Supporting Information for

Reducing the environmental impact of large-scale photovoltaic systems through technological progress and effective management

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1 Previous LCA studies of PV systems

LCA studies of large PV systems from 2013 to 2023 are collated in this study, and key system parameters affecting the LCA results of large PV systems, such as annual solar radiation, installed capacity, PV module technology, module efficiency, performance ratio, and lifetime, are summarized as shown in **Table S1**. In addition, the selected LCA evaluation methods this study also collated as shown in **Table S1**. Based on the research thrust of this study, the results of previous studies on GHG impact and energy recovery capacity were also collated. (see **Table S1** and **Fig. S1**).

Table S1 Design, characteristics, GHG and EPBT of the large-scale PV systems in previous studies.

NO.	References	Installation location	Annual solar irradiation ($kWh/m^2/year$)	Installed Capacity (MWp)	PV Module technology	Module efficiency (%)	Performance Ratio	Lifetime (years)	LCA method	GHG (gCO_2-eq/kWh)	EPBT (years)
1	de Wild-Scholten (2013)[1]	Europe	1700	120	Multi-Si	14.10	0.770	30	CED V1.08	27.20	1.24
					Mono-Si	14.80			IPCC 2007	38.10	1.96
2	Beylot et al. (2014)[2]	N/A	1700	5	Multi-Si	14.00	0.855	30	IMPACT 2002+ v2.04	37.50~53.50	N/A
3	Yu and Halog (2015)[3]	Australia	N/A	1.2	Multi-Si	14.70	0.750	30	CML 2 baseline 2000 V2.05	69.40	2.33
4	Ito et al. (2016)[4]	Morocco	2344	1040	Mono-Si	15.90&21.20	0.810&0.830	30	CED V1.08	30.20~40.10	1.20~1.70
		France	1737	1040			0.840&0.850		IPCC 2007	36.80~48.80	1.50~2.00
5	Hou et al. (2016)[5]	Northwest China	1575	N/A	Multi-Si	15.00~16.00	0.750	25	N/A	60.13	1.60
					Mono-Si	16.00~18.00				65.20	1.70
6	Wu et al. (2017)[6]	Gobi Desert of China	2017	1	Multi-Si	17.50	0.835	30	N/A	36.75	2.30
7	Yu et al. (2017)[7]	Ningxia, China	1654	10	Multi-Si	14.08	0.796	30	ISCP 2010 IPCC 2007 IMPACT 2002+	23.62	3.06

8	Constantino et al. (2018)[8]	Northeast Brazil	1971	1.1	Multi-Si	14.40~16.16	N/A	25	N/A	62.05~81.02	2.91~5.16
9	Cromratie Clemons et al. (2021)[9]	Thailand	1670~1895	150	Multi-Si	13.00	0.800	30	ReCiPe	73.30	N/A
10	Schultz and Carvalho (2022)[10]	Northeast Brazil	1887	16.4	Mono-Si	N/A	0.726	25	IPCC 2013	44.00	N/A
11	Pamponet et al. (2022)[11]	Brazil	N/A	158	N/A	16.75	N/A	30	CED V1.10 ReCiPe 2016	38.30~44.80	4.50~5.30
12	Mohd Nordin et al. (2022)[12]	Malaysia	1958.3	37.57	Multi-Si	17.10	0.751	30	CED V1.11 ReCiPe 2016	30.95	3.43

N/A-Not Applicable

2 LCA Method

2.1 System boundary

The system boundary for this study is the PV system established from cradle to grave. Firstly, it includes the mining of raw materials, transportation to the manufacturer, equipment manufacturing, and assembly. The equipment includes PV modules, BOS, and ESS. Then, it includes transportation from the production site to the PV system as well as site construction and equipment installation. Subsequently, it also includes electricity, fuel and water consumed in the operation and maintenance of the PV system. The final EoL includes equipment decommissioning and dismantling, transportation from the PV system to the disposal site, and solid waste disposal. Within the system boundary, all energy consumption and environmental impacts are considered, with the final functional unit being 1kWh of electricity generated by the PV system.

2.2 Study area

In this study, the study area for the six PV systems is located on the Tibetan Plateau, specifically in the Republican Basin of Qinghai, China, as shown in **Fig. S1**. The solar eco-electricity park in the Gonghe basin of Qinghai, China, has a planned installed capacity of 18.7 GW and a total area of 609.6 square kilometres. The PV park has five world's best: (1) the world's largest PV industrial park; (2) the world's largest single PV electricity station; (3) the world's largest water- solar complementary electricity station; (4) the world's largest PV electricity generation evidence base; (5) the world's largest cluster of new energy distributed phase regulators. The Gonghe region is rich in solar radiation, with a range of 4864.92−6185.55 MJ/m^2.

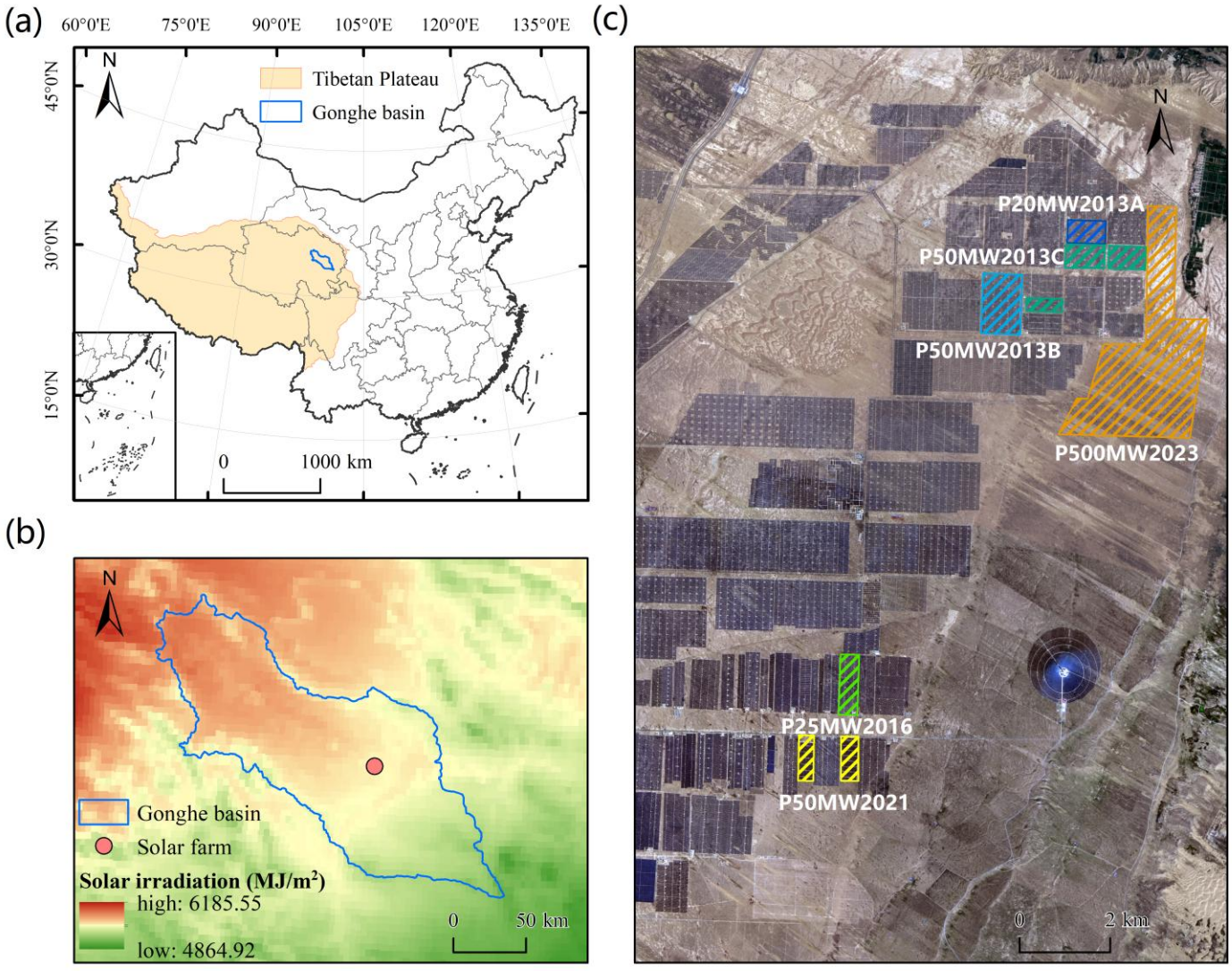

Fig. S1. The study area for this study. (a) The study area is situated in the Gonghe Basin of the Tibetan Plateau, China. (b) Solar irradiation data for 2019 in the Gonghe Basin, where Solar farm is located in the west-central part of the Gonghe Basin. (c) Location of six large PV systems in Solar farm.

2.3 The large-scale PV systems

The material composition of the PV module is shown in **Fig. 3b**. In this study, except for P500MW2023 which is a glass-glass module, all other photovoltaic systems have a glass-backsheet module[13]. Glass-glass module can absorb sunlight reflected from the ground and increase power generation.

In addition, the mounting structures of the six PV systems are not completely identical, as shown in **Fig. 3c**. There are fixed support bracket, fixed adjustable bracket (which can adjust four angles according to the different solar angles in different seasons), flexible bracket (which save materials), and flat single axis bracket (driven by a motor and can track the trajectory of the sun to ensure maximum received solar radiation). The on-site physical image of the PV system is shown in **Fig. S2**.

The grid connected power generation boosting process of the photovoltaic system is shown in **Fig. 3d**. The direct current (DC) electricity generated by PV modules is first converged by combiners, then converted into alternating current (AC) electricity by inverters, and finally the AC voltage is boosted up to 35kV by box transformers (integrated inverter and transformers in P50MW2021, and part of the integrated inverter and transformers in P500MW2023). The voltage is then boosted up to 110kV, 330kV (the P500MW2023 voltage is boosted directly from 35kV to 330kV) and 750kV by various transformer substations in turn, and finally delivered to the utility grid. The P500MW2023 with energy storage systems (ESS), with a specification of 150MW600MWh and a lifetime of 20 years. ESS is connected to the 35kV side of the 330kV substation, and sells 118,913.25 MWh of electricity annually.

The manufacturing processes flow of Mono-Si and Multi-Si PV modules are shown in **Fig. S3**. Mono-Si PV modules use crystal pulling process, while Multi-Si PV modules use ingot process. Other processes are the same, including silicon wafer process, cell manufacturing process and module manufacturing process.

The annual grid connected electricity generation of the six PV systems in this study over a period of 25 years is shown in **Table S2**. This study considers the degradation of PV modules, resulting in a decrease in annual electricity generation.

The selection criteria for PV systems are as follows: firstly, the technology coverage, which encompasses both polycrystalline and monocrystalline modules, with the inclusion of four types of mounting structures (fixed, fixed-adjustable, flexible and flat single axis). Secondly, authenticity, ensures that all PV systems are real and running stable PV plants, as opposed to hypothetical or simulated systems. The third criterion is comparability, which is ensured by locating all six PV systems in the world's largest Gonghe solar power park, thereby ensuring

they face the same solar radiation resources, climate, grid system, and system boundaries. The fourth and final criterion is data integrity, which is guaranteed by the use of real, first-hand data for the full lifecycle of the six PV systems, including materials, power generation, transport, and O&M data.

The primary data were validated in the following ways: firstly, information on PV modules and all other equipment materials was collated based on the feasibility investigation report, preliminary design report and project acceptance report of the PV power plants. Subsequently, through field research, we obtained first-hand data from personnel involved in power plant construction and operation and maintenance, as well as from personnel involved in the manufacturing of PV modules and equipment, and transport of equipment. This included the proportion of materials, power generation data, and the distance of equipment transport.

Multi-Si

P20MW2013A
P50MW2013B
P50MW2013C

fixed support bracket

Multi-Si

P25MW2016

fixed adjustable bracket

Mono-Si

P50MW2021

flexible bracket

Mono-Si

P500MW2023

fixed support bracket

Fig. S2.The site images of six large-scale PV systems.

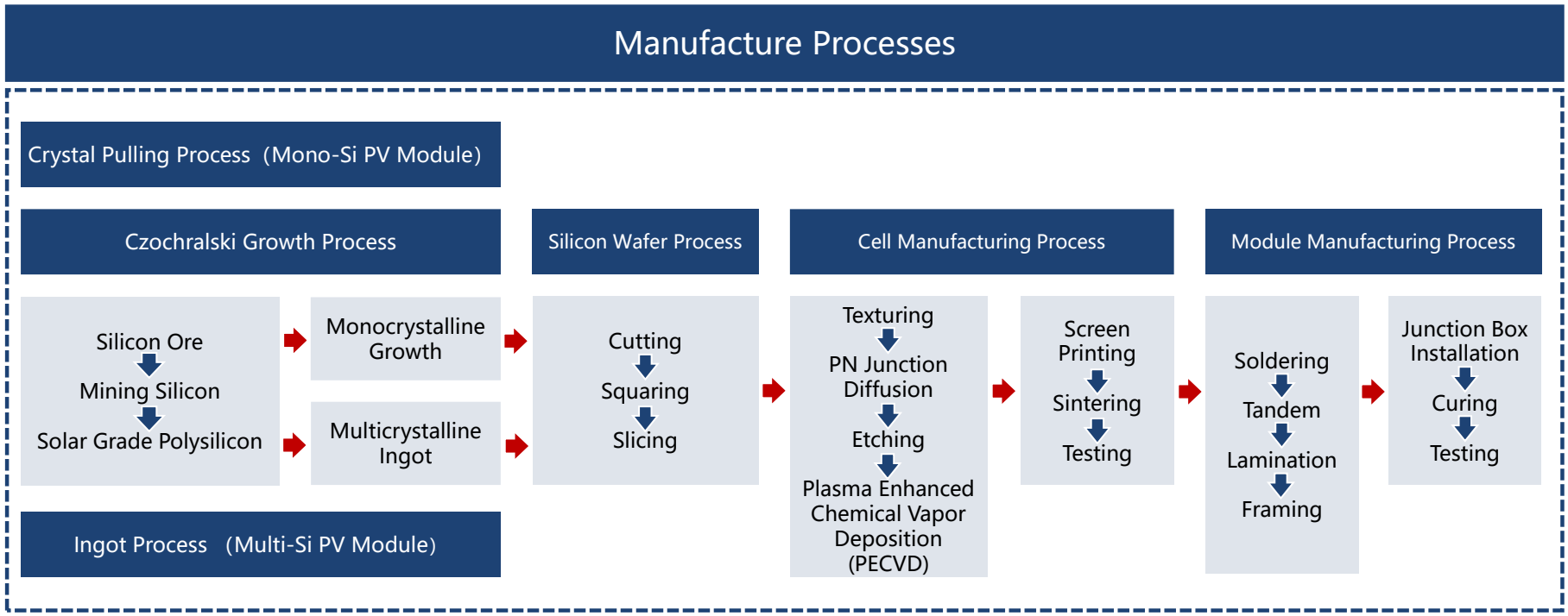

Fig. S3. The manufacture processes of Mono-Si and Multi-Si PV modules.

Table S2 The electricity generation on grid of PV systems (10^4kWh/year), with curtailment rate of 8%.

