Supplementary Information for

Life cycle climate performance of urban plant factory versus rural greenhouse under China's power-grid decarbonization: considering short-lived methane and nitrous oxide emissions

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Table. S1 Summarized materials inputs and uncertainties for the lettuce cultivation by the sunlight greenhouse.

Process	Quantitative reference	Inputs	Units	Mean	Triangle distribution (Likeliest)	Triangle distribution (Minimum)	Triangle Distribution (Maximum)	Lognormal distribution (Geometric mean)	Lognormal distribution (Geometric standard deviation)	References
Process 1	Seedlings	Seeds	g kg^{-1}	0.0375						[1]
	Seedlings	Organic fertilizer [a]	g kg^{-1}	28.500	36.750	17.500	56.000	25.178	1.711	[1, 2]
	Seedlings	Superphosphate	g kg^{-1}	0.838	1.150	1.050	1.250	1.113	1.106	[1, 2]
	Seedlings	Ammonium sulfate	g kg^{-1}	0.188	0.375	0.000	0.750			[2]
	Seedlings	Potassium chloride	g kg^{-1}	0.125	0.250	0.000	0.500			[2]
	Seedlings	NPK [b]	g kg^{-1}	3.125	6.250	0.000	12.500			[2]
	Seedlings	Irrigation water [c]	g kg^{-1}	0.001	0.002	0.001	0.003	0.001	2.012	[3-6]
Process 2	Lettuces	Seedlings	Item kg^{-1}	3750						[1]
	Lettuces	Organic fertilizer [a]	g kg^{-1}	452.000	562.500	375.000	750.000	432.650	1.365	[1-2, 7]
	Lettuces	Superphosphate	g kg^{-1}	9.000	22.500	0.000	45.000			[2]
	Lettuces	NPK [b]	g kg^{-1}	28.200	35.500	0.000	71.000	70.498	1.010	[1]
	Lettuces	Potassium chloride	g kg^{-1}	6.000	15.000	0.000	30.000			[2]
	Lettuces	Ammonium sulfate	g kg^{-1}	7.000	17.500	0.000	35.000			[2]
	Lettuces	Diammonium phosphate	g kg^{-1}	3.000	7.500	0.000	15.000			[7]
	Lettuces	Urea	g kg^{-1}	13.200	14.500	0.000	29.000	12.710	2.384	[1-2, 7]
	Lettuces	Potassium sulfate	g kg^{-1}	5.000	12.500	0.000	25.000			[7]
	Lettuces	Irrigation water [c]	g kg^{-1}	0.035	0.046	0.010	0.083	0.028	2.012	[3-6]
	Lettuces	Polyethylene	g kg^{-1}	0.012	0.013	0.004	0.021			[8-10]

[a] Nutrients of organic fertilizer were converted into standard N, P_2O_5, and K_2O with a mass content of 2.13%, 3.29%, and 1.98%, respectively[11-14].

[b] Compound fertilizer with N, P_2O_5, and K_2O equaling 15%.

[c] Area method was used to allocate the total volume of irrigation water into process 1 and process 2 with a ratio of 1:27.

Table. S2 N_2O emission factor for vegetable production in nitrogen fertilizer application (%).

	Organic N fertilizer	Uncertainty	Mineral N fertilizer	Uncertainty	References
G_1	1.0	1.3-1.9	1.0	1.3-1.9	15
G_2	0.65	0.52-0.81	0.65	0.52-0.81	16
G_3	0.26	±1.05	1.28	±0.55	17

