Geospatial assessment of the cost and energy demand of feedstock grinding for enhanced rock weathering in the coterminous United States

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SUPPORTING INFORMATION

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S1. Net Electricity Generation and Carbon Intensity

Net electricity generation refers to the amount of gross electricity produced by generators minus the electricity used for operating power plants. Total U.S. net electricity generation by the electric power industry (utility-scale electricity generation facilities) in 2018 was 4,178 million megawatthours (MWh) (U.S. Energy Information Administration). Approximately 64% of this electricity generation was from fossil fuels — coal, natural gas, petroleum, and other gases. Nuclear energy consisted of about 19%, and the remaining 17% was derived from renewable energy sources including hydroelectric, solar, and wind.

The state-level net electricity generation for the U.S. in 2018[1] indicates significant spatial heterogeneity in power production, ranging roughly two orders of magnitude from 2.18 million megawatthours (MWh) (Vermont) to 477.35 million MWh (Texas), with a national average of 86.71 million MWh (Figure S1A and Table S1). Most coastal states (e.g., Texas, California, Florida) and states near the Great Lakes region (e.g., Pennsylvania and Illinois) are characterized by relatively high net electricity generation (Figure S1A).

Carbon intensity of grid electricity generation is defined as the ratio of electricity-related CO_2 emissions to electricity produced (in $kgCO_2\ kWh^{-1}$), which provides a measure of life cycle CO_2 emissions to generate a unit of electricity on grid. The carbon intensity estimates presented here use data from electricity-only power plants (electric utility and independent power producer) and exclude combined heat and power (CHP) plants. The U.S. state-level carbon intensity ranges between 0.00 (Vermont) and 0.93 (Wyoming) $kgCO_2\ kWh^{-1}$ with a national average of 0.45 $kgCO_2\ kWh^{-1}$ (Figure S1B and Table S1). States with high carbon intensity (>0.67 $kgCO_2\ kWh^{-1}$) are located at the middle latitudes of the U.S. (e.g., Wyoming, West Virginia, Indiana, etc.), while the states at the northeastern and west coast of the U.S. (e.g., Vermont, Washington, New Hampshire) are characterized by relatively low carbon intensity (<0.22 $kgCO_2\ kWh^{-1}$). Differences in state-level carbon intensity can be ascribed to distinctions in the type of primary energy source and variations in power plant efficiency on a state scale. The CO_2 emission factor for natural gas, coal, and petroleum is 0.41, 1.01, and 0.95 in $kgCO_2\ kWh^{-1}$, respectively[2]. Nuclear power is carbon friendly, and renewable energy sources (biomass, hydroelectric, solar, wind, and geothermal) are carbon neutral. A state with most power plants burning fossil fuels would have a larger carbon intensity compared to those states in which electricity generators are mainly powered by nuclear or renewable energy. In 2018, fossil fuels are the most prevalent energy source for the U.S. electricity generation (the percentage of generating capacity for natural gas and coal is 35% and 28%, respectively), and account for nearly 99% electricity-related CO_2 emissions[3], which aligns with a national average carbon intensity of 0.45 $kgCO_2\ kWh^{-1}$.

S2. Industrial Electricity Price and LCOE of Solar PV

The cost of rock grinding is primarily composed of electricity consumption to power the milling machines. There are two potential pathways to gain electricity, industrial sector of grid and autonomous solar. The tariff of electricity of these two sources are explicitly described and compared.

According to the state electricity profiles published by the U.S. EIA[1], the U.S. industrial electricity price of in 2018 ranges from 4.72 (Washington) to 15.39 (Rhode Island) ¢ kWh^{-1} with a national average value of 7.56 ¢ kWh^{-1} (Figure S1C and Table S1). The geospatial pattern indicates that the states with cheap electricity price are in the southern (e.g., Oklahoma, Louisiana, Texas) and northwestern (e.g., Washington, Montana) regions, while California and a few states at the northeastern (e.g., Rhode Island, Massachusetts, New Hampshire) (Figure S1C). As electricity is secondary energy source, the variations of industrial electricity price by state are regulated by the availability of power plants and fuels, mix of primary energy sources, local fuel costs, and pricing policies.

By defining the country-level estimates for relevant parameters in Equation 1, the regional LCOE of PV is solely related to the geographical distribution of PVOUT. Here PVOUT refers to the Level 2 practical potential that considers land-use constraints due to physical/technical and possible regulatory limitations[4]. The GIS mapping of PVOUT and derived LCOE of PV for the U.S. in 2018 are from Global Solar Atlas 2.0[5]. The state-level LCOE of PV is derived by performing zonal average (a toolset in the Spatial Analyst toolbox) with the ArcGIS software via aggregating the raster data of the U.S. LCOE of PV within the zones defined by the state boundaries (Figure S1D).

