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Endogenizing long-term material and energy demand in response to power capacity changes by model soft-linking: application to Japan

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Abstract

Japan's decarbonization transition towards carbon neutrality by 2050 will be more dependent on the long-term development of renewables. However, the renewable power generation technologies themselves are highly material- and energy-intensive. We estimated such materials and energy demands in response to power capacity changes. Our main results show that: (1) achieving a 100% reduction of GHG emissions requires enormous and urgent investment during 2020–2030; (2) the largest gap of material demands would show in 2020–2030, especially for cement-related products, petrochemical products, cables, wood products, and steel products, but with different degrees of dispersion; (3) the largest gap of industrial energy demands would show later in 2030–2040 as a result of early investment (inter-period iterations). Increasing material efficiency and benefiting more and earlier from the increasingly low-carbon energy supply would be the key to Japan's industrial decarbonization.

Keywords Decarbonization transition · Endogenous material demand · Integrated Assessment Model · Life Cycle Assessment · Soft-linking

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1 Introduction

The transition towards a more ambitious climate goal, 100% emission reduction by 2050 in Japan, will be more dependent on renewables. However, the renewable power generation technologies themselves are highly material- and energy-insensitive. They require higher initial investments in infrastructure than fossil-based power systems [6, 19]. Moreover, the expansion of renewable energy capacities will lead to the expansion of infrastructure and electricity transmission/storage capacity [1]. Japan has been investing in renewable energy sources, low-carbon transportation, and energy-efficient buildings. These transition investments could lead to an increase in demand for bulk materials such as metals, minerals, petrochemical products, etc., which can then be rather environmentally impactful [3, 7]. The size of such demands, namely the material and energy demand induced by the changes in the energy supply side, has been poorly understood.

Partial Equilibrium Integrated Assessment Models (PE IAMs, or energy system models) are widely used to reveal the decarbonization pathways toward specific climate goals. The advantages of these models include the better modeling of energy supply technology details, with their associated capital and operation and maintenance costs. Therefore, they can be one of the best tools to estimate long-term inputs required by power infrastructures. However, they usually single out the energy system from the macro-economy [16]. Details of the interdependency among sectors and the indirect impacts on the supply chains of the energy system are neglected. Also, the interdependency between the energy supply side (e.g., electricity supply sectors) and the energy demand side (e.g., energy end-use sectors, building, industry, etc.) is usually not included in most of those models.

To include such a missing piece, one of the options is to combine bottom-up energy supply technologies and top-down aggregated economic models [2, 24]. Linking with the Input–Output (IO) analysis can be a solution [5, 30]. The advantages of IAMs which efficiently model the energy supply and demand technologies, as well as the advantages of IO models which reveal the indirect impacts in the macroeconomic framework, can be both considered. Life cycle assessment, on the other hand, is used to assess the impacts of a product or process over its entire lifecycle. By carefully mapping life cycle material inputs into the linked IAM-IO model, the overall demand for multiple types of bulk materials can be estimated under different long-term policy scenarios.

Besides the energy supply side, demand-side options also have a large potential for the achievement of carbon neutrality. Lifecycle engineering considers the entire lifecycle of a product or process and allows for the identification of industrial processes where materials can be conserved or used more efficiently. Products can be designed with less use of materials, more durable, or more easily recycled or repurposed at the end of their life. It is also necessary to examine the scenario that captures the potential of demand-side mitigation options and compare it with the one that includes the energy demand induced by the changes in the energy supply side.

In this paper, we introduced soft-linking Integrated Assessment Models and Input–Output analysis to address the gaps in understanding material and energy demands driven by energy transition, with a thorough Life-Cycle mapping when the material demand is revisited. Unlike conventional energy system models that focus primarily on energy supply technologies, our approach incorporates sectoral interdependencies and expands to have both supply-side and demand-side mitigation options, enabling a broader understanding of impacts across the macroeconomic framework.

In this paper, we estimated the industrial material and energy demand in response to the changes in the energy supply side (new renewable energy capacities and corresponding infrastructure construction activities) by 2050. Multiple scenarios were applied to examine the feasible pathways. The 23 types of materials are estimated in both physical and monetary units based on Life Cycle Assessment (LCA), considering the uncertainties in benchmark price (2011, 2015), the structure of power generation/ electricity transmission capacities, and the structure of small/large cases. The industrial energy demand is estimated by soft-linking an Integrated Assessment Model (IAM) and a national Input–Output (IO) framework with extended electricity supply sectors. Scenarios with lower energy service demands are also examined to show the potential of demand-side mitigation options, such as recycling materials, using less material by design, product life extension, etc. The results can be helpful in guiding policy and industrial practices by identifying feasible pathways where material and energy demands induced by Japan's ambitious decarbonization are endogenized. It provides insights that foster a holistic understanding of the industry's role in achieving carbon neutrality, emphasizing both supply- and demand-side contributions.

2 Methodology

As powerful tools to reveal the pathways toward a feasible low-carbon future, IAMs keep a strict energy balance across periods and are technology-rich on the energy supply side. The energy system boundary of IAMs is typically defined by the scope of processes and flows the model aims to capture, including primary energy, secondary energy (energy conversion and transformation), final energy, and useful energy. However, as we mentioned in the introduction, every modeling tradition has its own limitations. In Appendix i, we summarized the most relevant activities of the industry sector in IAMs that are hard to model (standard see [18, 26]) but may bring significant uncertainties to the model outputs. We started with equipping inter-model iterations to cover the power-material links in this paper, thus material and energy demand caused by power capacity changes can be endogenous.

