Sustainable Energy & Fuels

PAPER

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Cite this: *Sustainable Energy Fuels*, 2025, **9**, 3120

Quantifying mining requirement and waste for energy sustainability

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This study demonstrates the life-cycle assessment of different energy sources-coal, natural gas, solar, wind, nuclear, and hydro-particularly focused on mining activities and waste per given electricity capacity and generation. It also includes carbon dioxide emissions generated during the transportation of raw materials to build and operate electricity generating systems and their environmental impacts in the US from 2023 to 2050. We identify the raw material and metal requirements for the U.S.-based typical systems in each energy type and synthesize datasets on typical ore fraction and material recycling factors, while taking into account the capacity factor of the power plants. We then compute the total mass and volume of material requirements and waste mass and volume for the front-end (*i.e.*, mining, material needed for construction), operation (*i.e.*, fuel, maintenance), and back-end (*i.e.*, decommissioning) activities. The key findings are that (1) the energy transition from fossil fuel to low-carbon energy sources would reduce mining waste as well as the shipping carbon footprint; (2) the difference in capacity and actual electricity generation is significant for the life-cycle assessment due to low capacity factors of solar and wind energy; (3) several key metals with low abundance or high requirements dominate mining waste, which highlights the need for recycling and establishing a circular economy; (4) mining of critical minerals becomes important during the clean energy transition and (5) nuclear energy generates least waste and contributes least to shipping emissions among the low-carbon sources due to the high energy density and capacity factor and the small mass of materials it requires. Although the waste mass may not necessarily be equal to the environmental impact due to different waste isolation technologies, we aim to highlight the importance of considering mining and decommissioning waste, which are often ignored but important for accounting for the environmental impacts and addressing energy justice issues.

Received 24th October 2024
Accepted 13th April 2025

DOI: 10.1039/d4se01484g

rsc.li/sustainable-energy

Introduction

Decarbonizing the economy-the process of lowering the amount of carbon dioxide in the atmosphere, and working to achieve global sustainability goals-has accelerated the adoption of carbon-free electricity-generation systems in the U.S. This strategy aims to shift society away from using fossil fuels, a major source of carbon dioxide (CO_2) pollution, as a way of producing electricity to combat the effects of greenhouse gas (GHG) and climate change. CO_2 emissions are the leading cause of global warming, leading to weather-pattern changes and population displacement due to extreme weather events and agricultural crises. These GHG emissions have been chosen by the Intergovernmental Panel on Climate Change as one of the metrics to assess the environmental impact of human activities.[1,2]

In 2024, most electricity generated in the U.S. came from burning fossil fuels. Coal, natural gas, and oil generate almost 60% of electricity, making decarbonization difficult without a massive shift in supply systems.[3] Alternatives to fossil fuels include renewable and nuclear energy. The U.S. has adopted the strategy of deploying more renewable energy sources, such as solar and wind power, to reduce its carbon footprint, build a sustainable economy, and provide equitable access to electricity in remote areas.

From 1990 till date, the share of renewable energy sources, such as solar and wind power, has grown rapidly.[4] As per annual IEA report, Renewables 2024, the world is set to add more than 5500 gigawatts (GW) of new renewable energy capacity between 2024 and 2030-almost three times than the increase between

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2017 and 2023.[5] However, solar and wind energy are known to have lower capacity factors than coal, natural gas, nuclear, or hydropower, so the actual energy generation from solar and wind is lower.

There are other energy technologies that could help decarbonize the economy without relying on weather patterns, or storage, namely nuclear energy and emerging advanced nuclear reactor designs. As discussed in a report from the International Renewable Energy Agency,[6,7] there is a growing understanding that a proper combination and mixture of renewable and nuclear energy resources would be necessary to achieve the net-zero goal.

There have been many studies comparing different energy sources' CO_2 or environmental footprints. In these studies, a life cycle assessment (LCA) was used to evaluate an energy source's full impact, taking into account raw material extraction, usage, waste, and everything in between, to evaluate its impact and compare it to other sources.[8] In previous LCAs, CO_2 was used as a measure to compare how different energy sources affected the environment. In these LCA's, it was found that the coal power system emits the most CO_2 over its life cycle, followed by oil and natural gas,[9,10] whereas hydro, nuclear, wind, and solar are low-carbon sources.[9,10] For example, the GREET model (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model),[11] is a tool that examines the life-cycle impacts of vehicle technologies, fuels, products, and energy systems. It accounts for energy inputs and emissions at every stage for different energy systems.[12] However, it considers only GHG emissions, air pollutants, and water usage to analyze the environmental impacts of different energy and transport systems. The material waste associated in each of the stages is not considered, which other than CO_2 also has huge environmental impacts.

Comparative LCA studies often leave out important parts of environmental impact analyses, such as mining effects and waste management (including disposal and recycling). This is an environmental justice issue because most mining and waste disposal occurs in developing countries and low-income regions.[13,14] The effects are worse in "mining-friendly countries" with weaker environmental protection regulations, which are often the primary source of raw materials.[15] These impacts at mining sites affect geopolitics, leading to unpredictable price changes controlled by resource-owning countries.[15]

Unmanaged, the contaminants from waste can pollute waterways, groundwater, drinking water, and the air. Traditionally, nuclear energy communities have invested significantly on waste management and disposal strategies, having a high level of international agreement on standards and regulations.[16] On the other hand, coal ash does not require geologic disposal or special treatment, despite containing toxic metals like mercury, cadmium, and arsenic.[17] The U.S. does not have a federal end-of-life strategy for renewable energy sources that require solar panel reprocessing or safe disposal.[18] Although solar panels contain heavy metals and toxic substances such as lead and cadmium, there are no regulations and requirements for disposal or recycling.[19]

This study aims to compare the mass and volumes of waste generated from key energy sources (coal, hydro, nuclear, solar, wind, and natural gas) by quantifying the waste from various processes, specifically mining, operations, and decommissioning and carbon-dioxide release associated with respective transportation distances during the lifetime of each energy source. Data has been curated from government databases, and peer reviewed scientific journals. A Python-based framework was developed for our LCA model. Our target period is 2022–2050 in the U.S., projecting an increase in solar and wind capacities by 2050 and a decrease in nuclear and coal power plant capacities.[20] Note that to the authors' knowledge, this paper is the first in the scientific literature to analyze the impacts of mining waste during the transition to renewable energy.

Methods

(a) Electricity generation data collection

First, we gathered U.S. electricity generation data from the Energy Information Agency (EIA).[21] These data predict rising electricity production and consumption by 2050. We considered (1) the capacity of such systems, or the maximum amount of electricity a generator can produce in ideal conditions, and (2) the actual amount of electricity a generator produces over time. Comparing electricity generating systems' material consumption and waste generation requires both capacity and actual generation data. The capacity and energy generation are different metrics since the latter depends on a number of factors, such as weather conditions and maintenance schedules. The output of a generator depends on the power plant's condition, weather, maintenance, and the electrical grid's instructions. For each system described below, we used the average capacity factors to calculate the MWh generated for further analysis. Construction of a power plant yields the same amount of materials per MW of capacity of the same type, while the fuel utilization and maintenance waste generation would be different at different capacity factors due to the system availability to produce electricity 24/7. System boundaries used are materials per MWh, and sizes of plants are considered based on the US plant capacities data as of 2022.

Coal, natural gas, nuclear, hydro, solar, wind, and diesel are the major sources of electricity in the U.S. mix estimated from 2022 to 2050 (Fig. 1), contributing 95% of the total. Between 2022 and 2050, coal's installed capacity and electricity production will drop by half as shown in Fig. 1, which will add to the waste resulting from the decommissioning of plants. However, coal power plants will likely continue to provide electricity despite efforts to decarbonize the economy. Natural gas production will see an initial drop but will start growing again from 2036 and continue to increase through 2050. Wind and solar power will keep growing, whereas nuclear and hydropower will see a slight decrease in generation and installed capacity in the next 30 years.

