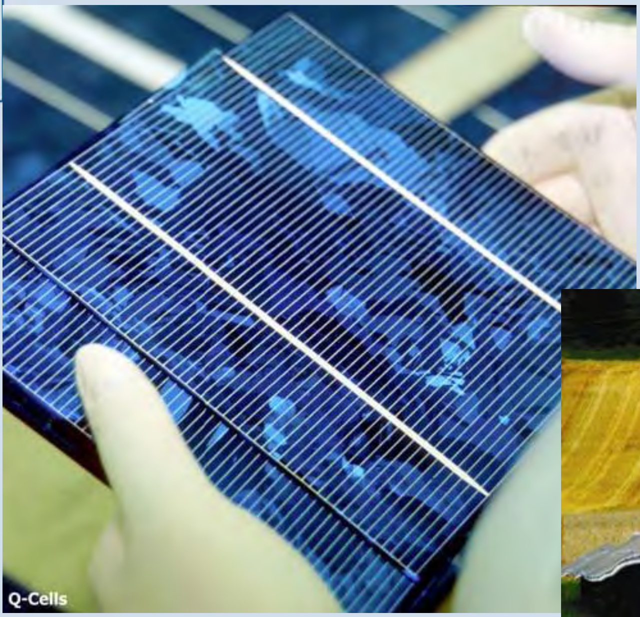
IEA INTERNATIONAL ENERGY AGENCY

Life Cycle Assessment of Future Photovoltaic Electricity Production from Residential-scale Systems Operated in Europe



Q-Cells

Karlstadt Laudenbach, Germany (810 kW); Phoenix Solar

PVPS

PHOTOVOLTAIC
POWER SYSTEMS
PROGRAMME

Report IEA-PVPS T12-05:2015

INTERNATIONAL ENERGY AGENCY PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

Life Cycle Assessment of Future Photovoltaic Electricity Production from Residential-scale Systems Operated in Europe

IEA-PVPS Task 12, Subtask 2.0, LCA Report IEA-PVPS T12-05:2015

March 2015
ISBN 978-3-906042-30-5

Operating Agent:
Garvin Heath, National Renewable Energy Laboratory, Golden, CO, USA

Authors:
Rolf Frischknecht, René Itten, Franziska Wyss,

Contributors:
Isabelle Blanc, Garvin Heath, Marco Raugei, Parikhit Sinha, Andreas Wade

Citation: R. Frischknecht, R. Itten, F. Wyss, I. Blanc, G. Heath, M. Raugei, P. Sinha, A. Wade, 2014, Life cycle assessment of future photovoltaic electricity production from residential-scale systems operated in Europe, Subtask 2.0 "LCA", IEA-PVPS Task 12.

Abbreviations and Acronyms

ADEME	Agency for Environment and Energy Management, France
APAC	Asia & Pacific
BAU	business-as-usual (scenario)
BWR	boiling water reactor (nuclear power plant)
CCS	carbon capture and storage
CdTe	cadmium-telluride
CFC	chlorofluorocarbon
CH	Switzerland
CN	China
CO_2	carbon dioxide
CO_2 eq	carbon dioxide equivalents
CSP	concentrating solar power (solar power production)
DE	Germany
EAA	European Aluminium Association
EH&S	environmental, health and safety
ENTSO	European Network of Transmission System Operators
EPIA	European Photovoltaic Industry Association
FBR	fluidized-bed reactor
FHI-ISE	Fraunhofer Institute for Solar Energy Systems
GHG	greenhouse gas
GLO	global average
HFC	hydrofluorocarbon
IEA	International Energy Agency
IEA-PVPS	International Energy Agency Photovoltaic Power Systems Programme
IIASA	International Institute of Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
kW	kilowatt
kWh	kilowatt-hour
kWp	kilowatt-peak
LCA	life cycle assessment
LCI	life cycle inventory analysis
LCIA	life cycle impact assessment
MG	Metallurgical grade silicon
MJ	megajoule
MJ oil-eq	megajoule oil equivalents
Multi-Si	multi-crystalline silicon based photovoltaics

MW	megawatt
NEEDS	New Energy Externalities Development for Sustainability
NMVOC	non-methane volatile organic compounds
NO	Norway
NREPBT	non-renewable energy payback time
OECD	Organization for economic cooperation and development
OPT	optimistic improvement (scenario)
PM_{10}	particulate matter with a diameter of 10 µm and lower
PV	photovoltaics
PVPS	Photovoltaic Power Systems Programme
PWR	pressure water reactor (nuclear power plant)
R & D	Research and development
REAL	Realistic improvement (scenario)
RER	Europe
RLA	Latin America and the Caribbean
single-Si	single-crystalline
SO_2	sulphur dioxide
tkm	ton kilometre, unit for transport services
UCTE	Union for the Coordination of the Transmission of Electricity
US	United States (as used to define world regions = North America)

Executive Summary

The photovoltaics (PV) industry is growing rapidly to meet the increasing demand of green power. As the industry grows, the manufacturing processes and the material and energy efficiencies of PV cells and panels are improving. To assess the impacts of this trend, future scenarios of single-crystalline (single-Si, also known as mono-crystalline) silicon and cadmium-telluride (CdTe) PV systems installed on European residences were established. Assessment of the improvement potential of PV electricity-generating technologies such as single-Si and CdTe could be considered in long-term energy strategy decisions.

This study aims to provide scenario-based information about the environmental performance of single-Si and CdTe PV modules produced and operated in the far future (2030 to 2050). The deployment application assessed considers European residential roofs. We made scenario-dependent projections of key parameters for single-Si and CdTe PV panels manufactured in 2050. The parameters included cell efficiency, module efficiency, wafer thickness, cutting losses, kerf losses, silver use, glass thickness and operational lifetime (see Tab. S.1).

Tab. S.1 Key parameters of silicon-based single-crystalline and CdTe photovoltaic cells and modules and values used in the three scenarios BAU, REAL and OPT.

Parameter	Single-Si				CdTe			
	TODAY	BAU	REAL	OPT	TODAY	BAU	REAL	OPT
Cell efficiency	16.5 %	25.0 %	27.0 %	29.0 %	15.6 %	22.8 %	24.4 %	26.0 %
Derate cell to module efficiency	8.5 %	8.5 %	6.8 %	5.0 %	13.9 %	10.0 %	7.5 %	5.0 %
Module efficiency	15.1 %	22.9 %	25.2 %	27.6 %	13.4 %	20.5 %	22.6 %	24.7 %
Wafer thickness / layer thickness	190 µm	150 µm	120 µm	100 µm	4.0 µm	2.0 µm	1.0 µm	0.1 µm
Electricity demand in CdTe laminate manufacture	-	-	-	-	100 %	86 %	81 %	74 %
Kerf loss	190 µm	150 µm	120 µm	100 µm	-	-	-	-
Silver per cell	9.6 g/m^2	9.6 g/m^2	5.0 g/m^2	2.0 g/m^2	-	-	-	-
Fluidized-bed reactor (FBR) Share of Poly Si Production	0 %	20 %	40 %	100 %		-	-	
Glass thickness	4.0 mm	4.0 mm	3.0 mm	2.0 mm	3.5 mm	3.5 mm	3.0 mm	2.0 mm
Operational lifetime	30 years	30 years	35 years	40 years	30 years	30 years	35 years	40 years

We combined developments for these parameters with projections of the environmental performance of electricity mixes in the main manufacturing countries/regions (European Union, China and the United States of America) and with projections of the environmental performance of basic material production (aluminium, copper, magnesium, nickel, pig iron, zinc, clinker and flat glass) in the far future. The three scenarios used in the assessment of future PV electricity were categorized into three classes: “business as usual” (BAU), “realistic improvement” (REAL) and “optimistic improvement” (OPT).

We estimate the current life cycle greenhouse gas emissions of single-Si PV electricity produced on the roofs of European residences to be approximately 80 grams CO_2-equivalent per kWh (g CO_2-eq per kWh). Based on the projected changes to key parameters and the background system, life cycle greenhouse gas (GHG) emissions could be reduced to 65 % (scenario BAU), 31 % (scenario REAL) and 18 % (scenario OPT) of that value in the far future. (The caption of Fig. S.1 specifies the module characteristics evaluated.) Results for other life cycle assessment (LCA) metrics assessed here are also shown in Fig. S.1: non-renewable cumulative energy demand, acidification potential, human toxicity potential, photochemical ozone creation potential, particulate matter formation potential, and land use.

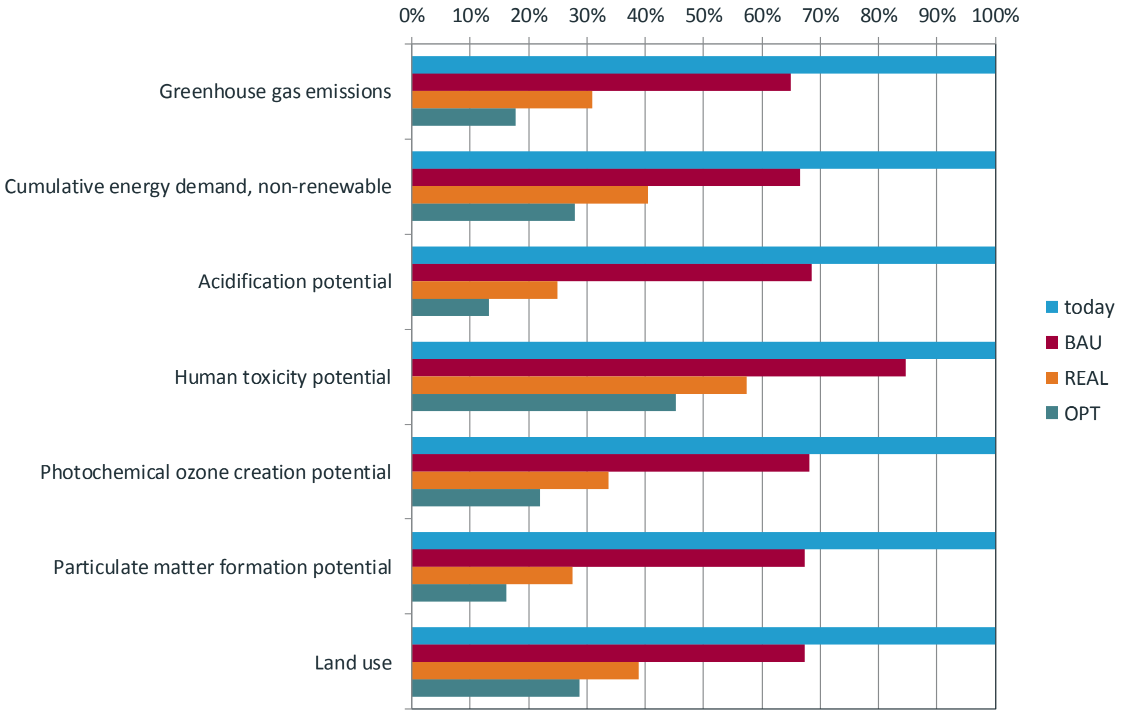


Fig. S.1 Estimates of life cycle greenhouse gas emissions (using 100 year global warming potentials from IPCC (2013)), non-renewable cumulative energy demand (following Frischknecht et al. (2007c)), acidification potential, human toxicity potential, photochemical ozone creation potential, particulate matter formation potential and land use (following Goedkoop et al. (2009)) of electricity produced in the far future with single-crystalline silicon-based photovoltaic laminates mounted on slanted roofs in Europe according to the three scenarios (BAU, REAL and OPT). Results for "today" are defined to be 100%, with the three scenarios as fractions thereof. Key assumptions are: module efficiency: 15.1 % (today), 22.9 % (BAU), 25.2 % (REAL), 27.6 % (OPT); annual yield (electricity generated per kWp of the PV power plant and year): 975 kWh/kWp including degradation (10.5 % average for lifetime); solar irradiation: 1 331 kWh/m^2. Lifetime of the PV power plant: 30 years (today and BAU), 35 years (REAL), 40 years (OPT). The system includes mounting, cabling, inverter and maintenance and considers production in different regions of the world (Europe, North America, China and Asia & Pacific) using region-specific electricity mixes. This is a prospective LCA for expected future development in the year 2050. The calculations are performed using the software SimaPro with ecoinvent v2.2+ as background database.

We calculated the total energy payback time (EPBT) and the non-renewable energy payback time (NREPBT) in the far future of single-crystalline silicon-based PV panels operated in Europe by dividing the estimate of non-renewable cumulative energy demand of PV electricity for the given scenario by the non-renewable cumulative energy demand of the scenario-dependent national and regional non-renewable residual electricity mixes.

We estimate the payback time could be reduced from 2.4 years today to 1.7, 1.2 and 1.2 years (scenarios BAU, REAL and OPT, respectively) in the far future, based on the assumptions and projections in our analysis.

We estimate the current life cycle greenhouse gas emissions of CdTe PV electricity produced on the roofs of European residences to be approximately 30 g CO_2-eq per kWh. Based on the projected changes to key parameters and the background system, life cycle GHG emissions could be reduced to 70 % (scenario BAU), 44 % (scenario REAL) and 32 % (scenario OPT) of that value in the far future (see Fig. S.2).

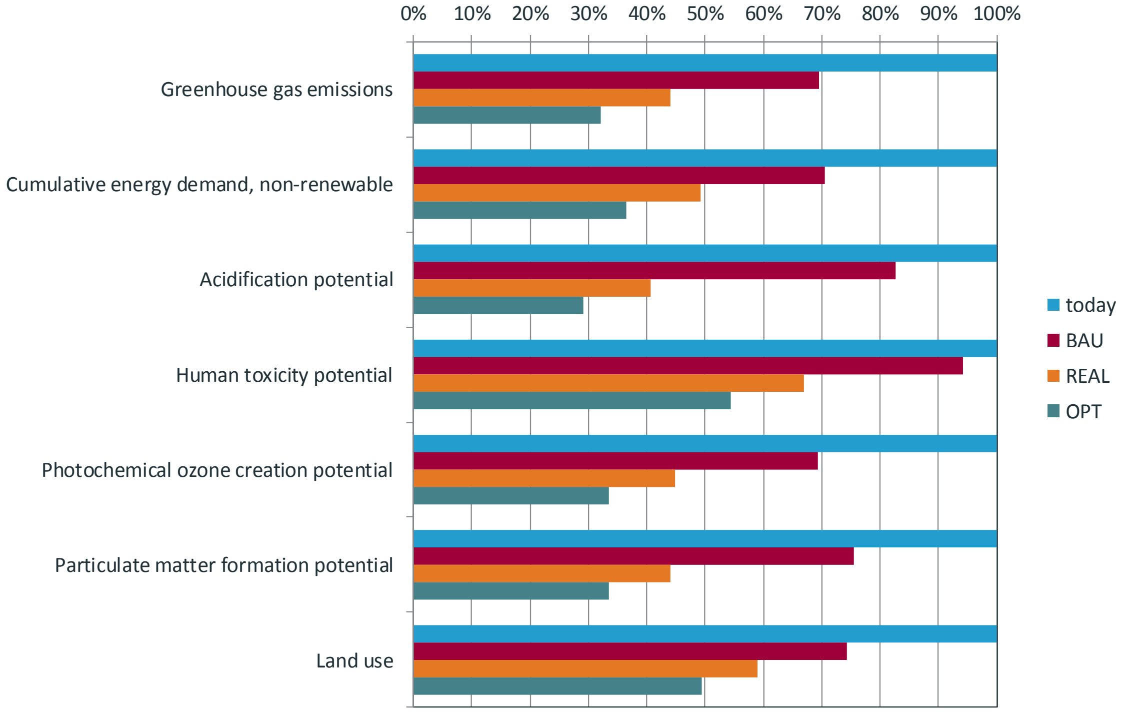


Fig. S.2 Estimates of life cycle greenhouse gas emissions (using 100 year global warming potentials from the most recent report of Working group 1 of the Intergovernmental Panel on Climate Change IPCC (2013)), non-renewable cumulative energy demand (following Frischknecht et al. (2007c)), acidification potential, human toxicity potential, photochemical ozone creation potential, particulate matter formation potential and land use (following Goedkoop et al. (2009)) of electricity produced in the far future with CdTe photovoltaic laminates mounted on slanted roofs in Europe, according to the three scenarios (BAU, REAL and OPT). Results for "today" are defined to be 100 %, with the three scenarios as fractions thereof. Key assumptions are: module efficiency: 13.4 % (today), 20.5 % (BAU), 22.6 % (REAL), 24.7 % (OPT); annual yield (electricity generated per kWp of the PV power plant and year): 975 kWh/kWp including degradation (10.5 % average for lifetime); solar irradiation: 1 331 kWh/m^2. Lifetime: 30 years (today and BAU), 35 years (REAL), 40 years (OPT). The system includes mounting, cabling, inverter and maintenance and considers production using region-specific electricity mixes. This is a prospective LCA for expected future development in the year 2050; the calculations are performed using the software SimaPro with ecoinvent v2.2+ as background database.

We estimate that the NREPBT of CdTe PV operated in Europe could be reduced from 1.1 years currently to 0.8, 0.7 and 0.7 years (scenarios BAU, REAL and OPT, respectively) in the far future, based on the assumptions and projections in our analysis. The NREPBT is lower in the scenario REAL than it is in the scenario OPT because of the different residual electricity mixes that are replaced. The total energy payback times (EPBT) are between 0 and 0.4 years higher than the NREPBT.