Compared to the industrial electricity price, the U.S. LCOE of PV has a smaller spread (8.52-12.33 ¢ kWh^{-1}) but a 42% higher in national average (10.74 ¢ kWh^{-1}) (Figure S1D and Table S1). The geospatial distribution of LCOE of

PV follows that of PVOUT but with an inverse pattern, implying the states with high PVOUT have low LCOE of PV (e.g., New Mexico, Arizona, California, Nevada) (Figure S1D).

S3. Energy Requirement of Feedstock Grinding

Using the fitted work index (Table S2), the grinding energy for product particle size P_{80} of 10, 50, and 100 μm (representing fine, medium, and coarse product grains, respectively) is calculated (Table S3). An order of magnitude increases in feed particle size F_{80} from 300 μm to 3 mm would result in an increase in grinding energy by 15.3%, 47.1%, and 93.5% respectively for product particle size P_{80} of 10, 50, and 100 μm (Table S3), which implies the growing impact of feed particle size on the energy requirement with the increasing product particle size.

The energy requirement of feedstock grinding yielded from our parameterization falls within the estimate of 10-316 kWh t_{rock}^{-1} for a range of product particle sizes (converted from surface area)[6]. Strefler et al.[7] estimates the electricity demands of grinding to produce 10 and 50 μm particles are 127.78 (with lower bound of 47.22 and upper bound of 333.33) kWh t_{rock}^{-1} and 19.44 (with lower bound of 5.56 and upper bound of 66.67) kWh t_{rock}^{-1}, respectively. In comparison, the energy input calculated from our parameterization is lower for product particle size of 10 μm but slightly higher for 50 μm (both lie within the range of estimates given by Ref. [7]).

S4. Impact of Feed Particle Size (F_{80})

Since feed particle size has equal importance as product particle size in determining grinding energy according to the Bond law, a 'coarse aggregate' scenario (F_{80} = 3 mm) is analyzed and compared with the default 'waste fine' scenario (F_{80} = 300 μm). The two representative feed particle sizes denote two types of initial feedstocks, silicate wastes ('waste fine') and basic rocks ('coarse aggregate') respectively, both of which have a high carbon capture potential for ERW.

We comprehensively evaluate the impacts of two feed particle sizes on carbon footprint, cost, and energy demand. For comparative assessment, product particle size P_{80} is kept constant at 50 μm. As for the 'coarse aggregate' scenario, the national average of carbon footprint, energy demand percentage, electricity cost of grinding on the grid and on autonomous solar PV is 16.31 (0.08-34.00) $kgCO_2\ t_{rock}^{-1}$, 12.41 (0.77-58.71) $\times 10^{-2}$ % Mt_{rock}^{-1}, 2.77 (1.73-5.64) \$ t_{rock}^{-1}, and 3.94 (3.12-4.52) \$ t_{rock}^{-1} (Table S8), respectively, which amounts to ca. 47.2% increase relative to the 'waste fine' scenario (Figure S2). The rise in carbon footprint and electricity demand associated with an order of magnitude increase in feed particle size cannot be differentiated from state-to-state variations, but only raising their upper bounds (Figure S2A- B). On the contrary, the impact of feed particle size on grinding cost is more statistically significant compared to the spatial variability, which is attributed to the less dispersion of state-level electricity price. Especially the cost of grinding powered by solar PV can clearly distinguish itself between the two feed particle size scenarios (Figure S2D). These signatures suggest that feed particle size should be considered together with locality for the prioritization of grinding practices in the U.S.

A thorough investigation of energy and economic impacts of feed particle size is of great relevance for the strategic rollout of ERW in the U.S., which is ascribed to the distinctions in the two initial feedstocks. Silicate waste fines (also referred as artificial silicates which are produced during industrial processes) include construction and demolition (C&D) waste, iron and steel slag, cement kiln dust, and so on[6, 8]. The fine particle size of silicate waste[9] provides energy and cost saving for grinding and a high CDR potential due to highly reactive surfaces, which renders silicate waste an ideal feedstock for ERW. Despite of these advantages, the sustainable ERW implementation with the use of silicate waste depends on the production capacity. The 2018 annual production of C&D debris in the U.S. is 600 Mt (more than 90% is demolition)[10], constituting the largest proportion of silicate waste generation. The total production of iron and steel slags in 2018 for the U.S. is 16.8 Mt (~3% global production), with blast furnace slag production of 6-7 Mt and steel furnace slag accounted for the remainder[11]. Assuming 115 kg of cement kiln dust is produced as a by-product per tonne of clinker generation[12], the U.S. production of cement kiln dust in 2018 is estimated to be 8.9 Mt with annual production of clinker being 77.1 Mt[13]. Taken together, the U.S. annual production of fine silicate waste is ca. 0.6 Gt in 2018, and is projected to reach about ~1.7 Gt yr^{-1} by 2100[12]. To achieve the U.S. national targets for net-zero carbon emissions by 2050, around 8% of the overall emissions reduction (roughly 6.5 $GtCO_2\ yr^{-1}$) should be covered by CDR technologies[14], which amounts to 0.5 $GtCO_2\ yr^{-1}$ (equivalent to feedstock of 1.7 Gt yr^{-1} assuming the basaltic CO_2 sequestration potential of 0.3 $tCO_2\ t_{rock}^{-1}$). Basalt ('coarse aggregate') extraction is likely to be required to fill the demand vacancy of feedstock for ERW, if other CDR technologies (e.g., DACCS or BECCS) are unable to capture enough amount of CO_2, or too uncompetitive to be undertaken.