PV systems / Years	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023
1	3202.8052	8078.0140	8067.7192	4150.6720	8349.9844	107764.8440
2	3170.7800	7996.4192	7986.2256	4099.8512	8303.1196	107270.0680
3	3137.8072	7914.8244	7904.7320	4057.4944	8256.2640	106775.2000
4	3105.1748	7833.2296	7823.2384	4023.6108	8209.3992	106280.3320
5	3072.8736	7751.6348	7741.7448	3989.7272	8162.5344	105785.5560
6	3046.6352	7670.0308	7660.2512	3955.8436	8115.6788	105290.6880
7	3020.6176	7588.4360	7578.7668	3921.9600	8068.8140	104795.8200
8	2994.8208	7506.8412	7497.2732	3888.0764	8021.9492	104301.0440
9	2969.2448	7425.2464	7415.7796	3854.1928	7975.0844	103806.1760
10	2943.8896	7343.6516	7334.2860	3820.3092	7928.2288	103311.3080
11	2918.7460	7289.2520	7279.9600	3790.6668	7881.3640	102816.4400
12	2893.8232	7234.8524	7225.6340	3761.0152	7834.4992	102321.6640
13	2869.1028	7180.4620	7171.2988	3731.3728	7787.6436	101826.7960
14	2844.6032	7126.0624	7116.9728	3701.7212	7740.7788	101331.9280
15	2820.3152	7071.6628	7062.6468	3672.0696	7693.9140	100837.1520
16	2796.2296	7017.2632	7008.3208	3642.4272	7647.0492	100342.2840
17	2772.3464	6962.8636	6953.9948	3612.7756	7600.1936	99847.4160
18	2748.6748	6908.4732	6899.6596	3583.1332	7553.3288	99352.6400

19	2725.1964	6854.0736	6845.3336	3553.4816	7506.4640	98857.7720
20	2701.9204	6799.6740	6791.0076	3523.8392	7459.6084	98362.9040
21	2678.8468	6745.2744	6736.6816	3494.1876	7412.7436	97868.1280
22	2655.9756	6690.8840	6682.3464	3464.5360	7365.8788	97373.2600
23	2633.2884	6636.4844	6628.0204	3439.1256	7319.0140	96878.3920
24	2610.8036	6582.0848	6573.6944	3413.7152	7272.1584	96383.6160
25	2588.5028	6527.6852	6519.3684	3388.3048	7225.2936	95888.7480
Average	2876.9228	7229.4152	7220.1968	3741.3640	7787.6436	101826.7960

2.4 The detailed life cycle inventory

The materials and processes in the LCIs are the sum of all the components in the different stages of the life cycle, and the main components in the different stages are listed below, and some components are only available at certain PV plants. (see **Tables S3 - S8**)

1 PV Module

2 BOS

2.1 Mounting Structure: fixed supporting bracket (in P20MW2013A, P50MW2013B and P50MW2013C), fixed adjustable bracket (in P25MW2016), Flexible bracket (in P50MW2021), fixed supporting bracket and flat single axis bracket (in P500MW2023).

2.2 Combiner.

2.3 Inverter: the inverter of which is replaced on twice occasions during the lifetime of the PV systems.

2.4 Transformer.

2.5 Integrated Inverter and Transformer.

2.6 Electric Transmission Line: 1kV (35kV) electric cable, PVC pipe, steel pipe, Galvanised steel pipes, PE pipe.

2.7 Boost Voltage Substation System: main transformer, 35kV (0.4kV) switchgear, 330kV Electric clearance, 330Kv Voltage transformer, 35kV Static Var Generator (SVG), station transformer, earthing transformer, Grounding electrode, cable bracket, arc-suppression coil, 1kV (10kV/35kV) electric cable.

2.8 Control and Protection System: workstation, printer, display, 35kV protective device, 450V (750V) control cable, Grounding conductor, communication cable, measuring and control device.

2.9 Firefighting and Ventilation systems.

2.10 Civil Works: site levelling, PV array foundation, box transformer foundation, electrical substation foundation, electrical distribution foundation, office building, inverter room, water pump room, guard room, fences, gates, roads, firefighting pools and C&I.

3 ESS: power conversion system (Energy storage converter, step-up transformer, container), energy storage battery system (Lithium iron phosphate

Battery, battery powered cabinet, battery convergence cabinet, switchgear), energy management system (workstation, uninterruptible power supply, control cabinet), 0.4kV/35kV cable, communication cable, Grounding conductor, and Civils Works of ESS (Levelling of site, battery box foundation, PCS foundation, auxiliary room, fire pump room, prefabricated cabin foundation, fence, gates, roads).

4 Transportation: transport from the production site to the PV systems, and transport from the PV systems to the disposal site.

5 O&M: petrol (the consumption of fuel by vehicles), water (the consumption of water by the building and the cleaning PV modules), and electricity (the PV systems are supplied with electricity via the national grid, e.g. for lighting, ventilation, heating).

6 EoL: decommissioning and dismantling (D&D), the municipal solid waste scenario of China (MSWS of CN). This disposal scenario commences with 85% recycling rate of metals and 30% recycling rate of plastics (including ferro metals, aluminium, steel, plastics, PE, PET, PP, PS, PVC), followed by proportional incineration of the remaining material, and finally landfilling and open dumping of the separated material.

As shown **in Table S9**, the transportation distance in LCIs is the actual transportation distance we surveyed from PV plants operators and equipment manufacturers. And when the PV system is retired, all equipment will be returned to its original path for safe recycling and disposal by the equipment manufacturers. **Table S10** shows the actual specifications and quantities of the current collection box, inverter, and transformer in LCIs.

Table S3 Life cycle inventory data for P20MW2013A. P20MW2013A=the grid-connected 20MW of A PV system in 2013.

P20MW2013A				
Assembly	**Materials/Processes**	**Amount**	**Unit**	**Source**
1. PV Module				
	Photovoltaic cell, multi-Si wafer {GLO}| market for photovoltaic cell, multi-Si wafer | Cut-off, U	69996	m^2	Primary
	Silver {GLO}| market for silver | Cut-off, U	2410	kg	data and
	Aluminium alloy, AlMg3 {GLO}| market for aluminium alloy, AlMg3 | Cut-off, U	141880	kg	Ecoinvent
	Solar glass, low-iron {GLO}| market for solar glass, low-iron | Cut-off, U	1184694	kg	3.9.1
	Polyvinylfluoride {GLO}| market for polyvinylfluoride | Cut-off, U	60416	kg	
	Ethylvinylacetate, foil {GLO}| market for ethylvinylacetate, foil | Cut-off, U	113440	kg	
	Silicone product {GLO}| market for | Cut-off, U	1446	kg	
	Polyphenylene sulfide {GLO}| market for polyphenylene sulfide | Cut-off, U	41336	kg	
	Copper {GLO}| market for copper | Cut-off, U	26356	kg	
	Tin {GLO}| market for tin | Cut-off, U	2410	kg	
	Electricity, low voltage {CN}| market for | Cut-off, U	803504	kWh	
2. Balance of System				
2.1 Mounting Structure				
	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	1355284	kg	Primary
	Forging, steel {GLO}| market for forging, steel | Cut-off, U	1355284	kg	data and
	Zinc coat, pieces {GLO}| market for zinc coat, pieces | Cut-off, U	19020	m^2	Ecoinvent
				3.9.1

2.2 Combiner			
Copper {GLO}| market for copper | Cut-off, U	8000	kg	Primary
Cast iron {GLO}| market for cast iron | Cut-off, U	1600	kg	data and
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	6400	kg	Ecoinvent
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	8000	kg	3.9.1
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	6400	kg	
2.3 Inverter			
Copper {GLO}| market for copper | Cut-off, U	60512	kg	Primary
Cast iron {GLO}| market for cast iron | Cut-off, U	87968	kg	data and
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	154080	kg	Ecoinvent
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	60512	kg	3.9.1
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	154080	kg	
2.4 Transformer			
Cast iron {GLO}| market for cast iron | Cut-off, U	42560	kg	Primary
Silicon, metallurgical grade {GLO}| market for silicon, metallurgical grade | Cut-off, U	2240	kg	data and
Copper {GLO}| market for copper | Cut-off, U	33600	kg	Ecoinvent
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	28000	kg	3.9.1
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	5600	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	33600	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	28000	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	5600	kg	

2.5 Electric Transmission Line				
	Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	179010	kg	Primary
	Polyvinylchloride, bulk polymerised {GLO}| market for polyvinylchloride, bulk polymerised | Cut-off, U	4544	kg	data and
	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	107844	kg	Ecoinvent
	Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	107844	kg	3.9.1
2.6 Boost Voltage Substation System				
	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	13105	kg	Primary
	Cast iron {GLO}| market for cast iron | Cut-off, U	6352	kg	data and
	Copper {GLO}| market for copper | Cut-off, U	6055	kg	Ecoinvent
	Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	1170	kg	3.9.1
	Silicon, metallurgical grade {GLO}| market for silicon, metallurgical grade | Cut-off, U	468	kg	
	Silver {GLO}| market for silver | Cut-off, U	105	kg	
	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	700	kg	
	Polycarbonate {GLO}| market for polycarbonate | Cut-off, U	245	kg	
	Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	29404	kg	
	Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	13105	kg	
	Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	6055	kg	
	Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	1170	kg	
2.7 Control and Protection System				
	Computer, desktop, without screen {GLO}| market for computer, desktop, without screen | Cut-off, U	3	p	Primary
	Display, liquid crystal, 17 inches {GLO}| market for display, liquid crystal, 17 inches | Cut-off, U	3	p	data and

Printer, laser, colour {GLO}| market for printer, laser, colour | Cut-off, U	2	p	Ecoinvent
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	7965	kg	3.9.1
Copper {GLO}| market for copper | Cut-off, U	4720	kg	
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	2976	kg	
Cast iron {GLO}| market for cast iron | Cut-off, U	1995	kg	
Polycarbonate {GLO}| market for polycarbonate | Cut-off, U	1822	kg	
Silicon, metallurgical grade {GLO}| market for silicon, metallurgical grade | Cut-off, U	722	kg	
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	10875	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	7965	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	4720	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	2976	kg	
2.8 Firefighting and Ventilation systems			
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	77819	kg	Primary
Copper {GLO}| market for copper | Cut-off, U	100	kg	data and
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	50	kg	Ecoinvent
Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, U	1600	kg	3.9.1
Cast iron {GLO}| market for cast iron | Cut-off, U	400	kg	
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	1470	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	77819	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	100	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	50	kg	

Sheet rolling, chromium steel {GLO}| market for sheet rolling, chromium steel | Cut-off, U	1600	kg	
2.9 Civil Works			
Concrete, 25MPa {GLO}| market for concrete, 25MPa | Cut-off, U	3950	m^3	Primary
Reinforcing steel {GLO}| market for reinforcing steel | Cut-off, U	433550	kg	data and
Concrete, 20MPa {GLO}| market for concrete, 20MPa | Cut-off, U	830	m^3	Ecoinvent
Brick {GLO}| market for | Cut-off, U	4973200	kg	3.9.1
Concrete, 30-32MPa {GLO}| market for concrete, 30-32MPa | Cut-off, U	525.8	m^3	
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	140910	kg	
Copper {GLO}| market for copper | Cut-off, U	600	kg	
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	150	kg	
Gravel, crushed {GLO}| market for | Cut-off, U	16187220	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	140910	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	600	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	150	kg	
2.9.1 Construction & Installation			
Diesel, burned in building machine {GLO}| diesel, burned in building machine | Cut-off, U	2385600	MJ	Primary
Tap water {GLO}| market group for tap water | Cut-off, U	8640000	kg	data and
Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | Cut-off, U	368000	MJ	Ecoinvent
Electricity, low voltage {CN}| market for | Cut-off, U	91000	kWh	3.9.1
3. Transportation			
Transport, freight, lorry >32 metric ton, EURO3 {RoW}| market for transport, freight, lorry >32 metric ton, EURO3 | Cut-off, U	6275181	tkm	Primary

Transport, freight, lorry >32 metric ton, EURO3 {RoW}| market for transport, freight, lorry >32 metric ton, EURO3 | Cut-off, U	6080934	tkm	data and Ecoinvent 3.9.1
4. Operation & Maintenance			
Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | Cut-off, U	5347500	MJ	Primary
Tap water {GLO}| market group for tap water | Cut-off, U	112500000	kg	data and
Electricity, low voltage {CN}| market for | Cut-off, U	3872500	kWh	Ecoinvent 3.9.1
5. End of Life			
Municipal solid waste (waste scenario) {CN}| Treatment of waste | Cut-off, U	100	%	Ecoinvent 3.9.1
5.1 Decommissioning & Dismantling			
Diesel, burned in building machine {GLO}| diesel, burned in building machine | Cut-off, U	2385600	MJ	Primary
Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | Cut-off, U	368000	MJ	data and
Electricity, low voltage {CN}| market for | Cut-off, U	91000	kWh	Ecoinvent 3.9.1

Table S4 Life cycle inventory data for P50MW2013B. P50MW2013B=the grid-connected 50MW of B PV system in 2013.

P50MW2013B				
Assembly	**Materials/Processes**	**Amount**	**Unit**	**Source**
1. PV Module				
	Photovoltaic cell, multi-Si wafer {GLO}| market for photovoltaic cell, multi-Si wafer | Cut-off, U	175893	m^2	Primary
	Silver {GLO}| market for silver | Cut-off, U	6057	kg	data and
	Aluminium alloy, AlMg3 {GLO}| market for aluminium alloy, AlMg3 | Cut-off, U	356533	kg	Ecoinvent
	Solar glass, low-iron {GLO}| market for solar glass, low-iron | Cut-off, U	2977031	kg	3.9.1
	Polyvinylfluoride {GLO}| market for polyvinylfluoride | Cut-off, U	151819	kg	
	Ethylvinylacetate, foil {GLO}| market for ethylvinylacetate, foil | Cut-off, U	285065	kg	
	Silicone product {GLO}| market for | Cut-off, U	3633.9732	kg	
	Polyphenylene sulfide {GLO}| market for polyphenylene sulfide | Cut-off, U	103958	kg	
	Copper {GLO}| market for copper | Cut-off, U	66568	kg	
	Tin {GLO}| market for tin | Cut-off, U	6057	kg	
	Electricity, low voltage {CN}| market for | Cut-off, U	2019345	kWh	
2. Balance of System				
2.1 Mounting Structure				
	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	3388210	kg	Primary
	Forging, steel {GLO}| market for forging, steel | Cut-off, U	3388210	kg	data and
	Zinc coat, pieces {GLO}| market for zinc coat, pieces | Cut-off, U	47549	m^2	Ecoinvent
				3.9.1

2.2 Combiner			
Copper {GLO}| market for copper | Cut-off, U	17500	kg	Primary
Cast iron {GLO}| market for cast iron | Cut-off, U	3500	kg	data and
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	14000	kg	Ecoinvent
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	17500	kg	3.9.1
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	14000	kg	
2.3 Inverter			
Copper {GLO}| market for copper | Cut-off, U	151280	kg	Primary
Cast iron {GLO}| market for cast iron | Cut-off, U	219920	kg	data and
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	385200	kg	Ecoinvent
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	151280	kg	3.9.1
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	385200	kg	
2.4 Transformer			
Cast iron {GLO}| market for cast iron | Cut-off, U	106400	kg	Primary
Silicon, metallurgical grade {GLO}| market for silicon, metallurgical grade | Cut-off, U	5600	kg	data and
Copper {GLO}| market for copper | Cut-off, U	84000	kg	Ecoinvent
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	70000	kg	3.9.1
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	14000	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	84000	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	70000	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	14000	kg	

2.5 Electric Transmission Line			
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	445318	kg	Primary
Polyvinylchloride, bulk polymerised {GLO}| market for polyvinylchloride, bulk polymerised | Cut-off, U	12353	kg	data and
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	323532	kg	Ecoinvent
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	323532	kg	3.9.1
2.6 Boost Voltage Substation System			
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	15320	kg	Primary
Cast iron {GLO}| market for cast iron | Cut-off, U	7646	kg	data and
Copper {GLO}| market for copper | Cut-off, U	7675	kg	Ecoinvent
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	2935	kg	3.9.1
Silicon, metallurgical grade {GLO}| market for silicon, metallurgical grade | Cut-off, U	1174	kg	
Silver {GLO}| market for silver | Cut-off, U	315	kg	
Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	2100	kg	
Polycarbonate {GLO}| market for polycarbonate | Cut-off, U	735	kg	
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	26679	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	15320	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	7675	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	2935	kg	
2.7 Control and Protection System			
Computer, desktop, without screen {GLO}| market for computer, desktop, without screen | Cut-off, U	3	p	Primary
Display, liquid crystal, 17 inches {GLO}| market for display, liquid crystal, 17 inches | Cut-off, U	3	p	data and

Printer, laser, colour {GLO}| market for printer, laser, colour | Cut-off, U	2	p	Ecoinvent
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	14637	kg	3.9.1
Copper {GLO}| market for copper | Cut-off, U	8332	kg	
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	5112	kg	
Cast iron {GLO}| market for cast iron | Cut-off, U	3147	kg	
Polycarbonate {GLO}| market for polycarbonate | Cut-off, U	3274	kg	
Silicon, metallurgical grade {GLO}| market for silicon, metallurgical grade | Cut-off, U	1298	kg	
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	20673	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	14637	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	8332	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	5112	kg	
2.8 Firefighting and Ventilation systems			
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	109530	kg	Primary
Copper {GLO}| market for copper | Cut-off, U	800	kg	data and
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	400	kg	Ecoinvent
Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, U	1600	kg	3.9.1
Cast iron {GLO}| market for cast iron | Cut-off, U	400	kg	
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	2669	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	109530	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	800	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	400	kg	

