Lecture 13: Life Cycle Analysis and multicriteria assessment of energy systems in view of sustainability indicators

A detailed solution will be available from the 20th of December on the website: http://www.psi.ch/ene/ret1

Questions: Xiaojin Zhang, xiaojin.zhang@psi.ch

Life Cycle Analysis (LCA) of photovoltaic (PV) energy systems and Application of Multi-criteria Decision Analysis (MCDA) to rank electricity generation systems

*The exercise consists of part **A** and **B** with **four questions** in total.*

The first part (A) addresses a simplified PV energy chain. The cumulative direct electricity demand based on various steps of the energy chain should be calculated. As the electricity generation is associated with emissions (to air), selected cumulative emissions per kWh of electricity produced from the PV plant should be calculated.

The second part (B) consists of the application of an MCDA for the sustainability assessment of four different electricity generation systems.

Part A

A1. LCA-based direct electricity requirements of a solar PV system

The system to analyse is a 5 kW_p[1] PV plant with single-crystalline silicon cells (sc-Si), mounted on the slanted roof of a house in the Swiss Middle-Lands and connected to the electricity grid. The yearly electricity production yield) is about 900 kWh/(year*kW_p).

Figure 1 shows a simplified exemplary PV energy chain. The names within boxes correspond to the products of individual production steps. The direct electricity requirements (or uses) of the steps are also shown (adapted from Jungbluth et al. 2010; *ecoinvent* 2015).

Calculate the **cumulative direct electricity requirements per 5 kW_p PV plant** throughout the energy chain. The LCA calculation is simplified in the sense that only the main route of silicon production is taken into account and no feedbacks from the material uses are considered. (1.5 Points)

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[1] The power rate of PV plants is always given as peak power obtained with optimal exposure to sunrays.