Table S1. Parameters fitted in the derivation of relationships between grinding energy, specific surface area, and particle size.

State	**Net electricity generation**[a] [MWh]	**Carbon intensity**[a] [kgCO$_2$ kWh^{-1}]	**Industrial electricity price**[a] [¢ kWh^{-1}]	**LCOE of PV**[b] [¢ kWh^{-1}]
AL	145057994	0.40	6.01	10.49
AR	67999352	0.58	5.64	10.64
AZ	111925144	0.42	6.55	8.55
CA	195265408	0.21	13.20	8.91
CO	55386279	0.63	7.47	9.30
CT	39453552	0.23	13.77	11.23
DE	6240644	0.50	7.95	10.93
FL	244252035	0.44	7.65	10.07
GA	129239371	0.42	6.00	10.33
IA	63380569	0.48	6.45	10.92
ID	18172120	0.07	6.47	10.71
IL	188003357	0.36	6.80	11.15
IN	113459711	0.87	7.38	11.44
KS	51710213	0.45	7.60	9.90
KY	78804497	0.84	5.68	11.34
LA	102128485	0.50	5.35	10.50
MA	27172882	0.37	14.89	11.34
MD	43809648	0.42	8.23	11.10
ME	11280700	0.17	9.32	11.94
MI	115837095	0.59	7.10	12.19
MN	61517441	0.47	7.52	11.29
MO	85095384	0.77	7.22	10.77
MS	63473771	0.42	6.00	10.51
MT	28212831	0.56	5.19	10.84
NC	13424947	0.37	6.33	10.52
ND	42615321	0.72	7.98	10.68
NE	36966216	0.66	7.60	10.11
NH	17087156	0.12	13.42	11.77
NJ	75033600	0.27	10.07	11.22
NM	32673682	0.56	5.84	8.52
NV	39640241	0.37	6.10	9.00
NY	132520501	0.22	6.02	12.25
OH	126184610	0.61	7.01	11.87
OK	86223721	0.40	5.34	9.99
OR	64113560	0.15	5.86	10.79

Table S1. continued

State	**Net electricity generation**[a] [MWh]	**Carbon intensity**[a] [kgCO$_2$ kWh^{-1}]	**Industrial electricity price**[a] [¢ kWh^{-1}]	**LCOE of PV**[b] [¢ kWh^{-1}]
PA	215385830	0.37	6.84	12.12
RI	8375257	0.39	15.39	11.12
SC	99364088	0.29	6.10	10.33
SD	12616396	0.23	7.77	10.44
TN	81554917	0.33	5.68	10.97
TX	477352425	0.52	5.39	9.80
UT	39375424	0.73	5.90	9.27
VA	95509121	0.34	6.86	10.87
VT	2178915	0.00	10.66	12.21
WA	116756729	0.09	4.72	12.33
WI	65936803	0.62	7.33	11.49
WV	67249025	0.91	6.40	11.89
WY	46112136	0.93	6.71	9.74

[a] The net electricity generation, carbon intensity, and industrial electricity price data are from EIA (2019b).
[b] The state-level LCOE of PV data are calculated based on Solargis (2020).

Table S2. Parameters fitted in the derivation of relationships between grinding energy, specific surface area, and particle size.

Parameters	**a_1**	**b_1**	**c_1**	**b_2**	**c_2**	W_i [kWh t_{rock}^{-1}]
Best fit	8.062	-19.30	75.03	-4.48	11.58	29.75
Upper 95% bound	11.13	15.34	146.70	-3.66	12.41	30.20
Lower 5% bound	4.994	-53.94	3.32	-5.29	10.74	29.29

Table S3. Energy requirement of grinding (in kWh t_{rock}^{-1}) for different product (P_{80}) and feed (F_{80}) particle sizes[a].

	F_{80} = 300 μm	**F_{80} = 3 mm**
P_{80} = 10 μm	76.90	88.65
P_{80} = 50 μm	24.90	36.64
P_{80} = 100 μm	12.57	24.32

[a] The values for energy requirement are calculated from the Bond law (Equation 4) with the fitted work index (W_i = 29.75 kWh t_{rock}^{-1}).