Tab. S.2 Future non-renewable residual electricity mixes for Europe (ENTSO-E) in the three scenarios BAU, REAL and OPT

Power plant technology/fuel	BAU	REAL	OPT
Hard coal	34.1 %	0.0	8.7 %
Hard coal with carbon capture and storage (CCS)	0.0 %	8.1 %	6.3 %
Lignite	12.5 %	0.0 %	0.0 %
Fuel oil	0.8 %	0.3 %	0.0 %
Natural gas	3.9 %	0.1 %	24.2 %
Natural gas, gas combined cycle	20.2 %	4.3 %	59.4 %
Natural gas, gas combined cycle, CCS	0.0 %	53.2 %	1.4 %
Natural gas, fuel cell	0.0 %	0.2 %	0.0 %
Nuclear	28.5 %	33.9 %	0.0 %
Total	**100.0 %**	**100.0 %**	**100.0 %**

The study suggests that future developments in the PV industry, the electricity sector and material supply could significantly reduce environmental impacts per kWh of PV-generated electricity compared to those of today. The LCA results of this analysis could help support long-term energy policy measures related to renewable energies. The results are based on a set of assumptions and projections that use the best available information and are specific to residential-scale rooftop systems operated in Europe. They are subject to considerable uncertainty, especially when projecting more than 30 years for such fast-evolving technologies. Therefore, the results of this analysis are best interpreted as indicating the currently expected direction and approximate relative magnitude of change for the PV industry rather than as precise predictions of absolute impacts in future years. While the absolute magnitude of results will change if different locations or applications are considered, the direction and relative magnitude of projected changes in impacts compared to the current situation is likely consistent with those reported here, and therefore informative to energy decisions with long-term consequences.

Foreword

The International Energy Agency (IEA), founded in November 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD) that carries out a comprehensive programme of energy co-operation among its member countries. The European Commission also participates in the work of the IEA.

The IEA PVPS is one of the collaborative R&D Agreements established within the IEA, and was established in 1993. The overall programme is headed by an Executive Committee composed of representatives from each participating country and/or organisation, while the management of individual research projects (Tasks) is the responsibility of Operating Agents. By early 2015, fifteen Tasks were established within the PVPS programme, of which six are currently operational.

The IEA PVPS Implementing Agreement presently has 29 members and covers the majority of countries active in photovoltaics, both in R&D, production and installation. The programme deals with the relevant applications of photovoltaics, both for on-grid and off-grid markets. It operates in a task-shared mode whereby member countries and/or organisations contribute with their experts to the different Tasks. The co-operation deals with both technical and non-technical issues relevant to a wide-spread use of photovoltaics in these different market segments.

The mission of the IEA PVPS programme is: "To enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems." The underlying assumption is that the market for PV systems is rapidly expanding to significant penetrations in grid-connected markets in an increasing number of countries, connected to both the distribution network and the central transmission network. At the same time, the market is gradually shifting from a policy to a business driven approach.

Task 12 engages in fostering international collaboration in communicating and assessing the environmental, health and safety aspects associated with the environmental, health and safety (EH&S) aspects of PV technology over the life cycle of the PV systems. Task 12 also disseminates reliable and accurate information on the EH&S impacts of PV technology to policymakers, industry participants and the public with the goal to improve consumer understanding and confidence, encourage industry best practices and aid policymakers to make informed decisions in the course of the energy transition. Furthermore, Task 12 brings its expertise in assessing methods and standards for the evaluation of EH&S aspects of PV systems. The overall objectives of Task 12 are to:

- Quantify the environmental profile of PV electricity using a life cycle approach, in order to contribute to the environmental sustainability of the supply chain and to compare it with the environmental profile of electricity produced with other energy technologies

- Aim for a closed-loop supply chain by and help improve waste management of PV by collective action on collection and recycling, including legislative developments as well as development of technical standards
- Distinguish and address actual and perceived issues touching the EH&S aspects of PV technology that are important for market growth.

The first objective of this task is well served by life cycle assessments (LCAs) that describe the energy-, material- and emission-flows in all the stages of the life cycle of PV. The second objective will be addressed by assisting the collective action of PV companies in defining material availability and product-recycling issues.

Within Task 12, a Subtask on “Life Cycle Assessment” includes three targets: to quantify the environmental profile of electricity produced with PV systems (compared to that from other sources); to evaluate trends in the environmental profile of PV; and, to assess this profile with the help of "external" costs and other life cycle impact assessment methods. In addition, Task 12 has produced and will continue to update methodological guidelines for PV LCA. Further information on the activities and results of the Task can be found at www.iea-pvps.org.

Content

1 Introduction, Motivation and Overview

Photovoltaics (PV) are considered a promising electricity producing technology that could play an important role in replacing fossil and nuclear power plants and reducing the environmental impacts of the electricity mixes of countries and regions. Long-term energy planning and assessment relies on scenarios of the future development of the price of oil, economic growth assumptions and the like. Similarly, the environmental assessment of future electricity supply should rely on information about possible future developments with regard to the energy and material efficiencies of electricity producing technologies as well as the environmental efficiency in manufacturing these technologies. Furthermore, possible developments in the supply chains of basic materials - such as aluminium (primary), copper, cement - and in the electricity mixes of producing countries and regions need to be taken into account.

Comprehensive and consistent assessments of the environmental impacts of power plants to be operated between 2030 and 2050 were carried out in NEEDS, a research project[1] within the 6th framework program of the European Union (Frischknecht et al. 2007a; Frischknecht & Krewitt 2008; Frischknecht 2010). The results showed that the environmental impacts depend on the scenario chosen and that it is important to adjust not only the foreground system (i.e., the PV supply chain) but also the background system (i.e., the material supply and the electricity mix used in the PV manufacturing supply chain).

Because the PV industry has advanced since the first assessment in 2008, an update of the environmental assessment of future PV electricity production would be helpful. It should be emphasized that the specific results found in this study are based on a set of assumptions and projections that use the best available information. As such, they are subject to considerable uncertainty, especially when projecting 30 or more years for such a fast-evolving technology. Therefore, the results of this assessment are best understood in the context of the information available today and for the purpose of clarifying the currently expected direction and approximate relative magnitude of change, rather than for their precise, absolute results. In addition, this report only considers one PV application: small power plants installed on European residential rooftops. While the absolute magnitude of results will change if different locations or applications are considered, the direction and relative magnitude of projected changes in impacts compared to the current situation is likely consistent with those reported here.

This report describes the goal and scope of the key parameters (Section 2) used in the future scenarios (Section 2.10) of the life cycle inventories (LCIs) of the systems analysed (Section 4), the LCIs used in the background system (Section 5) and the results of the future-oriented LCAs (Section 6). The report is completed with conclusions in Section 7.

---

[1] For more information about the New Energy Externalities Developments for Sustainability project, see www.needs-project.org.

2 Goal and Scope

2.1 Goal of the Study

The goal of this study is to assess the life cycle environmental impacts of the future production of electricity in Europe with two different types of PV laminates - silicon-based single-crystalline silicon and cadmium-telluride - manufactured globally and operated between 2030 and 2050 on Europe residential roofs.

PV laminates were selected for analysis because unframed and building-integrated laminates cause fewer environmental impacts than framed and mounted panel laminates. Projections for future material demand of the panel frames and the mounting structures are not part of this study; therefore, the relative importance of the panel frames and the mounting devices relative to the modules will increase over time (i.e., environmental impacts of the modules are decreasing, whereas the impacts of the frames and the mounting systems remain constant).

Although the report often refers to the year 2050, the analyses carried out rather reflect a situation between 2030 and 2050 and thus are long term future projections based on assessments of changes in key parameters rather than projections for the specific year 2050.

2.2 Functional Unit

The functional unit used in this study is 1 kWh of electricity supplied to the grid in the long term future.

2.3 System Boundary

The production system of the future PV electricity produced with crystalline silicon-based and cadmium-telluride (CdTe) solar cells comprises:

- raw material extraction
- wafer, cell and module manufacture
- mounting structures manufacture
- inverters manufacture
- system installation
- operation (cleaning of the modules)
- end-of-life treatment.

2.4 Assumptions Related to the Operation of Photovoltaic Panels

The use phase is characterised by three main parameters: annual yield, degradation rate and lifetime.

The annual yield of electricity depends on the location of installation, the mounting and orientation of the modules (façade versus roof top, inclination and orientation) and the degradation rate. Tab. 2.1 shows the cumulative installed PV power in Europe, according to IEA-PVPS (2013) and the country-specific average yield at optimal angle in urban areas, according to the report published by the European Photovoltaic Industry Association, EPIA (2012). The annual average yield of optimally oriented modules in Europe, weighted according to the cumulative installed PV power corresponds to 1 090 kWh/kWp (excluding degradation effects) with an average solar irradiation of about 1 330 kWh/m^2 and optimally oriented panels.

Tab. 2.1 Cumulative installed photovoltaic power in Europe in 2012 according to IEA-PVPS (2013), country specific average annual yield in kWh/kWp at optimal angle in urban areas according to EPIA (2012), and average solar irradiation at optimal angle, based on data retrieved from PVGIS[2]. Degradation is not included.

Country	**Cumulative installed power (MW)**	**Share**	**Average yield at optimal angle in urban areas (kWh/kWp)**	**Average solar irradiation at optimal angle (kWh/m^2)**
Austria	363	1%	1 027	1 314
Belgium	2 698	4%	930	1 100
Germany	32 462	51%	936	1 147
Denmark	332	1%	945	1 130
Spain	4 706	7%	1 471	1 812
France	4 033	6%	1 117	1 386
United Kingdom	1 901	3%	920	1 111
Italy	16 450	26%	1 326	1 611
Netherlands	345	1%	933	1 112
Portugal	210	0%	1 494	1 840
Sweden	24	0%	826	1 101
Europe (PVPS members)	**63 524**	**100%**	**1 090**	**1 331**

In line with the IEA-PVPS methodology guidelines (Fthenakis et al. 2011) and the Agency for Environment and Energy Management (ADEME) methodology guidelines (Payet et al. 2013), a degradation of 0.7 % per year is applied leading to a loss in yield of 21 % during the last year of an operation time of 30 years. Hence, the weighted average yield of a PV module installed in Europe and operated for 30 years is 10.5 % below the average yield shown in Tab. 2.1. The European PV modules are thus modelled with an annual yield of 975 kWh per kWp.

---

[2] re.jrc.ec.europa.eu/pvgis/ (accessed on 29.04.2014)

2.5 Geographical, Temporal and Technical Validity

The future PV supply chain covers four world regions and countries: Europe (RER), North America (US), Asia & Pacific (APAC) and China (CN). In combination with information on all levels of the PV supply chain, specific market mixes for the four regions are derived and modelled. This includes both produced and installed PV capacities in the four regions. For the purpose of this study, and without references providing alternative projections, the market shares for the year 2012 is assumed to remain constant for all projection scenarios analysed (see Section 2.6).

This project explores scenarios for the long term future, tied to projections for a set of key parameters. The three scenarios represent pessimistic, realistic and optimistic projections of technology development of producing polysilicon (also called metal grade silicon, the feedstock material for semiconductor and PV industries), solar-grade silicon, of manufacturing wafers, cells and panels (CdTe and single-crystalline silicon), of material and energy efficiency of cells and panels and of supplying basic materials and electricity used in the PV supply chain.

2.6 Scenarios

The future life cycle environmental impacts of two different major PV technologies are analysed in this study: silicon-based single-crystalline (single-Si) PV modules and cadmium telluride PV modules (CdTe). For each PV technology, three scenarios are evaluated: a business-as-usual scenario (BAU), a realistic improvement scenario (REAL) and an optimistic improvement scenario (OPT). Tab. 2.2 summarizes and describes the three scenarios. The scenarios BAU, REAL and OPT correspond to the scenarios “pessimistic”, “realistic-optimistic” and “very optimistic” according to the NEEDS terminology.

The assumptions and parameters being used in the three scenarios are described in detail in Subchapter 3.3 and in Chapter 5.

Tab. 2.2 Overview and characterisation of the three scenarios

Scenario name	Abbreviation	Comment	Corresponding scenarion in NEEDS
Business-as-usual	BAU	Pessimistic scenario with limited improvement	Scenario “pessimistic”: continuation of established policies. No energy goals are set.
Realistic improvements	REAL	Realistic scenario between BAU und OPT	Scenario “realistic optimistic”: renewable energy sources as well as energy efficient technologies are pushed intensely. Key technologies are advanced systematically and energy politics have a high priority.
Optimistic improvements	OPT	Optimistic scenario using the most ambitious future projections for the key parameters	Scenario “very optimistic”: highly ambitiousenergy policies. Efficient technologies are supported and pushed

2.7 Data Sources and Modelling

The SimaPro (version 7.3.3) a commercial LCA software, is used to model the production systems, to calculate the LCI and impact assessment results (PRé Consultants 2012). Most background data are represented by ecoinvent data v2.2 (ecoinvent Centre 2010) and further updates (LC-inventories 2012) unless otherwise noted. Key materials, electricity mixes of selected countries as well as the PV supply chains are represented by data meant to represent a longterm future. Data sets are documented and published in EcoSpold v1 format[3].

2.8 Impact Assessment Methods

The environmental impact assessment is performed on the mid-point level, at some point between the release of a substance and the potential damage it may cause. For instance, the greenhouse gases are aggregated according to their radiative forcing potential. Thus we are not quantifying environmental impacts in terms of damages but aggregating flows that contribute to the same effect (e.g. climate change).

The following indicators are used in this study:

- Greenhouse gas emissions (kg CO_2-eq), assessed assuming 100 year global warming potentials based on the latest IPCC 2013 (Tab. 8.A.1): This indicator aggregates greenhouse gases emitted according to their radiative forcing capacity relative to the reference substance CO_2.
- Cumulative energy demand, non-renewable (MJ oil-eq) (Frischknecht et al. 2007b): This indicator aggregates fossil and nuclear energy resources on the basis of their upper heating value (fossil energy resources) and the energy extractable from 1 kg fissible uranium in a nuclear light water reactor.
- Acidification potential (kg SO_2-eq) evaluated using the ReCiPe midpoint method (hierarchist perspective) (Goedkoop et al. 2009): This indicator aggregates pollutants potentially contributing to the acidification of water bodies and soils based on the capacity of binding H^+ ions relative to the reference substance SO_2.
- Human toxicity potential[4] (kg 1,4-DB eq), evaluated using the ReCiPe midpoint method (hierarchist perspective) (Goedkoop et al. 2009): This indicator aggregates substances potentially toxic to humans relative to the reference substance 1,4-dichlorobenzene.
- Photochemical ozone creation potential (kg NMVOC), evaluated using the ReCiPe midpoint method (hierarchist perspective) (Goedkoop et al. 2009): This indicator aggregates substances potentially contributing to summer smog situations (via ozone formation), expressed relative to the ozone creating potential of an average NMVOC.

---

[3] The files in the EcoSpold v1 format are available at www.treeze.ch/projects/case-studies/energy/photovoltaic

[4] More recent impact category indicators are available (USETox) which may lead to substantially different outcomes, in particular with regard to the impact reduction potential in the longterm future.

- Particulate matter formation potential (kg PM_{10}-eq), evaluated using the ReCiPe midpoint method (hierarchist perspective) (Goedkoop et al. 2009): This indicator aggregates particulate matter directly emitted and substances transformed in the atmosphere to particulate matter (secondary particulates). It covers PM, NO_X, SO_2 and NH_3 emitted to air with PM being the reference substance.
- Urban land occupation (m^2a), evaluated using the ReCiPe midpoint method (hierarchist perspective) (Goedkoop et al. 2009). This indicator quantifies the area multiplied by time of land being occupied by buildings, power plants, factories and other infrastructures (roads, railway tracks, dams).

2.9 Non-renewable Energy Payback Time (NREPBT)

The non-renewable energy payback time (Fthenakis et al. 2011, Frischknecht et al. 2007c) is defined as the period required for a renewable energy system to generate the same amount of energy (in terms of non-renewable primary energy equivalent) that was used to produce the system itself. It considers non-renewable energy sources such as hard coal, lignite, crude oil, natural gas and uranium. The NREPBT is calculated using the following formula:

$$NREPBT = \frac{E_{mat} + E_{manuf} + E_{trans} + E_{inst} + E_{EOL}}{\frac{E_{agen}}{\eta_G} - E_{O\&M}}$$

E_{mat}: Non renewable primary energy demand to produce materials comprising PV system

E_{manuf}: Non renewable primary energy demand to manufacture PV system

E_{trans}: Non renewable primary energy demand to transport materials used during the life cycle

E_{inst}: Non renewable primary energy demand to install the system

E_{EOL}: Non renewable primary energy demand for end-of-life management

E_{agen}: Annual electricity generation

$E_{O\&M}$: Annual Non renewable primary energy demand for operation and maintenance

η_G: Grid efficiency, average non renewable primary energy to electricity conversion efficiency at the demand side

2.10 Total Energy Payback Time (EPBT)

The total energy payback time (Fthenakis et al. 2011) is defined as the period required for a renewable energy system to generate the same amount of energy (in terms of total primary energy equivalent) that was used to produce the system itself. It considers all non renewable and renewable energy sources, except for the direct solar radiation input during the operation phase, which is not accounted for as part of $E_{O\&M}$. The EPBT is calculated using the following formula:

$$EPBT = \frac{E_{mat} + E_{manuf} + E_{trans} + E_{inst} + E_{EOL}}{\frac{E_{agen}}{\eta_G} - E_{O\&M}}$$

E_{mat}: Total primary energy demand to produce materials comprising PV system

E_{manuf}: Total primary energy demand to manufacture PV system

E_{trans}: Total primary energy demand to transport materials used during the life cycle

E_{inst}: Total primary energy demand to install the system

E_{EOL}: Total primary energy demand for end-of-life management

E_{agen}: Annual electricity generation

$E_{O\&M}$: Annual total primary energy demand for operation and maintenance, excluding direct solar radiation input

η_G: Grid efficiency, average total primary energy to electricity conversion efficiency at the demand side

3 Technologies Analysed and Key Parameters Varied

3.1 Overview

The PV technologies analysed in this project are described in Section 3.2. In Section 3.3, the key parameters varied over time are introduced, and scenario-dependent values are presented and substantiated.

3.2 Photovoltaic Technologies Analysed

This future analysis focuses on two PV technologies: unframed single-crystalline silicon-based PV laminate and unframed CdTe PV laminate. The use of framed PV panels mounted on roofs is not part of the analysis; only installation as unframed laminate integrated in the building is analysed for both technologies.

Single-crystalline (single-Si) silicon-based PV modules cover more than 40 % of the annual global production of PV power plants (kWp) in 2012, based on FHI-ISE (2013)[5], and they are selected for analysis here because of their high share in the PV electricity production mix.