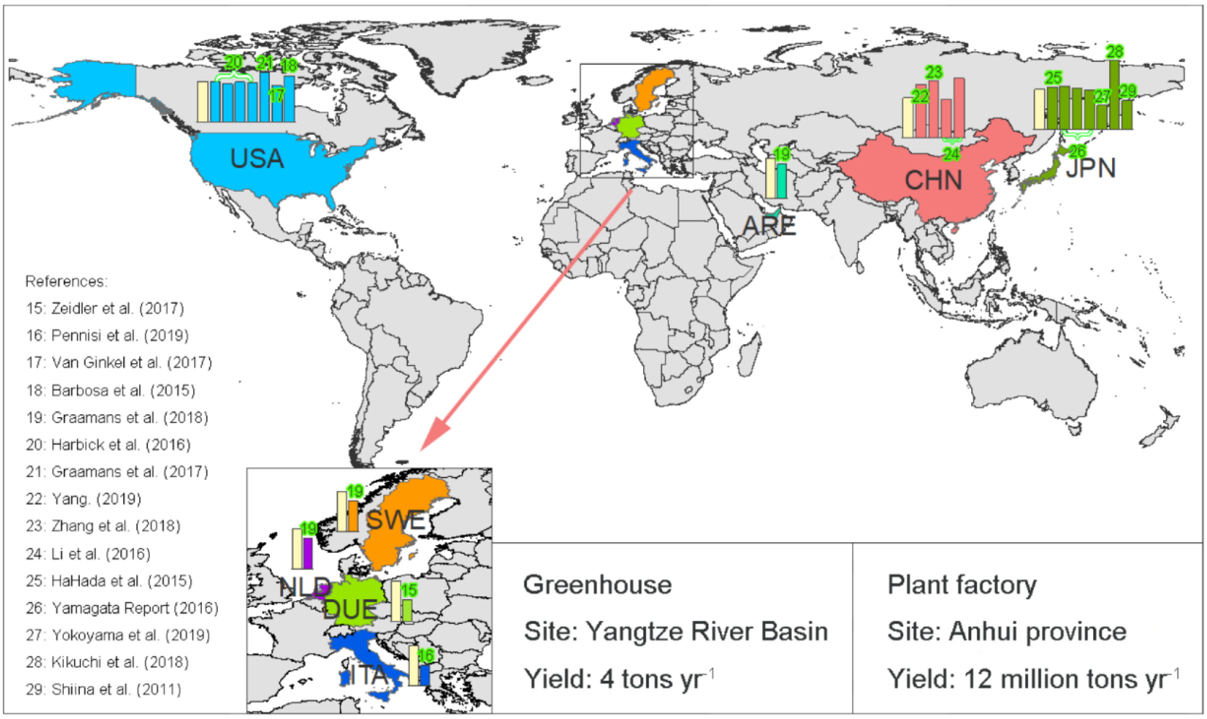

Figure. S1 Reviewed electricity consumption of one kilograms of lettuce by plant factories across economies. The two cases of greenhouse and plant factory locate in southern China.

Table. S3 Materials and energy inputs and uncertainties to produce one kilogram of lettuce by plant factory.

Process	Quantitative reference	Inputs	Units	Mean	Triangle distribution Likeliest (min, max)	Lognormal distribution Geometric mean (sd)	References
Process 1	Seedlings	Seed	g/kg	0.105	-	-	SANANBIO
	Seedlings	Polyurethane	g/kg	2.170	2.15 (2.0, 2.3)	-	SANANBIO
	Seedlings	Tap water a	kg/kg	2.456	3.304 (0.11, 6.5)	1.166 (4.77)	[18-22]
	Seedlings	Electricity a	kWh/kg	1.535	1.729 (0.77, 2.69)	1.405 (1.366)	Table S4
Process 2	Lettuces	Seedlings	item/kg	10.530	-	-	SANANBIO
	Lettuces	Calcium nitrate	g/L	0.446	0.61 (0.22, 1.0)	0.390 (1.699)	[25, 33-37]
	Lettuces	Potassium sulfate	g/L	0.176	0.53 (0.06, 1.0)	0.217 (4.147)	[25, 33, 35]
	Lettuces	Magnesium nitrate	g/L	0.214	0.75 (0.0, 1.5)	-	[33]
	Lettuces	Potassium nitrate	g/L	0.324	0.35 (0.10, 0.6)	0.283 (1.814)	[25, 33-37]
	Lettuces	Ammonium phosphate	g/L	0.071	0.25 (0, 0.5)	-	[33]
	Lettuces	Magnesium sulfate	g/L	0.119	0.155 (0.06, 0.25)	0.127 (1.593)	[25, 34-37]
	Lettuces	Diammonium hydrogen phosphate	g/L	0.030	0.105 (0.06, 0.15)	0.095 (1.912)	[25, 37]
	Lettuces	Ammonium dihydrogen phosphate	g/L	0.009	0.03 (0, 0.06)	-	[34]
	Lettuces	Ammonium nitrate	g/L	0.017	0.06 (0.04, 0.08)	0.057 (1.633)	[34]
	Lettuces	Potassium dihydrogen phosphate	g/L	0.059	0.135 (0.1, 0.17)	0.134 (1.308)	[25, 35, 36]
	Lettuces	Potassium chloride	g/L	0.021	0.075 (0, 0.15)	-	[37]
	Lettuces	Tap water[a]	kg/kg	32.624	43.896 (1.49, 86.3)	16.260 (4.770)	[18-22]
	Lettuces	Electricity[a]	kWh/kg	20.388	22.971 (10.23, 35.7)	19.597 (1.366)	Table S4