To capture the industrial energy consumption in response to the changes in the power generation mix, we mapped life cycle material inputs with a national input–output framework with extended electricity supply sectors Input–Output table for analysis of Next-Generation Energy System (IONGES), then linked it with the integrated assessment model Global Change Analysis Model (GCAM). The overview of the linking is shown in Fig. 1.

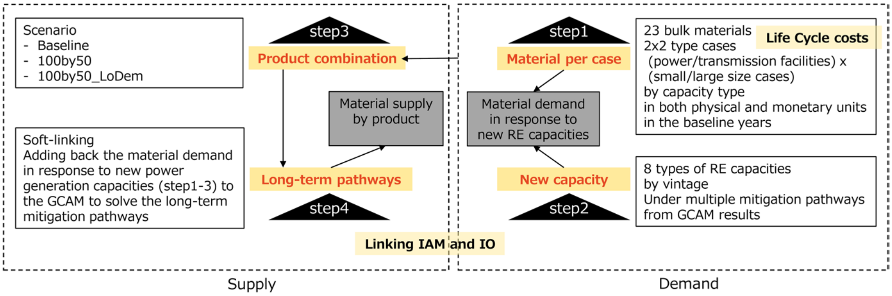

Fig. 1 Overview of the methodology

Details of direct material demand estimation (mainly steps 1–2) would be listed in Sect. 2.1. Details of energy demand estimation (mainly steps 3–4) would be listed in Sect. 2.2. Scenario assumptions and data sources are listed in Sects. 2.3 and 2.4.

2.1 Material demand

The direct demand for the mth type of material in the kth type of new power capacity in period t, $matl_{m,k,t}$, is formulated as Eq. 1.

$$matl_{m,k,t} = \begin{cases} matl\_int\_mon_{m,k} * inv\_capa_{k,t}, m \in s_1 \\ matl\_int\_phy_{m,k} * \frac{new\_capa_{k,t}}{conv\_capa_k}, m \in s_2 \end{cases} \tag{1}$$

$matl\_int\_mon_{m,k}$ represents the intensity of the mth type of material, namely the material demand (in both physical and monetary units) per monetary unit of new investment in the kth type of power capacity. It is adopted when the counter m falls in the subset s_1 where life cycle material intensity is only available in monetary cases (e.g., JPY/ton per million JPY). In this case, the intensity is multiplied by the new investment in the kth type of new power capacity in period t ($inv\_capa_{k,t}$).

Correspondingly, when the counter m falls in the subset s_2 where life cycle material intensity is only available in physical cases (e.g., JPY/ton per generator), we adopt $matl\_int\_phy_{m,k}$, the material demand (in both physical and monetary units) per physical unit of new investment in the kth type of power capacity. It is then multiplied by the total new capacity of the kth type power generation technology in period t ($new\_capa_{k,t}$), converted by $conv\_capa_k$, the average capacity of one kth-type power generator (e.g., averagely 55MW for one geothermal generator).

The multiple available production technologies of those types of bulk materials are then modeled in the system optimization in GCAM. In GCAM, industrial sectors such as metals (e.g., steel, aluminum) include explicit differentiation between primary production (e.g., ore-based) and secondary production (e.g., recycling-based), covering the Cradle-to-Grave/Cradle processes. The equations of GCAM variables and parameters are listed in the data source section.

The data sources of $matl\_int\_mon_{m,k}$, $matl\_int\_phy_{m,k}$, and $conv\_capa_k$ are listed in Sect. 2.4. The equations of $inv\_capa_{k,t}$ and $new\_capa_{k,t}$ are shown in Eq. 5, as the outputs of the GCAM model.

2.2 Energy service demand

The total output in one region, $\mathbf{x}$, meets the production balance in Eq. 2.

$$\mathbf{x} = [\mathbf{I} - \mathbf{A}]^{-1}\mathbf{y} \tag{2}$$

$\mathbf{A}$ represents the intermediate input coefficient matrix of one region with each element of it, A_{ij}, showing the intermediate input needed from sector i to produce one unit of the final product of sector j. $\mathbf{y}$ represents the total final demand vector, including exports and imports.

With the input–output framework extended in electricity supply sectors (taking the benchmark table IONGES 2015 as an example), the production balance can also be extended to

$$\begin{bmatrix} \mathbf{x}^{(1)} \\ \mathbf{x}^{(2)} \\ \mathbf{x}^{(3)} \\ \mathbf{x}^{(4)} \end{bmatrix} = \left[\mathbf{I} - \begin{bmatrix} \mathbf{A}^{(11)} & \mathbf{A}^{(12)} & \mathbf{A}^{(13)} & \mathbf{A}^{(14)} \\ \mathbf{A}^{(21)} & \mathbf{A}^{(22)} & \mathbf{A}^{(23)} & \mathbf{A}^{(24)} \\ \mathbf{A}^{(31)} & \mathbf{A}^{(32)} & \mathbf{A}^{(33)} & \mathbf{A}^{(34)} \\ \mathbf{A}^{(41)} & \mathbf{A}^{(42)} & \mathbf{A}^{(43)} & \mathbf{A}^{(44)} \end{bmatrix} \right]^{-1} \begin{bmatrix} \mathbf{y}^{(1)} \\ \mathbf{y}^{(2)} \\ \mathbf{y}^{(3)} \\ \mathbf{y}^{(4)} \end{bmatrix}, \tag{3}$$