Cadmium-telluride PV modules are selected as a comparably inexpensive and emerging technology in the PV market with a considerable annual global production of PV power plants (kWp) in 2012 (6.3 %, according to FHI-ISE (2013)[5]).

3.3 Key Parameters

3.3.1 Overview

Several key parameters determine the environmental performance of electricity produced with PV modules. Future projections of these key parameters of the different PV technologies are made for each of the three scenarios. The key parameters, which are part of the future scenario analysis in this study, are listed in Tab. 3.1. The definition of each key parameter is described in detail in Sections 3.3.2 to 3.3.9.

Balance of system components such as inverters or mounting structures were not subject to future forecasts. Hence, the material and environmental efficiency of these components is assumed to remain constant and reflects the current situation in all three scenarios.

---

[5] FHI-ISE (2013) cites the data originally published by Navigant Consulting (2012).

Tab. 3.1 Key parameters of silicon-based single-crystalline and CdTe photovoltaic cells and modules.

Parameter	Single-Si	CdTe	Comment	Section
Cell efficiency	yes	yes	Describes the efficiency of the solar cells	3.3.2
Derate cell to module efficiency	yes	yes	Describes the efficiency loss between cells and modules	3.3.3
Module efficiency	yes	yes	Describes the efficiency of the PV module	3.3.4
Wafer thickness / layer thickness	yes	yes	Describes the thickness of the silicon wafer and the CdTe layer, respectively	3.3.5
Electricity demand	no	yes	Describes the electricity demand during the manufacture of CdTe PV laminate	3.3.6
Kerf loss	yes	no	Describes the kerfing losses during single-Si wafer sawing	3.3.7
Silver per cell	yes	no	Describes the amount of silver used for electric contacts in a single-Si cell	3.3.8
Fluidized-bed reactor (FBR) Share of Poly Si Production	yes	no	Describes the share of the most efficient production technology for polysilicon (silicon feedstock): fluidized-bed reactor	3.3.9
Glass thickness	yes	yes	Describes the thickness of the solar glass used on the back and the front side of the solar cell	3.3.10
Operational lifetime	yes	yes	Describes the lifetime of the PV modules	3.3.11

The LCI data of all the modelled technologies and processes are available at www.treeze.ch. The LCI data can be downloaded and adjusted to model alternative future projections of certain parameters such as efficiency and lifetime.

3.3.2 Cell Efficiency

Tab. 3.2 shows the future projections of the single-Si and CdTe cell efficiencies used in the three scenarios. Each scenario shows a considerable increase in cell efficiency compared to the current average efficiency of single-Si PV cells (16.5 %, de Wild-Scholten 2013) and CdTe PV cells (15.6 %, module efficiency according to First Solar 2014) and own calculations using derate cell to module efficiency according to Garabedian (2013).

The calculated maximum efficiency for silicon-based crystalline PV cells is 33 %, according to the Shockley-Queisser limit (Shockley & Queisser 1961). This efficiency is 4 % higher than the efficiency of 29 % used in the scenario OPT. According to Swanson (2005) 29 % is the maximum efficiency, which can be achieved, due to practical reasons.

The calculated maximum efficiency for CdTe PV cells according to Garabedian (2013) is 30 %. The maximum practical efficiency is derived analogously as for silicon-based single-crystalline PV cells (maximum theoretical efficiency minus 4 %) and corresponds to 26 %.

Tab. 3.2 Scenario-dependent cell efficiency of single-Si and CdTe PV cells.

Cell Efficiency	Single-Si	Source	CdTe	Source
Unit	Percent		Percent	
Current LCI	16.5%	de Wild-Scholten 2013, Photon International 2013	15.6%	calculated based on module efficiency and cell to module derate
BAU	25.0%	Goodrich et al. 2013	22.8%	Garabedian 2014, mid term target
REAL	27.0%	interpolated	24.4%	interpolated
OPT	29.0%	Swanson 2005	26.0%	Garabedian 2013, max efficiency minus 4%
Theoretical maximum	33.0%	Shockley-Queisser	30.0%	Garabedian 2013

3.3.3 Derate from Cell to Module Efficiency

Tab. 3.3 shows the derate of the efficiency from cell to module of single-Si and CdTe PV modules used in the three scenarios. The derate of the current CdTe PV modules (13.9 %) is higher than the derate of the single-Si PV modules (8.5 %). Due to technological improvements, derates comparable to the single-Si PV modules are expected for the CdTe PV modules. Thus, the future derate varies between 5 % and 10 %, as reported by Goodrich et al. (2013) for single-Si. A derate of 5 % is assumed in the scenario OPT. Derates of 8.5 % and 10 % are used in the BAU scenario for single-Si and CdTe modules, respectively. For the scenario REAL, the average between the derates of the OPT and BAU scenarios is used.

Tab. 3.3 Scenario-dependent derate of the efficiency from cell to module of single-Si and CdTe PV modules.

Derate Cell to Module Efficiency	Single-Si	Source	CdTe	Source
Unit	Percent		Percent	
Current LCI	8.5%	calculated based on de Wild-Scholten 2013, Photon International 2013	13.9%	calculated based on Garabedian 2014
BAU	8.5%	based on current LCI	10.0%	Goodrich et al. 2013
REAL	6.8%	interpolated	7.5%	interpolated
OPT	5.0%	Goodrich et al. 2013	5.0%	Goodrich et al. 2013

3.3.4 Module Efficiency

Tab. 3.4 shows the scenario-dependent module efficiency of single-Si and CdTe PV modules. The future module efficiencies are calculated based on the future cell efficiencies (see Tab. 3.2) and the future cell-to-module derates (see Tab. 3.3).

Each scenario shows a considerable increase in the module efficiency compared to the current average efficiency of single-Si (15.1 %) and CdTe (13.4 %) PV modules.

Tab. 3.4 Scenario-dependent module efficiency of single-Si and CdTe PV modules.

Module Efficiency	Single-Si	Source	CdTe	Source
Unit	Percent		Percent	
Current LCI	15.1%	de Wild-Scholten 2013, Photon International 2013	13.4%	First Solar 2014
BAU	22.9%	calculated based on cell efficiency, derate 8.5%	20.5%	calculated based on cell efficiency, derate 10%
REAL	25.2%	calculated based on cell efficiency, derate 6.8%	22.6%	calculated based on cell efficiency, derate 7.5%
OPT	27.6%	calculated based on cell efficiency, derate 5%	24.7%	calculated based on cell efficiency, derate 5%
Shockley-Queisser	31.4%	calculated based on cell efficiency, derate 5%		

Fig. 3.1 shows the development of the module efficiency of silicon-based single-crystalline cells between 2000 and 2012, according to de Wild-Scholten (2013) and Photon International (2013), with linear extrapolation until 2050. Both the scenario-dependent module efficiencies of the single-Si technology and the Shockley-Queisser limit (33 % cell efficiency) at a derate of 5 % (dashed line) are also shown. Fig. 3.1 also shows that the expected module efficiency in the scenario OPT would require a slightly higher annual increase in efficiency as compared to the past 12 years, whereas the expected efficiency in the scenarios BAU and REAL reflect a decrease in annual efficiency improvements. The most optimistic module efficiency is about 4 % below the technical maximum given by the Shockley-Queisser limit.

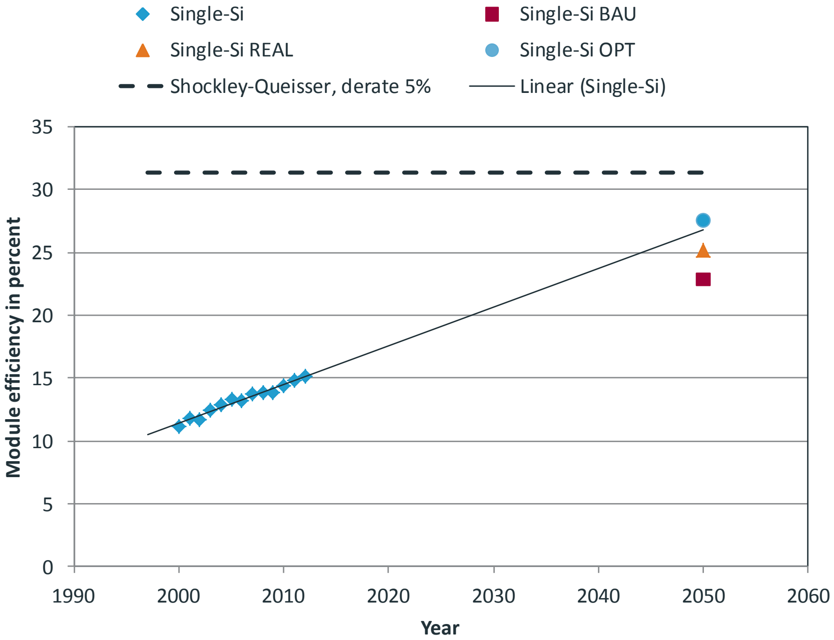


Fig. 3.1 Development of the module efficiency of silicon-based single-crystalline cells between 2000 and 2012 according to de Wild-Scholten (2013) and Photon International (2013) with linear extrapolation to the year 2050 and selected module efficiencies of the three scenarios BAU, REAL & OPT and the Shockley-Queisser limit (33 % cell efficiency) at a derate of 5 %.

3.3.5 Wafer / Layer Thickness

Tab. 3.5 shows the silicon wafer thickness of single-Si modules and CdTe layer thickness of CdTe PV modules. The wafer thickness and the thickness of the CdTe layer influence the silicon demand of the single-Si modules and the CdTe demand of CdTe modules.

The reduction in the wafer thickness of single-Si modules is based on future projections by the International Technology Roadmap for Photovoltaic (ITRPV 2013). The roadmap projects wafter thicknesses between 100 and 120 µm for the PV cells; these values are used in the scenarios REAL (120 µm) and OPT (100 µm). In the BAU scenario, a reduction of the wafer thickness to 150 µm is assumed, based on author expert judgment.

The reduction in the layer thickness of CdTe modules are based on future projections shown in Marwede & Reller (2012) and Woodhouse et al. (2013). The future projections of Marwede & Reller (2012) and Woodhouse et al. (2013) have different time references (2040 and 2030, respectively). However, the future projections are considered comparable because they are both long-term projections (i.e., more than 15 years).

The utilisation rate of CdTe per µm of the cell layer is assumed as constant. The amount of CdTe used in the production of the PV laminate is of only minor importance (compared to the energy use).

Tab. 3.5 Scenario-dependent silicon wafer and CdTe layer thickness of single-Si and CdTe PV modules.

Wafer thickness / layer thickness	Single-Si	Source	CdTe	Source
Unit	micrometer		micrometer	
Current LCI	190	Jungbluth et al. 2012	4.0	Jungbluth et al. 2012
BAU	150	Expert judgment	2.0	Marwede & Reller 2012 Woodhouse et al. 2013
REAL	120	ITRPV 2013 (upper range)	1.0	Marwede & Reller 2012 Woodhouse et al. 2013
OPT	100	ITRPV 2013 (lower range)	0.1	Marwede & Reller 2012 Woodhouse et al. 2013

3.3.6 Electricity Demand in CdTe Laminate Manufacture

Tab. 3.6 shows the electricity demand during the manufacturing of CdTe laminate relative to current demand. The reduction of the electricity demand was derived using the following assumptions[6] (the three effects are additive):

- 10 % overall reduction of the electricity demand (manufacturing efficiency gains)
- 4 % reduced electricity demand per 0.7 mm of reduced glass thickness
- 2 % reduced electricity demand per 1 µm of reduced CdTe layer

The electricity demand during the manufacturing of single-Si laminate remains unchanged, but the electricity demand of the global production of the raw materials (solar-grade silicon, fluidized-bed-reactor (FBR)) is reduced.

The electricity demand of the single-crystalline-silicon global production remains unchanged because no future projections of the energy demand have been available.

---

[6] Personal communication: Parikhit Sinha, First Solar, 08.01.2014

Tab. 3.6 Scenario-dependent electricity demand during the manufacturing of CdTe laminate, relative to today's electricity demand.

Electricity Demand	CdTe	Source
Unit	%	
Current LCI	100%	Jungbluth et al. 2012
BAU	86%	pers. Communication Parikhit Sinha, First Solar, 08.01.2014[6]
REAL	81%	pers. Communication Parikhit Sinha, First Solar, 08.01.2014[6]
OPT	74%	pers. Communication Parikhit Sinha, First Solar, 08.01.2014[6]

3.3.7 Kerf Loss

Tab. 3.7 shows the kerf loss (i.e., the loss of silicon due to slicing of multi- or single-crystalline silicon) of single-Si modules used in the three scenarios. The kerf loss is assumed to correspond to the wafer thickness shown in Tab. 3.5; hence, the thinner the wafer, the less the kerf loss. For a detailed description of the selected values, see Section 3.3.5.

Tab. 3.7 Scenario-dependent kerf loss of single-Si modules.

Kerf Loss	Single-Si	Source
Unit	micrometer	
Current LCI	190	Jungbluth et al. 2012
BAU	150	Expert judgment
REAL	120	ITRPV 2013 (upper range)
OPT	100	ITRPV 2013 (lower range)

3.3.8 Silver Contacts

Tab. 3.8 shows the scenario-dependent amount of silver used per cell of single-Si module. The silver is used for electrical contacts on the cells. Silver can be replaced with less-expensive copper. This replacement is taken into account in the LCIs by increasing the amount of copper used in the projection scenarios.

Tab. 3.8 Amount of silver per cell of single-Si module used in the three scenarios.

Silver per Cell	Single-Si	Source
Unit	g / m^2	
Current LCI	9.6	Jungbluth et al. 2012
BAU	9.6	unchanged
REAL	5.0	interpolated
OPT	2.0	ITRPV 2013

3.3.9 Fluidised Bed Reactor (FBR) Share in Polysilicon Production

Tab. 3.9 shows the share of FBR polysilicon global production in the silicon supply of single-Si modules used in the three scenarios. FBR polysilicon production is more energy efficient than traditional processes and therefore helps reduce environmental impacts in the silicon supply chain. A share of 100 % FBR is assumed in the scenario OPT.

Tab. 3.9 Scenario-dependent share of FBR polysilicon global production in the silicon supply of single-Si modules.

FBR Share of Poly Si Production	Single-Si	Source
Unit	percent	
Current LCI	100% Siemens	Jungbluth et al. 2012
BAU	20% FBR / 80% Siemens	expert judgement
REAL	40% FBR / 60% Siemens	ITRPV 2013
OPT	100% FBR	expert judgement

3.3.10 Glass Thickness

Tab. 3.10 shows the scenario-dependent thickness of the solar glass of single-Si and CdTe modules. The glass used in CdTe modules is slightly thinner than the one used in single-Si modules. For the future, a thickness of 2 mm is assumed for both technologies, as there are no major differences regarding the module construction that would justify different glass thicknesses.

Tab. 3.10 Scenario-dependent thickness of the solar glass of single-Si and CdTe modules used in the three scenarios. (The values in brackets indicate the thickness of the additional glass layer which is needed in case of frameless modules with glass-glass structure[7]. Such a scenario could be evaluated in future assessments of single-Si PV; it represents current technology of CdTe PV.)

Glass thickness	Single-Si	Source	CdTe	Source
Unit	mm		mm	
Current LCI	4.0 (+4.0)	de Wild-Scholten & Alsema 2007, Jungbluth et al. 2012	3.5 (+3.5)	Jungbluth et al. 2012, First Solar 2011
BAU	4.0 (+4.0)	unchanged	3.5 (+3.5)	unchanged
REAL	3.0 (+3.0)	interpolated	3.0 (+3.0)	interpolated
OPT	2.0 (+2.0)	ITRPV 2013	2.0(+2.0)	ITRPV 2013

3.3.11 Operational Lifetime

Tab. 3.11 shows the scenario-dependent operational lifetime of single-Si and CdTe modules. According to IEA (2010), an increase from 30 years to 40 years in the operational lifetime of the PV modules can be expected (scenario OPT). However, in the scenario BAU, an unchanged lifetime of 30 years is assumed. The lifetime used in the scenario REAL is interpolated between these two values.

Tab. 3.11 Operational lifetime of single-Si and CdTe modules used in the three scenarios.

Operational lifetime	Single-Si	Source	CdTe	Source
Unit	years		years	
Current LCI	30	Jungbluth et al. 2012	30	Jungbluth et al. 2012
BAU	30	current value	30	current value
REAL	35	interpolated	35	interpolated
OPT	40	IEA 2010	40	IEA 2010

---

[7] Personal communication: Andreas Wade, First Solar, 12.12.2013

4 Life Cycle Inventories in the PV Supply Chains

4.1 Overview

The data used in this analysis are based on the inventories of the PV supply chain described in Itten et al. (2014, Part I). The key parameters are adjusted in the scenarios according to the description in Section2.10. For sake of readability, only unit process raw data of the adjusted processes in the PV supply chain are described in this report; data sets of processes that remained unchanged can be found in Itten et al. (2014).

In Section 4.3, the unit process data of the newly introduced production technology for solar-grade silicon (fluidized bed reactor, FBR) are shown. In Section 4.4, the adjusted unit process data of the metallization paste (reduced use of silver) are shown. Section 4.5 documents the adjusted PV electricity production mixes, and Section 4.6 shows the non-renewable residual electricity mixes, which are used to calculate the NREPBT.

4.2 How to Read an EcoSpold Table

The Ecospold tables are the tables presented in the following Subchapters and in Chapter 5 describing the life cycle inventory datasets developed within this project.

How to read the tables.

The **light green fields** describe the name of the product/process, its region (e.g. RER stands for Europe) and the unit data it refers to. It is the output product (the reference output) of the process and always equal to '1'. The **yellow fields** show the inputs and outputs of the respective processes. The **grey fields** specify whether it is an input from or an output to nature or technosphere and the compartment to which a pollutant is emitted. For each product, additional descriptive information is given in separate tables.

