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Modeling the distributed energy resource aggregator services in a macroeconomic framework: The application to Japan

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ABSTRACT

Distributed energy resources (DER) are highly interconnected with public and private entities in one economy, thus often modeled in the long-term decarbonization transition pathways. However, at the initial stage of the DER integration scaling-up, barriers such as consumer behavior and market dynamics can impede progress, which has not yet been thoroughly considered and accurately represented even in models. Therefore, we proposed an approach to integrated DER aggregator services in the macroeconomic framework. It can reveal how industrial and household DER providers participate in demand response requests, as well as how thermal power can be substituted by distributed renewables. We applied the framework to the benchmark year in Japan. The results show that the DER aggregator services at a full scale may have occupied 33.2 % of all grid aggregator services in electricity transmission and distribution. Faster-pace implementation of policy supports related to DER aggregator services is required to match such a potential market size.

1. Introduction

The long-term energy transition towards low or even net-zero greenhouse gas emission, including via high penetration of solar and wind power [1] and via rising electrification in heavy industries [2], also puts pressure on the current grid management. Integrating distributed energy resources (DER; [3,4]) while considering their techno-economic features, locations and transmission costs, as well as the demand response potentials, is essential to maintaining a low-carbon and resilient electricity supply system.

However, the distributed energy resources are usually highly interconnected with the rest of the system. Instead of simply being another option for electricity supply, they play a dual role (net metering) when trading with the grid as both producers and consumers of electricity. The energy management services for such load balancing transactions also require economic incentives [5], which are also nested in the macroeconomic framework with monetary flows. Also, the distributed energy resources are owned by different industries, which are the producers and consumers of final goods and services. Such interconnections have not been thoroughly understood. The lack of a holistic understanding of the role of distributed energy resources in the macroeconomic framework may add uncertainties to the provision of a clear and feasible vision of future energy transition pathways.

Previous studies have quantified the potential of distributed energy resources. In some typical long-term energy system models [6–9], the level of integrating distributed energy resources can be determined by physical constraints (e.g., average solar radiation), regulatory environment (e.g., grid interconnection standards in each country), technological advances and economic viability (e.g., capital/operation costs and learning curves), grid infrastructure (e.g., best location of the resources), etc. However, especially at the initial stage of the DER integration scaling-up, barriers such as consumer behavior (e.g., the willingness of industry entities to participate in demand response requirements) and market dynamics (e.g., more energy storage capacities lead to lower load balancing prices) are preventing companies from investing in new or fully exploiting existing flexibility potentials [10]. These barriers are also difficult to be accurately represented in models [11]. Unfortunately approaches that consider both such barriers and the compatibility to

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long-term projections are not yet well developed.

Modeling the aggregated demand response potential of distributed energy resources in a macroeconomic framework can also reveal their social, economic, and environmental impacts. The aggregators of distributed energy resources, as profit-making enterprises [12], can contribute to the long-term decarbonization transition. When individuals and enterprises see the potential positive environmental effects of participating in DER programs or working with aggregators, they would be more likely to embrace clean energy solutions. At the same time, when the owners or investors of DERs see the potential positive impact of aggregator services, it may stimulate the growth of the DER aggregator service market [13,14]. This emphasizes the importance of consolidating the benchmark year data while seeing DER aggregator services as cost-effective sources of flexibility as DER providers as profit-driven entities.

DERs include a wide range of small to medium-scale energy generation and storage devices throughout a grid that can be aggregated as a virtual power plant (VPP). DER aggregators in Japan also included various entities, such as energy service companies and technology startups [15]. The DER aggregator service market has been emerging since the negawatt trading system was established in 2017 [15]. However, the regulatory framework for DER aggregators was being developed and refined to encourage more participation [16]. The feasibility of applying international standards of, e.g., the International Electrotechnical Commission (TC57 WG21), directly to Japan would be very low. The reality and potential of the current DER aggregator service market in Japan should be thoroughly investigated.

Given this specific context of Japan, we aim to propose a complementary approach to build a holistic understanding of distributed energy resources, so that their short-term and long-term potential can be clearly revealed. The research questions include: i) how to quantify the potential market size of DER aggregator services; ii) how to model DERs in a macro-economic framework; iii) what the impacts of it (on load management, on total economic activities, on CO_2 emissions) are once the DER aggregator service market scales up to its potential size.

In this paper, we modeled the distributed energy resource services in a macroeconomic framework (input-output framework), so that the interactions between DER owners and the grid (flows of electricity inputs in TWh units), the interactions between DER owners and aggregators (flows of energy management services in monetary units), as well as the economic activities of the actors with the rest of the system, are fully considered. Our approach also includes barriers in the practices (i.e., consumer behavior, etc.) as they may have large impacts at the initial stage of the DER integration scaling-up process. We left the modeling open for a possible link with long-term energy system models or energy-economic integrated assessment models, and a possible application to countries and regions with very different electricity trading systems. We then applied our approach to the case of Japan, providing the benchmark year results with a simulation in the near-term future (FY2030 projection based on FY2015). We investigated the social, economic, and environmental impacts of DER aggregation services in Japan. The results facilitate a better design of effective policies and regulations to bridge the DER aggregator market size gap to align with the future low-carbon or even net-zero emission scenario.

2. Methodology

2.1. System boundaries

The distributed energy resources (DERs) that are discussed in this paper include solar photovoltaic panels, small wind turbines, energy storage facilities, industrial production facilities, heat/cooling appliances, electric vehicles (EVs) and EV charging stations, etc.

The services that distributed energy resource aggregators can provide are shown by participating market and service type in Fig. 1. Based on the current regulatory frameworks in countries that allow VPP trading (Australia, the US, the UK, part of the European countries, etc.; [17]) and academic research coverages [18], also, considering the long-term potential brought by such evolving market regulation and technology readiness, DER aggregators would be possible to be engaged in the following markets: bilateral contract and future/forward market, day-ahead market, ancillary service market, reserve market, intraday market, and real-time balancing market, providing risk management services, reserve capacity management services, and load balancing services. Fig. 1 shows how the 3 main types of DER aggregator services are mapped into the 7 main markets (and a version with more details of it see Fig. S1). Such services in all mentioned markets should be included when modeling DERs in long-term energy system models.

