LCA of Si and Thin Film PV Systems: Impacts from Water, Toxicity, Embedded Energy, and Global Warming

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Jenny Collier, Civil Engineering

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Outline

- Intro to LCA (Defne)
- Application of LCA to PV systems (Jenny)
- Water use and toxicity findings (Jenny)
- Energy and GHG emission findings (Jenny and Khagendra)
- Future work (Jenny and Defne)

LCA Considers Entire Life Cycle of a Product or a Service

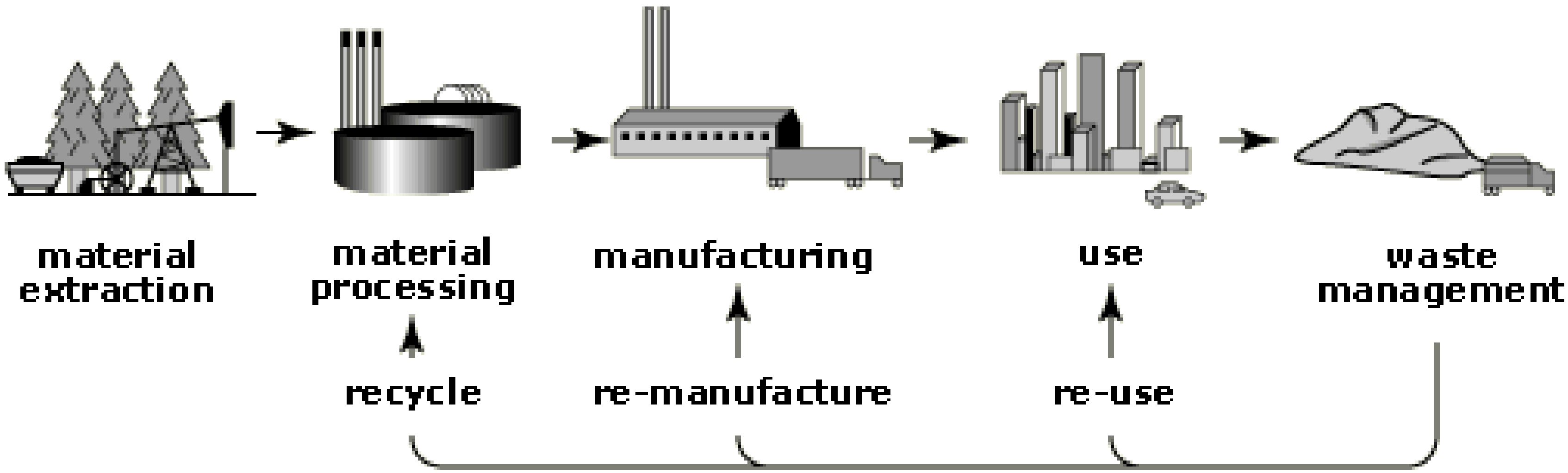
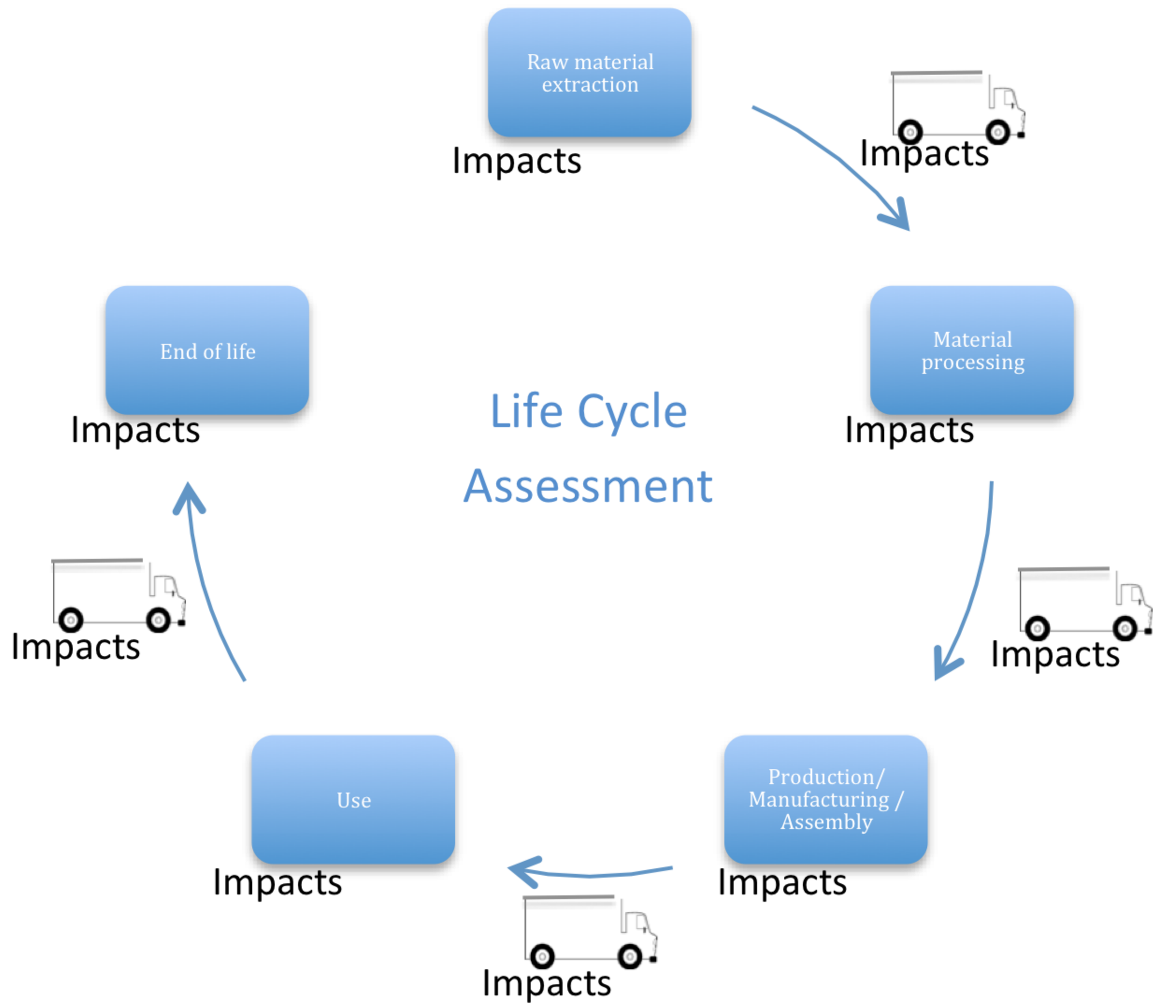