Table S4. Carbon footprint of grinding (in kgCO$_2$ t$_{rock}^{-1}$) powered by the grid for U.S. states in 2018. The feed particle size F$_{80}$ is 300 µm ('waste fine' scenario). The values for product particle size P$_{80}$ of 10, 50, and 100 µm are shown.

State	**P$_{80}$ = 10 µm**	**P$_{80}$ = 50 µm**	**P$_{80}$ = 100 µm**
AL	30.58	9.90	5.00
AR	44.33	14.35	7.25
AZ	32.12	10.40	5.25
CA	16.04	5.20	2.62
CO	48.23	15.61	7.89
CT	17.87	5.79	2.92
DE	38.69	12.53	6.33
FL	34.20	11.07	5.59
GA	32.44	10.50	5.30
IA	36.65	11.86	5.99
ID	5.66	1.83	0.93
IL	27.70	8.97	4.53
IN	67.12	21.73	10.98
KS	34.98	11.32	5.72
KY	64.87	21.00	10.61
LA	38.50	12.46	6.29
MA	28.22	9.14	4.61
MD	31.97	10.35	5.23
ME	12.91	4.18	2.11
MI	45.18	14.63	7.39
MN	35.88	11.62	5.87
MO	59.31	19.20	9.70
MS	32.14	10.41	5.26
MT	42.68	13.82	6.98
NC	28.14	9.11	4.60
ND	55.58	17.99	9.09
NE	50.86	16.47	8.32
NH	9.60	3.11	1.57
NJ	20.90	6.77	3.42
NM	43.43	14.06	7.10
NV	28.70	9.29	4.69
NY	16.93	5.48	2.77
OH	47.21	15.28	7.72
OK	30.73	9.95	5.02
OR	11.18	3.62	1.83
PA	28.30	9.16	4.63

Table S4. continued

State	**P_{80} = 10 μm**	**P_{80} = 50 μm**	**P_{80} = 100 μm**
RI	29.86	9.67	4.88
SC	22.49	7.28	3.68
SD	17.80	5.76	2.91
TN	25.20	8.16	4.12
TX	40.07	12.97	6.55
UT	55.83	18.08	9.13
VA	26.06	8.44	4.26
VT	0.18	0.06	0.03
WA	6.80	2.20	1.11
WI	48.06	15.56	7.86
WV	69.93	22.64	11.43
WY	71.36	23.10	11.67

Table S5. Cost of grinding (in $ t_{rock}^{-1}) powered by the grid or autonomous solar PV for U.S. states in 2018. The feed particle size F_{80} is 300 μm ('waste fine' scenario). The values for product particle size P_{80} of 10, 50, and 100 μm are shown.

State	**P_{80} = 10 μm** grid | PV	**P_{80} = 50 μm** grid | PV	**P_{80} = 100 μm** grid | PV
AL	4.62 | 8.06	1.50 | 2.61	0.76 | 1.32
AR	4.34 | 8.18	1.40 | 2.65	0.71 | 1.34
AZ	5.04 | 6.58	1.63 | 2.13	0.82 | 1.08
CA	10.15 | 6.85	3.29 | 2.22	1.66 | 1.12
CO	5.74 | 7.15	1.86 | 2.32	0.94 | 1.17
CT	10.59 | 8.63	3.43 | 2.80	1.73 | 1.41
DE	6.11 | 8.40	1.98 | 2.72	1.00 | 1.37
FL	5.88 | 7.75	1.90 | 2.51	0.96 | 1.27
GA	4.61 | 7.94	1.49 | 2.57	0.75 | 1.30
IA	4.96 | 8.40	1.61 | 2.72	0.81 | 1.37
ID	4.98 | 8.24	1.61 | 2.67	0.81 | 1.35
IL	5.23 | 8.57	1.69 | 2.78	0.86 | 1.40
IN	5.68 | 8.79	1.84 | 2.85	0.93 | 1.44
KS	5.84 | 7.62	1.89 | 2.47	0.96 | 1.25
KY	4.37 | 8.72	1.41 | 2.82	0.71 | 1.43
LA	4.11 | 8.07	1.33 | 2.61	0.67 | 1.32
MA	11.45 | 8.72	3.71 | 2.82	1.87 | 1.43
MD	6.33 | 8.54	2.05 | 2.76	1.03 | 1.40
ME	7.17 | 9.18	2.32 | 2.97	1.17 | 1.50
MI	5.46 | 9.38	1.77 | 3.04	0.89 | 1.53
MN	5.78 | 8.68	1.87 | 2.81	0.95 | 1.42
MO	5.55 | 8.28	1.80 | 2.68	0.91 | 1.35
MS	4.61 | 8.08	1.49 | 2.62	0.75 | 1.32
MT	3.99 | 8.34	1.29 | 2.70	0.65 | 1.36
NC	4.87 | 8.09	1.58 | 2.62	0.80 | 1.32
ND	6.14 | 8.21	1.99 | 2.66	1.00 | 1.34
NE	5.84 | 7.78	1.89 | 2.52	0.96 | 1.27
NH	10.32 | 9.05	3.34 | 2.93	1.69 | 1.48
NJ	7.74 | 8.63	2.51 | 2.79	1.27 | 1.41
NM	4.49 | 6.55	1.45 | 2.12	0.73 | 1.07
NV	4.69 | 6.92	1.52 | 2.24	0.77 | 1.13
NY	4.63 | 9.42	1.50 | 3.05	0.76 | 1.54
OH	5.39 | 9.13	1.75 | 2.96	0.88 | 1.49
OK	4.11 | 7.68	1.33 | 2.49	0.67 | 1.26
OR	4.51 | 8.30	1.46 | 2.69	0.74 | 1.36

