PEFCR pilot project „Photovoltaic Electricity Generation“

Andreas Wade
Director Technical Relations and Public Affairs Europe
First Solar

AGENDA

(1) OVERVIEW: THE PILOT PROCESS

(2) THE DRAFT PEFCR

(3) SCREENING STUDY RESULTS

(4) NEXT STEPS

MOTIVATION

"We believe the joint development and international endorsement of a standardized methodology for the environmental assessment of photovoltaic technologies presents an excellent opportunity to re-confirm the socio-economic and environmental profile of this increasingly important electricity generation technology and communicate the results in a consistent and harmonized way to allow conscious policy and consumer decisions when it comes to electricity generation."

Technical Secretariat Application Document for the Pilot Process, February 2014

SCOPE OF THE PILOT

- The **scope of the PEFCR** is the **production of DC electricity with photovoltaic modules** and includes the manufacturing, the operation and dismantling of the photovoltaic modules as well as the use of production equipment and facilities and the supply chain of the materials used.
- **Products in scope** are commercially available photovoltaic module technologies including mono-crystalline Silicon, multi-crystalline Silicon, amorphous/micro-crystalline thin film Silicon, Copper-Indium-(Gallium)-Selenide thin film, Cadmium Telluride thin film.
- **Products out of scope** are concentrator PV modules, tracked PV modules, micro-inverter PV modules, hybrid PV modules and tracked systems. Mounting (including mounting structures), inverters and all electric installations for AC cabling are part of the system, but excluded from the scope through the system boundary definition.

OVERVIEW ON THE PILOT PROCESS

DELIVERABLE OF THE PILOT PROJECT

Product Environmental Footprint Category Rules

PRODUCTION OF PHOTOVOLTAIC MODULES USED IN PHOTOVOLTAIC POWER SYSTEMS FOR ELECTRICITY GENERATION
(NACE/CPA class 27.90 "Manufacturing of other electrical equipment")[1)]

[1)] in accordance with Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations (2013/179/EU), Annex II

RELEVANCE OF THE PILOT PROJECT

Eco Design

Eco Labeling

Electricity Labeling

SINGLE MARKET FOR GREEN PRODUCTS INITIATIVE

Establishment of a unified method to measure the environmental performance of a product throughout the lifecycle (=PEFCR)

+

Recommendation to the use of this method to Member States, companies, private organisations and the financial community through a Commission Recommendation

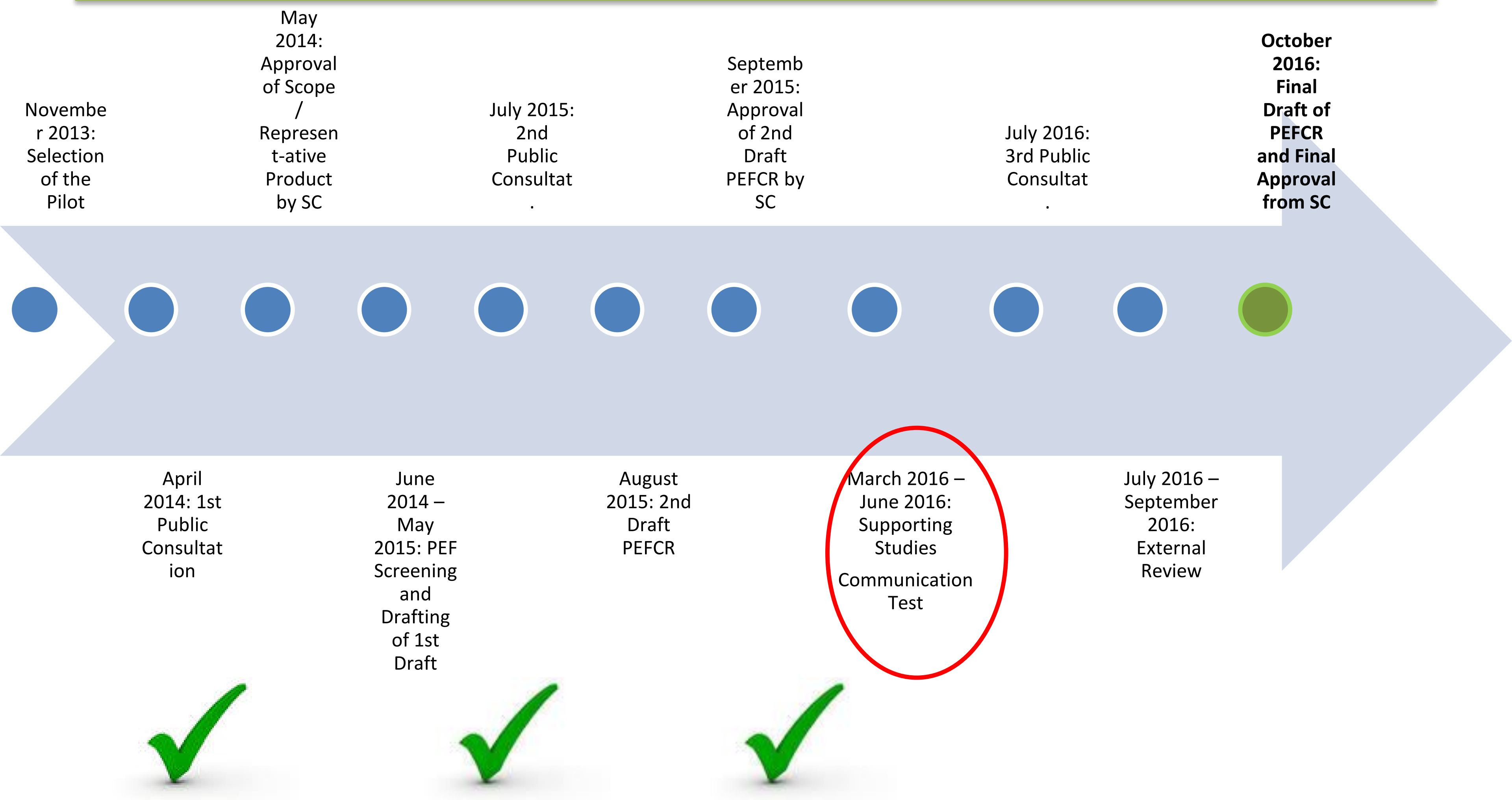
Green Public Procurement

Environmental Benchmarking in Public Tenders

TECHNICAL SECRETARIAT

International Energy Agency Photovoltaic Power Systems Program Task 12 (Environmental Health and Safety) / International Research Cooperation (international)	IEA-PVPS Task 12 PV Environmental Health And Safety
European Photovoltaic Industry Association (Europe) – now: SolarPower Europe	EPIA SolarPower Europe
International Thin-Film Solar Industry Association PVthin (international)	PVTHIN
Yingli Solar Energy (China)	YINGLI SOLAR
First Solar Inc. (USA)	First Solar
Total (France)	TOTAL
Calyxo GmbH (Germany)	calyxo
Energy Research Centre of the Netherlands / Solar Unit (ECN Solar) (Netherlands)	ECN
Treeze Ltd. (Switzerland)	treeze fair life cycle thinking

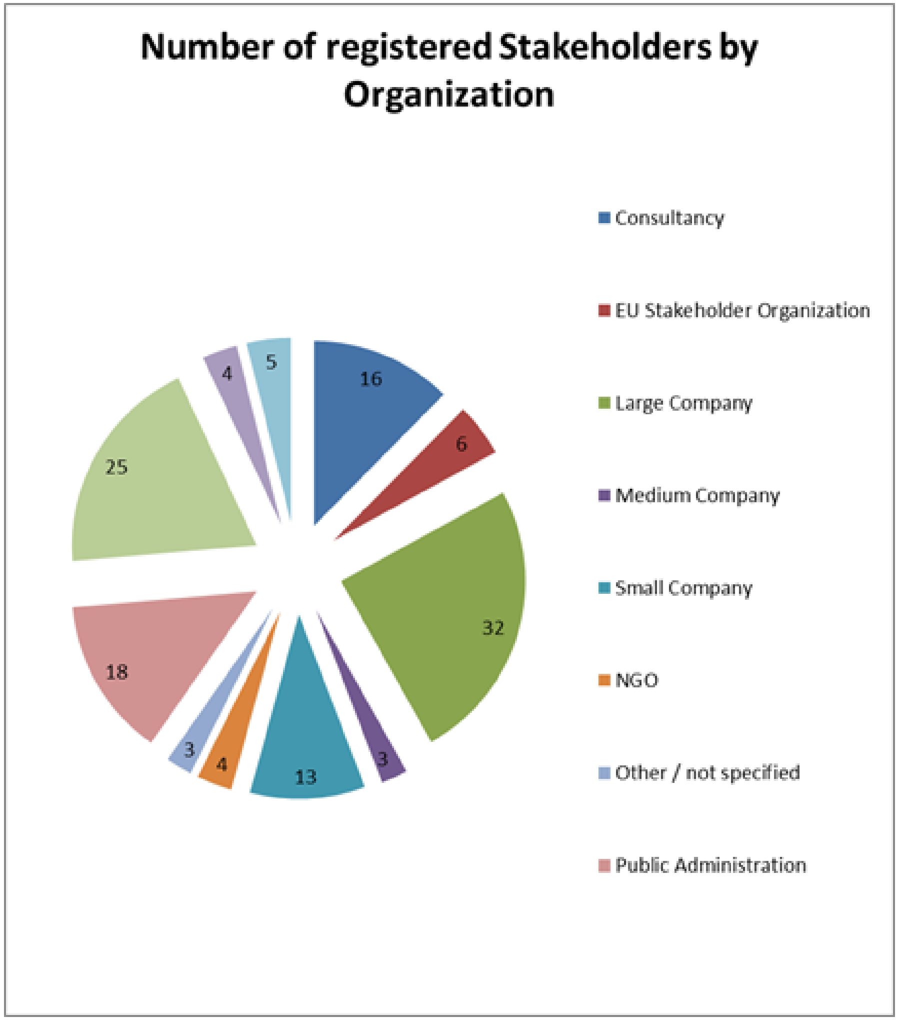
CURRENT STATUS OF THE PILOT PROJECT

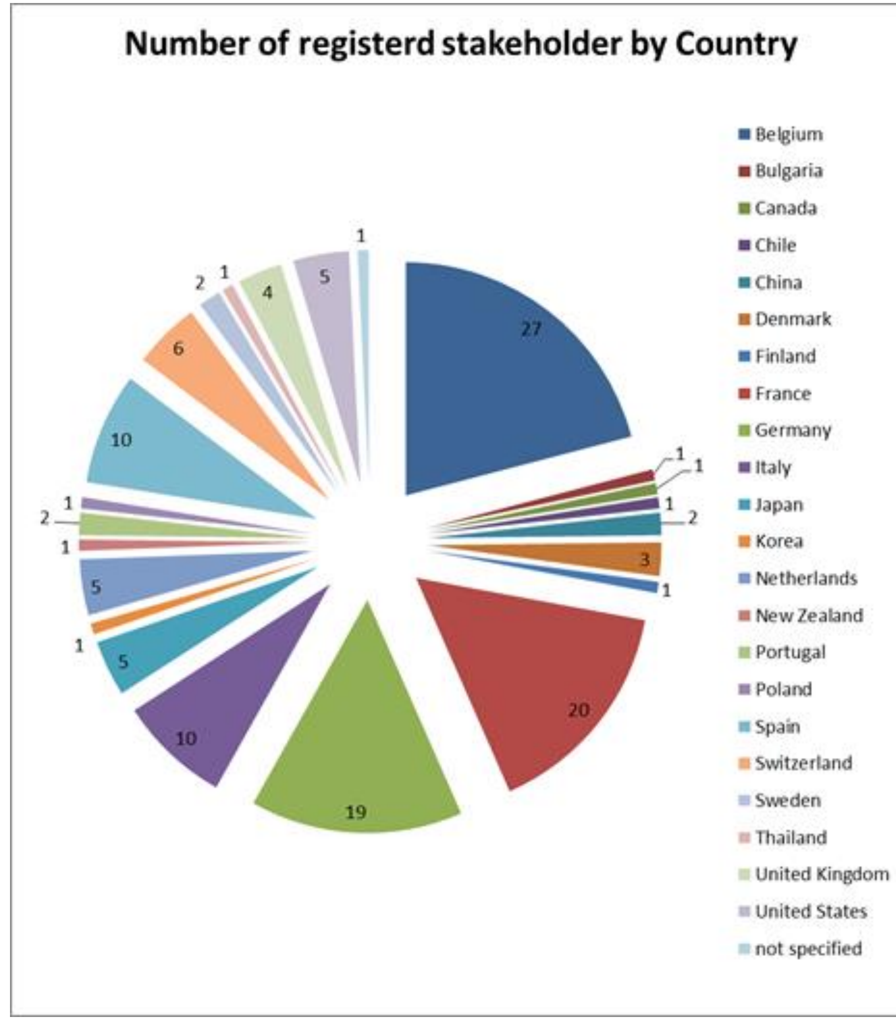


SCIENTIFIC REVIEW BOARDS

	Review Board Member	Institution
Scientific Review Board of the Technical Secretariat	Prof. Dr. Isabelle Blanc	MINES ParisTech – PSL Research University, France
	Dr. Sangwon Suh	Bren School of Environmental Science and Management, University of California, USA
	Prof. Dr. Edgar Hertwich	Department of Energy and Process Engineering, Industrial Ecology Program, Norwegian Technical University, Norway
Screening Report Review through Commission Contract	Ugo Pretato	Studiofieschi & Soci, Italy
Audit of Supporting Studies through Commission Contract	Tbd	Ernst & Young
Steering Committee	Adobe Acrobat-Dokument	
Technical Advisory Board		

STAKEHOLDER PARTICIPATION





1st Public Consultation (April 2014): 64 Comments received and incorporated

2nd Public Consultation (July 2015): 58 Comments received and incorporated

THE DRAFT PEFCR

Draft PEFCR
Product Category

- Photovoltaic (PV) modules used in photovoltaic power systems for electricity generation
- PV technologies
    - Cadmium-Telluride photovoltaic panels (CdTe)
    - Copper-Indium-Gallium-Selenide photovoltaic panels (CIS)
    - Micromorphous Silicon photovoltaic panels (micro-Si)
    - Multicrystalline Silicon photovoltaic panels (multi-Si)
    - Monocrystalline Silicon photovoltaic panels (mono-Si)
    - Novel technology concepts if data quality is sufficient
- NACE/CPA class 27.90
  “Manufacturing of other electrical equipment”

Draft PEFCR
Unit of Analysis

- The unit of analysis is defined as 1 kWh net of electricity generated
- The function(s) / service(s) provided (“what”):
    - electrical energy measured in kWh (provided power times unit of time)
- The magnitude of the function or service (“how much”):
    - 1 kWh of electrical energy
- The expected level of quality (“how well”):
    - DC electrical energy fed into the inverter at a given voltage level
- The amount of service provided over the life time (“how long”):
    - electrical energy fed into the grid in kWh over the service life of 30 years

Draft PEFCR
Impact Category Indicators

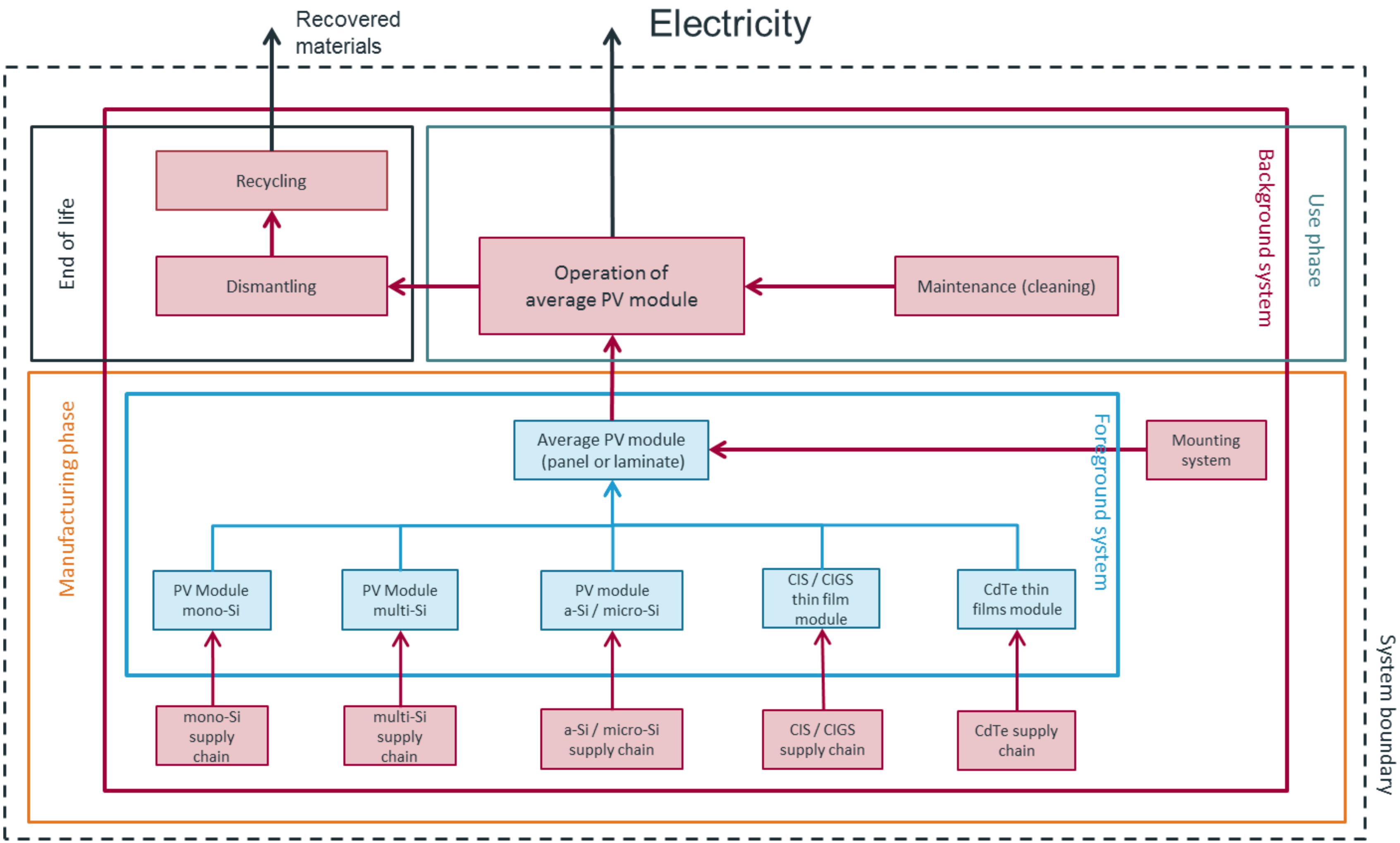
- Impact category indicators required by the PEF Guide
- 3 additional indicators
  - Renewable cumulative energy demand
  - Non-renewable cumulative energy demand
  - Nuclear waste
- Additional indicators shall
  - Be presented separate from default indicators
  - Not be normalized and weighted
- Long-term emissions shall be excluded

