Supplementary Information for

Strategic data center siting can mitigate dilemmas between decarbonization and digitalization in Japan

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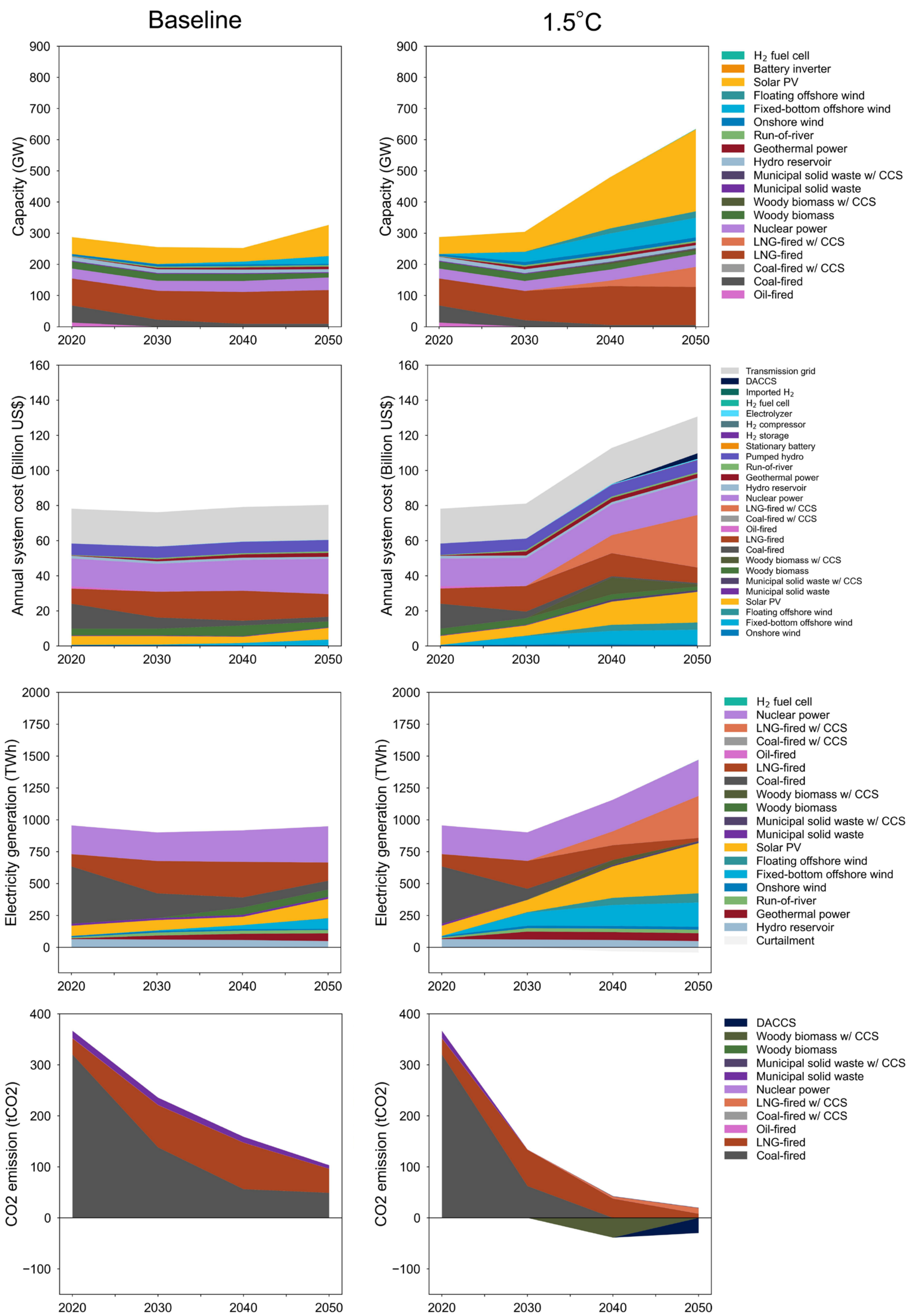
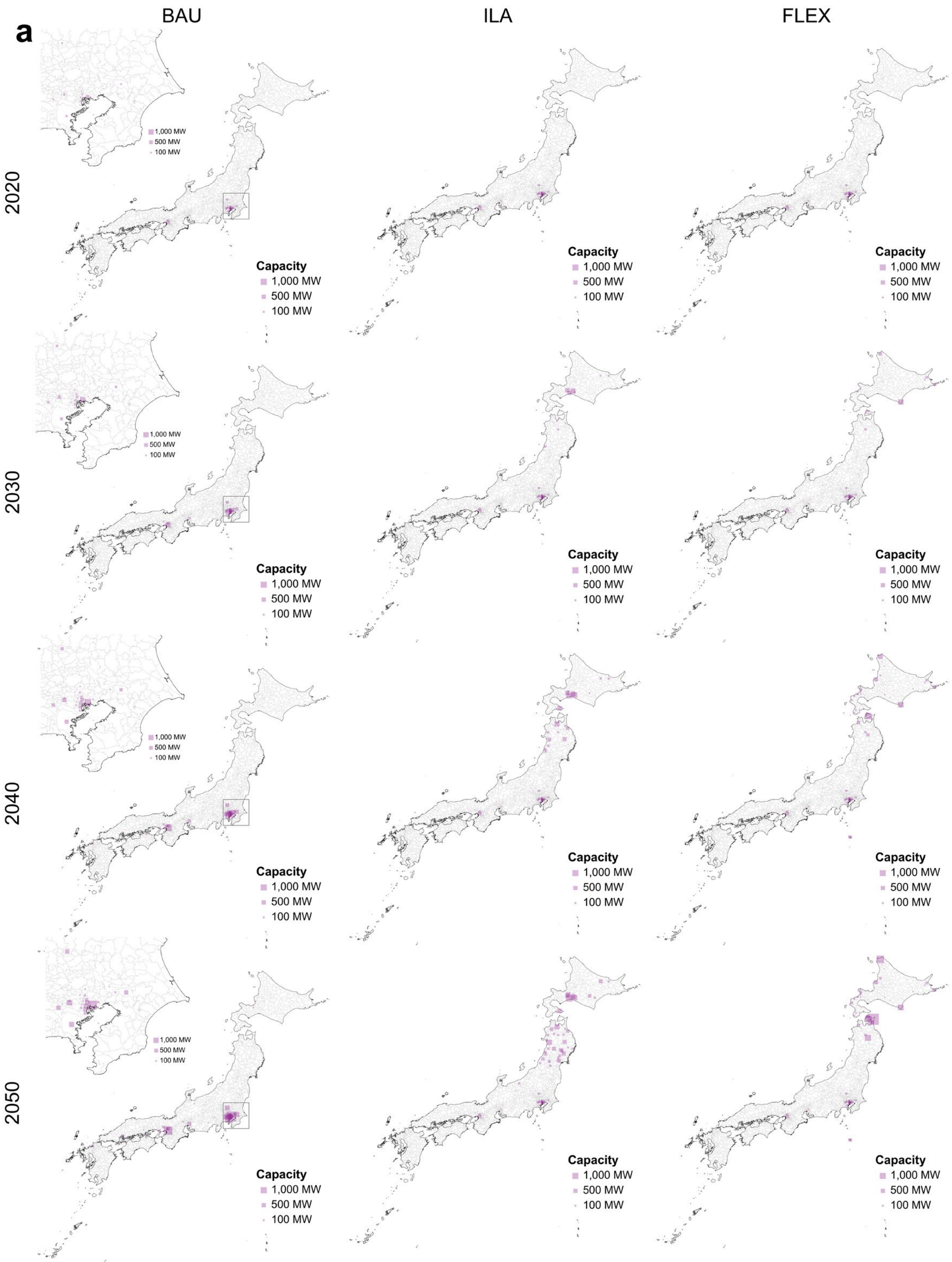
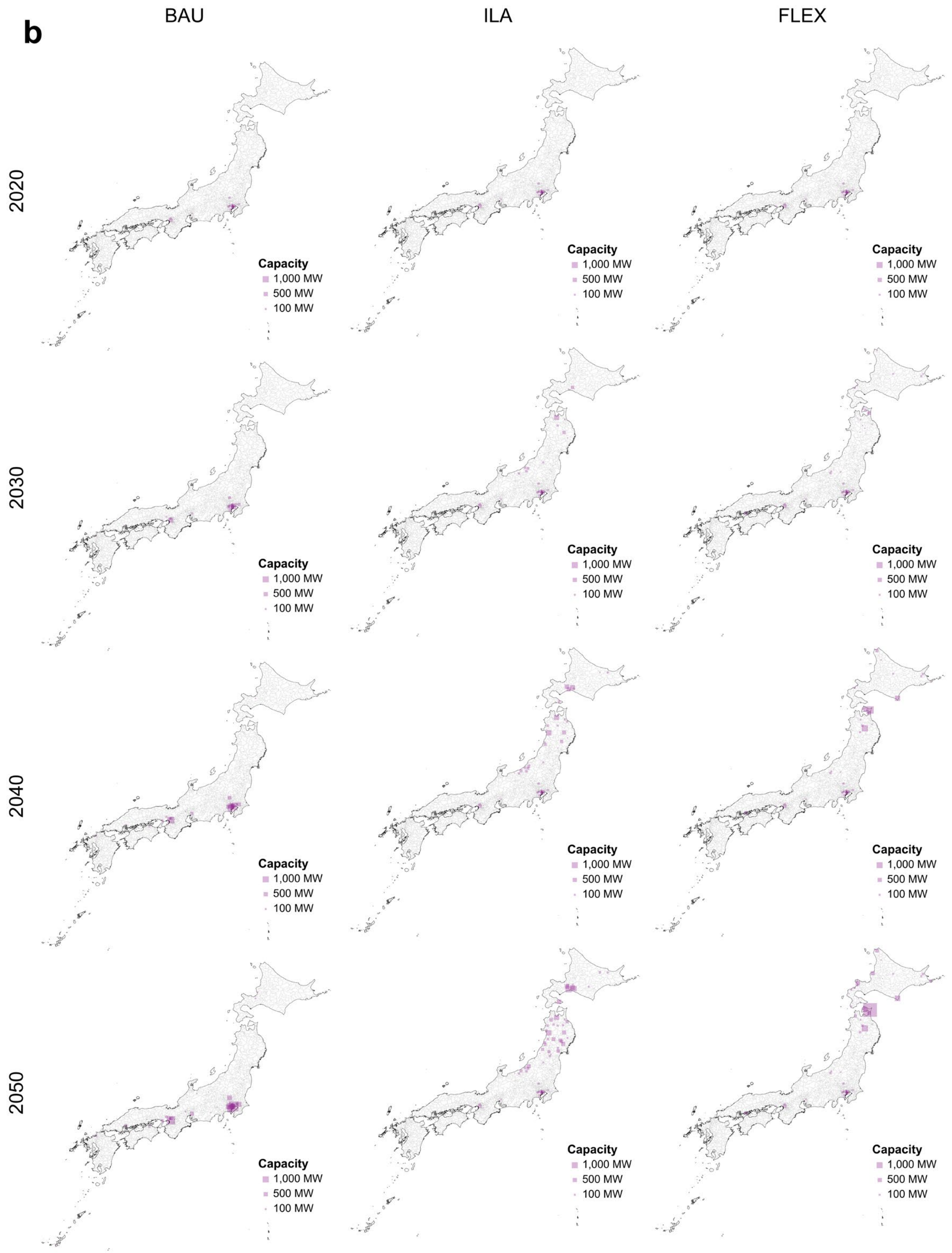
Supplementary Figures