Image taken from: http://www.ami.ac.uk/courses/topics/0109_lct/

Life Cycle Includes Transportation



What We Proposed

- Life cycle sustainability analysis (LCSA)
  - Life cycle costing (LCC)
  - Social life cycle assessment (SLCA)
  - Environmental life cycle assessment (LCA)

LCSA = LCC + SLCA + **LCA**

This presentation

LCA Definition

- Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. (ISO 14044, 2006)

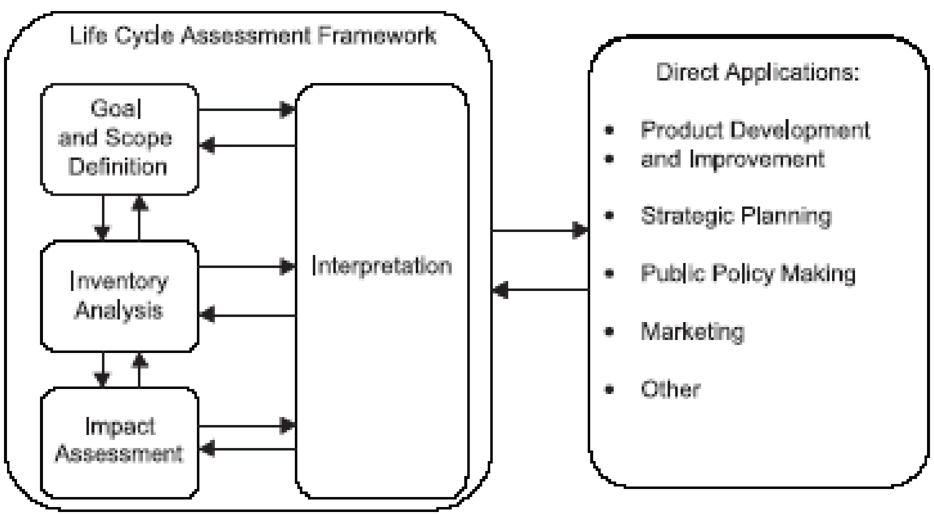
ISO LCA Guidelines

International Organization for Standardization

Life Cycle Inventory (LCI)

- Phase 1:Goal and Scope Definition
- Phase 2: Inventory analysis phase
- Phase 3: Impact assessment phase
- Phase 4: Interpretation Phase

Life Cycle Impact Assessment (LCIA)



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Life Cycle Inventory (LCI)

