Life Cycle Assessment and human health impacts of Electricity Production

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Contents

- Motivation and goal
- Scope
- Technologies analysed
- Results
- Conclusion

Motivation and goal

- Energy policy in Belgium:
  Early phase out of Nuclear Power plants
- Quantify environmental impacts and in particular human health damages caused by electricity production with current power plant technologies

Scope and source of information

- Scope
  - power plant construction/manufacture
  - fuel supply (where applicable)
  - operation
  - dismantling
- Functional unit: 1 kWh AC electricity fed into grid
- Information and data
  - hard coal and lignite DE: emission factors SO_2, NO_X, PM and Hg, supply mix
  - ecoinvent data v2.2, with updates and extensions up to 2016
  - IEA PVPS report T12-04:2015 (LCA of PV)

Environmental impacts

- ReCiPe 2008, human health impacts
  - Hierarchist perspective
  - European normalisation
  - Excluding climate change impacts on human health
- ILCD 2011, v1.07, complemented with the following indicators from the PEF pilot on PV electricity
  - cumulative energy demand, non renewable
  - cumulative energy demand, renewable
  - Toxicity potential of nuclear wastes
- Long term emissions (beyond 100 years) excluded

Technologies analysed

- German lignite power plant (average in operation)
- German hard coal power plant (average in operation)
- German Natural gas power plant (average in operation)
- 2 PV technologies, residential scale
  - CdTe thin film laminate (unframed)
  - crystalline Multi-silicon based laminate (unframed)
- Wind power plants, onshore and offshore
- Nuclear power plant (PWR, average in operation)

Lignite power plant, Germany

- Net efficiency: 33.1 %
- Flue gas treatment, efficiency
  - desulphurisation: 95 %
  - DeNOx: 73.9 %
- Emission factors
  - CO_2: 1’175 g/kWh
  - SO_2: 0.59 g/kWh
  - NO_X: 0.717 g/kWh
  - PM10: 0.014 g/kWh

Hard coal power plant, Germany

- Net efficiency: 35.9 %
- Flue gas treatment
  - desulphurisation: 90.4 %
  - DeNOx: 79 %
- Emission factors
  - CO_2: 925 g/kWh
  - SO_2: 0.433 g/kWh
  - NO_X: 0.618 g/kWh
  - PM10: 0.05 g/kWh

Natural gas power plant, Germany

- Net efficiency: 43.7 %
- Emission factors
  - CO_2: 461 g/kWh
  - SO_2: 0.004 g/kWh
  - NO_X: 0.29 g/kWh
  - PM10: 0.002 g/kWh

CdTe photovoltaic power plant

- Size: 3 kWp
- Module efficiency: 14 %
- Lifetime: 30 years
- Degradation rate: 0.7 % per year
- Annual electricity production: 880 kWh

Multi-Si photovoltaic power plant

- Size: 3 kWp
- Module efficiency: 14.7 %
- Lifetime: 30 years
- Degradation rate: 0.7 % per year
- Annual electricity production: 880 kWh

Wind power plant, on-/offshore

- Size: 800 kW / 2 MW
- Lifetime:
  - moving parts: 20 years
  - fixed parts: 40 years
- Annual electricity production: 1750 / 2630 kWh

Nuclear power plant, Europe

- Technology: Pressure water reactor
- Size: 1 GW
- Lifetime: 40 years
- Capacity factor: 80.4 %
- Net efficiency: 33 %
- Uranium demand: 2.8 g per GWh
- Spent fuel treatment:
  - 81 % reprocessing
  - 19 % conditioning

Nuclear accidents: radionuclide releases

- Radioactive releases of Tschernobyl 1986 & Fukushima 2011 accidents
  - Cs-134: 470 PBq
  - Cs-137: 97 PBq
  - I-131: 1’910 PBq
- Referred to cumulative nuclear electricity production 1965 -2015: 82’350 TWh

