	0	0	0	3	7	6	2	2	2	2	1	0	0	0	0	25
HUN	0	0	0	0	0	0	0	0	0	0	1	0	2	2	0	0	0	0	2	1	2	0	0	0	10
GD	0	0	0	0	0	0	0	0	0	0	5	0	0	2	10	12	4	0	1	0	0	0	0	0	34
GX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	0	1	1	2	2	0	0	12
HAN	0	0	0	0	0	0	0	0	0	3	2	0	0	0	0	0	2	0	1	2	0	0	0	0	10
CQ	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	2	0	0	0	0	0	0	0	6
SC	0	0	0	0	0	0	0	0	0	0	2	0	2	3	3	3	3	0	2	2	1	0	0	0	21
GZ	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	2	1	0	0	0	0	8
YN	0	0	0	0	0	0	0	0	0	0	22	0	0	0	0	0	0	31	1	0	0	0	0	0	54
TB	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3	2	0	0	6
SHX	0	0	0	0	0	0	0	0	0	0	0	1	14	12	8	10	4	0	4	4	9	0	0	0	66
GS	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	7	24	15	0	5	0	0	0	60
QH	0	0	0	0	0	0	15	10	9	0	0	0	19	17	36	41	9	12	33	11	40	3	5	17	277
NX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	7	14	26	0	0	0	51
XJ	0	0	0	0	0	0	0	0	0	0	1	8	36	5	5	5	9	30	43	46	45	57	48	9	347
	0	0	0	0	0	0	15	10	9	25	108	38	93	84	98	111	109	163	164	114	154	81	53	26	

Fig. 10. the hourly distributions of DR in different provinces Notes: the first column shows the short names of provinces, which have already been shown in Table 3. A darker color indicates a bigger number. The bottom and the right of the figure show the summed values of the table.

operation. DR is an important measure to address the short time period of constrained electricity balancing. However, the current DR development is still far below the long-term targets set by the government. To provide guidance for achieving the DR development targets, this study firstly develops five different mechanisms to allocate the national DR development targets to different provinces. Then, a framework is constructed to evaluate the benefits from DR implementation in China. At last, several key mechanism elements are designed to support the DR implementation. During this process, we have obtained the following conclusions:

(1) The duration of peak load time is short in China. Over 95% of the peak load, on average, only accounts for 1.6% of the annual time, which is much smaller than the break-even annual operating hours (5500 h) of coal generators. Therefore, it is very promising to conduct the DR during the peak load period rather than build new generators. Furthermore, the provinces that can achieve larger benefits from DR are located in the east coast of China, so it is better to scale-out the DR implementation from these economic developed provinces.
(2) If the national DR targets are evenly allocated to different provinces, the total benefits from DR implementation are 13 billion yuan annually. Avoided capacity cost is the major components of the attained benefits, representing over 80% of the total benefits in most provinces. Moreover, the benefits vary substantially among different provinces. Guangdong has the largest amount of total benefits, while Tibet benefits the least. In addition, 581 kt CO_2 could be reduced annually from the implementation of DR.
(3) The benefits from DR depend on the mechanisms employed to allocate the national targets to different provinces. The benefits under the profitability allocation mechanism are the largest, which are about 1.5 times than those of the other four mechanisms. Moreover, the obtained benefits estimated based on hourly duration curves can be used to guide the mechanism design in China. For example, the average trigger point of starting DR activities is 38 GW in China and 19:00 is the most needed daily time for conducting DR in most provinces.

5.2. Policy implications

Based on the above conclusions, we have proposed the following policy implications to contribute to a better achievement of DR implementation.

First, a well-functioning market mechanism needs to be established to efficiently utilize the DR resources, which can provide meaningful signals for DR development in different regions and at different time. The current electricity market reform is a good opportunity to integrate DR into the market design, thus enhancing the flexibility and reliability of the electricity system. The ancillary service market is a comprehensive platform which can provide online monitoring, execution response, communication and interaction for the demand response, thus significantly improving the speed of data processing and information exchange. Therefore, it is necessary for the Chinese government to accelerate the process of establishing ancillary service market to better utilizing the DR services.

Second, the implementation of DR programs requires proper infrastructure and tools to materialize the benefits, such as information and communication technology (ICT), advanced metering infrastructure (AMI) and decision support based on big data analytics. To facilitate the implementation of DR programs, many countries have set roll-out targets of deploying smart meters. For example, some European countries (France, Spain, Norway the Netherlands, Ireland and UK) have set deployment targets to achieve nearly 100% smart meter installation by 2020. Therefore, it is good time for China to design good plan for the DR infrastructure deployment, as well as enhancing the customer understanding and participation through well-designed pricing mechanisms.

Although we have answered several important questions concerning the DR, some questions are left to be resolved in future studies. More benefits could be added to the cost benefit analysis, such as the reduced pollution cost, reduced ancillary service cost, more stable electricity prices and better control of market power. The additional cost caused by DR can be well integrated into the price settings because new infrastructure is needed to conduct DR. With these improvements done, more useful support can be provided for the DR mechanism design.

CRediT authorship contribution statement

Hao Chen: Conceptualization, Methodology, Writing – original draft. **Boyan Zhang:** Writing – original draft, Software. **Haopeng Geng:** Methodology. **Ming-Ming Wang:** Data curation, Visualization. **Hongda Gao:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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