Supplementary Information

for

Private and Externality Costs and Benefits of Recycling Crystalline Silicon (c-Si) Photovoltaic Panels

Elizabeth Markert,[1] Ilke Celik[*],[2] Defne Apul,[1]
[1]University of Toledo, Department of Civil and Environmental Engineering
[2]University of Wisconsin – Platteville, Department of Electrical and Computer Engineering – Sustainability and Renewable Energy Systems Program
[*] Corresponding author

Table S. 1: PRIVATE Process Input Costs per 1 m^2

*Cost (USD) / 1 m2 = ((Amount Required for 1000 kg PV) * (Cost / Amount) * (Unit Conversion)) / (73 m2 [FU conversion])*

Process Inputs	Amount Required for 1000 kg PV[14]	Cost / Amount	Cost (USD) / 1 m2
Diesel Fuel	1.14 L	$ 3.03 / gal [1]	$1.3*10^{-2}$
HNO_3	7.08 kg	$ 315 / ton [2]	$3.4*10^{-2}$
Water	309.7 kg	$ 70.4 / 12,200 gal [3]	$6.0*10^{-3}$
$Ca(OH)_2$	36.5 kg	$ 120 / 500 metric tons [2]	$1.2*10^{-4}$
Electricity	113.5 kWh	12 cents / kWh [4]	0.2
Total Cost (USD) / 1 m2			**0.24**

Table S. 2: PRIVATE Investment Costs per 1 m^2

*Cost (USD) / 1 m2 = ((Cost (USD) / 1 unit) * (13.7 kg/m2 [FU conversion])) / ((Assumed Lifetime of Machinery years) * (Annual Rate of Recycling kg/yr))*
** = Assumed*

PV Recycling Machinery Required	Cost (USD) / 1 unit	Lifetime of Machinery (years)*	Annual Rate of Recycling (kg/yr)[14]	Cost (USD) / 1 m2
Cartesian robot system	62,500 [5]	20	7257480	$5.9*10^{-3}$
Automated dismantle system	11,000 [2]	20	7257480	$1.0*10^{-3}$
Industrial mechanical arm	2,206 [2]	20	7257480	$2.1*10^{-4}$
Industrial infra-red heater	65 [2]	20	7257480	$6.1*10^{-6}$
Industrial blade	378 [2]	20	7257480	$3.6*10^{-5}$
Optical separator	32,800 [2]	20	7257480	$3.1*10^{-3}$
Sieving machine	3,750 [2]	20	7257480	$3.5*10^{-4}$
Silicon wafer cutting machine	3,000 [2]	20	7257480	$2.8*10^{-4}$
Total Cost (USD) / 1 m2				1.1*10-2

Table S. 3: PRIVATE Transportation Costs per 1 m^2
*Cost (USD) / 1 m2 = ((Distance (km) Required for 1000 kg PV) * (Diesel Cost (USD/gal)) * (0.621 mile/km)) / ((Semi-truck Fuel Efficiency mile/gal) * (73 m2 [FU conversion]))*
** = Assumed*

Transportation Locations	Distance (km) Required for 1000 kg PV [6]	Diesel Cost (USD/gal) [7]	Semi-truck Fuel Efficiency (mile/gal)*	Cost (USD) / 1 m^2
Collection of PV waste from consumers	100	2.93	6.3	0.40
Collection point to PV recycling site	400	2.93	6.3	1.58
PV recycling site to incineration plant	200	2.93	6.3	0.79
Incineration plant to municipal waste landfill	50	2.93	6.3	0.20
Municipal waste landfill to hazardous waste landfill	100	2.93	6.3	0.40

Total Cost (USD) / 1 m^2				3.36

Table S. 4: PRIVATE Landfilling Costs per 1 m^2

*Cost (USD) / 1 m2 = ((Amount Discharged for 1000 kg PV) * (Tipping Fee (USD)) * (Unit Conversion)) / (73 m2 [FU conversion])*

Wastes	Landfill Type	Amount Discharged for 1000 kg PV [6]	Tipping Fee (USD)	Cost (USD) / 1 m2
Contaminated glass	Municipal	14 kg	50 / ton [8]	$1.0*10^{-2}$
Fly ash	Hazardous	2 kg	2.2 / lb [9]	0.13
Liquid waste	Municipal	306.1 kg	50 / ton [8]	0.23
sludge	Hazardous	50.2 kg	1.8 / lb [9]	2.73
Total Cost (USD) / 1 m2				3.11

Table S. 5: EXTERNAL Process Input Costs per 1 m^2

*Cost (USD) / 1 m2 = ((Recycling Process Emissions for 1000 kg PV) / (73 m2 [FU conversion])) * (External Cost Multiplier (USD) / unit)*