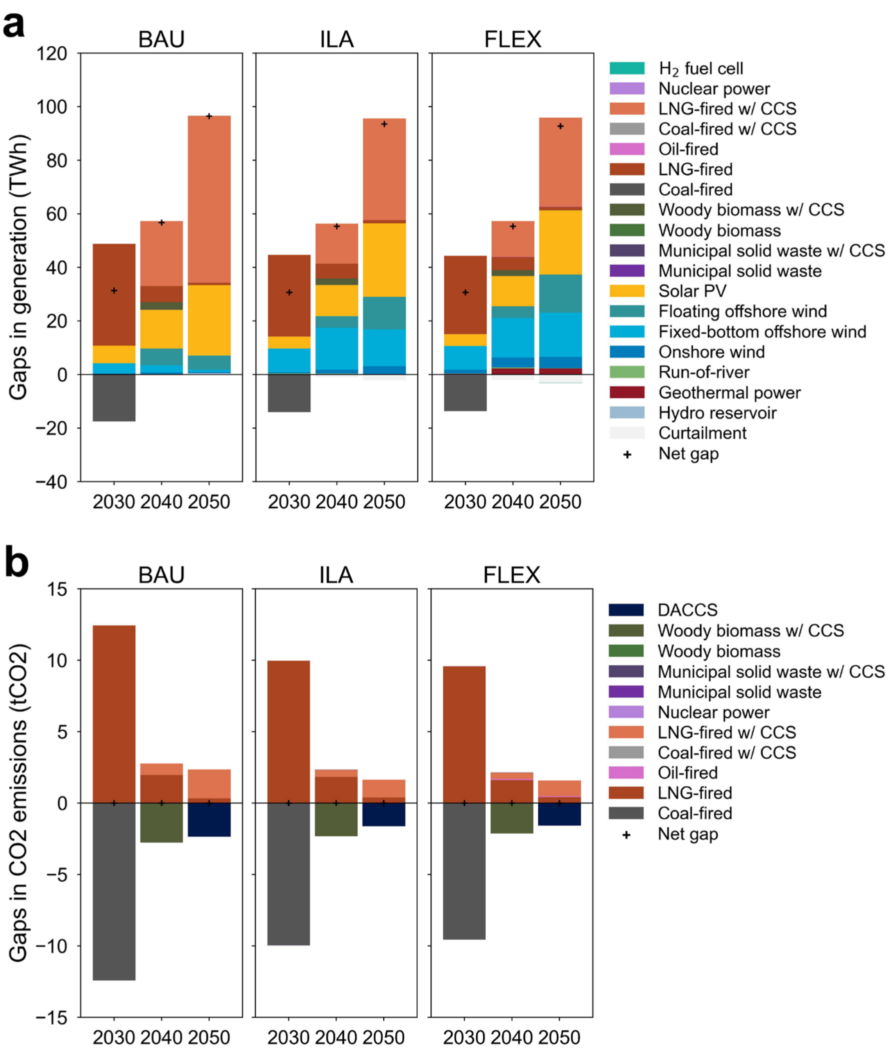
Supplementary Figure 1: Calculated trajectories of Japan's electricity sector under the baseline-Mid and 1.5°C-Mid scenarios. From top to bottom: installed capacity, annual system cost, electricity generation, and CO_2 emissions, each disaggregated by technology.


a
BAU
ILA
FLEX
2020
2030
2040
2050
Capacity
1,000 MW
500 MW
100 MW

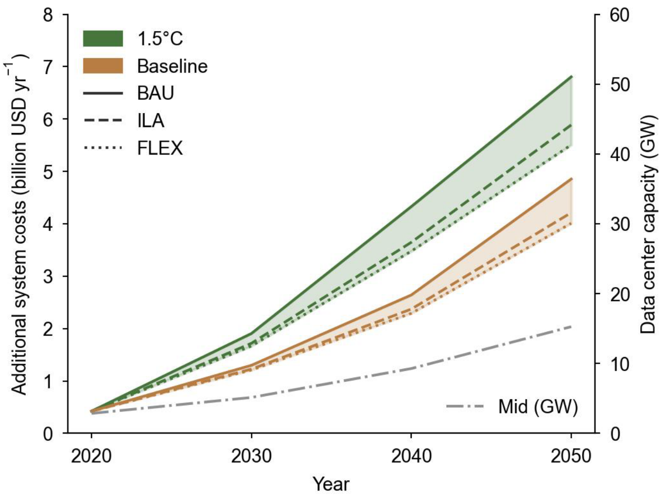
(continued)