The location codes (an extended ISO alpha-2 code-set) have the following meaning:

Regions:		Countries:			
APAC	Asia Pacific	*AU*	Australia	*JP*	Japan
ENTSO	European electricity network	*CH*	Switzerland	*KR*	South Korea
GLO	Global	*CN*	China	*NO*	Norway
OCE	Oceanic	*DE*	Germany	*NZ*	New Zealand
RER	Europe	*ES*	Spain	*US*	United States of America

4.3 Solar-grade Silicon Production Using FBR

Tab. 4.1 shows the unit process data of solar-grade silicon production using fluidised bed reactors (FBR) in Europe (RER), China (CN), North America (represented by US) and Asia & Pacific (APAC). The inventory is based on the solar-grade silicon production as described by Jungbluth et al. (2012).

The electricity consumption of the FBR deposition process is significantly lower than that of the Siemens process. de Wild-Scholten & Alsema (2005) estimate that the electricity consumption is about 30 kWh/kg, but no information is provided regarding possible other energy sources or working materials.

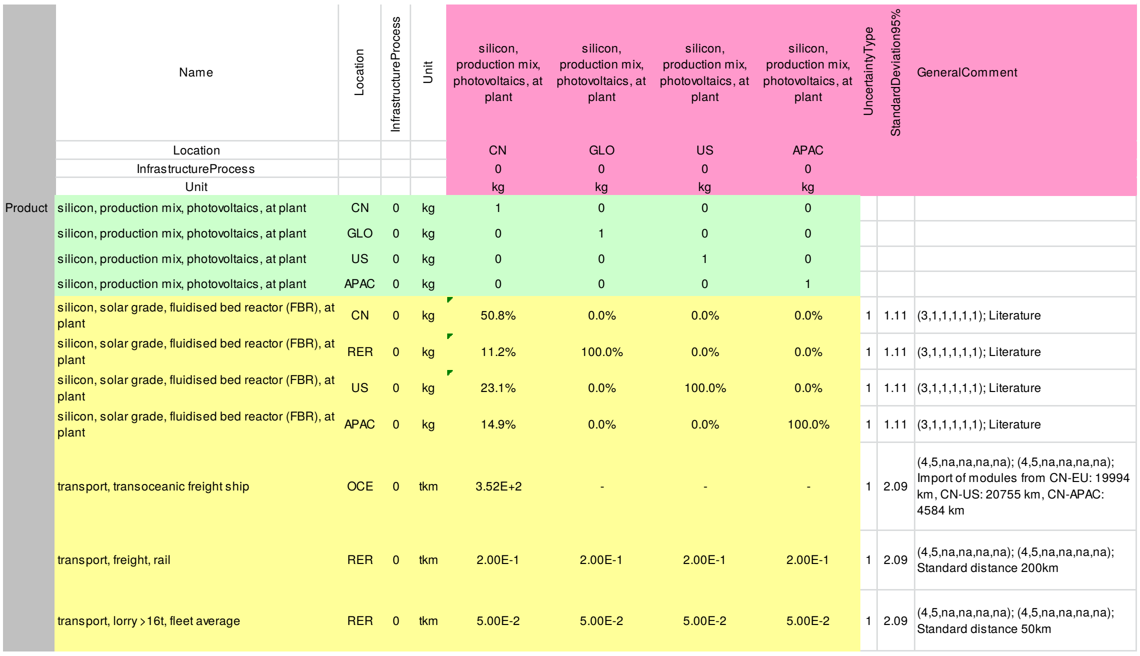
To approximate the new FBR technology, the electricity demand reported in the unit process data set of the Siemens process is reduced to 30 kWh/kg. All other material uses and emissions remain unchanged, as no detailed LCI data are available. This LCA could be updated after a complete LCI for the FBR process becomes available.

Tab. 4.2 shows the silicon production mixes for PV in the four different regions distinguished in this analysis. The share of the new FBR technology in supplying solar-grade silicon is varied between the scenarios as shown in Tab. 3.9. Tab. 4.2 shows the silicon production mixes for the scenario OPT with a share of 100 % FBR technology.

Tab. 4.1 Unit process data of solar-grade silicon production using fluidised bed reactors (FBR) in Europe (RER), China (CN), North America (US) and Asia & Pacific (APAC).

	Name	Location	InfrastructureProcess	Unit	silicon, solar grade, fluidised bed reactor (FBR), at plant	silicon, solar grade, fluidised bed reactor (FBR), at plant	silicon, solar grade, fluidised bed reactor (FBR), at plant	silicon, solar grade, fluidised bed reactor (FBR), at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER	CN	US	APAC			
	InfrastructureProcess				0	0	0	0			
	Unit				kg	kg	kg	kg			
product	silicon, solar grade, fluidised bed reactor (FBR), at plant	RER	0	kg	1	0	0	0			
	silicon, solar grade, fluidised bed reactor (FBR), at plant	CN	0	kg	0	1	0	0			
	silicon, solar grade, fluidised bed reactor (FBR), at plant	US	0	kg	0	0	1	0			
	silicon, solar grade, fluidised bed reactor (FBR), at plant	APAC	0	kg	0	0	0	1			
technosphere	MG-silicon, at plant	NO	0	kg	1.13E+0	0	0	0	1	1.10	(2,3,1,2,1,3); Literature
	MG-silicon, at plant	CN	0	kg	0	1.13E+0	0	0	1	1.10	(2,3,1,2,1,3); Literature
	MG-silicon, at plant	US	0	kg	0	0	1.13E+0	0	1	1.10	(2,3,1,2,1,3); Literature
	MG-silicon, at plant	APAC	0	kg	0	0	0	1.13E+0	1	1.10	(2,3,1,2,1,3); Literature
	hydrochloric acid, 30% in H2O, at plant	RER	0	kg	1.60E+0	1.60E+0	1.60E+0	1.60E+0	1	1.14	(3,3,1,2,1,3); de Wild 2007, share of NaOH, HCl and H2 estimated with EG-Si data
	hydrogen, liquid, at plant	RER	0	kg	5.01E-2	5.01E-2	5.01E-2	5.01E-2	1	1.14	(3,3,1,2,1,3); de Wild 2007, share of NaOH, HCl and H2 estimated with EG-Si data
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	3.48E-1	3.48E-1	3.48E-1	3.48E-1	1	1.14	(3,3,1,2,1,3); de Wild 2007, share of NaOH, HCl and H2 estimated with EG-Si data
	transport, lorry >16t, fleet average	RER	0	tkm	2.66E+0	2.66E+0	2.66E+0	2.66E+0	1	2.09	(4,5,na,na,na,na); Distance 2000km plus 100 km for chemicals
	transport, freight, rail	RER	0	tkm	2.40E+0	2.40E+0	2.40E+0	2.40E+0	1	2.09	(4,5,na,na,na,na); 600km for chemicals including solvent
	transport, transoceanic freight ship	OCE	0	tkm	5.30E+0	0	0	0	1	2.06	(2,3,2,2,3,2); Transport of REC silicon from US to European market
	electricity, at cogen 1MWe lean burn, allocation exergy	RER	0	kWh	9.78E+0	0	0	0	1	1.10	(2,3,1,2,1,3); on-site plant of Wacker in Germany
	electricity, hydropower, at run-of-river power plant	RER	0	kWh	1.68E+1	0	0	0	1	1.10	(2,3,1,2,1,3); production of REC and of Wacker's hydropower plant
	electricity, medium voltage, at grid	NO	0	kWh	3.40E+0	0	0	0	1	1.10	(2,3,1,2,1,3); de Wild-Scholten & Alsema 2005, Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic Module Production
	electricity, medium voltage, at grid	CN	0	kWh	0	3.00E+1	0	0	1	1.10	(2,3,1,2,1,3); de Wild-Scholten & Alsema 2005, Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic Module Production
	electricity, medium voltage, at grid	US	0	kWh	0	0	3.00E+1	0	1	1.10	(2,3,1,2,1,3); de Wild-Scholten & Alsema 2005, Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic Module Production
	electricity, medium voltage, at grid	KR	0	kWh	0	0	0	3.00E+1	1	1.10	(2,3,1,2,1,3); de Wild-Scholten & Alsema 2005, Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic Module Production
	heat, at cogen 1MWe lean burn, allocation exergy	RER	0	MJ	1.85E+2	1.85E+2	1.85E+2	1.85E+2	1	1.10	(2,3,1,2,1,3); literature, for process heat
	silicone plant	RER	1	unit	1.00E-11	1.00E-11	1.00E-11	1.00E-11	1	3.05	(1,3,1,2,3,3); Estimation
emission air	Heat, waste	-	-	MJ	9.58E+1	9.58E+1	9.58E+1	9.58E+1	1	1.10	(2,3,1,2,1,3); Calculation
emission water, river	AOX, Adsorbable Organic Halogen as Cl	-	-	kg	1.26E-5	1.26E-5	1.26E-5	1.26E-5	1	1.56	(1,2,1,1,3,3); Environmental report 2002, average Si product
	BOD5, Biological Oxygen Demand	-	-	kg	2.05E-4	2.05E-4	2.05E-4	2.05E-4	1	1.56	(1,2,1,1,3,3); Environmental report 2002, average Si product
	COD, Chemical Oxygen Demand	-	-	kg	2.02E-3	2.02E-3	2.02E-3	2.02E-3	1	1.56	(1,2,1,1,3,3); Environmental report 2002, average Si product
	Chloride	-	-	kg	3.60E-2	3.60E-2	3.60E-2	3.60E-2	1	3.05	(1,2,1,1,3,3); Environmental report 2002, average Si product
	Copper, ion	-	-	kg	1.02E-7	1.02E-7	1.02E-7	1.02E-7	1	5.06	(1,2,1,1,3,3); Environmental report 2002, average Si product
	Nitrogen	-	-	kg	2.08E-4	2.08E-4	2.08E-4	2.08E-4	1	1.56	(1,2,1,1,3,3); Environmental report 2002, average Si product
	Phosphate	-	-	kg	2.80E-6	2.80E-6	2.80E-6	2.80E-6	1	1.56	(1,2,1,1,3,3); Environmental report 2002, average Si product
	Sodium, ion	-	-	kg	3.38E-2	3.38E-2	3.38E-2	3.38E-2	1	1.56	(1,2,1,1,3,3); Environmental report 2002, average Si product
	Zinc, ion	-	-	kg	1.96E-6	1.96E-6	1.96E-6	1.96E-6	1	5.06	(1,2,1,1,3,3); Environmental report 2002, average Si product
	Iron, ion	-	-	kg	5.61E-6	5.61E-6	5.61E-6	5.61E-6	1	5.06	(1,2,1,1,3,3); Environmental report 2002, average Si product
	DOC, Dissolved Organic Carbon	-	-	kg	9.10E-4	9.10E-4	9.10E-4	9.10E-4	1	5.06	(1,2,1,1,3,3); Environmental report 2002, average Si product
	TOC, Total Organic Carbon	-	-	kg	9.10E-4	9.10E-4	9.10E-4	9.10E-4	1	1.56	(1,2,1,1,3,3); Environmental report 2002, average Si product

Tab. 4.2 Solar-grade silicon production mixes supplied to the four world regions in the scenario OPT

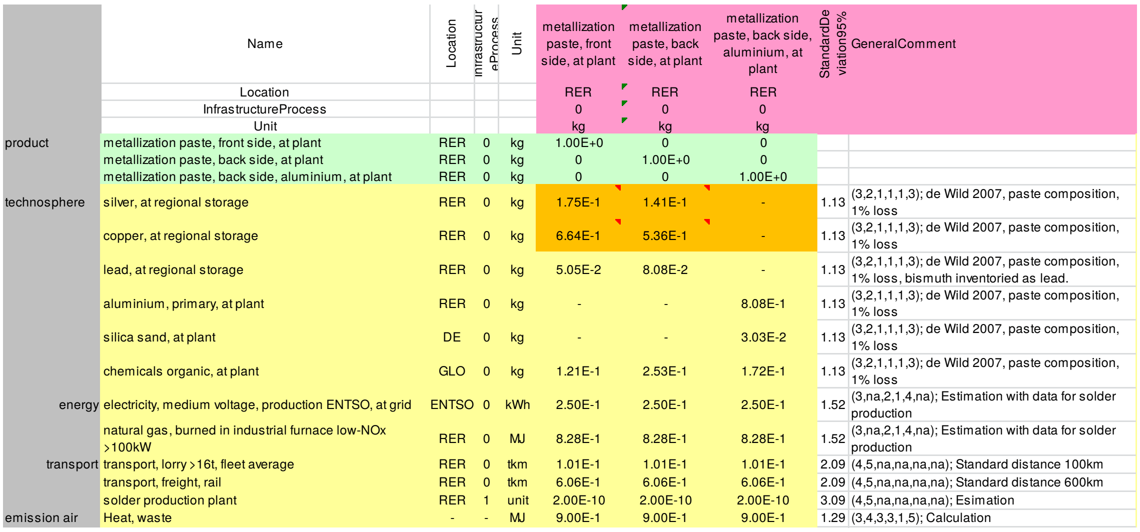


	Name	Location	InfrastructureProcess	Unit	silicon, production mix, photovoltaics, at plant	silicon, production mix, photovoltaics, at plant	silicon, production mix, photovoltaics, at plant	silicon, production mix, photovoltaics, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CN	GLO	US	APAC			
	InfrastructureProcess				0	0	0	0			
	Unit				kg	kg	kg	kg			
Product	silicon, production mix, photovoltaics, at plant	CN	0	kg	1	0	0	0			
	silicon, production mix, photovoltaics, at plant	GLO	0	kg	0	1	0	0			
	silicon, production mix, photovoltaics, at plant	US	0	kg	0	0	1	0			
	silicon, production mix, photovoltaics, at plant	APAC	0	kg	0	0	0	1			
	silicon, solar grade, fluidised bed reactor (FBR), at plant	CN	0	kg	50.8%	0.0%	0.0%	0.0%	1	1.11	(3,1,1,1,1,1); Literature
	silicon, solar grade, fluidised bed reactor (FBR), at plant	RER	0	kg	11.2%	100.0%	0.0%	0.0%	1	1.11	(3,1,1,1,1,1); Literature
	silicon, solar grade, fluidised bed reactor (FBR), at plant	US	0	kg	23.1%	0.0%	100.0%	0.0%	1	1.11	(3,1,1,1,1,1); Literature
	silicon, solar grade, fluidised bed reactor (FBR), at plant	APAC	0	kg	14.9%	0.0%	0.0%	100.0%	1	1.11	(3,1,1,1,1,1); Literature
	transport, transoceanic freight ship	OCE	0	tkm	3.52E+2	-	-	-	1	2.09	(4,5,na,na,na,na); (4,5,na,na,na,na); Import of modules from CN-EU: 19994 km, CN-US: 20755 km, CN-APAC: 4584 km
	transport, freight, rail	RER	0	tkm	2.00E-1	2.00E-1	2.00E-1	2.00E-1	1	2.09	(4,5,na,na,na,na); (4,5,na,na,na,na); Standard distance 200km
	transport, lorry >16t, fleet average	RER	0	tkm	5.00E-2	5.00E-2	5.00E-2	5.00E-2	1	2.09	(4,5,na,na,na,na); (4,5,na,na,na,na); Standard distance 50km

4.4 Metallization Paste

Tab. 4.3 shows the unit process data of the metallization paste. The unit process data of the metallization paste is adjusted to reduce the use of silver. In the future scenarios, the silver used for the metallization paste is replaced by copper due to cost reasons.