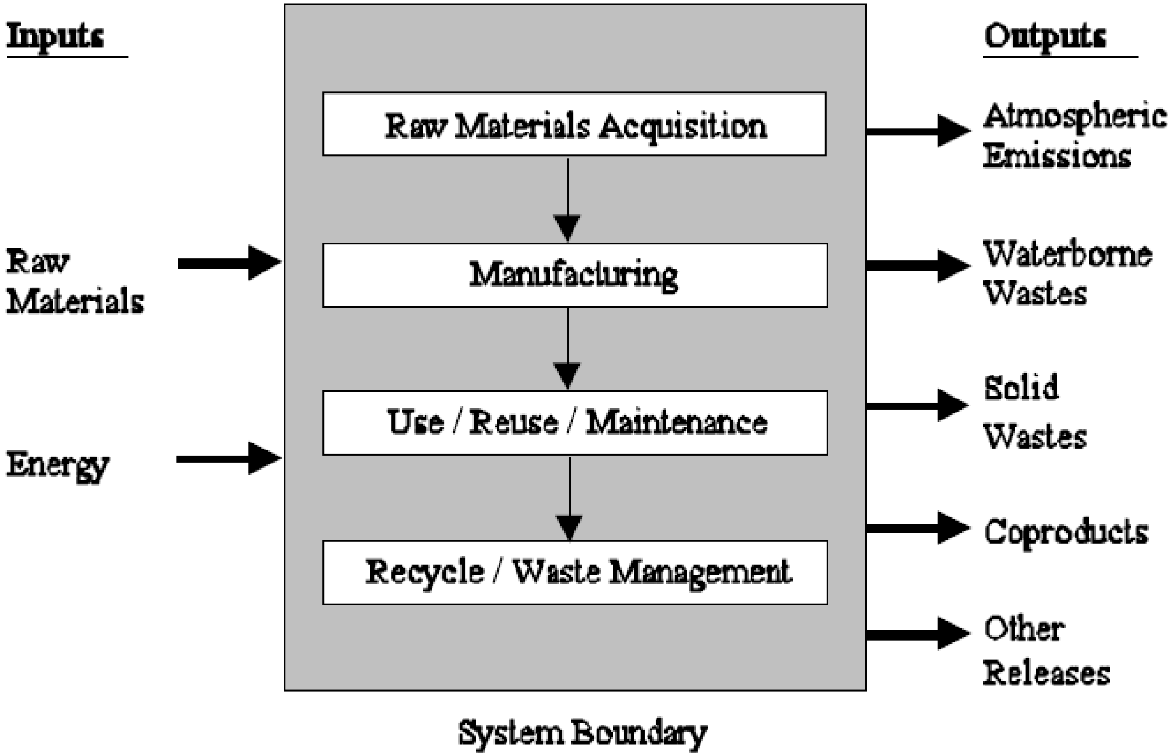

Figure Retrieved from http://www.epa.gov/ORD/NRMRL/lcaccess/lca101.htm

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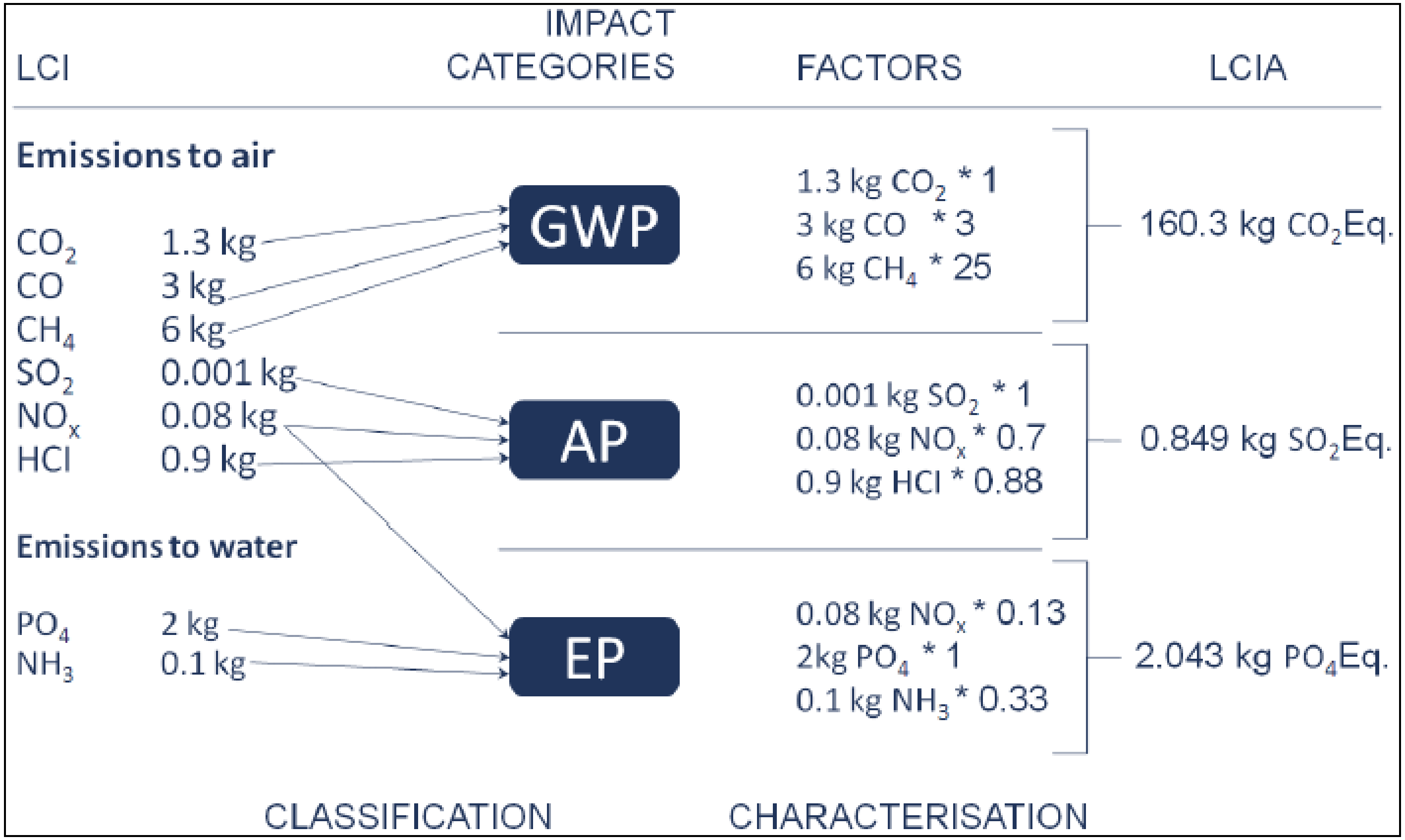
Life Cycle Impact Assessment (LCIA)