where the counter 1 represents all other sectors (68 sectors), counter 2 represents the industry sectors (63 sectors), counter 3 represents the construction of power capacity sectors (12 sectors), and counter 4 represents the electricity supply sectors (13 sectors, including the corresponding 12 sectors and 1 more electricity transmission and distribution sector). Sector lists see Appendix ii. The extended input–output framework can then include the presentation of the investment in the introduction of new power generation capacities (e.g., the increase in $\mathbf{y}^{(3)}$), the input from industry sectors to support the power generation with such new capacities (e.g., $\mathbf{A}^{(24)}\widehat{\mathbf{x}^{(4)}}$), and how they serve the needs of other sectors (e.g., $\mathbf{A}^{(41)}\widehat{\mathbf{x}^{(1)}}$).

The total energy demand in response to the introduction of new power capacities excluding the imported parts, $\Delta\mathbf{l}$, can be then formulated as,

$$\Delta\mathbf{l} = \hat{\mathbf{e}}[\mathbf{I} - \mathbf{A}]^{-1}\Delta\mathbf{y} = \hat{\mathbf{e}}[\mathbf{I} - (\mathbf{I} - \mathbf{M})\mathbf{A}]^{-1} \begin{bmatrix} 0 \\ 0 \\ \Delta\mathbf{y}^{(3)} \\ 0 \end{bmatrix}, \tag{4}$$

where $\Delta\mathbf{y}^{(3)}$ represent the vector of investment in new power capacities, $\hat{\mathbf{e}}$ represents the diagonalized energy intensity vector (each element of it see Eq. 6), and $\mathbf{M}$ represents the diagonalized matrix of the import share vector (the share of imports in the total domestic demand). Both $\Delta\mathbf{y}^{(3)}$ and $\hat{\mathbf{e}}$ require the outputs of the GCAM model.

Each element of the vector of investment in new power capacities, $\Delta y_{i,t}^{(3)}$, is calculated as

$$\Delta y_{i,t}^{(3)} = inv_{capa_{i,t}} = ex_{base} * new\_capa_{k,t} * capi\_cost_{i,t} = ex_{base} \frac{\Delta ele_{i,t}}{capa\_fact_{i,t}} capi\_cost_{i,t} \tag{5}$$

where $\Delta ele_{i,t}$ represents the ith type of electricity in year t generated by the plants built in year t (in the unit of EJ or GWh, to ensure that only new capacity is counted), $capa\_fact_{i,t}$ represents the capacity factor of the ith type electricity generation in year t (unitless), $capi\_cost_{i,t}$ represents the capital cost of the ith type electricity generation in year t (in the unit of USD1975/GW), and ex_{base} transfers the USD1975 price of IAM results to the benchmark year price to match the input–output framework. The vintages of power generation capacity are calculated at each 5-year period, including both power generation from new capacities and those that would retire. The paired common measuring point of investment in new power capacities ($\Delta y_{i,t}^{(3)}$) is noted as $\Delta inv\_capa_{i,t}$ in GCAM.

Each element of the energy intensity vector, $e_{n,t}$, is calculated as

$$e_{n,t} = \frac{ene_{k,t}}{x_{k,base}(gdp_t/gdp_{base})} \tag{6}$$

where $ene_{k,t}$ represents the energy consumption in the nth integrated sector in year t (in the unit of EJ), $x_{k,base}$ represents the total output in the nth integrated sector in the benchmark year.

Finally, when linking back the energy service demand results under the input–output framework back to the long-term optimization IAM, inter-period double counting should be carefully treated. We adopted the growth rate of the energy demand in the industry sector in year t (unitless) in the original IAM results, so that the natural growth within the industry sector (not caused by the changes in power capacities) can be excluded.

2.3 Scenarios

We applied the following scenarios listed in Table 1, which is along with the scenario design of JMIP scenarios (Energy Modeling Forum 35, Japan Model Intercomparison Project on long-term climate policy, [28]) so that the results can be compared with other IAMs. Models participating in JMIP have been investigating a wide range of possible climate and energy policy pathways that capture such energy transitions in Japan. The inter-model comparison activities attempt to capture pathways through sensitivity analyses of policy constraints, technology availability, and demand projections. In this paper, we applied the scenario sets subject to different national climate goals (e.g., Baseline, 100by50), together with the same set of scenarios but with different mitigation options (e.g., 100by50, 100by50_LoDem).