[a] Water and electricity inputs were allocated between the seedings process (7%) and lettuces growth process (93%), based on their occupied area percentage in SANANBIO Biotechnology Co., Ltd.

Table. S4 Electricity consumption of lettuce production through plant factories in varied economies.

Countries	City or provinces	Electricity (kWh·kg^{-1})	Countries	City or provinces	Electricity (kWh·kg^{-1})
American	Phoenix	16.3-27.1[20]	Italy	Emilia-Romagna	11. 0[16]
American	Helena	14.9-26.4[20]	Japan	Aomori	23.4[25]
American	Atlanta	16.2-27.2[20]	Japan	Yamagata	23.7[26]
American	Minneapolis	15.3-27.4[20]	Japan	Yamagata	22.7[26]
American	Florida	27.1[21]	Japan	Yamagata	21.9[26]
American	Atlanta	19.2-20[17]	Japan	Not mentioned	13.2[27]
American	Arizona	22-28[18]	Japan	Chiba	38.4[28]
China	Not mentioned	23.1-36.0[22]	Japan	Not mentioned	15.8[29]
China	Beijing	31.5[23]	the Netherlands	Not mentioned	17.2[19]
China	Beijing	21[24]	Sweden	Not mentioned	16.8[19]
China	Beijing	33[24]	United Arab Emirates	Not mentioned	18.9[19]
Germany	Not mentioned	11.8[15]			

Note: The average power consumption of lettuce production is 22.04 kWh kg^{-1} ranging 11-38.4 kWhkg^{-1}, with a standard deviation of 6.7 kWhkg^{-1}, on which two probability functions (triangular and lognormal distributions) for running Monte Carlo to quantify the uncertainties.

Table. S5 Pathways of China's power grid decarbonizations (%) reviewed from previous publications.

ID	Years	Coal	Natural gas	Nuclear	Hydro	Wind	Solar	Biomass	Liquid fuels	Biomass with CCS	Coal with CCS	Others	References
1	2025	60.00	2.00	10.00	16.00	7.00	5.00						[38]
2	2025	54.00	1.00	10.00	16.00	8.00	10.00						[38]
3	2025	36.00	1.00	10.00	16.00	12.00	25.00						[38]
4	2025	24.00	4.00	10.00	16.00	28.00	19.00						[38]
5	2025	37.00	12.00	5.00	17.00	18.00	10.00						[38]
6	2025	33.00	8.00	5.00	15.00	19.00	19.00						[38]
7	2025	19.00	6.00	3.00	11.00	21.00	33.00						[38]
8	2025	10.00	7.00	3.00	9.00	47.00	21.00						[38]
9	2025	50.25	6.73	5.24	15.94	11.32	10.37		0.12			0.01	[39]
10	2025	50.82	7.36	5.07	15.43	11.17	10.04		0.12				[39]
11	2025	52.44	3.32	5.42	16.49	11.46	10.73		0.13				[39]
12	2025	50.93	7.66	5.02	15.27	11.05	9.95		0.12				[39]
13	2025	51.73	3.55	5.45	16.57	11.77	10.78		0.13			0.01	[39]
14	2030	53.00	2.00	10.00	14.00	14.00	8.00						[38]
15	2030	38.00		9.00	14.00	11.00	28.00						[38]
16	2030	23.00	1.00	9.00	14.00	15.00	39.00						[38]
17	2030	9.00	2.00	9.00	13.00	28.00	39.00						[38]
18	2030	27.00	11.00	4.00	13.00	30.00	13.00						[38]
19	2030	20.00	5.00	3.00	10.00	19.00	35.00						[38]
20	2030	11.00	5.00	3.00	8.00	22.00	42.00						[38]
21	2030	4.00	7.00	2.00	6.00	36.00	35.00						[38]
22	2030	44.00	10.40	4.00	13.60	13.90	14.30						[40]
23	2030	40.00	10.40	5.00	13.80	15.00	15.90						[40]
24	2030	42.08	8.20	6.37	15.79	11.84	15.44		0.02			0.25	[39]