(b) Electricity generating system material flow system

For this work, we are focused on materials needed for construction— front needs, the waste generated during the

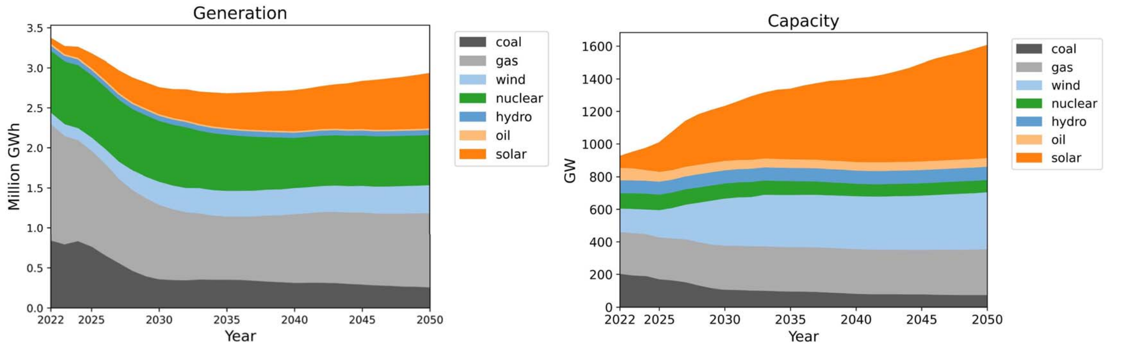

Fig. 1 Nameplate electricity generation and capacity in the U.S. from 2022 to 2050 (EIA).

materials extraction— front waste; the materials needed for the operation and maintenance of the power plant— operational needs; and the waste generated at this stage— operational waste, and the last stage of any project is the decommissioning of these projects— back-end waste. Depending on the system, there may or may not be an operational waste. In the cases of

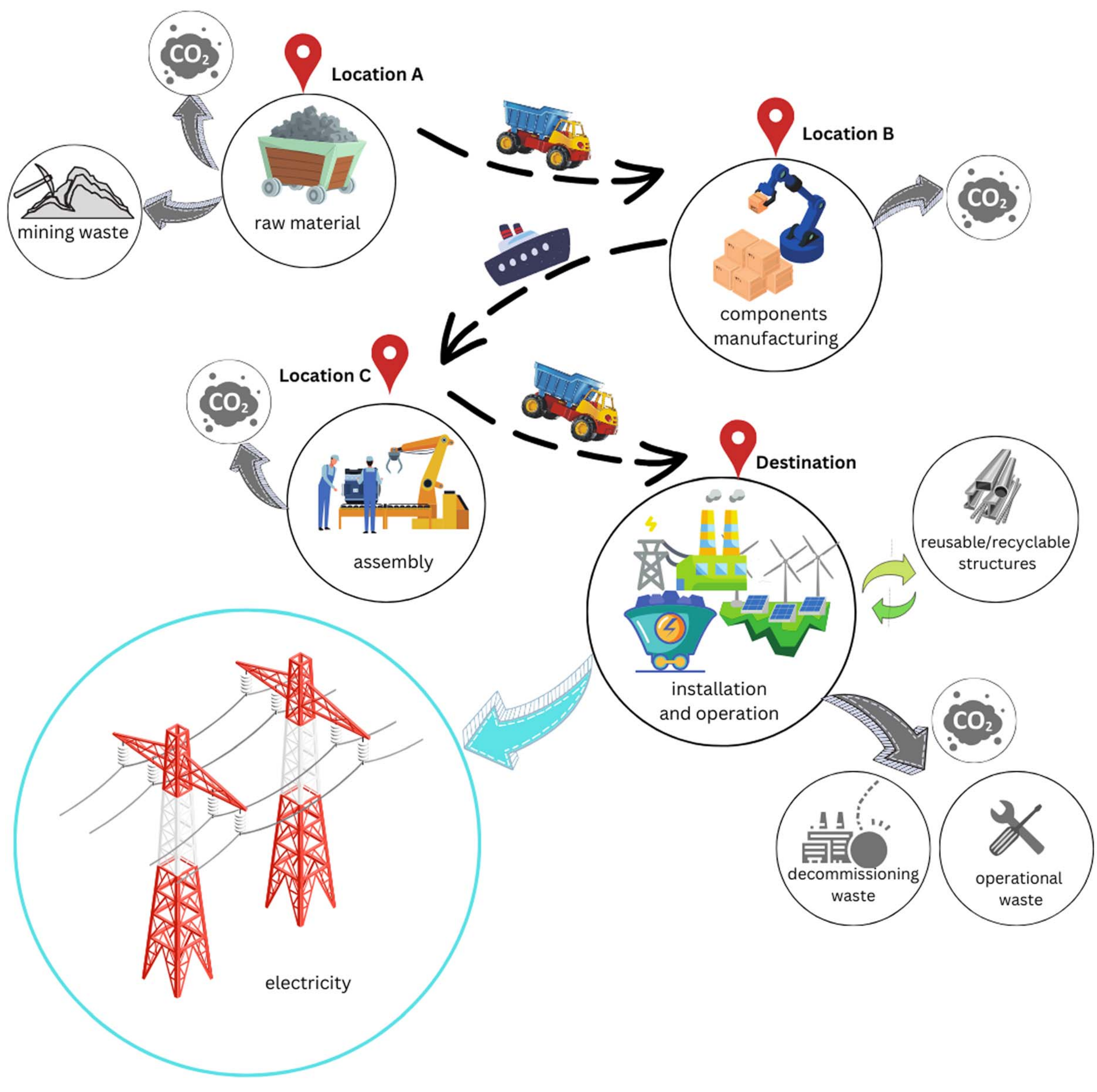

Fig. 2 General material flow for energy systems.

coal, nuclear power, and gas, there is a need for fuel and waste generation during the operation in the form of spent fuel, ash, limestone, and other operational waste materials. In the case of solar, wind, and hydropower, there is no fuel, but there are materials required for system maintenance, such as lubricants, oils, and protective coatings. Fig. 2 exemplifies the material flow for electricity-generating systems.

(c) Electricity generating system material requirement data

Data on each energy system's materials– such as ore fractions, and recycling factors – was taken from peer-reviewed sources and agency reports. Some energy systems, such as coal power plants and nuclear power plants, have well-developed life-cycle assessments owing to technology maturity, waste-management strategies, or substantial research on the environmental impact or lack thereof.[22] On the other hand, solar, wind, natural gas, and diesel power systems still lack enough information about end-of-life strategies and deployable technology changes.[23] Diesel/oil power plants, biomass, and a few other smaller energy systems were left out of the analysis, either because they didn't produce much electricity or because there wasn't enough information about their systems.

(d) Power plant data and curation

The information on electricity generating systems was extracted from the EIA data on generator-level specific information about existing and planned generators and associated environmental equipment at electric power plants with 1 megawatt or greater of combined nameplate capacity.[24] This data contained information about the power plant's location, installed capacity, operational year, and year of decommissioning.

(e) Raw material locations data

Data was collected based on the list of materials needed to build and operate a power plant. Most of the materials are imported to the U.S. from abroad, and there are leaders in the export of every particular raw material. There is localized production of coal, steel, cement, and limestone. The information about the exports was taken from the U.S. Geological Survey report.[25]

Data analysis

Since most GHG emissions from renewable technologies are embedded in the infrastructure or the manufacturing process (up to 99% for photovoltaics), life-cycle impacts may vary widely depending on the source of raw materials, the mix of energy used in production, the mode of transportation used at different stages of manufacturing and installation, *etc.* Unlike operational carbon emissions, which can be reduced with efficiency improvements, the embedded carbon emissions are fixed once a project is finished. Load factor and expected equipment lifetime are important factors in the final LCA score because impacts are embodied in the capital. If infrastructure is more durable than expected, the final LCA score may be affected.[26] Fig. 3 shows a detailed diagram of the methods used to collect and curate data and steps used to provide the current analysis.

• Excluded from the analysis: energy sources that contribute <1% of total capacity or have no expected capacity changes or based on data availability.

• Included: natural gas combined cycle, wind, nuclear, coal, hydroelectric power, solar PV.

• Each CSV data file has (common for all energy sources) streams specifications: mining (front) waste and material (front) need, fuel waste and need, backend (decommissioning) waste.

