Supplementary Information

Global PV Supply Chains: Costs and Energy Savings, GHG Emission Reductions

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Table S1 | Data for cumulative energy demand and energy payback time of multicrystalline silicon solar cells, modules, and systems.

Ref.	Data Year	CED (MJp Wp-1)			EPBT (years)		
		Cells	Modules	Systems	Cells	Modules	Systems
[1]	1976	246.0			16.7		
[1]	1976	510.0			34.6		
[1]	1977	93.6			6.3	6.5	
[1]	1985	166.0			11.3		
[2]	1989		59.4	72.0		4.0	4.9
[3]	1991				2.1	2.7	5.7
[4]	1993	60.6	63.2	68.4	4.1	4.3	4.6
[5]	1995		47.4			3.2	
[5]	1995		44.0			3.0	
[6]	1996	24.3	33.0		1.7	2.2	
[2]	1997		27.0	32.4		1.8	2.2
[7]	1997	23.9	30.5		1.6	2.1	
[7]	1997	22.5	28.9		1.5	2.0	
[7]	1997	10.7	14.4		0.7	1.0	
[8]	1997	70.3	93.1		4.8	6.3	
[8]	1997	24.1	36.2		1.6	2.5	
[9]	1998		36.8			2.5	
[10]	1998		35.4			2.4	
[8]	1999	25.7	36.2		1.7	2.5	
[11]	1999	29.6	36.2	57.9	2.0	2.5	3.9
[11]	1999	26.9	35.4	41.8	1.8	2.4	2.8
[12]	1999	43.1	48.1	53.2	2.9	3.3	3.6
[1]	1999			49.2			3.3
[13]	2003		34.0			2.3	
[14]	2004		29.5	32.6		2.0	2.2
[15]	2004		29.8	32.5		2.0	2.2
[15]	2005	22.0	29.8	32.5	1.5	2.0	2.2
[14]	2005			32.5			2.2
[16]	2005		25.6	35.3		1.7	2.4
[17]	2005		23.2	28.2		1.6	1.9
[18]	2006		16.9	32.5		1.1	2.2
[19]	2006		25.8	29.6		1.8	2.0
[16]	2007		69.4	78.6		4.7	5.3
[16]	2007		25.3	34.4		1.7	2.3
[20]	2007		16.5	31.3		1.1	2.1
[20]	2007		13.1	25.2		0.9	1.7
[19]	2007		22.1	25.9		1.5	1.8
[21]	2008			33.1			2.2
[22]	2009			23.5			1.6
[15]	2009		19.7	23.9		1.3	1.6
[23]	2011	6.3	14.8	15.8	0.4	1.0	1.1
[23]	2011	6.2	17.9	18.9	0.4	1.2	1.3
[24]	2013		13.7			0.9	
[25]	2015		15.0	20.0		1.0	1.3
[26]	2015	9.8	14.4	19.5	0.7	1.0	1.3
[27]	2017	8.3	10.7	11.7	0.6	0.7	0.8
[27]	2017	8.2	10.4	11.4	0.6	0.7	0.8
[27]	2017	8.6	9.8	10.8	0.6	0.7	0.7
[26]	2020	5.3	10.2	14.8	0.4	0.7	1.0
[28]	2021			16.1			1.1

Table S2 | Data for cumulative energy demand and energy payback time of mono-crystalline silicon solar cells, modules, and systems.