ID	Years	Coal	Natural gas	Nuclear	Hydro	Wind	Solar	Biomass	Liquid fuels	Biomass with CCS	Coal with CCS	Others	References
25	2030	38.70	13.06	5.86	15.03	12.87	14.20		0.02			0.25	[39]
26	2030	45.21	4.93	6.83	16.92	11.98	13.77		0.11			0.25	[39]
27	2030	39.39	12.31	5.87	15.05	12.82	14.29		0.02			0.25	[39]
28	2030	43.99	5.30	6.86	17.00	12.75	13.82		0.03			0.25	[39]
29	2030	43.12	3.72	7.81	15.24	18.22	9.67	2.23					[39]
30	2030	30.17	3.84	3.45	12.28	24.94	24.17	1.15					[39]
31	2035	38.92	7.84	7.37	15.12	10.95	19.42					0.37	[39]
32	2035	35.26	8.96	6.54	14.05	13.30	21.52					0.36	[39]
33	2035	39.83	6.87	8.22	16.86	12.22	15.60		0.02			0.38	[39]
34	2035	35.77	8.28	6.56	14.09	13.16	21.78					0.37	[39]
35	2035	39.46	7.23	8.22	16.86	12.21	15.64					0.38	[39]
36	2040	41.00	12.40	5.00	13.60	13.50	14.50						[39]
37	2040	30.00	14.60	5.00	12.50	18.20	20.10						[39]
38	2040	35.75	7.47	7.99	14.55	10.06	23.81					0.37	[39]
39	2040	30.57	8.58	6.83	12.45	11.78	29.43					0.36	[39]
40	2040	37.57	6.48	9.16	16.70	11.54	18.17					0.38	[39]
41	2040	30.76	7.89	6.84	12.46	11.64	30.05					0.36	[39]
42	2040	37.10	6.81	9.15	16.66	11.52	18.38					0.38	[39]
43	2045	33.06	7.27	8.42	13.46	9.30	28.12					0.37	[39]
44	2045	27.25	8.40	6.94	11.09	10.50	35.47					0.36	[39]
45	2045	36.27	6.18	9.96	15.92	11.01	20.28					0.38	[39]
46	2045	27.45	7.73	6.99	11.17	10.44	35.92					0.31	[39]
47	2045	35.75	6.47	9.89	15.82	10.94	20.75					0.38	[39]
48	2050	38	13.80	5.00	13.80	14.00	15.10						[40]
49	2050	25.00	16.90	4.00	11.90	19.90	21.90						[40]
50	2050	31.66	7.15	8.92	12.89	8.91	30.09					0.37	[39]

ID	Years	Coal	Natural gas	Nuclear	Hydro	Wind	Solar	Biomass	Liquid fuels	Biomass with CCS	Coal with CCS	Others	References
51	2050	24.99	8.28	7.04	10.17	9.63	39.53					0.36	[39]
52	2050	35.25	6.09	10.87	15.71	10.86	20.85					0.38	[39]
53	2050	25.45	7.75	7.16	10.35	9.67	39.29					0.32	[39]
54	2050	34.75	6.36	10.77	15.56	10.75	21.43					0.38	[39]
55	2050	31.93	2.98	17.28	12.63	22.02	12.98						[42]
56	2050	22.02	3.11	20.00	12.44	25.71	16.64	0.08					[42]
57	2050	3.44	2.98	17.94	11.22	37.18	22.6	0.31		1.45	3.05		[42]
58	2050	0.77	2.66	16.36	10.35	40.21	21.75	0.21		2.03	5.52		[42]
59	2050	21.36	5.53	7.74	11.33	29.37	24.68						[42]
60	2050	13.59	4.66	7.62	9.61	32.34	32.18	0.05					[42]
61	2050	2.16	3.52	5.75	7.28	40.66	38.78	0.11		0.56	1.20		[42]
62	2050	0.51	3.18	5.20	6.62	43.6	37.67	0.08		0.76	2.37		[42]
63	2050		4.03	10.07	14.77	35.23	28.19	7.72					[41]
64	2050		6.06	2.70	7.40	34.69	33.67	3.69					[41]