• Further data processing was performed using Python to assess the mass and volume of material needed and waste

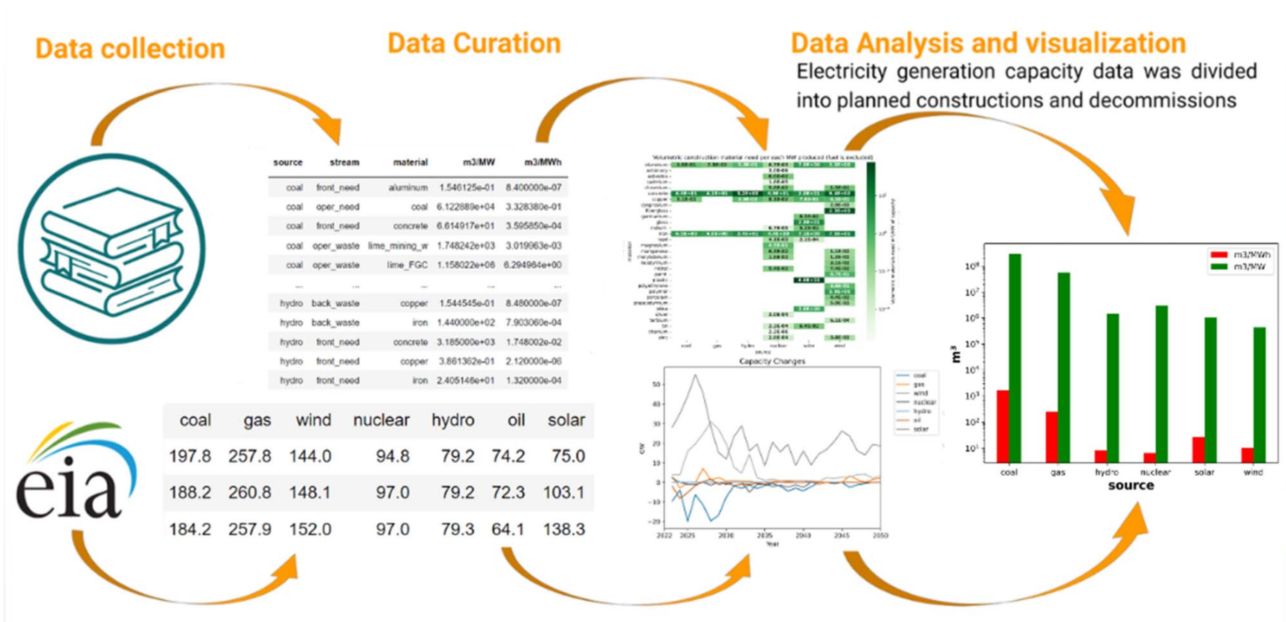

Fig. 3 Data collection, curation, and analysis diagram.

Table 1 Material use, ore fraction, mining waste volume (m^3 MW^{-1}), and recycling factor for a coal power system

Material type	Material amount (kg MW^{-1})	Material volume (m^3 MW^{-1})	Ore fraction	Mining waste (kg MW^{-1})	Mining waste volume (m^3 MW^{-1})	Recycling and reusing factors	Source
Iron	51340.67	0.15	65%	27644.99	17.34	—	31
Concrete	158758	66.15		22337.26	13093.35	—	28
Aluminum	419	0.15	30%	977.7	0.25	0.76	31
Copper	454	0.05	2%	22246	12.78	0.6	22
Coal	8.24×10^7	61228.89	40–90% recovery, 65% mineral component	316977230.8	1.86×10^8	—	27, 28, 31 and 32
Lime for Fgc waste treatment	1287720	1158022	45%	4952769.23	1748.24	—	25 and 33
Limestone	16556 400	6107.12	100%	—		—	27
Antimony	0.75	0.000 11	Released during combustion			—	27 and 29
Arsenic	9.01	0.001 6	Released during combustion			—	27 and 29
Barium	2.39	0.000 66	Released during combustion			—	27 and 29
Beryllium	0.29	0.000 16	Released during combustion			—	27 and 29
Boron	3127.32	1.34	Released during combustion			—	27 and 29
Cadmium	0.75	8.68×10^{-5}	Released during combustion			—	27 and 29
Chromium	10.85	0.001 5	Released during combustion			—	27 and 29
Cobalt	1.27	0.000 14	Released during combustion			—	27 and 29
Copper	4.23	0.000 47	Released during combustion			—	27 and 29
Lead	5.52	0.000 49	Released during combustion			—	27 and 29
Manganese	7910.28	1.06	Released during combustion			—	27 and 29
Mercury	6.81	0.000 50	Released during combustion			—	27 and 29
Molybdenum	6.99	0.000 68	Released during combustion			—	27 and 29
Nickel	10.67	0.001 2	Released during combustion			—	27 and 29
Selenium	75.42	0.016	Released during combustion			—	27 and 29
Vanadium	16.19	0.002 7	Released during combustion			—	27 and 29
CO_2	188 042 792.92	1.01×10^8	Released during combustion				27, 29 and 32
SO*x*	1 348 058.88	512569.92	Released during combustion				28 and 29
Ash	5064090.3	1838145.30	Released during combustion			Assuming that 30% reused	27–30
NO*x*	559054.44	292239.64	Released during combustion				28 and 29
CO	24 650.64	31.243	Released during combustion				28 and 29
Particulates	33297	50.07	Released during combustion				28 and 29
VOC	2943.36	3529.21	Released during combustion			—	28
FGC	11773 440	10587 626	Released during combustion			—	28

Table 2 Material use, ore fraction, mining waste volume (m^3 MW^{-1}), and recycling factor for a solar power system

Material type	Material Mass (kg MW^{-1})	Material volume (m^3 MW^{-1})	Ore fraction	Mining waste (kg MW^{-1})	Mining waste volume (m^3 MW^{-1})	Recycling and reusing factors	Source
Silica	7000	3.017	Ore grade about 35% and 50% of Si goes into waste during manufacturing	363000	128.13	0	39
Aluminum	19000	7.011	30%	44333.3	11.28	0.76	40–42
Concrete	47000	19.58	67% for cement and concrete contains 21% of cement	6612.9	3876.26	1	41 and 43
Glass	70000	28	35%	130000		0	39
Copper	7000	0.78	2%	343000	197.13	0.6	39 and 44
Steel	56000		65%	30153.85		0	39 and 45
Germanium	440	0.083	0.015%	1099560	388.12	0	39 and 46
Indium	380	0.052	0.01%	3799620	1341.2	0	39 and 47
Plastic	6000	6000	—	—		0	39
Lead	2.4	0.000 21	1.732%	136.17	0.048 0	0	36, 48 and 49
CO_2	1971000	1054010.69	—	—		—	50
Polyamide injection molded	485	0.42	—	—		0	51 and 52
Polyester	300	0.22	—	—		0	51 and 52
Polyethylene, HD	150	0.16	—	—		0	51 and 52
Vegetable oil	6001	6.52	—	—		0	51 and 52
Tin	463.1	0.063	50%	463.1	0.163466	0	52–54

generated throughout the lifetime of the power plant, as well as waste and material demand generated and needed annually.

- First, we calculated the annual capacity/generation change based on EIA data. Each year, there is an increase or decrease in the capacity and generation of different energy sources. This step allows us to quantify material flow. A preprocessing algorithm sorts annual changes into "decommissioning" and "construction" categories.

$$\text{Capacity changes} = \text{capacity in year } `n' - \text{capacity in year } '(n-1)'$$

$$\text{Generation changes} = \text{generation in year } `n' - \text{generation in year } '(n-1)'$$

- We assumed the annual change in capacity was due to new installation or decommissioning (MW). We then calculated the equivalent energy change from mining waste and decommissioning waste.

- Each energy system (coal, solar, nuclear, wind, hydro, natural gas) had front-end, back-end, and operations material flow. Front-end is raw material, back-end is used material, and operations are fuel (for coal, natural gas, and nuclear power) and maintenance materials. Each category has waste and need.

- A set of algorithms has been developed to convert the electricity in MWh to material need or mining volume requirements. The assumptions and approaches for each source are described below.

$$\text{Volumetric material need or volumetric mining waste } \left(\text{m}^3\ \text{MW}^{-1}\right) = \frac{\text{material need or mining waste } \left(\text{kg MW}^{-1}\right)}{\text{average density } \left(\text{kg m}^3\right)}$$

- Next, we convert m^3 MW^{-1} to m^3 MW h^{-1} using the following method:

$$\Rightarrow \int_{2023}^{2050} \text{Capacity (MW).dt} = \text{MW. year} = \text{MW. year} \times (365 \text{ days/year} \times 24 \text{ hours/ day}) = \text{MWh}$$

Assumptions and parameters for each system

Coal power. Coal power systems have been widely used in LCA as a well-understood base-case technology.[21,23,27] The capacity factor and lifetime are 70% and 30 years, respectively. Building a power plant requires mining and transporting raw materials. Once the coal power plant is operational, coal mining, transport, and combustion begin. Coal combustion produces coal ash and a variety of gasses after reacting with oxygen; 30% of coal ash is used for construction materials, and 70% is disposed of in landfills.[28–30] At the end of the power plant's life, it is decommissioned, and some materials are recycled. A detailed description of material flow and recycling rates is shown in Table 1.

Solar power. Photovoltaic capacity in the U.S. has grown by 65% annually on average in the last decade.[34] Which solar module technology will dominate in 10–30 years is hard to predict, because of the market's diversity. As a result of their mature technology and low prices, crystalline silicon (c-Si) module solar photovoltaic panel makers have the largest market share.[35] The global share of these panels is 91%. Such panels were used for this research.[33]

For material demand and waste calculations, the solar panel's power-producing capacity was assumed to be 1 kW m^{-2} and set to be constant regardless of ambient temperature.[36] The size of this panel would be 5 m^2.[36]

The solar panel's end-of-life strategy is nonexistent. There are no regulations on how much material should be recycled. In this study, we assume the aluminum frame, copper wiring, and concrete foundation will be recycled or reused beyond the solar panel's lifetime. The rest of the panel components are assumed to go to landfill. The capacity factor based on the global weighted average maximum and lifetime of the panels used for this research are 18% and 27 years, respectively.[37,38] For the calculation of mining waste volume, the average density of each material type is considered. Table 2 provides material amount values, their recycling factor, and ore fractions for the solar plant projects.