Sheet rolling, chromium steel {GLO}| market for sheet rolling, chromium steel | Cut-off, U	1600	kg	
2.9 Civil Works			
Concrete, 25MPa {GLO}| market for concrete, 25MPa | Cut-off, U	9900	m^3	Primary
Reinforcing steel {GLO}| market for reinforcing steel | Cut-off, U	1050550	kg	data and
Concrete, 20MPa {GLO}| market for concrete, 20MPa | Cut-off, U	657	m^3	Ecoinvent
Brick {GLO}| market for | Cut-off, U	8391880	kg	3.9.1
Concrete, 30-32MPa {GLO}| market for concrete, 30-32MPa | Cut-off, U	877	m^3	
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	910	kg	
Copper {GLO}| market for copper | Cut-off, U	600	kg	
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	150	kg	
Gravel, crushed {GLO}| market for | Cut-off, U	19798800	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	910	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	600	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	150	kg	
2.9.1 Construction & Installation			
Diesel, burned in building machine {GLO}| diesel, burned in building machine | Cut-off, U	5964000	MJ	Primary
Tap water {GLO}| market group for tap water | Cut-off, U	21600000	kg	data and
Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | Cut-off, U	920000	MJ	Ecoinvent
Electricity, low voltage {CN}| market for | Cut-off, U	277000	kWh	3.9.1
3. Transportation			
Transport, freight, lorry >32 metric ton, EURO3 {RoW}| market for transport, freight, lorry >32 metric ton, EURO3 | Cut-off, U	15425366	tkm	Primary

Transport, freight, lorry >32 metric ton, EURO3 {RoW}| market for transport, freight, lorry >32 metric ton, EURO3 | Cut-off, U	15187781	tkm	data and Ecoinvent 3.9.1
4. Operation & Maintenance			
Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | Cut-off, U	13340000	MJ	Primary
Tap water {GLO}| market group for tap water | Cut-off, U	186875000	kg	data and
Electricity, low voltage {CN}| market for | Cut-off, U	3462500	kWh	Ecoinvent 3.9.1
5. End of Life			
Municipal solid waste (waste scenario) {CN}| Treatment of waste | Cut-off, U	100	%	Ecoinvent 3.9.1
5.1 Decommissioning & Dismantling			
Diesel, burned in building machine {GLO}| diesel, burned in building machine | Cut-off, U	5964000	MJ	Primary
Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | Cut-off, U	920000	MJ	data and
Electricity, low voltage {CN}| market for | Cut-off, U	277000	kWh	Ecoinvent 3.9.1

Table S5 Life cycle inventory data for P50MW2013C. P50MW2013C=the grid-connected 50MW of C PV system in 2013.

P50MW2013C				
Assembly	**Materials/Processes**	**Amount**	**Unit**	**Source**
1. PV Module				
	Photovoltaic cell, multi-Si wafer {GLO}| market for photovoltaic cell, multi-Si wafer | Cut-off, U	175669	m^2	Primary
	Silver {GLO}| market for silver | Cut-off, U	6049	kg	data and
	Aluminium alloy, AlMg3 {GLO}| market for aluminium alloy, AlMg3 | Cut-off, U	356079	kg	Ecoinvent
	Solar glass, low-iron {GLO}| market for solar glass, low-iron | Cut-off, U	2973236	kg	3.9.1
	Polyvinylfluoride {GLO}| market for polyvinylfluoride | Cut-off, U	151626	kg	
	Ethylvinylacetate, foil {GLO}| market for ethylvinylacetate, foil | Cut-off, U	284702	kg	
	Silicone product {GLO}| market for | Cut-off, U	3629	kg	
	Polyphenylene sulfide {GLO}| market for polyphenylene sulfide | Cut-off, U	103732	kg	
	Copper {GLO}| market for copper | Cut-off, U	66107	kg	
	Tin {GLO}| market for tin | Cut-off, U	6049	kg	
	Electricity, low voltage {CN}| market for | Cut-off, U	2016535	kWh	
2. Balance of System				
2.1 Mounting Structure				
	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	3388210	kg	Primary
	Forging, steel {GLO}| market for forging, steel | Cut-off, U	3388210	kg	data and
	Zinc coat, pieces {GLO}| market for zinc coat, pieces | Cut-off, U	47549	m^2	Ecoinvent
				3.9.1

2.2 Combiner			
Copper {GLO}| market for copper | Cut-off, U	20000	kg	Primary
Cast iron {GLO}| market for cast iron | Cut-off, U	4000	kg	data and
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	16000	kg	Ecoinvent
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	20000	kg	3.9.1
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	16000	kg	
2.3 Inverter			
Copper {GLO}| market for copper | Cut-off, U	151280	kg	Primary
Cast iron {GLO}| market for cast iron | Cut-off, U	219920	kg	data and
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	385200	kg	Ecoinvent
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	151280	kg	3.9.1
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	385200	kg	
2.4 Transformer			
Cast iron {GLO}| market for cast iron | Cut-off, U	106400	kg	Primary
Silicon, metallurgical grade {GLO}| market for silicon, metallurgical grade | Cut-off, U	5600	kg	data and
Copper {GLO}| market for copper | Cut-off, U	84000	kg	Ecoinvent
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	70000	kg	3.9.1
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	14000	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	84000	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	70000	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	14000	kg	

2.5 Electric Transmission Line			
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	370956	kg	Primary
Polyvinylchloride, bulk polymerised {GLO}| market for polyvinylchloride, bulk polymerised | Cut-off, U	2970	kg	data and
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	138188	kg	Ecoinvent
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	138188	kg	3.9.1
2.6 Boost Voltage Substation System			
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	27285	kg	Primary
Cast iron {GLO}| market for cast iron | Cut-off, U	12414	kg	data and
Copper {GLO}| market for copper | Cut-off, U	12090	kg	Ecoinvent
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	2565	kg	3.9.1
Silicon, metallurgical grade {GLO}| market for silicon, metallurgical grade | Cut-off, U	1026	kg	
Silver {GLO}| market for silver | Cut-off, U	252	kg	
Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	1680	kg	
Polycarbonate {GLO}| market for polycarbonate | Cut-off, U	588	kg	
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	129336	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	27285	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	12090	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	2565	kg	
2.7 Control and Protection System			
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	18657	kg	Primary
Copper {GLO}| market for copper | Cut-off, U	10912	kg	data and

Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	6788	kg	Ecoinvent
Cast iron {GLO}| market for cast iron | Cut-off, U	4527	kg	3.9.1
Polycarbonate {GLO}| market for polycarbonate | Cut-off, U	4116	kg	
Silicon, metallurgical grade {GLO}| market for silicon, metallurgical grade | Cut-off, U	1600	kg	
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	22733	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	18657	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	10912	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	6788	kg	
2.8 Firefighting and Ventilation systems			
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	15795	kg	Primary
Copper {GLO}| market for copper | Cut-off, U	600	kg	data and
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	300	kg	Ecoinvent
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	3699	kg	3.9.1
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	15795	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	600	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	300	kg	
2.9 Civil Works			
Concrete, 25MPa {GLO}| market for concrete, 25MPa | Cut-off, U	9875	m^3	Primary
Reinforcing steel {GLO}| market for reinforcing steel | Cut-off, U	1056445	kg	data and
Concrete, 20MPa {GLO}| market for concrete, 20MPa | Cut-off, U	864	m^3	Ecoinvent
Brick {GLO}| market for | Cut-off, U	9963320	kg	3.9.1

Concrete, 30-32MPa {GLO}| market for concrete, 30-32MPa | Cut-off, U	909.3	m^3	
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	2570	kg	
Copper {GLO}| market for copper | Cut-off, U	1800	kg	
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	450	kg	
Gravel, crushed {GLO}| market for | Cut-off, U	42765660	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	2570	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	1800	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	450	kg	
2.9.1 Construction & Installation			
Diesel, burned in building machine {GLO}| diesel, burned in building machine | Cut-off, U	5964000	MJ	Primary
Tap water {GLO}| market group for tap water | Cut-off, U	21600000	kg	data and
Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | Cut-off, U	920000	MJ	Ecoinvent
Electricity, low voltage {CN}| market for | Cut-off, U	720000	kWh	3.9.1
3. Transportation			
Transport, freight, lorry >32 metric ton, EURO3 {RoW}| market for transport, freight, lorry >32 metric ton, EURO3 | Cut-off, U	15031957	tkm	Primary
Transport, freight, lorry >32 metric ton, EURO3 {RoW}| market for transport, freight, lorry >32 metric ton, EURO3 | Cut-off, U	14518769	tkm	data and Ecoinvent 3.9.1
4. Operation & Maintenance			
Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | Cut-off, U	13340000	MJ	Primary
Tap water {GLO}| market group for tap water | Cut-off, U	251157250	kg	data and

Electricity, low voltage {CN}| market for | Cut-off, U	1837500	kWh	Ecoinvent 3.9.1
5. End of Life			
Municipal solid waste (waste scenario) {CN}| Treatment of waste | Cut-off, U	100	%	Ecoinvent 3.9.1
5.1 Decommissioning & Dismantling			
Diesel, burned in building machine {GLO}| diesel, burned in building machine | Cut-off, U	5964000	MJ	Primary data and Ecoinvent 3.9.1
Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | Cut-off, U	920000	MJ	
Electricity, low voltage {CN}| market for | Cut-off, U	720000	kWh	

Table S6 Life cycle inventory data for P25MW2016. P25MW2016=the grid-connected 25MW of PV system in 2016.

P25MW2016				
Assembly	**Materials/Processes**	**Amount**	**Unit**	**Source**
1. PV Module				
	Photovoltaic cell, multi-Si wafer {GLO}| market for photovoltaic cell, multi-Si wafer | Cut-off, U	72810	m^2	Primary
	Silver {GLO}| market for silver | Cut-off, U	2441	kg	data and
	Aluminium alloy, AlMg3 {GLO}| market for aluminium alloy, AlMg3 | Cut-off, U	154482	kg	Ecoinvent
	Solar glass, low-iron {GLO}| market for solar glass, low-iron | Cut-off, U	1291127	kg	3.9.1
	Polyvinylfluoride {GLO}| market for polyvinylfluoride | Cut-off, U	65908	kg	
	Ethylvinylacetate, foil {GLO}| market for ethylvinylacetate, foil | Cut-off, U	123620	kg	
	Silicone product {GLO}| market for | Cut-off, U	1569	kg	
	Polyphenylene sulfide {GLO}| market for polyphenylene sulfide | Cut-off, U	42761	kg	
	Copper {GLO}| market for copper | Cut-off, U	27894	kg	
	Tin {GLO}| market for tin | Cut-off, U	2615.382	kg	
	Electricity, low voltage {CN}| market for | Cut-off, U	871901	kWh	
2. Balance of System				
2.1 Mounting Structure				
	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	1157680	kg	Primary
	Forging, steel {GLO}| market for forging, steel | Cut-off, U	1157680	kg	data and
	Zinc coat, pieces {GLO}| market for zinc coat, pieces | Cut-off, U	16247	m^2	Ecoinvent
				3.9.1

2.2 Combiner			
Copper {GLO}| market for copper | Cut-off, U	7452	kg	Primary data and Ecoinvent 3.9.1
Cast iron {GLO}| market for cast iron | Cut-off, U	1490	kg	
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	5962	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	7452	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	5962	kg	
2.3 Inverter			
Copper {GLO}| market for copper | Cut-off, U	20700	kg	Primary data and Ecoinvent 3.9.1
Cast iron {GLO}| market for cast iron | Cut-off, U	31050	kg	
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	51750	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	20700	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	51750	kg	
2.4 Transformer			
Cast iron {GLO}| market for cast iron | Cut-off, U	48944	kg	Primary data and Ecoinvent 3.9.1
Silicon, metallurgical grade {GLO}| market for silicon, metallurgical grade | Cut-off, U	2576	kg	
Copper {GLO}| market for copper | Cut-off, U	38640	kg	
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	32200	kg	
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	6440	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	48944	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	32200	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	6440	kg	

2.5 Electric Transmission Line			
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	83545	kg	Primary data and Ecoinvent 3.9.1
Polyvinylchloride, bulk polymerised {GLO}| market for polyvinylchloride, bulk polymerised | Cut-off, U	4212	kg	
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	268815	kg	
Zinc coat, pieces {GLO}| market for zinc coat, pieces | Cut-off, U	3698	m^2	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	268815	kg	
2.6 Boost Voltage Substation System			
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	9570	kg	Primary data and Ecoinvent 3.9.1
Cast iron {GLO}| market for cast iron | Cut-off, U	3898	kg	
Copper {GLO}| market for copper | Cut-off, U	3945	kg	
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	955	kg	
Silicon, metallurgical grade {GLO}| market for silicon, metallurgical grade | Cut-off, U	382	kg	
Silver {GLO}| market for silver | Cut-off, U	105	kg	
Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	700	kg	
Polycarbonate {GLO}| market for polycarbonate | Cut-off, U	245	kg	
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	28307	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	9570	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	3945	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	955	kg	
2.7 Control and Protection System			
Computer, desktop, without screen {GLO}| market for computer, desktop, without screen | Cut-off, U	4	p	Primary data and Ecoinvent 3.9.1

Display, liquid crystal, 17 inches {GLO}| market for display, liquid crystal, 17 inches | Cut-off, U	4	p	data and
Printer, laser, colour {GLO}| market for printer, laser, colour | Cut-off, U	2	p	Ecoinvent
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	7428	kg	3.9.1
Copper {GLO}| market for copper | Cut-off, U	4258	kg	
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	2601	kg	
Cast iron {GLO}| market for cast iron | Cut-off, U	1668	kg	
Polycarbonate {GLO}| market for polycarbonate | Cut-off, U	1559.6	kg	
Silicon, metallurgical grade {GLO}| market for silicon, metallurgical grade | Cut-off, U	585.6	kg	
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	7053	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	7428	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	4258	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	2601	kg	
2.8 Firefighting and Ventilation systems			
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	32850	kg	Primary
Copper {GLO}| market for copper | Cut-off, U	300	kg	data and
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	150	kg	Ecoinvent
Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, U	1200	kg	3.9.1
Cast iron {GLO}| market for cast iron | Cut-off, U	400	kg	
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	120	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	32850	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	300	kg	

Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	150	kg	
Sheet rolling, chromium steel {GLO}| market for sheet rolling, chromium steel | Cut-off, U	1200	kg	
2.9 Civil Works			
Concrete, 30-32MPa {GLO}| market for concrete, 30-32MPa | Cut-off, U	3347	m^3	Primary
Reinforcing steel {GLO}| market for reinforcing steel | Cut-off, U	332150	kg	data and
Concrete, 20MPa {GLO}| market for concrete, 20MPa | Cut-off, U	1466	m^3	Ecoinvent
Brick {GLO}| market for | Cut-off, U	2810400	kg	3.9.1
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	9910	kg	
Copper {GLO}| market for copper | Cut-off, U	600	kg	
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	150	kg	
Steel, unalloyed {GLO}| market for steel, unalloyed | Cut-off, U	28200	kg	
Gravel, round {GLO}| market for | Cut-off, U	378000	kg	
Gravel, crushed {GLO}| market for | Cut-off, U	4620000	kg	
Concrete, 25MPa {GLO}| market for concrete, 25MPa | Cut-off, U	41	m^3	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	38110	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	600	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	150	kg	
2.9.1 Construction & Installation			
Diesel, burned in building machine {GLO}| diesel, burned in building machine | Cut-off, U	2982000	MJ	Primary
Tap water {GLO}| market group for tap water | Cut-off, U	10800000	kg	data and
Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | Cut-off, U	460000	MJ	Ecoinvent

	Electricity, low voltage {CN}| market for | Cut-off, U	90000	kWh	3.9.1
3. Transportation				
	Transport, freight, lorry >32 metric ton, EURO3 {RoW}| market for transport, freight, lorry >32 metric ton, EURO3 | Cut-off, U	6043370	tkm	Primary
	Transport, freight, lorry >32 metric ton, EURO3 {RoW}| market for transport, freight, lorry >32 metric ton, EURO3 | Cut-off, U	5983394	tkm	data and Ecoinvent 3.9.1
4. Operation & Maintenance				
	Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | Cut-off, U	6670000	MJ	Primary
	Tap water {GLO}| market group for tap water | Cut-off, U	85553500	kg	data and
	Electricity, low voltage {CN}| market for | Cut-off, U	3000000	kWh	Ecoinvent 3.9.1
5. End of Life				
	Municipal solid waste (waste scenario) {CN}| Treatment of waste | Cut-off, U	100	%	Ecoinvent 3.9.1
5.1 Decommissioning & Dismantling				
	Diesel, burned in building machine {GLO}| diesel, burned in building machine | Cut-off, U	2982000	MJ	Primary
	Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | Cut-off, U	460000	MJ	data and
	Electricity, low voltage {CN}| market for | Cut-off, U	90000	kWh	Ecoinvent 3.9.1

Table S7 Life cycle inventory data for P50MW2021. P50MW2021=the grid-connected 50MW of PV system in 2021.