RESULTS OF THE SCREENING STUDY

Screening Study
Key Parameters and Assumptions

- Lifetime: 30 years
- Installation in Europe
- Annual yield: 975 kWh/kWp
  Installed capacity weighted average in the EU
  Degradation of 0.7% per year included
- Inverter is not included
- Recycling modelled in accordance with WEEE requirements
- Multi-functionality is disregarded because the reference PV system is mounted on a slanted roof

Screening Study
System Boundaries



Screening Study
Scope

5 different technologies

Techno-logy	Rated power [Wp/m²]	Share in rep. product [%]	Data source
CdTe	140	6.3	[1]
CIS	108	3.5	[1]
Micro-Si	100	4.5	[2]
Multi-Si	147	45.2	[1]
Mono-Si	151	40.5	[1]

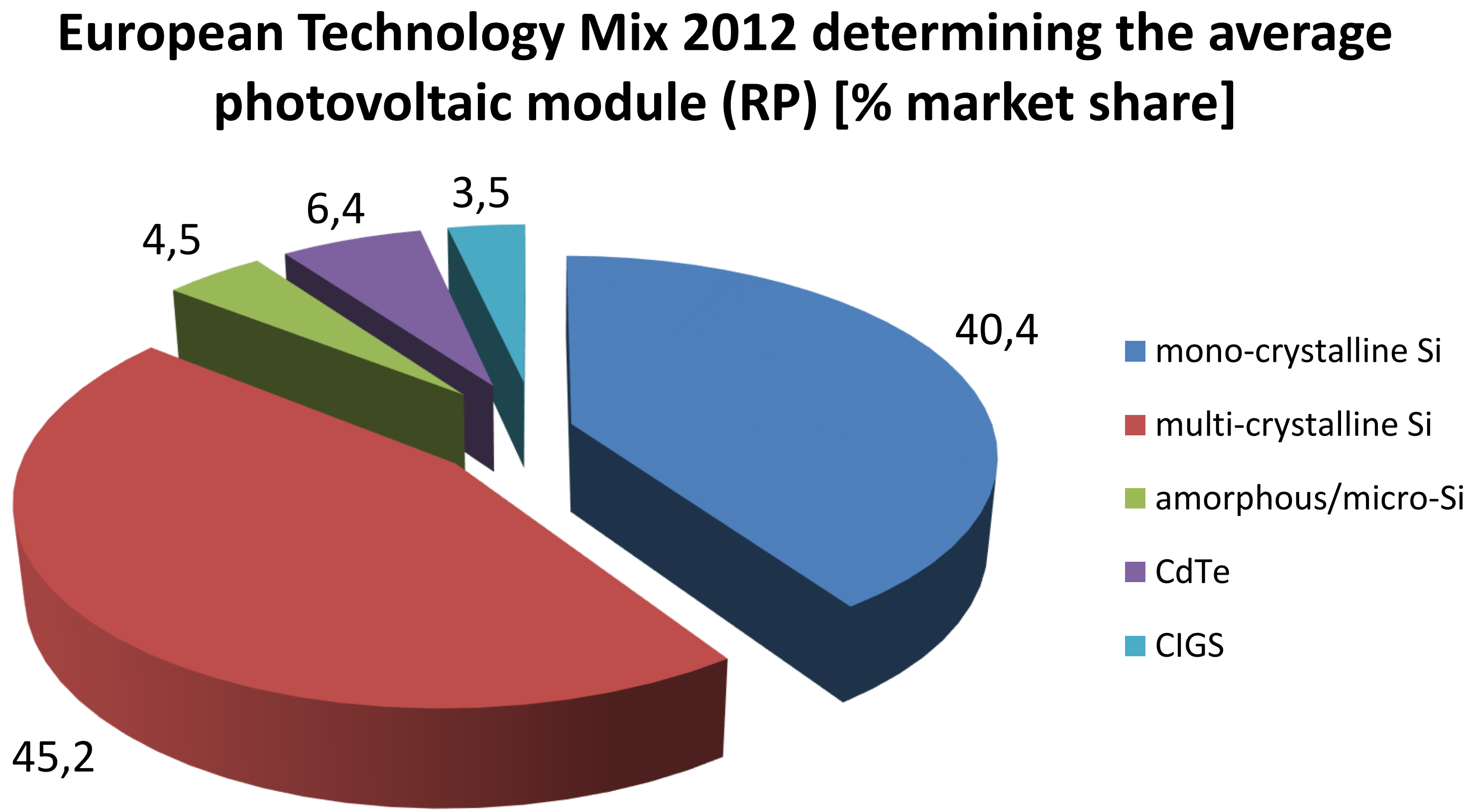
Zhang J., Fthenakis V., Kim H. C., Raugei M., Stucki M. (2015). *Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems.* IEA PVPS Task 12.

[2] Flury K., Frischknecht R.,Itten R. (2012). *Life cycle assessment of Oerlikon Solar μC-Si solar modules.* treeze Ltd., Uster.

Representative product:

Average PV module *(virtual product)*
Technology shares determined by global production volumes in 2012

Representative Product



Screening Study
Scope

5 different technologies

Techno-logy	Rated power [Wp/m²]	Share in rep. product [%]	Data source
CdTe	140	6.3	[1]
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[2] Flury K., Frischknecht R.,Itten R. (2012). *Life cycle assessment of Oerlikon Solar μC-Si solar modules.* treeze Ltd., Uster.

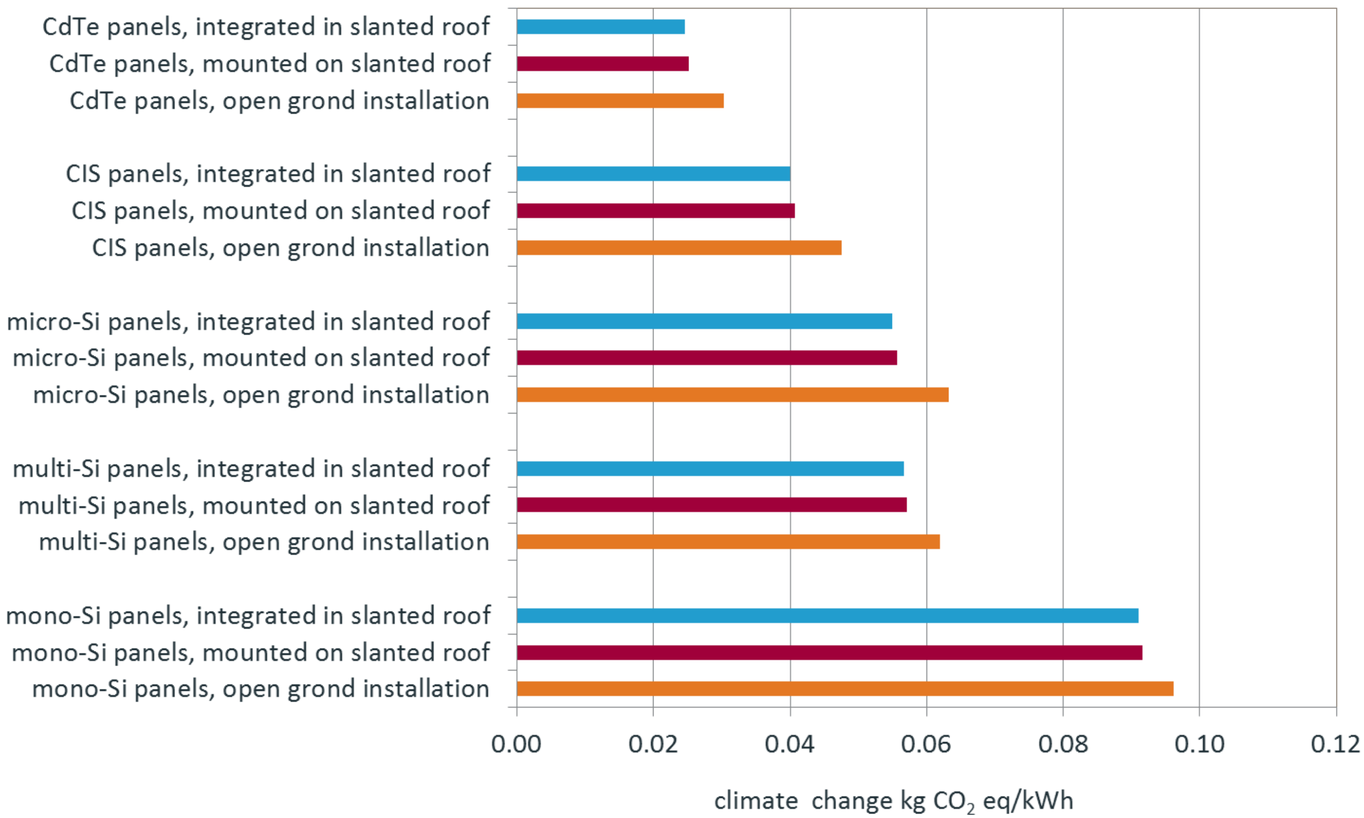
3 different applications

Application	Maximum power output [kWp]
Integrated in roof	3
Mounted on roof	3
Open ground	570

Screening Study
Impact Category Indicators

- Impact category indicators required by the PEF Guide
- 3 additional indicators
    - Renewable cumulative energy demand
    - Non-renewable cumulative energy demand
    - Nuclear waste
- Additional indicators are not included in normalized and weighted results
- Long-term emissions are excluded

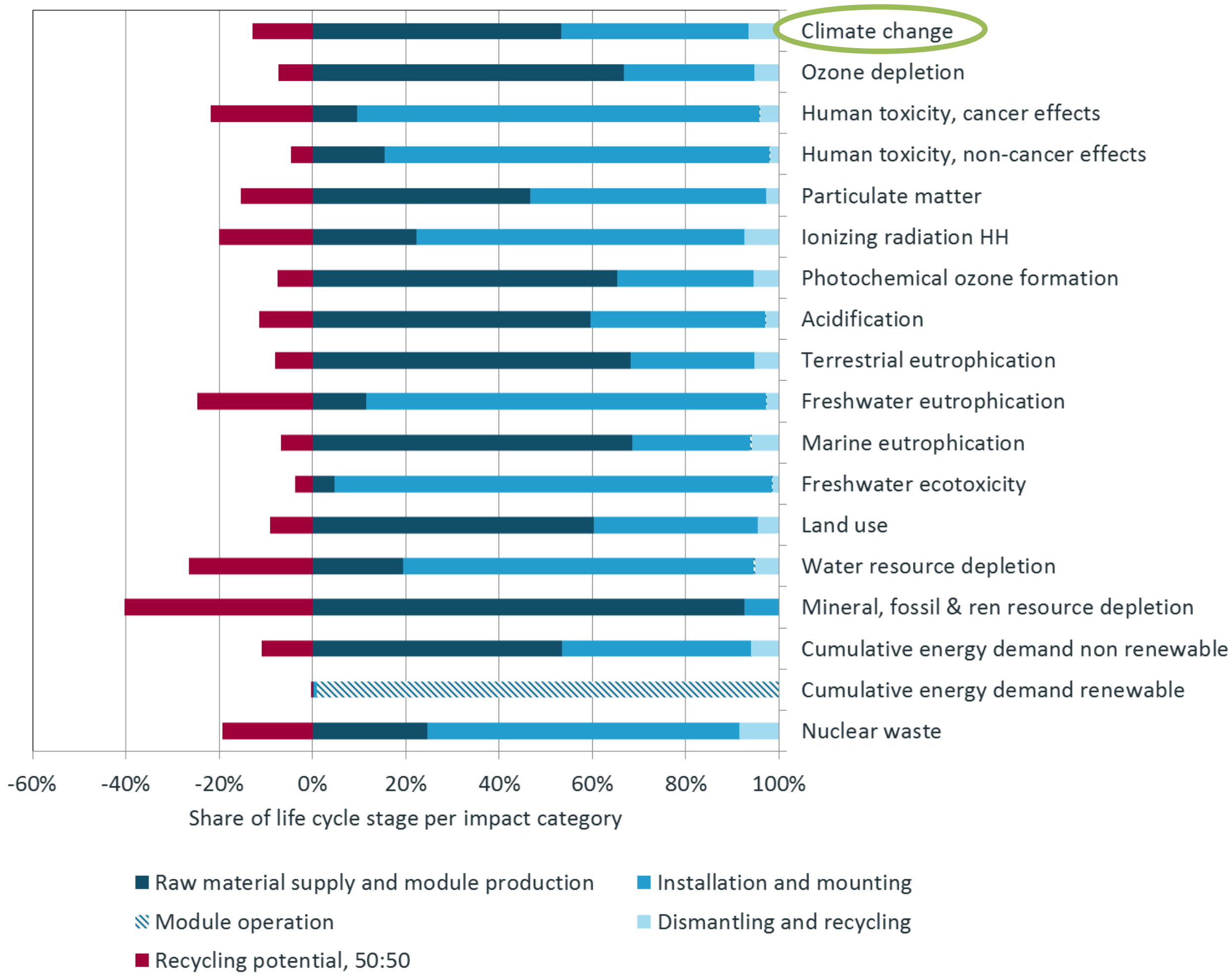
Screening Study
Climate Change Indicator



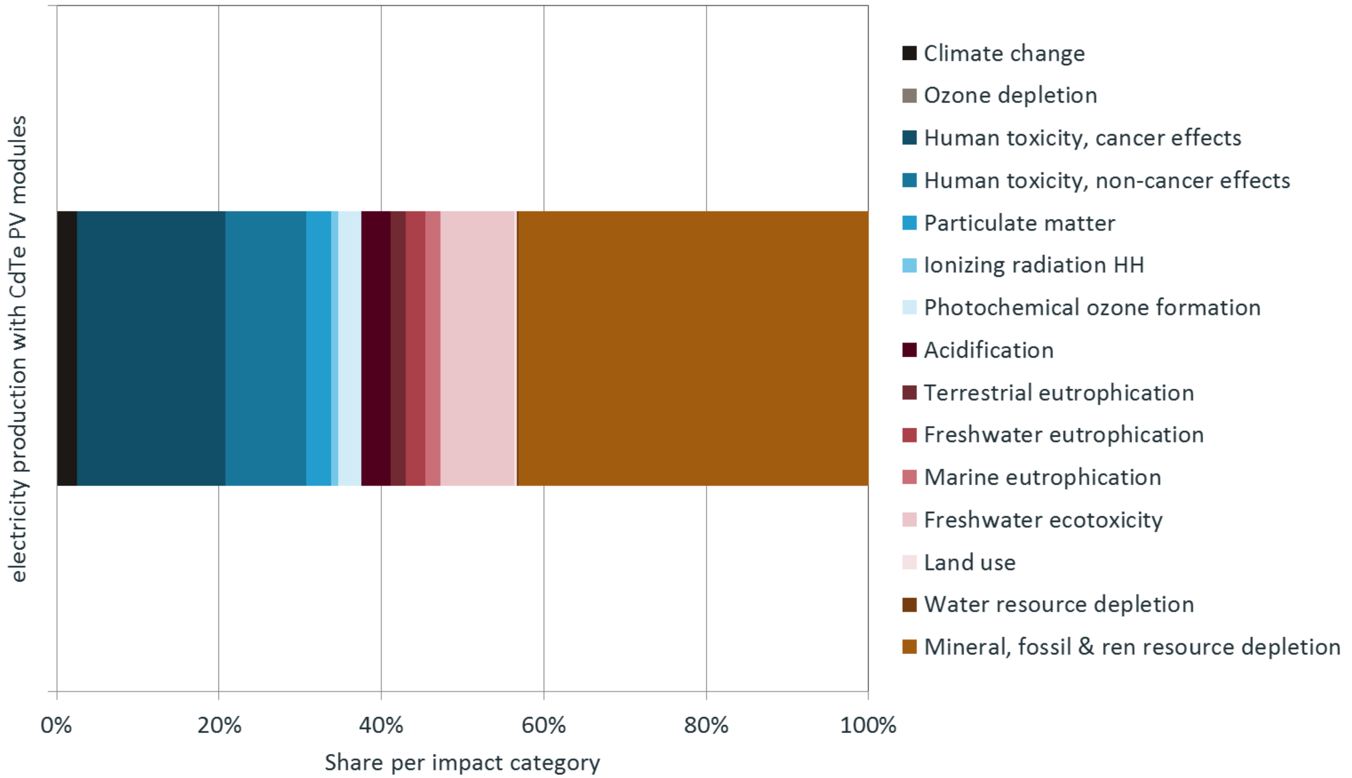
- CdTe PV system integrated in a slanted roof causes lowest climate change impacts
- Open ground mono-Si PV system causes highest climate change impacts