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Impact Categories Used in LCIA

- Input related impact categories
  - Abiotic resources (e.g. minerals, fossil fuel, water)
  - Biotic resources (e.g. forests, animals, plants)
  - Land
- Output related impact categories
  - Global warming
  - Depletion of stratospheric ozone
  - Human toxicological impact
  - Ecotoxicological impacts
  - Photo-oxidant formation
  - Acidification
  - Eutrophication
  - Odor
  - Noise
  - Radiation
  - Casualties

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  - Odor
  - Noise
  - Radiation
  - **Casualties**

Outline

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- **Application of LCA to PV systems (Jenny)**
- Water use and toxicity findings (Jenny)
- Energy and GHG emission findings (Jenny and Khagendra)
- Future work (Jenny and Defne)

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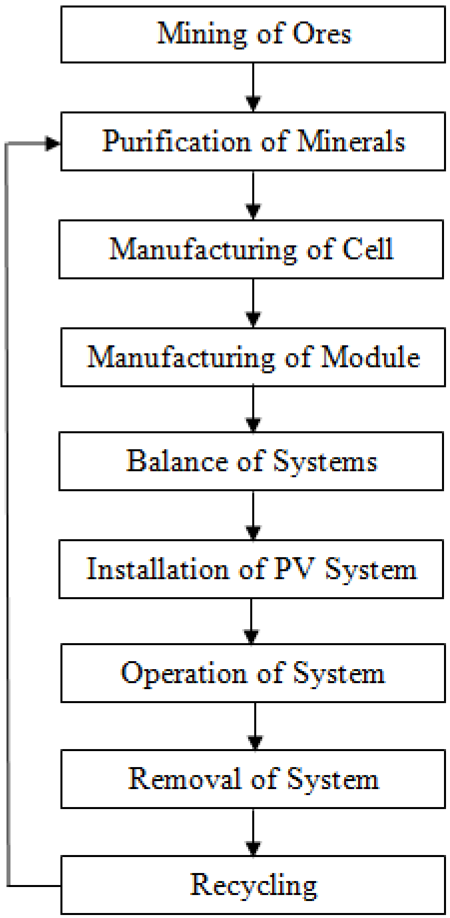
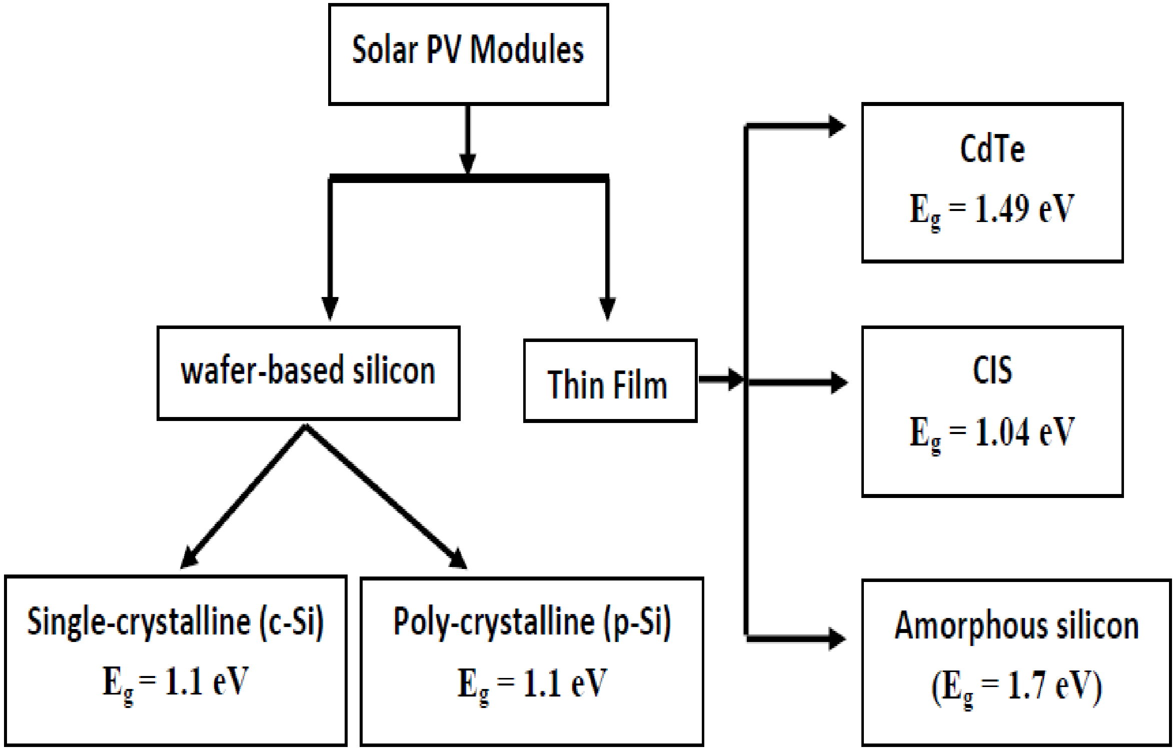
Life Cycle of PV Systems