Nuclear power. Information on nuclear power plants was provided by the United States Atomic Energy Commission (USAEC) system.[55] It defines all plant buildings and structures, the reactor and associated systems in the reactor building, the turbine generator, and associated systems for a 1000 MW(e) pressurized water reactor (PWR) plant.[55] A PWR fuel assembly can weigh 655 kg, with 460 kg of uranium and 100 kg of zircaloy (98% Zr, 1.5% tin).[56] A 1000 MWe reactor uses 250 tons of natural uranium annually.[57,58] The lifespan of nuclear power plants globally is 60 years, with a 90% capacity factor.[23,59] This research presents a conservative view of the nuclear power system in which no component can be recycled. The U.S. does not offer commercial-scale spent fuel reprocessing and material reuse. For the calculation of mining waste volume, the average density of each material type is considered. Table 3 provides material amount values, their recycling factor, and ore fractions for the nuclear power plant projects.

Natural gas power. Natural gas provided 23% of the world's electricity in 2020. The main power plant technology today is the natural gas combined cycle, with an 85% capacity factor and 30 year lifetime (Table 4).[62,63]

Wind power. Wind energy is a renewable energy source. Wind-energy infrastructure is concrete and steel-intensive, and if a wind turbine lasts 20 years with a 40% capacity factor, some structures can potentially be reused and recycled (Table 5).[65]

Large hydroelectric power (hydropower). Hydropower is another carbon-free source of energy. It requires the building of massive concrete structures and thus has embedded CO_2 emissions. Here, we use a 52% capacity factor and 40 years of plant life (Table 6).[80]

Transportation emissions calculations. After power plant data curation, the location information was extracted for further shipping distance calculation. The retirement year was approximated by the average project time. Here we did not take into account the construction time of the power plant nor its decommissioning timing, as for some projects it still poses a great deal of uncertainty and there is no information on how long it takes to decommission solar or wind power plants. The assumption was that once the project was approved, it would be built in the same year and start producing power. The total number of real planned power plants used for this work is roughly 14 000.

In order to make the total installed capacity of the projects compatible with modeled projections for future years, we have created a list of dummy power plants and assumed that they will be built in a year when the difference between planned and real power plant capacity was identified. These power plants would be created in a way to match the capacity projected for each particular source: coal, gas, hydropower, nuclear, solar, and wind. The locations of these power plants have been chosen as a U.S. geographical center with a coordinate of (45.610 794496 760 27, −103.682 337590 772 29). Two manufacturing sites for all systems were also selected based on the prevalence of manufacturing activities: one in Houston, TX, which is

Table 3 Material use, ore fraction mining waste (kg MW^{-1}), and recycling factor for a nuclear power system

Material type	Material amount (kg MW^{-1})	Material volume (m MW^{-1})	Ore fraction	Mining waste (kg MW^{-1})	Mining waste volume (m^3 MW^{-1})	Recycling and reusing factors	Source
Aluminum	18.07	0.006 7	30.00%	42.16	0.010 7	—	55
Antimony	0.02	2.99×10^{-6}	0.68%	2.92	0.001 0	—	55
Asbestos	138.24	0.086	5.00%	2626.56	0.93	—	55
Chromium	414.85	0.058	30.82%	931.19	0.33	—	55
Copper	725.71	0.081	2.00%	35559.79	20.44	—	55
Iron	64 936.85		65.00%	34 965.996	21.94	—	56 and 60
Lead	46.65	0.004 1	1.73%	2646.77	0.93	—	55
Manganese	467.36	0.063	35.00%	867.95	0.31	—	55
Molybdenum	163.66	0.016	0.50%	32568.34	11.50	—	55
Nickel	484.34	0.054	9.00%	4897.22	1.73	—	55
Silver	3.12	0.000 30	0.01%	52878.24	18.66	—	55
Tin	1.64	0.000 22	50.00%	1.64	0.000 58	—	55
Titanium	0.01	2.22×10^{-6}	2.50%	0.39	0.000 14	—	55
Zinc	2.02	0.000 28	0.42%	478.93	0.17	—	55
Magnesium	782.38	0.45	28.00%	2011.83	0.71	—	55
Concrete	166348.67	69.31		23405.26	13719.38	—	55
Indium	0.49	6.70×10^{-5}	0.01%	4899.51	1.73	—	55
Cd	0.16	1.84×10^{-5}	0.00%	10666.51	3.76	—	55
Natural uranium	15 000		0.21%	7127857.14	2516.01	—	57
Zirconium	804.168	0.12	1%	80416.8	28.38	—	59
Gadolinium	0.022	0.000 36	1%	284.26	0.10	—	61
Total CO_2	5676480	3 035 551	—	—		—	22

Table 4 Material use, ore fraction mining waste (kg MW^{-1}), and recycling factor for a natural gas power system

Material type	Material amount kg MW^{-1}	Material volume (m^3 MW^{-1})	Ore fraction	Mining waste (kg MW^{-1})	Mining waste volume (m^3 MW^{-1})	Recycling and reusing factors	Source
Steel	31030		65%	16 708	7850	—	62
Concrete	97749	40.73	67% for cement and concrete contains 21% of cement + sand + gravel and water	13 753.28	2400	—	43 and 62
Aluminum	204	0.075	30%	476	2710	0.76	62 and 64
Iron	408		65%	219.69	7800	—	45 and 62
Natural gas waste	1.044	0.000 37	—	—		—	62
CO_2	26576.68	14212.13	Construction emissions	—		—	62
Natural gas	37795896	58 147 532.31	—	—		—	62
Coal	402084	298.73	—	—		—	62
Oil	134028	162.46	—	—		—	62
Limestone	134028	49.44	—	—		—	62
Pipeline iron	134028	17.024	65%	72168.92	7800	—	62
NH3	4690.98	6426.00	—	—		—	62
SO_x	72375.12	27 519.06	—	—		—	62
NMHCs	140282.64	3 404 918.45	—	—		—	62
NO_x	127326.6	66558.60	—	—		—	62
CO	64110.06	81.25	—	—		—	62
Particulates	29709.54	44.68	—	—		—	62
CO_2	98287 200	52560 000.00	Combustion product	—		—	62
Formaldehyde	1943.406	2.38	—	—		—	62
Methane leak	629931.6	958 800	—	—		—	62
Benzene	14117.616	16.12	—	—		—	62
H_2S	0.003 1	0.002 3	—	—		—	62

Table 5 Material use, ore fraction mining waste (kg MW^{-1}), and recycling factor for a wind power system

Material type	Material amount (kg MW^{-1})	Material volume (m^3 MW^{-1})	Ore fraction	Mining waste (kg MW^{-1})	Mining waste volume (m^3 MW^{-1})	Recycling and reusing factors	Source
Aluminum	8026.8	2.96	30%	18729.2	4.76	0.76	66
Brass Cu	52.38	0.02	2%	2566.5		0	66
Brass Zn	26.2	0.01	3%	847.13		0	67
Cast iron	47350.4	18.94	65%	25496.37		1	66
Concrete	2246400	936.00	67% for cement and concrete contains 21% of cement + sand + gravel and water	316068.48	185268.7	1	66
Copper	5568	2.46	2%	272832	158.27	0.6	66
Fiberglass	3490.8	2327.20	—	—		0	66
Steel	540710	68.88	65%	291151.54	2285539 589	1	66
Lubricant	3304	4.004 8	—	—		0	66
Paint	1311.12	0.87	—	—		0	66
Polyethylene	329.4	0.36	—	—		0	66
Polymer	5888	5.89	—	—		0	66
Porcelain	104.98	0.04	—	—		0	66
Neodymium	216	0.031	5%	4104	1.45	0	68–70
Praseodymium	40	0.005 9	5%	760	0.27	0	69 and 71
Terbium	5	0.000608	5%	95	0.033	0	69
Dysprosium	17	0.002 0	5%	323	0.11	0	53 and 69
Cr	902	0.13	31%	2024.67	0.71	0	72–74
Manganese	80.5	0.010 8	35%	149.5	0.053	0	72, 73 and 75
Molybdenum	136.6	0.013	0.50%	27183.4	9.59	0	72, 73 and 76
Nickel	663.4	0.074	9%	6707.71	2.37	0	72, 73, 77 and 78
CO_2	481800	257647.06	—	—		—	79

Table 6 Material use, ore fraction mining waste (kg MW^{-1}), and recycling factor for a hydropower system

Material type	Material amount (kg MW^{-1})	Material volume (m MW^{-1})	Ore fraction	Mining waste (kg MW^{-1})	Mining waste volume (m^3 MW^{-1})	Recycling and reusing factors	Source
CO_2	2733120	1461561.50	—	—		—	81
Aluminum	1585.21	0.58	30%	3698.82	0.94	0.76	82
Concrete	7644000	3185	67% for cement and concrete contains 21% of cement + sand + gravel and water	1075510.8		—	83
Copper	874.6	0.39	2%	42855.32	24.63	0.6	82
Iron	60128.64	24.051	65%	32376.96	20.31	—	83

considered an energy business capital[24] and the coordinates for this location (29.803 623938 502025, −95.294 260 833 951 6); and one in Colorado State, since the largest U.S. wind manufacturer has invested in several facilities in the state, including the biggest wind nacelles and blades manufacturing plants.[24] The location coordinates for this site are (38.170 105180 129 34, −104.617 165418 328 95). The final number of power plants used was over 47 000 since there was almost no planned power plant deployment information for the years 2030–2050. The detailed map of real power plant data used for modeling is shown below in Fig. 4.