Table S5. continued

State	**P_{80} = 10 μm** grid | PV	**P_{80} = 50 μm** grid | PV	**P_{80} = 100 μm** grid | PV
PA	5.26 | 9.32	1.70 | 3.02	0.86 | 1.52
RI	11.84 | 8.55	3.83 | 2.77	1.94 | 1.40
SC	4.69 | 7.94	1.52 | 2.57	0.77 | 1.30
SD	5.98 | 8.03	1.93 | 2.60	0.98 | 1.31
TN	4.37 | 8.43	1.41 | 2.73	0.71 | 1.38
TX	4.14 | 7.53	1.34 | 2.44	0.68 | 1.23
UT	4.54 | 7.13	1.47 | 2.31	0.74 | 1.17
VA	5.28 | 8.36	1.71 | 2.71	0.86 | 1.37
VT	8.20 | 9.39	2.65 | 3.04	1.34 | 1.54
WA	3.63 | 9.48	1.18 | 3.07	0.59 | 1.55
WI	5.64 | 8.84	1.82 | 2.86	0.92 | 1.45
WV	4.92 | 9.15	1.59 | 2.96	0.80 | 1.50
WY	5.16 | 7.49	1.67 | 2.43	0.84 | 1.22

Table S6. Energy demand percentage of grinding (in ×10^{-2}% Mt_{rock}^{-1}) powered by the grid for U.S. states in 2018. The feed particle size F_{80} is 300 µm ('waste fine' scenario). The values for product particle size P_{80} of 10, 50, and 100 µm are shown.

State	**P_{80} = 10 µm**	**P_{80} = 50 µm**	**P_{80} = 100 µm**
AL	5.30	1.72	0.87
AR	11.31	3.66	1.85
AZ	6.87	2.22	1.12
CA	3.94	1.28	0.64
CO	13.88	4.50	2.27
CT	19.49	6.31	3.19
DE	123.23	39.89	20.15
FL	3.15	1.02	0.51
GA	5.95	1.93	0.97
IA	12.13	3.93	1.98
ID	42.32	13.70	6.92
IL	4.09	1.32	0.67
IN	6.78	2.19	1.11
KS	14.87	4.81	2.43
KY	9.76	3.16	1.60
LA	7.53	2.44	1.23
MA	28.30	9.16	4.63
MD	17.55	5.68	2.87
ME	68.17	22.07	11.15
MI	6.64	2.15	1.09
MN	12.50	4.05	2.04
MO	9.04	2.93	1.48
MS	12.12	3.92	1.98
MT	27.26	8.82	4.46
NC	57.28	1.85	0.94
ND	18.05	5.84	2.95
NE	20.80	6.73	3.40
NH	45.01	14.57	7.36
NJ	10.25	3.32	1.68
NM	23.54	7.62	3.85
NV	19.40	6.28	3.17
NY	58.03	1.88	0.95
OH	60.94	1.97	1.00
OK	89.19	2.89	1.46
OR	11.99	3.88	1.96

Table S6. continued

State	**P_{80} = 10 μm**	**P_{80} = 50 μm**	**P_{80} = 100 μm**
PA	3.57	1.16	0.58
RI	91.82	29.73	15.01
SC	7.74	2.51	1.27
SD	60.95	19.73	9.97
TN	9.43	3.05	1.54
TX	1.61	0.52	0.26
UT	19.53	6.32	3.19
VA	8.05	2.61	1.32
VT	352.90	114.26	57.51
WA	6.59	2.13	1.08
WI	11.66	3.78	1.91
WV	11.44	3.70	1.87
WY	16.68	5.40	2.73

Table S7. The time-series forecasts (2018-2050) of U.S. total electricity generation (in GWh), industrial electricity price (in ¢ kWh^{-1}), and electricity demand percentage of grinding (in % Gt$_{rock}^{-1}$) for product particle size P_{80} of 10, 50, and 100 μm. The feed particle size F_{80} is 300 μm ('waste fine' scenario) for the electricity demand calculations.