Impacts:
Energy payback time
Global warming potential
Metal toxicity
Water use

Types of PV Systems



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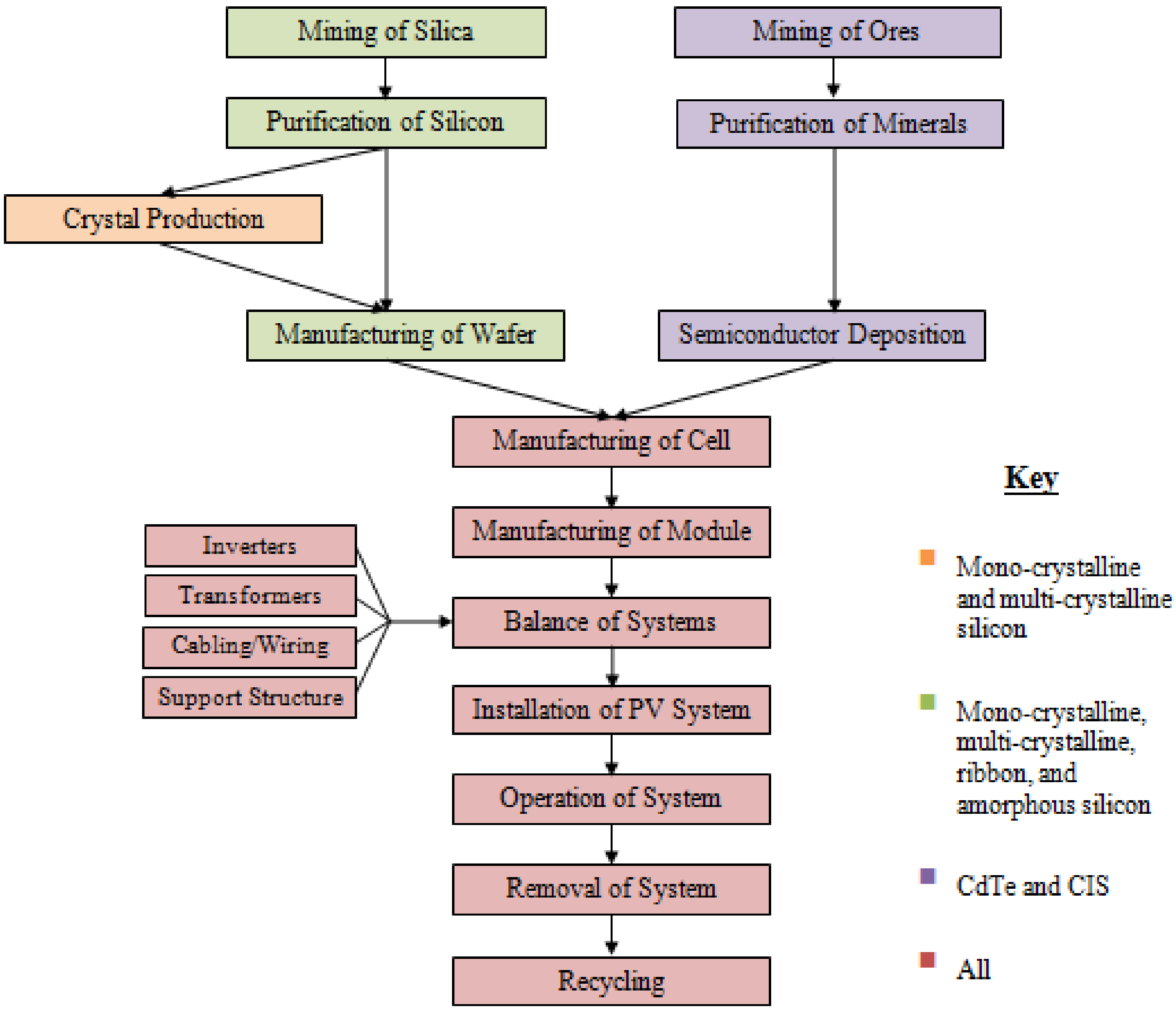
Life Cycle Phases of Si and Thin Film PV



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Summary of Data Compiled

- 218 papers collected
- Data from following papers have been compiled into tables
  - 12 references on water
  - 4 references on toxicity
  - 63 references on energy and GHG emissions
    - 25 references on thin film
    - 13 references on single crystalline Si
    - 14 references on poly crystalline Si
    - 11 references on amorphous Si

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Preliminary Results on Water Use

Table 2: Construction phase water use

Source No.	Type of PV	Reference	Manufacturing Stage Total	Units	Data Source
1	Mono-crystalline	Alsema and Wild-Scholten (2005)	109.8	kg/m^2	PV companies and literature
2		Fthenakis et al. (2011)	126.6	kg/m^2	PV companies and literature
3		Fthenakis and Kim (2010)	190	L/MWh	PV companies and literature
4		Harto et al. (2010)	0.058-0.152	gal/kWh	PV companies, literature, and EIOLCA
3	Multi-crystalline	Alsema and Wild-Scholten (2005)	109.7	kg/m^2	PV companies and literature
4		Fthenakis et al. (2011)	126.6	kg/m^2	PV companies and literature
6		Meijer et al. (2003)	210,000	kg/kW_p	literature
7		Traverso et al. (2012)	21,286	kg/m^2	SimaPro database
1		Fthenakis and Kim (2010)	200	L/MWh	PV companies and literature

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Preliminary Results on Toxicity