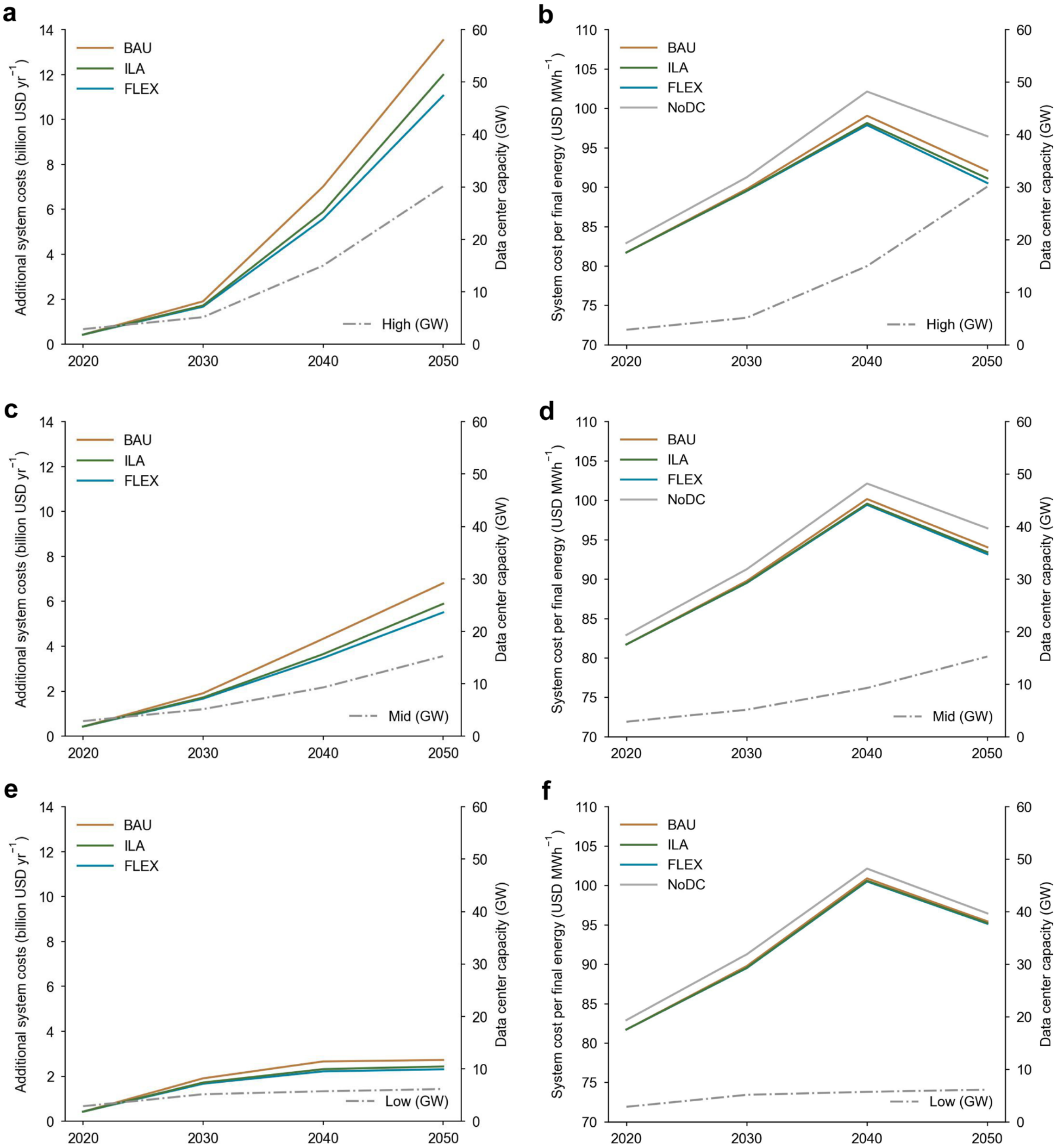
Supplementary Figure 2: Data center location scenarios under different siting strategies. **a** and **b** show baseline-Mid and 1.5°C-Mid scenarios, respectively.



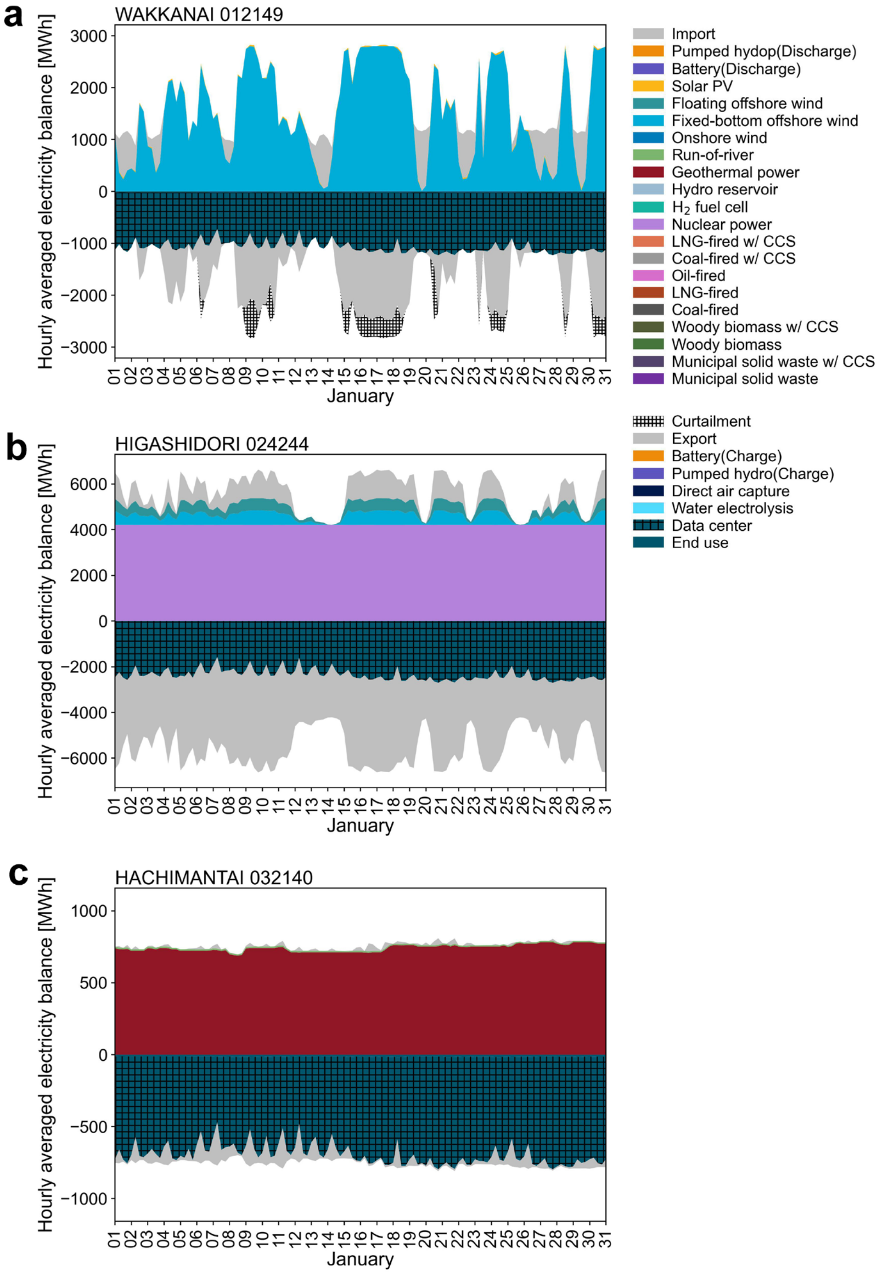
Supplementary Figure 3: Impacts of data center growth on annual electricity generation and CO_2 emissions, shown in **a** and **b**, respectively, by siting strategies under the 1.5°C-Mid scenario.