Screening Study
CdTe, mounted, characterized

- Product and construction stage are very important for most indicators
- End-of-life stage is less important
- Operation stage is only relevant for renewable cumulative energy demand

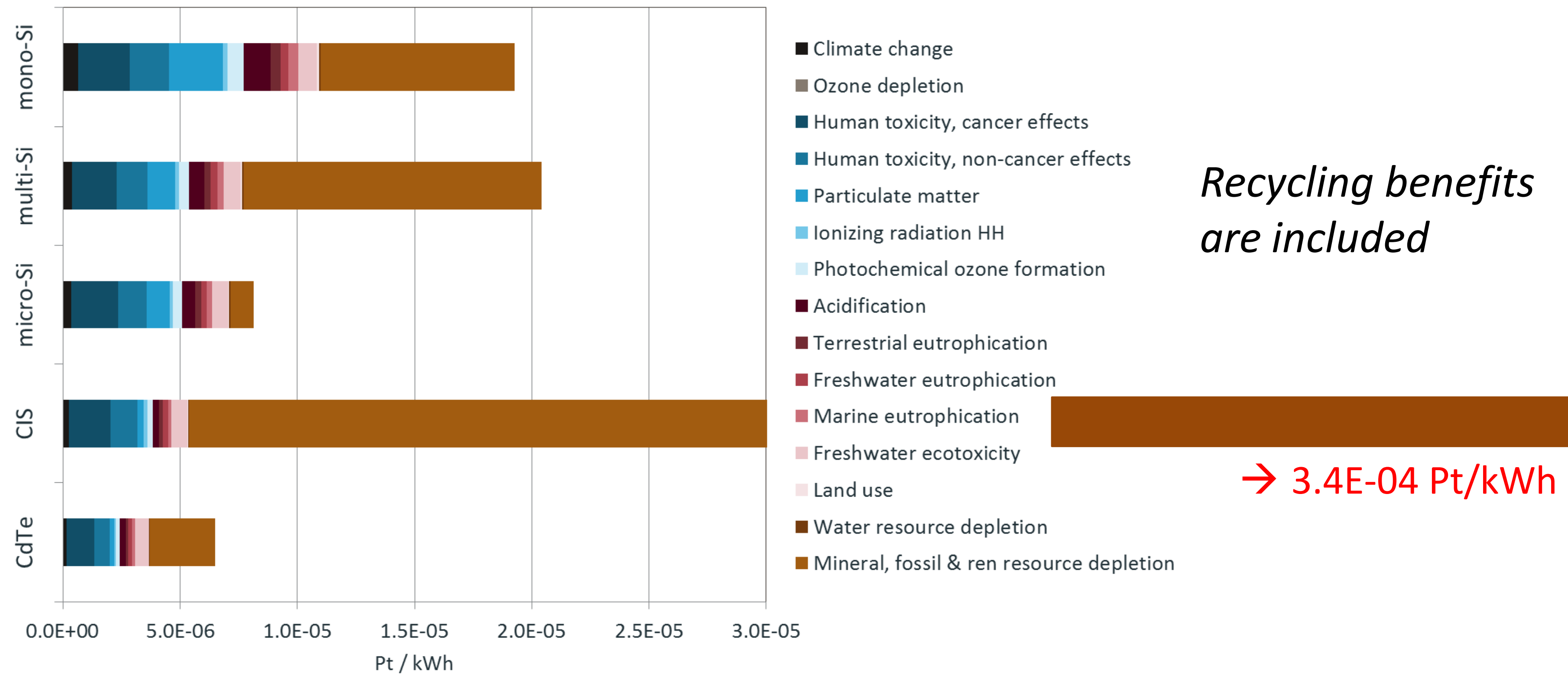


Screening Study
CdTe, mounted, weighted



Recycling benefits are included

Screening Study
All, mounted, weighted



- Weighted results can be determined by one single substance (e.g., indium resource for CIS)
- Ozone depletion, land use and water use have minor contributions (< 1%)

Screening Study
Hotspot Analysis (1)

- Supply chain of electricity
- Supply chain of aluminium
  mounting structure, in some cases frame
- Supply chain for copper
  electric installations
- Flat glass production
- Abiotic resource hotspots
  indium, cadmium, tellurium
- Transport services
  transoceanic freight ship, in some cases lorry

Screening Study
Hotspot Analysis (2)

- Life cycle stages
  - Product stage
  - Construction stage
- Most relevant Impact Categories

  Similar for all PV technologies, but in changing order
  - Mineral, fossil and renewable resource depletion
  - Human toxicity (cancer and non-cancer effects)
  - Freshwater ecotoxicity
  - Particulate matter potential
  - Acidification potential

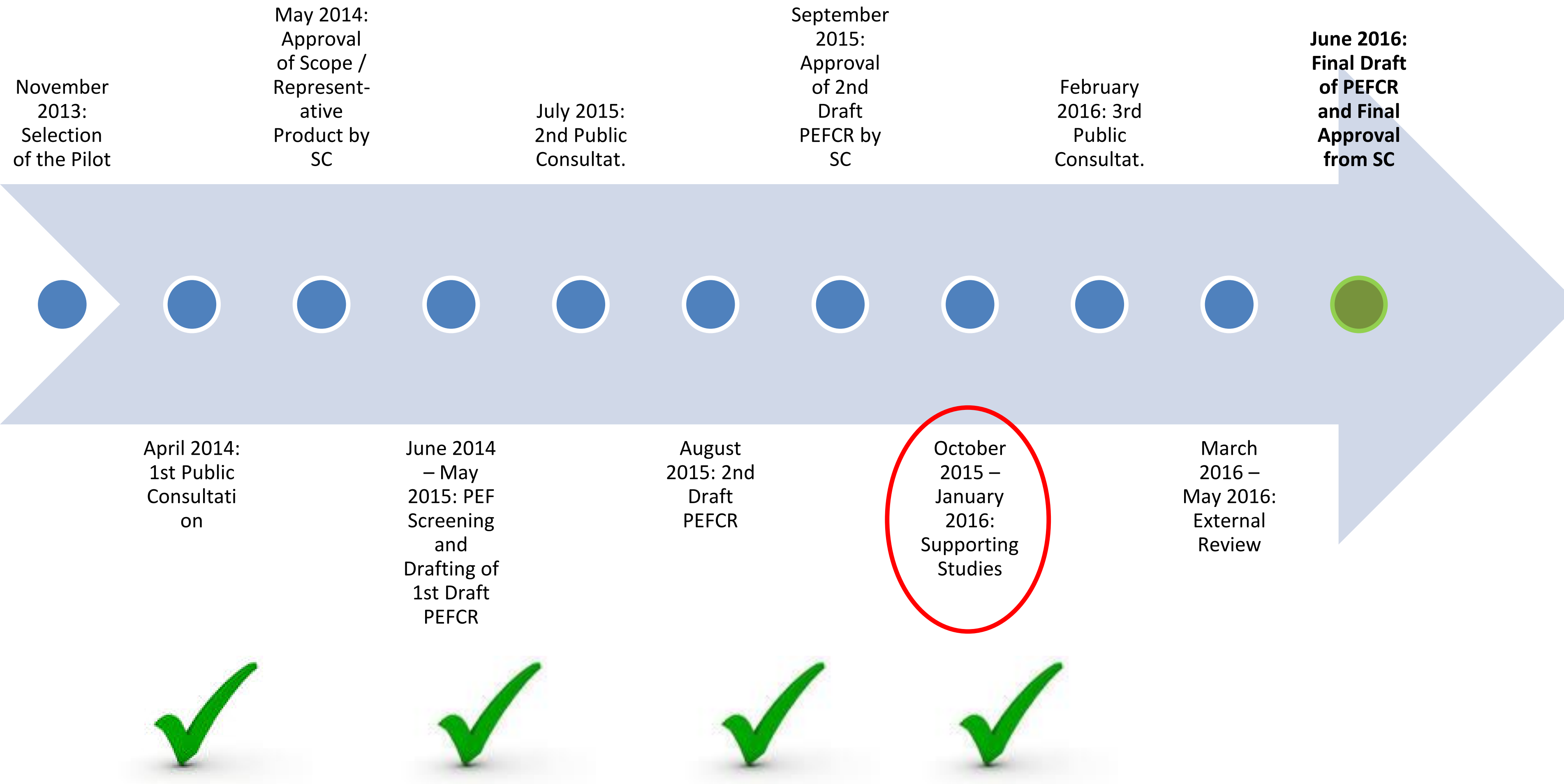
Screening Study
Data Quality Assessment

- A minimum “fair” data quality rating is required for data contributing to at least 90 % of the impact for each impact category
- 1: very good / 3: fair / 5: very poor

Technology	Product stage	Construction stage	Use stage	End-of-life stage	Potential benefits due to
	data quality scores	data quality scores	data quality scores	data quality scores	data quality scores
CdTe PV technology	1.5	1.7	1.5	1.8	1.9
CIS PV technology	1.9	1.7	1.5	1.9	2.0
micro-Si PV technology	2.3	1.7	1.5	1.9	2.0
multi-Si PV technology	2.5	1.7	1.5	1.9	2.0
mono-Si PV technology	2.5	1.7	1.5	1.9	2.0

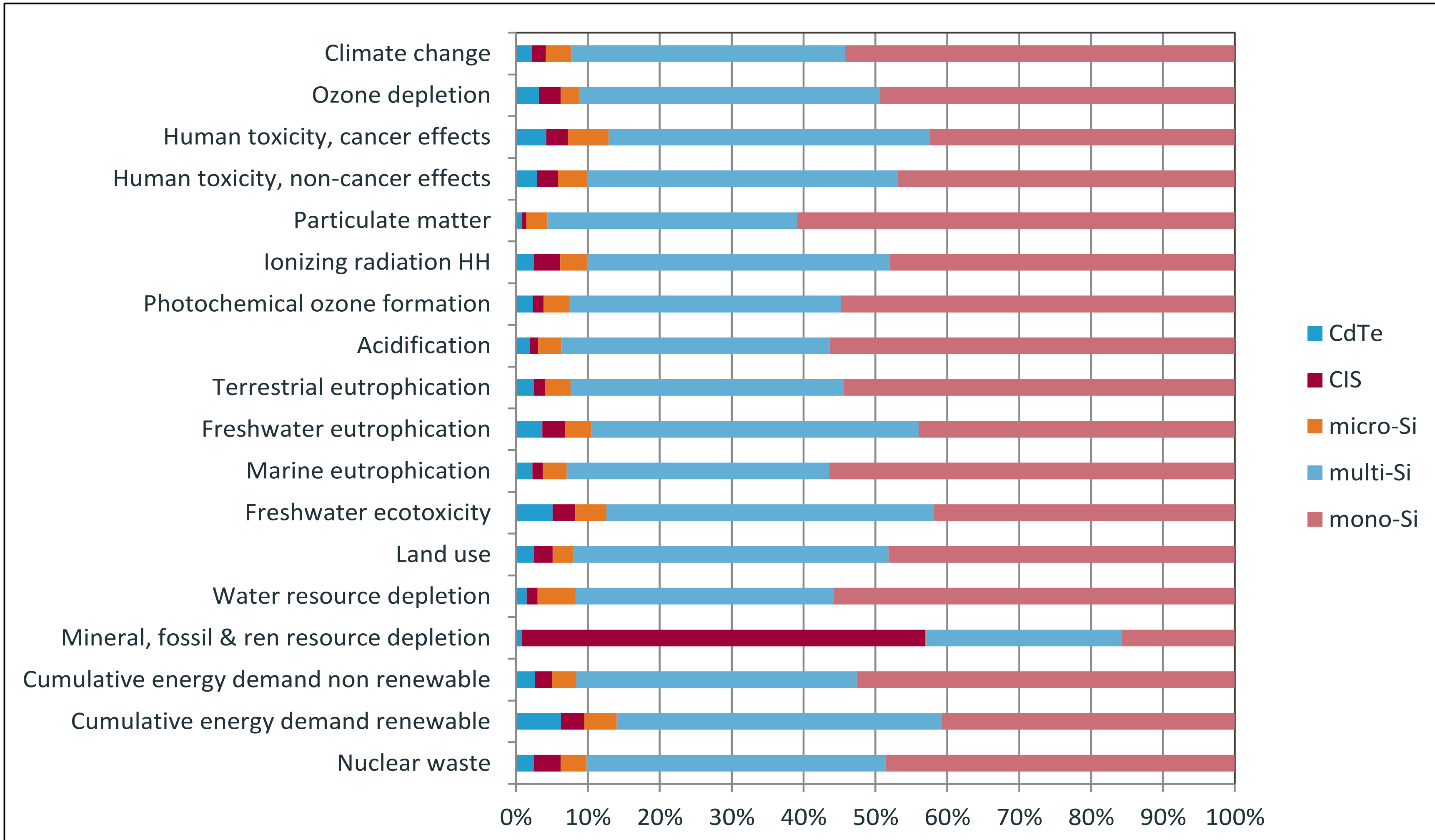
NEXT STEPS

CURRENT STATUS OF THE PILOT PROJECT



APPENDIX
ADDITIONAL SCREENING RESULTS PER TECHNOLOGY
CASE: ROOF MOUNTED 3 kWp PV SYSTEM

AVERAGE EU MODULE



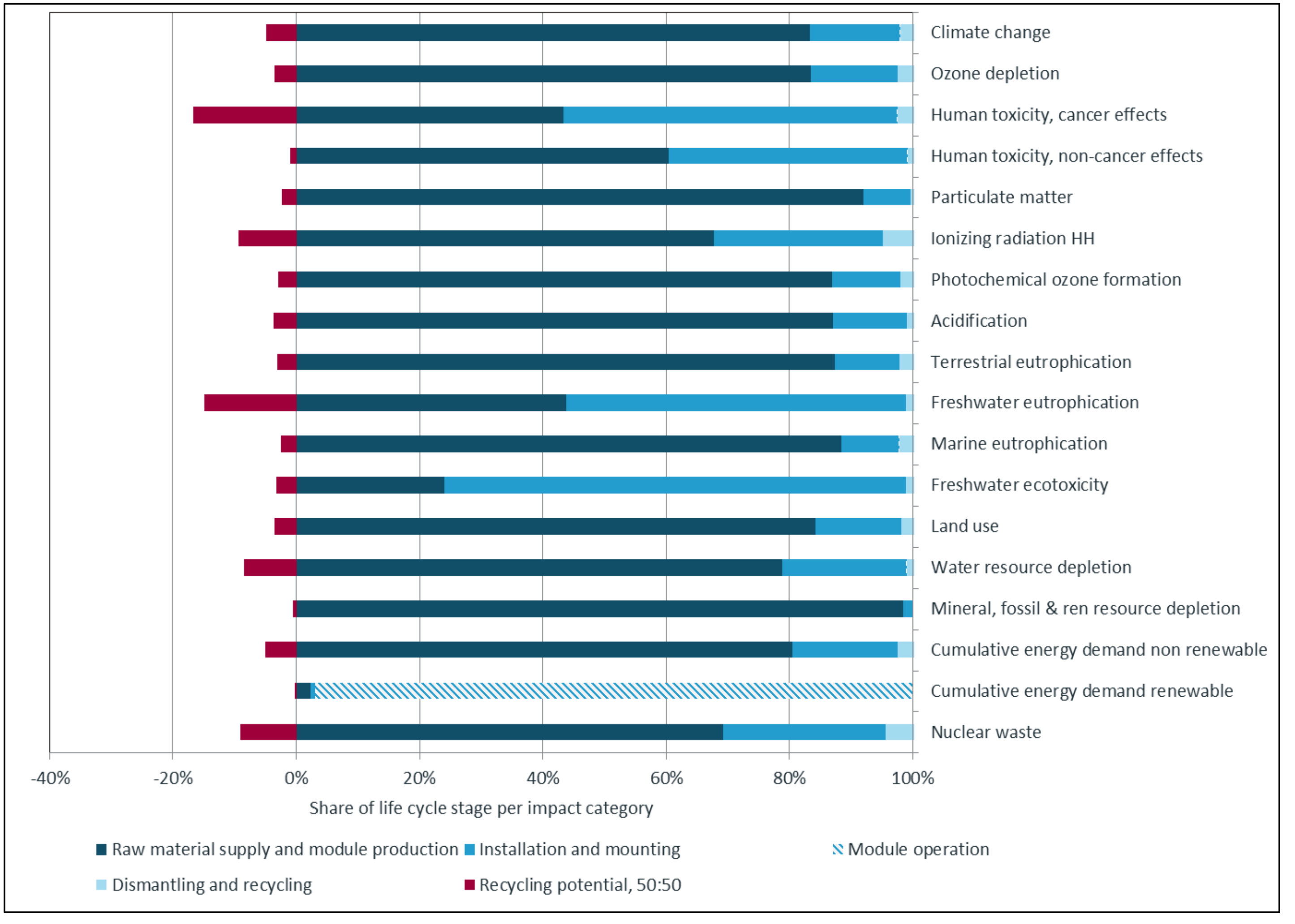
Environmental impact (indexed to 100%) of 1 kWh of DC electricity production (all life cycle stages included) with the average PV module mounted on a slanted residential roof in Europe