Table 1 Scenario design

Scenario	Details
Baseline	Baseline scenario, no specific carbon pricing instrument applied
80by50	80% CO_2 emission reduction[1] by 2050, with 26% reduction by 2030 (26% compared to the 2010 level); default energy technologies[2]
100by50	105% CO_2 emission reduction (~ net zero GHG emissions) by 2050, with 46% reduction by 2030 (46% compared to the 2010 level); default energy technologies
100by50_w/oLink	Same climate goal as 100by50 but excluding the industrial energy demand induced by the investment in the energy supply (stand-alone IAM, without linking with IO)
100by50_w/Foreign	Same climate goal as 100by50 but including the overseas industrial energy service demand induced by the investment in the energy supply (replacing the domestic intermediate input coefficient matrix with the total intermediate input coefficient matrix)
100by50_LoDem	Same climate goal as 100by50 but with (energy service) demand reduction options[3] such as recycling of materials, using less material by design, product life extension

(1) CO_2 emission from the AgLU sector are separate from the CO_2 emission from the energy sources and industrial processes. Any change in atmospheric carbon occurs as a function of anthropogenic fossil fuel and industrial emissions, land-use change emissions, and the atmospheric-ocean and atmosphere-land carbon fluxes. We adopt an approximately 105% reduction in CO_2 emission as a 100% reduction in total GHG gases. (2) Limitations on nuclear power generation. (3) Details see Appendix iii. For all scenarios, the GDP growth rates and population growth rates from SSP2 (SSP [27]) were adopted throughout. The COVID-19 impacts have been adjusted for GDP growth around 2020

2.4 Data sources

The variables, parameters, and counters from the integrated assessment model (GCAM) and the input–output framework (IONGES), together with exogenous parameters from life cycle assessment databases are summarized in Table 2.

3 Results

3.1 Key context

For a better understanding of the demand for bulk materials, some key contexts should be introduced first. Figure 2 shows the structure of the final energy consumption of Japan, including the historical data (2010–2015) and the projection (by 2050) from the GCAM model. This shows the role of the industry sector in Japan's overall energy balance, namely the scale of industrial energy consumption in which a part can be potentially induced by the increase in bulk material demand in the future.

The final energy consumption of the industry sector in Japan was 6.4 EJ in 2015, occupying 46.8% of the overall national final energy consumption. This is a quite high share, higher than the G7 average and closer to the average of the G20 which includes emerging economies (summarized from IEA World energy balances, [14]). As a country with insufficient fossil fuel energy resources, Japan

Table 2 List of variables, parameters, and counters

Counters	Description
i, j	127 sectors, aggregation see supplemental information
t	time periods, 1975–2100, 5-year interval
m	23 types of bulk materials
k	12 types of power generation technologies
n	3 integrated energy end-use sectors, industry, transportation, building

	Description	Source
Exogenous		
$matl\_int\_mon_{m,k}$	The intensity of the m th type of material input, namely the material demand (in both physical and monetary units) per monetary unit of new investment in the k th type of power capacity	[22, 23],price mapped with [20, 21]
$matl\_int\_phy_{m,k}$	the intensity of the m th type of material input, namely the material demand (in both physical and monetary units) per physical unit of new investment in the k th type of power capacity	IDEA v2
From IO framework		
$\mathbf{x}, \mathbf{A}, \mathbf{y}, \mathbf{M}$	The total output vector, intermediate input coefficient matrix, final demand vector, diagonalized matrix of import share vector	[10], 2015, IONGES 2030 projection Table (2015-based)
From IAM		
$ele_{i,t}$	The i th type of electricity generation in the year t	GCAM variable
gdp_t	Total gross domestic products in year t	GCAM parameter, from SSP [27]
$ene_{k,t}$	The energy consumption in the k th integrated sector in year t	GCAM variable
$capa\_fact_{i,t}$	The capacity factor of the i th type of electricity generation in the year t	GCAM parameter
$capi\_cost_{i,t}$	The capital cost of the i th type of electricity generation in the year t	GCAM parameter

The equations of GCAM variables and parameters are available at the GCAM documentation: https://jgcri.github.io/gcam-doc/toc.html. IDEA (Inventory Database for Environmental Analysis, v2), available at: https://idea-lca.com/

still holds strong domestic industries such as manufacturing, steel making, petrochemicals, cement, etc. Moreover, according to the projection results under the Baseline scenario, this share will not decline by 2050 (6.15EJ, occupying 51.04% of the overall national final energy consumption). Without any additional energy consumption reduction actions or specific carbon pricing instruments applied, an increase in the material demand in the future would very likely lead to an increase in industrial final energy consumption within Japan.

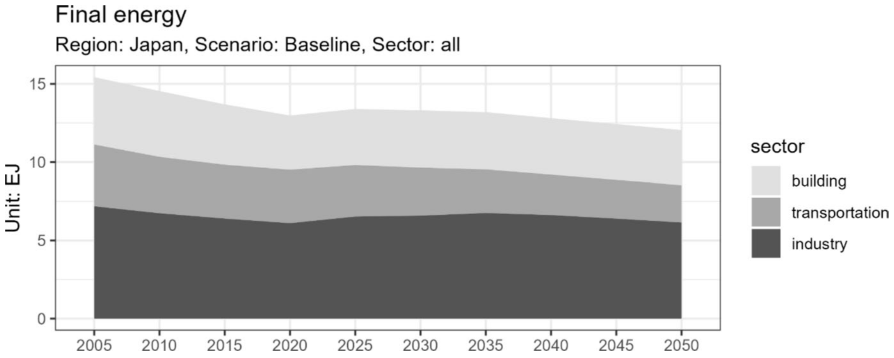

Fig. 2 The structure of final energy consumption of Japan (2005–2050, baseline scenario). Final energy consumption from three non-manufacturing sub-sectors (construction, mining energy use, and agricultural energy use) are aggregated into the industry sector

Figure 3 shows the investment in new power generation capacities by 2050, under both Baseline and 100by50 scenarios. It shows the gap that the achievement of an ambitious by necessary climate goal would need. The gap of investment in new power generation capacities would determine the potential scale of bulk materials that are needed to support Japan's energy transition towards carbon neutrality by 2050.