We further look into the reserve capacity management services and load balancing services considering the frequency adjustment requests, response time, and duration. We took the application in Japan, where the energy resource aggregation business has been emerging after the

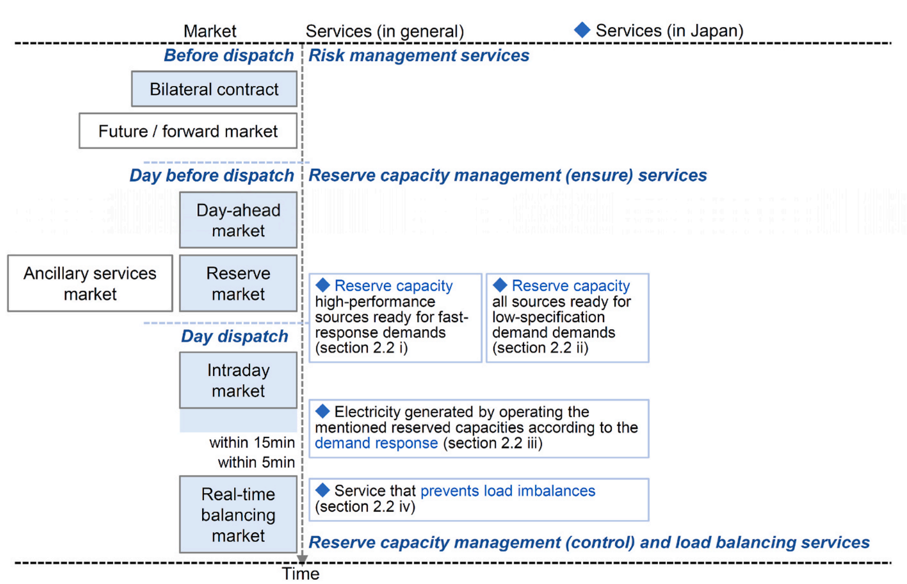

Fig. 1. The system boundary of DER aggregator services in this paper (matching 3 main types of services to 7 main markets). Notes: a more detailed version see Fig. S1 in the supplemental information.

negawatt trading system established in 2017 [15] but the system still has difficulties in applying international standards [16]. At the same time, the electricity security concern has been rising and the movement to community-based energy systems is growing. This made Japan a great example of investigating the dynamic changes of DER potentials in the long run. To assess its benchmark year, we included the reserve capacity management services and load balancing services in the day-ahead market, reserve market, intraday market, and real-time balancing market (marked as dark blue dots in Fig. 1) considering the mentioned ongoing trading systems and market regulations. The current regulatory framework and market design in Japan may not adequately support the participation of DER aggregators in the frequency control market and fast response (less than 15 min, real-time balancing) market, since they require precise, abundant, and fast response times to maintain grid stability. DER aggregators may need to meet stringent technical requirements and performance standards to participate effectively, which can be challenging and costly to implement. Therefore, the following four DER aggregator services are included in the application for the benchmark year in Japan.

i) keeping reserve capacity (high-performance balancing)
ii) keeping reserve capacity (low-specification demand)
iii) operating for demand response
iv) preventing load imbalances

In this chapter, we presented the methodology for evaluating the overall potential of distributed energy resources that aggregators can manage, which is determined by the smaller value of DER aggregator activities (as examined in section 2.2) and DER provider activities (as examined in section 2.3). With this overall potential, we mapped the DER aggregator service sector into a macro-economic framework (a DER-integrated Input-Output table, section 2.4) and assessed its economic and climate impact (section 2.5).

2.2. DER aggregator activities

The total economic value generated from the load transaction of DER aggregators with the grid is calculated by aggregating all the economic activities by DER aggregator services. In the benchmark year in Japan, these activities refer to.

i) keeping reserve capacity (high-performance balancing)

The total economic activities of DER aggregators providing reserve capacities (high-performance balancing), *ctvpp_er*, is formulated as follows,

$$ctvpp\_er = \sum_n \sum_k p\_er_{n,k} \bullet er_{n,k} \tag{1}$$

where $er_{n,k}$ refers to the quantity of the n th type of the reserve capacities (*Dengen I-a, I-b, I′*) of the k th power companies (10 in all) and $p\_er_{n,k}$ refers to the corresponding clearing prices in 2021. Specifically, the reserve capacities in this category are high-performance sources, capable of responding in short times (less than 5 min for *Dengen I-a,* 15 min for *I-b,* and 3 h for *I′*) and providing frequency control (GF- and EDC-signal-based ancillary services for *I-a*). This feature of high performance makes them possible to participate in multiple reserve markets, thus we assess their economic activities separately here. The public recruitment of such capacity providers in each power company is expected to be integrated into the capacity market from FY2024 in Japan. Therefore, the calibration may change in a long-term model.

ii) keeping reserve capacity (low-specification demand)

The total economic activities of DER aggregators providing reserve capacities (low-specification demand), *ctvpp_er*, is formulated as follows,

$$ctvpp\_adj = \sum_m \sum_t^{8*365} p\_adj_{m,t} \bullet adj_{m,t} \tag{2}$$

where $adj_{m,t}$ refers to the quantity of the m th type of the reserve capacities (capacities that participate in the market *Primary; Secondary 1, 2; Tertiary 1, 2*) in the t th time block in one year and $p\_adj_{m,t}$ refers to the corresponding clearing prices (using the average clearing prices of every 30 min within each 3-h block in the reserve market, unit: JPY/kWh/30min) in 2021. Specifically, depending on the frequency adjustment requests, response time, and duration, the reserve capacities in this category (not directly controlled by the central power supply control station) can be categorized by the market they participate in. *Primary* adjustment market provides governor-free equivalent ancillary services to stop frequency increases/decreases (expected to be started from FY2024). *Secondary 1, 2* adjustment market provides LFC-signal- and EDC-signal-based ancillary services to restore frequency to the reference level (expected to be started from FY2024). *Tertiary 1* adjustment markets operate reserve capacities by price incentives with a response time of less than 15 min and 3-h duration (started from FY2022), and *Tertiary 2* adjustment which operates reserve capacities by price incentives with a response time of less than 45 min and 3-h duration (started from FY2021). Therefore, only *Tertiary 2* is considered in the benchmark year but its calibration may change in a long-term model.