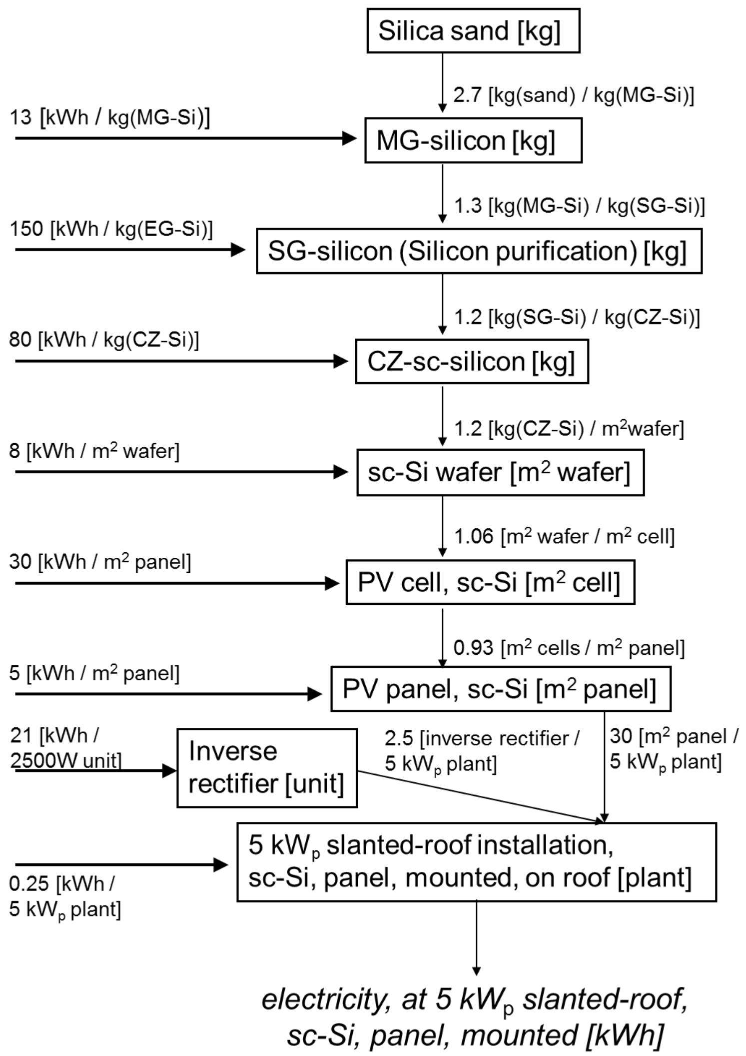

Figure 1: The horizontal arrows give the direct electricity requirements for the main steps of the PV energy chain for a 5 kW_p PV plant with single-crystalline silicon cells (sc-Si) mounted on slanted roof (simplified and adjusted, after Jungbluth et al., 2010). The vertical arrows represent the exchanges between two consecutive steps of the chain. MG=Metallurgical Grade; SG=Solar Grade; CZ=Czochralski Process.

A2. LCA-based cumulative emissions from the electricity requirements of the PV chain

The ENTSO-E[2] electricity mix of 2012 is given in Table 1. Selected cumulative air emissions associated with the most important power generation systems in the ENTSO-E are given in Table 2 as calculated from the LCA database *ecoinvent*. Assume that all electricity requirements for the fabrication of the PV plant (i.e. all electricity inputs shown in Figure 1) are from the ENTSO-E Mix 2012.[3]

Calculate the selected cumulative air emissions associated with the unit of electricity produced at the PV plant in **kg emission / kWh produced from the PV plant** for each pollutant separately. Assume 25 years lifetime of the PV modules. (1.5 Points)

[2] European Network of Transmission System Operators for Electricity. Since 2009, the Union for the Co-ordination of Transmission of Electricity (UCTE) has transferred its tasks to ENTSO-E.

[3] In *ecoinvent*, every step in the production chain includes specific electricity supply, e.g. electricity from hydro and natural gas power plants for the production of SG-silicon. This exercise is therefore simplified.

Table 1 Share [%] of the different types of electricity generation in the average electricity mix in the ENTSO-E in 2012 (simplified and adjusted, after *ecoinvent* 2015). The category "Wind and others" includes electricity from solar, geothermal, biogas, wood and waste. Wind alone is 6%.

Electricity mix ENTSO-E 2012	Lignite	Hard coal	Oil	Natural gas	Nuclear	Hydro	Wind and others
[%]	12	16	2	16	25	16	13

Table 2 Selected LCA-based cumulative air emissions from the electricity generation of different full energy chains (adjusted, *ecoinvent* 2015). *Reservoir and run-of-river hydropower.

Emission species[4]	Lignite	Hard coal	Oil	Natural gas	Nuclear	Hydro*	Wind
GHG [kg CO_2-equivalent/kWh]	1.15E+0	1.07E+0	8.85E-1	6.40E-1	7.79E-3	4.46E-3	1.13E-2
SO_2 [kg/kWh]	1.42E-3	1.54E-3	2.75E-3	6.94E-4	3.07E-5	1.43E-5	2.42E-5
NO_x [kg/kWh]	6.95E-3	3.24E-3	4.38E-3	2.18E-4	3.21E-5	5.32E-6	3.23E-5
$PM_{2.5}$ [kg/kWh]	5.1E-4	1.93E-4	1.26E-4	1.14E-5	1.93E-5	3.92E-6	9.38E-6
NMVOC [kg/kWh]	3.20E-5	9.78E-5	3.87E-4	3.62E-4	6.91E-6	2.65E-6	6.51E-6

Note: You can use the data for wind for all the 13% of wind and others in table 1.

Part B

B1. Application of Multi-criteria Decision Analysis (MCDA) to rank four electricity generation systems: Trade-off assessment

Table 3 presents an overview of indicators assembled to characterize four different power generation systems (hydro power, wind, nuclear and natural gas; current technologies, German case) concerning the three pillars (or dimensions) of sustainability: Economy, Environment and Society (Hirschberg et al. 2004).