Compared to the Baseline scenario, much more investment in new capacities would be required under the 100by50 scenario in the early period (2020–2030), reaching an average of over 2000 billion JPY per year. In our previous results [28],

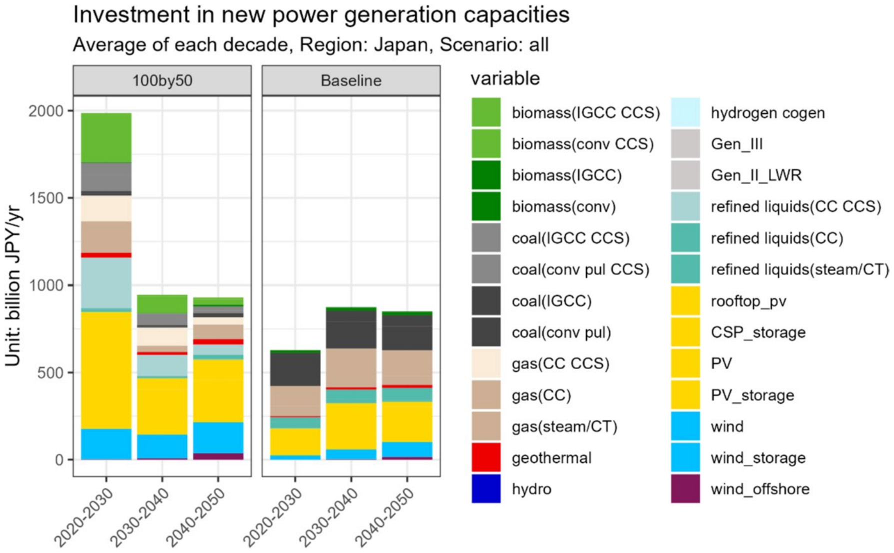

Fig. 3 The investment in new power generation capacities in Japan (2020–2050, all scenarios)

where Japan's national climate goal was 80% CO_2 emission reduction by 2050, the shares of fossil fuels in the primary energy and power generation mix would be still high (around 80%) during 2020–2030. A trend showing the expansion of investment in new capacities along with the high penetration of renewables would be observed after 2030 in multiple participating models (AIM/Enduse—Japan, AIM/Hub—Japan, IEEJ_Japan 2017, TIMES—Japan). With a more ambitious national climate goal (80% CO_2 reduction → 100% GHG reduction by 2050, plus 46% reduction by 2030), much more investment in new capacities would be required in the early period.

Among all power generation technologies, with lower operating rates, the share of new renewable capacities will be larger. The average investment in their new capacity will reach over 1000 billion JPY under the 100by50 scenario, including more in the solar capacities (over 500 billion JPY), as well as the wind capacities (over 200 billion JPY). Since renewable power generation technologies are highly material- and energy-insensitive [6], with a such large investment in them during 2020–2030, the scale of the corresponding bulk material demand (shown in Sect. 3.2) and industrial energy demand (shown in Sect. 3.3) should be thoroughly assessed.

3.2 Material demand

The bulk material demand related to the new power generation capacities is shown in this section, with Table 3 showing the amount per case and Fig. 4 showing the amount overall by 2050.

At the case level, we summarized the amount of 23 types of bulk materials in physical units based on the national survey of civil engineering construction cost [22, 23], which is carefully mapped with the prices of each final product from the survey of sectoral Input–Output structure in the year 2011 and 2015 [20, 21]. Though the number listed in Table 3 represents the average of the years 2011 and 2015 weighted by their total investment in each size category, the prices are adopted separately when we assessed the aggregated amount of bulk material demand.

We then compared all types of bulk materials that are consumed in the construction of power generation and electricity transmission capacities with those that are consumed in the main civil engineering construction activities (e.g., railway, bay, industrial water pipes, etc.) averagely. The input intensity (physical unit / per case construction cost) of cables and concrete products is relatively higher, especially for the copper wires in large power capacity construction projects reaching over 1000 t and in large electricity transmission construction projects reaching over 350 t per case (3.8 times of the average), as well as the cement in large power capacity construction projects reaching over 140 kt per case (3.5 times of the average). Also, the inputs of other construction soil and stone products in large electricity transmission construction projects reach over 500 t, as a result of more demand for high-temperature-resistant insulators. On the other hand, the input intensities of steel products, plastics, and timbers are relatively lower, especially for the inputs in electricity power capacity construction projects.