AVERAGE EU MODULE

Impact category	Unit per kWh electricity	Product stage	Construction stage	Use stage	End-of-life stage	Total, recycling benefits excluded	Potential benefits due to recycling	Total, recycling benefits included
electricity, 3 kWp installation, mounted with average PV technology, characterized		Raw material supply and module production	Installation and mounting	Module operation	Dismantling and recycling	Total all life stages, recycling benefits excluded	Recycling potential, 50:50	Total all life cycle stages, benefits for recycling included
Climate change	kg CO2 eq	5.69E-02	1.00E-02	3.33E-06	1.47E-03	6.84E-02	-3.40E-03	6.50E-02
Ozone depletion	kg CFC-11 eq	1.66E-09	2.78E-10	2.07E-13	4.99E-11	1.99E-09	-7.12E-11	1.91E-09
Human toxicity, cancer effects	CTUh	5.69E-10	7.11E-10	5.12E-13	3.43E-11	1.32E-09	-2.21E-10	1.09E-09
Human toxicity, non-cancer effects	CTUh	6.89E-09	4.42E-09	7.96E-12	1.03E-10	1.14E-08	-1.29E-10	1.13E-08
Particulate matter	kg PM2.5 eq	8.20E-05	6.74E-06	1.77E-09	4.40E-07	8.92E-05	-2.21E-06	8.69E-05
Ionizing radiation HH	kBq U235 eq	2.17E-03	8.79E-04	6.24E-07	1.58E-04	3.21E-03	-3.02E-04	2.91E-03
Photochemical ozone formation	kg NMVOC eq	2.16E-04	2.75E-05	1.20E-08	5.31E-06	2.49E-04	-7.50E-06	2.41E-04
Acidification	molc H+ eq	5.22E-04	7.12E-05	2.49E-08	6.46E-06	5.99E-04	-2.25E-05	5.77E-04
Terrestrial eutrophication	molc N eq	7.74E-04	9.36E-05	6.57E-08	1.91E-05	8.86E-04	-2.74E-05	8.59E-04
Freshwater eutrophication	kg P eq	3.14E-06	3.95E-06	4.46E-09	8.28E-08	7.18E-06	-1.08E-06	6.10E-06
Marine eutrophication	kg N eq	7.46E-05	7.85E-06	9.80E-08	1.89E-06	8.45E-05	-2.21E-06	8.23E-05
Freshwater ecotoxicity	CTUe	2.41E-02	7.57E-02	1.98E-05	1.14E-03	1.01E-01	-3.29E-03	9.78E-02
Land use	kg C deficit	6.06E-02	1.01E-02	1.38E-05	1.34E-03	7.20E-02	-2.61E-03	6.94E-02
Water resource depletion	m3 water eq	6.22E-05	1.58E-05	8.93E-08	8.56E-07	7.89E-05	-6.75E-06	7.22E-05
Mineral, fossil & ren resource depletion	kg Sb eq	3.18E-05	5.18E-07	1.42E-12	5.99E-09	3.23E-05	-2.15E-07	3.21E-05
Cumulative energy demand non renewable	MJ	6.74E-01	1.43E-01	5.12E-05	2.08E-02	8.38E-01	-4.26E-02	7.95E-01
Cumulative energy demand renewable	MJ	8.20E-02	2.80E-02	3.60E+00	1.34E-03	3.71E+00	-1.13E-02	3.70E+00
Nuclear waste	m3 HAA eq	5.09E-11	1.93E-11	1.16E-14	3.34E-12	7.36E-11	-6.76E-12	6.68E-11

Environmental impact results (characterized) of 1 kWh of DC electricity produced with a residential scale (3 kWp) PV system with average PV panels on a slanted roof

AVERAGE EU MODULE

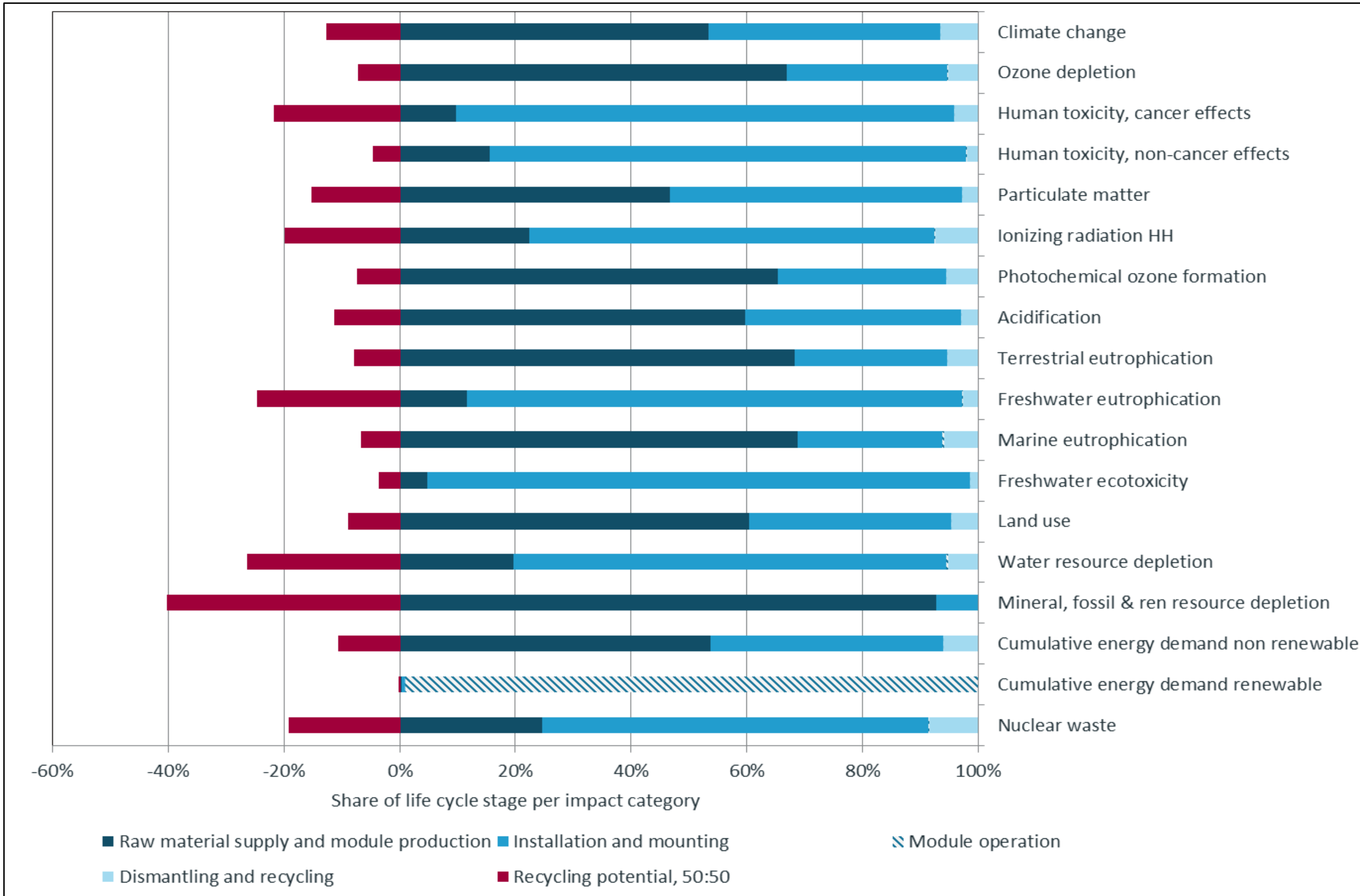


Environmental impact results (characterized, indexed to 100 %) of 1 kWh of DC electricity produced with a residential scale (3 kWp) PV system with average PV panels mounted on a slanted roof.

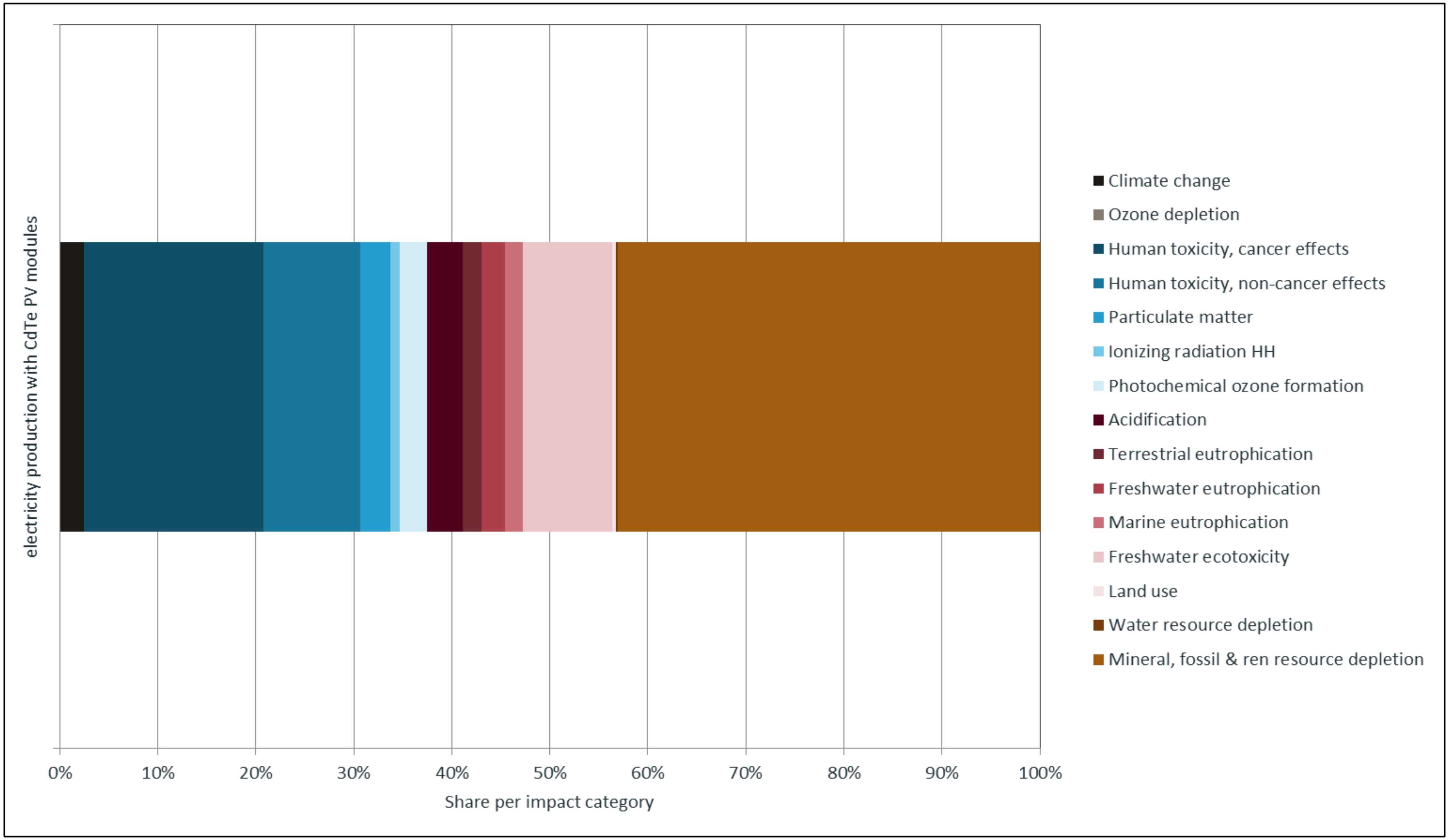
CDTE PV TECHNOLOGY

Impact category	Unit per kWh electricity	Product stage	Construction stage	Use stage	End-of-life stage	Total, recycling benefits excluded	Potential benefits due to recycling	Total, recycling benefits included
electricity, 3 kWp installation, mounted with CdTe PV technology, characterized		Raw material supply and module production	Installation and mounting	Module operation	Dismantling and recycling	Total all life stages, recycling benefits excluded	Recycling potential, 50:50	Total all life cycle stages, benefits for recycling included
Climate change	kg CO2 eq	1.34E-02	1.01E-02	3.45E-06	1.63E-03	2.52E-02	-3.22E-03	2.20E-02
Ozone depletion	kg CFC-11 eq	6.73E-10	2.83E-10	2.13E-13	5.23E-11	1.01E-09	-7.41E-11	9.34E-10
Human toxicity, cancer effects	CTUh	8.07E-11	7.26E-10	5.25E-13	3.42E-11	8.41E-10	-1.84E-10	6.57E-10
Human toxicity, non-cancer effects	CTUh	8.35E-10	4.44E-09	8.15E-12	1.03E-10	5.39E-09	-2.52E-10	5.14E-09
Particulate matter	kg PM2.5 eq	6.24E-06	6.76E-06	1.89E-09	3.70E-07	1.34E-05	-2.06E-06	1.13E-05
Ionizing radiation HH	kBq U235 eq	2.83E-04	8.95E-04	6.40E-07	9.43E-05	1.27E-03	-2.54E-04	1.02E-03
Photochemical ozone formation	kg NMVOC eq	6.12E-05	2.75E-05	1.25E-08	5.08E-06	9.38E-05	-7.01E-06	8.68E-05
Acidification	molc H+ eq	1.14E-04	7.14E-05	2.59E-08	5.37E-06	1.91E-04	-2.18E-05	1.69E-04
Terrestrial eutrophication	molc N eq	2.40E-04	9.35E-05	6.78E-08	1.84E-05	3.52E-04	-2.79E-05	3.24E-04
Freshwater eutrophication	kg P eq	5.31E-07	3.96E-06	4.57E-09	1.22E-07	4.61E-06	-1.14E-06	3.47E-06
Marine eutrophication	kg N eq	2.14E-05	7.84E-06	1.00E-07	1.83E-06	3.11E-05	-2.08E-06	2.90E-05
Freshwater ecotoxicity	CTUe	3.79E-03	7.59E-02	2.03E-05	1.12E-03	8.08E-02	-3.04E-03	7.78E-02
Land use	kg C deficit	1.75E-02	1.01E-02	1.42E-05	1.32E-03	2.89E-02	-2.62E-03	2.63E-02
Water resource depletion	m3 water eq	4.18E-06	1.61E-05	9.14E-08	1.09E-06	2.14E-05	-5.66E-06	1.58E-05
Mineral, fossil & ren resource depletion	kg Sb eq	6.57E-06	5.19E-07	2.81E-11	6.06E-09	7.09E-06	-2.85E-06	4.24E-06
Cumulative energy demand non renewable	MJ	1.92E-01	1.45E-01	5.29E-05	2.15E-02	3.59E-01	-3.87E-02	3.20E-01
Cumulative energy demand renewable	MJ	8.05E-03	2.85E-02	3.60E+00	1.04E-03	3.64E+00	-9.44E-03	3.63E+00
Nuclear waste	m3 HAA eq	7.24E-12	1.97E-11	1.19E-14	2.49E-12	2.94E-11	-5.67E-12	2.37E-11

Environmental impact results (characterized) of 1 kWh of DC electricity produced with a residential scale (3 kWp) PV system with CdTe PV panels mounted on a slanted roof



Environmental impact results (characterized, indexed to 100 %) of 1 kWh of DC electricity produced with a residential scale (3 kWp) PV system with CdTe PV panels mounted on a slanted roof. The potential benefits due to recycling are illustrated relative to the overall environmental impacts from production to end-of-life.