iii) operating for demand response

The total economic activities of DER aggregators operating the mentioned reserved capacities according to the demand response, *ctvpp_dr*, is formulated as follows,

$$ctvpp\_dr = \sum_k \sum_t^{24*365*2} p\_dr_t \bullet dr_{k,t} \tag{3}$$

where $dr_{k,t}$ refers to the actual power generation amount from operating reserved capacities according to the demand response of the k th power companies in the t th time block (unit: kWh/30min) and p_dr_t refers to the corresponding clearing prices (using the average clearing prices of all 10 power companies every 30 min, unit: JPY/kWh/30min) in 2021.

iv) preventing load imbalances

The total economic activities of DER aggregators preventing load imbalances, *ctvpp_inb*, is formulated as follows,

$$ctvpp\_imb = \sum_k \sum_t^{24*365*2} p\_imb_t \bullet imb_{k,t} \tag{4}$$

where $imb_{k,t}$ refers to the potential power generation amount to prevent load imbalances of the k th power companies in the t th time block (unit: kWh/30min) and p_imb_t refers to the corresponding clearing prices (using the average clearing prices of all 10 power companies every 30 min, unit: JPY/kWh/30min) in 2021. We also compared the imbalances in the positive and negative directions in all 5 years before the benchmark year in Japan, see Fig. S1 in the supplemental information.

Overall, the total economic value generated from the load transaction of DER aggregators with the grid in the benchmark year in Japan, *ctvpp*, can be calculated as follows.

$$ctvpp = ctvpp\_er + ctvpp\_adj + ctvpp\_dr + ctvpp\_imb \tag{5}$$

The total load transaction involved in DER aggregator activities is calculated as follows.

$$xvpp = \sum_t \left(\sum_n \sum_k er_{n,k} + \sum_m adj_{m,t} + \sum_k dr_{k,t} + \sum_k imb_{k,t} \right) \tag{6}$$

2.3. DER provider activities

We then estimate the total DER provider activities, namely how much DER providers (the energy end-use sectors that own DERs) would use DER aggregator services for the transactions with the grid.

It can be determined by multiple constraints: i) the total amount of all distributed energy resources in industrial processes, transportation, and buildings by capacity size (physical constraints), ii) their load shed/shift potential by season, by hour, and by response time (technological constraints), iii) the willingness of DER providers to participate in demand response requests (behavioral constraints), iv) the overall capacities that are allowed to participate in the reserve market (regulatory and market constraints), as shown in Fig. 2. In the long-term energy system models, the physical and technological constraints can be modeled by endogenous variables such as hourly electricity system operation, industrial final energy demand, EV ownership, commercial & residential cooling & heating energy services, solar power potential, etc. [19,20], while behavioral, regulatory, and reserve market constraints simply modeled by adjusting the capacity factor parameter (the share of actual electricity output to the theoretical maximum electricity output) in each period.

While in the benchmark year, the latter constraints usually play a more important role than the former constraints. In the benchmark year, the total overall DER provider activities would be determined by the lower level of the overall capacities that are allowed to participate in the reserve market (regulatory and market constraints) and the overall potential of DER load supply (physical constraints, technological constraints, behavioral constraints). Therefore, for the application to the benchmark year in Japan, we calibrated the shares of energy end-use sectors (industrial sectors, transportation and commercial service sectors, residential sectors, and their sub-sectors) according to.

i) the physical constraints

The physical constraint is determined by the available distributed energy resources in industrial processes, transportation, and buildings. For the benchmark year estimation, it is estimated by the appliance-level benchmark value and extended by Japan's national industry survey of production processes and on-site power generation [21]. For example, the aggregated distribution of DER provider activities by energy end-use sector in the benchmark year would be 0.6:1.0:4.0 (industry: transportation & commercial: residential).

ii) the technological constraints

The technological constraint is determined by the load shed/shift potential of all available distributed energy resources that aggregators are capable of managing (by season, by hour, by response time). For the benchmark year estimation, it is estimated by the potential availability of DERs to load shed and load shift requests based on an industry survey conducted by Japan's Central Research Institute of Electric Power Industry [22]. 7952 surveys were sent to factories from 29 sub-sectors, containing survey questions on capacity size, voltage, operating days and hours, share of on-site generation and electricity purchase, response potential (day and night in summer, winter, and the rest), response time (10min, 1h, 3h, one-day, one-week ahead), and duration (2h, 3–12h, 13–24h, above). With such constraints, the distribution of DER provider activities by industry sub-sectors and commercial service sub-sectors can be mapped, see Figure S3 and Figure S4 in the supplemental information accordingly.

iii) the behavioral constraints

Given the physical and technological constraints, the willingness of industrial entities and households to participate in the demand response requests can also be different [22]. Some key barriers to the willingness to participate can be the concerns about emergency load shedding disrupting daily operations, lack of data track records on the actual load pattern, too complicated power purchase contracts, and limited economic incentives [23]. The aggregated distribution of DER provider activities by energy end-use sector in the benchmark year, after considering the behavioral constraints and being standardized (specifically, household willingness from [24]), would be 0.24:0.40:0.36 (industry: transportation & commercial: residential).

2.4. A DER-integrated input-output table: assumptions and compilation

The DER aggregator activities (quantified in section 2.2) and the DER provider activities (quantified in section 2.3) are adequate for capturing the role of the DERs in the energy system (shown as the left part in Fig. 3), however cannot reveal how flexible loads from DERs can alleviate the pressures on electricity suppliers, as well as how electricity end-users can benefit from participating in demand responses with their DERs.