Results: inventory, excerpt per kWh electricity

	per kWh electricity	unit	lignite	hard coal	natural gas	PV, CdTe	PV, multi-Si	wind, onshore	wind, offshore	nuclear
air	Nitrogen oxides	mg	769.89	974.52	444.56	91.06	198.60	23.33	31.76	30.32
	Sulfur dioxide	mg	635.91	679.18	210.47	133.97	336.62	30.61	35.57	31.46
	Particulates, < 2.5 um	mg	69.69	62.66	7.54	10.10	26.88	9.20	9.75	19.21
	Particulates, > 2.5 um, < 10um	mg	11.71	18.75	3.87	8.20	13.08	10.69	11.92	24.34
	Mercury	mg	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00
	Arsenic	mg	0.01	0.02	0.00	0.07	0.08	0.01	0.01	0.10
	Ammonia	mg	7.11	24.61	0.21	3.53	4.25	0.51	0.63	0.69
	PM10	mg	0.07	0.12	0.00	0.06	0.09	0.01	0.01	0.15
	Hydrogen fluoride	mg	9.11	13.37	0.04	0.54	1.47	0.08	0.08	0.25
	Cadmium	mg	0.00	0.00	0.00	0.02	0.03	0.00	0.00	0.00
	Carbon-14	Bq	0.32	0.43	0.03	0.16	0.32	0.05	0.07	39.00
water	Arsenic	mg	8.55	1.60	0.02	0.60	0.79	0.09	0.10	0.97
	Manganese	mg	2020.46	215.65	2.18	45.35	56.95	7.40	7.78	7.14
	Selenium	mg	7.39	0.96	0.01	0.28	0.36	0.04	0.04	0.13
	Lead	mg	1.96	0.49	0.05	0.39	0.51	0.09	0.10	1.85