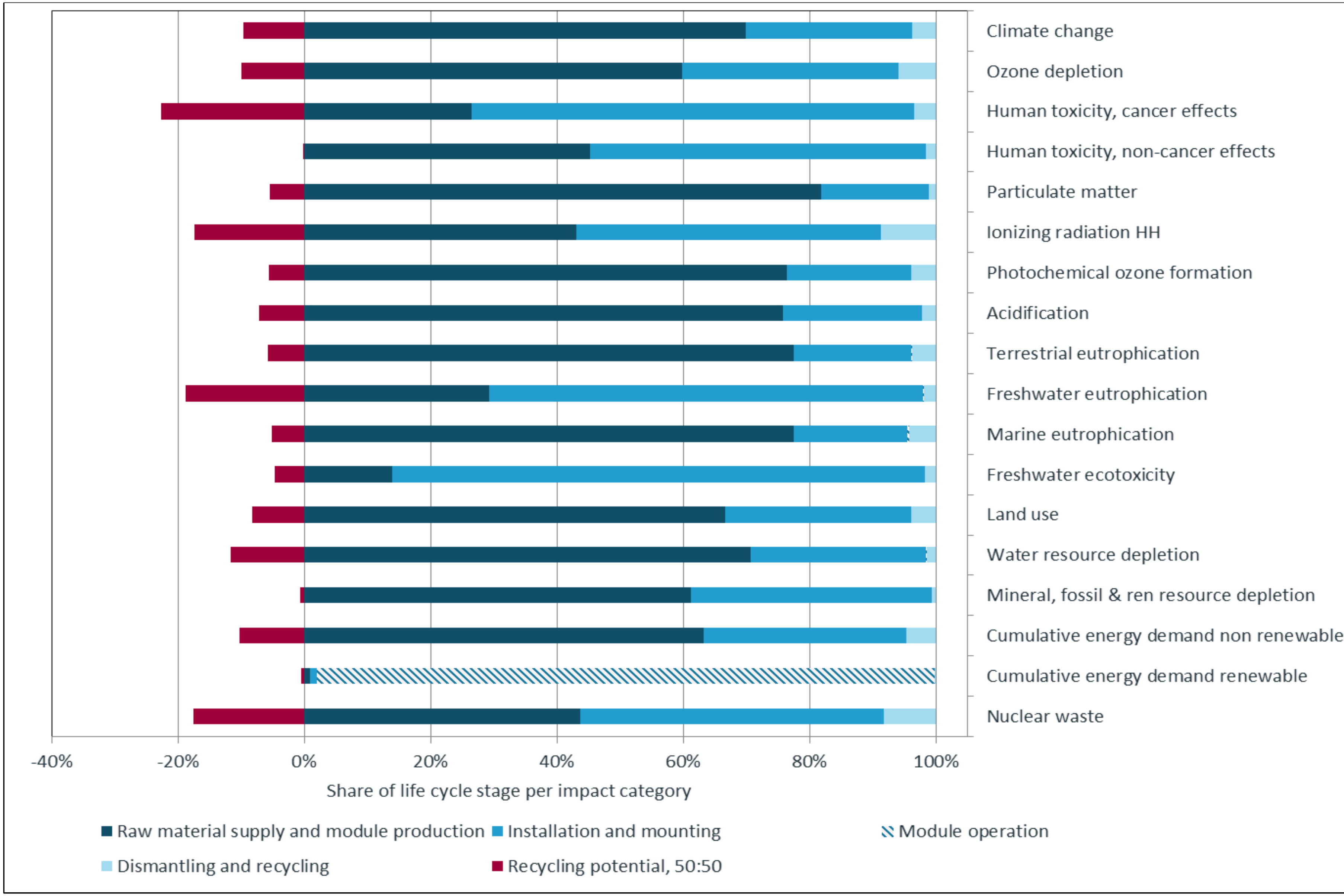


Share per impact category on the weighted result for the production of 1 kWh DC electricity produced with a residential scale CdTe PV system mounted on a slanted roof

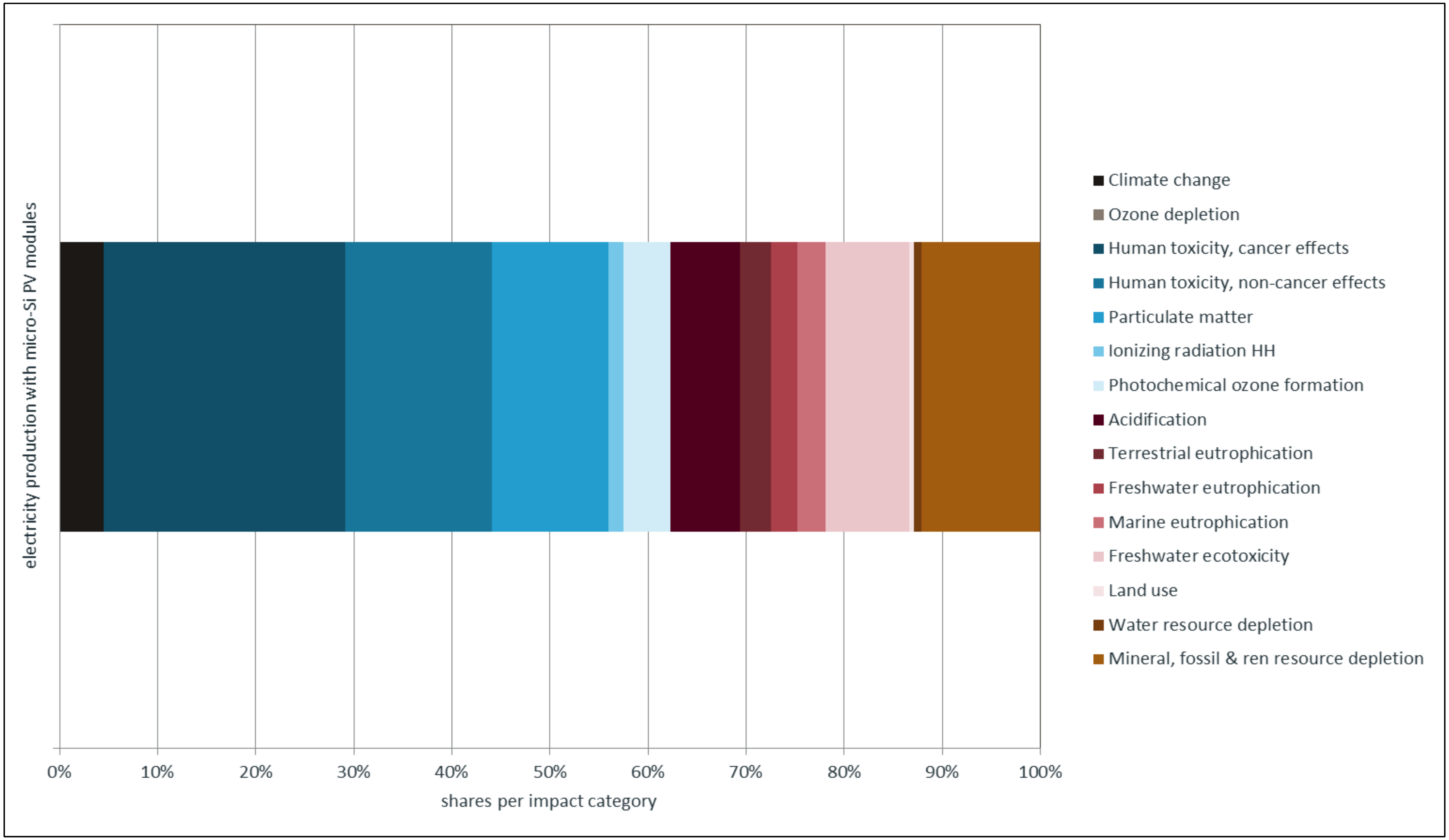
MICRO-SI PV TECHNOLOGY

Impact category	Unit per kWh electricity	Product stage	Construction stage	Use stage	End-of-life stage	Total, recycling benefits excluded	Potential benefits due to recycling	Total, recycling benefits included
electricity, 3 kWp installation, mounted with micro-Si PV technology, characterized		Raw material supply and module production	Installation and mounting	Module operation	Dismantling and recycling	Total all life stages, recycling benefits excluded	Recycling potential, 50:50	Total all life cycle stages, benefits for recycling included
Climate change	kg CO2 eq	3.89E-02	1.47E-02	4.81E-06	2.04E-03	5.56E-02	-5.31E-03	5.03E-02
Ozone depletion	kg CFC-11 eq	7.14E-10	4.08E-10	2.98E-13	6.93E-11	1.19E-09	-1.17E-10	1.07E-09
Human toxicity, cancer effects	CTUh	3.80E-10	1.01E-09	7.34E-13	4.79E-11	1.44E-09	-3.25E-10	1.11E-09
Human toxicity, non-cancer effects	CTUh	4.44E-09	5.20E-09	1.14E-11	1.43E-10	9.80E-09	-1.75E-11	9.78E-09
Particulate matter	kg PM2.5 eq	4.78E-05	9.98E-06	2.61E-09	6.20E-07	5.84E-05	-3.16E-06	5.52E-05
Ionizing radiation HH	kBq U235 eq	1.13E-03	1.27E-03	8.95E-07	2.27E-04	2.63E-03	-4.54E-04	2.17E-03
Photochemical ozone formation	kg NMVOC eq	1.50E-04	3.90E-05	1.74E-08	7.42E-06	1.97E-04	-1.09E-05	1.86E-04
Acidification	molc H+ eq	3.34E-04	9.75E-05	3.61E-08	9.11E-06	4.40E-04	-3.12E-05	4.09E-04
Terrestrial eutrophication	molc N eq	5.53E-04	1.34E-04	9.47E-08	2.67E-05	7.14E-04	-4.13E-05	6.72E-04
Freshwater eutrophication	kg P eq	1.78E-06	4.16E-06	6.39E-09	1.12E-07	6.05E-06	-1.13E-06	4.92E-06
Marine eutrophication	kg N eq	4.93E-05	1.14E-05	1.40E-07	2.64E-06	6.35E-05	-3.25E-06	6.02E-05
Freshwater ecotoxicity	CTUe	1.32E-02	8.00E-02	2.84E-05	1.59E-03	9.48E-02	-4.45E-03	9.04E-02
Land use	kg C deficit	3.24E-02	1.43E-02	1.99E-05	1.87E-03	4.86E-02	-4.00E-03	4.46E-02
Water resource depletion	m3 water eq	6.14E-05	2.42E-05	1.28E-07	1.17E-06	8.68E-05	-1.01E-05	7.67E-05
Mineral, fossil & ren resource depletion	kg Sb eq	9.23E-07	5.77E-07	4.78E-11	8.35E-09	1.51E-06	-8.75E-09	1.50E-06
Cumulative energy demand non renewable	MJ	4.04E-01	2.05E-01	7.39E-05	2.90E-02	6.39E-01	-6.57E-02	5.73E-01
Cumulative energy demand renewable	MJ	3.52E-02	4.05E-02	3.60E+00	1.90E-03	3.68E+00	-1.68E-02	3.66E+00
Nuclear waste	m3 HAA eq	2.53E-11	2.79E-11	1.66E-14	4.74E-12	5.79E-11	-1.02E-11	4.78E-11

Environmental impact results (characterized) of 1 kWh of DC electricity produced with a residential scale (3 kWp) PV system with micro-Si PV panels mounted on a slanted roof



Environmental impact results (characterized, indexed to 100 %) of 1 kWh of DC electricity produced with a residential scale (3 kWp) PV system with micro-Si PV panels mounted on a slanted roof. The potential benefits due to recycling are illustrated relative to the overall environmental impacts from production to end-of-life.

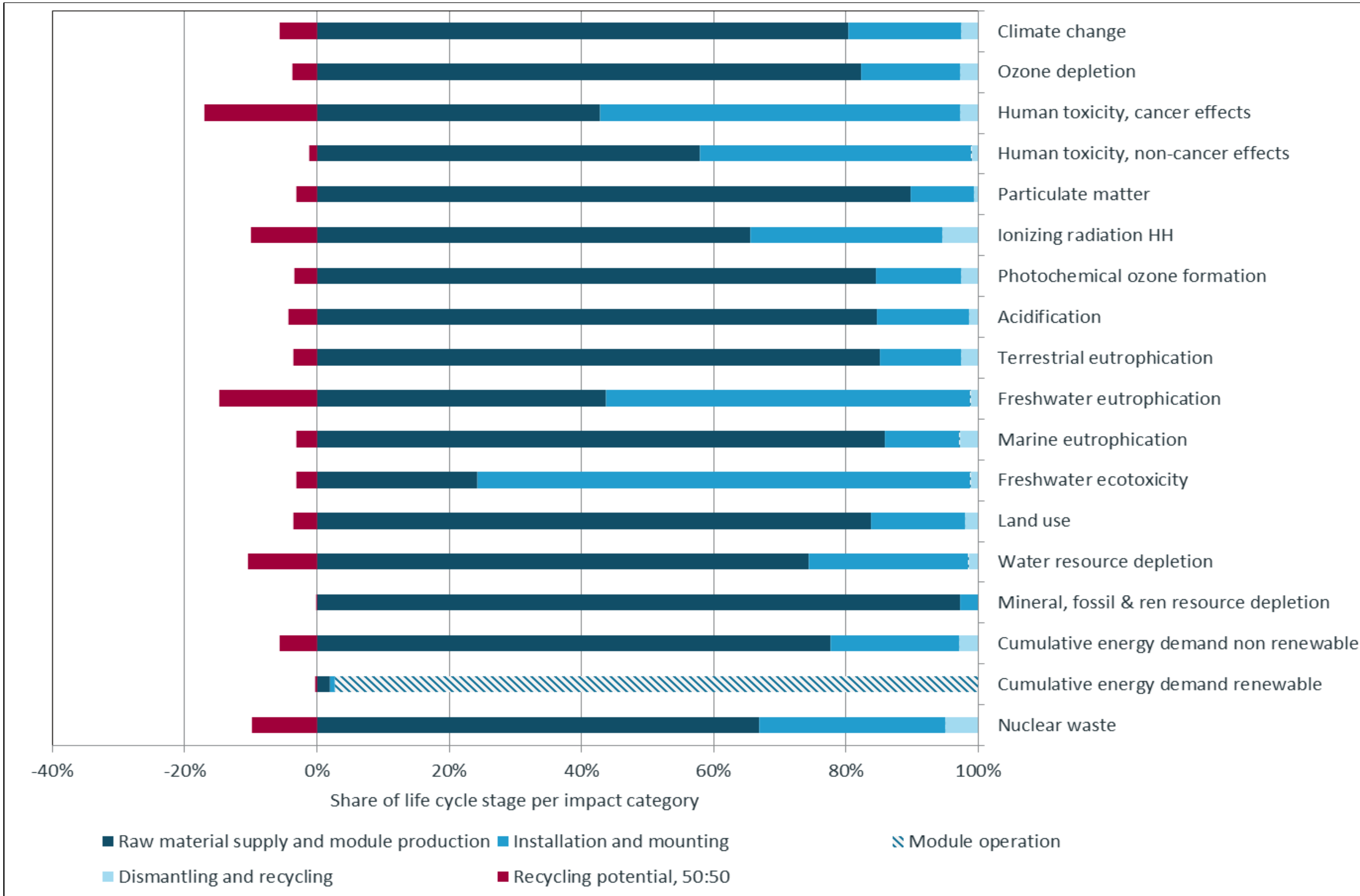


Share per impact category on the weighted result for the production of 1 kWh DC electricity produced with a residential scale micro-Si PV system mounted on a slanted roof