Therefore, we integrated the energy system with DERs into a national input-out framework (shown as the right part in Fig. 3), where the interdependencies of all actors (DER aggregator service sector, electricity transmission and distribution sectors, electricity supply sectors, and electricity end-use sectors) can be covered in an intermediate demand matrix, where the inputs of one actor to another sector are contained in the columns and the outputs of one actor to another sector are contained in the rows. More importantly, this matrix can model the electricity end-

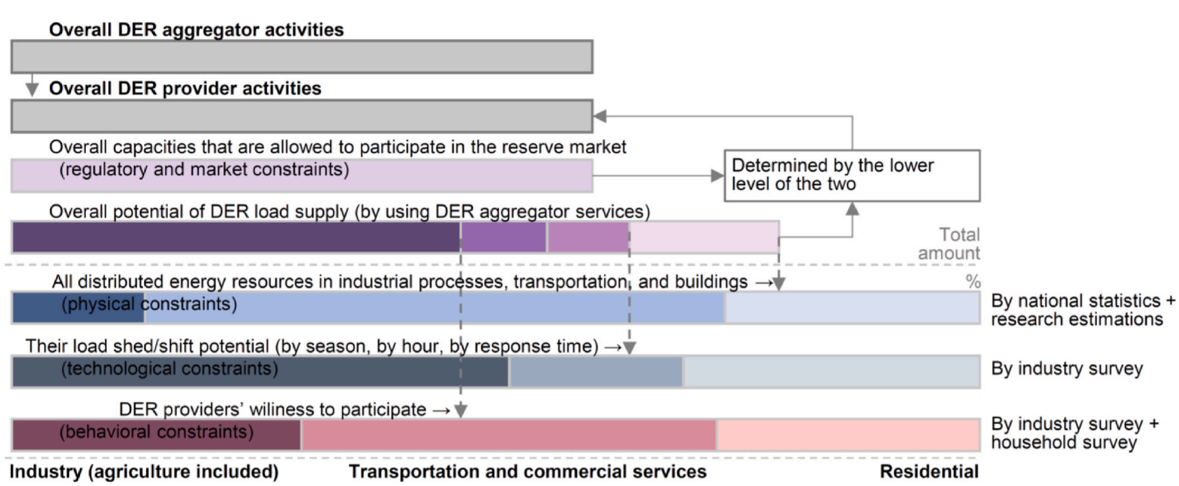

Fig. 2. The overall DER provider activities determined by multiple constraints.

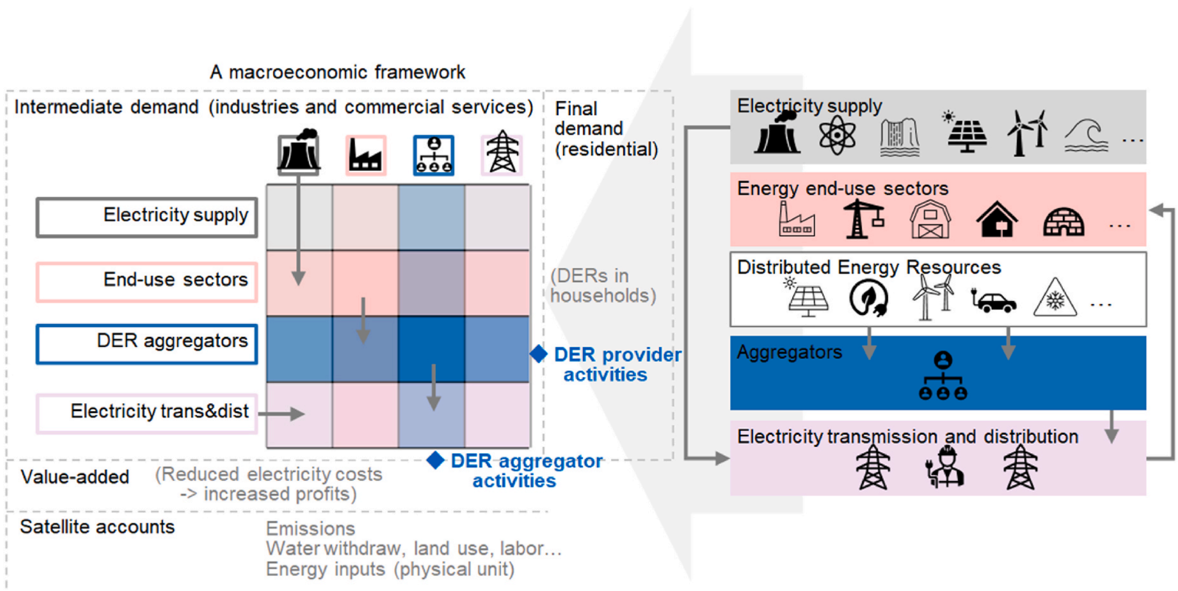

Fig. 3. DER-integrated macroeconomic framework.

uses simultaneously as the providers of DERs and the consumers of DER aggregator services. Also, with an extension to the macroeconomic framework, how final demand (e.g., household DERs) can induce economic transactions in the overall supply chain, how cost reduction through using DER aggregator services may increase the value-added in electricity end-use sectors, as well as how greenhouse gas emissions, employment level, cost reduction, etc. (by introducing satellite accounts) may change along with the scale-up of DER aggregator services, can also be modeled.

We follow the subsequent assumptions in this framework.

- the distributed energy resources that are discussed in this paper refer to those that are less emission-intensive compared to the grid average, e.g., solar power replacing thermal power;
- the DER aggregators participate in multiple markets by transactions with the grid, namely, in the model such transactions occur between the "DER aggregator service" sector and the "electricity transmission and distribution" sector;
- the total input of DER aggregator services (row sum of the "DER aggregator service" sector) should be equal to the total output of DER provider activities (column sum of the "DER aggregator service" sector);

Based on such framework and assumptions, the compilation of a DER-integrated input-output table (namely, the concept shown in the left-side part of Fig. 3 with hands-on applications to all of its expanded sectors) is shown in Fig. 4.

In order to model distributed energy resources in one economy, the electricity transmission and distribution sector need to be split from an aggregated energy supply sector, as well as the power generation activities by type. Similarly, the DER aggregator service sector needs to be split from the electricity transmission and distribution sector.

For the benchmark year in Japan, we start such splits and the

	No.	Sector	Intermediate demand 1	2	3	4	5	6	Final demand	Total output
Intermediate inputs	1	Non-electricity-supply sectors					$A_{15}x_5$			
	2	Ele supply| thermal power	$-\delta_{21}$	$-\delta_{22}$	$-\delta_{23}$	$-\delta_{24}$	$A_{25}x_5$	$-\delta_{26}$	$-\delta_{2f}$	$-\Sigma\delta_{2j}$
	3	Ele supply| distributed REs	+	+	+	+	$A_{35}x_5$	+	+	+
	4	Ele supply| other sources					$A_{45}x_5$			
	5	DER aggregator services	δ_{51}	δ_{52}	δ_{54}	δ_{54}	0	0	δ_{5f}	$x_5 = \Sigma\delta_{5j}$
	6	Ele transmission & distribution	–	–	–	–	0	–	–	–
Value added		Operating surplus					v_5			
		Other value-added								
Total inputs		Total inputs					x_5			

◆ DER provider activities

◆ DER aggregator activities

Fig. 4. The Structure of a DER-integrated input-output table.

following calibration based on the Input-Output table for analysis of the Next-Generation Energy System [25] compiled by the Institute for Economic Analysis of Next-generation Science and Technology in Japan. It is a 2030 national table (power generation mix projected based on the “ambitious outlook” in Japan’s Sixth Basic Energy Plan, [26]) based on the 2015 table. It contains 12 electricity supply sectors, 1 electricity transmission and distribution sector, and 144 non-electricity-supply sectors. For details see our previous work [27].