Year	**Total electricity generation**[a] [GWh]	**Industrial electricity price**[a] [¢ kWh^{-1}]	**Electricity demand percentage** (P_{80} = 10 | 50 | 100 μm)
2018	4178277	7.0	1.8405 | 0.5959 | 0.3008
2019	4127855	6.8	1.8630 | 0.6032 | 0.3045
2020	4007135	6.7	1.9191 | 0.6214 | 0.3137
2021	4115540	7.3	1.8686 | 0.6050 | 0.3054
2022	4235380	7.4	1.8157 | 0.5879 | 0.2968
2023	4334800	7.1	1.7740 | 0.5744 | 0.2900
2024	4364310	6.9	1.7620 | 0.5705 | 0.2880
2025	4400250	6.8	1.7476 | 0.5659 | 0.2857
2026	4428470	6.7	1.7365 | 0.5623 | 0.2838
2027	4449660	6.7	1.7282 | 0.5596 | 0.2825
2028	4471720	6.7	1.7197 | 0.5568 | 0.2811
2029	4498480	6.7	1.7095 | 0.5535 | 0.2794
2030	4520600	6.7	1.7011 | 0.5508 | 0.2781
2031	4549920	6.8	1.6901 | 0.5473 | 0.2763
2032	4579460	6.8	1.6792 | 0.5437 | 0.2745
2033	4609580	6.8	1.6683 | 0.5401 | 0.2727
2034	4641130	6.8	1.6569 | 0.5365 | 0.2708
2035	4679500	6.7	1.6433 | 0.5321 | 0.2686
2036	4721610	6.7	1.6287 | 0.5274 | 0.2662
2037	4767850	6.7	1.6129 | 0.5222 | 0.2636
2038	4815110	6.6	1.5971 | 0.5171 | 0.2611
2039	4860410	6.6	1.5822 | 0.5123 | 0.2586
2040	4903020	6.6	1.5684 | 0.5079 | 0.2564
2041	4952060	6.6	1.5529 | 0.5028 | 0.2538
2042	5003250	6.5	1.5370 | 0.4977 | 0.2512
2043	5055110	6.5	1.5212 | 0.4926 | 0.2487
2044	5106860	6.5	1.5058 | 0.4876 | 0.2461
2045	5161540	6.4	1.4899 | 0.4824 | 0.2435
2046	5215730	6.4	1.4744 | 0.4774 | 0.2410
2047	5269610	6.4	1.4593 | 0.4725 | 0.2385
2048	5322140	6.4	1.4449 | 0.4679 | 0.2362
2049	5380160	6.4	1.4293 | 0.4628 | 0.2336
2050	5445820	6.3	1.4121 | 0.4572 | 0.2308

Table S8. The grinding information (carbon footprint, energy demand percentage, and grinding costs operated on the grid and autonomous solar PV) of 'coarse aggregate' scenario (F_{80} = 3 mm) for U.S. states in 2018. The product particle size P_{80} is 50 μm.

State	**Carbon footprint** [kgCO$_2$ t$_{rock}^{-1}$]	**Energy demand** [×10^{-2}% Mt$_{rock}^{-1}$]	**Cost (grid)** [\$ t$_{rock}^{-1}$]	**Cost (solar PV)** [\$ t$_{rock}^{-1}$]
AL	14.56	2.53	2.20	3.84
AR	21.12	5.39	2.07	3.90
AZ	15.31	3.27	2.40	3.13
CA	7.65	1.88	4.84	3.27
CO	22.98	6.62	2.74	3.41
CT	8.51	9.29	5.05	4.11
DE	18.43	58.71	2.91	4.00
FL	16.30	1.50	2.80	3.69
GA	15.46	2.84	2.20	3.78
IA	17.46	5.78	2.36	4.00
ID	2.70	20.16	2.37	3.92
IL	13.20	1.95	2.49	4.08
IN	31.98	3.23	2.70	4.19
KS	16.67	7.09	2.78	3.63
KY	30.91	4.65	2.08	4.15
LA	18.34	3.59	1.96	3.85
MA	13.45	13.48	5.46	4.16
MD	15.23	8.36	3.02	4.07
ME	6.15	32.48	3.41	4.38
MI	21.53	3.16	2.60	4.47
MN	17.09	5.96	2.76	4.14
MO	28.26	4.31	2.65	3.95
MS	15.32	5.77	2.20	3.85
MT	20.34	12.99	1.90	3.97
NC	13.41	2.73	2.32	3.85
ND	26.48	8.60	2.92	3.91
NE	24.23	9.91	2.78	3.70
NH	4.58	21.44	4.92	4.31
NJ	9.96	4.88	3.69	4.11
NM	20.69	11.21	2.14	3.12
NV	13.68	9.24	2.24	3.30
NY	8.07	2.76	2.21	4.49
OH	22.50	2.90	2.57	4.35
OK	14.64	4.25	1.96	3.66
OR	5.33	5.72	2.15	3.96