Supplementary Figure 4: Additional system costs due to data center growth. Green and orange lines show 1.5°C-Mid and baseline-Mid scenarios, respectively. Colored solid, dashed, and dotted lines indicate data center siting strategies of BAU, ILA, and FLEX, respectively. A grey dash-dotted line indicates the data center capacity assumption.



Supplementary Figure 5: **a**, **c**, and **e** present the additional system cost due to data center expansion under the 1.5°C pathway. **b**, **d**, and **f** present the system cost per final energy, assuming high, medium, and low data center electricity demand projections, respectively. The grey solid line corresponds to the NoDC scenario and the grey dash-dotted lines show the total data center capacity (right axis).



Supplementary Figure 6: Hourly averaged electricity balance in January 2050 under the 1.5°C-Mid scenario with the FLEX strategy. **a**, **b**, and **c** represent Wakkanai City, Higashidori Village, and Hachimantai City, respectively.

Supplementary Notes.

1 Model description

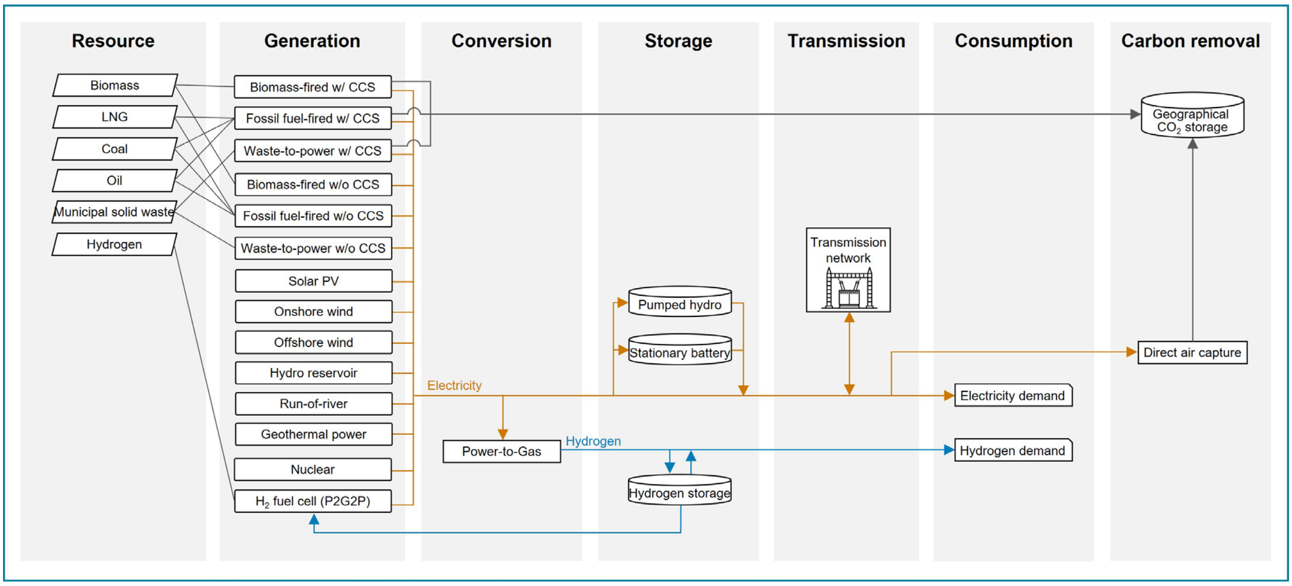
In this study, we employ a substantially enhanced version of the ReGRID model[1], designed to strengthen both continuity with the existing electricity grid and consistency across regions. In previous studies, this model was used to design snapshots of fully renewable energy systems in a greenfield context, based on a hierarchical optimization approach. The updated version enables recursive optimization of transition pathways in a brownfield setting without relying on the hierarchical approach.

1.1 System configuration

Technological resolution

The ReGRID model is a linear programming model that simultaneously optimizes region-specific capacity planning and hourly operational dispatch across technologies including electricity generation, energy conversion, storage, transmission, and carbon capture and sequestration (CCS). The technological configurations are detailed in Supplementary Figure 8. Final energy demand is treated as an exogenous input (see Supplementary Section 1.3), and technologies for end-use energy consumption are not explicitly modeled.

The model assumes that no new fossil fuel power plants will be constructed under increasing decarbonization pressure; their installed capacity is capped at existing levels. However, retrofitting existing plants with carbon capture facilities is allowed. Given the high uncertainty of nuclear power development to democratic and political decisions, nuclear capacity is treated as exogenously fixed. Following the Japanese government's latest policy direction (outlined in the 7th Strategic Energy Plan), this study assumes that currently suspended nuclear reactors (under regulatory review) will gradually resume operation. However, the replacement of reactors beyond their statutory lifetime (60 years) is considered highly uncertain and is therefore excluded from the analysis.

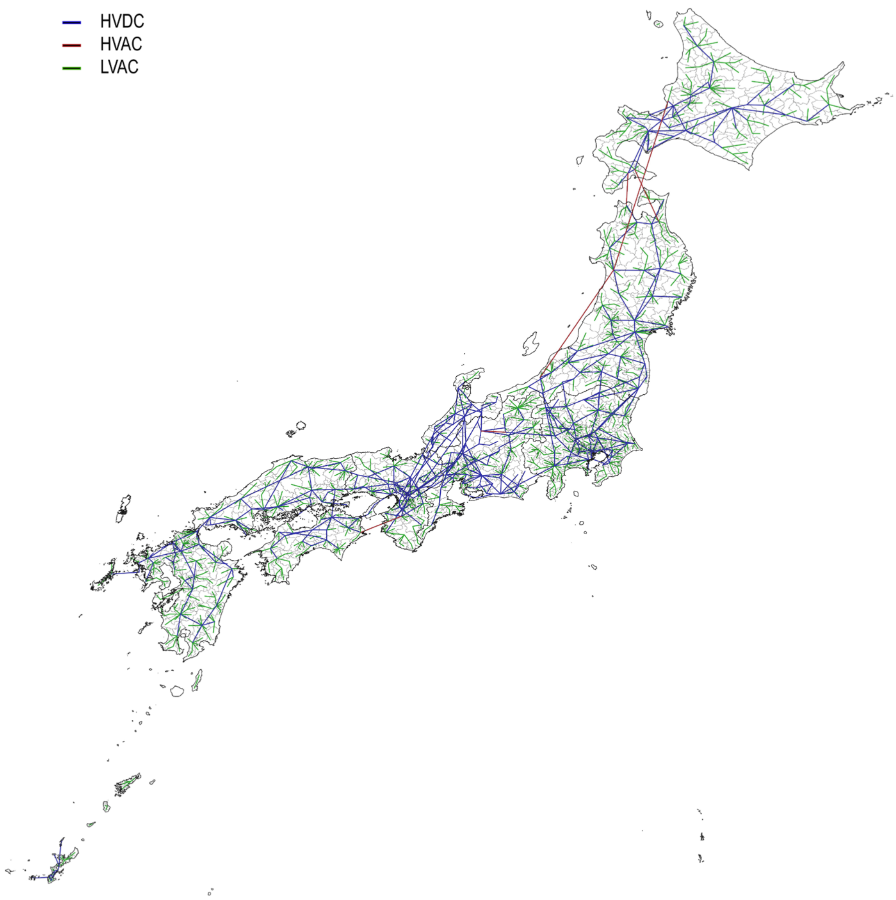


Supplementary Figure 7: Technological configurations and energy flows. Yellow, blue, and grey arrows represent electricity flows, hydrogen, and carbon flows, respectively.

Spatial resolution

The model employs a spatial resolution of 1,741 nodes, corresponding to municipal administrative units in Japan. Among these, 403 nodes correspond to the locations of high-voltage substations and selected nodes representing remote islands. These are hereafter referred to as "substation nodes." These nodes can accommodate dispatchable and variable renewable energy (VRE) generation as well as grid-connected battery storage. The remaining 1,338 nodes, referred to as branch nodes, host VRE generation and balance electricity supply and demand through interregional transmission and curtailment.