Tab. 4.3 Unit process data of the metallization paste (adjusted use of silver)

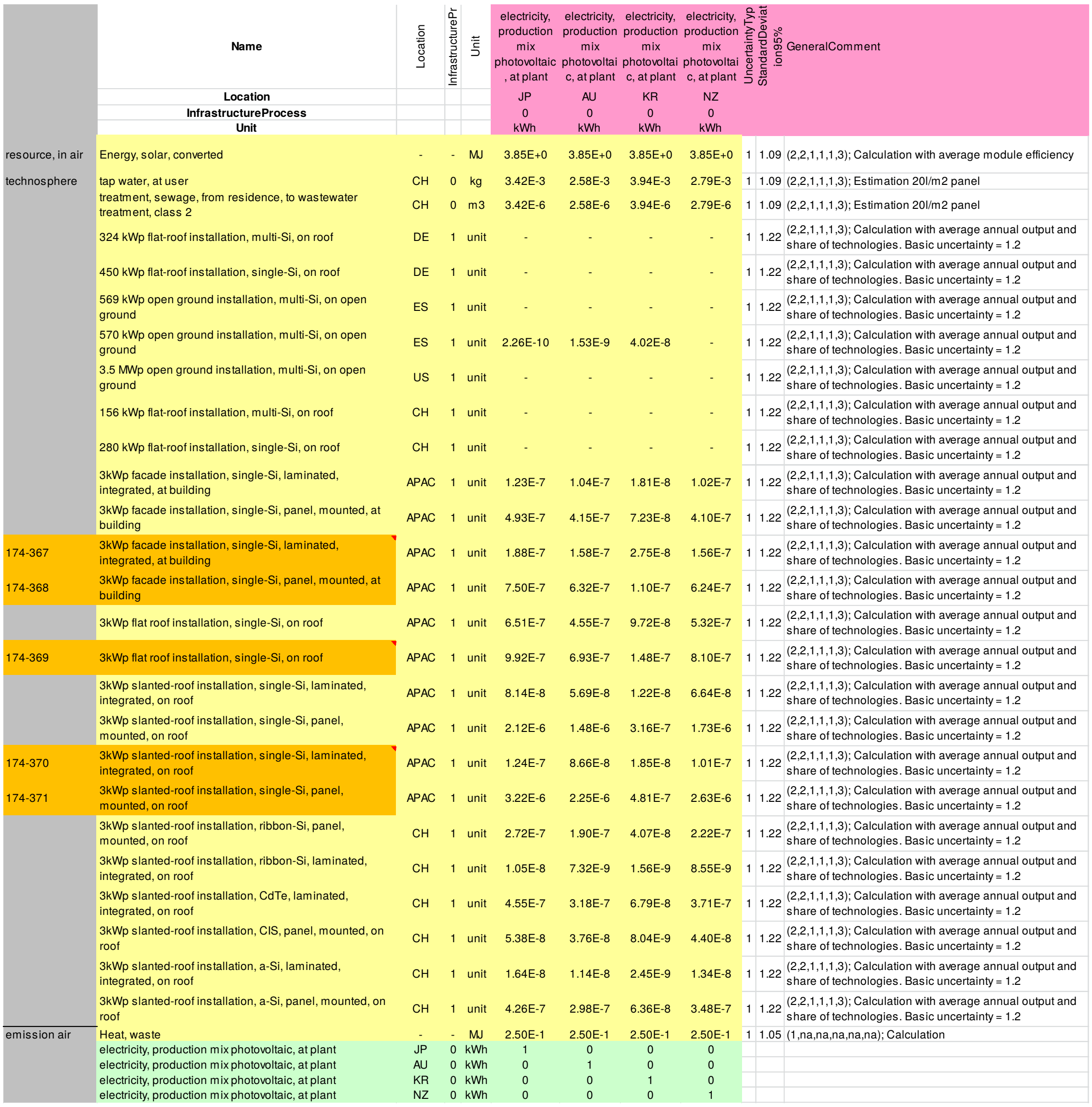


	Name	Location	InfrastructureProcess	Unit	metallization paste, front side, at plant	metallization paste, back side, at plant	metallization paste, back side, aluminium, at plant	StandardDeviation95%	GeneralComment
	Location				RER	RER	RER		
	InfrastructureProcess				0	0	0		
	Unit				kg	kg	kg		
product	metallization paste, front side, at plant	RER	0	kg	1.00E+0	0	0		
	metallization paste, back side, at plant	RER	0	kg	0	1.00E+0	0		
	metallization paste, back side, aluminium, at plant	RER	0	kg	0	0	1.00E+0		
technosphere	silver, at regional storage	RER	0	kg	1.75E-1	1.41E-1	-	1.13	(3,2,1,1,1,3); de Wild 2007, paste composition, 1% loss
	copper, at regional storage	RER	0	kg	6.64E-1	5.36E-1	-	1.13	(3,2,1,1,1,3); de Wild 2007, paste composition, 1% loss
	lead, at regional storage	RER	0	kg	5.05E-2	8.08E-2	-	1.13	(3,2,1,1,1,3); de Wild 2007, paste composition, 1% loss, bismuth inventoried as lead.
	aluminium, primary, at plant	RER	0	kg	-	-	8.08E-1	1.13	(3,2,1,1,1,3); de Wild 2007, paste composition, 1% loss
	silica sand, at plant	DE	0	kg	-	-	3.03E-2	1.13	(3,2,1,1,1,3); de Wild 2007, paste composition, 1% loss
	chemicals organic, at plant	GLO	0	kg	1.21E-1	2.53E-1	1.72E-1	1.13	(3,2,1,1,1,3); de Wild 2007, paste composition, 1% loss
energy	electricity, medium voltage, production ENTSO, at grid	ENTSO	0	kWh	2.50E-1	2.50E-1	2.50E-1	1.52	(3,na,2,1,4,na); Estimation with data for solder production
	natural gas, burned in industrial furnace low-NOx >100kW	RER	0	MJ	8.28E-1	8.28E-1	8.28E-1	1.52	(3,na,2,1,4,na); Estimation with data for solder production
transport	transport, lorry >16t, fleet average	RER	0	tkm	1.01E-1	1.01E-1	1.01E-1	2.09	(4,5,na,na,na,na); Standard distance 100km
	transport, freight, rail	RER	0	tkm	6.06E-1	6.06E-1	6.06E-1	2.09	(4,5,na,na,na,na); Standard distance 600km
	solder production plant	RER	1	unit	2.00E-10	2.00E-10	2.00E-10	3.09	(4,5,na,na,na,na); Esimation
emission air	Heat, waste	-	-	MJ	9.00E-1	9.00E-1	9.00E-1	1.29	(3,4,3,3,1,5); Calculation

4.5 Photovoltaic Electricity Production Mixes

Tab. 4.4 shows unit process data of the PV electricity production mixes in different countries of the APAC region. The technology shares of the multi-crystalline silicon-based PV technologies have been replaced with the corresponding counterparts of the single-crystalline technology. The multi-crystalline technologies have been replaced because they are not part of the future analysis and do not improve in the future scenarios. The single-crystalline technology is used as proxy for multi crystalline technology because similar improvements (for single- and multi-crystalline technology) are expected. This approach was used for all four world regions.

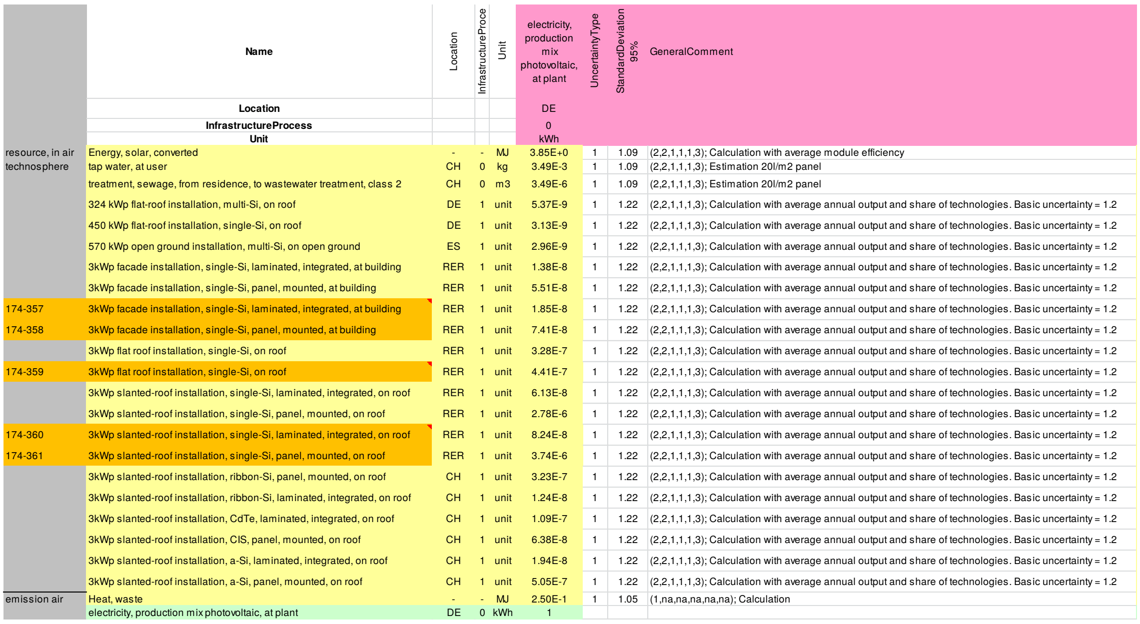
Tab. 4.4 Unit process data of the photovoltaic electricity production mixes in different countries of the region Asia & Pacific



	Name	Location	InfrastructureProcess	Unit	electricity, production mix photovoltaic, at plant	electricity, production mix photovoltaic, at plant	electricity, production mix photovoltaic, at plant	electricity, production mix photovoltaic, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				JP	AU	KR	NZ			
	InfrastructureProcess				0	0	0	0			
	Unit				kWh	kWh	kWh	kWh			
resource, in air	Energy, solar, converted	-	-	MJ	3.85E+0	3.85E+0	3.85E+0	3.85E+0	1	1.09	(2,2,1,1,1,3); Calculation with average module efficiency
technosphere	tap water, at user	CH	0	kg	3.42E-3	2.58E-3	3.94E-3	2.79E-3	1	1.09	(2,2,1,1,1,3); Estimation 20l/m2 panel
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	3.42E-6	2.58E-6	3.94E-6	2.79E-6	1	1.09	(2,2,1,1,1,3); Estimation 20l/m2 panel
	324 kWp flat-roof installation, multi-Si, on roof	DE	1	unit	-	-	-	-	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	450 kWp flat-roof installation, single-Si, on roof	DE	1	unit	-	-	-	-	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	569 kWp open ground installation, multi-Si, on open ground	ES	1	unit	-	-	-	-	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	570 kWp open ground installation, multi-Si, on open ground	ES	1	unit	2.26E-10	1.53E-9	4.02E-8	-	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3.5 MWp open ground installation, multi-Si, on open ground	US	1	unit	-	-	-	-	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	156 kWp flat-roof installation, multi-Si, on roof	CH	1	unit	-	-	-	-	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	280 kWp flat-roof installation, single-Si, on roof	CH	1	unit	-	-	-	-	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp facade installation, single-Si, laminated, integrated, at building	APAC	1	unit	1.23E-7	1.04E-7	1.81E-8	1.02E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp facade installation, single-Si, panel, mounted, at building	APAC	1	unit	4.93E-7	4.15E-7	7.23E-8	4.10E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
174-367	3kWp facade installation, single-Si, laminated, integrated, at building	APAC	1	unit	1.88E-7	1.58E-7	2.75E-8	1.56E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
174-368	3kWp facade installation, single-Si, panel, mounted, at building	APAC	1	unit	7.50E-7	6.32E-7	1.10E-7	6.24E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp flat roof installation, single-Si, on roof	APAC	1	unit	6.51E-7	4.55E-7	9.72E-8	5.32E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
174-369	3kWp flat roof installation, single-Si, on roof	APAC	1	unit	9.92E-7	6.93E-7	1.48E-7	8.10E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, single-Si, laminated, integrated, on roof	APAC	1	unit	8.14E-8	5.69E-8	1.22E-8	6.64E-8	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, single-Si, panel, mounted, on roof	APAC	1	unit	2.12E-6	1.48E-6	3.16E-7	1.73E-6	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
174-370	3kWp slanted-roof installation, single-Si, laminated, integrated, on roof	APAC	1	unit	1.24E-7	8.66E-8	1.85E-8	1.01E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
174-371	3kWp slanted-roof installation, single-Si, panel, mounted, on roof	APAC	1	unit	3.22E-6	2.25E-6	4.81E-7	2.63E-6	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, ribbon-Si, panel, mounted, on roof	CH	1	unit	2.72E-7	1.90E-7	4.07E-8	2.22E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, ribbon-Si, laminated, integrated, on roof	CH	1	unit	1.05E-8	7.32E-9	1.56E-9	8.55E-9	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, CdTe, laminated, integrated, on roof	CH	1	unit	4.55E-7	3.18E-7	6.79E-8	3.71E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, CIS, panel, mounted, on roof	CH	1	unit	5.38E-8	3.76E-8	8.04E-9	4.40E-8	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, a-Si, laminated, integrated, on roof	CH	1	unit	1.64E-8	1.14E-8	2.45E-9	1.34E-8	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, a-Si, panel, mounted, on roof	CH	1	unit	4.26E-7	2.98E-7	6.36E-8	3.48E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
emission air	Heat, waste	-	-	MJ	2.50E-1	2.50E-1	2.50E-1	2.50E-1	1	1.05	(1,na,na,na,na,na); Calculation
	electricity, production mix photovoltaic, at plant	JP	0	kWh	1	0	0	0			
	electricity, production mix photovoltaic, at plant	AU	0	kWh	0	1	0	0			
	electricity, production mix photovoltaic, at plant	KR	0	kWh	0	0	1	0			
	electricity, production mix photovoltaic, at plant	NZ	0	kWh	0	0	0	1			

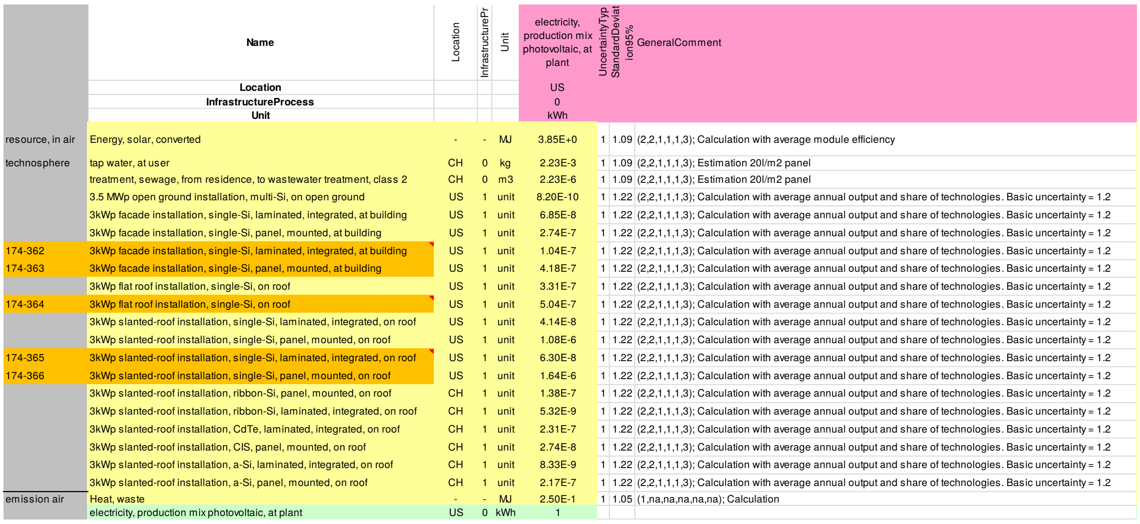
The Chinese PV electricity mix is modelled with the Corean PV electricity mix, as shown in Tab. 4.4. Tab. 4.5 and Tab. 4.6 show the PV electricity mixes from Europe and the US respectively.

Tab. 4.5 Unit process data of the photovoltaic electricity production mix in Europe



	Name	Location	InfrastructureProce	Unit	electricity, production mix photovoltaic, at plant	UncertaintyType	StandardDeviation 95%	GeneralComment
	Location				DE			
	InfrastructureProcess				0			
	Unit				kWh			
resource, in air	Energy, solar, converted	-	-	MJ	3.85E+0	1	1.09	(2,2,1,1,1,3); Calculation with average module efficiency
technosphere	tap water, at user	CH	0	kg	3.49E-3	1	1.09	(2,2,1,1,1,3); Estimation 20l/m2 panel
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	3.49E-6	1	1.09	(2,2,1,1,1,3); Estimation 20l/m2 panel
	324 kWp flat-roof installation, multi-Si, on roof	DE	1	unit	5.37E-9	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	450 kWp flat-roof installation, single-Si, on roof	DE	1	unit	3.13E-9	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	570 kWp open ground installation, multi-Si, on open ground	ES	1	unit	2.96E-9	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp facade installation, single-Si, laminated, integrated, at building	RER	1	unit	1.38E-8	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp facade installation, single-Si, panel, mounted, at building	RER	1	unit	5.51E-8	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
174-357	3kWp facade installation, single-Si, laminated, integrated, at building	RER	1	unit	1.85E-8	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
174-358	3kWp facade installation, single-Si, panel, mounted, at building	RER	1	unit	7.41E-8	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp flat roof installation, single-Si, on roof	RER	1	unit	3.28E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
174-359	3kWp flat roof installation, single-Si, on roof	RER	1	unit	4.41E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, single-Si, laminated, integrated, on roof	RER	1	unit	6.13E-8	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, single-Si, panel, mounted, on roof	RER	1	unit	2.78E-6	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
174-360	3kWp slanted-roof installation, single-Si, laminated, integrated, on roof	RER	1	unit	8.24E-8	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
174-361	3kWp slanted-roof installation, single-Si, panel, mounted, on roof	RER	1	unit	3.74E-6	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, ribbon-Si, panel, mounted, on roof	CH	1	unit	3.23E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, ribbon-Si, laminated, integrated, on roof	CH	1	unit	1.24E-8	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, CdTe, laminated, integrated, on roof	CH	1	unit	1.09E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, CIS, panel, mounted, on roof	CH	1	unit	6.38E-8	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, a-Si, laminated, integrated, on roof	CH	1	unit	1.94E-8	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, a-Si, panel, mounted, on roof	CH	1	unit	5.05E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
emission air	Heat, waste	-	-	MJ	2.50E-1	1	1.05	(1,na,na,na,na,na); Calculation
	electricity, production mix photovoltaic, at plant	DE	0	kWh	1			

Tab. 4.6 Unit process data of the photovoltaic electricity production mix in the US



	Name	Location	InfrastructurePr	Unit	electricity, production mix photovoltaic, at plant	UncertaintyTyp	StandardDeviation95%	GeneralComment
	Location				US			
	InfrastructureProcess				0			
	Unit				kWh			
resource, in air	Energy, solar, converted	-	-	MJ	3.85E+0	1	1.09	(2,2,1,1,1,3); Calculation with average module efficiency
technosphere	tap water, at user	CH	0	kg	2.23E-3	1	1.09	(2,2,1,1,1,3); Estimation 20l/m2 panel
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	2.23E-6	1	1.09	(2,2,1,1,1,3); Estimation 20l/m2 panel
	3.5 MWp open ground installation, multi-Si, on open ground	US	1	unit	8.20E-10	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp facade installation, single-Si, laminated, integrated, at building	US	1	unit	6.85E-8	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp facade installation, single-Si, panel, mounted, at building	US	1	unit	2.74E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
174-362	3kWp facade installation, single-Si, laminated, integrated, at building	US	1	unit	1.04E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
174-363	3kWp facade installation, single-Si, panel, mounted, at building	US	1	unit	4.18E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp flat roof installation, single-Si, on roof	US	1	unit	3.31E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
174-364	3kWp flat roof installation, single-Si, on roof	US	1	unit	5.04E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, single-Si, laminated, integrated, on roof	US	1	unit	4.14E-8	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, single-Si, panel, mounted, on roof	US	1	unit	1.08E-6	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
174-365	3kWp slanted-roof installation, single-Si, laminated, integrated, on roof	US	1	unit	6.30E-8	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
174-366	3kWp slanted-roof installation, single-Si, panel, mounted, on roof	US	1	unit	1.64E-6	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, ribbon-Si, panel, mounted, on roof	CH	1	unit	1.38E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, ribbon-Si, laminated, integrated, on roof	CH	1	unit	5.32E-9	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, CdTe, laminated, integrated, on roof	CH	1	unit	2.31E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, CIS, panel, mounted, on roof	CH	1	unit	2.74E-8	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, a-Si, laminated, integrated, on roof	CH	1	unit	8.33E-9	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, a-Si, panel, mounted, on roof	CH	1	unit	2.17E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
emission air	Heat, waste	-	-	MJ	2.50E-1	1	1.05	(1,na,na,na,na,na); Calculation
	electricity, production mix photovoltaic, at plant	US	0	kWh	1			

4.6 Non-renewable Residual Electricity Mixes for EPBT and NREPBT

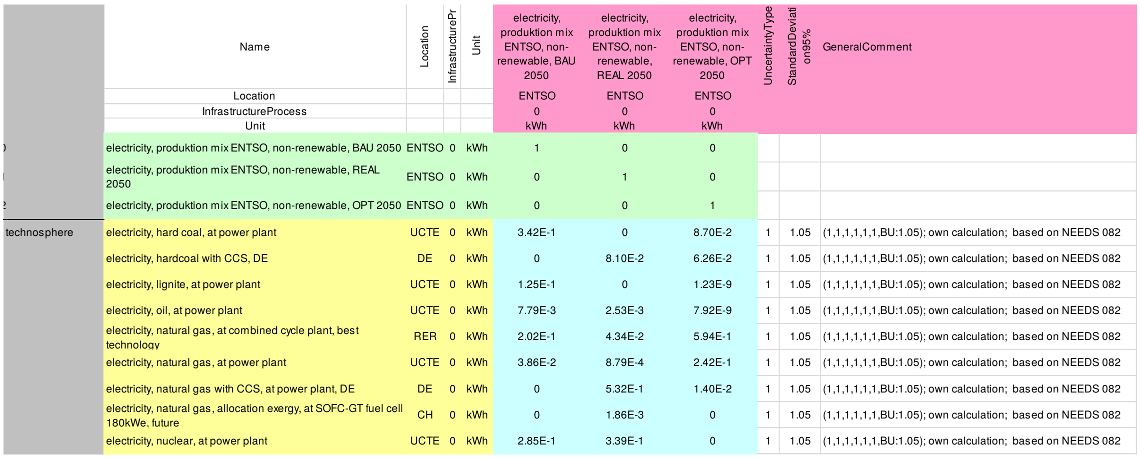
Tab. 4.7 shows the unit process data of the non-renewable residual electricity mixes for Europe (European Network of Transmission System Operators (ENTSO)) in the three scenarios: BAU, REAL and OPT. The non-renewable residual electricity mixes correspond to the electricity mixes of all non-renewable electricity generation technologies in a specific country or region (in this case, Europe).