Next, in order to provide a location from where the material is coming, we assumed that the biggest mine is used to extract raw materials for internal production and export. When conducting the research, it was necessary to determine if materials could be produced locally or imported, and the latest USGS mineral commodity summaries had that information. Then, using global search engines, such as Google results, and boolean operators, determine the largest mine, quarry, or oil field for the mineral in the US or in the world. Most of the results came from market research companies, specifically GlobalData, and news websites. If there was no data on particular materials in the largest mine, the data was compiled from peer-reviewed journal articles, especially for the rare earth elements. Additionally, there were times when it was impossible to locate the largest mine, and the mine that was considered "one of the largest…" was used for further analysis. The mine locations as well as assumptions are provided in Table 7.

Knowing the power plant location data, amount of raw materials needed per power plant, the manufacturing facility and raw material origin location we were able to calculate the distance and emissions. As we do not account for the logistics inside the supply chain and take direct distance from a point to point, the assumption was to use the freight truck emissions data rather than sea shipping container data using the following steps:[121]

Step 1: determine the total amount of ton-miles.

Step 2: get the weight-based truck emissions factor for a freight truck. The average freight truck in the U.S. emits 161.8 grams of CO_2 per ton-mile. This was calculated based on the distance traveled in miles, the capacity of the power plant in MW, and materials needed in kg MW^{-1}.

Step 3: multiply this emissions factor with the total ton-miles, which gives us a total mass of CO_2. Convert the total grams into kilograms. There are 1000 grams in a kilogram.

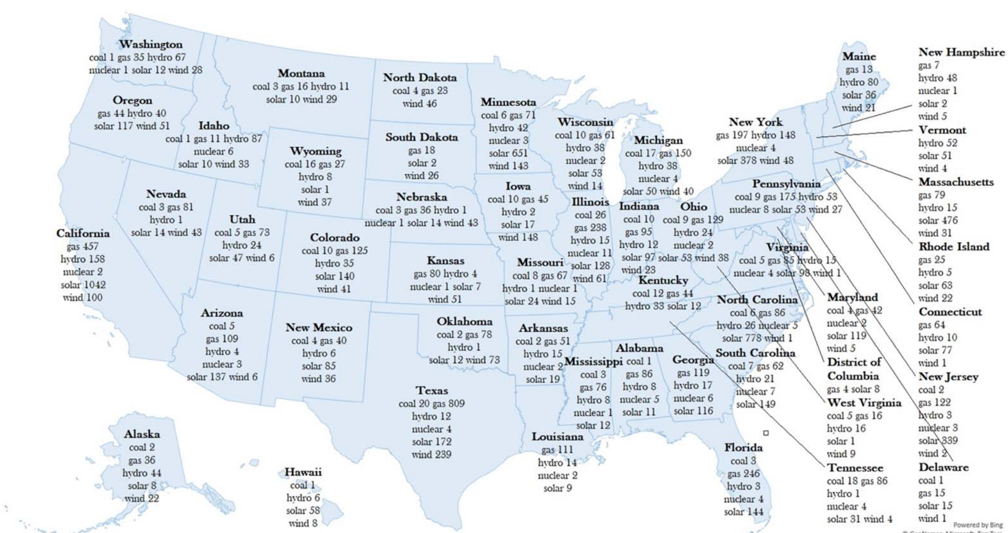

Fig. 4 The power plant database used for the modeling.

Table 7 Mining sites locations

Material	Coordinate of a mining site	Location	Mining assumptions	Reference
Aluminum	(31.006 9,−88.010 3)	Weipa mine	The most important aluminum ore is bauxite, hence the search for the largest bauxite mine in the world	84
Antimony	(34.205 6,−117.334 4)	Xikuangshan mine		85
Asbestos	(57.008 3, 61.491 93)	Uralasbest mine	Many articles refer to a mine in asbestos as the world's largest asbestos mine. The latest web article that we could find dated back to 2016	86
Cadmium	(39.101 67,−108.345 56)	Fankou mine, China	The world's largest cadmium refinery and production facility occurs in China. Cadmium is found in zinc ores. Searched for the largest zinc mine in China	87 and 88
Chromium	(40.741 5,−124.210 3)	Bushveld igneous complex, South Africa	South Africa produces the most chromium in the world (70% of the world's total chromium reserves)	89 and 90
Coal	(43.558 89,−105.288 3)	North antelope Rochelle mine	Based on US mines	91
Concrete	(29.614 08, −98.572 72)	Beckmann quarry	One of the largest aggregate mines in Texas and the nation	92
Copper	(33.090 56,-109.365 83)	Morenci mine	Local production	93
Dysprosium	(24.839 02114.836 98)	Foot cave		94
Fiberglass	(41.346 98,−88.865 11)	Ottawa Plant	Because one of the main ingredients of fiberglass is silica sand, we located the largest silica sand mine in the	94 and 95
Gadolinium	(24.839 02114.836 98)	Foot cave		94
Germanium	(68.071 99,−162.876 04)	Red dog mine	Alaska is believed to be the primary source for significant amounts of germanium mined in the U.S.	96
Glass (silica sand)	(35.942 92,−82.082 68)	Spruce pine mining district		97
Indium	(23.350 00104.533 33)	Dulong Ore field		98
Iron	(47.544 72, −92.654 44)	Minntac mine		99
Lead	(-20.696 74, 139.298 89)	Mount isa zinc mine	Assumed that lead was imported, according to USGS data. The website lists the "largest lead mines", but lists the largest mine as a zinc mine	100
Limestone	(45.415 83, −83.803 06)	Calcite quarry		101
Lubricant	(28.990 7, −98.049 9)	Eagleville (Eagle Ford shale)	Assume that mobil SHC Gear 320 WT is used. 320 WT uses polyalphaolefin technology, which is synthesized from ethylene. While ethylene is made either from petroleum or natural gas, we assumed petroleum since ethylene has historically been made from petroleum	102
Magnesium	(40.666 67, 122.833 33)	Xiafangshen mine		103

Table 7 (*Contd.*)