P50MW2021				
Assembly	**Materials/Processes**	**Amount**	**Unit**	**Source**
1. PV Module				
	Photovoltaic cell, single-Si wafer {GLO}| market for photovoltaic cell, single-Si wafer | Cut-off, U	162673	m^2	Primary
	Silver {GLO}| market for silver | Cut-off, U	7933	kg	data and
	Aluminium alloy, AlMg3 {GLO}| market for aluminium alloy, AlMg3 | Cut-off, U	247501	kg	Ecoinvent
	Solar glass, low-iron {GLO}| market for solar glass, low-iron | Cut-off, U	1991378	kg	3.9.1
	Polyvinylfluoride {GLO}| market for polyvinylfluoride | Cut-off, U	101539	kg	
	Ethylvinylacetate, foil {GLO}| market for ethylvinylacetate, foil | Cut-off, U	188799	kg	
	Silicone product {GLO}| market for | Cut-off, U	2380	kg	
	Polyphenylene sulfide {GLO}| market for polyphenylene sulfide | Cut-off, U	12164	kg	
	Copper {GLO}| market for copper | Cut-off, U	22212	kg	
	Tin {GLO}| market for tin | Cut-off, U	3966	kg	
	Electricity, low voltage {CN}| market for | Cut-off, U	1322121	kWh	
2. Balance of System				
2.1 Mounting Structure				
	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	576495	kg	Primary
	Aluminium alloy, AlMg3 {GLO}| market for aluminium alloy, AlMg3 | Cut-off, U	134300	kg	data and
	Forging, steel {GLO}| market for forging, steel | Cut-off, U	576495	kg	Ecoinvent
	Zinc coat, pieces {GLO}| market for zinc coat, pieces | Cut-off, U	8090	m^2	3.9.1

2.2 Combiner			
Copper {GLO}| market for copper | Cut-off, U	4914	kg	Primary
Cast iron {GLO}| market for cast iron | Cut-off, U	983	kg	data and
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	3931	kg	Ecoinvent
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	4914	kg	3.9.1
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	3931	kg	
2.3 Integrated Inverter and Transformer			
Cast iron {GLO}| market for cast iron | Cut-off, U	69825	kg	Primary
Silicon, metallurgical grade {GLO}| market for silicon, metallurgical grade | Cut-off, U	3675	kg	data and
Copper {GLO}| market for copper | Cut-off, U	52500	kg	Ecoinvent
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	73500	kg	3.9.1
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	10500	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	52500	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	73500	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	10500	kg	
2.4 Electric Transmission Line			
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	94089	kg	Primary
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	11192	kg	data and
Polyethylene, high density, granulate {GLO}| market for polyethylene, high density, granulate | Cut-off, U	36260	kg	Ecoinvent
Zinc coat, pieces {GLO}| market for zinc coat, pieces | Cut-off, U	157	m^2	3.9.1
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	11192	kg	

2.5 Boost Voltage Substation System			
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	27089	kg	Primary data and Ecoinvent 3.9.1
Cast iron {GLO}| market for cast iron | Cut-off, U	7930	kg	
Copper {GLO}| market for copper | Cut-off, U	8031	kg	
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	612	kg	
Silicon, metallurgical grade {GLO}| market for silicon, metallurgical grade | Cut-off, U	245	kg	
Silver {GLO}| market for silver | Cut-off, U	72	kg	
Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	480	kg	
Polycarbonate {GLO}| market for polycarbonate | Cut-off, U	168	kg	
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	17346	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	27089	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	8031	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	612	kg	
2.6 Control and Protection System			
Computer, desktop, without screen {GLO}| market for computer, desktop, without screen | Cut-off, U	4	p	Primary data and Ecoinvent 3.9.1
Display, liquid crystal, 17 inches {GLO}| market for display, liquid crystal, 17 inches | Cut-off, U	4	p	
Printer, laser, colour {GLO}| market for printer, laser, colour | Cut-off, U	1	p	
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	52049	kg	
Copper {GLO}| market for copper | Cut-off, U	2274	kg	
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	1418	kg	
Cast iron {GLO}| market for cast iron | Cut-off, U	1179	kg	

Polycarbonate {GLO}| market for polycarbonate | Cut-off, U	776	kg	
Silicon, metallurgical grade {GLO}| market for silicon, metallurgical grade | Cut-off, U	284	kg	
Battery, lead acid, rechargeable, stationary {GLO}| market for battery, lead acid, rechargeable, stationary | Cut-off, U	1480	kg	
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	5833	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	52049	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	2274	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	1418	kg	
Zinc coat, pieces {GLO}| market for zinc coat, pieces | Cut-off, U	46	m^2	
2.7 Firefighting and Ventilation systems			
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	17210	kg	Primary
Copper {GLO}| market for copper | Cut-off, U	5849	kg	data and
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	149.4	kg	Ecoinvent
Cast iron {GLO}| market for cast iron | Cut-off, U	5737	kg	3.9.1
Polycarbonate {GLO}| market for polycarbonate | Cut-off, U	60	kg	
Silicon, metallurgical grade {GLO}| market for silicon, metallurgical grade | Cut-off, U	15	kg	
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	800	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	17210	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	5849	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	149	kg	
2.8 Civil Works			
Concrete, 30-32MPa {GLO}| market for concrete, 30-32MPa | Cut-off, U	1431	m^3	Primary

Reinforcing steel {GLO}| market for reinforcing steel | Cut-off, U	152060	kg	data and
Concrete, 20MPa {GLO}| market for concrete, 20MPa | Cut-off, U	62.5	m^3	Ecoinvent
Brick {GLO}| market for | Cut-off, U	298000	kg	3.9.1
Gravel, round {GLO}| market for | Cut-off, U	1340640	kg	
Steel, unalloyed {GLO}| market for steel, unalloyed | Cut-off, U	52236	kg	
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	640	kg	
Concrete, 25MPa {GLO}| market for concrete, 25MPa | Cut-off, U	260	m^3	
Gravel, crushed {GLO}| market for | Cut-off, U	10208728	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	52876	kg	
2.8.1 Construction & Installation			
Diesel, burned in building machine {GLO}| diesel, burned in building machine | Cut-off, U	3834000	MJ	Primary
Tap water {GLO}| market group for tap water | Cut-off, U	21600000	kg	data and
Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | Cut-off, U	690000	MJ	Ecoinvent
Electricity, low voltage {CN}| market for | Cut-off, U	180000	kWh	3.9.1
3. Transportation			
Transport, freight, lorry >32 metric ton, EURO3 {RoW}| market for transport, freight, lorry >32 metric ton, EURO3 | Cut-off, U	7727005	tkm	Primary
Transport, freight, lorry >32 metric ton, EURO3 {RoW}| market for transport, freight, lorry >32 metric ton, EURO3 | Cut-off, U	7265030	tkm	data and Ecoinvent 3.9.1
4. Operation & Maintenance			
Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | Cut-off, U	5290000	MJ	Primary

Tap water {GLO}| market group for tap water | Cut-off, U	40000000	kg	data and
Electricity, low voltage {CN}| market for | Cut-off, U	1475000	kWh	Ecoinvent
			3.9.1
5. End of Life			
Municipal solid waste (waste scenario) {CN}| Treatment of waste | Cut-off, U	100	%	Ecoinvent
			3.9.1
5.1 Decommissioning & Dismantling			
Diesel, burned in building machine {GLO}| diesel, burned in building machine | Cut-off, U	3834000	MJ	Primary
Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | Cut-off, U	690000	MJ	data and
Electricity, low voltage {CN}| market for | Cut-off, U	180000	kWh	Ecoinvent
			3.9.1

Table S8 Life cycle inventory data for P500MW2023. P500MW2023+ESS=the grid-connected 500MW of PV system in 2023 considering ESS.

P500MW2023				
Assembly	**Materials/Processes**	**Amount**	**Unit**	**Source**
1. PV Module				
	Photovoltaic cell, single-Si wafer {GLO}| market for photovoltaic cell, single-Si wafer | Cut-off, U	2215463	m^2	Primary
	Silver {GLO}| market for silver | Cut-off, U	97001	kg	data and
	Solar glass, low-iron {GLO}| market for solar glass, low-iron | Cut-off, U	28381876	kg	Ecoinvent
	Ethylvinylacetate, foil {GLO}| market for ethylvinylacetate, foil | Cut-off, U	2270550	kg	3.9.1
	Aluminium alloy, AlMg3 {GLO}| market for aluminium alloy, AlMg3 | Cut-off, U	2866929	kg	
	Silicone product {GLO}| market for | Cut-off, U	28741	kg	
	Polyphenylene sulfide {GLO}| market for polyphenylene sulfide | Cut-off, U	883790	kg	
	Copper {GLO}| market for copper | Cut-off, U	549674	kg	
	Tin {GLO}| market for tin | Cut-off, U	50297	kg	
	Electricity, low voltage {CN}| market for | Cut-off, U	17963213	kg	
2. Balance of System				
2.1 Mounting Structure				
	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	20860678	kg	Primary
	Aluminium alloy, AlMg3 {GLO}| market for aluminium alloy, AlMg3 | Cut-off, U	898016	kg	data and
	Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, U	449008	kg	Ecoinvent
	Polyphenylene sulfide {GLO}| market for polyphenylene sulfide | Cut-off, U	44900.8	kg	3.9.1
	Copper {GLO}| market for copper | Cut-off, U	67351	kg	

Forging, steel {GLO}| market for forging, steel | Cut-off, U	20860678	kg	
Zinc coat, pieces {GLO}| market for zinc coat, pieces | Cut-off, U	281348	m^2	
Sheet rolling, chromium steel {GLO}| market for sheet rolling, chromium steel | Cut-off, U	449008	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	67351	kg	
2.2 Combiner			
Copper {GLO}| market for copper | Cut-off, U	30800	kg	Primary
Cast iron {GLO}| market for cast iron | Cut-off, U	6160	kg	data and
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	24640	kg	Ecoinvent
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	30800	kg	3.9.1
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	24640	kg	
2.3 Inverter			
Copper {GLO}| market for copper | Cut-off, U	66528	kg	Primary
Cast iron {GLO}| market for cast iron | Cut-off, U	99792	kg	data and
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	166320	kg	Ecoinvent
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	66528	kg	3.9.1
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	166320	kg	
2.4 Transformer			
Cast iron {GLO}| market for cast iron | Cut-off, U	444600	kg	Primary
Silicon, metallurgical grade {GLO}| market for silicon, metallurgical grade | Cut-off, U	23400	kg	data and
Copper {GLO}| market for copper | Cut-off, U	351000	kg	Ecoinvent
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	292500	kg	3.9.1

Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	58500	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	351000	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	292500	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	58500	kg	
2.5 Integrated Inverter and Transformer			
Cast iron {GLO}| market for cast iron | Cut-off, U	478800	kg	Primary
Silicon, metallurgical grade {GLO}| market for silicon, metallurgical grade | Cut-off, U	25200	kg	data and
Copper {GLO}| market for copper | Cut-off, U	360000	kg	Ecoinvent
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	504000	kg	3.9.1
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	72000	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	360000	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	504000	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	72000	kg	
2.6 Electric Transmission Line			
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	1522537	kg	Primary
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	850110	kg	data and
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	850110	kg	Ecoinvent
			3.9.1
2.7 Boost Voltage Substation System			
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	227729	kg	Primary
Cast iron {GLO}| market for cast iron | Cut-off, U	152457	kg	data and

Silicon, metallurgical grade {GLO}| market for silicon, metallurgical grade | Cut-off, U	8083	kg	Ecoinvent
Copper {GLO}| market for copper | Cut-off, U	171725	kg	3.9.1
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	28188	kg	
Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, U	27840	kg	
Synthetic rubber {GLO}| market for synthetic rubber | Cut-off, U	6960	kg	
Zinc oxide {GLO}| market for zinc oxide | Cut-off, U	6960	kg	
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	11178	kg	
Silver {GLO}| market for silver | Cut-off, U	480	kg	
Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	3200	kg	
Polycarbonate {GLO}| market for polycarbonate | Cut-off, U	1120	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	227729	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	171725	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	28188	kg	
Sheet rolling, chromium steel {GLO}| market for sheet rolling, chromium steel | Cut-off, U	27840	kg	
2.8 Control and Protection System			
Computer, desktop, without screen {GLO}| market for computer, desktop, without screen | Cut-off, U	6	p	Primary
Display, liquid crystal, 17 inches {GLO}| market for display, liquid crystal, 17 inches | Cut-off, U	6	p	data and
Printer, laser, colour {GLO}| market for printer, laser, colour | Cut-off, U	2	p	Ecoinvent
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	418842	kg	3.9.1
Copper {GLO}| market for copper | Cut-off, U	11305	kg	

Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	6601	kg	
Cast iron {GLO}| market for cast iron | Cut-off, U	3884	kg	
Polycarbonate {GLO}| market for polycarbonate | Cut-off, U	2905	kg	
Silicon, metallurgical grade {GLO}| market for silicon, metallurgical grade | Cut-off, U	1248	kg	
Battery, lead acid, rechargeable, stationary {GLO}| market for battery, lead acid, rechargeable, stationary | Cut-off, U	7186	kg	
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	61720	kg	
Polyphenylene sulfide {GLO}| market for polyphenylene sulfide | Cut-off, U	847	kg	
Tin {GLO}| market for tin | Cut-off, U	24	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	418842	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	11305	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	6601	kg	
Zinc coat, pieces {GLO}| market for zinc coat, pieces | Cut-off, U	88	m^2	
2.9 Firefighting and Ventilation systems			
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	12990	kg	Primary
Copper {GLO}| market for copper | Cut-off, U	1500	kg	data and
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	750	kg	Ecoinvent
Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, U	1500	kg	3.9.1
Cast iron {GLO}| market for cast iron | Cut-off, U	160	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	12990	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	1500	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	750	kg	

Sheet rolling, chromium steel {GLO}| market for sheet rolling, chromium steel | Cut-off, U	1500	kg	
2.10 Civil Works			
Concrete, 30-32MPa {GLO}| market for concrete, 30-32MPa | Cut-off, U	35004	m^3	Primary
Reinforcing steel {GLO}| market for reinforcing steel | Cut-off, U	2201733	kg	data and
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	1011950	kg	Ecoinvent
Concrete, 20MPa {GLO}| market for concrete, 20MPa | Cut-off, U	668	m^3	3.9.1
Brick {GLO}| market for | Cut-off, U	8994560	kg	
Gravel, round {GLO}| market for | Cut-off, U	11023950	kg	
Steel, unalloyed {GLO}| market for steel, unalloyed | Cut-off, U	159075	kg	
Concrete, 40MPa {RoW}| concrete production 40MPa | Cut-off, U	92	m^3	
Concrete, 25MPa {GLO}| market for concrete, 25MPa | Cut-off, U	4392	m^3	
Concrete block {GLO}| market for concrete block | Cut-off, U	419328	kg	
Gravel, crushed {GLO}| market for | Cut-off, U	102532500	kg	
Concrete, 35MPa {GLO}| market for concrete, 35MPa | Cut-off, U	480	m^3	
Copper {GLO}| market for copper | Cut-off, U	4000	kg	
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	1000	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	1171025	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	4000	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	1000	kg	
2.10.1 Construction & Installation			
Diesel, burned in building machine {GLO}| diesel, burned in building machine | Cut-off, U	38340000	MJ	Primary