Regarding the intermediate inputs to the DER aggregator service sector (column 5), each element of the intermediate input vector, $A_{i5}x_5$, is formulated as,

$$A_{i5}x_5 = A_{is} \bullet ctvpp \tag{7}$$

where A_{is} refers to the unit intermediate input from the i th sector to the sector “other commercial services” (we use the input structure of general commercial services to estimate the inputs of DER aggregators), while *ctvpp* refers to the overall DER aggregator activities. This is a split from the electricity transmission and distribution sector (column 6).

Regarding the changes in the intermediate inputs to the thermal power electricity supply sectors (decrease, see row 2) and to the solar power electricity supply sectors (increase, see row 3) due to the DER aggregator services (DER aggregators control flexible loads and integrated distributed renewable resources which, as a result, leads to the replacement of thermal power with the solar power), the changes in each element of vectors, $-\delta_{2j}$ in row 2 and δ_{3j} in row 3, are formulated as follows.

$$-\delta_{2j} = (Ax_{2j} / x_2) \bullet (p\_pro \bullet xvpp) \tag{8}$$

$$\delta_{3j} = (Ax_{3j} / x_3) \bullet (p\_pro \bullet xvpp) \tag{9}$$

According to the production balance, the increases in the total output of electricity supply sub-sectors, calculated by the producer’s price of the homogenous final product of electricity supply (*p_pro*) times the total load transaction involved in DER aggregator services (*xvpp*), should be the same to the decreases. They are then distributed in each row according to the intermediate output ratio (e.g., Ax_{2j}/x_2, Ax_{3j}/ x_3). We should also clarify that the sector numbers (e.g., sector 3) in the simplified framework include multiple subsectors (e.g., mega solar, roof PV panels). Also, before conducting the replacement in Eqs. (8) and (9), with the same changes in the total input ($p\_pro \bullet xvpp$), the decreases in the intermediate inputs of thermal power electricity supply (column 2) and the increases in the intermediate inputs of solar power electricity supply (column 3) should also be adjusted according to their intermediate input ratios, similarly to the adjustment in Eq. (7).

Regarding the changes in the intermediate inputs to the electricity transmission and distribution sector (decrease, see row 6) and to the DER aggregator service sectors (increase, see row 5) due to the DER aggregator services (DER providers use DER aggregator services, as a result, leads to the replacement of original grid aggregator services with the DER aggregator services), the changes in each element of the vectors, δ_{5j} in row 5 and $-\delta_{6j}$ in row 6, are formulated as follows.

$$\delta_{5j} = share_j \bullet ctvpp \tag{10}$$

$$-\delta_{6j} = \delta_{5j} \tag{11}$$

The total output of DER aggregator services (*ctvpp*) would be distributed to electricity end-use sectors (δ_{51}) including industry, transportation, commercial service sub-sectors, other electricity supply sectors (δ_{52}, δ_{53}, δ_{54}), and the residential DER providers in the final demand vectors (δ_{5f}), according to the output ratio of DER provider activities ($share_j$, calibration see section 2.3). All negative changes in the inputs from the electricity transmission and distribution sector ($-\delta_{6j}$) represent the possible savings by using DER aggregator services instead of the original grid aggregator services. In this macroeconomic framework, the electricity end-use sectors that use more DER aggregator services (namely the sectors actively participating in demand response requests) would benefit from less emission-intensive electricity consumption and lower average electricity consumption prices.

Regarding such average price decline, namely the decrease in the intermediate electricity inputs to electricity end-use sectors ($\Delta\theta_{21}$, $\Delta\theta_{31}$, $\Delta\theta_{41}$), $\Delta\theta_{i1}$, is formulated as

$$\Delta\theta_{i1} = marg \bullet Ax_{i1}, i = 2, 3, 4 \tag{12}$$

where Ax_{i1} represents the intermediate inputs from the i th electricity supply sector ($i = 2, 3, 4$) to electricity end-use sectors, *marg* represents the average electricity price decline in each electricity end-use sector. For the benchmark year in Japan, we use the aggregated data from R.E. A.L. New Energy Platform® and other expert interviews (by an average of 4.889 %). To keep the production balance, such savings achieved by the average price decline would be adding back to the operating surplus in each electricity end-use sector (v_1), and then balanced to the fixed capital formation in each electricity end-use sector (f_1), since the cost savings from the use of DER aggregator services allow for new investments in electricity transmission and distribution system upgrades.

2.5. Impact on emission reduction and economic activities

Based on the DER-integrated macroeconomic framework built in section 2.4, we further investigate the impact of DER aggregator services on the emission reduction of one economy and the cost reduction of all sectors.

The overall emission within one economy is formulated as

$$\mathbf{c} = \mathbf{E} \bullet [\mathbf{I} - (\mathbf{I} - \widehat{\mathbf{M}})\mathbf{A}]^{-1}(\mathbf{I} - \widehat{\mathbf{M}})\mathbf{f} + \mathbf{E}^{\mathrm{d}}(\mathbf{I} - \widehat{\mathbf{M}})\mathbf{f}$$

$$\mathbf{c}^* = \mathbf{E} \bullet [\mathbf{I} - (\mathbf{I} - \widehat{\mathbf{M}})\mathbf{A}^*]^{-1}(\mathbf{I} - \widehat{\mathbf{M}})\mathbf{f}^* + \mathbf{E}^{\mathrm{d}}(\mathbf{I} - \widehat{\mathbf{M}})\mathbf{f}^* \tag{13}$$