Results: environmental impacts ILCD 2011 per kWh electricity

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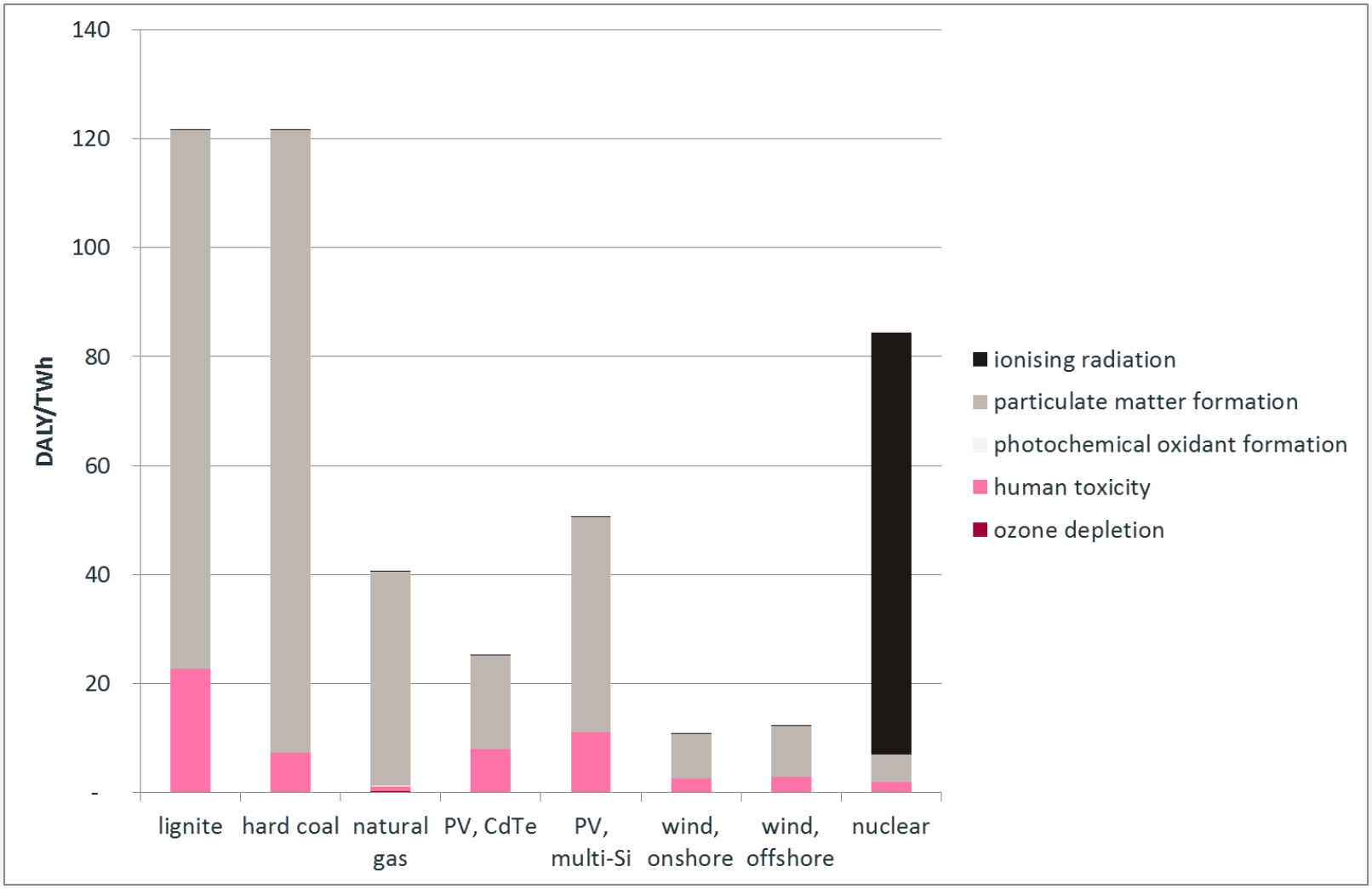
impact category	unit	lignite	hard coal	natural gas	PV, CdTe	PV, multi-Si	wind, onshore	wind, offshore	nuclear
Climate change	g CO2 eq	1'219.22	1'092.27	537.12	28.64	62.37	10.97	14.02	7.68
Ozone depletion	µg CFC-11 eq	1.12	1.85	81.94	1.41	2.28	0.51	0.60	18.67
Human toxicity, cancer effects	nanoCTUh	6.08	1.32	0.59	0.74	1.15	2.37	2.48	0.60
Human toxicity, non-cancer effects	nanoCTUh	53.37	19.68	3.00	9.62	14.75	5.01	5.84	1.56
Particulate matter	mg PM2.5 eq	73.44	81.66	27.89	17.10	78.49	8.10	9.10	5.45
Ionizing radiation	Bq U235 eq	3.36	4.59	0.35	1.75	3.41	0.58	0.69	412.89
Ionizing radiation, accidents	Bq U235 eq								4306.39
Photochemical ozone formation	mg NMVOC eq	838.06	1'125.70	650.66	123.75	259.35	32.10	42.69	39.79
Acidification	molc H+ eq	1.42	1.69	0.61	0.25	0.60	0.06	0.07	0.07
Terrestrial eutrophication	molc N eq	3.38	4.48	1.90	0.44	0.90	0.11	0.14	0.14
Freshwater eutrophication	mg P eq	304.08	36.98	0.43	10.43	13.12	1.58	1.65	0.52
Marine eutrophication	mg N eq	307.55	390.84	173.06	38.45	82.31	11.32	14.90	15.50
Freshwater ecotoxicity	milliCTUe	144.42	46.56	8.39	101.95	122.81	31.03	33.07	26.64
Land use	g C deficit	-8.20	489.67	459.61	51.84	98.38	131.31	18.90	34.24
Water resource depletion	cm3 water eq	421.77	341.19	31.82	11.62	54.50	5.45	6.52	122.12
Mineral, fossil & ren resource depletion	mg Sb eq	0.22	0.26	0.13	19.99	33.28	0.62	0.89	4.69
Cumulative energy demand non renewable	MJ oil eq	12.76	12.68	9.26	0.44	0.83	0.16	0.19	12.64
Cumulative energy demand renewable	MJ oil eq	0.03	0.10	0.01	3.88	3.95	3.88	3.88	0.01
Nuclear waste	mm3 HAA eq	0.07	0.09	0.01	0.04	0.08	0.01	0.01	8.95