In the spirit of sustainability equal weight are assigned to each pillar. Therefore, a weight of 33.3 should initially be assumed for each dimension as it is shown in Tables 3 and 4. The sum of these first level weights must be 100. Weights provided for lower levels in the criteria hierarchy represent a consensus within a stakeholder group. The sum of the weighting must be 100 in each set.[5]

Table 4 shows the linearly normalised values assigning to each indicator 100 for the best performer and 0 for the worst performer among the four electricity generation systems. That way, all indicators are expressed in the same unit (Hirschberg et al. 2004).

Use Table 4 for the calculation of total sustainability score for the four power generation systems, using the weighted sum approach explained in the lecture slides. Apply the algorithm in sequence to each level were weights are given, starting from the lowest level. In some cases, level 2 and level 3 have the same indicator or, seen the other way around, criteria at level 2 do not need sub-criteria at level 3 in order to provide a more refined description. (1.5 points)

[4] The greenhouse gas (GHG) emissions are calculated using the greenhouse warming potentials from (IPCC 2007) for the 100 year time horizon. SO_2: Sulfur Dioxide, NO_x: Nitrogen Oxides, $PM_{2.5}$: Particulate Matter <2.5μm diameter, NMVOC: Non-Methane Volatile Organic Compounds.

[5] In the slides of the lesson, the weights are given as fractions and the sum of the weights is set to 1.

B2. Establish your own weighting profile

Of course weighting can be different depending on stakeholder-specific preferences. **Establish your own weighting profile** including the highest level if your priorities for the three dimensions of sustainability are not equal. Carry out the MCDA calculation again, establish a new ranking of technologies and discuss the differences. (0.5 points)

Table 3 Full set of indicators and weights (Base Case MCDA); after (Hirschberg et al. 2004).

Economic Indicators

Level 1	Level 2		Level 3			Electricity systems			
Weight	**Impact Area**	**Weight**	**Indicator**	**Weight**	**Unit**	**Hydro**	**Wind**	**Nuclear**	**Natural Gas**
33.3	Financial Requirements	**60**	Production cost	**70**	*c€/kWh*	7	9	2.1	3.6
			Fuel price increase sensitivity	**30**	*Factor*	1	1.03	1.3	1.8
	Resources	**40**	Availability (load factor)	**30**	*%*	40	20	80	80
			Geopolitical factors	**20**	*Relative scale*	100	90	80	40
			Long-term sustainability: Energetic	**10**	*Years*	∞	∞	5E+02	1E+02
			Long-term sustainability: Non-energetic (Cu)	**20**	*kg/GWh*	1	38	5	4
			Peak load response	**20**	*Relative scale*	30	0	10	100

Environmental Indicators

Level 1	Level 2	Level 3			Electricity systems			
Weight	**Impact Area**	**Indicator**	**Weight**	**Units**	**Hydro**	**Wind**	**Nuclear**	**Natural Gas**
33.3	Global Warming	CO_2-equivalents	**40**	*tons/GWh*	4	10	10	423[6]
	Regional Environmental Impact	Change in unprotected ecosystem area	**30**	*km^2/GWh*	0.0009	0.0029	0.0017	0.0163
	Non-Pollutant Effects	Land use	**10**	*m^2/GWh*	92	28	7	47
	Severe accidents	Fatalities	**15**	*Fatalities/ GWh*	0.003	0.0001	0.02	0.091
	Total Waste	Mass	**5**	*tons/GWh*	24	23	15	2