Note: The energy resources composite of the power grid was dominated by Coal (C), Gas (G), Nuclear (N), Hydro (H), Wind (W), and Solar (S), while Biomass (B) and Liquid fuels (L) were excluded from analysis due to neglectable contributions. The Years column is sourced from the original references to generate the scenarios of grid decarbonization and has no relationship with the temporal decay of CH_4 and N_2O.

Table. S6 Average power sources composites of the targeted scenarios for China's power grid decarbonization at high and low levels. [a]

Scenario	Year	Decarbonization Levels	Coal (%)	Gas (%)	Solar (%)	Wind (%)	Nuclear (%)	Hydro (%)
S0	Current	Baseline[b]	52.98	1.5	0	1.25	0.02	38.62
S1	2025	Low	52.96	4.52	9.57	10.26	6.62	15.98
S2	2025	High	26.87	6.47	21.71	24.69	6.05	14.21
S3	2030	Low	43.33	7.82	13.28	13.74	6.52	15.18
S4	2030	High	20.76	4.60	33.30	24.32	5.41	11.61
S5	2035	Low	39.40	7.31	16.88	11.79	7.94	16.28
S6	2035	High	35.52	8.62	21.65	13.23	6.55	14.07
S7	2040	Low	36.28	9.55	18.99	12.96	7.26	14.80
S8	2040	High	30.66	8.23	29.74	11.71	6.83	12.45
S9	2045	Low	35.02	6.64	23.05	10.42	9.42	15.07
S10	2045	High	27.35	8.06	35.69	10.47	6.96	11.13
S11	2050	Low	27.64	7.51	24.97	17.56	9.67	12.40
S12	2050	High	1.19	4.07	32.69	41.39	10.32	10.34

[a] The average energy resource composites were produced by cluster analysis on the 64 reviewed China's decarbonization pathways. [b] The baseline of China Southern Power Grid is built in the Ecoinvent database for LCA model development. All scenarios were separately input into the LCA models to calculate the TWP metrics further.

Table. S7 Radiative efficiency (RE) values of CO_2, CH_4, and N_2O.

	Direct RE ($W\ m^{-2}\ ppb^{-1}$)	Relative direct + indirect RE (per ppb or molar basis)	Relative direct + indirect RE (per kg basis)
CO_2	1.37×10^{-5}	1	1
CH_4	3.63×10^{-4}	44	121
N_2O	3.00×10^{-3}	219	219

Note: The parameters were cited from (Climate Change, 2013)[43].

Table. S8 Parameters of CO_2 impulse-response functions.