Tap water {GLO}| market group for tap water | Cut-off, U	216000000	kg	data and
Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | Cut-off, U	6900000	MJ	Ecoinvent
Electricity, low voltage {CN}| market for | Cut-off, U	1800000	kWh	3.9.1
3. Energy Storage Systems			
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	1107041	kg	Primary
Copper {GLO}| market for copper | Cut-off, U	310625	kg	data and
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	163350	kg	Ecoinvent
Silicon, metallurgical grade {GLO}| market for silicon, metallurgical grade | Cut-off, U	96455	kg	3.9.1
Polycarbonate {GLO}| market for polycarbonate | Cut-off, U	44820	kg	
Battery, Li-ion, LFP, rechargeable, prismatic {GLO}| market for battery, Li-ion, LFP, rechargeable, prismatic | Cut-off, U	4178304	kg	
Battery, lead acid, rechargeable, stationary {GLO}| market for battery, lead acid, rechargeable, stationary | Cut-off, U	1500	kg	
Computer, desktop, without screen {GLO}| market for computer, desktop, without screen | Cut-off, U	4	kg	
Cast iron {GLO}| market for cast iron | Cut-off, U	37.5	kg	
Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U	225348	kg	
Zinc coat, pieces {GLO}| market for zinc coat, pieces | Cut-off, U	570	m^2	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	1107041	kg	
Wire drawing, copper {GLO}| market for wire drawing, copper | Cut-off, U	310625	kg	
Sheet rolling, aluminium {GLO}| market for sheet rolling, aluminium | Cut-off, U	163350	kg	
3.1 Civil Works of Energy Storage Systems			
Gravel, crushed {GLO}| market for | Cut-off, U	3161078	kg	Primary
Concrete, 20MPa {GLO}| market for concrete, 20MPa | Cut-off, U	2429	m^3	data and

Concrete, 30-32MPa {GLO}| market for concrete, 30-32MPa | Cut-off, U	4785	m^3	Ecoinvent
Reinforcing steel {GLO}| market for reinforcing steel | Cut-off, U	516836	kg	3.9.1
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	37350	kg	
Brick {GLO}| market for | Cut-off, U	1066052	kg	
Polyester resin, unsaturated {GLO}| market for | Cut-off, U	29702	kg	
Glass fibre {GLO}| market for glass fibre | Cut-off, U	4243	kg	
Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U	37350	kg	
4. Transportation			
4.1 Transportation of P500MW2023			
Transport, freight, lorry >32 metric ton, EURO3{RoW}| market for transport, freight, lorry >32 metric ton, EURO3 | Cut-off, U	111941341	tkm	Primary
Transport, freight, lorry >32 metric ton, EURO3 {RoW}| market for transport, freight, lorry >32 metric ton, EURO3 | Cut-off, U	109670212	tkm	data and Ecoinvent 3.9.1
4.2 Transportation of Energy Storage Systems			
Transport, freight, lorry >32 metric ton, EURO3 {RoW}| market for transport, freight, lorry >32 metric ton, EURO3 | Cut-off, U	6570688	tkm	Primary
Transport, freight, lorry >32 metric ton, EURO3 {RoW}| market for transport, freight, lorry >32 metric ton, EURO3 | Cut-off, U	6507467	tkm	data and Ecoinvent 3.9.1
5. Operation & Maintenance			
Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | Cut-off, U	10005000	MJ	Primary
Tap water {GLO}| market group for tap water | Cut-off, U	300000000	kg	data and

Electricity, low voltage {CN}| market for | Cut-off, U	53750000	kWh	Ecoinvent 3.9.1
6. End of Life			
Municipal solid waste (waste scenario) {CN}| Treatment of waste | Cut-off, U	100	%	Ecoinvent 3.9.1
6.1 Decommissioning & Dismantling			
Diesel, burned in building machine {GLO}| diesel, burned in building machine | Cut-off, U	38340000	MJ	Primary data and Ecoinvent 3.9.1
Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | Cut-off, U	6900000	MJ	
Electricity, low voltage {CN}| market for | Cut-off, U	1800000	kWh	

Prior to the C&I and disposal stages, this study investigated the true transportation distances from manufacturing plants to deliver the PV Module, Combiner, Inverter and transformer to the site. The materials for the civil works were obtained from the nearest location, the Gonghe of Qinghai, China. All the other equipment was obtained from within 1000km around the electricity generation system, which was taken as 1000km for this study.

Table S9 The PV systems equipment transportation distance and production location.

Transportation/km / PV Systems	PV Module	Combiner	Inverter	Transformer	Integrated inverter and transformer	Civil Works	The other equipment
P20MW2013A	2200 (*Changzhou, Jiangsu, China*)	2247 (*Wuxi, Jiangsu, China*)	2247 (*Wuxi, Jiangsu, China*)	1804 (*Taian, Shandong, China*)	/	12 (*Gonghe, Qinghai, China*)	1000
P50MW2013B	2200 (*Changzhou, Jiangsu, China*)	2247 (*Wuxi, Jiangsu, China*)	2247 (*Wuxi, Jiangsu, China*)	2489 (*Ningbo, Zhejiang, China*)	/	12 (*Gonghe, Qinghai, China*)	1000
P50MW2013C	2200 (*Changzhou, Jiangsu, China*)	2247 (*Wuxi, Jiangsu, China*)	694 (*Jiuquan, Gansu, China*)	2489 (*Ningbo, Zhejiang, China*)	/	12 (*Gonghe, Qinghai, China*)	1000
P25MW2016	2200 (*Changzhou, Jiangsu, China*)	2247 (*Wuxi, Jiangsu, China*)	2247 (*Wuxi, Jiangsu, China*)	1804 (*Taian, Shandong, China*)	/	12 (*Gonghe, Qinghai, China*)	1000
P50MW2021	2228 (*Changzhou, Jiangsu, China*)	2275 (*Wuxi, Jiangsu, China*)	/	/	722 (*Jiuquan, Gansu, China*)	40 (*Gonghe, Qinghai, China*)	1000
P500MW2023	2208 (*Changzhou, Jiangsu, China*)	2253 (*Wuxi, Jiangsu, China*)	2253 (*Wuxi, Jiangsu, China*)	702 (*Jiuquan, Gansu, China*)	702 (*Jiuquan, Gansu, China*)	20 (*Gonghe, Qinghai, China*)	1000

Table S10 Specifications and quantities of combiners, inverters and transformers for PV systems.

Specification (quantity) / PV System	Combiner	Inverter	Transformer	Integrated inverter and transformer
P20MW2013A	1000V DC (320)	500kW (40)	1000kW (20)	/
P50MW2013B	1000V DC (700)	500kW (100)	1000kW (50)	/
P50MW2013C	1000V DC (800)	500kW (100)	1000kW (50)	/
P25MW2016	1000V DC (276)	1000kW (23)	1000kW (23)	/
P50MW2021	1500V DC (182)	/	/	3150kW (14)
P500MW2023	1500V DC (1120)	225kW (1120)	3150kW (78)	3150kW (80)

3 Results

3.1 Contribution Analysis

The CED of each component in the life cycle of the PV systems is shown in **Table S11**, and the GHG impact is shown in **Table S12**.

Table S11 CED (TJ/MW) during the life cycle of PV systems.

Life cycle stages / PV systems	Total	PV Module	BOS						Transportation	O&M	EoL	
			Total	Mounting Structure	C&I&T	ETL	OAS	Civil Works				
P20MW2013A	26.30	14.42	8.16	2.88	0.91	1.17	0.53	2.67	1.03	2.41	0.29	
P50MW2013B	24.04	14.42	7.23	2.86	0.90	1.19	0.32	1.96	1.01	1.09	0.29	
P50MW2013C	24.06	14.42	7.51	2.87	0.91	0.91	0.52	2.31	0.98	0.77	0.39	
P25MW2016	19.95	12.22	5.02	1.99	0.47	0.71	0.33	1.53	0.81	1.63	0.26	
P50MW2021	18.88	15.89	1.85	0.75	0.22	0.28	0.17	0.44	0.50	0.45	0.18	
P500MW2023	21.49	16.97	2.84	1.65	0.24	0.32	0.10	0.54	0.60	0.93	0.15	**ESS**
P500MW2023+ESS	22.88	16.97	2.84	1.65	0.24	0.32	0.10	0.54	0.63	0.93	0.15	1.35

Table S12 GHG emissions (gCO_2-eq/kWh) during the life cycle of PV systems.

Life cycle stages / Photovoltaics Plants	Total	PV Module	BOS						Transportation	O&M	EoL	
			Total	Mounting Structure	C&I&T	ETL	OAS	Civil Works				
P20MW2013A	54.68	25.12	17.77	6.14	1.88	1.86	0.98	6.91	1.83	6.42	3.55	
P50MW2013B	48.42	25.12	15.65	6.10	1.86	1.92	0.59	5.18	1.80	2.75	3.09	
P50MW2013C	48.52	25.12	16.28	6.11	1.87	1.42	0.86	6.02	1.74	1.85	3.53	
P25MW2016	38.84	20.30	10.76	4.03	0.92	1.24	0.56	4.02	1.37	4.07	2.34	
P50MW2021	32.54	25.85	3.55	1.49	0.42	0.35	0.29	1.01	0.82	1.05	1.26	
P500MW2023	35.76	25.96	5.37	3.06	0.43	0.44	0.17	1.27	0.93	2.24	1.26	**ESS**
P500MW2023+ESS	35.03	23.74	4.91	2.80	0.40	0.40	0.16	1.16	0.90	2.05	1.27	2.16

3.2 Uncertainty Analysis

The GHG impacts and CED of uncertainty analysis of six large-scale PV systems. Monte Carlo method is used by 1000 iterations with 95% confidence intervals. (see **Fig. S4**) The uncertainty analysis results of the CED and GHG impacts of the PV systems in this study, such as mean, median, lower range, upper range, SD, CV and SEM, are shown in **Table S13** and **Table S14**, respectively.

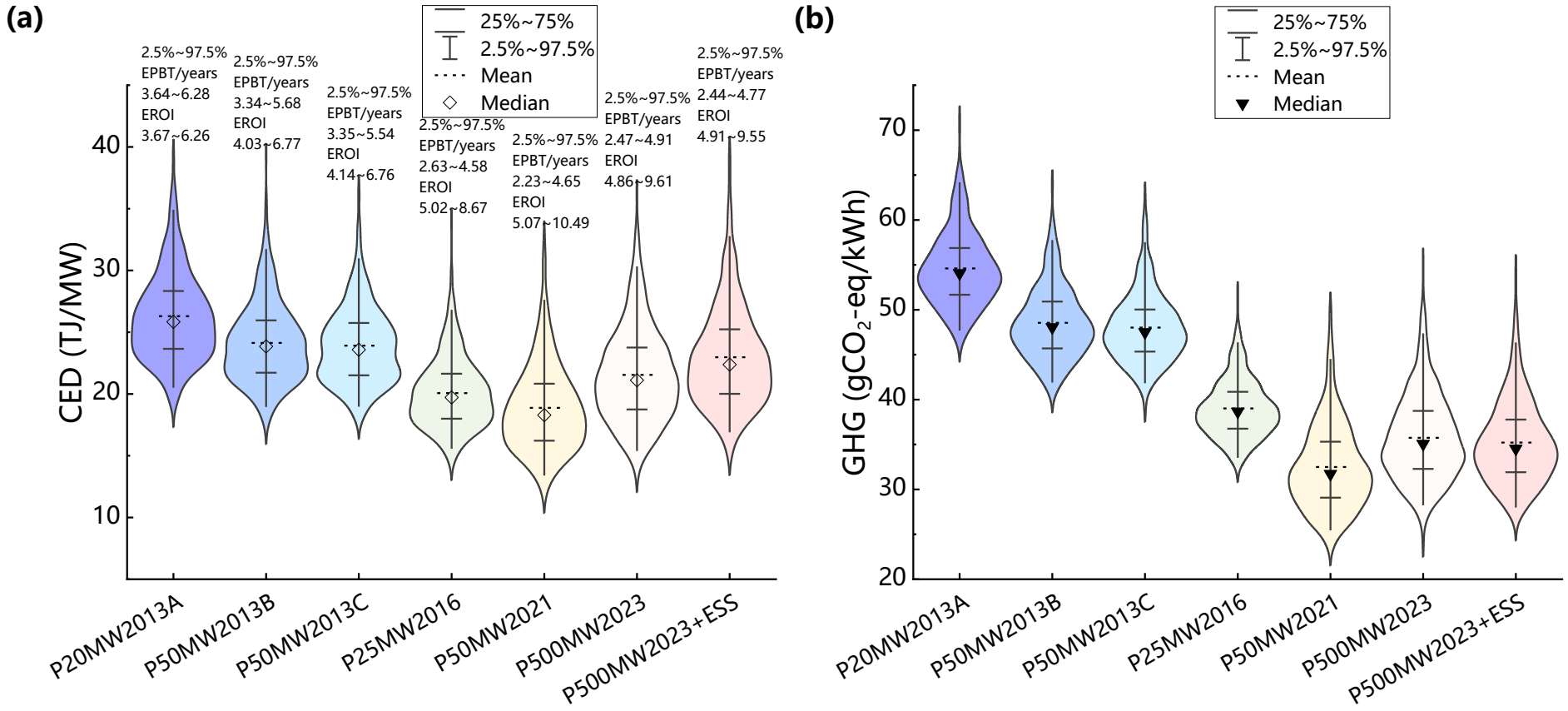

Fig. S4. Uncertainty analysis of six large-scale PV systems. (a) Uncertainty analyses for CED and the range of EPBT and EROI values within the upper and lower ranges (2.5%~97.5%). (b) Uncertainty analysis for GHG impacts.

Table S13 Uncertainty analysis results of CED impacts.

Photovoltaics systems	Impact category	Mean	Median	Lower range - upper range (2.5%-97.5%)	SD	CV/%	SEM
		TJ/MW	TJ/MW	TJ/MW			
P20MW2013A		26.30	25.84	20.49-34.92	3.71	14.12	0.1174
P50MW2013B		24.14	23.85	18.93-31.80	3.34	13.84	0.1056
P50MW2013C		23.92	23.59	18.97-31.01	3.21	13.44	0.1017
P25MW2016	**CED**	20.07	19.71	15.56-26.86	2.91	14.50	0.0920
P50MW2021		18.88	18.29	13.38-27.68	3.66	19.40	0.1158
P500MW2023		21.55	21.11	15.34-30.35	3.89	18.07	0.1231
P500MW2023+ESS		22.97	22.38	16.87-32.80	4.07	17.71	0.1286

Table S14 Uncertainty analysis results of GHG impacts.

Photovoltaics systems	Impact category	Mean	Median	Lower range - upper range (2.5%-97.5%)	SD	CV/%	SEM
		gCO_2-eq/kWh	gCO_2-eq/kWh	gCO_2-eq/kWh			
P20MW2013A		54.61	54.07	47.68-64.21	4.28	7.83	0.1352
P50MW2013B		48.55	48.04	41.90-57.86	4.14	8.53	0.1309
P50MW2013C		48.01	47.50	41.81-57.60	3.86	8.05	0.1222
P25MW2016	**GHG**	39.01	38.65	33.50-46.46	3.34	8.55	0.1055
P50MW2021		32.50	31.73	25.43-44.54	4.85	14.91	0.1532
P500MW2023		35.74	35.07	28.16-47.38	4.86	13.61	0.1538
P500MW2023+ESS		35.21	34.54	27.98-46.39	4.64	13.17	0.1466

3.3 Sensitivity Analysis

In both the sensitivity and scenario analysis, the assumptions about the parameter ranges are based on the current state of technological and managerial advances in the PV industry, as well as on forecasts of future developments. Specifically, (i) the market generally accepts a financing model with a PV system lifetime of 35 years[14], with 30-40 years of lifetime[15] providing considerable environmental benefits. Therefore, we adopt a 35/40 years dual parameter setting with the aim of examining the impact of lifetime extension on the full life cycle GHG emissions and energy payback of the PV systems. (ii) Current cell manufacturing processes, mainly through multi-busbar technology and reduced busbar width, can reduce silver consumption by 40.6%-54.6%.[16] Therefore, a 50% reduction is used as the range of silver usage reduction due to technological advances. (iii) The assumption of -50% Low alloy steel stems from the technological iteration of PV mounting structures: the new flexible and flat single axis brackets can achieve a significant reduction in the amount of low alloy steel under the premise of maintaining the structural stiffness through topology optimization design, as shown in Fig. 2a for the mounting structure of the CED. Therefore, the range of 50 % reduction in low alloy steel consumption is adopted. (iv) The ranges of PV module efficiency and wafer thickness parameters are reasonable assumptions based on the development roadmap of the Chinese PV industry released by the China Photovoltaic Industry Association (CPIA) over the years.[17] (v) The parameter ranges for the curtailment rate and performance ratio are assumed to be based on real local power plant operations and ideal conditions. It is important to note that all assumptions are based on a steady-state technology analysis framework, with the time dimension implicit in the range of technological advances.

The base case values of sensitivity analysis are shown in **Table S15**.