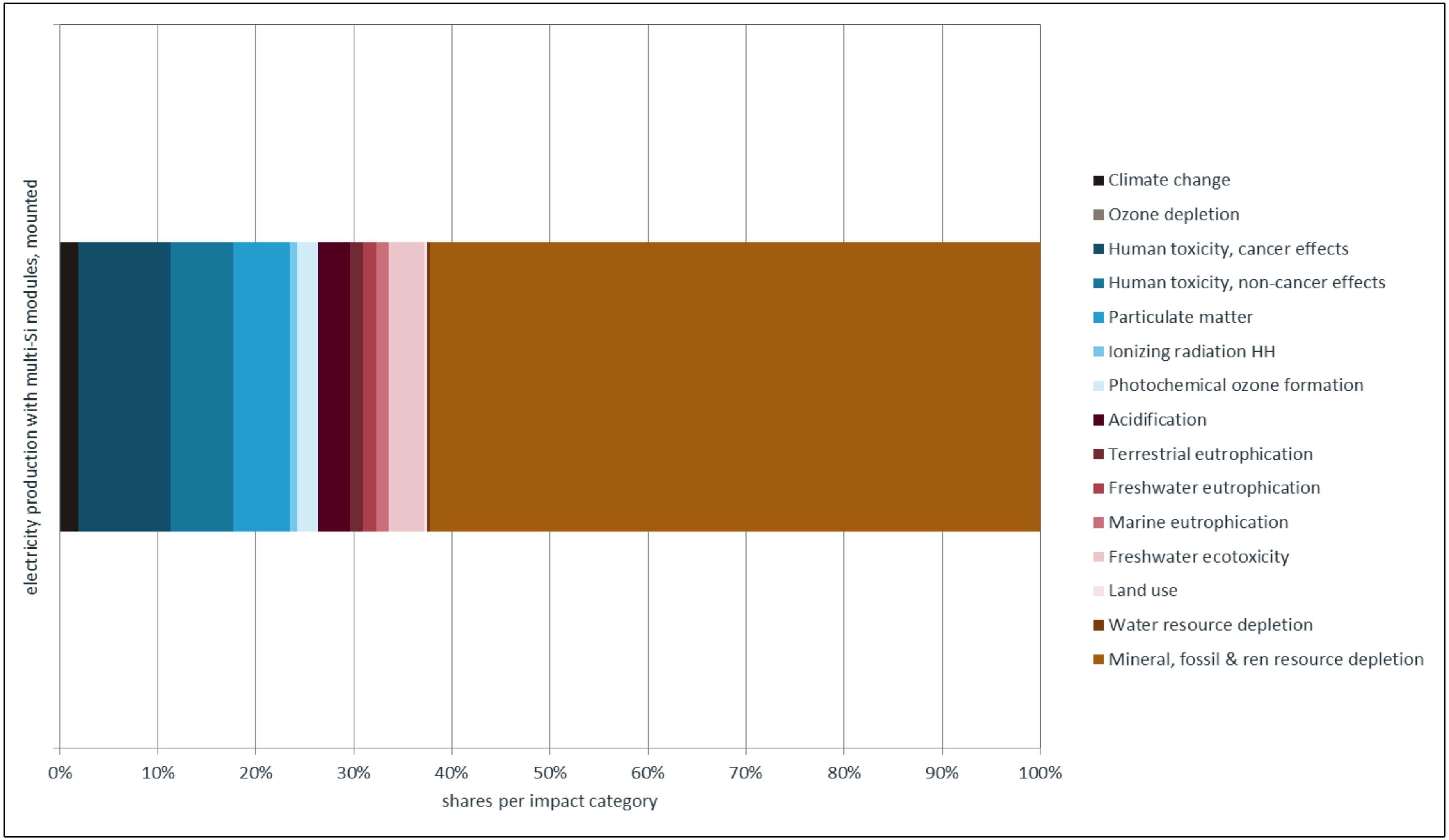
MULTICRYSTALLINE-SI PV TECHNOLOGY

Impact category	Unit per kWh electricity	Product stage	Construction stage	Use stage	End-of-life stage	Total, recycling benefits excluded	Potential benefits due to recycling	Total, recycling benefits included
electricity, 3 kWp installation, mounted with multi-Si PV technology, characterized		Raw material supply and module production	Installation and mounting	Module operation	Dismantling and recycling	Total all life stages, recycling benefits excluded	Recycling potential, 50:50	Total all life cycle stages, benefits for recycling included
Climate change	kg CO2 eq	4.59E-02	9.74E-03	3.25E-06	1.43E-03	5.71E-02	-3.29E-03	5.38E-02
Ozone depletion	kg CFC-11 eq	1.49E-09	2.71E-10	2.02E-13	4.86E-11	1.81E-09	-6.79E-11	1.74E-09
Human toxicity, cancer effects	CTUh	5.46E-10	6.94E-10	4.99E-13	3.35E-11	1.27E-09	-2.18E-10	1.06E-09
Human toxicity, non-cancer effects	CTUh	6.16E-09	4.37E-09	7.75E-12	1.01E-10	1.06E-08	-1.25E-10	1.05E-08
Particulate matter	kg PM2.5 eq	6.20E-05	6.56E-06	1.74E-09	4.35E-07	6.90E-05	-2.17E-06	6.69E-05
Ionizing radiation HH	kBq U235 eq	1.94E-03	8.56E-04	6.08E-07	1.59E-04	2.95E-03	-2.96E-04	2.66E-03
Photochemical ozone formation	kg NMVOC eq	1.76E-04	2.69E-05	1.18E-08	5.21E-06	2.08E-04	-7.33E-06	2.01E-04
Acidification	molc H+ eq	4.20E-04	6.97E-05	2.44E-08	6.39E-06	4.97E-04	-2.20E-05	4.75E-04
Terrestrial eutrophication	molc N eq	6.35E-04	9.15E-05	6.42E-08	1.88E-05	7.46E-04	-2.64E-05	7.19E-04
Freshwater eutrophication	kg P eq	3.12E-06	3.94E-06	4.35E-09	7.84E-08	7.14E-06	-1.06E-06	6.08E-06
Marine eutrophication	kg N eq	5.86E-05	7.67E-06	9.55E-08	1.85E-06	6.82E-05	-2.15E-06	6.61E-05
Freshwater ecotoxicity	CTUe	2.45E-02	7.55E-02	1.93E-05	1.11E-03	1.01E-01	-3.24E-03	9.79E-02
Land use	kg C deficit	5.78E-02	9.83E-03	1.35E-05	1.32E-03	6.90E-02	-2.52E-03	6.65E-02
Water resource depletion	m3 water eq	4.72E-05	1.53E-05	8.70E-08	8.22E-07	6.34E-05	-6.64E-06	5.68E-05
Mineral, fossil & ren resource depletion	kg Sb eq	1.88E-05	5.15E-07	1.36E-11	5.86E-09	1.93E-05	-3.83E-08	1.93E-05
Cumulative energy demand non renewable	MJ	5.59E-01	1.40E-01	5.00E-05	2.03E-02	7.19E-01	-4.15E-02	6.78E-01
Cumulative energy demand renewable	MJ	7.22E-02	2.73E-02	3.60E+00	1.33E-03	3.70E+00	-1.11E-02	3.69E+00
Nuclear waste	m3 HAA eq	4.48E-11	1.88E-11	1.13E-14	3.32E-12	6.69E-11	-6.64E-12	6.03E-11

Environmental impact results (characterized) of 1 kWh of DC electricity produced with a residential scale (3 kWp) PV system with multicrystalline-Si PV panels mounted on a slanted roof



Environmental impact results (characterized, indexed to 100 %) of 1 kWh of DC electricity produced with a residential scale (3 kWp) PV system with multicrystalline-Si PV panels mounted on a slanted roof. The potential benefits due to recycling are illustrated relative to the overall environmental impacts from production to end-of-life.

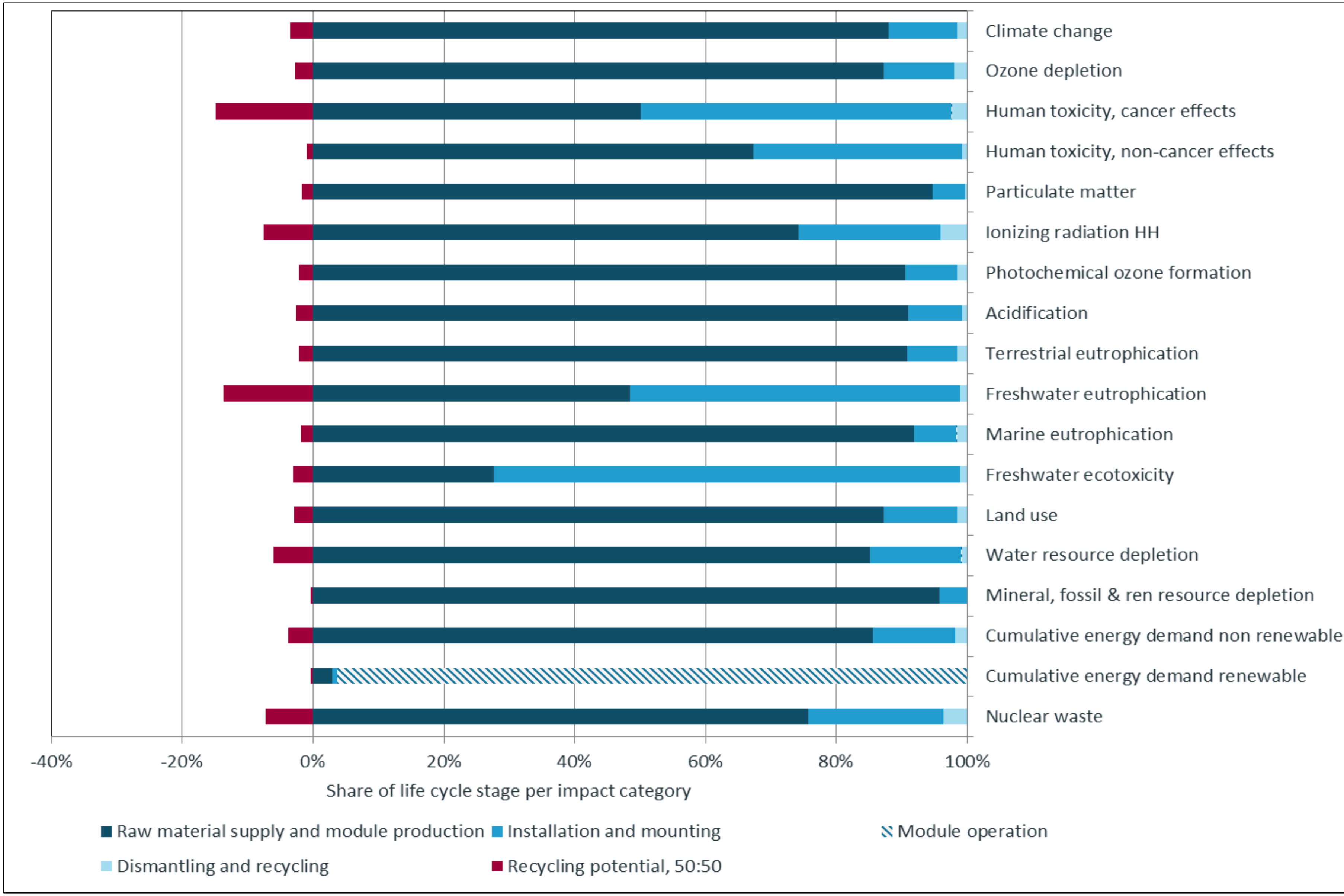


Share per impact category on the weighted result for the production of 1 kWh DC electricity produced with a residential scale multicrystalline-Si PV system mounted on a slanted roof

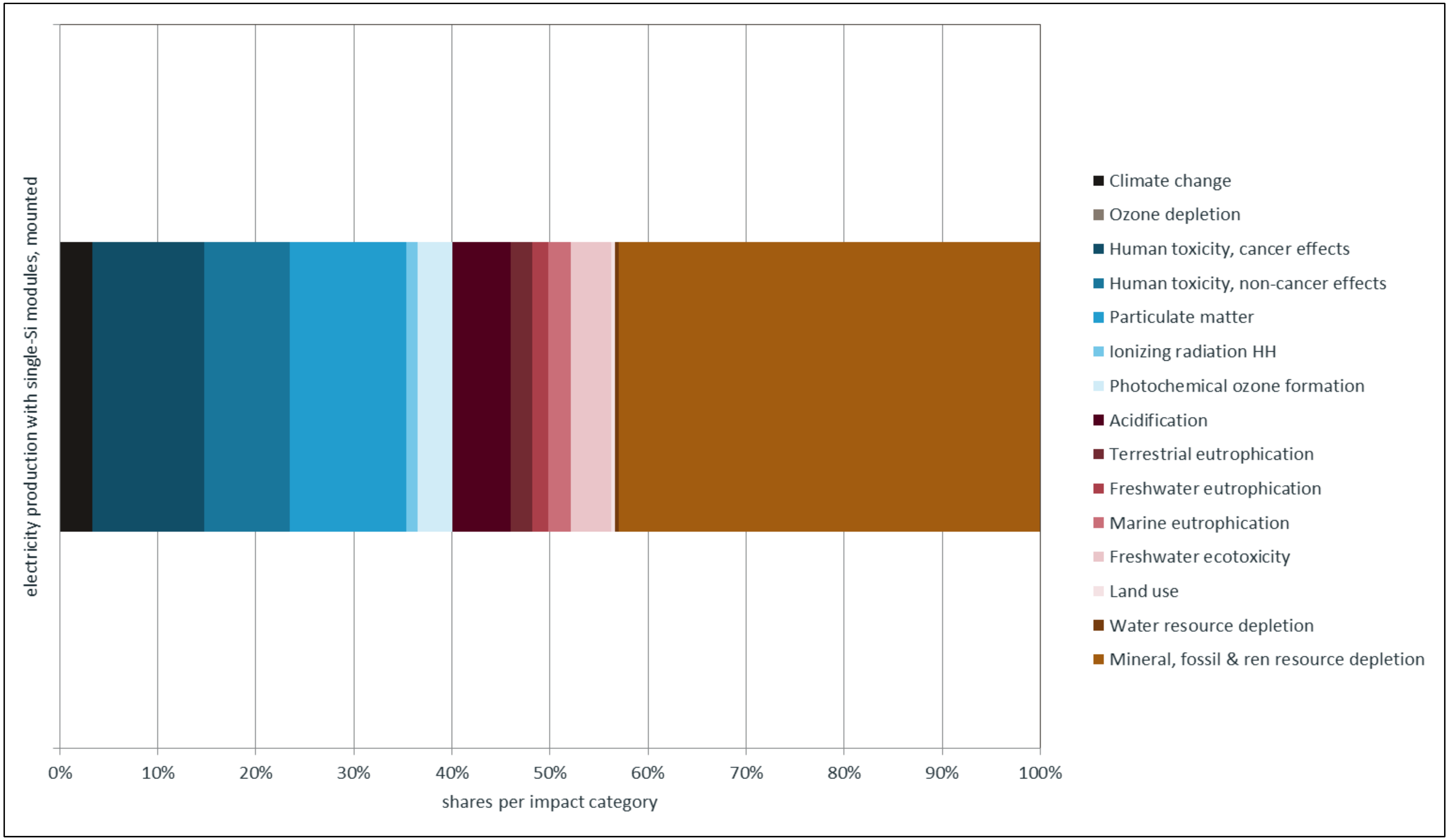
MONOCRYSTALLINE-SI PV TECHNOLOGY

Impact category	Unit per kWh electricity	Product stage	Construction stage	Use stage	End-of-life stage	Total, recycling benefits excluded	Potential benefits due to recycling	Total, recycling benefits included
electricity, 3 kWp installation, mounted with mono-Si PV technology, characterized		Raw material supply and module production	Installation and mounting	Module operation	Dismantling and recycling	Total all life stages, recycling benefits excluded	Recycling potential, 50:50	Total all life cycle stages, benefits for recycling included
Climate change	kg CO2 eq	8.06E-02	9.52E-03	3.13E-06	1.39E-03	9.15E-02	-3.21E-03	8.83E-02
Ozone depletion	kg CFC-11 eq	2.13E-09	2.64E-10	1.96E-13	4.73E-11	2.44E-09	-6.62E-11	2.38E-09
Human toxicity, cancer effects	CTUh	7.15E-10	6.77E-10	4.86E-13	3.27E-11	1.43E-09	-2.13E-10	1.21E-09
Human toxicity, non-cancer effects	CTUh	9.16E-09	4.33E-09	7.54E-12	9.79E-11	1.36E-08	-1.31E-10	1.35E-08
Particulate matter	kg PM2.5 eq	1.26E-04	6.45E-06	1.63E-09	4.23E-07	1.33E-04	-2.12E-06	1.31E-04
Ionizing radiation HH	kBq U235 eq	2.85E-03	8.35E-04	5.91E-07	1.55E-04	3.84E-03	-2.88E-04	3.55E-03
Photochemical ozone formation	kg NMVOC eq	3.04E-04	2.64E-05	1.13E-08	5.07E-06	3.36E-04	-7.17E-06	3.29E-04
Acidification	molc H+ eq	7.53E-04	6.87E-05	2.34E-08	6.22E-06	8.28E-04	-2.16E-05	8.07E-04
Terrestrial eutrophication	molc N eq	1.08E-03	8.99E-05	6.19E-08	1.83E-05	1.19E-03	-2.59E-05	1.16E-03
Freshwater eutrophication	kg P eq	3.78E-06	3.93E-06	4.23E-09	7.63E-08	7.79E-06	-1.06E-06	6.72E-06
Marine eutrophication	kg N eq	1.08E-04	7.52E-06	9.29E-08	1.80E-06	1.18E-04	-2.11E-06	1.15E-04
Freshwater ecotoxicity	CTUe	2.93E-02	7.53E-02	1.88E-05	1.08E-03	1.06E-01	-3.18E-03	1.02E-01
Land use	kg C deficit	7.52E-02	9.62E-03	1.31E-05	1.28E-03	8.61E-02	-2.46E-03	8.36E-02
Water resource depletion	m3 water eq	9.16E-05	1.50E-05	8.47E-08	8.00E-07	1.07E-04	-6.46E-06	1.01E-04
Mineral, fossil & ren resource depletion	kg Sb eq	1.21E-05	5.14E-07	2.00E-11	5.70E-09	1.26E-05	-3.99E-08	1.25E-05
Cumulative energy demand non renewable	MJ	9.31E-01	1.37E-01	4.83E-05	1.98E-02	1.09E+00	-4.04E-02	1.05E+00
Cumulative energy demand renewable	MJ	1.13E-01	2.66E-02	3.60E+00	1.29E-03	3.74E+00	-1.08E-02	3.73E+00
Nuclear waste	m3 HAA eq	6.74E-11	1.83E-11	1.10E-14	3.23E-12	8.90E-11	-6.46E-12	8.25E-11

Environmental impact results (characterized) of 1 kWh of DC electricity produced with a residential scale (3 kWp) PV system with monocrystalline-Si PV panels mounted on a slanted roof



Environmental impact results (characterized, indexed to 100 %) of 1 kWh of DC electricity produced with a residential scale (3 kWp) PV system with monocrystalline-Si PV panels mounted on a slanted roof. The potential benefits due to recycling are illustrated relative to the overall environmental impacts from production to end-of-life.