where $\mathbf{A}$ represents the intermediate input coefficient matrix, $\widehat{\mathbf{M}}$ represents the diagonalized matrix of import share (the share of imports in the total domestic final demand), $[\mathbf{I} - (\mathbf{I} - \widehat{\mathbf{M}})\mathbf{A}]^{-1}$ represents the domestic Leontief inverse matrix, $\mathbf{f}$ represents the final input, while $\mathbf{A}^*$, $\mathbf{f}^*$, and $[\mathbf{I} - (\mathbf{I} - \widehat{\mathbf{M}})\mathbf{A}^*]^{-1}$ represent the same variables in the DER-integrated IO table correspondingly. $\mathbf{E}$ represents the emission intensity vector and $\mathbf{E}^{\mathrm{d}}$ represents the direct emission intensity of household energy consumption, thus industry-related emissions and household emissions are both included. The emission reduction, $\Delta\mathbf{c}$, is then calculated as the difference between the overall emission based on the original IO table ($\mathbf{c}$) and the DER-integrated IO table ($\mathbf{c}^*$).

$$\Delta\mathbf{c} = \mathbf{c} - \mathbf{c}^* \tag{14}$$

The overall economic activities induced by the investment in DER aggregator services within one economy are formulated as

$$\mathbf{q} = [\mathbf{I} - (\mathbf{I} - \widehat{\mathbf{M}})\mathbf{A}]^{-1}(\mathbf{I} - \widehat{\mathbf{M}})\mathbf{f}^{\mathrm{v}}$$

$$\mathbf{q}^* = [\mathbf{I} - (\mathbf{I} - \widehat{\mathbf{M}})\mathbf{A}^*]^{-1}(\mathbf{I} - \widehat{\mathbf{M}})\mathbf{f}^{\mathrm{v}*} \tag{15}$$

where $\mathbf{f}^{\mathrm{v}}$ and $\mathbf{f}^{\mathrm{v}*}$ represents the final demand of DER aggregator services in the original IO table and DER-integrated IO table. The cost reduction, $\Delta\mathbf{q}$, is then calculated as the difference between the overall DER-related economic activities based on the original IO table ($\mathbf{q}$) and DER-integrated IO table ($\mathbf{q}^*$).

$$\Delta\mathbf{q} = \mathbf{q} - \mathbf{q}^* \tag{16}$$

2.6. List of parameters & variables

All parameters and variables, together with their data sources, are listed in Table 1.

Table 1
List of counters, parameters and variables.

Key results	Definition	Data source (Japan case)
ctvpp	the total economic value generated from the load transaction of DER aggregators with the grid	
xvpp	the total load transaction involved in DER aggregator activities	
$\Delta\mathbf{c}$	the emission reduction achieved by DER aggregator services	
$\Delta\mathbf{q}$	cost reduction of electricity end-users achieved by DER aggregator services	
Counter	Definition	Data source (Japan case)
i	Counter of row sectors in IO tables	Range from 1 to 6 in the simplified model
j	Counter of column sectors in IO tables	Range from 1 to 6 in the simplified model
t	Counter of time blocks in one day (e.g., 30min -> 2x24x365)	
k	Counter of power companies in one economy	
m	Counter of reserve capacity types (e.g., *Primary; Secondary 1, 2; Tertiary 1, 2*)	
n	Counter of reserve capacity types (e.g., *Dengen I-a, I-b, I'*)	
IO framework	Definition	Data source (Japan case)
$\mathbf{A}, \mathbf{x}, \mathbf{f}, \mathbf{v}$	The intermediate coefficient matrix, total output vector, final demand vector, and value-added vector in the IO table	[25]
$\mathbf{A}^*, \mathbf{x}^*, \mathbf{f}^*, \mathbf{v}^*$	The intermediate coefficient matrix, total output vector, final demand vector, and value-added vector in the DER-integrated IO table	
δ_{ij}	Sub-matrix by aggregated sectors in the DER-integrated IO table	
θ_{ij}	The decrease in the *i* th type of intermediate electricity inputs to the *j* th electricity end-use sectors	
$\mathbf{M}$	The diagonalized matrix of import share	[25]
$\mathbf{E}$	CO_2 emission intensity vector	[28]
$\mathbf{E}^d$	Household energy-consumption-related CO_2 emission intensity vector	[29]
Other parameters	Definition	Data source (Japan case)
er, *p_er*	the quantity of reserve capacities (*Dengen I-a, I-b, I'*) and the corresponding prices	From each power company, see references started with "PowerGrid_" (see reference SI, together with [30]
adj, *p_adj*	the quantity of reserve capacities (*Primary; Secondary 1, 2; Tertiary 1, 2*) and the corresponding prices	TDGC, 2021
dr, *p_dr*	the actual power generation amount from operating reserved capacities and the corresponding prices	[31], 2021
imb, *p_imb*	the potential power generation amount to prevent load imbalances and the corresponding prices	The FY2019 and FY2021 load imbalance data from each power company, see references started with "PowerGrid_" (see reference SI)
p_pro	the producer's price of the homogenous final product of the electricity supply	[25]
share	the output ratio of DER provider activities	[21–24]
marg	average electricity price decline in each electricity end-use sector	From interviews, see the acknowledgment

3. Results

3.1. A snapshot of the DER aggregator services

The total economic value generated from the load transaction of DER aggregators with the grid in the benchmark year in Japan, as well as the total load transaction involved in DER aggregator activities, are shown in Table 2 by aggregator service types.

We use the higher level (104.80 TWh/hour/year and 1435.1 billion JPY/year in FY2021) as the benchmark year data. Among all DER aggregator services, the flexible load from demand response in 2021 reached 70.60 TWh/hour/year, accounting for a demand response market size of 873.7 billion JPY. The reserve market size also reached 353.3 billion JPY, but the additional electricity actually sold to the grid was 7.81 TWh/hour/year.

Overall, the DER aggregator services at a full scale (1435 billion JPY) may have occupied 33.2 % of all grid aggregator services on electricity transmission and distribution (4317 billion JPY). Such a potential market size does not match the slow pace of establishing and implementing DER-service-related policy supports. The maximum substitution of thermal power with distributed solar power (2376 billion JPY) would have accounted for 27.5 % of the total thermal power generation (8641 billion JPY). The cost of intermediate electricity inputs that electricity end-use sectors can save would reach 758 billion JPY in the benchmark year. Chen et al. [32] found that the annual total benefits from implementing demand response in China were 13 billion yuan in their benchmark year. Though not fully scaled, that will be approximately 2 % of China's annual electricity and transmission output.