Material	Coordinate of a mining site	Location	Mining assumptions	Reference
Manganese	(−26.752 29, 23.043 81)	Tshipi Borwa Open pit mine	Kalahari manganese field is one of the largest mines, and Tshipi is one of the mines located within Kalahari	104
Molybdenum	(34.332 30, 109.954 00)	Jinduicheng	The Qinling Orogenic Belt is a very big reserve. Based on a journal article, Jinduicheng is considered a large deposit	105
Natural_gas	(39.281 84,−80.694 33)	MPLX sherwood gas processing complex		106
Natural_uranium	(44.240 86, 68.923 06)	Muyunkum uranium mine		107
Neodymium	(41.795 83, 109.96 944)	Bayan Obo mine		108
Nickel	(69.428 63, 30.778 77)	Severny mine	The Zhdanovskoye deposit had the highest output	109
Oil (diesel)	(28.990 7, −98.049 9)	Eagleville (Eagle Ford shale)	Assumed that diesel oil is produced from petroleum, (which is the most common feedstock)	102
Paint (Epoxy zinc)	(68.071989, −162.876 04)	Red dog mine	Assumed Teknos paint systems, specifically the Teknos coating solutions for wind turbine towers	110–113
Plastic	(39.281 84, −80.694 33)	MPLX sherwood gas processing complex	Assumed plastic refers to polyethylene. Assumed natural gas as the main feedstock. MPLX sherwood gas processing complex is considered US's largest gas processing facility, so the assumption is that the gas is delivered by trucks to the processing plant	106
Polyamide	(28.990 7,−98.049 9)	Eagleville (Eagle Ford shale)	Assumed petroleum oil as the main ingredient	102
Polyester	(28.990 7, −98.049 9)	Eagleville (Eagle Ford shale)	Assumed petroleum oil as the main ingredient	102
Polyethylene	(39.281 84, −80.694 33)	MPLX sherwood gas processing complex		106
Polymer	(28.990 7, −98.049 9)	Eagleville (Eagle Ford shale)	Eagleville is one of the largest oil fields in the US according to EIA report (2015)	102
Porcelain/Ceramic coating ((aluminum oxide)	(31.006 9,−88.010 3)	Weipa mine		84
Praseodymium	(41.795 83109.969 44)	Bayan Obo mine		85
Silica for solar	44.482 05, 86.706 79	XinJiang		114
Silver	(51.472 78, 16.040 28)	Polkowice-Sieroszowice mine		115
Terbium	(24.839 02, 114.836 98)	Foot cave		94
Tin	(23.312 17, 103.093 55)	Gejiu		116
Titanium	(58.333 92, 6.421 22)	Tellnes mine		117
Vegetable_oil	(-15.529 78, −56.093 76)	Bom Futuro Farm	Soybeans are the “dominant biodiesel feedstock” in the US and a popular vegetable oil; it is assumed the oil is imported	118 and 119
Zinc	(68.071 99, −162.876 04)	Red dog mine		110 and 111
Zirconium	(−30.909 26132.220 41)	Iluka's Jacinth-ambrosia mine	Most zirconium comes from zircon	120

Table 8 Sensitivity of mining waste to ±50% variation in ore fraction for selected high-uncertainty materials

Material	Ore fraction range	Mining waste range (kg MW^{-1})	Change in mining waste (%)
Silica (solar)	0.175–0.525	20 000–6667	+100%/−33%
Uranium (nuclear)	0.00105–0.00315	14,285714–4,761,905	+100%/−33%
Neodymium (wind)	0.025–0.075	8640–2880	+100%/−33%

Uncertainty prioritization and sensitivity check

To address data uncertainty, we identified three high-impact variables with limited data availability: silica in solar PV, neodymium in wind turbines, and natural uranium in nuclear power. These materials are characterized by low ore fractions and/or high variability in reported values.

We used a simple one-at-a-time sensitivity approach, varying the ore fraction of each material by ±50%, as the mining waste is calculated using:

$$\text{Mining waste (kg)} = \frac{1}{\text{ore fraction}} \times \text{material required (kg)}$$

This results in a doubling of mining waste when the ore grade is halved. For example, reducing uranium ore grade from 0.21% to 0.105% increases nuclear mining waste from ~7.1 million kg to ~14.3 million kg per MW. Similar impacts were seen for silica and neodymium. While these parameters are uncertain, their variation does not alter the overall trend: wind and solar remain more mining-intensive than nuclear when evaluated on a per-MWh basis due to their low capacity factors and high raw material needs. This suggests that the study's conclusions are robust under plausible input variability (Table 8).

The mining waste was calculated using the formula: mining waste (kg) = material required (kg)/ore fraction. For simplicity, average values were used from Tables 2,3 and 5, assuming 7000 kg of silica, 15 000 kg of uranium, and 216 kg of neodymium per MW installed.

Silica (solar). From Table 2:

• Mass of silica: 7000 kg MW^{-1}.

• Ore fraction: ~35% (*i.e.*, 0.35)

• 50% of Si goes to waste during manufacturing, so only 50% of extracted material is used.

Effective material needed = 7000/(0.35 × 0.50) = 40 000 kg.

Therefore, approx. 20 000 kg waste is produced during manufacturing.

Varying ore fraction by ±50%:

• At 0.175 → 40 000 kg waste.

• At 0.525 → ~13333 kg waste.

• Using simplified 50% of base 14 000 → 6667 kg.

Natural uranium (nuclear). From Table 3:

• Mass of natural uranium = 15 000 kg MW^{-1}.

• Ore fraction = 0.21% = 0.0021.

Mass of waste = (15 000/0.0021) kg ≈ 7,142,857 kg.

Varying ore fraction by ±50%:

• At 0.00105 → ~14,285,714 kg waste.

• At 0.00315 → ~4,761,905 kg waste.

Neodymium (wind). From Table 5:

• Neodymium mass = 216 kg MW^{-1}.

• Ore fraction = 0.05.

Mass of waste = (216/0.05) kg = 4320 kg.

Varying ore fraction by ±50%:

• 0.025 → 8640 kg waste.

• 0.075 → 2880 kg waste.

Results

Cumulative mining needs and waste generation per MW and MWh

The mining volume for fossil-fuel-based systems is related to regular operations, such as fuel materials (Fig. 5a), while the main material needed for renewable systems is related to construction and maintenance materials, such as transformer oils, lubricants, protective coatings, and paints. For nuclear energy, the main material need is fuel, which is based on uranium oxide. Hydropower plants require the most building materials per MW, but need no fuel to spin the turbine. Wind, solar, coal, and nuclear are the next-most construction-material-intensive systems, while natural gas is the least intensive.

In the electricity output (in MWh) (Fig. 5b), wind systems require the most mining volume to build and operate, followed by hydropower and solar power. The capacity factor of wind turbines is 40%, solar is 18%, while hydropower is 52%. Wind power systems require more steel and cement for their foundations compared to hydro and solar power, even in the case of solar power having the lowest capacity factor. Solar power requires more maintenance and operation materials than nuclear and wind power, since the solar power capacity factor is only 18%.

Comparing the capacity and output, the material demand for nuclear energy decreases relative to coal and natural gas for both construction and operation. This is because of the high capacity factor for nuclear energy. Solar and wind, on the other hand, increases for both construction and operation since their capacity factors are low.

The waste-generation streams include operation waste (such as used fuel, coal ash), front-end waste (construction and mining), and back-end waste (decommissioning) (Fig. 5c). Mining wastes dominate wind and solar power generation per MW and MWh. Hydropower plants have more end-of-life waste due to their concrete structures. The mining waste per MW of installed capacity of nuclear power is comparable to that of solar power, and hydropower has no operational waste. Most systems (coal, natural gas, nuclear, and solar) generate a similar

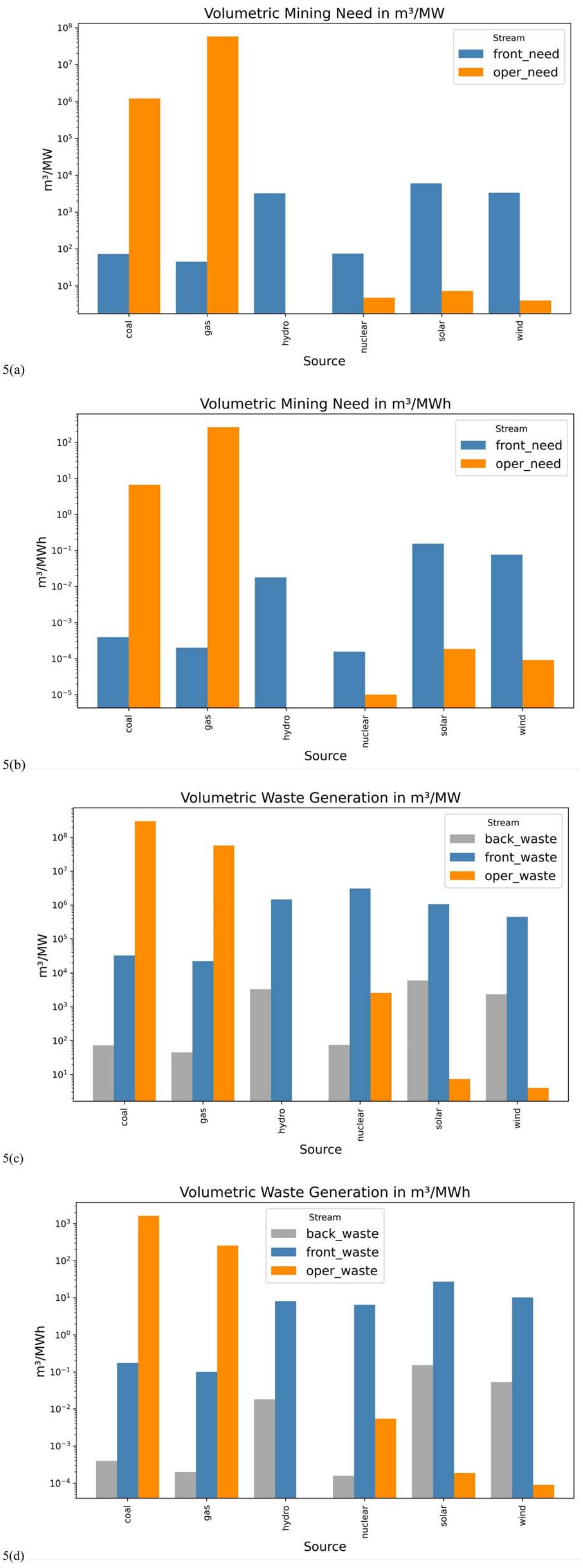

Fig. 5 (a) Total mining need per MW, (b) total mining need per MWh, (c) total volumetric waste generation per MW and (d) total volumetric waste generation per MWh.

amount of decommissioning waste, while wind systems generate the least (with their potentially reusable cement foundations and steel towers), hydro generates the most per MW capacity. Solar power would produce the most mining waste per MW, followed by nuclear and hydropower.