Table 3 Bulk material demand per case in physical unit

	Construction of power generation capacities		Construction of electricity transmission capacities		
	Small project (≤ 100 M. JPY)	Large project (> 100 M. JPY)	Small project (≤ 100 M. JPY)	Large project (> 100 M. JPY)	
Average case size	18.3	1072.1	22.4	328.9	
Material type					Unit
Timbers	0.4	17.6	0.4	6.1	k m^3
Ordinary plywood and other wood products	0.4	17.1	0.4	5.8	k m^3
Crushed stone	17.6	856.7	18.8	294.0	kt
Cement	3,055.2	147,629.7	3,249.5	50,488.7	t
Concrete	1,286.8	67,837.8	1,448.0	24,384.4	m^3
Cement products	924.0	48,283.7	1,033.7	17,274.1	t
Steel pipe	162.5	8008.1	175.0	2,771.7	t
Hot rolled steel	200.3	8157.3	191.7	2,471.6	t
Cold finished and plating steel	152.5	7432.2	163.1	2,555.3	t
Steel structure	111.4	5578.7	121.2	1,948.7	t
Metal products for construction	187.3	8964.8	198.0	3,047.6	t
Cast iron pipe	67.9	3219.9	71.3	1,088.8	t
Cast iron products	4.3	209.9	4.6	72.6	t
Asphalt	249.0	11,914.0	263.2	4,050.2	t
Petroleum products	361.7	17,310.4	382.4	5,884.7	kl
Paint	38.4	1862.5	40.9	638.4	t
Plastic products	50.8	2570.0	55.6	903.1	t
Rubber products	28.7	1373.1	30.3	466.8	km
Copper wire	21.1	1025.8	22.5	351.9	t_conductor

Table 3 (continued)

	Construction of power generation capacities		Construction of electricity transmission capacities		
	Small project ($\leq$100 M. JPY)	Large project ($>$100 M. JPY)	Small project ($\leq$100 M. JPY)	Large project ($>$100 M. JPY)	
Average case size	18.3	1072.1	22.4	328.9	
Material type					Unit
Power/communication cable	20.7	981.1	21.7	331.8	t_conductor
Optical fiber cable	2,109.6	100,953.9	2,230.0	34,319.7	kmcore
Chemical products	78.7	3766.3	83.2	1,280.4	t
Other construction soil and stone products	36.0	1724.4	38.1	586.2	t

The numbers of material in physical units are the average results based on the national survey of civil engineering construction cost conducted in the year 2011 and 2015 [22, 23],weighted by total investment

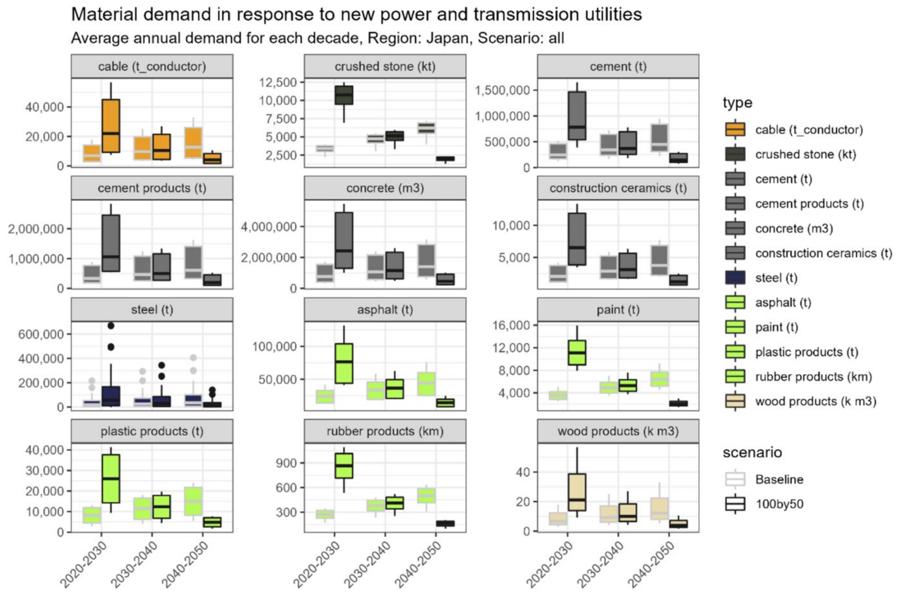

Fig. 4 Material demand in response to new power and transmission capacities (2020–2050, all scenarios)

Additionally, we compared our results in Fig. 4 with previous studies (e.g., [1, 29, 31], details see Appendix iv).

Based on the result of bulk material demand per case, we estimated the total material demand in response to new power and transmission capacities by 2050, as shown in Fig. 4. For each aggregated type of bulk materials (12 in all), the range of its average annual demand is shown in 3 periods (2020–2030, 2030–2040, 2040–2050) in physical units, with the projection under 2 scenarios (Baseline on the left and 100by50 on the right). Each range is determined by the uncertainty factors including: (i) benchmark price (2011, 2015), (ii) the structure of power generation/ electricity transmission capacities, (iii) the structure of small/large cases.

When comparing the medium value of the Baseline scenario and 100by50 scenario for each aggregated type of bulk materials, we can observe a significantly higher level under the 100by50 scenario in the period 2020–2030. Especially among the petrochemical materials (asphalt, paint, plastic products, rubber products), in the period 2020–2030, the lower bound of their material demand under the 100by50 scenario exceed the upper bound of their material demand under the Baseline scenario. The gaps between the Baseline scenario and 100by50 scenario in the period 2020–2030 are far larger compared to those in the period 2030–2040 and 2040–2050, as a result of more early investment in new capacities (shown in Fig. 3), especially on solar and wind energy. Although the intensity of material input in renewable power generation technologies (physical unit per MW) is not always higher than in fossil fuel power generation technologies (e.g., the input of cast iron products to solar capacities per MW only 10.9% of those to coal capacities, 2015 benchmark), due to the lower operation rates, the overall material demand would be driven higher by the much more introduction of renewable capacities.