Impact Category	Recycling Process Emissions for 1000 kg PV [6]	External Cost Multiplier (USD) / unit	Cost (USD) / 1 m2
Cumulative energy demand (MJ)	$3.2*10^{3}$	$9.3*10^{-3}$ [10]	0.40
Freshwater ecotoxicity (CTUe)	$1.3*10^{3}$	$5*10^{-2}$ [11]	0.83
Marine eutrophication (kg N eq)	1.1	14.18 [11]	0.21
Freshwater eutrophication (kg P eq)	$5.6*10^{-2}$	2.02 [11]	$1.5*10^{-3}$
Acidification (molc H+eq)	2.68	64.47 [12]	2.4
Photochemical ozone formation (kg NMVOC eq)	3.0	2.33 [13]	$9.6*10^{-2}$
Ionizing radiation human health (kg U235 eq)	30.5	$5*10^{-2}$ [13]	$2.2*10^{-2}$
Particulate matter (kg PM2.5 eq)	$9.8*10^{-2}$	3.4*10 [7]	0.46

Human toxicity non-cancer effects(CTUh)	$1.9*10^{-5}$	$2*10^{-2}$[11]	$6.2*10^{-9}$
Human toxicity cancer effects (CTUh)	$3.0*10^{-5}$	$2*10^{-2}$[11]	$9.4*10^{-9}$
Ozone depletion (kg CFC 11 eq)	$3.2*10^{-5}$	44.34[11]	$1.9*10^{-5}$
Global warming potential (kg CO2 eq)	$4.5*10^{2}$	$4*10^{-2}$ [12]	0.24
Total Cost (USD) / 1 m2			**4.62**

Table S. 6: EXTERNAL Transportation Costs per 1 m²

*Cost (USD) / 1 m2 = ((Transportation Emissions for 1000 kg PV) / (73 m2 [FU conversion])) * (External Cost Multiplier (USD) / unit)*

Impact Category	Transportation Emissions for 1000 kg PV [6]	External Cost Multiplier (USD) / unit	Cost (USD) / 1 m2
Acidification (kg SO2 eq)	0.5	64.47 [12]	0.44
Ecotoxicity (CTUe)	190.8	$5*10^{-2}$ [11]	0.12
Marine Eutrophication (kg N eq)	0.02784	14.18 [11]	$5.4*10^{-3}$
Global warming potential (kg CO2 eq)	79.6	$4*10^{-2}$ [12]	$4*10^{-2}$
Particulate matter (kg PM2.5 eq)	0.02324	$3.4*10^{2}$ [12]	0.11
Human toxicity cancer effects (CTUh)	1.884E-08	$2*10^{-2}$[11]	$6.0*10^{-12}$
Human toxicity non-cancer effects (CTUh)	0.00001048	$2*10^{-2}$[11]	$3.4*10^{-9}$
Ozone depletion (kg CFC 11 eq)	3.008E-09	44.34[11]	$1.8*10^{-9}$
Cumulative energy demand (MJ)	140.4	$9.3*10^{-3}$[10]	$1.8*10^{-2}$
Total Cost (USD) / 1 m2			**0.73**

Table S. 7: EXTERNAL Landfilling Costs per 1 m²

*Cost (USD) / 1 m2 = (((Landfilling Emissions for 1000 kg PV) - (Credits for 1000 kg PV)) / (73 m2 [FU conversion])) * (External Cost Multiplier (USD) / unit)*

Impact Category	Landfilling Emissions for 1000 kg PV [6]	Credits for 1000 kg PV [6]	External Cost Multiplier (USD) / unit	Cost (USD) / 1 m2
Cumulative energy demand (MJ)	31.7	$3.7*10^{2}$	$9.3*10^{-3}$[10]	$-4*10^{-2}$
Freshwater ecotoxicity (CTUe)	$1.1*10^{3}$	21.5	$5*10^{-2}$ [11]	0.65
Marine eutrophication (kg N eq)	$2.2*10^{-2}$	$4.2*10^{-2}$	14.18 [11]	$-3.9*10^{-3}$