Per MWh of electricity produced (Fig. 5d), the wind has the least operational waste and coal has the most. Solar systems produce the most mining waste, followed by wind, hydroelectric, and nuclear. Hydropower has the most decommissioning waste, followed by solar, coal, nuclear, and wind. Some systems generate more operational or decommissioning waste, while others have heavy raw construction-material mining waste.

Cumulative demand and waste generation

Fig. 6(a) and (b) show how U.S. material need and waste generation have changed over time. Reducing the capacity of coal power plants from 2023 to 2025 could significantly reduce overall material need and waste generation. Despite this, coal is still likely to be the main contributor to material demand and waste generation over the next three decades, making up more than half of all the waste generated. The same is true for natural gas-powered plants, and their share is growing; hence, the material need and waste generation, respectively, are growing. From 2023 to 2025, the material need for wind and solar is the

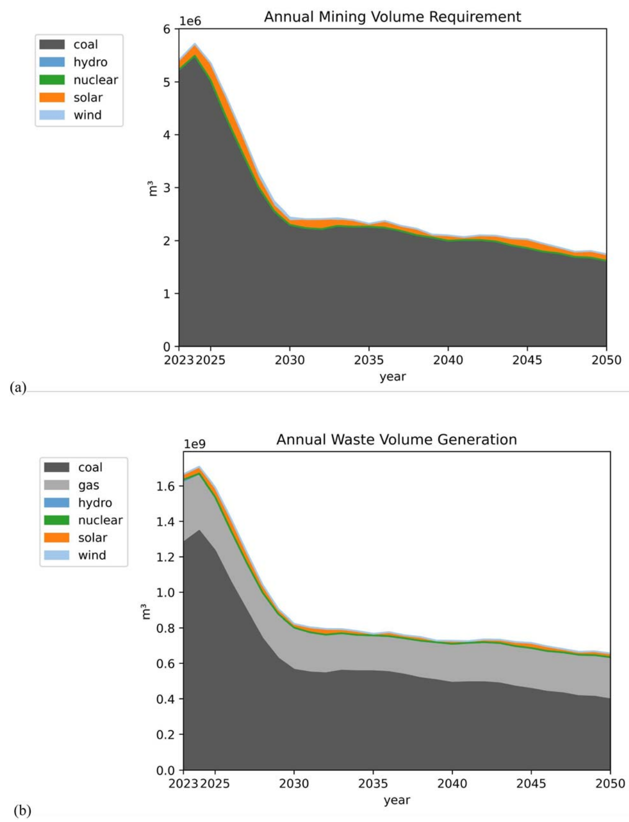

Fig. 6 Temporal evolution of (a) mining volume demand and (b) waste generation for construction and fuel from 2023 to 2050.

highest, with solar responsible for one of the largest shares of waste generated after coal and natural gas-powered plants, generating thousands of tons of mining waste and end-of-life energy system decommissioning waste. As the share of hydroelectric and nuclear power capacities is not expected to change, their material needs and waste generation will also not substantially change over the next three decades.

From its peak in 2024 to the level expected in 2050, annual material demand will fall by 20%. Even though more renewable energy will be used, our analysis (and EIA projections) show that coal power systems will be the biggest polluters. Reducing coal use will cut waste by nearly 28% and material demand by almost 30%. At the same time, the material needs and waste generation of natural gas power plants will be growing the most.

Detailed mining waste and demand per MWh electricity generated

The front-end need (*i.e.*, raw materials) can be further broken down into specific materials or metals (Fig. 7a). Coal, natural gas, and hydropower require commonly available materials such as iron, concrete, Al, and Cu. On the other hand, nuclear,

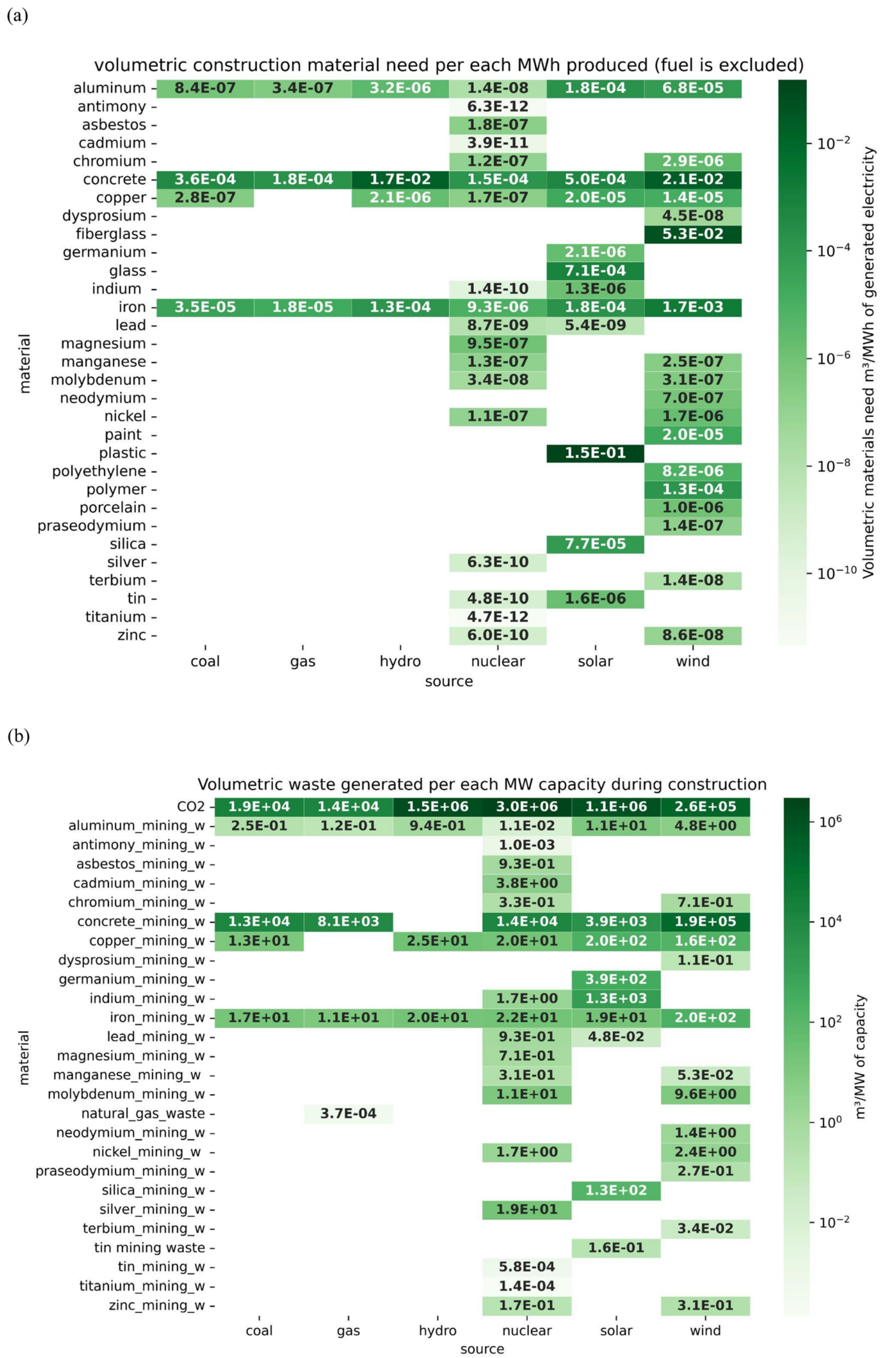

Fig. 7 (a) Material demand (fuel excluded) and (b) mining waste generation per MWh electricity generated.