The future residual mixes are based on the future projections of the European electricity mixes in the year 2050 for the scenarios described in the Section 5.3.

The non-renewable residual mix used in the scenario BAU mainly consists of hard coal (34 %), nuclear power (28 %) and natural gas (24 %). The scenario REAL uses a non-renewable residual electricity mix mainly consisting of natural gas (58 %), nuclear power (34 %) and hard coal (8 %). And, the non-renewable residual electricity mix used in the scenario OPT mainly consists of natural gas (85 %) and hard coal (15 %).

These non-renewable residual electricity mixes are used to calculate the NREPBT of PV systems. It is assumed that these electricity mixes of non-renewable electricity generation technologies are replaced by the newly installed PV systems in the corresponding countries or regions of installation.

Tab. 4.7 Unit process data of the non-renewable residual electricity mixes for Europe (ENTSO) in the three scenarios (BAU, REAL, OPT).



	Name	Location	InfrastructurePr	Unit	electricity, produktion mix ENTSO, non-renewable, BAU 2050	electricity, produktion mix ENTSO, non-renewable, REAL 2050	electricity, produktion mix ENTSO, non-renewable, OPT 2050	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				ENTSO	ENTSO	ENTSO			
	InfrastructureProcess				0	0	0			
	Unit				kWh	kWh	kWh			
	electricity, produktion mix ENTSO, non-renewable, BAU 2050	ENTSO	0	kWh	1	0	0			
	electricity, produktion mix ENTSO, non-renewable, REAL 2050	ENTSO	0	kWh	0	1	0			
	electricity, produktion mix ENTSO, non-renewable, OPT 2050	ENTSO	0	kWh	0	0	1			
technosphere	electricity, hard coal, at power plant	UCTE	0	kWh	3.42E-1	0	8.70E-2	1	1.05	(1,1,1,1,1,1,BU:1.05); own calculation; based on NEEDS 082
	electricity, hardcoal with CCS, DE	DE	0	kWh	0	8.10E-2	6.26E-2	1	1.05	(1,1,1,1,1,1,BU:1.05); own calculation; based on NEEDS 082
	electricity, lignite, at power plant	UCTE	0	kWh	1.25E-1	0	1.23E-9	1	1.05	(1,1,1,1,1,1,BU:1.05); own calculation; based on NEEDS 082
	electricity, oil, at power plant	UCTE	0	kWh	7.79E-3	2.53E-3	7.92E-9	1	1.05	(1,1,1,1,1,1,BU:1.05); own calculation; based on NEEDS 082
	electricity, natural gas, at combined cycle plant, best technology	RER	0	kWh	2.02E-1	4.34E-2	5.94E-1	1	1.05	(1,1,1,1,1,1,BU:1.05); own calculation; based on NEEDS 082
	electricity, natural gas, at power plant	UCTE	0	kWh	3.86E-2	8.79E-4	2.42E-1	1	1.05	(1,1,1,1,1,1,BU:1.05); own calculation; based on NEEDS 082
	electricity, natural gas with CCS, at power plant, DE	DE	0	kWh	0	5.32E-1	1.40E-2	1	1.05	(1,1,1,1,1,1,BU:1.05); own calculation; based on NEEDS 082
	electricity, natural gas, allocation exergy, at SOFC-GT fuel cell 180kWe, future	CH	0	kWh	0	1.86E-3	0	1	1.05	(1,1,1,1,1,1,BU:1.05); own calculation; based on NEEDS 082
	electricity, nuclear, at power plant	UCTE	0	kWh	2.85E-1	3.39E-1	0	1	1.05	(1,1,1,1,1,1,BU:1.05); own calculation; based on NEEDS 082

5 Life Cycle Inventories in the Background System

5.1 Overview

LCI background data are adjusted for the global production of various basic materials and electricity mixes according to the three scenarios (BAU, REAL and OPT) for the reference year 2050 according to NEEDS (Frischknecht et al. 2008). The scenarios and the modelling are described below in Sections 5.2 to 5.7.

The materials and electricity mixes for which LCI data are adjusted are:

- Electricity mix ENTSO-E
- Electricity mix in China
- Electricity mix the United States
- Aluminium
- Electricity mix for aluminium production
- Clinker
- Flat glass, uncoated
- Copper RLA and RER
- Magnesium-silicone
- Nickel
- Pig iron
- Sinter
- Zinc for coating

The characteristics of the three scenarios are described in Section 5.2. The unit process raw data of the electricity mixes of Europe, China and United States are described in Sections 5.3 to 5.5, and the scenario-dependent LCIs of material production (except aluminium) are documented in Section 5.6. Since the completion of the NEEDS project, new inventory data representing the supply of primary aluminium are available. That is why new scenario-dependent LCIs of aluminium production are developed; they are described in Section 5.7.

5.2 Scenarios Applied

The three scenarios defined in the NEEDS project (Frischknecht et al. 2008) are taken to describe possible energy situations in the year 2050. The LCIs of the production of commodities in the future are modelled considering further development of production techniques (in terms of energy and raw material efficiency, energy carriers used and emission factors). For further information on modelling of the scenarios, refer to the NEEDS reports (Frischknecht 2010).

One NEEDS scenario describes a “pessimistic” case where hardly any technological change happens up to 2050. Energy is produced with present technologies, and no substantial change in energy politics takes place. The NEEDS scenario “pessimistic” corresponds to the BAU scenario used in this report and described in Section 2.6.

The scenario “realistic-optimistic” follows the pathway of technological development as far as possible, according to future projections and goals of the industry that seem reasonably achieved. European electricity supply is modelled according to an electricity mix scenario compatible with a global-average CO_2 concetration target of 440 ppm (Frischknecht et al. 2008). The NEEDS scenario "realistic-optimistic" corresponds to the scenario REAL used in this report and described in Section 2.6.

The scenario "very optimistic" introduces improvements that exceed the improvements modelled in the scenario REAL. The switch to cleaner energy-generating technologies (e.g., oil to gas) is more pronounced. The European electricity supply is modelled according to an enhanced renewables electricity mix scenario. The NEEDS scenario "very optimistic" corresponds to the scenario OPT used in this report and described in Section 2.6.

5.3 Electricity Mix ENTSO-E

The ENTSO-E electricity mix is modelled according to the scenarios of electricity mixes in Europe, based on the NEEDS project (Frischknecht et al. 2008).

Carbon capture and storage (CCS) is taken into account for hard coal and natural gas power production in scenarios REAL and OPT. CCS technologies are modelled based on average German hard coal and natural gas power plants. The CO_2 emissions per kWh are reduced by 90 % and the overall efficiency is diminished by 7 %. An efficiency enhancement due to future technological improvement of CCS technology is accounted for. No CCS technologies for lignite are applied because of lignite's small share in the mix. Tab. 5.1 to Tab. 5.3 show the scenario-dependent unit process raw data of the ENTSO electricity mix in 2050.

The share of each technology per kWh electricity produced in each scenario is illustrated in Fig. 5.1.

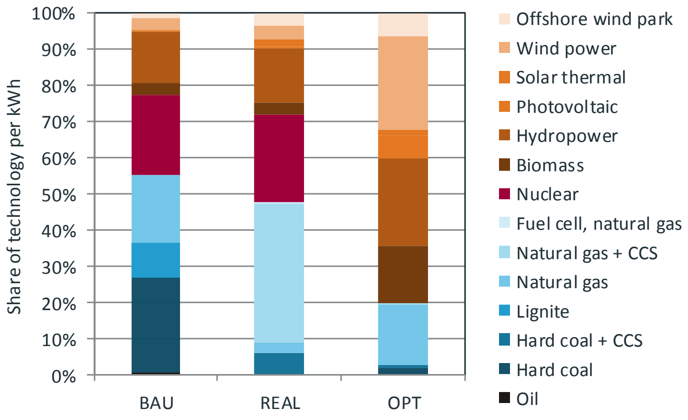


Fig. 5.1 European electricity mix scenarios according to the NEEDS project (Frischknecht et al. 2008) in the year 2050

Tab. 5.1 Unit process data of 1 kWh of the European electricity mix in 2050, scenario BAU

Technology according to NEEDS	ecoinvent unit process used for modelling in this study	Country/Region code[8]	Amount
Hard coal power, average	electricity, hard coal, at power plant	UCTE	26.4 %
Lignite, at power plant 950 MF	electricity, lignite, at power plant	UCTE	9.7 %
Oil at power plant	electricity, oil, at power plant	UCTE	0.6 %
Natural gas, at combined cycle plant 500 Mwe	electricity, natural gas, at combined cycle plant, best technology	RER	15.6 %
Natural gas, at turbine, 50 Mwe	electricity, natural gas, at power plant	UCTE	3.0 %
Nuclear, average	electricity, nuclear, at power plant	UCTE	22.0 %
Biomass, average	electricity, at cogen 6400 kWth, wood, allocation exergy	CH	3.6 %
Hydropower, at run-of-river power plant	electricity, hydropower, at run-of-river power plant	RER	5.6 %
Hydropower, at reservoir power plant, alpine region	electricity, hydropower, at reservoir power plant, alpine region	RER	8.0 %
Hydropower, at pumped storage power plant	electricity, hydropower, at pumped storage power plant	RER	0.7 %
Wind power plant	electricity, at wind power plant	RER	3.2 %
Offshore wind park, 1440 MW	electricity, at wind power plant 2 MW, offshore	OCE	1.4 %
Photovoltaic average	electricity, production mix photovoltaic, at plant	DE	0.3 %
Solar, thermal average	electricity, production mix photovoltaic, at plant	DE	0.1 %

---

[8] See the list of abbreviations and acronyms in the front matter.

Tab. 5.2 Unit process data of 1 kWh of the European electricity mix in 2050, scenario REAL

Technology according to NEEDS	ecoinvent unit process used for modelling in this study	Country/region code	Amount
Hard coal with CCS, average UCTE	electricity, hard coal with CCS, DE	DE	<0.1 %
Hard coal IGCC with CCS, average UCTE	electricity, hard coal with CCS, DE	DE	5.8 %
Oil, at power plant UCTE	electricity, oil, at power plant	UCTE	0.2 %
Natural gas, at combined cycle plant, 500 MWe RER	electricity, natural gas, at combined cycle plant, best technology	RER	3.1 %
Natural gas, CC plant, 500MWe post CCS, 400-km and 2500-m depleted gasfield RER	electricity, natural gas with CSS, at power plant, DE	DE	38.3 %
Natural gas, at cogeneration 200 kWe lean burn, allocation exergy RER	electricity, natural gas, at power plant	UCTE	0.1 %
Fuel cell, natural gas, average UCTE	electricity, natural gas, allocation exergy, at SOFC-GT fuel cell 180 kWe, future	CH	0.1 %
Nuclear, average UCTE	electricity, nuclear, at power plant	UCTE	24.4 %
Biomass, average UCTE	electricity, at cogen 6400 kWth, wood, allocation exergy	CH	3.3%
Hydropower, at run-of-river power plant RER	electricity, hydropower, at run-of-river power plant	RER	4.4 %
Hydropower, at reservoir power plant, alpine region RER	electricity, hydropower, at reservoir power plant, alpine region	RER	10.2 %
Hydropower, at pumped storage power plant UCTE	electricity, energy strategy 2050, POM, hydropower, at pumped storage plant	CH	0.5 %
Wind power plant RER	electricity, at wind power plant	RER	3.4 %
Offshore wind park 1944 MW DK	electricity, at wind power plant 2 MW, offshore	OCE	3.6 %
Photovoltaic, average UCTE	electricity, production mix photovoltaic, at plant	DE	0.3 %
Solar thermal, average UCTE	electricity, production mix photovoltaic, at plant	DE	<0.1 %
Wave energy, 7 MW RER	electricity, hydropower, at run-of-river power plant without reservoir	RER	2.2 %

Tab. 5.3 Unit process data of 1 kWh of the European electricity mix in 2050, scenario OPT

Technology according to NEEDS	ecoinvent unit process used for modelling in this study	Country/region code	Amount
Hard coal, average UCTE	electricity, hard coal, at power plant	UCTE	1.6 %
Hard coal with CCS, average UCTE	electricity, hard coal with CCS, DE	DE	0.8 %
Hard coal, at IGCC power plant 450 MW RER	electricity, hard coal, at power plant	UCTE	0.1 %
Hard coal IGCC with CCS, average UCTE	electricity, hard coal with CCS, DE	DE	0.4 %
Lignite, at power plant 950 MW RER	electricity, lignite, at power plant	UCTE	<0.1%
Oil, at power plant UCTE	electricity, oil, at power plant	UCTE	<0.1%
Natural gas, at combined cycle plant, 500 MWe RER	electricity, natural gas, at combined cycle plant, best technology	RER	11.7 %
Natural gas, at turbine, 50 MWe RER	electricity, natural gas, at power plant	UCTE	4.8 %
Natural gas, CC plant, 500 MWe post CCS, 400-km and 2500-m depleted gasfield RER	electricity, natural gas with CCS, at power plant, DE	DE	0.3 %
Biomass, average UCTE	electricity, at cogen 6400 kWth, wood, allocation exergy	CH	15.8 %
Hydropower, at run-of-river power plant RER	electricity, hydropower, at run-of-river power plant	RER	7.2 %
Hydropower, at reservoir power plant, alpine region RER	electricity, hydropower, at reservoir power plant, alpine region	RER	16.1 %
Hydropower, at pumped storage power plant UCTE	electricity, energy strategy 2050, NEP, hydropower, at pumped storage plant	CH	0.9 %
Wind power plant RER	electricity, at wind power plant	RER	26.0 %
Offshore wind park 2496 MW DK	electricity, at wind power plant 2 MW, offshore	OCE	6.3 %
Photovoltaic, average UCTE	electricity, production mix photovoltaic, at plant	DE	6.5 %
Solar thermal, average UCTE	electricity, production mix photovoltaic, at plant	DE	1.4 %

5.4 Electricity Mix in China

The electricity mixes in China in the year 2050 are matched with scenarios outlined by the International Institute of Applied Systems Analysis (IIASA) (Gambhir et al. 2012). The BAU scenario represents the Chinese scenario "baseline", the scenario REAL represents the Chinese scenario "efficiency" and the scenario OPT represents the Chinese scenario "mix". The original scenarios and the corresponding technology mixes for electricity production are illustrated in Fig. 5.2.

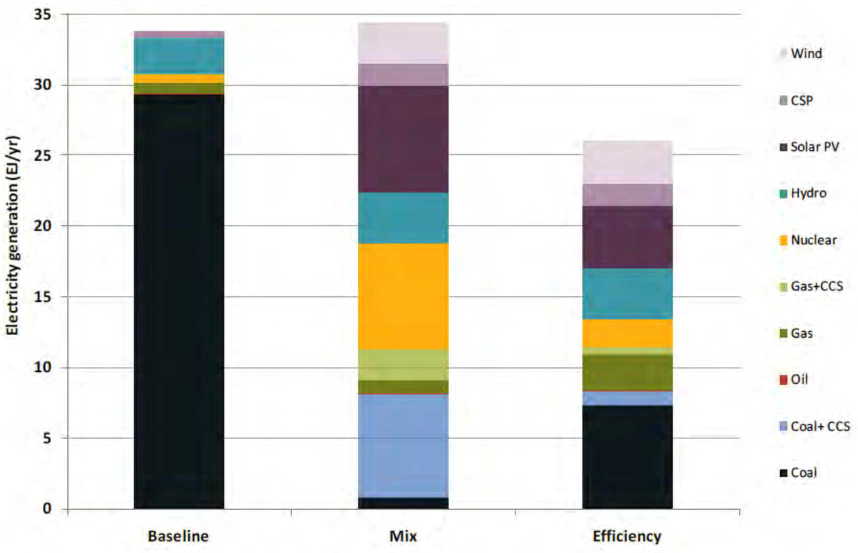


Fig. 5.2 Chinese electricity mix scenarios according to Gambhir et al. (2012) in the year 2050 CCS: Carbon Capture and Storage; CSP: Concentrated Solar Power; IIASA: International Institute for Applied Systems Analysis; CPA: Central and Planned Asia

Where data on Chinese or Asian power plant technologies are lacking, the technology mix is modelled with European data. Tab. 5.4 to Tab. 5.6 describe the scenario-dependent modelling of Chinese electricity mixes according to the three scenarios: BAU, REAL and OPT.