Table S15 The base case values of sensitivity analysis.

variables \ PV systems		P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023	P500MW2023+ESS
		Base case values						
Fig. 3	PV module efficiency/%	14.98	14.98	14.98	16.20	20.89	21.10	21.10
	Disposal scenario	MSWS of CN	MSWS of CN	MSWS of CN	MSWS of CN	MSWS of CN	MSWS of CN	MSWS of CN
	Lifetime/years	25	25	25	25	25	25	25
Fig. S7	silicon wafer thickness/ μ m	200	200	200	185	170	150	150
	mass change of silver/%	0	0	0	0	0	0	0
Fig. S8	mass change of low alloy steel/%	0	0	0	0	0	0	0
	mass change of concrete/%	0	0	0	0	0	0	0
Fig. S9	curtailment rate/%	8	8	8	8	8	8	8
	performance ratio	0.799	0.799	0.799	0.802	0.834	0.823	0.823

Fig. S5 shows the sensitivity analysis of silicon wafer thickness and mass change of silver on PV module. **Fig. S6** shows the sensitivity analysis of mass change of low alloy steel on mounting structure and mass change of concrete on civil works. **Fig. S7** shows the sensitivity analysis of curtailment rate and performance ratio on PV systems.

The raw data and fitting results for all the sensitivity analyses in this study are shown in the **Tables S16 − S38**, and the fits are replicated.

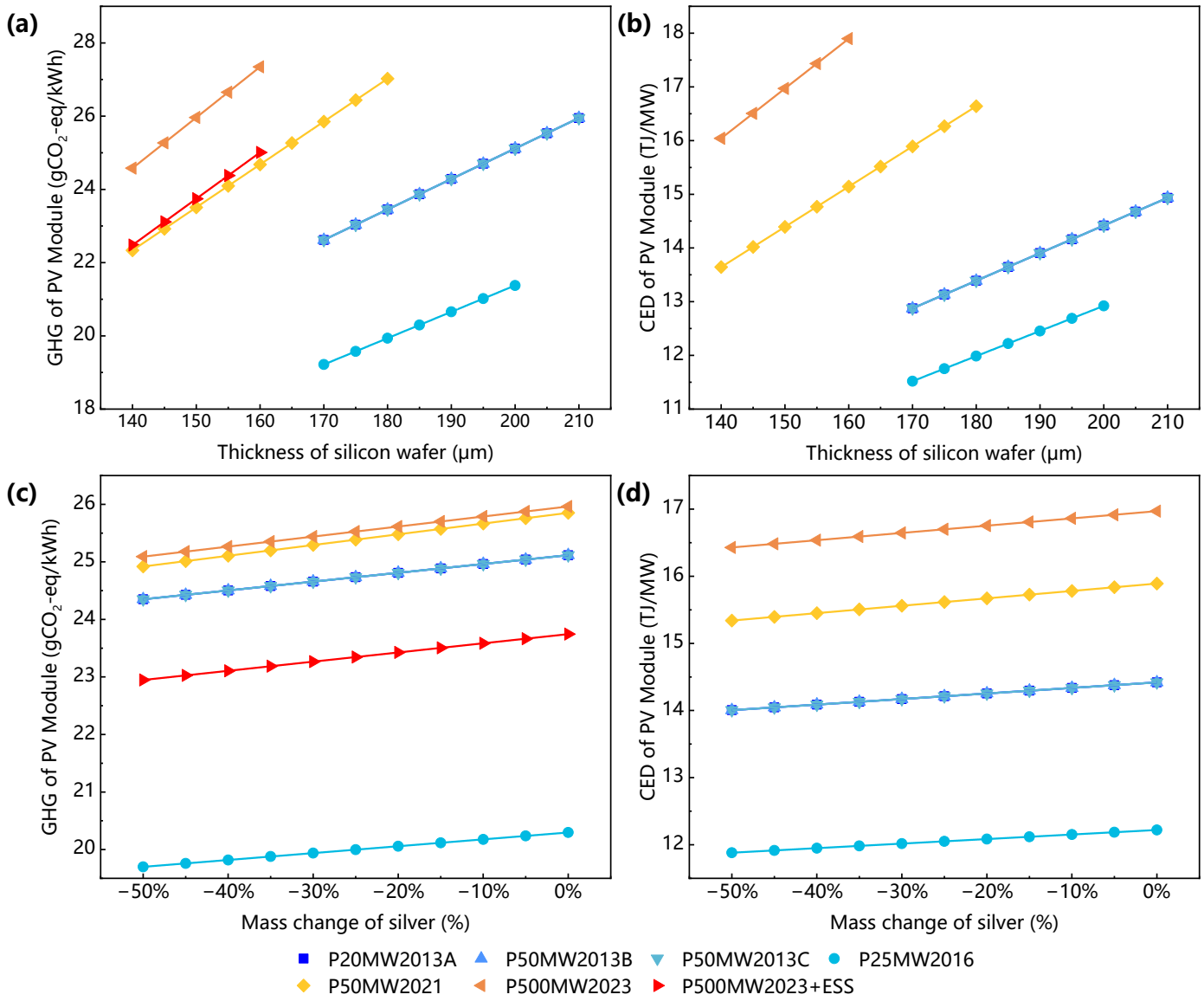

Fig. S5. The sensitivity analysis results on silicon wafer thickness variation for (a) GHG and (b) CED of PV module. The sensitivity analysis results on mass change of silver on PV module for (c) GHG and (d) CED of PV module.

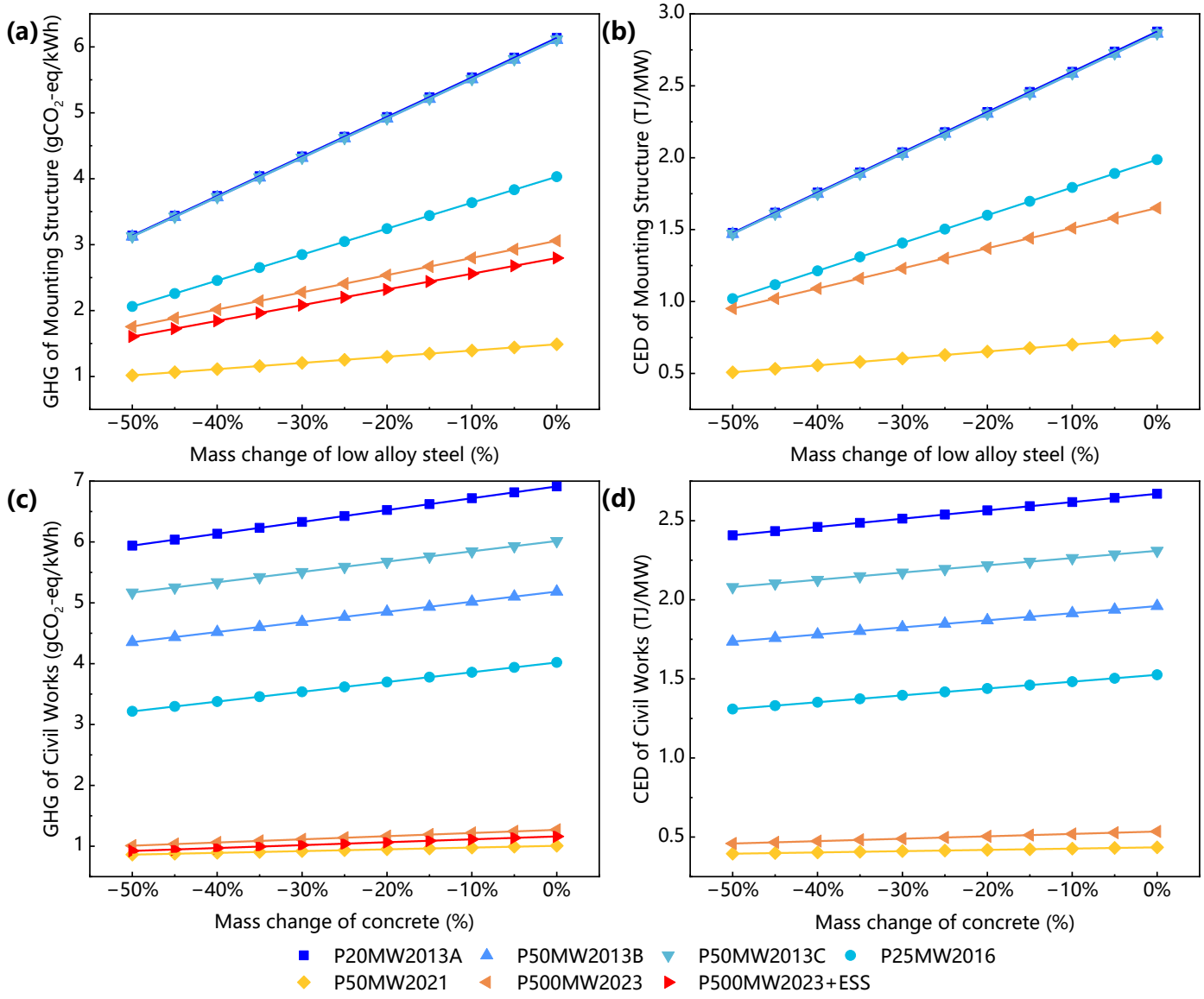

Fig. S6. The sensitivity analysis results on mass change of low alloy steel for (a) GHG and (b) CED of mounting structure. The sensitivity analysis results on mass change of concrete for (c) GHG and (d) CED of civil works.

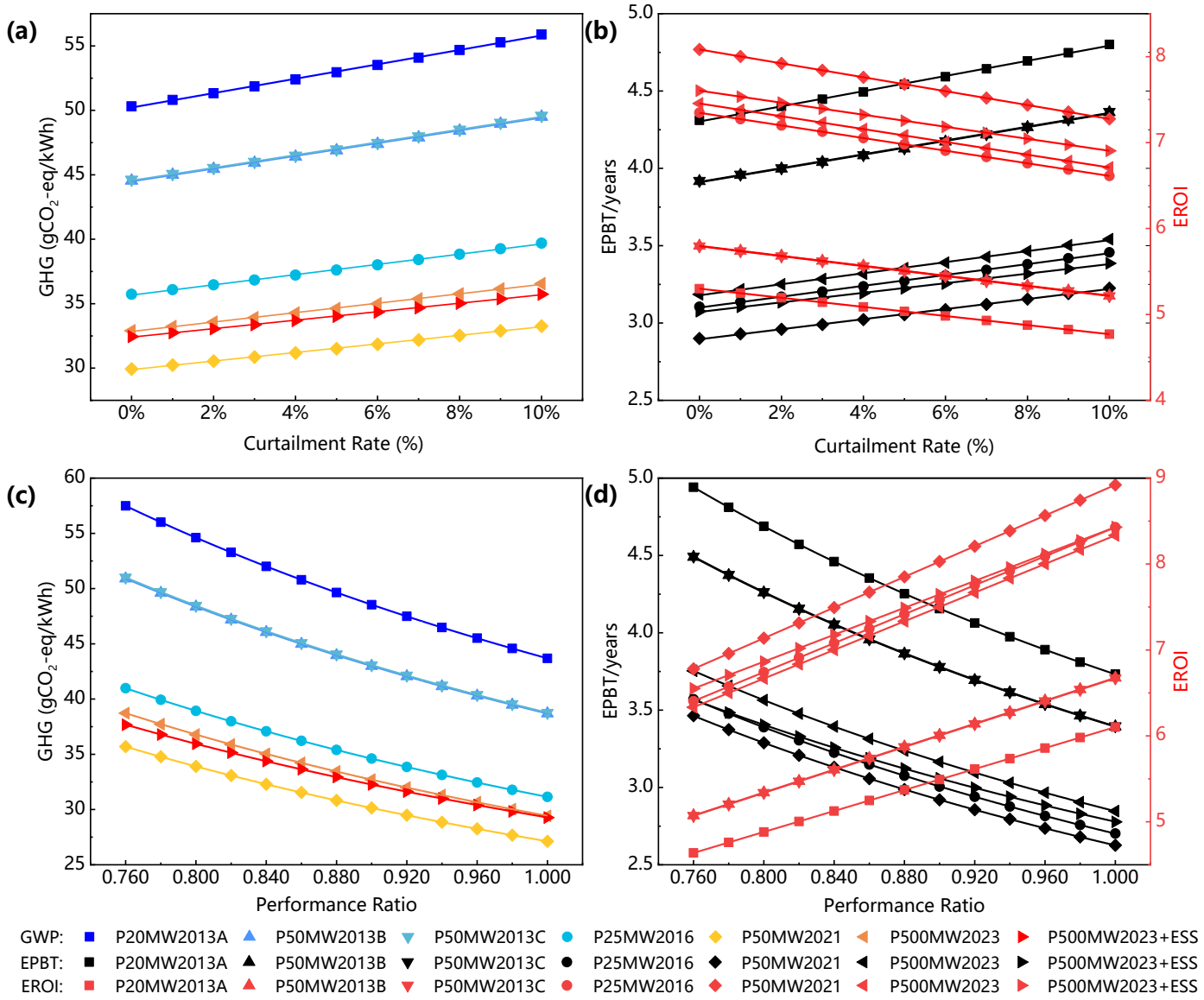

Fig. S7. The sensitivity analysis results on the curtailment rate for (a) GHG, (b) EPBT and EROI of PV systems lifecycle. The sensitivity analysis results on the performance ratio for (c) GHG, (d) EPBT and EROI of PV systems lifecycle.

Table S16 Data and fitting results for sensitivity of PV module efficiency change to GHG (gCO_2-eq/kWh) of PV systems.

PV systems / Efficiency/%	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023	P500MW2023+ESS
15%	54.60618	48.35726	48.45165				
16%	51.1933	45.33493	45.42342	39.32141			
17%	48.18193	42.66817	42.75145	37.00838			
18%	45.50515	40.29772	40.37637	34.95236			
19%	43.11014	38.17678	38.2513	33.11276			
20%	40.95464	36.26795	36.33873	31.45713	33.98787		
21%	39.00442	34.5409	34.60832	29.95917	32.3694	35.93245	35.1842
22%	37.23149	32.97086	33.03521	28.59739	30.89806	34.29916	33.71643
23%	35.61273	31.53734	31.5989	27.35402	29.55467	32.80789	32.36622
24%					28.32322	31.4409	31.11999
25%					27.19029	30.18326	29.96617
26%					26.14451	29.02237	28.89485
27%					25.1762	27.94746	27.89749
Fitting	$y=8.1909x^{-1}$	$y=7.2536x^{-1}$	$y=7.2678x^{-1}$	$y=6.2914x^{-1}$	$y=6.7976x^{-1}$	$y=7.5458x^{-1}$	$y=8.3330x^{-0.9231}$
R^2	1	1	1	1	1	1	1

Table S17 Data and fitting results for sensitivity of PV module efficiency change to EPBT (years) of PV systems.

PV systems / Efficiency/%	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023	P500MW2023+ESS
15%	4.688156	4.259777	4.263146				
16%	4.388535	3.997489	3.990223	3.423403			
17%	4.124163	3.756769	3.751827	3.218559			
18%	3.890318	3.542797	3.53992	3.036475			
19%	3.682245	3.351348	3.350319	2.874614			
20%	3.494979	3.179044	3.179678	2.729213	3.296601		
21%	3.325547	3.02315	3.025289	2.59766	3.137989	3.480873	3.333101
22%	3.171519	2.883872	2.886121	2.478066	2.993831	3.321382	3.195132
23%	3.030884	2.757142	2.759293	2.368872	2.862924	3.175759	3.068043
24%					2.742926	3.042272	2.950805
25%					2.632528	2.919837	2.842406
26%					2.530622	2.807001	2.741654
27%					2.436265	2.702523	2.647767
Fitting	$y=0.6766x^{-1.0202}$	$y=0.6149x^{-1.0209}$	$y=0.6178x^{-1.0180}$	$y=0.5333x^{-1.0145}$	$y=0.6513x^{-1.0076}$	$y=0.7226x^{-1.0073}$	$y=0.7986x^{-0.9157}$
R^2	1	1	1	1	1	1	1

Table S18 Data and fitting results for sensitivity of PV module efficiency change to EROI of PV systems.