Ref.	Data Year	CED (MJp Wp-1)			EPBT (years)		
		Cells	Modules	Systems	Cells	Modules	Systems
[29]	1986		84.0	198.0		5.7	13.4
[2]	1989		63.0	73.8		4.3	5.1
[4]	1993	57.4	59.6	63.3	3.9	4.1	4.3
[30]	1995		63.1			4.3	
[30]	1995		40.8			2.8	
[2]	1997		39.6	43.9		2.7	3.0
[31]	1997			63.2			4.3
[7]	1997	123.0	127.0		8.5	8.7	
[7]	1997	91.5	95.7		6.3	6.6	
[8]	1997	44.5	49.6	53.5	3.1	3.4	
[8]	1997	107.0	116.0	123.0	7.3	7.9	
[9]	1998		63.7			4.4	
[32]	1999	52.2	64.0		3.6	4.4	
[11]	1999		44.3	58.1		3.0	4.0
[11]	1999		44.3	50.3		3.0	3.5
[1]	1999			56.4			3.9
[33]	2000		26.4	33.8		1.8	2.3
[34]	2003		31.9	45.2		2.2	3.1
[34]	2003		31.9	56.0		2.2	3.8
[15]	2004		37.6	40.3		2.5	2.7
[14]	2005			39.8			2.7
[1]	2005	37.8	41.3		2.6	2.8	
[17]	2005		27.6	32.1		1.9	2.2
[35]	2006		37.1	39.8		2.6	2.7
[19]	2006			31.8		1.9	2.2
[36]	2006		14.6			1.0	
[21]	2008			41.9			2.9
[19]	2008			25.9		1.5	1.8
[22]	2009			23.3			1.6
[15]	2009		27.9	32.0		1.9	2.2
[23]	2011	13.4	25.3	26.2	0.9	1.7	1.8
[23]	2011	13.2	30.8	31.7	0.9	2.1	2.2
[37]	2012	16.3	21.2	29.2	1.1	1.5	2.0
[24]	2013		16.2			1.1	
[25]	2015		22.0	27.5		1.5	1.8
[26]	2015	17.6	21.4	26.1	1.2	1.4	1.8
[38]	2018		15.5			1.5	
[37]	2020	6.9	10.3	17.1	0.5	0.7	1.2
[39]	2020		12.9	17.1		0.9	1.1
[40]	2020		9.1	13.1		0.6	0.9
[26]	2020	5.6	9.6	13.6	0.4	0.7	0.9
[28]	2021			16.1			1.1

Table S3 | Data for cumulative energy demand and energy payback time of Perovskite Perovskite-Tandem solar cells, modules, and systems.

Ref.	Data Year	CED (MJp Wp-1)			EPBT (years)		
		Cells	Modules	Systems	Cells	Modules	Systems
[41]	2017	2.0			0.2		
[38]	2019		3.4			0.4	
[39]	2020		2.7	5.6		0.2	0.4

Table S4 | Data for cumulative energy demand and energy payback time of Perovskite-silicon Tandem solar cells, modules, and systems.

Ref.	Data Year	CED (MJp Wp-1)			EPBT (years)		
		Cells	Modules	Systems	Cells	Modules	Systems
[41]	2017	14.3			1.1		
[42]	2017					1.5	
[38]	2015		14.8			1.5	
[39]	2020		10.4	13.4		0.7	0.9

Table S5 | Data for cumulative energy demand and energy payback time of Perovskite solar cells, modules, and systems.

Ref.	Data Year	CED (MJp Wp-1)			EPBT (years)		
		Cells	Modules	Systems	Cells	Modules	Systems
[43]	2015		4.3			0.3	
[44]	2015	114.9			7.8		
[44]	2015	109.9			7.4		
[45]	2015			527.7			35.8
[42]	2017					1.1	
[39]	2020		2.5	6.8		0.1	0.5

Table S6 | Data for life cycle greenhouse gas emissions of multi-crystalline silicon PV systems.

Ref.	Data Year	Reported GHG (gCO2-eq/kWh)				Harmonised module GHG	
		Cells	Modules	BOS	System	gCO2-eq/kWh	KgCO2-eq/Wp
[2]	1989				245.0		
[3]	1991	57.9	76.4		188.0	38.6	1.3
[1]	1993	42.9	55.4	58.3	114.0	57.3	2.0
[1]	1993	58.8	76.0	67.6	144.0	57.5	2.0
[1]	1993	57.5	73.1	59.0	132.0	75.9	2.6
[30]	1995		138.0			80.6	2.8
[30]	1995		78.0			45.6	1.6
[46]	1995				189.0		
[12]	1996						`
[2]	1997				110.0		
[8]	1997				60.0		
[8]	1997				150.0		
[7]	1998				73.3	55.5	1.9
[7]	1998				66.0		
[10]	1998				87.0		
[11]	1999				60.0		
[14]	2004		32.0		37.0	35.8	1.2
[15]	2004		30.5	4.5	35.0	34.1	1.2
[16]	2005		52.0	20.0	72.0	38.7	1.3
[47]	2005		28.3		53.0	32.6	1.1
[17]	2005				55.0	31.0	1.1
[35]	2006				35.0		
[19]	2006		29.1		35.0	29.1	1.0
[48]	2007	17.6	21.1		29.5	21.1	0.7
[19]	2007		23.8		28.0	23.8	0.8
[20]	2007				44.4	27.7	0.9
[20]	2007				34.5	21.2	0.7
[23]	2011	14.0	21.7	5.5	27.2	22.1	0.8
[23]	2011	35.5	43.6	5.5	49.1	44.4	1.5
[24]	2013		28.0			23.0	0.8
[26]	2015					30.0	1.0
[39]	2016					24.8	0.9
[27]	2017	21.0	26.0	4.2	30.2	20.6	0.7
[27]	2017	20.5	25.2	4.0	29.2	19.9	0.7
[27]	2017	16.2	17.8	3.1	20.9	18.7	0.6
[39]	2020					21.6	0.7
[49]	2020				34.6		
[26]	2020				25.0	23.9	0.8
[28]	2021		27.4				