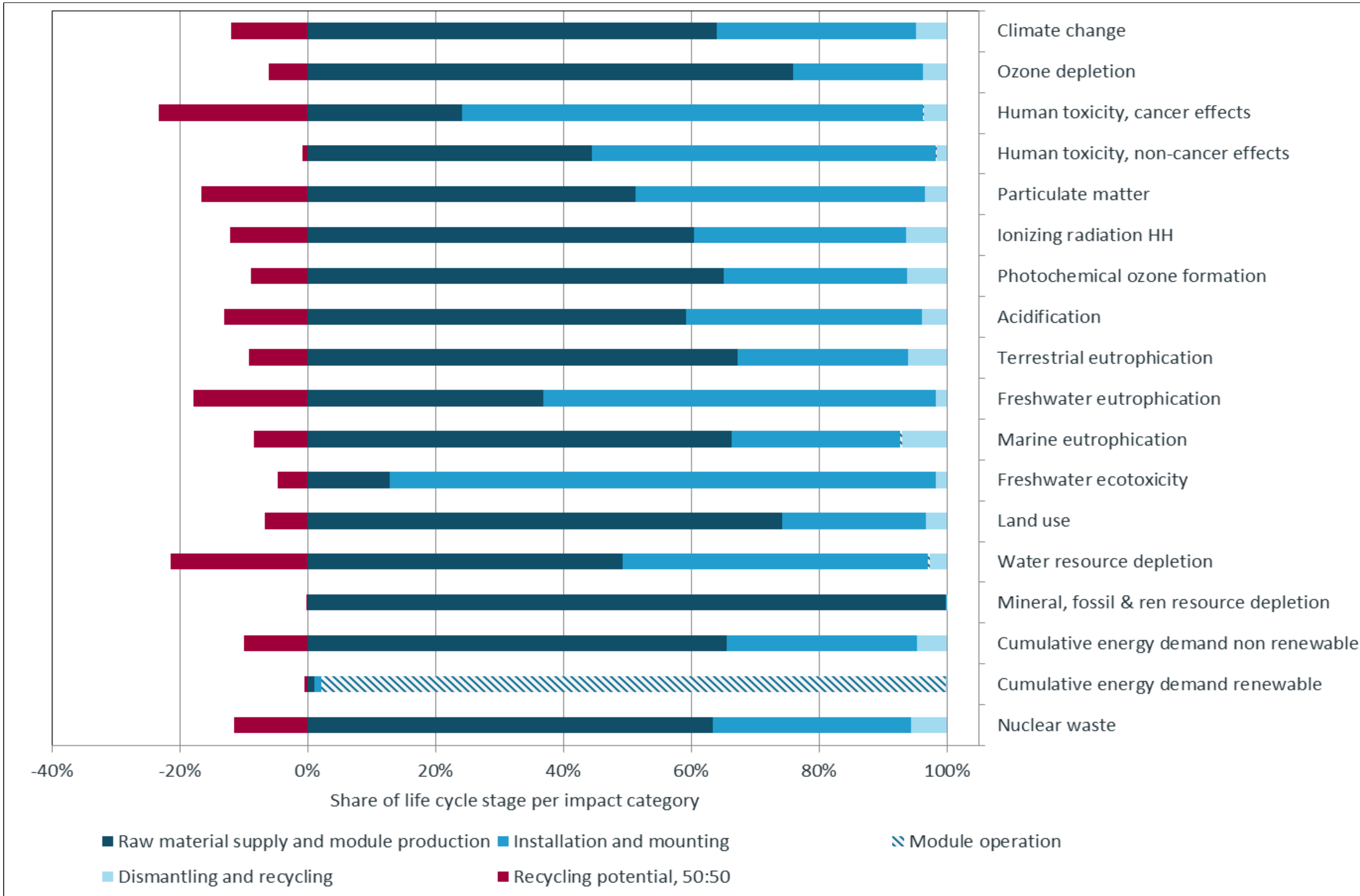


Share per impact category on the weighted result for the production of 1 kWh DC electricity produced with a residential scale monocrystalline-Si PV system mounted on a slanted roof

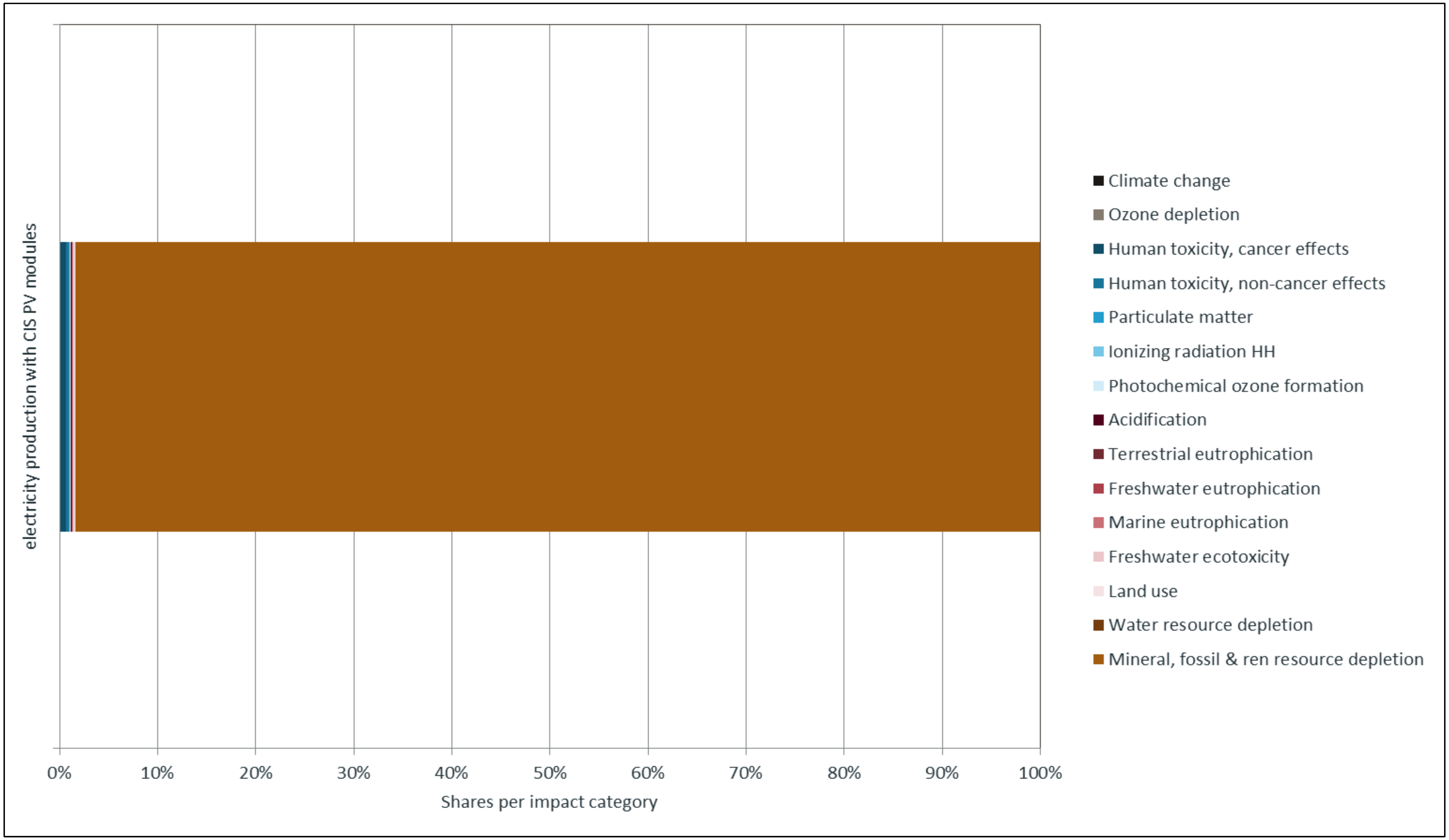
CIS PV TECHNOLOGY

Impact category	Unit per kWh electricity	Product stage	Construction stage	Use stage	End-of-life stage	Total, recycling benefits excluded	Potential benefits due to recycling	Total, recycling benefits included
electricity, 3 kWp installation, mounted with CIS PV technology, characterized		Raw material supply and module production	Installation and mounting	Module operation	Dismantling and recycling	Total all life stages, recycling benefits excluded	Recycling potential, 50:50	Total all life cycle stages, benefits for recycling included
Climate change	kg CO2 eq	2.60E-02	1.27E-02	4.46E-06	1.95E-03	4.06E-02	-4.87E-03	3.58E-02
Ozone depletion	kg CFC-11 eq	1.35E-09	3.61E-10	2.75E-13	6.61E-11	1.78E-09	-1.08E-10	1.67E-09
Human toxicity, cancer effects	CTUh	3.11E-10	9.26E-10	6.80E-13	4.56E-11	1.28E-09	-2.98E-10	9.85E-10
Human toxicity, non-cancer effects	CTUh	4.05E-09	4.91E-09	1.06E-11	1.37E-10	9.11E-09	-7.54E-11	9.03E-09
Particulate matter	kg PM2.5 eq	9.18E-06	8.10E-06	2.45E-09	5.92E-07	1.79E-05	-2.96E-06	1.49E-05
Ionizing radiation HH	kBq U235 eq	2.09E-03	1.15E-03	8.28E-07	2.17E-04	3.45E-03	-4.15E-04	3.04E-03
Photochemical ozone formation	kg NMVOC eq	7.48E-05	3.30E-05	1.61E-08	7.07E-06	1.15E-04	-1.02E-05	1.05E-04
Acidification	molc H+ eq	1.34E-04	8.36E-05	3.36E-08	8.69E-06	2.26E-04	-2.96E-05	1.97E-04
Terrestrial eutrophication	molc N eq	2.83E-04	1.12E-04	8.79E-08	2.55E-05	4.21E-04	-3.87E-05	3.82E-04
Freshwater eutrophication	kg P eq	2.45E-06	4.07E-06	5.92E-09	1.07E-07	6.63E-06	-1.18E-06	5.45E-06
Marine eutrophication	kg N eq	2.41E-05	9.50E-06	1.30E-07	2.52E-06	3.62E-05	-3.03E-06	3.32E-05
Freshwater ecotoxicity	CTUe	1.18E-02	7.87E-02	2.63E-05	1.51E-03	9.20E-02	-4.22E-03	8.78E-02
Land use	kg C deficit	4.14E-02	1.26E-02	1.84E-05	1.79E-03	5.58E-02	-3.72E-03	5.21E-02
Water resource depletion	m3 water eq	2.14E-05	2.07E-05	1.18E-07	1.12E-06	4.33E-05	-9.25E-06	3.40E-05
Mineral, fossil & ren resource depletion	kg Sb eq	5.12E-04	5.39E-07	-4.77E-10	7.96E-09	5.12E-04	-2.36E-08	5.12E-04
Cumulative energy demand non renewable	MJ	4.00E-01	1.81E-01	6.84E-05	2.77E-02	6.09E-01	-6.02E-02	5.48E-01
Cumulative energy demand renewable	MJ	4.14E-02	3.66E-02	3.60E+00	1.81E-03	3.68E+00	-1.54E-02	3.66E+00
Nuclear waste	m3 HAA eq	5.16E-11	2.52E-11	1.54E-14	4.52E-12	8.14E-11	-9.28E-12	7.21E-11

Environmental impact results (characterized) of 1 kWh of DC electricity produced with a residential scale (3 kWp) PV system with CIS PV panels mounted on a slanted roof

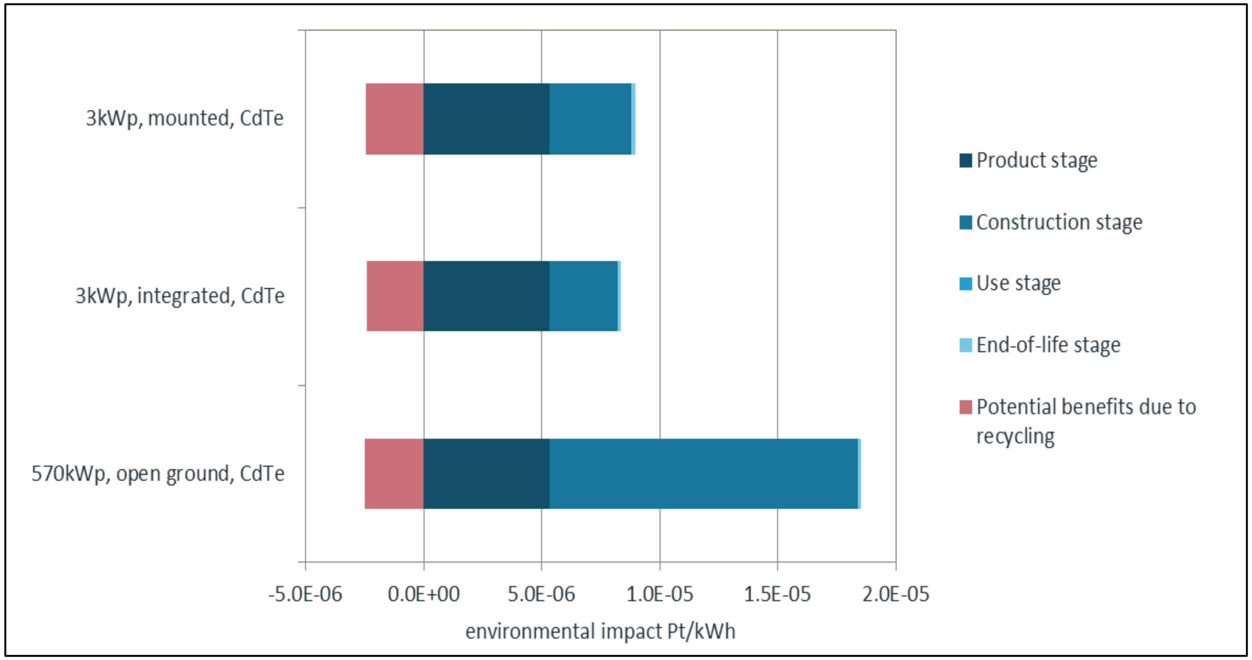


Environmental impact results (characterized, indexed to 100 %) of 1 kWh of DC electricity produced with a residential scale (3 kWp) PV system with CIS PV panels mounted on a slanted roof. The potential benefits due to recycling are illustrated relative to the overall environmental impacts from production to end-of-life.