Substation nodes are interconnected following the potential routes of existing and planned high-voltage transmission lines, categorized as HVAC, offshore HVDC, or onshore HVDC (Supplementary Figure 9). Branch nodes are linked to their nearest substation node via routes that minimize the total line distance; looped or redundant connections among branch nodes are not considered. The dataset on the existing transmission infrastructure is compiled from open sources such as OpenStreetMap[2] and publicly available information from OCCTO and Transmission System Operators (TSOs)[3–13]. We thank the developers of PyPSA meets Earth for providing the useful tool earth-osm (https://github.com/pypsa-meets-earth/earth-osm).



Supplementary Figure 8: Transmission network model. Blue and red lines indicate high-voltage AC (HVAC) and high-voltage DC (HVDC) transmission lines connecting substation nodes, respectively. Green lines show low-voltage AC lines, which connect substation and branch nodes, or between branch nodes.

1.2 Mathematical formulation

Objective function

$$\min\left[\sum_{r,g} c_g \cdot W_{r,g} + \sum_{r,r'} c_{r,r'} \cdot G_{r,r'} + \sum_{r,g,t} \dot{c}_g \cdot P_{r,g,t} + \sum_{r,f,t} \dot{c}_f \cdot I_{r,f,t} + \sum_{r,t} \dot{c}_c \cdot C_{r,t} + M\right] \tag{S1}$$

$$M = \sum_{r,r',t} \varepsilon \cdot (T^{+}_{r,r',t} + T^{-}_{r,r',t}) + \sum_{r,s,t} \varepsilon \cdot (S^{+}_{r,s,t} + S^{-}_{r,s,t}) \tag{S2}$$

where c_g are the fixed annualized costs for capacity $W_{n,g}$ of technology g at each regional node r; $c_{r,r'}$ are the fixed annualized costs for transmission line capacity $G_{r,r'}$ between nodes r and r'; $\dot{c}_g$ are the variable costs for generation $P_{r,g,t}$ at each time step t, $\dot{c}_f$ are the variable costs for the import $I_{r,f,t}$ of fuel f (hydrogen in this study); and $\dot{c}_c$ are the variable costs for carbon sequestration $C_{r,t}$. M is a penalty term introduced to ensure numerical stability of the optimal solution, representing the sum of transmission (electricity import $T^{+}_{r,r',t}$ and export $T^{-}_{r,r',t}$ from r to r') and charge $S^{+}_{r,s,t}$ and discharge $S^{-}_{r,s,t}$ of storage s, each multiplied by minuscule weight ε (10^{-2} ¥/kWh).

Electricity balance constraints

For substation nodes

$$\begin{aligned}\sum_{g\in VRE} h_{r,g,t} \cdot W_{r,g} + \sum_{g\in DG} P_{r,g,t} + \sum_{r'} T^{+}_{r,r',t} + \sum_{g\in ST} S^{-}_{r,g,t} \\ = d_{r,t} + D^{DAC}_{r,t} + D^{P2G}_{r,t} + \sum_{r'} T^{-}_{r,r',t} + \sum_{g\in ST} S^{+}_{r,g,t} + R_{r,t} + l'_{r,t} \cdot W^{DC}_{r} \quad \forall r \in SN\end{aligned} \tag{S3}$$

$l'_{r,t}$ represents the normalized power load profiles of a data center (i.e., the capacity factor), and W^{DC}_r denotes the capacity of data centers. The product of these two represents the electricity demand of data centers in node r at time t. The range of W^{DC}_r is constrained based on the location strategies, as represented by Equations (S4) to (S7). To calculate the integrated cost of demand, this term is omitted, and the dummy term from Equation (1) in the main text is added to the right-hand side of Equations (S3).

Data center siting constraints

For the BAU strategy

Data centers are located according to existing distribution.

$$W^{DC}_r = a \cdot \frac{w_r}{\sum_{n\in R} w_n} \quad \forall r \in R \tag{S4}$$

For the DEV and ILA strategies

The total capacity of data centers is a given, and the existing capacity is the lower bound of capacity at each regional node.

$$\sum_r W^{DC}_r = g \tag{S5}$$

$$W^{DC}_r \geq w_r \quad \forall r \in R \tag{S6}$$

For the ILA strategy

The capacity of data centers at each regional node is capped based on integrated location assessment.

$$W_r^{DC} \leq w_r^{max} \quad \forall r \in R \tag{S7}$$

Other constraints

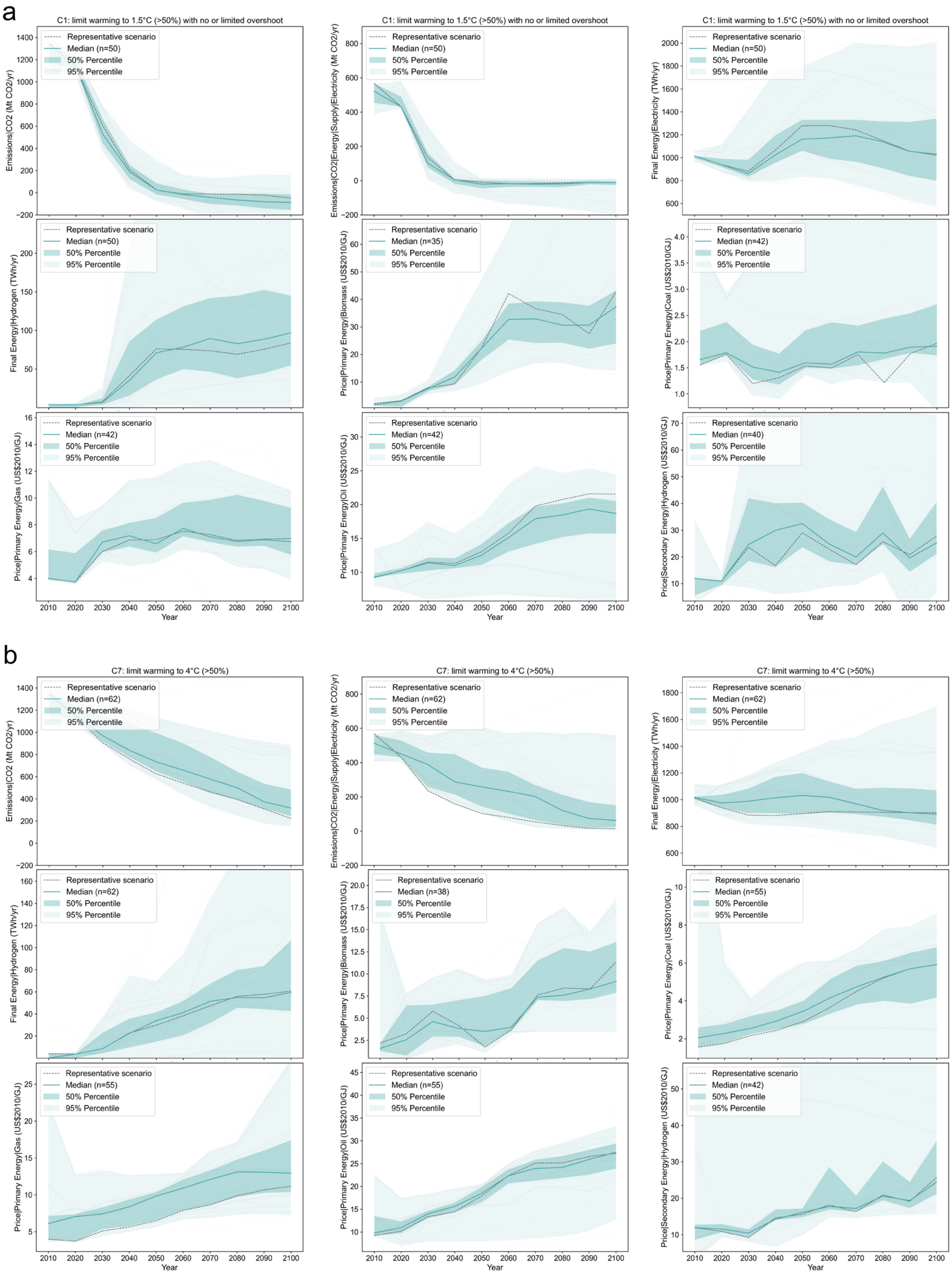
All other constraints, regarding grid operation, resource limits, CO_2 emission caps, etc., are provided in the GitHub: https://github.com/hiroakionodera/ReGRID/wiki.