Figure 4: Ecotoxicity Potential of Multi-crystalline Silicon Photovoltaics

Source No.	Reference	Life Cycle Stage	Total	Units	Data Source
	Jungbluth (2005)	Quartz reduction, Silicon Purification, Wafer, panel, & laminate production, Mounting structure, operation, and dismantling	2.5E-4	Pt	ETH-data 1996
			3.3E-4	Pt	Ecoinvent 2000 database
	Desideri et al. (2012)	PV plant, Decommissioning and Maintenance	.66	mPt	Ecoinvent, Idemat 2001, BUWAL 250, ETH-ESU 96
	Laleman et al. (2011)		30	Pt	Ecoinvent database
	Zhong et al. (2011)	Assembly and Disposal	3E-6	Average European person /year	Energy Research Centre of the Netherlands (ECN) and SimaPro Ecoinvent database
		Assembly, Disposal, and Recycling	1.505E-6		

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Example Compiled Data on Life Cycle Energy of PV Systems

S No.	Reference	PV Technology	Location	Module Efficiency (%)	Power Rating	Performance Ratio	Life Time (years)	Irradiance ($kWh/m^2/yr$)	Embodied Energy (MJ/m^2)	EPBT (years)
	Alsema (1996)	CdTe	Global average	9.4		0.75	15	1700	301	0.5
		CIS	Global average	9.4		0.75	15	1700	481	1.9
	Alsema (1998)	CdTe	Mediterranean	6	--	0.8	--	1700	790-1270	0.9-1.5
	Alsema et al. (2006)	CdTe	South-Europe	9	--	0.75	30	1700	--	1.1
		CIGS	South-Europe	11.5	--	0.75	30	1700	--	1.3
	Bossert et al. (2000)	CdTe	--	10	--	--	--	1100	85-150	0.5-0.9
		CIGS	--	12	--	--	--	1100	255-360	1.3-1.8
	Cucchiella (2012)	CdTe	Palermo, Italy	9	--	--	20	1.623 kWh/m^2	2570 kWh	1.8
		CIS	Palermo, Italy	9.5	--	--	20	1.623	3510 kWh	2.4
	de Wild-Scholten (2009)	CdTe	South-Europe	10.9	--	0.75	--	1700	811	0.84
		CIGS	South-Europe	10.5	--	0.75	--	1700	1684	1.4
	Filippidou et al. (2010)	CdTe	Xanthi, Greece	9	70 Wp	--	--	1.420	1217.60	2.52

Solar PV modules

Country	Irradiance ($kWhm^{-2}year^{-1}$)	Module Efficieny (%)		
		SC-Si	MC-Si	a:Si
Netherlands	1700	14	13	7
Germany	1025			6
China	1715		12.8	6.9
USA	2359		12.9	6.3
USA	1570			5
USA	1671			6
USA	2100		12.2	
Japan	1427	12.2	11.6	10
Japan	1209		10	
Spain	1825			7
Switzerland	1117	14	13.2	
France	1400			6
Canada	950	14	13.2	6.5
Italy	1700			5.5
Italy	1530		10.7	
India	1200	8 & 11		
Singapore	1635	9		
UK	800	11.5		

SC-Si : η varies from 8 – 14
MC-Si: η varies from 10 – 13
a:Si: η varies from 5– 10

Power rating

SC-Si	1 - 300 kW
MC-Si	1kW - 100 MW
a:Si	1kW - 100 MW

Lifetime of Module

Majority of PV module have lifetime of 30 years

Embodied Energy (MWh/kWp) or (MJ/m^2)

