Comparative Life Cycle Assessment of End-of-Life Silicon Solar Photovoltaic Modules

Marina M. Lunardi [1], J. P. Alvarez-Gaitan [2], J. I. Bilbao [1] and Richard Corkish [1,*]

Ecoinvent database [1]:

Landfill and Reuse

- disposal, slag from Metallurgical Grade (MG) silicon production, 0% water, to inert material landfill
- disposal, waste, Si waferprod., inorg, 9.4% water, to residual material landfill
- disposal, aluminium, 0% water, to sanitary landfill
- inert material disposal, glass, 0% water, to landfill
- plastics, mixture, 15.3% water, to sanitary landfill

Incineration

- disposal, plastics, mixture, 15.3% water, to municipal incineration
- disposal, aluminum, 0% water, to municipal incineration
- disposal, glass, 0% water, to municipal incineration

Inventory from the Literature:

Thermal Recycling Process

- Controlled burning of EVA (400 - 500°C).
- Intact glass: recovered without breaking and could be directly used in a new module [2,3].
- Broken cells: 100% of the raw silicon is from this recycling process [2,3].
- Total energy consumption: natural gas and electrical energy for the exhaust gas cleaning [4,5].
- Nitrogen atmosphere [4,5].

Table S1. Energy consumption by process step.

Process step	Consumed energy (kWh/wafer)
Silicon production	7.55
Recycling process	0.4

Chemical Recycling Process [6]

- EVA Solvents: tetrahydrofuran, o-dichlorobenzene and toluene.
- Glass: completely recovered and directly used again as a module component.
- Si wafers recovery (80% of the wafers used in new modules):
  - Potassium hydroxide (KOH) to remove Al metal coatings.
  - Nitric acid (HNO_3), hydrogen fluoride (HF) and acetic acid (CH_3COOH) to remove metal and anti-reflection coatings and n-p junctions

Table S2. Material inputs by process step.

Process step	Material inputs (per 1 m² module)
Hydrogen fluoride	0.0678 kg
Acetic acid	5.92 kg
Nitric acid	13.1 kg
Potassium hydroxide	`0.0522 kg
Water	0.223 kg
Electricity	76 MJ

References

1. Hedemann, J.; König, U.; Cuche, A.; Egli, N. Technical documentation of the ecoinvent database, Final report ecoinvent data v2, 2007. Available online: https://www.ecoinvent.org/database/older-versions/ecoinvent-version-2/reports-on-ecoinvent-2/reports-on-ecoinvent-2.html (accessed on 10 June 2018).
2. Wang, T.-Y.; Hsiao, J.-C.; Du, C.-H. Recycling of materials from silicon base solar cell module. In Proceedings of thePhotovoltaic Specialists Conference (PVSC), 38th IEEE,3–8 June 2012,Austin, TX, USA; pp. 002355–002358.
3. Komoto, K. Developments on PV Recycling in Japan, In Proceedings of the 24th European Photovoltaic Solar Energy Conference, 21–25 September 2009, Hamburg, Germany.
4. Frisson, L.; Lieten, K.; Bruton, T.; Declercq, K.; Szlufcik, J.; De Moor, H.; Goris, M.; Benali, A.; Aceves, O. Recent improvements in industrial PV module recycling. In Proceeding of the 16th European Photovoltaic Solar Energy Conference,1–5 May 2000; Glasgow, UK.
5. Born, M.; Wambach, K. Pyrolysis of EVA and its application in recycling of photovoltaic modules. *J. Environ. Sci.* **2004**, *16*, 889–893.
6. Vellini, M.; Gambini, M.; Prattella, V. Environmental impacts of PV technology throughout the life cycle: Importance of the end-of-life management for Si-panels and CdTe-panels, Energy 2017, 138, 1099-1111.