Table S8. continued

State	**Carbon footprint** [kgCO$_2$ t$_{rock}^{-1}$]	**Energy demand** [×10^{-2}% Mt$_{rock}^{-1}$]	**Cost (grid)** [$ t$_{rock}^{-1}$]	**Cost (solar PV)** [$ t$_{rock}^{-1}$]
PA	13.48	1.70	2.51	4.44
RI	14.23	43.75	5.64	4.07
SC	10.71	3.69	2.24	3.78
SD	8.48	29.04	2.85	3.83
TN	12.01	4.49	2.08	4.02
TX	19.09	0.77	1.97	3.59
UT	26.60	9.31	2.16	3.40
VA	12.42	3.84	2.51	3.98
VT	0.08	168.16	3.91	4.48
WA	3.24	3.14	1.73	4.52
WI	22.90	5.56	2.69	4.21
WV	33.32	5.45	2.35	4.36
WY	34.00	7.95	2.46	3.57

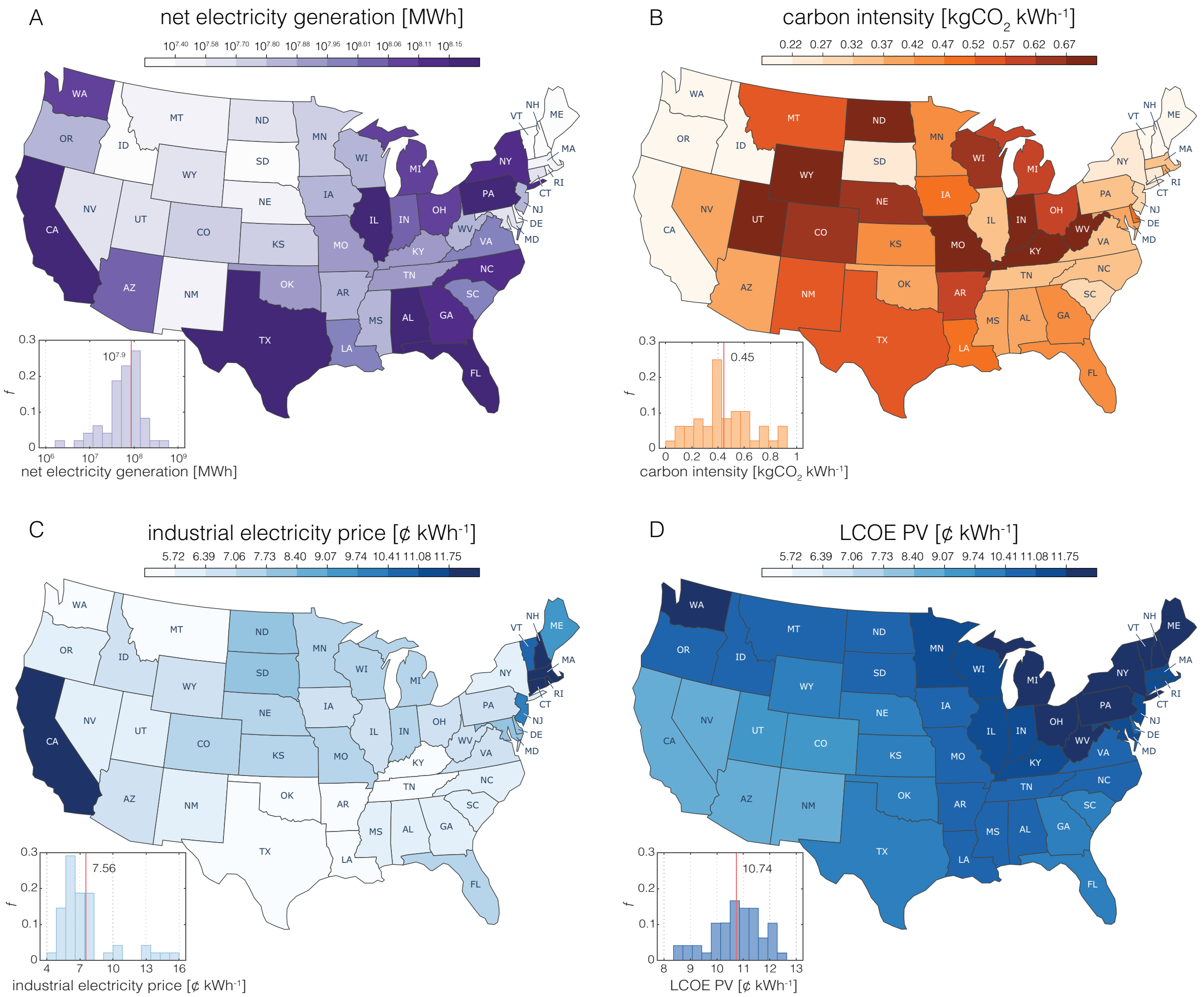

Figure S1. State-level U.S. map (2018) of input data used in our pipeline for estimating cost, carbon intensity, and energy demand for feedstock grinding in ERW. (A) Net electricity generation (in MWh). (B) Carbon intensity of grid electricity generation (in kgCO_2 kWh^{-1}). (C) Industrial electricity price (in ¢ kWh^{-1}). (D) Levelized cost of energy (LCOE) for solar photovoltaic (PV) power (in ¢ kWh^{-1}). The statistical distribution of each parameter for the U.S. is shown in the corresponding histogram at the bottom left corner of each panel, with the national average value indicated by the red vertical line.