Energy invested in PV power station depends on system boundary

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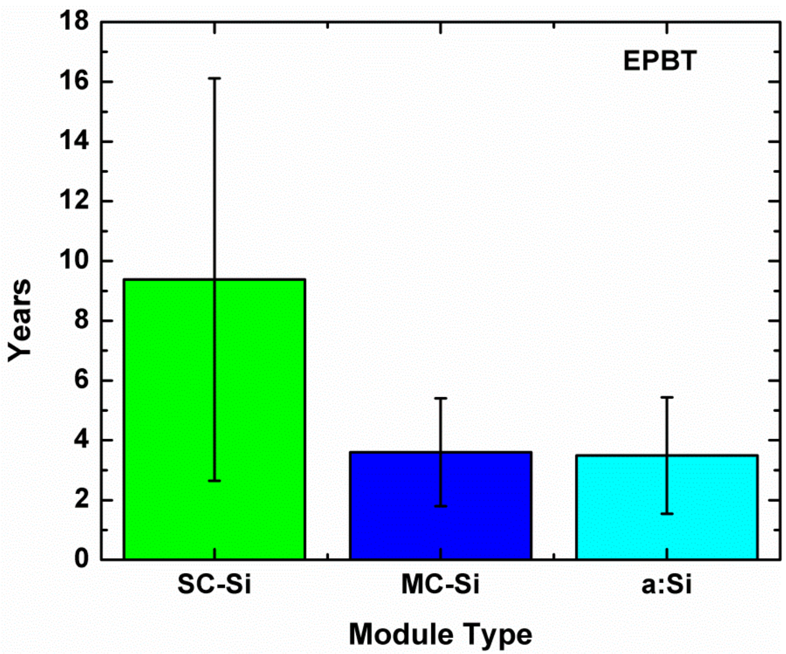
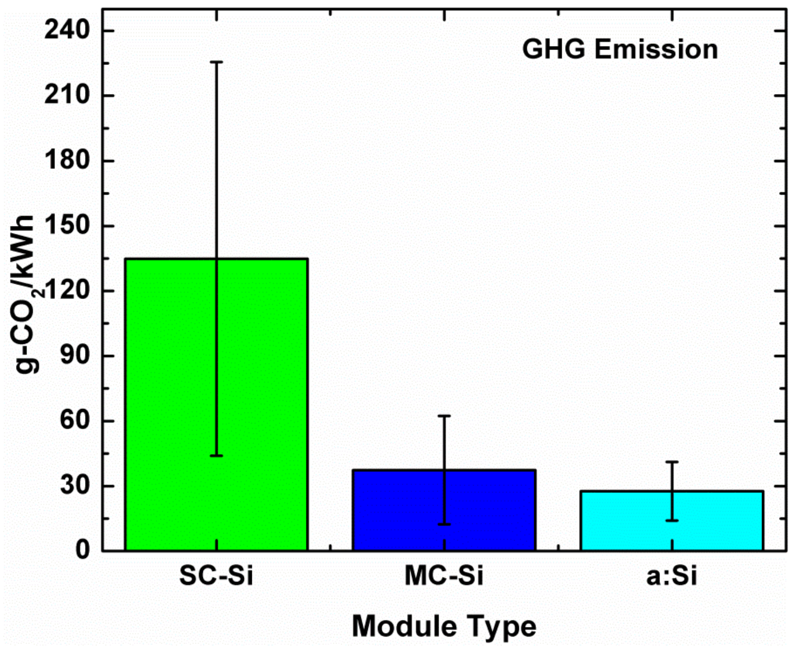
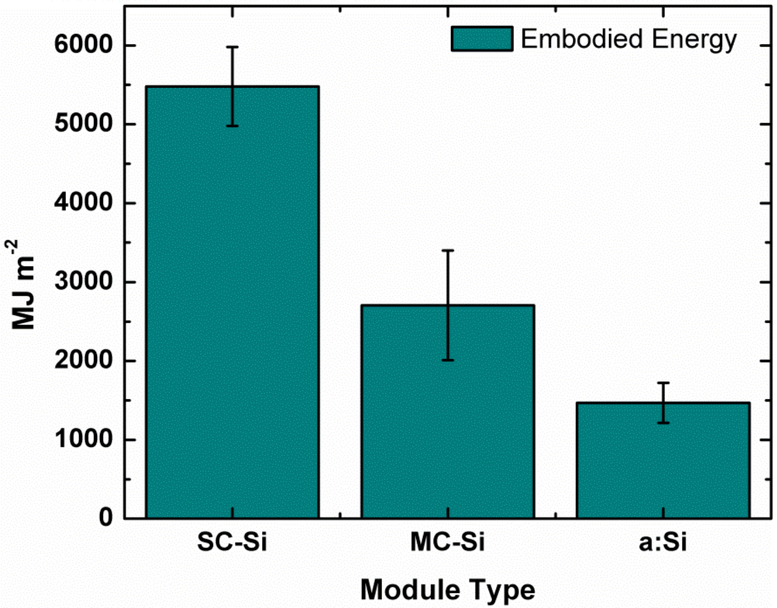
EPBT, GHG and Embodied Energy







- ❖ Large error bar in EPBT depends on where and when the PV module was made
- ❖ Large error bar in GHG depends on the grade of silicon
- ❖ Embodied energy consists of module manufacturing and BOS but not disposal

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Solar PV modules

Location	Irradiance ($kWhm^{-2}year^{-1}$)	Module Efficiency (%)	
		CdTe	CIS
Belgium	950	7.1	10.7
China	1702	9	11
Germany	1200	10	
India	1000	9.4	9.4
Italy	1625	9	9.5
Italy	1700	10.9	
Japan	1343		10.1
Japan	1725		11.2
Japan	1803	10.3	
Malaysia	1810.4	11.2	
Mediterranean	1700	6	
Switzerland	1117	7.1	10.7
US	1800	9	
US	1700	10.9	
Global Average	1700	9.4	9.4

CdTe : η varies from 6 – 11.2
CIS: η varies from 9.4– 11.2

Power rating

CdTe	65W-10MW
CIS	38W-10kW

Lifetime of Module

The lifetime is between 15 and 30 years

Embodied Energy (MWh/kWp) or (MJ/m^2)