Table 3 shows the sectors participating more in demand response requests, namely, those using more DER aggregator services.

Among all electricity end-use sectors, the level of cooperation with DER aggregators would be high in the pulp, paper and processed paper products and general business. This is also aligned with the results in Figs. S3 and S4, as these sectors have a higher level of electricity purchase as necessary intermediate inputs, and are more willing to participate in demand response requests.

3.2. Impacts on national emission reduction

By applying the DER aggregator services in the benchmark year (FY2021 in Japan) to a macroeconomic framework (2030 IO table based on 2015), the total CO_2 emission in one economy can reduce 69.8 Mt-CO_2, accounting for approximately 5 % of the annual emission.

Although the introduction of DER aggregator services will increase the emissions in some sectors (e.g., the electricity that DER aggregators use, etc.), the total of those increases would be very small (4.6 Mt-CO_2) compared to the total emissions reductions in other sectors (69.8 Mt-CO_2). The sectoral reduction is shown in Table 4. The largest CO_2 reduction would be in the thermal power generation sector, followed by the business sector, and other service sectors.

We then mapped all sectors by unit replaceable thermal power input and unit emission reduction, as shown in Fig. 5. The unit emission reduction (x-axis) reveals the direct reduction impact of expanding DER aggregator services, while the unit replaceable thermal power input (y-axis) reveals the indirect impact.

The sectors with relatively large direct impacts but smaller indirect effects include the service sectors such as real estate brokerage and leasing, warehousing, residential rental, etc. The sectors with relatively

Table 2
A snapshot of the DER aggregator services.

Services	Load (TWh/hour/year)		Economic activities (billion JPY/year)	
	FY2019	FY2021	FY2019	FY2021
Preventing load imbalances	24.30	26.40	204.1	388.8
Operating for demand response[a]	71.40	70.60	515.8	873.7
Keeping reserve capacity (low-specification)[b]	–	7.79	–	201.0
Keeping reserve capacity (high-performance)[b]	–	0.02	–	152.5
Total	95.70	104.80	720.0	1435.1

Key sectors in the benchmark year	Economic activities (billion JPY/year)	Notes
Thermal power generation	8641	Among which, DER flexible loads can replace 2376 billion JPY (27.5 %).
Solar power generation (roof PV)	790	
Solar power generation (Mega Solar)	2582	
Electricity transmission and distribution	4317	Among which, DER aggregator services can replace 1435 billion JPY (33.2 %), and the reduced cost of electricity end-users can be 758 billion JPY.

Notes: Regarding the unit "TWh/hour/year", the response time of research capacity are standardized to per hour ("/hour").
[a] The publicly available data of FY2020 are partially missing, thus we calculated FY2019 and FY2021 for the calibration of the benchmark year.
[b] The *Tertiary 1* and *Tertiary 2* markets started after 2021, thus 2019 data are not included.

Table 3
Sectors using more DER aggregator services (participating more in demand response requests).

Top sectors	Intermediate inputs from DER aggregator services (billion JPY)
Pulp, paper and processed paper products	2261.9
Business (general)	1799.0
Waste treatment	667.5
Education	528.2
Food and restaurant services	527.7
Printing, plate making, bookbinding	372.6
Public services	371.5
Entertainment services	298.7
Real estate brokerage and leasing	219.2
Gas and heat supply	190.4
other commercial services	181.3
Paper products	170.9
Research	160.1

large indirect impacts but smaller direct effects include the industry sectors such as iron castings and forgings, chemical fiber, wood chips, etc. This suggests that, if more substitution of thermal power with distributed renewable power would take place in these basic material sectors (i.e., iron casting, chemical fiber, etc.), additional emission reductions can be achieved.

3.3. Impacts on national economic activities

Sectors with more cost reduction by using DER aggregator services are shown in Table 5.

In industry sectors such as inorganic chemical products, pulp, paper and processed paper products, iron casting, etc. (the sectors that used to require a larger share of fossil-fuel electricity intermediate inputs and show a higher willingness to participate in demand responses), a cost reduction ranging from 0.2 % to 0.6 % can be achieved by using DER aggregator services and actively participating in demand response requests.

Table 4
Sectors with more emission reduction by using DER aggregator services.

Top sectors	Emission reduction (kt-CO_2)
Thermal power generation	−19,980
Business (general)	−6272
Food and restaurant services	−3757
Medical and healthcare	−3038
Public services	−2752
Education	−2572
Construction	−2516
Food and groceries	−1488
Manufacturing machinery	−1447
Entertainment services	−1386
Research	−1339
Rail transportation	−1222
Total	−65,252

4. Discussion

DER aggregators in Japan currently face several limitations that restrict their participation in various markets due to the specific regulatory environment, energy market structure, and the relatively nascent stage of DER integration (e.g., ancillary services, such as frequency regulation and spinning reserves, usually require precise and rapid responses to grid conditions. The current DER aggregators in Japan might face challenges meeting the technical and operational standards currently set by the regulatory bodies; thus not participating in all markets that involve ancillary services.). More advanced regulatory frameworks may accelerate DER rollout and expand the potential market size. The Technical Committee on Smart Facilities of IEEJ (The Institute of Electrical Engineers of Japan) has been compiling the technical requirements of "use cases" for international standard specifications from domestic demonstration projects, and then communicated them to international standardization bodies (IEC, International Electrotechnical Commission). All of these regulatory efforts could improve the current situation that DER aggregators in Japan are still highly dependent on direct contracting from power companies.

The methodology we presented for evaluating the overall DER potential that aggregators can manage in the benchmark year is determined by the smaller value of DER aggregator activities (as examined in section 2.2) and DER provider activities (as examined in section 2.3, with multiple restraints). If further modeling it a long-term model, e.g., an energy system model or energy-economic integrated assessment model, the DER aggregator activities would be more coupled with regional GDP, sectoral electricity demand, solar/fossil-fuel power generation trajectories. Based on it, similarly, it is then limited by the smaller value of DER provider activities, which is constrained by the parameters showing physical, technical, and behavioral constraints.