PV systems / Efficiency/%	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023	P500MW2023+ESS
15%	4.882369	5.341482	5.337363				
16%	5.20786	5.697581	5.693187	6.675463			
17%	5.533351	6.05368	6.049011	7.09268			
18%	5.858842	6.409778	6.404835	7.509896			
19%	6.184334	6.765877	6.76066	7.927113			
20%	6.509825	7.121976	7.116484	8.344329	7.119993		
21%	6.835316	7.478075	7.472308	8.761546	7.475993	6.826362	7.013545
22%	7.160807	7.834174	7.828132	9.178762	7.831992	7.151427	7.318863
23%	7.486299	8.190272	8.183956	9.595979	8.187992	7.476492	7.624181
24%					8.543991	7.801557	7.9295
25%					8.899991	8.126622	8.234818
26%					9.255991	8.451687	8.540137
27%					9.61199	8.776752	8.845455
Fitting	y=32.5491x	y=35.6099x	y=35.5824x	y=41.7217x	y=35.6000x	y=32.5065x	y=30.5318x+0.6019
R^2	1	1	1	1	1	11	1

Table S19 Data and fitting results for sensitivity of silicon wafer thickness variation to GHG (gCO_2-eq/kWh) of PV modules.

PV systems / μm	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023	P500MW2023+ESS
140					22.33703	24.5795	22.47939
145					22.92283	25.27101	23.11182
150					23.50863	25.96253	23.74425
155					24.09443	26.65404	24.37668
160					24.68023	27.34556	25.00911
165					25.26603		
170	22.61873	22.6202	22.61871	19.21693	25.85184		
175	23.03499	23.03645	23.03497	19.57688	26.43764		
180	23.45125	23.45271	23.45123	19.93682	27.02344		
185	23.8675	23.86897	23.86748	20.29676			
190	24.28376	24.28523	24.28374	20.65671			
195	24.70001	24.70149	24.7	21.01665			
200	25.11627	25.11775	25.11626	21.37659			
205	25.53253	25.53401	25.53252				
210	25.94878	25.95026	25.94878				
Fitting	y=0.0833x+8.4660	y=0.0833x+8.4674	y=0.0833x+8.4659	y=0.0720x+6.9789	y=0.1172x+5.9346	y=0.1383x+5.2171	y=0.1265x+4.7713
R^2	1	1	1	1	1	1	1

Table S20 Data and fitting results for sensitivity of silicon wafer thickness variation to CED (TJ/MW) of PV modules.

PV systems / μm	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023
140					13.6444	16.04176
145					14.01886	16.50584
150					14.39333	16.96992
155					14.76779	17.43401
160					15.14226	17.89809
165					15.51672	
170	12.87523	12.87598	12.87514	11.51895	15.89119	
175	13.13256	13.13332	13.13247	11.75286	16.26565	
180	13.38989	13.39065	13.38981	11.98677	16.64012	
185	13.64723	13.64799	13.64714	12.22068		
190	13.90456	13.90532	13.90448	12.45459		
195	14.1619	14.16266	14.16181	12.6885		
200	14.41923	14.41999	14.41915	12.92241		
205	14.67657	14.67733	14.67648			
210	14.9339	14.93466	14.93381			
Fitting	y=0.0515x+4.1259	0.0515x+4.1266	0.0515x+4.1258	0.0468x+3.5660	0.0749x+3.1594	0.0928x+3.0475
R^2	1	1	1	1	1	1

Table S21 Data and fitting results for sensitivity of silver usage variation to GHG (gCO_2-eq/kWh) of PV modules.

PV systems / change	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023	P500MW2023+ESS
-50%	24.34955	24.35103	24.34954	19.69966	24.9196	25.09071	22.94692
-45%	24.42623	24.4277	24.42621	19.75937	25.01282	25.17789	23.02665
-40%	24.5029	24.50437	24.50288	19.81908	25.10605	25.26508	23.10639
-35%	24.57957	24.58104	24.57956	19.87879	25.19927	25.35226	23.18612
-30%	24.65624	24.65772	24.65623	19.9385	25.29249	25.43944	23.26585
-25%	24.73291	24.73439	24.7329	19.99821	25.38572	25.52662	23.34558
-20%	24.80958	24.81106	24.80957	20.05792	25.47894	25.6138	23.42532
-15%	24.88626	24.88773	24.88624	20.11763	25.57216	25.70098	23.50505
-10%	24.96293	24.9644	24.96292	20.17734	25.66539	25.78817	23.58478
-5%	25.0396	25.04108	25.03959	20.23705	25.75861	25.87535	23.66452
0	25.11627	25.11775	25.11626	20.29676	25.85184	25.96253	23.74425
Fitting	y=1.5334x+25.1163	y=1.5334x+25.1178	y=1.5334x+25.1163	y=1.1942x+20.2968	y=1.8645x+25.8518	y=1.7436x+25.9625	y=1.5947x+23.7443
R^2	1	1	1	1	1	1	1

Table S22 Data and fitting results for sensitivity of silver usage variation to CED (TJ/MW) of PV modules.

PV systems / change	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023
-50%	14.00511	14.00587	14.00502	11.88166	15.34005	16.4288
-45%	14.04652	14.04728	14.04643	11.91556	15.39516	16.48291
-40%	14.08793	14.08869	14.08785	11.94946	15.45027	16.53703
-35%	14.12935	14.13011	14.12926	11.98337	15.50539	16.59114
-30%	14.17076	14.17152	14.17067	12.01727	15.5605	16.64525
-25%	14.21217	14.21293	14.21208	12.05117	15.61562	16.69936
-20%	14.25358	14.25434	14.2535	12.08507	15.67073	16.75348
-15%	14.295	14.29576	14.29491	12.11897	15.72585	16.80759
-10%	14.33641	14.33717	14.33632	12.15288	15.78096	16.8617
-5%	14.37782	14.37858	14.37773	12.18678	15.83607	16.91581
0	14.41923	14.41999	14.41915	12.22068	15.89119	16.96992
Fitting	y=0.8283x+14.4192	y=0.8283x+14.4200	y=0.8383x+14.4192	y=0.6780x+12.2207	y=1.1023x+15.8912	y=1.0822x+16.9699
R^2	1	1	1	1	1	1

Table S23 Data and fitting results for sensitivity of low alloy steel usage variation to GHG (gCO_2-eq/kWh) of Mounting Structures.

PV systems / change	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023	P500MW2023+ESS
-50%	3.137136	3.12103	3.125015	2.06058	1.016585	1.754378	1.604481
-45%	3.436944	3.4193	3.423665	2.257504	1.063697	1.884757	1.723721
-40%	3.736753	3.717569	3.722316	2.454429	1.110809	2.015136	1.84296
-35%	4.036561	4.015839	4.020966	2.651354	1.157921	2.145516	1.962199
-30%	4.33637	4.314108	4.319616	2.848279	1.205033	2.275895	2.081439
-25%	4.636178	4.612378	4.618267	3.045204	1.252145	2.406274	2.200678
-20%	4.935987	4.910648	4.916917	3.242128	1.299257	2.536653	2.319917
-15%	5.235795	5.208917	5.215568	3.439053	1.346369	2.667032	2.439157
-10%	5.535604	5.507187	5.514218	3.635978	1.393481	2.797411	2.558396
-5%	5.835412	5.805457	5.812869	3.832903	1.440592	2.92779	2.677635
0%	6.135221	6.103726	6.111519	4.029827	1.487704	3.05817	2.796875
Fitting	y=5.9962x+6.1352	y=5.9654x+6.1037	y=5.9730x+6.1115	y=3.9385x+4.0298	y=0.9422x+1.4877	y=2.6076x+3.0582	y=2.3848x+2.7969
R^2	1	1	1	1	1	1	1

Table S24 Data and fitting results for sensitivity of low alloy steel usage variation to CED (TJ/MW) of Mounting Structures.

PV systems / change	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023
-50%	1.47758	1.469986	1.471863	1.020197	0.508094	0.950946
-45%	1.617529	1.609216	1.61127	1.116825	0.532166	1.020883
-40%	1.757478	1.748445	1.750677	1.213453	0.556237	1.09082
-35%	1.897427	1.887675	1.890085	1.310081	0.580308	1.160758
-30%	2.037376	2.026905	2.029492	1.406709	0.604379	1.230695
-25%	2.177324	2.166135	2.1689	1.503337	0.628451	1.300632
-20%	2.317273	2.305364	2.308307	1.599965	0.652522	1.370569
-15%	2.457222	2.444594	2.447715	1.696593	0.676593	1.440506
-10%	2.597171	2.583824	2.587122	1.793221	0.700664	1.510443
-5%	2.73712	2.723054	2.72653	1.889849	0.724736	1.58038
0%	2.877069	2.862283	2.865937	1.986477	0.748807	1.650317
Fitting	y=2.7990x+2.8771	y=2.7846x+2.8623	y=2.7882x+2.8659	y=1.9326x+1.9865	y=0.4814x+0.7488	y=1.3987x+1.6503
R^2	1	1	1	1	1	1

Table S25 Data and fitting results for sensitivity of concrete usage variation to GHG (gCO_2-eq/kWh) of Civil Works.

PV systems / change	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023	P500MW2023+ESS
-50%	5.939952	4.353405	5.168342	3.215898	0.861711	1.008722	0.922535
-45%	6.037232	4.436474	5.253073	3.296258	0.876188	1.034769	0.946357
-40%	6.134512	4.519543	5.337804	3.376619	0.890665	1.060817	0.970179
-35%	6.231793	4.602612	5.422535	3.456979	0.905141	1.086864	0.994001
-30%	6.329073	4.685681	5.507266	3.537339	0.919618	1.112911	1.017822
-25%	6.426354	4.76875	5.591997	3.6177	0.934095	1.138959	1.041644
-20%	6.523634	4.851819	5.676727	3.69806	0.948572	1.165006	1.065466
-15%	6.620915	4.934888	5.761458	3.77842	0.963048	1.191053	1.089288
-10%	6.718195	5.017957	5.846189	3.85878	0.977525	1.2171	1.113109
-5%	6.815476	5.101026	5.93092	3.93914	0.992002	1.243148	1.136931
0%	6.912756	5.184095	6.015651	4.019501	1.006478	1.269195	1.160753
Fitting	y=1.9456x+6.9128	y=1.6614x+5.1841	y=1.6946x+6.0157	y=1.6072x+4.0195	y=0.2895x+1.0065	y=0.5210x+1.2692	y=0.4764x+1.1608
R^2	1	1	1	1	1	1	1

Table S26 Data and fitting results for sensitivity of concrete usage variation to CED (TJ/MW) of Civil Works.

PV systems / change	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023
-50%	2.407522	1.73541	2.080384	1.309192	0.394933	0.459245
-45%	2.433756	1.757883	2.103301	1.330828	0.398966	0.466835
-40%	2.45999	1.780357	2.126217	1.352465	0.402999	0.474424
-35%	2.486224	1.802831	2.149134	1.374102	0.407032	0.482013
-30%	2.512458	1.825304	2.17205	1.395738	0.411065	0.489603
-25%	2.538692	1.847778	2.194966	1.417375	0.415098	0.497192
-20%	2.564926	1.870252	2.217883	1.439012	0.419131	0.504781
-15%	2.59116	1.892726	2.240799	1.460648	0.423165	0.512371
-10%	2.617394	1.915199	2.263715	1.482285	0.427198	0.51996
-5%	2.643628	1.937673	2.286631	1.503921	0.431231	0.52755
0%	2.669862	1.960147	2.309548	1.525558	0.435264	0.535139
Fitting	y=0.5247x+2.6699	y=0.4495x+1.9602	y=0.4583x+2.3096	y=0.4327x+1.5256	y=0.0807x+0.4353	y=0.1518x+0.5351
R^2	1	1	1	1	1	1

Table S27 Data for sensitivity of disposal scenarios to GHG (gCO_2-eq/kWh) of PV Modules.

PV systems / scenarios	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023	P500MW2023+ESS
NRS	55.05569	48.79905	48.88771	39.13776	32.75131	35.96748	35.22166
MSWS of CN	54.67909	48.42182	48.51633	38.83596	32.53984	35.76216	35.0317
RS	54.44252	48.19038	48.29073	38.65465	32.43266	35.64542	34.92247

Table S28 Data for sensitivity of disposal scenarios to EPBT (years) of PV Modules.

PV systems / scenarios	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023	P500MW2023+ESS
NRS	4.699174	4.269885	4.273006	3.383406	3.155547	3.465853	3.320307
MSWS of CN	4.694556	4.265605	4.268978	3.380411	3.154693	3.464244	3.318775
RS	4.693645	4.264736	4.26817	3.37977	3.154426	3.463871	3.318425

Table S29 Data for sensitivity of disposal scenarios to EROI of PV Modules.

PV systems / scenarios	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023	P500MW2023+ESS
NRS	4.871173	5.329142	5.325343	6.753027	7.43484	6.85571	7.040849
MSWS of CN	4.875859	5.33436	5.330246	6.758907	7.436833	6.858869	7.044076
RS	4.876785	5.335421	5.331231	6.760166	7.437455	6.859601	7.044812

Table S30 Data and fitting results for sensitivity of curtailment rate variation to GHG (gCO_2-eq/kWh) of PV systems.

PV systems / rate/%	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023	P500MW2023+ESS
0	50.30476	44.54808	44.63503	35.72908	29.93666	32.90118	32.45098
1%	50.81289	44.99806	45.08589	36.08998	30.23905	33.23352	32.75258
2%	51.33139	45.45722	45.54595	36.45825	30.54761	33.57264	33.05984
3%	51.86058	45.92585	46.01549	36.8341	30.86253	33.91875	33.37292
4%	52.40079	46.40425	46.49482	37.21779	31.18402	34.27207	33.69199
5%	52.95238	46.89271	46.98424	37.60956	31.51227	34.63283	34.01722
6%	53.5157	47.39157	47.48407	38.00966	31.84751	35.00126	34.34879
7%	54.09114	47.90116	47.99465	38.41837	32.18995	35.37762	34.68688
8%	54.67909	48.42182	48.51633	38.83596	32.53984	35.76216	35.0317
9%	55.27996	48.95393	49.04948	39.26273	32.89742	36.15515	35.38344
10%	55.89418	49.49786	49.59448	39.69898	33.26295	36.55687	35.74232
Fitting	y=55.8495x+50.2187	y=49.4583x+44.4719	y=49.5549x+44.5587	y=39.6673x+35.6680	y=33.2364x+29.8854	y=36.5277x+32.8449	y=32.8913x+32.404
R^2	0.9991	0.991	0.9991	0.9991	0.9991	1	0.9993

Table S31 Data and fitting results for sensitivity of curtailment rate variation to EPBT (years) of PV systems.

PV systems / rate/%	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023	P500MW2023+ESS
0	4.310529	3.916811	3.919882	3.105262	2.900147	3.184869	3.076025
1%	4.355138	3.957007	3.960108	3.137224	2.929614	3.217322	3.104425
2%	4.400658	3.998022	4.001167	3.169838	2.959682	3.250437	3.13335
3%	4.447116	4.040303	4.043501	3.203124	2.990369	3.284235	3.162814
4%	4.494542	4.083486	4.086718	3.237104	3.02182	3.318736	3.192832
5%	4.542967	4.127578	4.130844	3.2718	3.053989	3.353965	3.223421
6%	4.592421	4.172608	4.175909	3.307233	3.086843	3.389942	3.254596
7%	4.64294	4.218607	4.221943	3.343429	3.120403	3.426694	3.286375
8%	4.694556	4.265605	4.268978	3.380411	3.154693	3.464244	3.318775
9%	4.747308	4.313637	4.317047	3.418206	3.189736	3.50262	3.351814
10%	4.801231	4.362736	4.366183	3.456841	3.225558	3.541848	3.385513
Fitting	y=4.9031x+4.3030	y=4.4588x+3.9095	y=4.4625x+3.9125	y=3.5130x+3.0999	y=3.2524x+2.8949	y=3.5669x+3.1794	y=3.0929x+3.0717
R^2	0.9991	0.9991	0.9991	0.9991	0.9991	0.9991	0.9993

Table S32 Data and fitting results for sensitivity of curtailment rate variation to EROI of PV systems.

PV systems / rate/%	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023	P500MW2023+ESS
0	5.299847	5.798217	5.793746	7.346638	8.083514	7.455292	7.604269
1%	5.246848	5.740235	5.735809	7.273171	8.002679	7.380739	7.534245
2%	5.19385	5.682253	5.677871	7.199705	7.921843	7.306186	7.464221
3%	5.140851	5.624271	5.619934	7.126239	7.841008	7.231633	7.394197
4%	5.087853	5.566289	5.561996	7.052772	7.760173	7.15708	7.324173
5%	5.034854	5.508307	5.504059	6.979306	7.679338	7.082528	7.254149
6%	4.981856	5.450324	5.446121	6.905839	7.598503	7.007975	7.184125
7%	4.928857	5.392342	5.388184	6.832373	7.517668	6.933422	7.114101
8%	4.875859	5.33436	5.330246	6.758907	7.436833	6.858869	7.044076
9%	4.82286	5.276378	5.272309	6.68544	7.355997	6.784316	6.974052
10%	4.769862	5.218396	5.214371	6.611974	7.275162	6.709763	6.904028
Fitting	y=-5.2999x+5.2999	y=-5.7982x+5.7982	y=-5.7928x+5.7938	y=-7.3466x+7.3466	y=-8.0835x+8.0835	y=-7.4553x+7.4553	y=-7.0024x+7.6043
R^2	1	1	1	1	1	1	1

Table S33 Data and fitting results for sensitivity of performance ratio variation to GHG (gCO_2-eq/kWh) of PV systems.