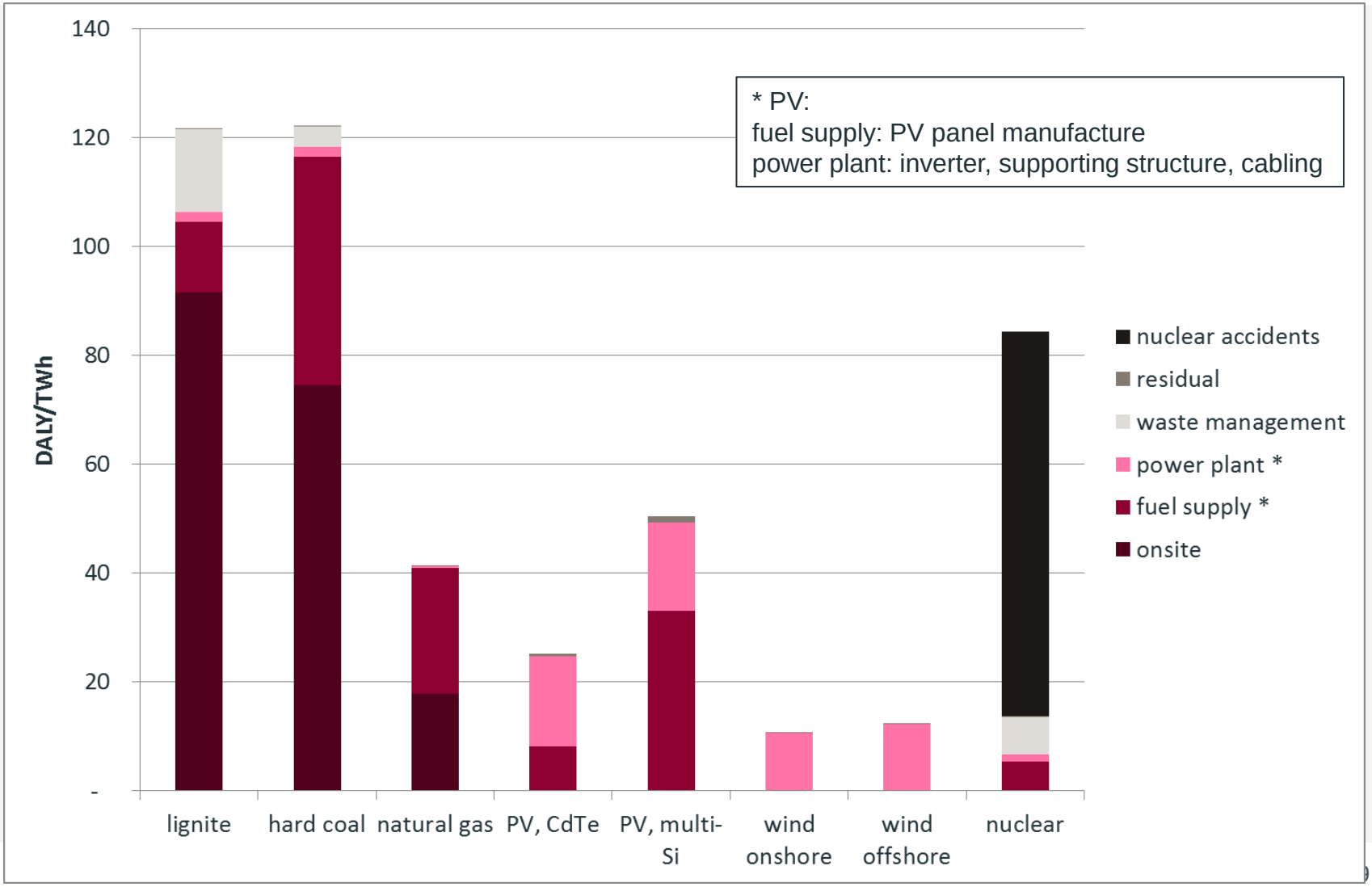
Results: human health impacts (excluding climate change)