When comparing the uncertainty (degree of dispersion) of all aggregated types of bulk materials, we can observe larger ranges in the estimation of cement-related products (cement, cement products, concrete, construction ceramics), plastic products, cables, and steel products. As one of the factors that determine the uncertainties, the structure of power generation/ electricity transmission capacities varies between the Baseline scenario and the 100by50 scenario, where the latter includes more distributed renewable energy sources that require a higher share of electricity transmission infrastructures. Based on the per-case results in Table 3, we further examined the material input intensity (physical unit/million JPY). Relatively more inputs of cables are required in the construction of electricity transmission capacities, while more inputs of steel products are required in the construction of power generation capacities. A scenario with more distributed renewable energy sources (100by50) would affect those materials more, namely the ones that are required more differently between power generation and electricity transmission capacities, leading to a large gap between the upper and lower bounds. The gaps would further expand when the size of total investment increases, resulting in a higher degree of dispersion in basically all aggregated material types in the period 2020–2030.

3.3 Energy demand

Figure 5 shows the result of energy service demand in the industry sector that includes the part induced by new power generation capacities. The results under Baseline and 100by50 scenarios are shown continuously from 2020 to 2050 (Fig. 5A) with 5-year periods. To better display the slight differences among scenarios subject to the same climate goal (100by50 scenarios), the results under all scenarios in 2050 are shown independently (Fig. 5B).

In 2025 and 2030, mainly as a result of solar capacity introduction, the final industrial energy under the 100by50 scenario largely increase compared to the Baseline scenario. Moreover, with the inter-period iterations, such increases in

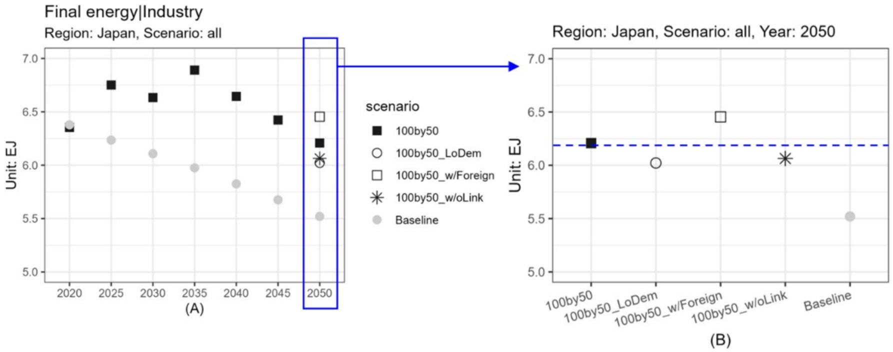

Fig. 5 Industrial energy service demand in response to new capacities during 2020–2050 (**A**) and a zoom-in for 2050 (**B**)

industrial energy in the early periods would further bring continuous growth afterward, resulting in an even larger gap of 0.9 EJ in 2035 and 0.8 EJ in 2040. While under the 80by50 scenario, where Japan's national climate goal was 80% CO_2 emission reduction by 2050 and the national CO_2 emission in 2035 and 2040 can still keep at 120–190 MTC, this gap would be around 0.5 EJ. Again, from the perspective of industrial energy demand, the difficulty of achieving a 100% reduction would be enormous, not simply and linearly vary based on the understanding of achieving an 80% reduction. An urgent and large amount of energy inputs during 2020–2030 would be inevitable.

In 2050, this gap would fall back to 0.7 EJ, among which 0.1 EJ would be induced by the changes in the energy supply side and not out of the growth in the energy demand side (shown as the difference between 100by50 and 100by50_w/oLink). If the total induced industrial energy service demand is considered, both domestic and overseas, another 0.2 EJ energy demand would be required to meet the needs of Japan's imported bulk materials (shown as the difference between 100by50 and 100by50_w/Foreign).

We then examined to what extent demand-side mitigation options may contribute to the reduction of emissions and energy service demand. The result shows that, though as a hard-to-abate sector, the industry sector can still benefit from a 0.2 EJ reduction in its final energy consumption materials (shown as the difference between 100by50 and 100by50_LoDem).

Figure 6 shows additional information regarding the structure of industrial energy demand. Given the longer lifespan of industrial infrastructure that requires a longer time for production technology shifts, the results would be shown in the period from 2020 to 2070.

Compared to the Baseline scenario, the delivered coal in industrial energy would continuously decrease under the 100by50 scenario, while the electrification rate would increase more after 2050. As an important stock input in the manufacture of industry final products, the uptake of refined liquids may remain similar under both scenarios. Under the 100by50 scenario, the uptake of hydrogen would increase but increase slowly (first exceeding 10% in 2050). This result is also similar to our

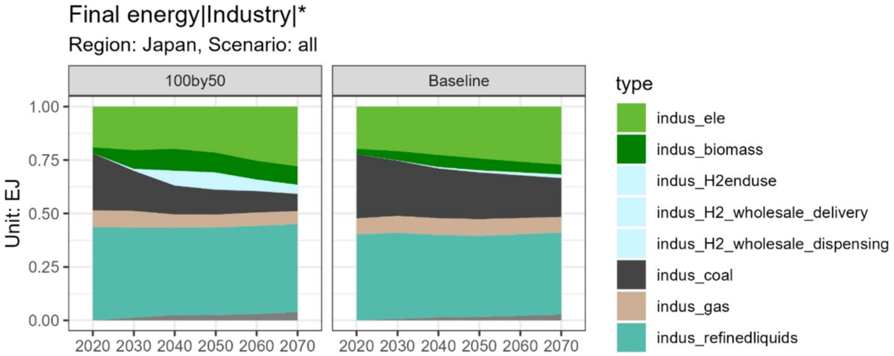

Fig. 6 Structure of industrial final energy

previous study [14], where we found that the electrification rate and the introduction of biomass use in industries will still be limited in Japan by 2050. Together these all suggest the difficulties in large-scale fuel switching in the industries.