5. Conclusion

In this paper, we modeled the distributed energy resource services (DER) in a macroeconomic framework. We quantified the DER aggregator activities and DER provider activities, and then integrated them into an input-output table. The table modeled how DER aggregators provide aggregator services as a substitute to the current grid services, how industrial and household DER providers participate in demand response requests (with physical, technical, and behavioral constraints), as well as, as a result, how thermal power can be substituted by distributed renewables. We clarified the mechanism of DER aggregators from a holistic perspective and specified the potential size of all flexible

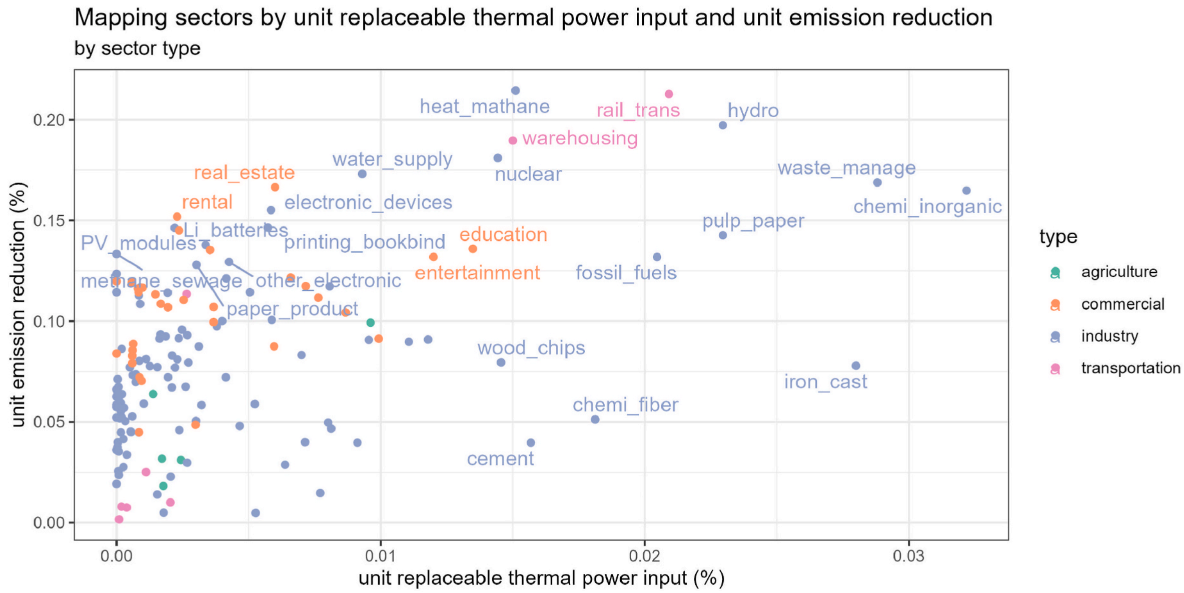

Fig. 5. Mapping sectors by unit replaceable thermal power input and unit emission reduction.

Table 5
Sectors with more cost reduction by using DER aggregator services.

Top sectors	Cost reduction (%)
Inorganic chemical products	0.58 %
Pulp, paper and processed paper products	0.51 %
Waste treatment	0.44 %
Castings and forgings (iron)	0.42 %
Hydropower	0.35 %
Chemical fiber	0.34 %
Heat supply (livestock manure methane fermentation)	0.34 %
Cement and cement products	0.26 %
Nuclear power	0.25 %
Livestock manure methane power generation	0.24 %
Chemical fertilizer	0.24 %
Coal, crude oil, natural gas	0.24 %

loads that can be controlled by them, which has been generally believed as “helpful” in mitigating carbon emissions but “a cup of water on a burning cart of firewood” (an utterly inadequate measure).

We applied our approach to the case of Japan, providing the benchmark year results with a simulation in the near-term future (FY2030 projection based on FY2015). The results show that, in the benchmark year, the DER aggregator services at a full scale (1435 billion JPY) may have occupied 33.2 % of all grid aggregator services on electricity transmission and distribution. Faster-pace implementation of policy supports related to DER aggregator services is required to match such a potential market size.

The maximum substitution of thermal power with distributed solar power would have accounted for 27.5 % of the total thermal power generation. By such substitution, the total CO_2 emission in one economy can reduce 69.8 Mt-CO_2, accounting for approximately 5 % of the annual emission. The cost of intermediate electricity inputs that electricity end-use sectors can save would reach 758 billion JPY. These reductions in both CO_2 emissions and energy costs highlight the significant role of DER adoption in driving Japan towards a more environmentally and economically sustainable energy future.

At the sector level, industry sectors such as inorganic chemical products and paper products can benefit from using DER aggregator services and actively participating in demand response requests, achieving a cost reduction ranging from 0.2 % to 0.6 %. Also, if more substitution of thermal power with distributed renewable power would take place in the basic material sectors (i.e., iron casting, chemical fiber, etc.), additional emission reductions can be achieved.

We left the modeling open for a possible link with long-term energy system models or energy-economic integrated assessment models, and a possible application to countries and regions with very different electricity trading systems, since our modeling is able to track the flows of load, costs, and carbon footprints among private and public stakeholders. This is extremely important to reveal a long-term energy transition aiming at a more resilient and low-carbon electricity supply. Our application to benchmark year in Japan emphasized the urgency and importance of closing the gap between the current DER aggregator market and its large future potential. The barriers to achieving the potential environmental and economic benefits of the DERs can be not only the constraints on all available distributed energy resources, but also the regulations of DER participating energy markets and the willingness of DER providers to participate in demand responses, which should be removed by policymakers should in the early-stage of business scaling.

CRediT authorship contribution statement

Ayu Washizu: Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Yiyi Ju:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization. **Akira Yoshida:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **Masashi Tayama:** Writing – review & editing, Validation, Data curation. **Yoshiharu Amano:** Writing – review & editing, Supervision, Investigation, Formal analysis.

Data availability statement

Regarding the Input-Output table for analysis of the Next-Generation Energy System, it will be soon at https://washizu.w.waseda.jp/table.html.

Regarding other key parameters, e.g., the margin of DER aggregators (the average profit they may make in one contract or one demand response request), as well as the willingness of industrial entities to participate in demand response requests, considering the privacy of those data, they can be partly available by reasonable requests.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2024.133561.

Data availability

Data will be made available on request.

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