Nomenclature

Variable	Description	Unit or Range
	Static variables	
c_g	Unit fixed cost for generation, conversion, and storage ($/MWh for energy capacity of storage)	$/MW or $/MWh
$c_{r,r'}$	Unit fixed cost for transmission line	$/MW
$\dot{c}_g$	Unit variable cost for generation	$/MWh
$\dot{c}_f$	Unit variable cost for fuel import	$/MWh
$\dot{c}_c$	Unit variable cost for carbon sequestration	$/tCO2
h	Capacity factor of generation	[0,1]
ε	Minuscule cost	$/MWh
l'	Normalized electricity demand of a data center	[0,1]
w	Existing data center capacity	MW
w^{max}	Data center siting potential	MW
a	Total data center capacity	MW
d	Final electricity demand	MWh
	Decision variables	
P	Electricity generation	MWh
R	Curtailment	MWh
S^+	Charge to storage	MWh
S^-	Discharge from storage	MWh
C	Carbon sequestration	tCO2
I	Fuel import	MWh
D^{DAC}	Electricity demand of DAC	MWh
D^{P2G}	Electricity demand of P2G	MWh
T^+	Electricity import	MWh
T^-	Electricity export	MWh
G	Transmission line capacity	MW
W^{DC}	Capacity of data center	MW
W	Capacity of generation, conversion, and storage technologies	MW or MWh
	Subscript	
r	Node	
r'	Adjacent node	
t	Time	
g	Technology	
f	Fuel	
	Set	
R	All nodes	
SN	All substation nodes	
RN	All branch nodes	
VRE	Variable renewable energy technologies	
DG	Dispatchable generation technologies	
ST	Storage technologies	

1.3 Input data and assumptions

Socioeconomic and emissions pathways



Supplementary Figure 9: Socioeconomic and emissions pathways from the AR6 scenarios database[14]. *n* denotes the number of scenarios. **a** shows scenarios classified as C1 (limit warming to 1.5°C (>50%) with no or limited overshoot). **b** presents scenarios classified as

Category C7 (limit warming to 4°C (>50%), represented by REMIND-MAgPIE 2.1-4.2_EN_NPi2100. Solid lines and dotted lines represent median and representative senarios.

Energy demand and renewable energy resources

The data sources for energy demand and renewable energy technical potential follow the methodology of a previous study[1] and are publicly available in the Japan Energy Database[15]. However, deploying renewable energy up to its technical potential could provoke social resistance, thereby substantially undermining feasibility. Accordingly, this study assumes an upper limit of renewable energy deployment at 50% of the technical potential.

Power plants

The location, capacity, and commissioning year of power plants were obtained from the Electrical Japan[16] with developer's permission. Although some fossil-fuel power plants have been retrofitted for biomass co-firing, this study assumes that each plant operates based on its primary fuel.

Hydrogen sector

Regional hydrogen demand was estimated based on national-level values from the representative scenario, scaled using estimated regional fuel consumption[1] and fuel substitution ratios derived from the IEA Net Zero Emissions (NZE) scenario[17], according to the previous study[18]. To reduce model dimensionality and reflect economies of scale, hydrogen production, storage, and fuel cell-based power generation were aggregated at the substation node within each prefecture exhibiting the highest hydrogen demand. As previous studies[18,19] have shown that hydrogen transport offers limited economic advantages where the electricity grid is well developed, it is not explicitly modeled. Hydrogen imports from overseas are allowed; however, the import price is assumed to be uniform across all regions.

Carbon sector

To support CO_2 emissions reductions, the model allows for the retrofitting of existing fossil fuel and waste incineration power plants with carbon capture technologies. Moreover, in line with many scenarios aiming to achieve the 1.5°C target, negative emissions in the power sector are considered essential. Accordingly, two negative emissions technologies are included: bioenergy with carbon capture and storage (BECCS) and direct air capture and sequestration (DACCS). DACCS is assumed to be deployable at substation nodes located near five areas currently undergoing feasibility studies and pilot demonstrations[20]. For each site, the estimated storage potential is treated as the upper bound for CO_2 sequestration.

Technology costs and specifications

For power generation technologies, this study adopts the median of technology assumptions for Japan used across 16 integrated assessment models[21,22]. Other sources for each technology are shown in Supplementary Table 1. Technology specifications, such as fixed operation and management cost, lifetime, and efficiency, provided in Supplementary Table 2.

Supplementary Table 1: Overnight cost

Technology	Unit	2020	2030	2040	2050	Source
Solar PV	$/kW	1,450	1,384	1,236	1,025	[21,22]
Onshore wind	$/kW	1,278	1,168	1,180	1,096	[21,22]
Floating offshore wind	$/kW	3,027	2,767	2,588	2,366	[21–23]
Fixed offshore wind	$/kW	2,066	1,889	1,726	1,577	[21,22]
Geothermal	$/kW	3,663	3,663	3,663	3,663	[21,22]
Run-of-river	$/kW	3,266	3,266	3,220	3,220	[21,22]
Hydro reservoir	$/kW	2,208	2,162	2,162	2,162	[21,22]
Biomass	$/kW	2,046	2,046	2,046	2,046	[21,22]
Biomass w/ CCS	$/kW	5,510	4,908	4,305	3,688	[21,22]
Waste-to-power	$/kW	1,572	1,572	1,572	1,572	[24]
Waste-to-power w/ CCS	$/kW	3,781	2,813	2,705	2,597	[24,25]
Coal power	$/kW	1980	1980	1980	1980	[21,22]
Coal power w/ CCS	$/kW	4113	3810	3496	3447	[21,22]
Gas power	$/kW	986	942	924	924	[21,22]
Gas power w/ CCS	$/kW	2046	1860	1773	1771	[21,22]
Oil power	$/kW	1253	1253	1253	1253	[21,22]
Nuclear	$/kW	5854	5854	5854	5854	[26]
Fuel cell	$/kW	182	72	60	48	[27]
PEM electrolyzer	$/kW$_{H2}$	1,058	1,127	774	421	[28]
Pumped hydro storage	$/kWh	622	622	622	622	[23]
LiB battery - Energy capacity	$/kWh	478	342	273	216	[23]
LiB battery - Power capacity	$/kW	444	444	410	376	[23]
H2 compressor	$/kW	171	171	132	93	[29,30]
Compressed H2 storage	$/kWh	50	50	38	25	[29,30]
AC transmission line	$/kWkm	1.14	1.14	1.14	1.14	[31]
HVAC transmission line	$/kWkm	3.07	3.07	3.07	3.07	[32]
HVDC transmission line (Onshore)	$/kWkm	2.51	2.51	2.51	2.51	[32]
HVDC transmission line (Offshore)	$/kWkm	3.76	3.76	3.76	3.76	[32]
Voltage source converter	$/kW	228	228	228	228	[32]
Direct air capture	$/kW$_{el}$	5,762	2,813	2,323	1,834	[33]