4 Discussion

Studies on the long-term demand projection of multiple types of bulk materials have not been fruitful. Kawase et al. [17] focused on the steel demand to achieve a low-carbon and de-materialized society. They found that the scenario with better material efficiency will require 27% steel final products compared to the BAU scenario. In this study, though our results also show a declining trend during 2020–2050, the demand for steel under the 100by50 scenario actually would be slightly higher than it under the Baseline scenario in the year 2050. This is due to the large investments during 2020–2030 under 100by50 scenarios. In another study, Li et al. [19] found that the material stocks of China's power infrastructure will further increase to 1188–1487 Mt in 2050. Increasing use of steel and aluminum in renewable energy generation and the use of copper and aluminum in power transmission and distribution can be projected in the future. This trend is along with our examination in the case of Japan. As suggested by Wang et al. [31], as the material intensity of different power generation technologies varies, technological choices will strongly influence the spectrum of future material requirements.

One key feature of the material industries lies in the potential of recycling. The dynamics of in-use stocks and flows need to be explicitly addressed. Unfortunately in this study, only the flows (both materials and energy) at each period by 2050 are considered, the recyclable materials from end-of-life products and their dynamics are not included. This is because it is very difficult to estimate the energy inputs to the production of recycled materials accurately, also to trace them in the long-term model separately. However, this does not hurt our overall objection: to reveal the material demand gap induced by new power infrastructures. A module that considers in-use stocks, retirement distribution, and their dynamics for multiple material types (e.g., such as the integration of a dynamic material flow analysis in [33]) would be our next step.

5 Conclusion and policy implications

In this paper, we summarized the most relevant activities of the industry sector in IAMs that are hard to model and started with including the power-material links through inter-model iterations (build common measurement points in a partial IAM and an IO framework, mapping LCA parameters to industrial activities), so that material and energy demand caused by power capacity changes (e.g., introduction of power generation and electricity transmission capacities) can be assessed in the long-term pathways endogenously.

We applied it to a single country, investigating the pathways toward achieving carbon neutrality in Japan by 2050. The difficulty of achieving a 100% reduction of

GHG emissions there would be enormous. Feasible pathways require a large amount of investment in new capacities (mainly solar and wind) in the earlier period during 2020–2030, reaching an average of over 2000 billion JPY per year. This leads to a corresponding increase in the material and energy service demand, not only in that period but also afterward through inter-period iterations.

We strongly recommend that energy policymakers need to consider a wide range of long-term energy consumption projections as their reference, and especially should not ignore the energy and material gap brought by new power capacities, as our approach shows.

The largest gap in material demands can be observed in 2020–2030, especially for cement-related products, petrochemical products, cables, wood products, and steel products. Relatively more inputs of cables are required in the construction of electricity transmission capacities, while more inputs of steel products are required in the construction of power generation capacities. We examined several factors that would affect the uncertainty range, including (i) benchmark price (2011, 2015), (ii) the structure of power generation/ electricity transmission capacities, (iii) the structure of small/large cases. We found that the degree of dispersion would be higher in the materials that are required more differently between power generation and electricity transmission capacities, especially under the 100% GHG reduction scenario with more distributed renewable energy sources.

The largest gap in industrial energy demands shows later in 2030–2040 as a result of inter-period iterations, reaching a difference of 0.9 EJ in 2035 and 0.8 EJ in 2040 compared to the baseline scenario. In 2050, this gap would fall back to 0.7 EJ, among which 0.1 EJ would be induced by the changes in the energy supply side and not purely out of the growth in the energy demand side. If the induced industrial energy demand overseas is also considered, another 0.2 EJ energy demand would be required to meet the needs of imports. We also examined to what extent demand-side mitigation options may contribute to the reduction of GHG emissions. The result shows that, though as a hard-to-abate sector, the industry sector can still benefit from a 0.2 EJ reduction in its final energy consumption materials.

By decomposing the industrial final energy, a relatively low electrification level before 2050 and late uptake of hydrogens can be observed. This also emphasized the necessity to investigate how industries can benefit from an increasingly low-carbon energy supply.

Overall, we would suggest policymakers incorporate comprehensive demand projections into energy and infrastructure planning, ensuring that investments in renewable energy are complemented by strategies that curb the acceleration of bulk material production growth. Special attention should be paid to the early deployment phase (2020–2030), where the demand for bulk materials such as steel, cement, and petrochemical products will peak. Policies promoting material efficiency, such as circular economy practices, product redesign, and advanced recycling technologies, should be prioritized to alleviate pressure on supply chains. Additionally, industrial energy policies should facilitate the electrification of processes and the expansion of clean fuel adoption, ensuring a deep mitigation transition in the long run (by 2050). International cooperation is also essential considering a significant portion of the induced industrial energy demand may occur outside Japan overseas.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request. All data sources used in this study have been appropriately cited within the manuscript.

Declarations

Conflict of 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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