Tab. 5.4 Unit process data of 1 kWh of the Chinese electricity mix in 2050, scenario BAU

Technology according to NEEDS	ecoinvent unit process used for modelling in this study	Country/region code	Amount
Hard coal	electricity, hard coal, at power plant	CN	85.3%
Oil	electricity, oil, at power plant	UCTE	0.6%
Natural gas	electricity, natural gas, at power plant	JP	2.3%
Pressurized water reactor (PWR)	electricity, nuclear, at power plant pressure water reactor	CN	2.1%
Reservoir power	electricity, hydropower, at reservoir power plant, non-alpine regions	RER	6.6%
Run-of-river power	electricity, hydropower, at run-of-river power plant	RER	2.2%
Concentrating solar power (CSP)	electricity, production mix photovoltaic, at plant	JP	0.9%

Tab. 5.5 Unit process data of 1 kWh of the Chinese electricity mix in 2050, scenario REAL

Technology according to NEEDS	ecoinvent unit process used for modelling in this study	Country/region code	Amount
Hard coal	electricity, hard coal, at power plant	CN	26.9%
Hard coal CCS	electricity, hardcoal with CCS, DE	DE	3.9%
Oil	electricity, oil, at power plant	UCTE	1.9%
Natural gas	electricity, natural gas, at power plant	JP	11.5%
Natural gas CCS	natural gas with CCS, burned in combined cycle plant, best technology, DE	DE	3.8%
PWR	electricity, nuclear, at power plant pressure water reactor	CN	7.7%
Reservoir power	electricity, hydropower, at reservoir power plant, non alpine regions	RER	7.2%
Run-of-river power	electricity, hydropower, at run-of-river power plant	RER	2.4%
CSP	electricity, production mix photovoltaic, at plant	JP	7.7%
PV	electricity, production mix photovoltaic, at plant	JP	15.4%
Wind	electricity, at wind power plant	RER	11.5%

Tab. 5.6 Unit process data of 1 kWh of the Chinese electricity mix in 2050, scenario OPT

Technology according to NEEDS	ecoinvent unit process used for modelling in this study	Country/region code	Amount
Hard coal	electricity, hard coal, at power plant	CN	2.9%
Hard coal CCS	electricity, hard coal with CCS, DE	DE	20.3%
Oil	electricity, oil, at power plant	UCTE	1.5%
Natural gas	electricity, natural gas, at power plant	JP	2.9%
Natural gas CCS	natural gas with CCS, burned in combined cycle plant, best technology, DE	DE	7.3%
PWR	electricity, nuclear, at power plant pressure water reactor	CN	23.2%
Reservoir power	electricity, hydropower, at reservoir power plant, non-alpine regions	RER	6.5%
Run-of-river power	electricity, hydropower, at run-of-river power plant	RER	2.2%
CSP	electricity, production mix photovoltaic, at plant	JP	4.4%
PV	electricity, production mix photovoltaic, at plant	JP	21.7%
Wind	electricity, at wind power plant	RER	7.3%

5.5 Electricity Mix in the United States

The electricity mixes in 2050 in the United States are modelled according to Clemmer et al. (2013). Clemmer et al. (2013) designed four scenarios to analyse future impacts of US electricity production.

In Scenario 1 of Clemmer et al. (2013), the model projects the future electricity mix in the United States based on existing state and federal energy policies and the relative economics of different electricity generating technologies (see Fig. 5.3). Scenario 1 forms the basis for the scenario BAU defined in this study.

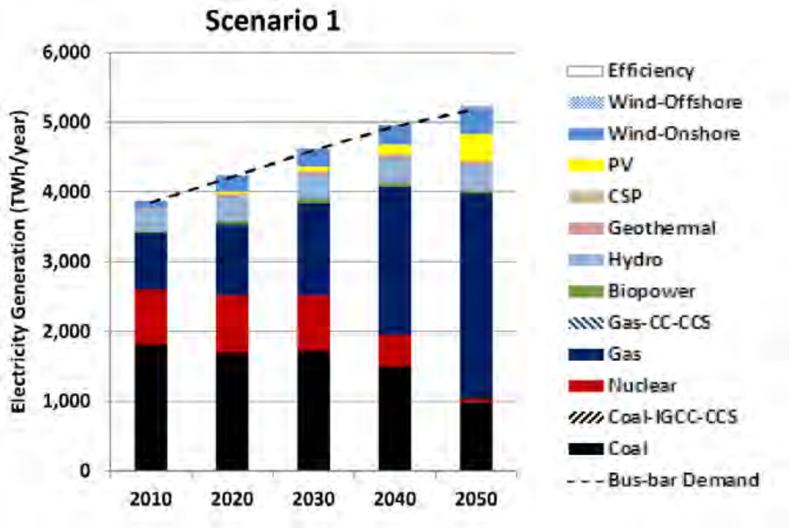


Fig. 5.3 Scenario BAU: Development of the US electricity mix according to "Scenario 1" of Clemmer et al. (2013)

Scenario 2 of Clemmer et al. (2013) assumes that the United States meets a cumulative economy-wide carbon budget (CO_2 eq) of 170 gigatons from 2012 to 2050 (see Fig. 5.4). Scenario 2 forms the basis for the scenario REAL defined in this study.

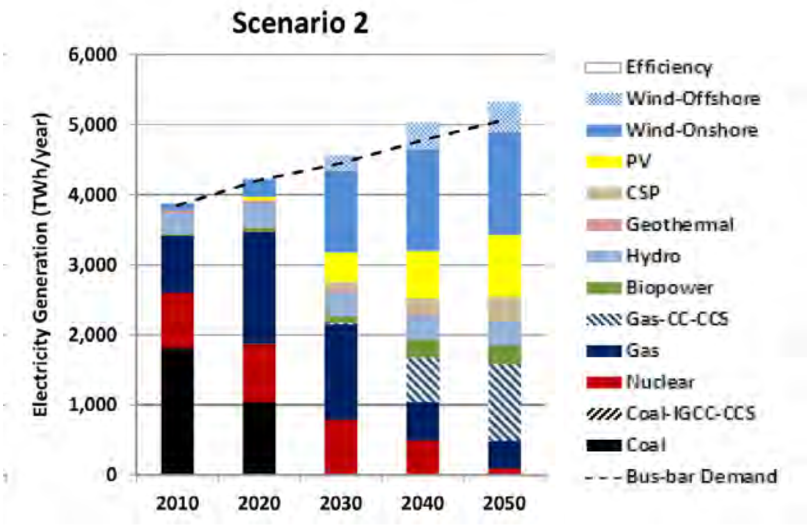


Fig. 5.4 Scenario REAL: Development of the US electricity mix according to "Scenario 2" of Clemmer et al. (2013)

For Scenario 4 of Clemmer et al. (2013) (see Fig. 5.5), it was assumed that the emissions reductions would be met by aggressive deployment of energy efficiency and renewable energy technologies over the next 40 years. Scenario 4 forms the basis for the scenario OPT defined in this study.

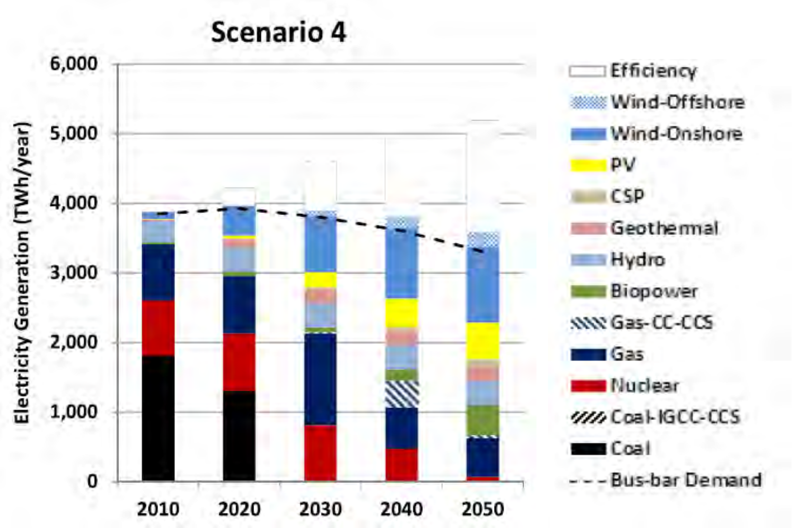


Fig. 5.5 Scenario OPT: Development of the US electricity mix according to "Scenario 4" of Clemmer et al. (2013)

It was assumed that the shares within the nuclear power production (boiling water reactor (BWR) and pressurized water reactor (PWR)) and the shares within hydropower production (run-of-river power, reservoir power and pumped storage power) remain constant up to the year 2050. Tab. 5.7 to Tab. 5.9 describe the modelling of the scenario-dependent US electricity mix.

Tab. 5.7 Unit process data of 1 kWh of the US electricity mix in 2050, scenario BAU

Technology according to NEEDS	ecoinvent unit process used for modelling in this study	Country/region code	Amount
Hard coal	electricity, hard coal, at power plant	US	19.6%
PWR power	electricity, nuclear, at power plant pressure water reactor	US	0.7%
BWR power	electricity, nuclear, at power plant boiling water reactor	US	0.3%
Natural gas	electricity, natural gas, at power plant	US	58.8%
Reservoir power	electricity, hydropower, at reservoir power plant, non-alpine regions	RER	1.4%
Run-of-river power	electricity, hydropower, at run-of-river power plant	RER	5.7%
Pumped storage power	electricity, hydropower, at pumped storage power plant	US	0.7%
Geothermal power	electricity, at wind power plant	RER	1.0%
Photovoltaic power	electricity, production mix photovoltaic, at plant	US	5.9%
Onshore wind power	electricity, at wind power plant	RER	5.9%

Tab. 5.8 Unit process data of 1 kWh of the US electricity mix in 2050, scenario REAL

Technology according to NEEDS	ecoinvent unit process used for modelling in this study	Country/region code	Amount
PWR power	electricity, nuclear, at power plant pressure water reactor	US	0.6%
BWR power	electricity, nuclear, at power plant boiling water reactor	US	0.3%
Natural gas	electricity, natural gas, at power plant	US	8.7%
Gas CC-CCS	natural gas with CCS, burned in combined cycle plant, best technology, DE	DE	23.1%
Wood and biomass power	electricity, at cogen 6400 kWth, wood, allocation exergy	CH	3.9%
Reservoir power	electricity, hydropower, at reservoir power plant, non alpine regions	RER	1.1%
Run-of-river power	electricity, hydropower, at run-of-river power plant	RER	4.2%
Pumped storage power	electricity, hydropower, at pumped storage power plant	US	0.5%
Geothermal power	electricity, at wind power plant	RER	1.0%
CSP power	electricity, production mix photovoltaic, at plant	US	5.8%
Solar PV power	electricity, production mix photovoltaic, at plant	US	14.4%
Offshore wind power	electricity, at wind power plant 2 MW, offshore	OCE	8.7%
Onshore wind power	electricity, at wind power plant	RER	27.9%

Tab. 5.9 Unit process data of 1 kWh of the US electricity mix in 2050, scenario OPT

Technology according to NEEDS	ecoinvent unit process used for modelling in this study	Country code	Amount
Hard coal power	electricity, hard coal, at power plant	US	0.0%
PWR power	electricity, nuclear, at power plant pressure water reactor	US	0.9%
BWR power	electricity, nuclear, at power plant boiling water reactor	US	0.5%
Natural gas power	electricity, natural gas, at power plant	US	16.7%
Gas CC-CCS power	natural gas with CCS, burned in combined cycle plant, best technology, DE	DE	1.4%
Wood and biomass power	electricity, at cogen 6400 kWth, wood, allocation exergy	CH	11.1%
Reservoir power power	electricity, hydropower, at reservoir power plant, non alpine regions	RER	1.6%
Run-of-river power power	electricity, hydropower, at run-of-river power plant	RER	6.5%
Pumped storage power	electricity, hydropower, at pumped storage power plant	US	0.8%
Geothermal power	electricity, at wind power plant	RER	4.2%
CSP power	electricity, production mix photovoltaic, at plant	US	2.2%
Solar PV power	electricity, production mix photovoltaic, at plant	US	12.5%
Offshore Wind power	electricity, at wind power plant 2 MW, offshore	OCE	8.3%
Onshore Wind power	electricity, at wind power plant	RER	33.3%

5.6 Metals and Materials

LCI data for future production of clinker, ferronickel, flat glass (uncoated), copper (produced in Latin America and Europe), magnesium-silicone, nickel, pig iron, sinter and zinc (used for coatings) are modelled according to the LCI established in the NEEDS project (Frischknecht et al. 2008). The LCI data used in the BAU scenario represent the present situation (ecoinvent data v2.2). LCI data used in the scenarios REAL and OPT are modified according to the changes documented in the NEEDS report (Frischknecht et al. 2008).

Tab. 5.10 to Tab. 5.19 show the LCI unit process data of the production of materials within the scenario REAL, corresponding to the realistic-optimistic scenario of the NEEDS project.

Tab. 5.10 Unit process data of 1 kg of clinker, at plant, scenario REAL, corresponding to the NEEDS scenario realistic-optimistic (Frischknecht et al. 2008)

Explanations	Name	Location	Category	Sub-Category	Infrastructure-Process	Unit	clinker, at plant	uncertaintyType	StandardDeviation95%	GeneralComment
	Location						CH			
	InfrastructureProcess						0			
	Unit						kg			
Technosphere	ammonia, liquid, at regional storehouse	CH			0	kg	9.08E-4	1	1.22	(2,1,1,1,1,5);
	lubricating oil, at plant	RER			0	kg	4.71E-5	1	1.22	(2,1,1,2,1,5);
	calcareous marl, at plant	CH			0	kg	4.66E-1	1	1.22	(2,1,1,1,1,5);
	clay, at mine	CH			0	kg	3.31E-1	1	1.22	(2,1,1,2,1,5);
	limestone, milled, loose, at plant	CH			0	kg	8.41E-1	1	1.22	(2,1,1,1,1,5);
	sand, at mine	CH			0	kg	9.26E-3	1	1.22	(2,1,1,1,1,5);
	lime, hydrated, loose, at plant	CH			0	kg	3.92E-3	1	1.22	(2,1,1,1,1,5);
	refractory, basic, packed, at plant	DE			0	kg	1.90E-4	1	1.22	(2,1,1,1,1,5);
	refractory, fireclay, packed, at plant	DE			0	kg	8.21E-5	1	1.22	(2,1,1,1,1,5);
	refractory, high aluminium oxide, packed, at plant	DE			0	kg	1.37E-4	1	1.22	(2,1,1,1,1,5);
	cement plant	CH			1	unit	6.27E-12	1	3.05	(2,1,1,1,1,5);
	diesel, burned in building machine	GLO			0	MJ	1.34E-2	1	1.22	(2,1,1,2,1,5);
	Industrial machine, heavy, unspecified, at plant	RER			1	kg	3.76E-5	1	3.10	(4,4,1,1,1,5);
	electricity, medium voltage, at grid	CH			0	kWh	5.80E-2	1	1.22	(2,1,1,1,1,5);
technology	hard coal, at regional storage	WEU			0	kg	2.10E-2	1	1.22	(2,1,1,2,1,5);
	bauxite, at mine	GLO			0	kg	1.20E-4	1	1.22	(2,1,1,2,1,5);
	chromium steel 18/8, at plant	RER			0	kg	5.86E-5	1	1.22	(2,1,1,2,1,5);
	natural gas, high pressure, at consumer	CH			0	MJ	1.49E-1	1	1.22	(2,1,1,1,1,5);
	heavy fuel oil, at regional storage	CH			0	kg	1.51E-2	1	1.22	(2,1,1,1,1,5);
	light fuel oil, at regional storage	CH			0	kg	2.48E-4	1	1.22	(2,1,1,1,1,5);
	petroleum coke, at refinery	RER			0	kg	2.59E-3	1	1.22	(2,1,1,2,1,5);
	charcoal, at plant	GLO			0	kg	0			
	transport, lorry 16t	CH			0	tkm	8.61E-5	1	2.06	(3,3,1,1,1,5);
	transport, lorry 28t	CH			0	tkm	2.68E-3	1	2.05	(2,1,1,1,1,5);
	transport, lorry 40t	CH			0	tkm	2.11E-3	1	2.05	(2,1,1,1,1,5);
	transport, van <3.5t	CH			0	tkm	7.09E-5	1	2.05	(2,1,1,2,1,5);
	transport, barge	RER			0	tkm	7.22E-3	1	2.05	(2,1,1,2,1,5);
	transport, freight, rail	RER			0	tkm	7.09E-3	1	2.05	(2,1,1,2,1,5);
	transport, freight, rail	CH			0	tkm	1.77E-2	1	2.06	(3,3,1,1,1,5);
	disposal, inert waste, 5% water, to inert material landfill	CH			0	kg	8.00E-5	1	1.22	(2,1,1,1,1,5);
	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH			0	kg	4.50E-5	1	1.22	(2,1,1,1,1,5);
	tap water, at user	RER			0	kg	3.40E-1	1	1.22	(2,1,1,2,1,5);
resource, in water	Water, unspecified natural origin		resource	in water		m3	1.62E-3	1	1.22	(2,1,1,1,1,5);
air, unspecified	Ammonia		air	unspecified		kg	2.28E-5	1	1.56	(2,1,1,1,1,5);
	Antimony		air	unspecified		kg	2.00E-9	1	5.06	(2,1,1,1,1,5);
	Arsenic		air	unspecified		kg	1.20E-8	1	1.56	(2,1,1,1,1,5);
	Beryllium		air	unspecified		kg	3.00E-9	1	1.56	(2,1,1,1,1,5);
	Cadmium		air	unspecified		kg	7.00E-9	1	1.56	(2,1,1,1,1,5);
	Carbon dioxide, biogenic		air	unspecified		kg	1.79E-2	1	1.22	(2,1,1,1,1,5);
Air, unspecified	Carbon dioxide, fossil		air	unspecified		kg	7.70E-1	1	1.22	(2,1,1,1,1,5);
	Carbon monoxide, fossil		air	unspecified		kg	1.00E-4	1	2.05	(2,1,1,1,1,5);
	Chromium		air	unspecified		kg	1.45E-9	1	1.56	(2,1,1,1,1,5);
	Chromium VI		air	unspecified		kg	5.50E-10	1	1.56	(2,1,1,1,1,5);
	Cobalt		air	unspecified		kg	4.00E-9	1	1.56	(2,1,1,1,1,5);
	Copper		air	unspecified		kg	1.40E-8	1	1.56	(2,1,1,1,1,5);
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin		air	unspecified		kg	9.60E-13	1	2.05	(2,1,1,1,1,5);
	Heat, waste		air	unspecified		MJ	3.62E+0	1	1.22	(2,1,1,1,1,5);
	Hydrogen chloride		air	unspecified		kg	6.31E-6	1	1.56	(2,1,1,1,1,5);
	Lead		air	unspecified		kg	8.50E-8	1	5.06	(2,1,1,1,1,5);
	Mercury		air	unspecified		kg	3.30E-8	1	1.56	(2,1,1,1,1,5);
	Methane, fossil		air	unspecified		kg	8.88E-6	1	2.05	(2,1,1,1,1,5);
	Nickel		air	unspecified		kg	5.00E-9	1	1.56	(2,1,1,1,1,5);
	Nitrogen oxides		air	unspecified		kg	1.60E-4	1	1.56	(2,1,1,1,1,5);
	NMVOC, non-methane volatile organic compounds, unspecified origin		air	unspecified		kg	5.64E-5	1	2.05	(2,1,1,1,1,5);
	Zinc		air	unspecified		kg	6.00E-8	1	1.56	(2,1,1,1,1,5);
	Vanadium		air	unspecified		kg	5.00E-9	1	1.56	(2,1,1,1,1,5);
	Tin		air	unspecified		kg	9.00E-9	1	5.06	(2,1,1,1,1,5);
	Thallium		air	unspecified		kg	1.30E-8	1	1.56	(2,1,1,1,1,5);
	Sulfur dioxide		air	unspecified		kg	1.00E-5	1	1.56	(2,1,1,1,1,5);
	Selenium		air	unspecified		kg	2.00E-9	1	5.06	(2,1,1,1,1,5);
air, low population density	Particulates, < 2.5 um		air	low population density		kg	6.40E-6	1	3.05	(2,1,1,1,1,5);
	Particulates, > 10 um		air	low population density		kg	1.50E-6	1	1.56	(2,1,1,1,1,5);
	Particulates, > 2.5 um, and < 10um		air	low population density		kg	2.10E-6	1	2.05	(2,1,1,1,1,5);
Outputs	clinker, at plant	CH			0	kg	1.00E+0			