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Table S7 | Data for life cycle greenhouse gas emission of mono-crystalline silicon PV systems.

Ref.	Data Year	Reported GHG (gCO2-eq/kWh)				Harmonised module GHG	
		Cells	Modules	BOS	System	gCO2-eq/kWh	KgCO2-eq/Wp
[29]	1986		117.5		280.0	173.7	5.9
[29]	1986				43.0		
[29]	1986				29.0		
[2]	1989				250.0		
[50]	1992				334.0		
[50]	1992				238.0		

[50]	1992				77.0		
[2]	1997				150.0		
[46]	1995		99.2	14.8	114.0	62.5	2.6
[30]	1995		192.0			112.2	3.8
[30]	1995		74.0			43.2	1.5
[30]	1995				72.0	54.6	1.9
[28]	1996				121.0		
[7]	1998				304.3		6.7
[7]	1998				223.7		4.9
[33]	2000	62.4	69.6	32.4	102.0	41.0	1.4
[28]	2003				72.0		
[15]	2004		40.6	4.4	45.0	45.4	1.6
[14]	2005				45.0		
[17]	2005				62.0	35.5	1.2
[35]	2006				45.0		
[19]	2006		32.0		37.0	32.0	1.1
[36]	2006					22.5	0.8
[28]	2007				76.0		
[48]	2008	16.4	20.3		30.0	20.3	0.7
[19]	2008		24.0		29.2	24.0	0.8
[23]	2011	26.0	33.0	5.0	38.0	35.6	1.2
[23]	2011	69.0	76.0	5.0	81.0	82.6	2.8
[37]	2012				38.0		
[24]	2013		36.0			28.8	1.0
[26]	2015					49.3	1.7
[38]	2018		24.6			25.5	0.9
[37]	2020				25.0		
[39]	2020		15.6			20.9	0.7
[49]	2020				42.3		
[28]	2020				42.9		
[26]	2020				23.0	22.4	0.8
[28]	2021		27.0		42.9	23.1	0.8

Table S8 | Data for life cycle greenhouse gas emission of Perovskite-Tandem PV systems.

Ref.	Data Year	Reported GHG (gCO2-eq/kWh)				Harmonised module GHG	
		Cells	Modules	BOS	System	gCO2-eq/kWh	KgCO2-eq/Wp
[38]	2019		10.7		10.7	5.8	0.2
[39]	2020		3.2		3.2	4.3	0.1

Table S9 | Data for life cycle greenhouse gas emission of Perovskite-silicon Tandem PV systems.

Ref.	Data Year	Reported GHG (gCO2-eq/kWh)				Harmonised module GHG	
		Cells	Modules	BOS	System	gCO2-eq/kWh	KgCO2-eq/Wp
[42]	2017		5900.0		5900.0	219.7	7.5
[51]	2017		27.7		47.0	22.3	0.8
[38]	2018		47.5		47.5	25.5	0.9
[39]	2020		12.7		12.7	17.0	0.6

Table S10 | Data for life cycle greenhouse gas emission of Perovskite PV systems.

Ref.	Data Year	Reported GHG (gCO2-eq/kWh)				Harmonised module GHG	
		Cells	Modules	BOS	System	gCO2-eq/kWh	KgCO2-eq/Wp
[43]	2015		82.5		82.5	6.1	0.2
[44]	2015	350.0			350.0		
[44]	2015	370.0			370.0		
[45]	2015	5866.7			5866.7		
[42]	2017		6600.0		6600.0	245.8	8.4
[51]	2017		17.2		40.0	13.9	0.5
[39]	2020		3.4		3.4	4.6	0.2

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