PV systems / ratio/%	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023	P500MW2023+ESS
76%	57.48499	50.90663	51.00599	40.98215	35.69107	38.72665	37.66885
78%	56.01101	49.60133	49.69814	39.93133	34.77592	37.73366	36.78965
80%	54.61074	48.3613	48.45569	38.93305	33.90652	36.79032	35.95055
82%	53.27877	47.18175	47.27384	37.98346	33.07953	35.89299	35.14888
84%	52.01023	46.05838	46.14828	37.07909	32.29192	35.0384	34.38218
86%	50.80069	44.98725	45.07506	36.21679	31.54095	34.22355	33.64821
88%	49.64613	43.96481	44.05063	35.39368	30.82411	33.44574	32.94493
90%	48.54288	42.98782	43.07172	34.60715	30.13913	32.70251	32.27044
92%	47.4876	42.0533	42.13538	33.85482	29.48393	31.99158	31.62302
94%	46.47722	41.15855	41.23888	33.13451	28.85661	31.31091	31.00106
96%	45.50895	40.30108	40.37974	32.44421	28.25543	30.6586	30.4031
98%	44.5802	39.47861	39.55566	31.78208	27.67879	30.03291	29.82776
100%	43.68859	38.68904	38.76455	31.14644	27.12521	29.43226	29.2738
Fitting	$y=43.6886x^{-1}$	$y=38.6890x^{-1}$	$y=38.7646x^{-1}$	$y=31.1464x^{-1}$	$y=27.1252x^{-1}$	$y=29.4323x^{-1}$	$y=29.2873x^{-0.9185}$
R^2	1	1	1	1	1	1	1

Table S34 Data and fitting results for sensitivity of performance ratio variation to EPBT (years) of PV systems.

PV systems / ratio/%	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023	P500MW2023+ESS
76%	4.94089	4.4899	4.493446	3.570481	3.463517	3.753727	3.566219
78%	4.811488	4.372075	4.37553	3.477419	3.37383	3.656762	3.483792
80%	4.688556	4.260142	4.26351	3.389009	3.288628	3.564644	3.405061
82%	4.571621	4.153668	4.156955	3.304913	3.207583	3.47702	3.329782
84%	4.460254	4.052265	4.055473	3.224821	3.130396	3.393569	3.257735
86%	4.354067	3.956041	3.959142	3.148454	3.0568	3.313999	3.188714
88%	4.252707	3.864711	3.867741	3.075559	2.986625	3.238046	3.122533
90%	4.155851	3.777439	3.780402	3.005903	2.919877	3.165468	3.059021
92%	4.063207	3.693963	3.696861	2.939783	2.856031	3.096047	2.998027
94%	3.97477	3.614038	3.616874	2.876524	2.794902	3.029579	2.939637
96%	3.890648	3.537443	3.540221	2.8159	2.736321	2.966039	2.883468
98%	3.80996	3.463975	3.466696	2.757751	2.68013	2.905224	2.829395
100%	3.732499	3.393446	3.396112	2.701928	2.626187	2.846841	2.777304
Fitting	$y=3.7316x^{-1.0228}$	$y=3.3928x^{-1.0201}$	$y=3.3955x^{-1.0201}$	$y=2.7013x^{-1.0162}$	$y=2.6258x^{-1.0086}$	$y=2.8466x^{-1.0080}$	$y=2.7785x^{-0.9111}$
R^2	1	1	1	1	1	1	1

Table S35 Data and fitting results for sensitivity of performance ratio variation to EROI of PV systems.

PV systems / ratio/%	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023	P500MW2023+ESS
76%	4.637863	5.073985	5.070072	6.404949	6.780222	6.333828	6.55093
78%	4.759912	5.20751	5.203495	6.5735	6.958649	6.500507	6.707484
80%	4.881961	5.341036	5.336917	6.742052	7.137075	6.667187	6.864039
82%	5.00401	5.474562	5.47034	6.910603	7.315502	6.833867	7.020593
84%	5.126059	5.608088	5.603763	7.079154	7.493929	7.000547	7.177148
86%	5.248108	5.741614	5.737186	7.247705	7.672356	7.167226	7.333702
88%	5.370157	5.87514	5.870609	7.416257	7.850783	7.333906	7.490257
90%	5.492206	6.008666	6.004032	7.584808	8.02921	7.500586	7.646811
92%	5.614256	6.142192	6.137455	7.753359	8.207637	7.667265	7.803366
94%	5.736305	6.275718	6.270878	7.921911	8.386064	7.833945	7.95992
96%	5.858354	6.409244	6.404301	8.090462	8.564491	8.000625	8.116475
98%	5.980403	6.54277	6.537724	8.259013	8.742917	8.167304	8.27303
100%	6.102452	6.676295	6.671147	8.427564	8.921344	8.333984	8.429584
Fitting	y=6.1025x	y=6.6712x	y=6.6763x	y=8.4276x	y=x	y=x	y=x
R^2	1	1	1	1	1	1	1

Table S36 Data and fitting results for sensitivity of lifetime variation to GHG (gCO_2-eq/kWh) of PV systems.

PV systems / lifetime/years	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023	P500MW2023+ESS
25	54.67909	48.42182	48.51633	38.83596	32.53984	35.76216	35.0317
26	53.04269	46.85386	46.91022	37.64514	31.42337	34.557	33.9503
27	51.52975	45.40346	45.42422	36.54348	30.39039	33.44192	32.94376
28	50.12717	44.05812	44.04555	35.52153	29.43196	32.40726	32.00463
29	48.82368	42.80705	42.76321	34.57115	28.54037	31.44471	31.12643
30	47.60947	41.6409	41.56762	33.68527	27.70895	30.54707	30.3035
31	46.476	40.5515	40.45044	32.85773	26.93189	29.70806	29.53085
32	45.4158	39.53173	39.40439	32.08314	26.20408	28.92219	28.80405
33	44.42228	38.5753	38.42304	31.35673	25.52106	28.18464	28.11922
34	43.48964	37.67666	37.50073	30.6743	24.87889	27.49114	27.47288
35	42.61272	36.83092	36.63243	30.03215	24.27407	26.83792	26.86193
36	41.78694	36.03369	35.8137	29.42695	23.70349	26.22163	26.28359
37	41.00822	35.28108	35.04053	28.85576	23.16438	25.63929	25.73536
38	40.27289	34.56961	34.30937	28.31591	22.65427	25.08822	25.21502
39	39.57767	33.89614	33.61702	27.80504	22.17092	24.56601	24.72053
40	38.9196	33.25785	32.96059	27.32101	21.71234	24.0705	24.25005
Fitting	$y=563.7400x^{-0.7260}$	$y=637.4574x^{-0.8017}$	$y=688.2243x^{-0.8248}$	$y=433.7662x^{-0.7507}$	$y=521.7764x^{-0.8627}$	$y=540.3175x^{-0.8443}$	$y=436.3857x^{-0.7840}$
R^2	0.9995	0.9997	0.9998	0.9996	0.9999	0.9999	0.9999

Table S37 Data and fitting results for sensitivity of lifetime variation to EPBT (years) of PV systems.

PV systems / lifetime/years	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023	P500MW2023+ESS
25	4.694556	4.265605	4.268978	3.380411	3.154693	3.464244	3.318775
26	4.712113	4.273516	4.274582	3.391663	3.15774	3.470283	3.324206
27	4.72967	4.281427	4.280186	3.402914	3.160787	3.476323	3.329638
28	4.747227	4.289338	4.285789	3.414166	3.163834	3.482362	3.33507
29	4.764784	4.297249	4.291393	3.425417	3.16688	3.488402	3.340502
30	4.782341	4.30516	4.296997	3.436669	3.169927	3.494441	3.345933
31	4.799898	4.313071	4.302601	3.44792	3.172974	3.500481	3.351365
32	4.817455	4.320982	4.308205	3.459172	3.176021	3.50652	3.356797
33	4.835012	4.328892	4.313808	3.470423	3.179068	3.51256	3.362229
34	4.852568	4.336803	4.319412	3.481675	3.182115	3.518599	3.36766
35	4.870125	4.344714	4.325016	3.492926	3.185162	3.524639	3.373092
36	4.887682	4.352625	4.33062	3.504178	3.188209	3.530678	3.378524
37	4.905239	4.360536	4.336224	3.515429	3.191256	3.536718	3.383956
38	4.922796	4.368447	4.341827	3.526681	3.194303	3.542757	3.389387
39	4.940353	4.376358	4.347431	3.537933	3.19735	3.548797	3.394819
40	4.95791	4.384269	4.353035	3.549184	3.200397	3.554836	3.400251
Fitting	y=0.176x+4.2556	y=0.0079x+4.0678	y=0.0056x+4.1289	y=0.0113x+3.0991	y=0.0031x+3.0785	y=0.0060x+3.3133	y=0.0054x+3.1830
R^2	1	1	1	1	1	1	1

Table S38 Data and fitting results for sensitivity of lifetime variation to EROI of PV systems.

PV systems / lifetime/years	P20MW2013A	P50MW2013B	P50MW2013C	P25MW2016	P50MW2021	P500MW2023	P500MW2023+ESS
25	4.875859	5.33436	5.330246	6.758907	7.436833	6.858869	7.044076
26	5.031476	5.515435	5.514093	6.979083	7.703675	7.103606	7.273671
27	5.184511	5.694257	5.695869	7.196003	7.968221	7.346171	7.501273
28	5.334993	5.870839	5.875583	7.409699	8.230478	7.586575	7.726894
29	5.482948	6.045192	6.053243	7.620203	8.490453	7.824829	7.950542
30	5.628404	6.217328	6.228856	7.827545	8.748152	8.060944	8.172227
31	5.771389	6.38726	6.402431	8.031755	9.003581	8.294932	8.391958
32	5.911927	6.554998	6.573976	8.232864	9.256748	8.526802	8.609746
33	6.050046	6.720556	6.743497	8.430901	9.507658	8.756566	8.825599
34	6.185772	6.883944	6.911002	8.625896	9.756317	8.984235	9.039526
35	6.319128	7.045174	7.0765	8.817877	10.00273	9.209819	9.251538
36	6.450142	7.204258	7.239998	9.006873	10.24691	9.433329	9.461642
37	6.578836	7.361207	7.401503	9.192913	10.48886	9.654776	9.669849
38	6.705235	7.516032	7.561024	9.376023	10.72858	9.874169	9.876167
39	6.829364	7.668745	7.718566	9.556232	10.96609	10.09152	10.08061
40	6.951246	7.819356	7.874139	9.733566	11.20138	10.30684	10.28317
Fitting	y=0.1383x+1.4616	y=0.1656x+1.2319	y=0.1696x+1.1265	y=0.1982x+1.8576	y=0.2510x+1.2027	y=0.2298x+1.1501	y=0.2159x+1.6803
R^2	0.9987	0.9993	0.9994	0.9990	0.9997	0.9997	0.9997

References

1 M. J. de Wild-Scholten, Energy payback time and carbon footprint of commercial photovoltaic systems, *Sol. Energy Mater. Sol. Cells*, 2013, **119**, 296-305, DOI: 10.1016/j.solmat.2013.08.037.

2 A. Beylot, J. Payet, C. Puech, N. Adra, P. Jacquin, I. Blanc and D. Beloin-Saint-Pierre, Environmental impacts of large-scale grid-connected ground-mounted PV installations, *Renew. Energ.*, 2014, **61**, 2-6, DOI: 10.1016/j.renene.2012.04.051.

3 M. Yu and A. Halog, Solar Photovoltaic Development in Australia-A Life Cycle Sustainability Assessment Study, *Sustainability*, 2015, **7**, 1213-1247, DOI: 10.3390/su7021213.

4 M. Ito, S. Lespinats, J. Merten, P. Malbranche and K. Kurokawa, Life cycle assessment and cost analysis of very large-scale PV systems and suitable locations in the world, *Prog. Photovoltaics*, 2016, **24**, 159-174, DOI: 10.1002/pip.2650.

5 G. Hou, H. Sun, Z. Jiang, Z. Pan, Y. Wang, X. Zhang, Y. Zhao and Q. Yao, Life cycle assessment of grid-connected photovoltaic power generation from crystalline silicon solar modules in China, *Appl. Energy.*, 2016, **164**, 882-890, DOI: 10.1016/j.apenergy.2015.11.023.

6 P. Wu, X. Ma, J. Ji and Y. Ma, Review on Life Cycle Assessment of Greenhouse Gas Emission Profit of Solar Photovoltaic Systems, *Energy Procedia*, 2017, **105**, 1289-1294, DOI: 10.1016/j.egypro.2017.03.460.

7 Z. Q. Yu, W. H. Ma, K. Q. Xie, G. Q. Lv, Z. J. Chen, J. J. Wu and J. Yu, Life cycle assessment of grid-connected power generation from metallurgical route multi-crystalline silicon photovoltaic system in China, *Appl. Energy.*, 2017, **185**, 68-81, DOI: 10.1016/j.apenergy.2016.10.051.

8 G. Constantino, M. Freitas, N. Fidelis and M. G. Pereira, Adoption of Photovoltaic Systems Along a Sure Path: A Life-Cycle Assessment (LCA) Study Applied to the Analysis of GHG Emission Impacts, *Energies.*, 2018, **11**, 28, DOI: 10.3390/en11102806.

9 S. K. Cromratie Clemons, C. R. Salloum, K. G. Herdegen, R. M. Kamens and S. H. Gheewala, Life cycle assessment of a floating photovoltaic system and feasibility for application in Thailand, *Renew. Energ.*, 2021, **168**, 448-462, DOI: 10.1016/j.renene.2020.12.082.

10 H. S. Schultz and M. Carvalho, Design, Greenhouse Emissions, and Environmental Payback of a Photovoltaic Solar Energy System, *Energies.*, 2022, **15**, 24, DOI: 10.3390/en15166098.

11 M. C. Pamponet, H. L. Maranduba, J. A. D. Neto and L. B. Rodrigues, Energy balance and carbon footprint of very large-scale photovoltaic power plant, *Int. J. Energy Res.*, 2022, **46**, 6901-6918, DOI: 10.1002/er.7529.

12 A. H. Mohd Nordin, S. I. Sulaiman, S. Shaari and R. F. Mustapa, Energy and environmental impacts of a 37.57 MW dc ground-mounted large-scale photovoltaic system in Malaysia: A life-cycle approach, *J. Clean. Prod.*, 2022, **335**, 130326, DOI: 10.1016/j.jclepro.2021.130326.

13 A. Muller, L. Friedrich, C. Reichel, S. Herceg, M. Mittag and D. H. Neuhaus, A comparative life cycle assessment of silicon PV modules: Impact of module design, manufacturing location and inventory, *Sol. Energy Mater. Sol. Cells*, 2021, **230**, 13, DOI: 10.1016/j.solmat.2021.111277.

14 WHAT ARE THE IMPACTS OF SHIFTING SOLAR LIFETIME FROM 25 TO 35 YEARS?, https://www.k2management.com/news/shifting-solar-lifetime-to-35-years, (accessed May 28, 2020).

15 A. B. Paç and A. Gok, Assessing the Environmental Benefits of Extending the Service Lifetime of Solar Photovoltaic Modules, 2024, **8**, 2300245, DOI: https://doi.org/10.1002/gch2.202300245.

16 Y. Zhang, M. Kim, L. Wang, P. Verlinden and B. Hallam, Design considerations for multi-terawatt scale manufacturing of existing and future photovoltaic technologies: challenges and opportunities related to silver, indium and bismuth consumption, *Energy & Environmental Science*, 2021, **14**, 5587-5610, DOI: 10.1039/D1EE01814K.

17 China PV Industry development roadmap (2023-2024),

https://www.ntsibpv.com/Public/Admin/20240312161334132537.pdf, (accessed March 12, 2024).