DALY per TWh	compartment	lignite	hard coal	natural gas	PV, CdTe	PV, multi-Si	wind, onshore	wind, offshore	nuclear
Nitrogen oxides	air	44.07	55.78	25.45	5.21	11.37	1.34	1.82	1.74
Sulfur dioxide	air	33.07	35.32	10.95	6.97	17.51	1.59	1.85	1.64
Particulates, < 2.5 um	air	18.09	16.25	1.96	2.61	6.95	2.39	2.53	1.14
Arsenic	water	12.53	1.67	0.06	0.31	1.14	0.11	0.20	0.15
Manganese	water	6.69	1.48	0.01	0.07	0.13	0.02	0.02	0.71
Particulates, > 2.5 um, and < 10um	air	3.00	4.81	1.00	2.10	3.35	2.77	3.09	0.55
Mercury	air	1.17	1.16	0.57	0.30	0.77	0.93	1.11	0.16
Selenium	water	0.88	0.13	0.00	0.02	0.05	0.00	0.01	0.30
Arsenic	air	0.60	0.94	0.07	3.58	4.09	0.66	0.67	0.15
Ammonia	air	0.59	2.05	0.02	0.29	0.35	0.04	0.05	0.06
Lead	water	0.23	0.88	0.10	2.36	2.89	0.60	0.68	0.12
Selenium	air	0.22	0.37	0.00	0.06	0.07	0.01	0.01	0.00
Vanadium	air	0.09	0.13	0.01	0.11	0.19	0.02	0.02	0.06
Hydrogen fluoride	air	0.05	0.09	0.00	0.06	0.22	0.01	0.01	0.00
Cadmium	air	0.05	0.07	0.02	0.77	0.87	0.11	0.11	0.03
Carbon-14	air	0.05	0.07	0.01	0.03	0.05	0.01	0.01	6.40
remaining	air	0.25	0.70	0.56	0.74	1.53	0.12	0.14	0.86
accidental releases									70.16
total		**121.63**	**121.91**	**40.78**	**25.60**	**51.52**	**10.73**	**12.33**	**84.23**

Human health impacts, the five impact sources



Human health impacts, main phases



Data quality considerations (I)

- Data representing lignite, hard coal, natural gas, wind and nuclear electricity
  - operation: 2000, main air pollutants coal and lignite: 2013
  - supply chain: hard coal 2016, natural gas 2012, else: 2000
- Data representing PV electricity
  - module efficiency and manufacture: 2014
  - supply chain: 2012
- Data about radionuclide releases of nuclear accidents
  - Pavel Povinec, Katsumi Hirose, Michio Aoyama (2013), Fukushima Accident; Radioactivity Impact on the Environment, Elsevier

Data quality considerations (II)

- Performance of lignite, hard coal, natural gas and nuclear power plants still similar
- Efficiency of flue gas treatment in lignite and hard coal power plants is between 75 and more than 90 %
- Fuel supply chains today (provenience natural gas and uranium) may differ from the ones modelled
- Full load hours of wind power are at the lower bound
- PV module efficiencies continued to improve since 2014

Data quality considerations (III)

- Share of specific human health impacts caused by nuclear accidents highly dependent on cumulative electricity production
- Approach used in this study does not reflect the pulse nature of the radionuclide emissions
- Study does not include impacts related to
  - long-term evacuation, clean up efforts, securing and decommissioning of damaged nuclear reactors
  - other accidents (e.g. in coal mines)

Conclusions

- Factor 10 between highest (hard coal) and lowest (onshore wind) human health impacts
- Power plant operation is most important for fossil fueled power plants
- Fuel supply important for natural gas and hard coal power generation
- Power plant construction/manufacture important for renewable technologies
- Releases from nuclear accidents contribute significantly to total score of nuclear electricity

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