Energy invested in PV power station depends on system boundary

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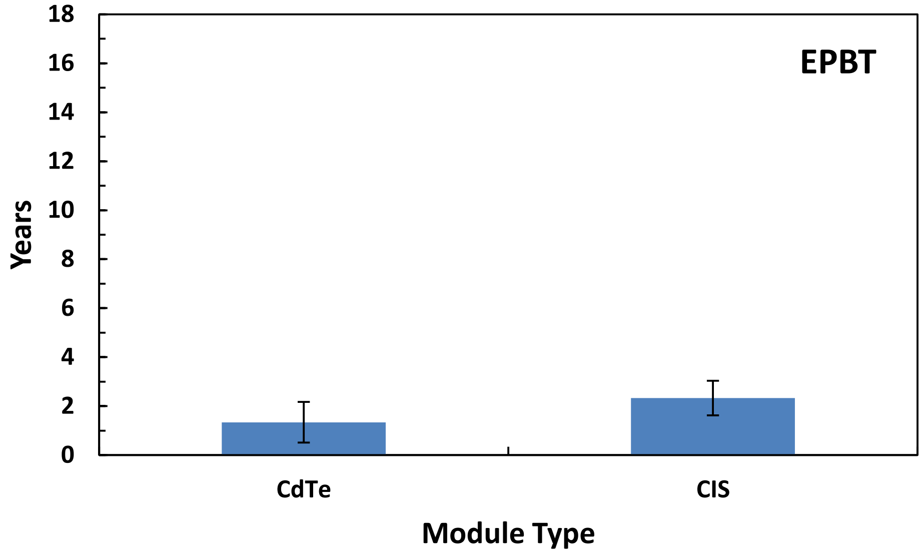
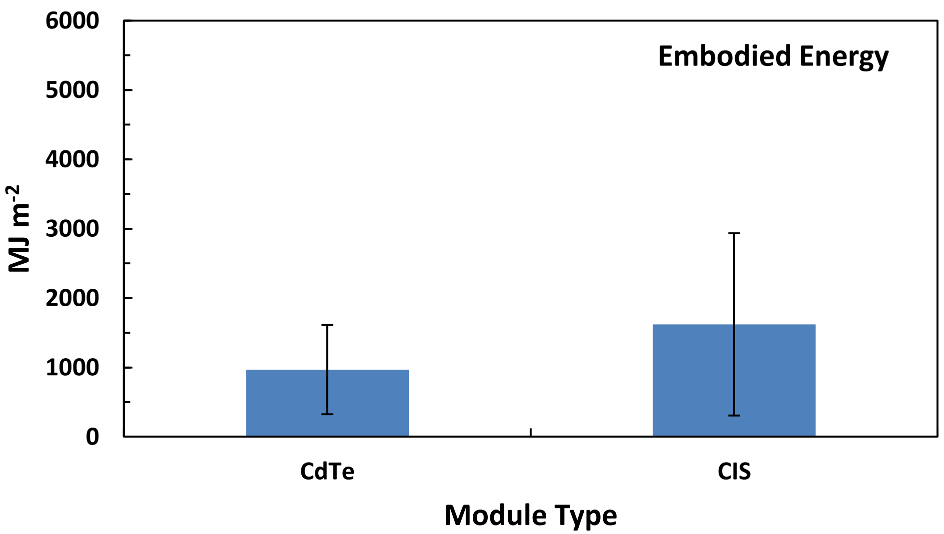
EPBT and Embodied Energy





- ❖The error bars show one standard deviation
- ❖Energy payback time depends on efficiency and irradiance
- ❖The large error bars for embodied energy are due to studies setting different boundaries

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Summary

- Compiled comprehensive list of articles on PV LCA
- Some preliminary analysis on water use and toxicity
- Manuscript in prep on embedded energy

Future Work (Defne, Jenny, Khagendra, Randy, Yanfa)

PV LCA review manuscript on embedded energy and EPBT

- Eliminate some of the data (May)
- Harmonize the data (May)
- Analyze results (May)
- Write it up (June)

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Barriers Encountered

2012:

Life Cycle Greenhouse Gas Emissions of Crystalline Silicon Photovoltaic Electricity Generation

Systematic Review and Harmonization

David D. Hsu, Patrick O'Donoughue, Vasilis Fthenakis, Garvin A. Heath, Hyung Chul Kim, Pamala Sawyer, Jun-Ki Choi, and Damon E. Turney

Life Cycle Greenhouse Gas Emissions of Thin-film Photovoltaic Electricity Generation

Systematic Review and Harmonization

Hyung Chul Kim, Vasilis Fthenakis, Jun-Ki Choi, and Damon E. Turney

2013:

Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems

Jinqing Peng, Lin Lu*, Hongxing Yang

Renewable Energy Research Group (RERG), Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong, China

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Future work (Jenny)

- Begin modeling: Zn_3P_2 and CZTS
- FYSRE
  - Task 1: Review and finalize data for existing PV systems
  - Task 2: Collect life cycle inventory data on Zn_3P_2 and CZTS
  - Task 3: Use GaBi to model mining and purification stages of Zn_3P_2 and CZTS
  - Task 4: Use GaBi to model cell manufacturing stage of Zn_3P_2 and CZTS
  - Task 5: Compare Zn_3P_2 and CZTS impacts to those of existing PV systems. Revise and improve data
  - Task 6: Write report

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Future Work (new PhD student)

- Expect to arrive in mid summer or fall
- Will work with Jenny on LCA of Zn_3P_2 and CZTS
- Will work on Bayesian inverse modeling

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Energy and GHG Related Definitions

- *Embodied Energy*

  MJ/m²

- *Energy Payback Time (EPBT)*

$$EPBT\ (year) = \frac{Total\ primary\ energy\ requirement\ of\ system\ throughout\ its\ life\ cycle\ (MJ)}{Annual\ primary\ energy\ generation\ by\ the\ system\ (\frac{MJ}{year})}$$

- *GHG Emissions*

$$GHG\ \left(\frac{g.CO_2}{kWh}\right) = \frac{Total\ CO_2\ emissions\ throughout\ its\ life\ time\ (g.CO_2)}{Annual\ power\ generation\ \left(\frac{kWh}{year}\right) \times lifetime\ (year)}$$