Supplementary Table 2: Technology specification

Technology	FOM[a] [%/a]	Lifetime [a]	Efficiency	Loss rate	Source
Solar PV	1.5	25			[21,22]
Onshore wind	2.0	20			[21,22]
Floating offshore wind	3.8	25			[21–23]
Fixed offshore wind	3.8	25			[21,22]
Geothermal	4.0	40			[21,22]
Run-of-river	2.0	60			[21,22]
Hydro reservoir	2.6	100			[21,22]
Biomass	4.3	30	0.37		[21,22]
Biomass w/ CCS	2.2	30	0.36		[21,22]
Waste-to-power	4.3	40	0.19		[24]
Waste-to-power w/ CCS	3.8	40	0.19		[24,34]
Coal power	2.7	30	0.45		[21,22]
Coal power w/ CCS	1.9	30	0.40		[21,22]
Gas power	2.6	30	0.56		[21,22]
Gas power w/ CCS	1.8	30	0.55		[21,22]
Oil power	3.0	30	0.40		[21,22]
Nuclear	3.6	60	0.35		[26]
Fuel cell	5.0	10	0.50		[25]
PEM electrolyzer	1.4	25	0.80		[28]
Pumped hydro storage[b]	0.5	100	0.80		[23]
LiB battery - Energy capacity[b]	2.5	15	0.85		[23]
LiB battery - Power capacity	2.5	15	0.85		[23]
Compressed H2 storage[b]	4.5	30	0.99		[29]
H2 compressor	8.5	15			[29]
AC transmission linec[c]	1.6	40		0.07	[32,35,36]
HVAC transmission line[c]	1.6	40		0.07	[35,36]
HVDC transmission line (Onshore) [c]	1.6	40		0.03	[35,36]
HVDC transmission line (Offshore) [c]	1.6	40		0.03	[35,36]
Voltage source converter[d]	2.8	30		0.01	[32,35]
Direct air capture[e]	3.7	30			[33]

a. Fixed Operation and Maintenance (FOM) cost is expressed as a ratio to the overnight cost.
b. The efficiency of battery storage refers to the round-trip efficiency of charging–discharging cycle.
c. The loss rate of transmission refers to the energy loss per 1000 km of transmission distance.
d. The loss rate of VSC refers to the AC-DC conversion loss.
e. The energy efficiency of DAC is 13.2 kWh of electricity to remove 1.0 tCO_2.

Data center growth assumptions

Supplementary Table 3: Data center capacity (GW)

Scenario	2020	2030	2040	2050
High	2.7	5.1	15.0	30.1
Mid	2.7	5.1	9.3	15.3
Low	2.7	5.1	5.7	6.1

* TWh-based forecasts from Mase et al. (2024) are converted to GW-based values, assuming a capacity factor of 0.8 from the same literature.

2 Integrated location assessment

2.1 Assessment framework

The Integrated Location Assessment (ILA) framework estimates the siting potential of each region using the following equation:

$$P_r = R_r \times (A_r - E_r) \tag{S4}$$

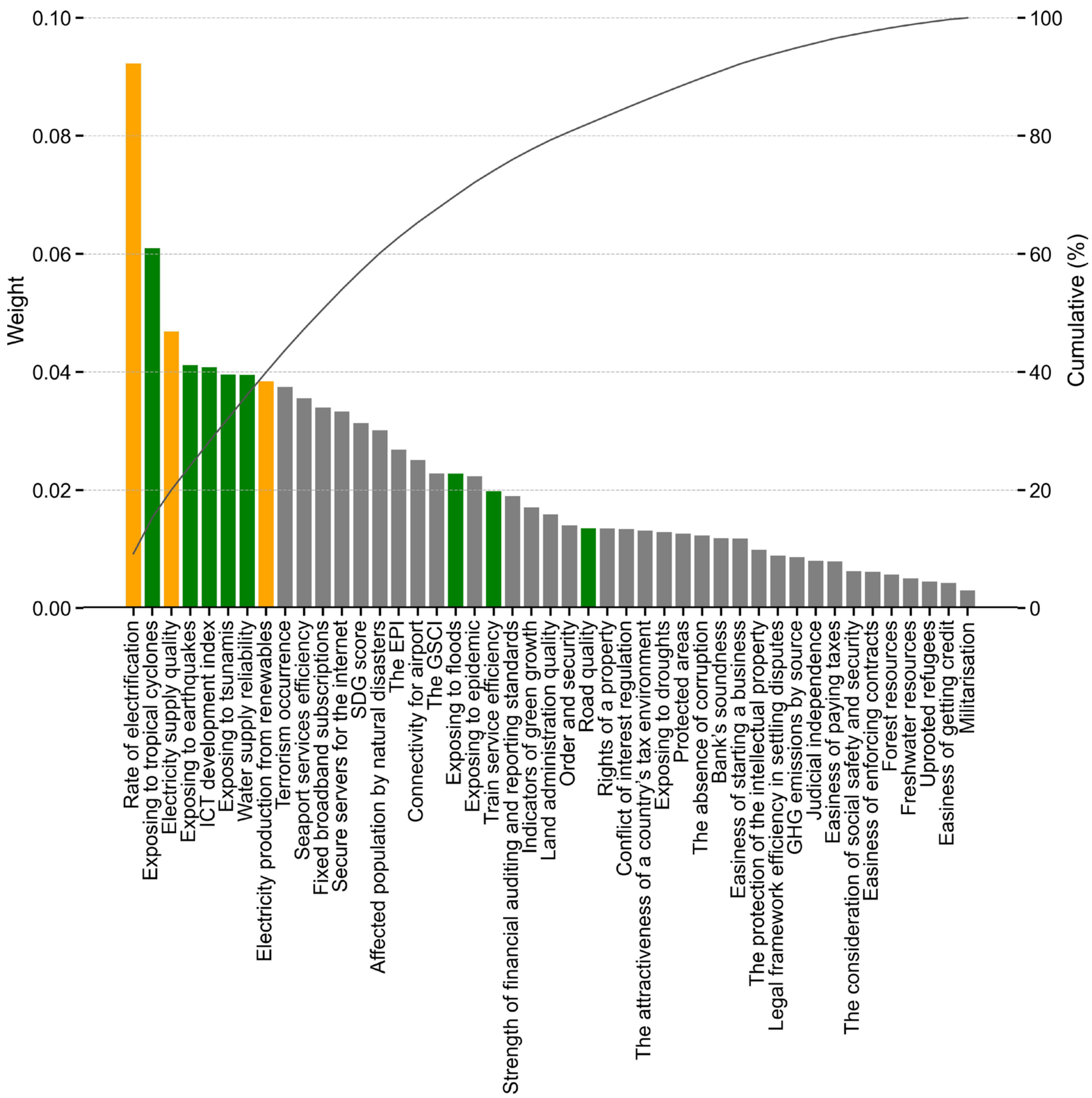
where P_r represents the maximum developable land area in region r. First, the total land area A_r is adjusted by subtracting the excluded area E_r, which accounts for site-specific constraints. Then, a regional suitability factor R_r is applied. This is a binary indicator (0 or 1) that reflects whether the remaining land can be utilized, based on region-specific conditions. In this study, to avoid land-use conflicts and ensure infrastructure access and social acceptance, A_r is defined as the available area within industrial zones. The polygon data of industrial zones is obtained from municipal zoning data provided by the Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT)[37]. Since data on actual vacancy is not available, we assume a 4.8% average vacancy rate based on a random sample of 50 existing industrial parks from the literature[38]. The land-based potential is then converted into server load capacity using an empirical capacity density of 480 MW/km^2 based on a random sample of 20 existing data centers from publicly available data (mainly from the Data Center Map[39]). The sample data for these assumptions are provided at the GitHub repository: https://github.com/hiroakionodera/DC-tools.

Note that the potential of less than 100 MW is truncated to reflect economies of scale and to align with the electricity demand simulation, which assumes a 100 MW data center.