ID	Categories	Name	a_0	a_1	a_2	a_3	tau_1	tau_2	tau_3
1	Earth system model	NCAR CSM1.4	2.94E-07	3.67E-01	3.54E-01	2.79E-01	1.69E+03	2.84E+01	5.32E+00
2	Earth system model	HADGEM2-ES	4.34E-01	1.97E-01	1.89E-01	1.80E-01	2.31E+01	2.31E+01	3.92E+00
3	Earth system model	MPI-ESM	1.25E-07	5.86E-01	1.83E-01	2.31E-01	1.78E+02	9.04E+00	8.99E+00
4	EMICs	Bern3D-LPJ-R	6.35E-10	5.15E-01	2.63E-01	2.22E-01	1.96E+03	4.58E+01	3.87E+00
5	EMICs	Bern3D-LPJ	2.80E-01	2.38E-01	2.38E-01	2.44E-01	2.76E+02	3.85E+01	4.93E+00
6	EMICs	Bern2.5D-LPJ	2.36E-01	9.87E-02	3.85E-01	2.80E-01	2.32E+02	5.85E+01	2.59E+00
7	EMICs	Climber2.4-LPJ	2.32E-01	2.76E-01	4.90E-01	2.58E-03	2.73E+02	6.69E+00	6.69E+00
8	EMICs	DCESS	2.16E-01	2.91E-01	2.41E-01	2.52E-01	3.80E+02	3.63E+01	3.40E+00
9	EMICs	GENIE	2.15E-01	2.49E-01	1.92E-01	3.44E-01	2.70E+02	3.93E+01	4.31E+00
10	EMICs	LOVECLIM	8.54E-08	3.61E-01	4.50E-01	1.89E-01	1.60E+03	2.17E+01	2.28E+00
11	EMICs	MESMO	2.85E-01	2.94E-01	2.38E-01	1.83E-01	4.54E+02	2.50E+01	2.01E+00
12	EMICs	Uvic-2.9	3.19E-01	1.75E-01	1.92E-01	3.15E-01	3.05E+02	2.66E+01	3.80E+00
13	Box-type model	ACC2	1.78E-01	1.65E-01	3.80E-01	2.77E-01	3.86E+02	3.69E+01	3.72E+00
14	Box-type model	Bern-SAR	1.99E-01	1.76E-01	3.45E-01	2.79E-01	3.33E+02	3.97E+01	4.11E+00
15	Box-type model	MAGICC	2.05E-01	2.53E-01	3.32E-01	2.10E-01	5.96E+02	2.20E+01	3.00E+00
16	Box-type model	TOTEM	7.18E-06	2.03E-01	7.00E-01	9.74E-02	8.58E+04	1.12E+02	1.58E-02
17		IPCC AR5	2.17E-01	2.24E-01	2.82E-01	2.76E-01	3.94E+02	3.65E+01	4.30E+00

Note: This table was cited from Joos et al. (2013)[44]. Parameters in the final row represent the IPCC AR5 that were the averages of corresponding parameters of the models 1-16. All parameters were used to quantify the uncertainties and enhance the robustness.

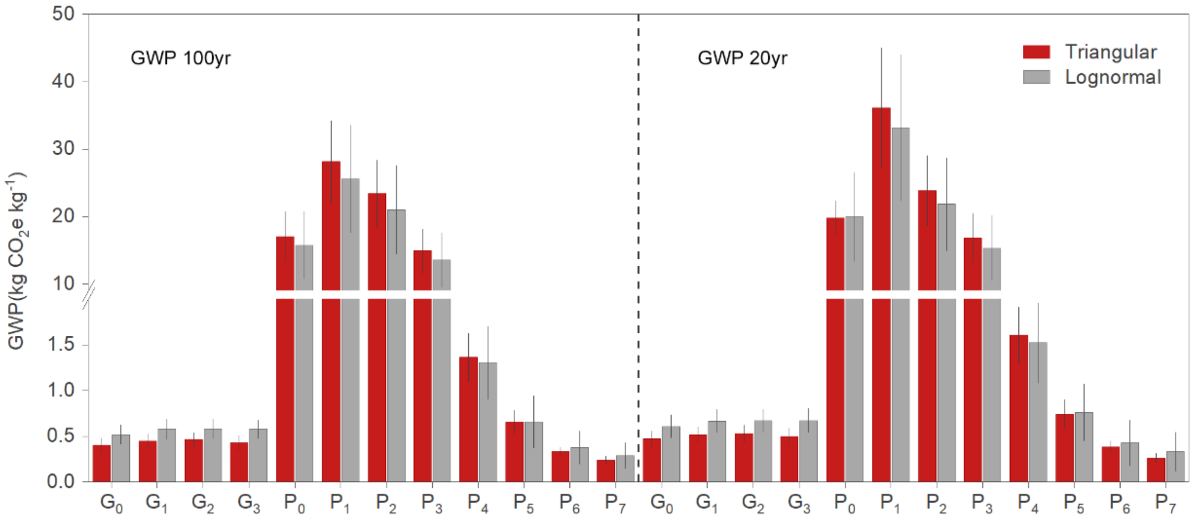

Figure. S2 Uncertainties of GWP estimated by Monte Carlo simulations. Traditional film greenhouse: G_0 excludes the N_2O emission of nitrogen fertilizer uses, and $G_{1\text{-}3}$ covers three separately measured N_2O coefficients. Plant factory: P_0 represents the power baseline of China Southern Power Grid, and others represent power entirely generated by coal (P_1), oil (P_2), natural gas (P_3), solar (P_4), wind (P_5), nuclear (P_6) and hydro (P_7) sources.

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