Freshwater eutrophication (kg P eq)	$5.0*10^{-3}$	$1.0*10^{-2}$	2.02 [11]	$-1.4*10^{-4}$
Acidification (molc H+eq)	$2.7*10^{-2}$	0.26	64.47 [12]	-0.21
Photochemical ozone formation (kg NMVOC eq)	$3.0*10^{-2}$	0.14	2.33 [13]	$-3.4*10^{-3}$
Ionizing radiation human health (kg U235 eq)	1.2	7.7	$5*10^{-2}$ [13]	$-4.6*10^{-3}$
Particulate matter (kg PM2.5 eq)	$2.9*10^{-3}$	$1.6*10^{-2}$	$3.4*10^{2}$ [12]	$-6.0*10^{-2}$
Human toxicity non-cancer effects(CTUh)	$3.9*10^{-6}$	$1.1*10^{-6}$	$2*10^{-2}$ [11]	$9.0*10^{-10}$
Human toxicity cancer effects (CTUh)	$1.5*10^{-5}$	$1.3*10^{-6}$	$2*10^{-2}$ [11]	$4.5*10^{-9}$
Ozone depletion (kg CFC 11 eq)	$1.6*10^{-7}$	$8.7*10^{-6}$	44.34 [11]	$-5.2*10^{-6}$
Global warming potential (kg CO2 eq)	$1.3*10^{2}$	75.9	$4*10^{-2}$ [12]	$3.0*10^{-2}$
Total Cost (USD) / 1 m2				**0.36**

Table S. 8: Market Prices of Materials for Recovery

*Total Cost (USD) / 1 m2 = ((Amount Recovered (kg)) / (73 m2 [FU conversion])) * (Material Cost (USD) / unit) * (2.204 lb / kg)*

**silver scrap calculation converts from kg to troy ounce instead of kg to lb*

Recovered Materials	Amount Recovered (kg) [6]	Material Cost (USD) / unit	Total Cost (USD) / 1 m2
Aluminum scrap	182.65	1.15 / lb [14]	6.34
Glass scrap	686	0.10 / lb [15]	2.07
Copper scrap	4.38	3 / lb [14]	0.40
Silicon metal scrap	34.68	1.38 / lb [14]	1.44
Silver scrap	0.5	15.3 / troy ounce [14]	3.37
Total Cost (USD) / 1 m2			**13.62**

References

1. U.S. Gasoline and Diesel Fuel Update.

2. Alibaba Manufacturers, Suppliers, Exporters & Importers Available online: https://www.alibaba.com/?spm=a2700.details.scGlobalHomeHeader.9.df0b7eeeTwMxhR (accessed on Jul 19, 2019).

3. Walton, B. Price of Water 2017: Four Percent Increase in 30 Large U.S. Cities Available online: https://www.circleofblue.org/2017/water-management/pricing/price-water-2017-four-percent-increase-30-large-u-s-cities/ (accessed on Oct 14, 2019).

4. Jiang, J. The Price Of Electricity In Your State Available online: https://www.npr.org/sections/money/2011/10/27/141766341/the-price-of-electricity-in-your-state (accessed Oct 9, 2019). (accessed on Oct 9, 2019).

5. Robot Worx. How Much Do Industrial Robots Cost? Available online: https://www.robots.com/faq/how-much-do-industrial-robots-cost (accessed on Oct 8, 2019).

6. Latunussa, C.E.L.; Ardente, F.; Blengini, G.A.; Mancini, L. Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels. *Sol. Energy Mater. Sol. Cells* 2016, *156*, 101–111.

7. AAA STATE GAS PRICE AVERAGES.

8. Southern Indiana, U.S. Solid Waste & Landfill Facts Available online: https://www.usi.edu/recycle/solid-waste-landfill-facts/ (accessed on Oct 19, 2019).

9. Hazardous Waste Disposal Costs—What to Know about Transportation Fees Available online: https://mcfenvironmental.com/hazardous-waste-disposal-costs-what-to-know-about-transportation-fees/ (accessed on Oct 19, 2019).

10. Pizzol, M.; Weidema, B.; Brandao, M.; Osset, P. Monetary valuation in Life Cycle Assessment : a review. *J. Clean. Prod.* 2015, *86*, 170–179.

11. Keijzer, E. The environmental impact of activities after life: life cycle assessment of funerals. *Int. J. Life Cycle Assess.* 2017, *22*, 715–730.

12. Martinez-Sanchez, V.; Levis, J.W.; Damgaard, A.; DeCarolis, J.F.; Barlaz, M.A.; Astrup, T.F. Evaluation of Externality Costs in Life-Cycle Optimization of Municipal Solid Waste Management Systems. *Environ. Sci. Technol.* 2017, *51*, 3119–3127.

13. De Bruyn, S.; Ahdour, S.; Bijleveld, M.; De Graaff, L.; Schep, E.; Schroten, A.; Vergeer, R. Environmental Prices Handbook 2017 Methods and numbers for valuation of environmental impacts. 2018, 177.

14. USGS *Commodity Statistic and Information*;

15. Scrap metal prices Available online: https://www.scrapmonster.com/scrap-yard/price/glass-bottles/378] (accessed on May 15, 2020).