Social Indicators

Level 1	Level 2	Level 3			Electricity systems			
Weight	**Impact Area**	**Indicator**	**Weight**	**Units**	**Hydro**	**Wind**	**Nuclear**	**Natural Gas**
33.3	Employment	Technology-specific job opportunities	**5**	*person-years / GWh*	1.2	0.36	0.16	0.65
	Proliferation	Potential [7]	**10**	*Relative scale*	0	0	100	0
	Human Health Impacts (normal operation)	Mortality (reduced life-expectancy)	**55**	*YOLL[8]/GWh*	0.011	0.007	0.005	0.023
	Local Disturbances	Noise, visual amenity	**5**	*Relative scale*	5	7	4	2
	Critical Waste confinement	"Necessary" confinement time	**10**	*Years*	1E+01	1E+03	1E+06	1E+01
	Risk Aversion	Maximum credible number of fatalities per accident	**15**	*max fatalities/ accident*	2000	5	50000	100

[6] Modern Natural Gas Combined Cycle (NGCC) power plant.
[7] Issue specific to nuclear energy.
[8] Years Of Life Lost.

Table 4 Full set of normalized (*Norm.*) indicators and weights, using a scale of merit (100=Best, 0=Worst); after (Hirschberg et al. 2004).

Economic Indicators

Level 1	Level 2		Level 3			Electricity systems (p_{ij})			
Weight (w_i)	**Impact Area**	**Weight (w_i)**	**Indicator**	**Weight (w_i)**	**Unit**	**Hydro**	**Wind**	**Nuclear**	**Natural Gas**
33.3	Financial Requirements	60	Production cost	70	*Norm.*	29	0	100	78
			Fuel price increase sensitivity	30	*Norm.*	100	96	63	0
	Resources	40	Availability (load factor)	30	*Norm.*	33	0	100	100
			Geopolitical factors	20	*Norm.*	100	83	67	0
			Long-term sustainability: Energetic	10	*Norm.*	100	100	0	0
			Long-term sustainability: Non-energetic (Cu)	20	*Norm.*	100	0	88	91
			Peak load response	20	*Norm.*	30	0	10	100

Environmental Indicators

Level 1	Level 2	Level 3			Electricity systems (p_{ij})			
Weight (w_i)	**Impact Area**	**Indicator**	**Weight (w_i)**	**Units**	**Hydro**	**Wind**	**Nuclear**	**Natural Gas**
33.3	Global Warming	CO_2-equivalents	40	*Norm.*	100	99	99	0
	Regional Environmental Impact	Change in unprotected ecosystem area	30	*Norm.*	100	87	95	0
	Non-Pollutant Effects	Land use	10	*Norm.*	0	75	100	53
	Severe accidents	Fatalities	15	*Norm.*	97	100	78	0
	Total Waste	Mass	5	*Norm.*	0	5	41	100

Social Indicators

Level 1	Level 2	Level 3			Electricity systems (p_{ij})			
Weight (w_i)	**Impact Area**	**Indicator**	**Weight (w_i)**	**Units**	**Hydro**	**Wind**	**Nuclear**	**Natural Gas**
33.3	Employment	Technology-specific job opportunities	5	*Norm.*	100	19	0	45
	Proliferation	Potential[9]	10	*Norm.*	100	100	0	100
	Human Health Impacts (normal operation)	Mortality (reduced life-expectancy)	55	*Norm.*	67	89	100	0
	Local Disturbances	Noise, visual amenity	5	*Norm.*	40	0	60	100
	Critical Waste confinement	"Necessary" confinement time	10	*Norm.*	100	100	0	100
	Risk Aversion	Maximum credible number of fatalities per accident	15	*Norm.*	96	100	0	100

[9] Issue specific to nuclear energy.

References

ecoinvent 2015	*ecoinvent* (2015) ecoinvent data v3.2. Swiss Centre for Life Cycle Inventories, Dübendorf, www.ecoinvent.org
Hirschberg et al. 2004	Hirschberg S., Dones R., Heck T., Burgherr P., Schenler W., Bauer C., “Sustainability of Electricity Supply Technologies under German Conditions: A Comparative Evaluation.” PSI report Nr. 04-15. December 2004.
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