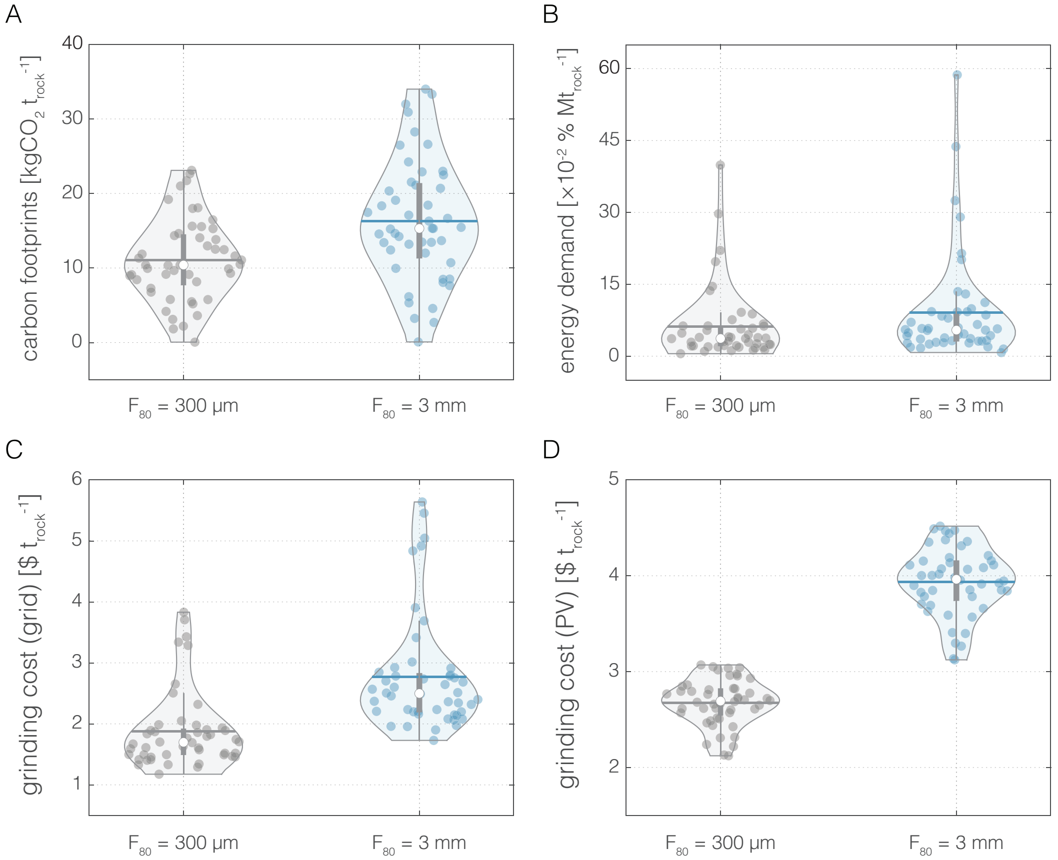

Figure S2. Violin plots showing the impact of feed particle size F_{80} (300 μm for 'waste fine' scenario and 3 mm for 'coarse aggregate' scenario) on the grinding in the U.S. (A) Carbon footprints of grinding on the grid (in kgCO$_2$ t$_{rock}^{-1}$). (B) Energy demand percentage of grinding on the grid (in ×10^{-2}% Mt$_{rock}^{-1}$). (C) Cost of grinding on the grid (in $ t$_{rock}^{-1}$). (D) Cost of grinding powered by solar PV (in $ t$_{rock}^{-1}$). The horizontal lines (dark grey and dark blue) and void circles are mean and average values, respectively. The vertical grey bars within violins denote the interquartile range (IQR) with the vertical line segments representing 1.5× IQR. The edge of a violin is a kernel density estimation displaying the distribution shape of the values. The product particle size P_{80} is 50 μm for all four panels.

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