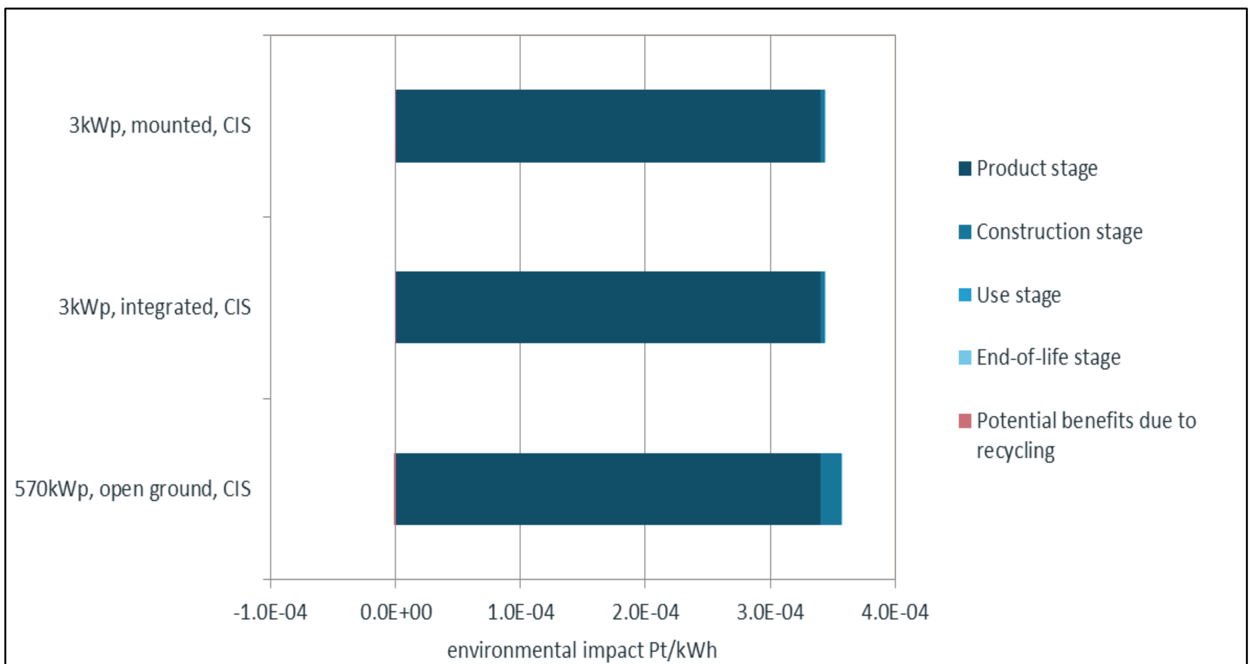


Share per impact category on the weighted result for the production of 1 kWh DC electricity produced with a residential scale CIS PV system mounted on a slanted roof

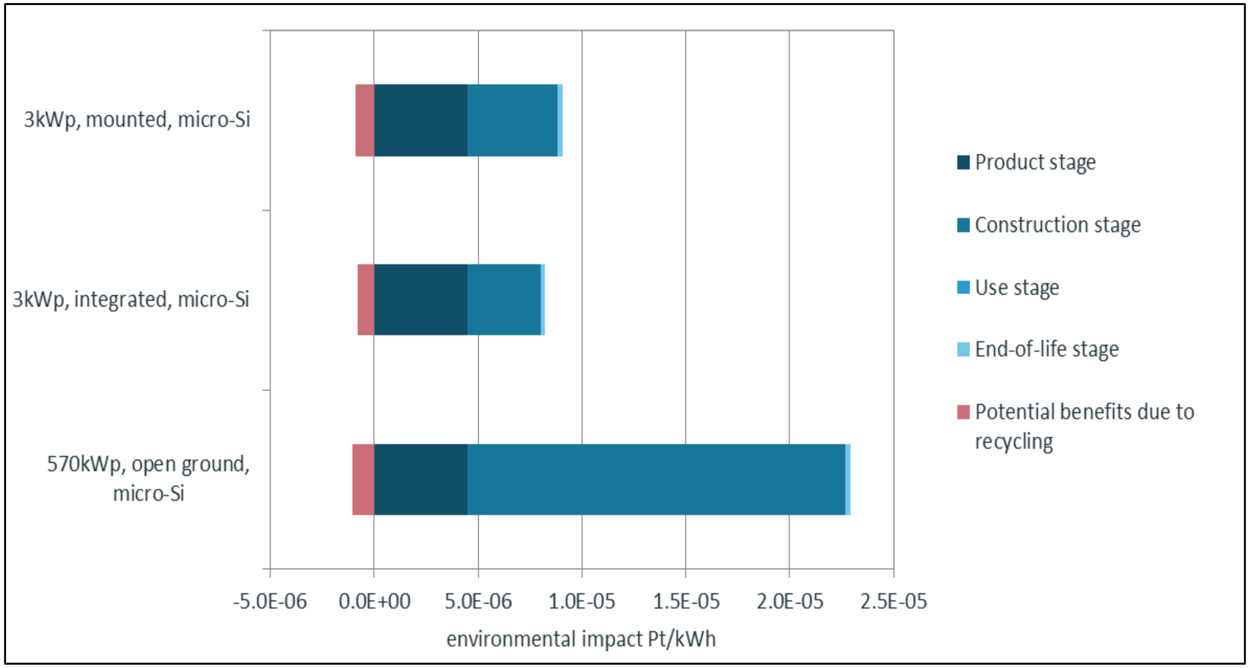
TECHNOLOGY COMPARISON – APPLICATION CASE SENSITIVITY ANALYSIS



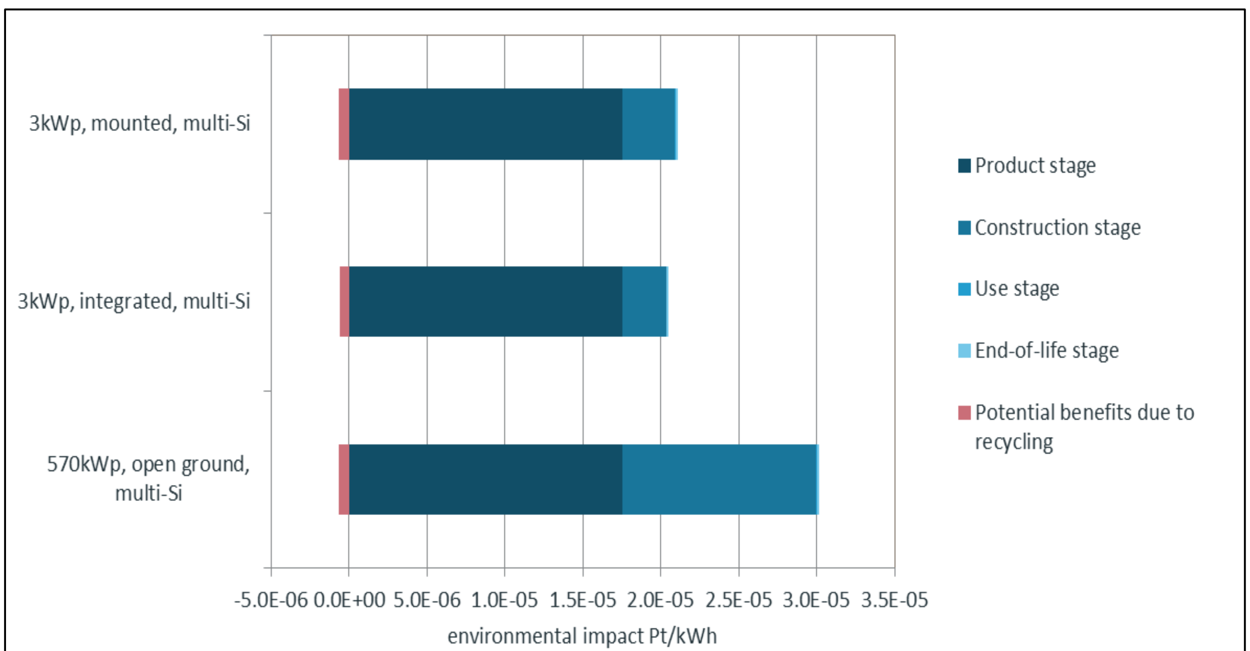
CdTe PV



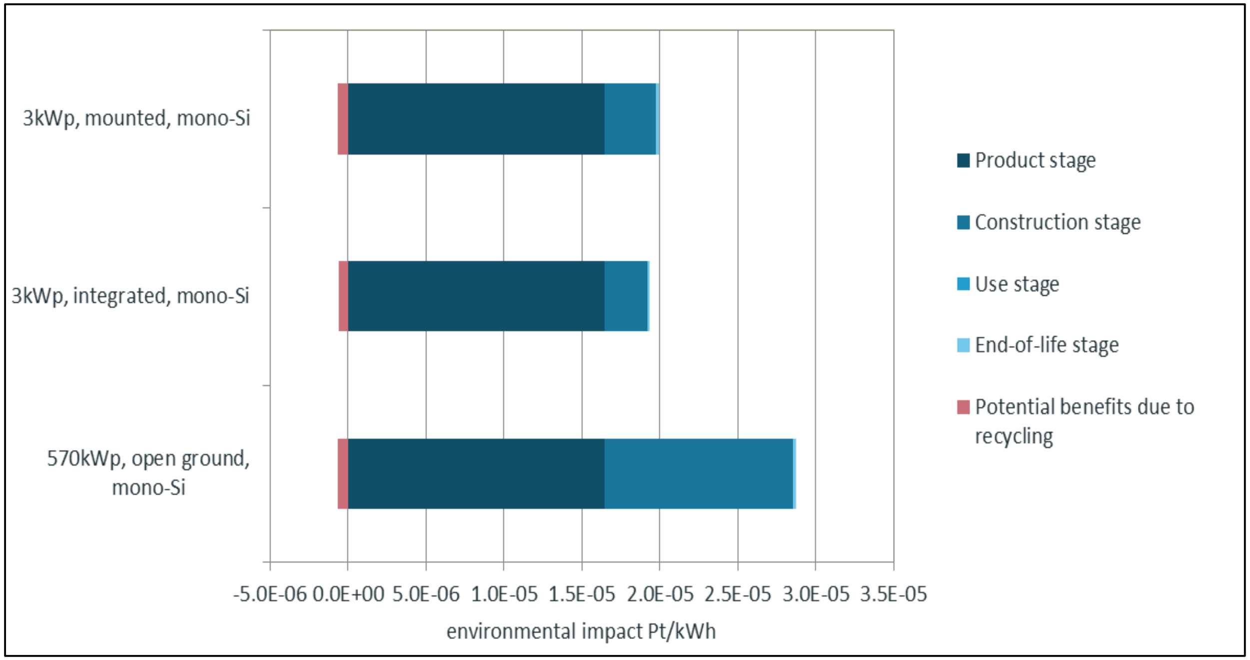
CIS PV



micro-Si

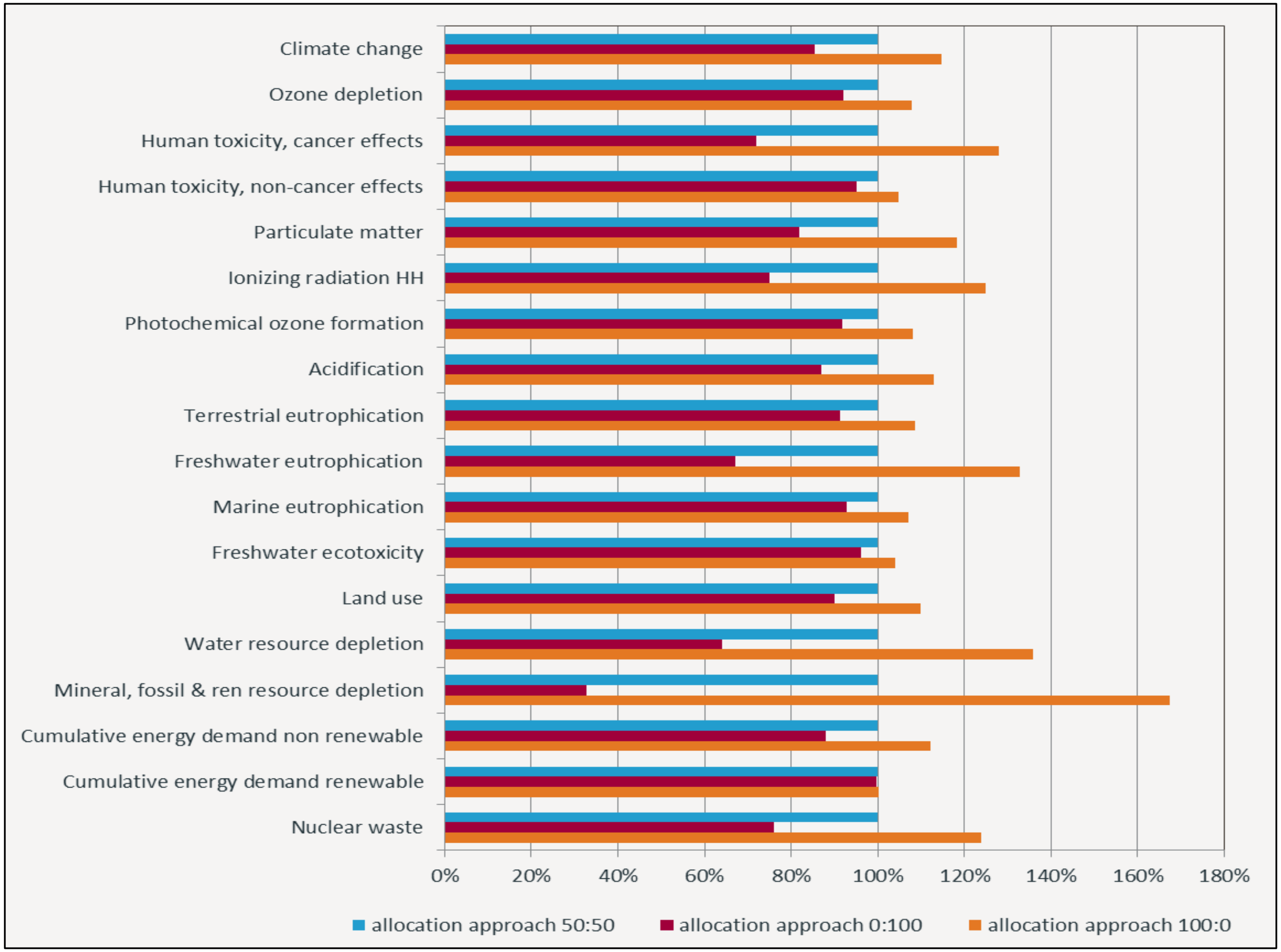


multi-Si


3kWp, mounted, mono-Si
3kWp, integrated, mono-Si
570kWp, open ground, mono-Si
-5.0E-06
0.0E+00
5.0E-06
1.0E-05
1.5E-05
2.0E-05
2.5E-05
3.0E-05
3.5E-05
environmental impact Pt/kWh
Product stage
Construction stage
Use stage
End-of-life stage
Potential benefits due to recycling

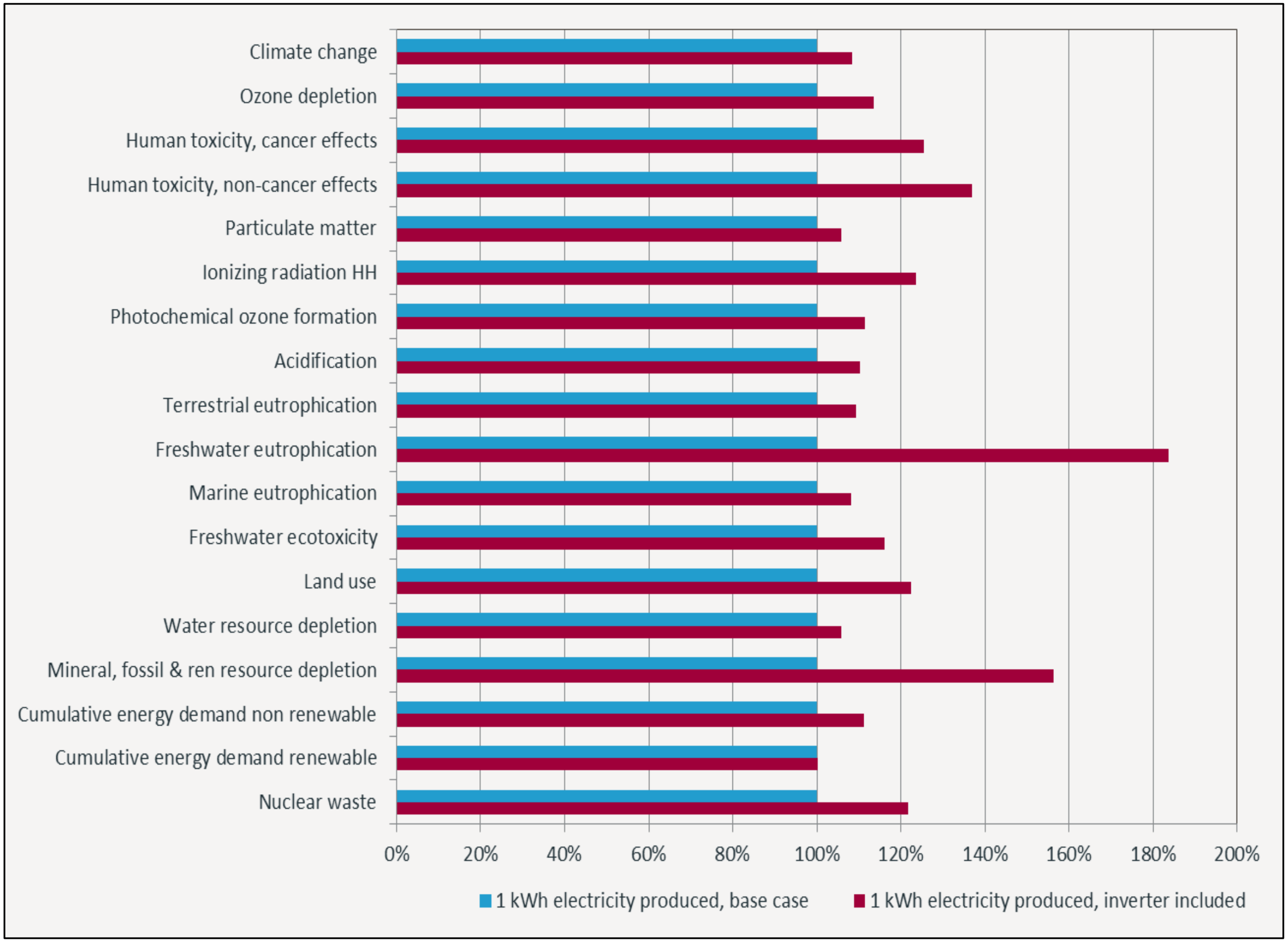
mono-Si

SENSITIVITY ANALYSIS
EOL ALLOCATION APPROACH



Relative results (characterized) of the sensitivity analyses of allocation of benefits for recycling at the end-of-life stage when producing 1 kWh DC electricity with a residential scale CdTe PV system mounted on a slanted roof top. The allocation 50:50 is the base case and its impacts are indexed to 100 %. The results of the other allocation approaches are shown in relation to the base case.

SENSITIVITY ANALYSIS
INVERTER INCLUSION



Relative results (characterized) of the sensitivity analyses when producing 1 kWh of DC electricity including and excluding the inverter with a residential scale multi-Si PV system mounted on a slanted roof top. The base case represents the situation without inverter. Results are indexed to the base case (100 %).