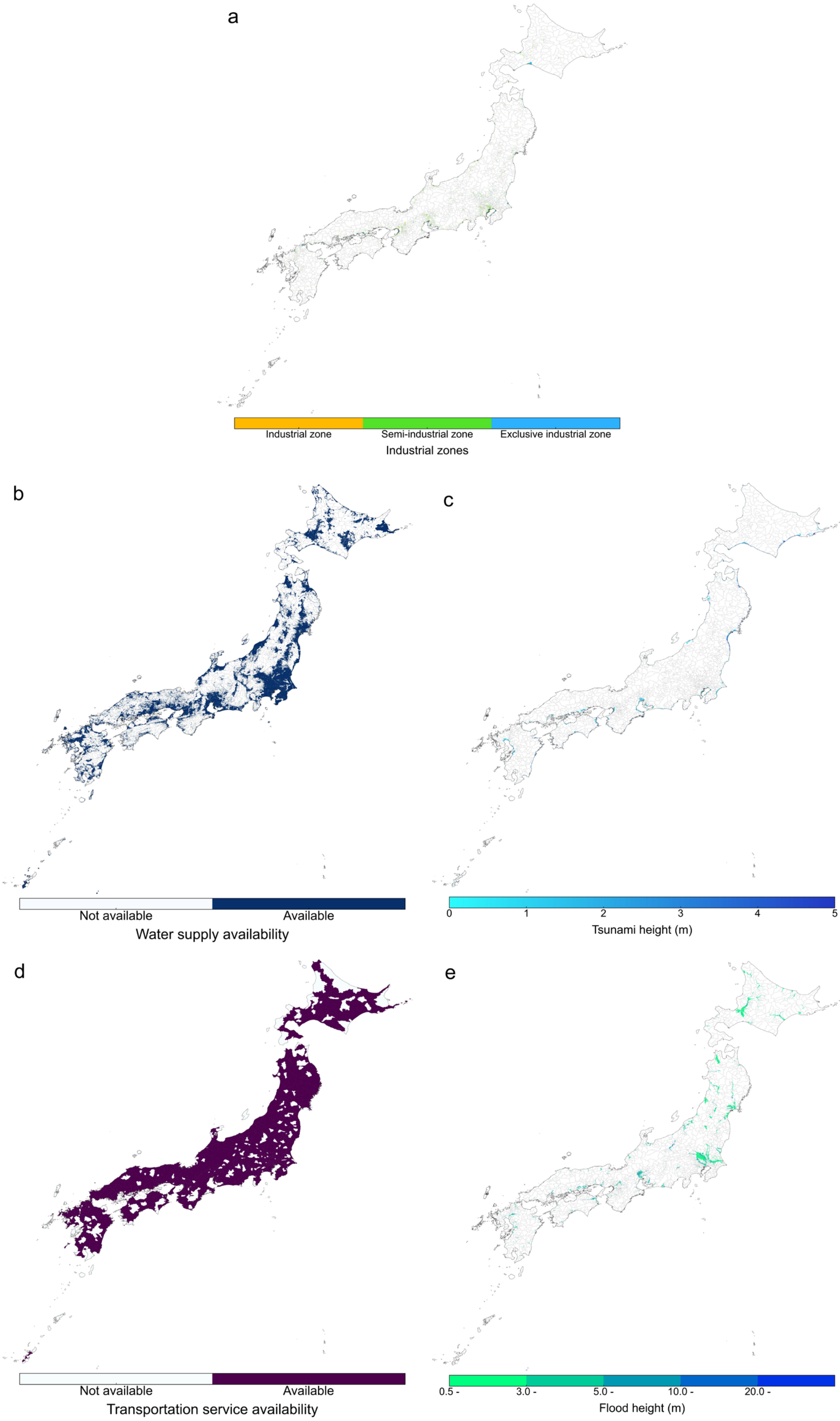
2.2 Criteria selection

45 decision-making criteria for data center siting have been systematically identified by Erdem et al.(2024), with quantified weights assigned to each criterion (Supplementary Figure 10). From these, we selected seven region-specific and site-specific criteria, as shown in Table 4. Criteria related to electricity supply were excluded, as they are endogenously represented within the energy system model. Additionally, the following regional criteria were excluded:

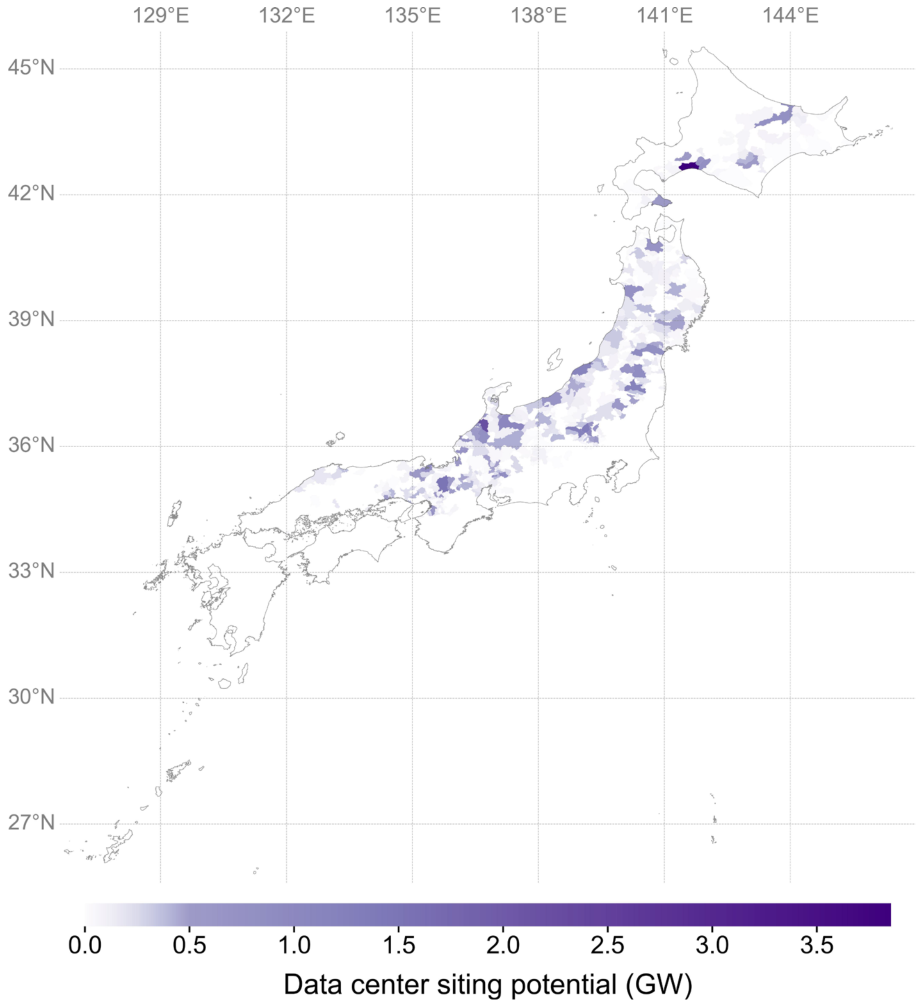
- Affected population by natural disasters: Excluded as direct disaster risks are considered through other criteria.
- Exposure to droughts: Interpreted as a regional climatic factor influencing cooling demand in the energy system model.
- Protected area: Excluded as industrial zones is implemented instead.
- Forest resources: Excluded due to their limited weight.
- Freshwater resources: Also excluded due to their limited weight.



Supplementary Figure 10: Pareto chart of decision factors for data center siting. Green indicates the indicators adopted in this study, yellow represents factors related to the power sector, and grey corresponds to national indicators and regional indicators that were not adopted. Original data are obtained from Erdem and Özdemir (2024)[40].



Supplementary Figure 11: Regional factors relevant to data center siting. **a** indicates industrial zones; **b**, water supply areas; **c**, potential tsunami inundation height; **d**, availability of highway interchanges or railway stations; and **e**, potential flood inundation heigh. Data sources are summarized in the Supplementary Table 4.



Supplementary Figure 12: Data center siting potential based on integrated locational assessment.

Supplementary Table 4: Location assessment criteria

Criterion	Spatial scope	Data
Exposing to earthquakes	Site-specific	Probabilistic seismic hazard maps[41]
Exposing to tsunamis	Site-specific	Tsunami inundation estimation data[37]
Exposing to floods	Site-specific	Flood inundation estimation data[37]
Exposing to tropical cyclones	Region-specific	d4PDF tropical cyclone track dataset [42]
ICT development index	Region-specific	Speedtest by Ookla Global Fixed and Mobile Network Performance Map Tiles[43]
Train service efficiency	Region-specific	Railway data[37]
Road quality	Region-specific	Expressway time series data[37]
Water supply reliability	Region-specific	Waterworks-related facility data[37]

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