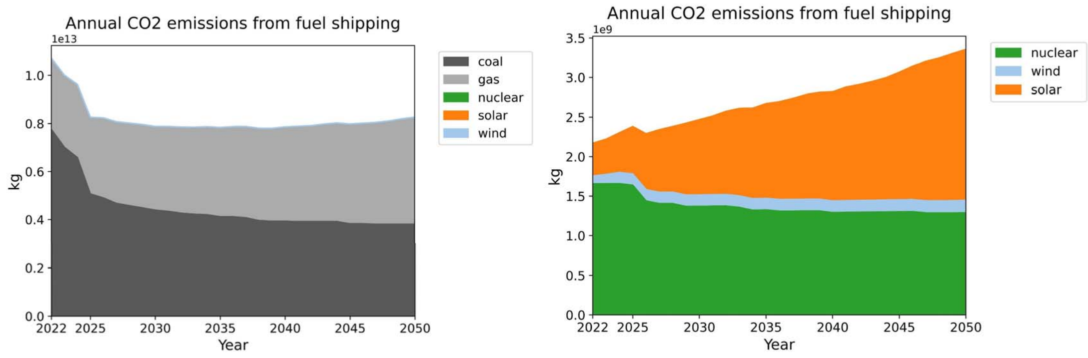

Fig. 8 Temporal evolution of (a) coal and gas, and (b) nuclear, wind and solar along with maintenance materials shipping carbon emissions from 2020 to 2050.

wind, and solar require rare-earth materials, Cr and Ni. Nuclear and wind power require a diverse scope of materials: 18 different metals and minerals. Solar power needs Al, glass, iron, and Te in large amounts. Note that wind power plants require the largest amount of concrete, followed by hydropower plants. Also, wind power requires the largest amount of iron, followed by solar plants. Wind and solar technologies require the largest amounts of Al and Cu. Overall, nuclear systems use less per MWh generated due to their longer lifetimes and capacity factors near 90%. Wind technology uses Mo, Zn, Ni, and Cr at least an order of magnitude more than nuclear.

The above-mentioned factors increase mining waste per MWh generated. The short lifespan and low capacity factor of wind and solar power would make each MWh generated "mining expensive." Fig. 7b shows how much mining waste would be generated by constructing different power systems. Construction of all technologies would emit CO_2; among all technologies, solar and hydropower are the most CO_2 intensive when the fuel component is excluded. The nuclear and wind energy sectors would generate a variety of mining-related wastes because they need a variety of materials. Solar power produces a high amount of mining waste from Cu and Si. Also, materials such as Ge and In are rare in the earth's crust, and to extract them, large amounts of ore must be processed.

Hydropower and wind power would produce the largest amount of concrete mining waste, with wind power producing the most. Wind power would also produce the largest amount of mining waste related to iron and molybdenum extraction.

Shipping emissions

Fig. 8a shows the shipping emissions attributed to the shipping of the fuel, such as coal, nuclear, and gas (it is assumed that it also needs to be transported by trucks), and maintenance materials, such as lubricants, protective coatings, and oils for wind and solar. The role of coal and gas is very important, although the coal capacity is expected to decline by 2025, and as a result, that would significantly reduce the shipping emissions from the electricity generating sector. On the other hand, gas capacity is expected to increase significantly by 2050, increasing the carbon footprint associated with natural gas transportation.

Fig. 8 (b) provides a closer look at the shipping emissions from transporting fuel and maintenance materials for wind, solar, and nuclear electricity generating systems. The growth of solar power systems would impact the need for transformer oil and transmission line fluids such as polyamide, polyester, and polyethylene. In this research, wind turbines only require lubricants. The demand for these materials will also slightly increase until it reaches a constant annual demand amount corresponding to the wind power capacity. The need for fuel for nuclear power plants is expected to decrease, and the capacity of nuclear energy power plants is expected to be reduced in the next several years due to the decommissioning of the existing aging fleet. As the advanced reactor technologies get more mature, we can expect them to be included in future projections.

Discussion

The difference in capacity (MW) and output (MWh) for each of these energy technologies is critical for assessing the life-cycle assessment. Due to external conditions, a power plant cannot run 100% of the time. Hence its actual electricity output will depend on the relative time the power plant operates and its lifespan. They must be considered when calculating their environmental impact. Currently, most policy recommendations focus on increasing the installed capacity of renewable energy and storage increase.[5,122,123] However, the same installed capacity from wind and solar produces much less electricity compared to fossil-based plants or nuclear energy. Our studies have shown that energy generation should be considered when we compare different sources. Also, if the system needs to be replaced every 20 years, we must account for the need to mine every 20 years again to replace it.

Our analysis showed that the energy transition from fossil fuel to low-carbon energy sources would reduce mining and waste, as well as the shipping carbon footprint. Coal and gas produce more mining, operational, and decommissioning waste than others. They are also responsible for the higher shipping emissions to ship fuel to the power plants even though the coal and gas reserves are located within the U.S. Per capacity installed, nuclear power produces more waste than hydro, solar, and wind technologies, but per MWh generated, solar power systems are responsible for more waste than nuclear, wind, and hydropower, due to lower capacity factors (*i.e.*, the smaller number of hours those projects can operate due to weather conditions), and they will also impact shipping emissions. Despite ambitious decarbonization plans in the U.S., the reliance on fossil fuels is still predicted to be high; hence, overall material demand will not significantly change from 2025 to 2050.

Solar and wind—often considered in a similar setting as renewable energy sources—have significantly different material needs and waste mass. Wind turbines need concrete foundations and steel towers to harness the energy from the wind. Solar panels need concrete foundations, silica for the cells, and glass and other metals. Wind power systems have a smaller waste footprint than solar plants because most material-intensive structures can be reused for many lifetimes, such as concrete foundations and steel towers. Also, solar panels use rare elements like germanium and indium, which are not currently recycled and have a low ore content. That being said, germanium and indium mining waste can be reduced if their components are reused and recycled. There is a great interest in recycling these materials because of the expected shortages and the present lack of end-of-life strategies related to solar panels.[122–126] Shipping emissions can also be significantly reduced if materials are recycled or extracted locally. Alongside, the mining of critical minerals becomes significant in the clean energy transition.

Nuclear power is responsible for the least amount of waste per energy generation due to its high capacity factor and longevity of power plants. This also can be greatly improved if (1) the fuel and structural components could be reprocessed and recycled and (2) the lifetime of the power plants could be extended. Various materials are needed to build a nuclear power plant, and some of the needed raw materials are also rare-earth; such needs must be addressed through materials recycling.

This study highlights the need to consider improving the recycling of materials and establishing a circular economy. These points have been raised by previous studies with regard to the materials which will face shortages in the near future.[124–126] Demand and waste generation depend on technology, but concrete, Al, Fe, and Cu are used across the electricity generation sector. These materials are reusable or recyclable. Indeed, recycling and reuse of these materials are needed to support new projects and minimize waste. The overall waste generation will remain an issue until recycling practices can be implemented for all electricity-generating systems. Our study emphasizes the importance of implementing these practices to reduce mining waste and hence reduce overall waste generation.

There are several limitations inherent in this study. Coal and nuclear energy systems tend to have better quantification in various life-cycle assessment studies.[22,23,27] For distributed energy systems like solar and wind energy, rapid technology development may change future material demands and associated waste production. This is also true for the expected recycling rates, since, currently there is no policy on recycling wind and solar systems, nor are there developed decommissioning strategies. Although we assumed certain recycling rates in this paper, there is great uncertainty related to the strategies that will be adopted within the next three decades. At the same time, the depletion of mining reserves may also increase the amount of mining waste, as depleted ores contain smaller fraction of raw materials, while improvement in material processing and recycling may decrease the amount of mining waste. In addition, we also note that the mining waste mass might not be equivalent to environmental impacts and health concerns, since site conditions (such as hydrology) have a significant influence on contaminant transport, release as well as regulatory framework, which can be different for different countries.

Conclusion

We aim this study to highlight commonly ignored or hidden elements—such as mining and decommissioning waste. Although there is some uncertainty (as mentioned above), some material requirements and amount of waste generated by different electricity generating systems are different by more than one order of magnitude, so that such uncertainty may not affect our conclusion. Our study—the first of its kind— suggests the need to quantify the waste volume from energy technologies and include it in the choice of energy sources. Inclusion of these aspects highlights the need for recycling of material, better waste management, and environmental regulation. Although many studies have highlighted the impact of reducing CO_2,[127,128] to the authors' knowledge, this is the first study that investigates the impact of mining and waste as well as shipping emissions from the energy transition.

Data availability

The data files used and code written to obtain final results of this work are available at **https://github.com/drish3/waste_emissions**. Sources of the data files are mentioned in the 'References' section of the submitted work.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This research is made possible by the Jane Lewis Fellowship, the Gateway for Accelerated Innovations in Nuclear internship support, the Nuclear Science and Security Consortium Fellowship, the Undergraduate Fellowship in International Studies Mentorship program, and the Oak Ridge National Laboratory Graduate Summer internship.

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