Tab. 5.11 Unit process data of 1 kg of copper, primary, at refinery RER, scenario REAL, corresponding to the NEEDS scenario realistic-optimistic (Frischknecht et al. 2008)

Explanations	Name	Location	Infrastructure-Process	Unit	copper, primary, at refinery	uncertaintyType	StandardDeviation 95%	GeneralComment
	Location				RER			
	InfrastructureProcess				0			
	Unit				kg			
Technosphere	limestone, milled, packed, at plant	CH	0	kg	2.50E-1	1	1.51	(5,2,2,3,1,3,4)
	electricity, hydropower, at run-of-river power plant	RER	0	kWh	3.08E-1	1	1.1	(2,2,2,3,1,3,2)
	oxygen, liquid, at plant	RER	0	kg	3.00E-1	1	1.1	(2,2,2,3,1,3,4)
	silica sand, at plant	DE	0	kg	7.50E-1	1	1.51	(5,2,2,3,1,3,4)
	electricity, high voltage, production UCTE, at grid	UCTE	0	kWh	2.06E-1	1	1.1	(2,2,2,3,1,3,2)
	anode, aluminium electrolysis	RER	0	kg	1.00E-3	1	2.07	(5,5,5,6,4,6,4)
	non-ferrous metal smelter	GLO	1	unit	1.14E-11	1	3.07	(3,2,2,1,3,4,9)
	natural gas, burned in industrial furnace >100kW	RER	-	MJ	3.52E+0	1	1.1	(2,2,2,3,1,3,1)
	heavy fuel oil, burned in industrial furnace 1MW, non-modulating	RER	-	MJ	4.26E+0	1	1.1	(2,2,2,3,1,3,1)
	disposal, nickel smelter slag, 0% water, to residual material landfill	CH	-	kg	9.25E-1	1	1.1	(2,2,2,3,1,3,6)
	treatment, sewage, unpolluted, to wastewater treatment, class 3	CH	-	m3	5.80E-3	1	1.13	(2,2,1,1,1,4,13)
	copper concentrate, at beneficiation	RER	-	kg	4.14E+0	1	1.1	(2,2,2,3,1,3,4)
resource, in water	Water, river			m3	5.80E-3	1	1.13	(2,2,1,1,1,4,12)
air, low population density	Antimony			kg	1.00E-6	1	5.08	(3,2,1,1,3,4,22)
	Arsenic			kg	1.50E-5	1	5.08	(3,2,1,1,3,4,22)
	Cadmium			kg	3.00E-6	1	5.08	(3,2,1,1,3,4,22)
	Carbon dioxide, fossil			kg	1.10E-1	1	1.89	(5,4,1,3,3,5,7)
	Chromium			kg	5.00E-8	1	5.08	(3,2,1,1,3,4,22)
	Copper			kg	2.00E-4	1	5.08	(3,2,1,1,3,4,22)
	Heat, waste			MJ	1.97E+0	1	1.14	(2,3,2,1,1,4,13)
	Lead			kg	5.00E-5	1	5.08	(3,2,1,1,3,4,22)
	Manganese			kg	5.00E-6	1	5.08	(3,2,1,1,3,4,22)
	Mercury			kg	1.00E-7	1	5.08	(3,2,1,1,3,4,22)
	Nickel			kg	1.00E-5	1	5.08	(3,2,1,1,3,4,22)
	Particulates, < 2.5 um			kg	3.54E-7	1	3.07	(3,2,1,1,3,4,27)
	Particulates, > 10 um			kg	7.11E-5	1	1.5	(3,2,1,1,3,4,29)
	Particulates, > 2.5 um, and < 10um			kg	2.12E-4	1	1.34	(3,2,1,1,3,4,28)
	Selenium			kg	1.00E-6	1	5.08	(3,2,1,1,3,4,22)
	Zinc			kg	1.50E-4	1	5.08	(3,2,1,1,3,4,22)
	Vanadium			kg	2.50E-7	1	5.08	(3,2,1,1,3,4,22)
	Tin			kg	2.50E-6	1	5.08	(3,2,1,1,3,4,22)
	Sulfur dioxide			kg	1.60E-2	1	1.64	(5,4,1,3,3,5,15)
	NMVOC, non-methane volatile organic compounds, unspecified origin			kg	1.50E-5	1	1.59	(3,2,1,1,3,4,16)
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin			kg	1.13E-12	1	3.07	(3,2,1,1,3,4,21)
	Carbon monoxide, fossil			kg	3.00E-5	1	5.08	(3,2,1,1,3,4,22)
water, river	Arsenic, ion			kg	1.08E-7	1	10	reported values
	Cadmium, ion			kg	1.58E-8	1	10	reported values
	Chromium, ion			kg	1.66E-7	1	10	reported values
	Copper, ion			kg	3.05E-7	1	10	reported values
	Lead			kg	9.26E-8	1	10	reported values
	Mercury			kg	1.66E-9	1	10	reported values
	Nickel, ion			kg	1.23E-7	1	10	reported values
	Zinc, ion			kg	4.91E-7	1	10	reported values
	Tin, ion			kg	1.66E-7	1	10	reported values
Outputs	copper, primary, at refinery	RER	0	kg	1.00E+0			

Tab. 5.12 Unit process data of 1 kg of copper, primary, at refinery RLA, scenario REAL, corresponding to the NEEDS scenario realistic-optimistic (Frischknecht et al. 2008)

Explanations	Name	Location	Infrastructure-Process	Unit	copper, primary, at refinery	uncertaintyType	StandardDeviation 95%	GeneralComment
	Location				RLA			
	InfrastructureProcess				0			
	Unit				kg			
Technosphere	oxygen, liquid, at plant	RER	0	kg	9.86E-02	1	1.10	(2,2,2,3,1,3,4)
	silica sand, at plant	DE	0	kg	4.88E-01	1	1.51	(5,2,2,3,1,3,4)
	limestone, milled, packed, at plant	CH	0	kg	1.63E-01	1	1.51	(5,2,2,3,1,3,4)
	electricity, high voltage, production UCTE, at grid	UCTE	0	kWh	1.21E-01	1	1.10	(2,2,2,3,1,3,2)
	electricity, hydropower, at run-of-river power plant	RER	0	kWh	1.82E-01	1	1.10	(2,2,2,3,1,3,2)
	anode, aluminium electrolysis	RER	0	kg	6.50E-05	1	2.07	(5,5,5,6,4,6,4)
	copper concentrate, at beneficiation	RLA	0	kg	2.07E+00	1	1.10	(2,2,2,3,1,3,4)
	copper, SX-EW, at refinery	GLO	0	kg	1.39E-01	1	1.10	(2,2,2,3,1,3,1)
	non-ferrous metal smelter	GLO	1	unit	8.75E-12	1	3.07	(3,2,2,1,3,4,9)
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	1.74E+00	1	1.10	(2,2,2,3,1,3,1)
	heavy fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	4.96E+00	1	1.10	(2,2,2,3,1,3,1)
	disposal, nickel smelter slag, 0% water, to residual material landfill	CH	0	kg	5.70E-01	1	1.10	(2,2,2,3,1,3,6)
	treatment, sewage, unpolluted, to wastewater treatment, class 3	CH	0	m3	2.90E-03	1	1.13	(2,2,1,1,1,4,13)
resource, in water	Water, river			m3	2.90E-03	1	1.13	(2,2,1,1,1,4,12)
air, low population density	Antimony			kg	3.25E-05	1	5.08	(3,2,1,1,3,4,22)
	Arsenic			kg	3.25E-04	1	5.08	(3,2,1,1,3,4,22)
	Cadmium			kg	1.30E-04	1	5.08	(3,2,1,1,3,4,22)
	Carbon dioxide, fossil			kg	9.07E-02	1	1.89	(5,4,1,3,3,5,7)
	Carbon monoxide, fossil			kg	2.47E-05	1	5.08	(3,2,1,1,3,4,22)
	Chromium			kg	6.50E-07	1	5.08	(3,2,1,1,3,4,22)
	Copper			kg	9.75E-04	1	5.08	(3,2,1,1,3,4,22)
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin			kg	1.65E-12	1	3.07	(3,2,1,1,3,4,21)
	Heat, waste			MJ	1.39E+00	1	1.14	(2,3,2,1,1,4,13)
	Lead			kg	6.50E-04	1	5.08	(3,2,1,1,3,4,22)
	Manganese			kg	6.50E-05	1	5.08	(3,2,1,1,3,4,22)
	Mercury			kg	1.43E-06	1	5.08	(3,2,1,1,3,4,22)
	Nickel			kg	5.85E-04	1	5.08	(3,2,1,1,3,4,22)
	NMVOC, non-methane volatile organic compounds, unspecified origin			kg	1.24E-05	1	1.59	(3,2,1,1,3,4,16)
	Particulates, < 2.5 um			kg	4.19E-07	1	3.07	(3,2,1,1,3,4,27)
	Particulates, > 10 um			kg	8.38E-05	1	1.50	(3,2,1,1,3,4,29)
	Particulates, > 2.5 um, and < 10um			kg	2.51E-04	1	1.34	(3,2,1,1,3,4,28)
	Selenium			kg	3.25E-05	1	5.08	(3,2,1,1,3,4,22)
	Sulfur dioxide			kg	2.44E-02	1	1.64	(5,4,1,3,3,5,15)
	Tin			kg	3.25E-05	1	5.08	(3,2,1,1,3,4,22)
	Vanadium			kg	3.25E-06	1	5.08	(3,2,1,1,3,4,22)
	Zinc			kg	3.25E-04	1	5.08	(3,2,1,1,3,4,22)
water, river	Arsenic, ion			kg	6.86E-08	1	10.00	reported values
	Cadmium, ion			kg	1.00E-08	1	10.00	reported values
	Chromium, ion			kg	1.05E-07	1	10.00	reported values
	Copper, ion			kg	1.93E-07	1	10.00	reported values
	Lead			kg	5.86E-08	1	10.00	reported values
	Mercury			kg	1.05E-09	1	10.00	reported values
	Nickel, ion			kg	7.80E-08	1	10.00	reported values
	Tin, ion			kg	1.05E-07	1	10.00	reported values
	Zinc, ion			kg	3.11E-07	1	10.00	reported values
Outputs	copper, primary, at refinery	RLA	0	kg	1.00E+0			

Tab. 5.13 Unit process data of 1 kg of ferronickel, 25 % Ni, at plant, scenario REAL, corresponding to the NEEDS scenario realistic-optimistic (Frischknecht et al. 2008)

Explanations	Name	Location	Infrastructure-Process	Unit	ferronickel, 25% Ni, at plant	uncertaintyType	StandardDeviation 95%	GeneralComment
	Location				GLO			
	InfrastructureProcess				0			
	Unit				kg			
Technosphere	limestone, milled, packed, at plant	CH	0	kg	4.69E-1	1	1.51	(5,2,2,3,1,3,4)
	blasting	RER	0	kg	1.20E-3	1	1.13	(2,2,2,1,1,4,4)
	conveyor belt, at plant	RER	1	m	8.00E-7	1	1.26	(3,2,2,1,3,4,4)
	diesel, burned in building machine	GLO	0	MJ	1.91E+0	1	1.13	(2,2,2,1,1,4,4)
	electricity, high voltage, production UCTE, at grid	UCTE	0	kWh	7.01E+0	1	1.10	(2,2,2,3,1,3,2)
	hard coal, burned in industrial furnace 1-10MW	RER	0	MJ	3.60E+1	1	1.10	(2,2,2,3,1,3,1)
	electricity, hydropower, at run-of-river power plant	RER	0	kWh	1.34E+0	1	1.10	(2,2,2,3,1,3,2)
	non-ferrous metal smelter	GLO	1	unit	6.48E-11	1	3.07	(3,2,2,1,3,4,9)
	non-ferrous metal mine, surface	GLO	1	unit	2.00E-9	1	3.07	(3,2,2,1,3,4,9)
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	2.69E+1	1	1.10	(2,2,2,3,1,3,1)
	heavy fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	3.38E+0	1	1.10	(2,2,2,3,1,3,1)
	disposal, nickel smelter slag, 0% water, to residual material landfill	CH	0	kg	1.27E+1	1	2.15	(4,5,1,3,5,5,6)
resource, in ground	Nickel, 1.98% in silicates, 1.04% in crude ore, in ground			kg	1.74E+0	1	1.13	(2,2,2,1,1,4,12)
resource, land	Occupation, mineral extraction site			m2a	1.65E-3	1	1.59	(3,2,2,1,3,4,7)
	Transformation, from unknown			m2	5.49E-5	1	3.07	(3,2,2,1,3,4,9)
	Transformation, to mineral extraction site			m2	5.49E-5	1	2.08	(3,2,2,1,3,4,8)
air, low population density	Antimony			kg	7.07E-10	1	1.59	(3,2,1,1,3,4,31)
	Arsenic			kg	5.04E-6	1	5.08	(3,2,1,1,3,4,22)
	Beryllium			kg	9.21E-9	1	1.59	(3,2,1,1,3,4,31)
	Boron			kg	3.54E-8	1	1.59	(3,2,1,1,3,4,31)
	Cadmium			kg	3.89E-10	1	1.59	(3,2,1,1,3,4,31)
	Zinc			kg	8.75E-5	1	5.08	(3,2,1,1,3,4,22)
	Tin			kg	5.64E-6	1	5.08	(3,2,1,1,3,4,22)
	Selenium			kg	1.77E-10	1	1.59	(3,2,1,1,3,4,31)
	Particulates, > 2.5 um, and < 10um			kg	1.83E-3	1	3.69	(3,2,1,1,5,4,20)
	Particulates, > 10 um			kg	2.61E-4	1	2.69	(3,2,1,1,5,4,19)
	Particulates, < 2.5 um			kg	1.80E-3	1	2.31	(4,2,2,5,4,4,23)
	Nickel			kg	1.11E-5	1	5.08	(3,2,1,1,3,4,22)
	Mercury			kg	1.77E-10	1	1.59	(3,2,1,1,3,4,31)
	Manganese			kg	3.36E-6	1	1.59	(3,2,1,1,3,4,31)
	Lead			kg	2.69E-5	1	5.08	(3,2,1,1,3,4,22)
	Heat, waste			MJ	3.34E+1	1	1.10	(2,2,2,3,1,3,2)
	Fluorine			kg	9.60E-6	1	1.59	(3,2,1,1,3,4,31)
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin			kg	1.00E-11	1	3.07	(3,2,1,1,3,4,21)
	Copper			kg	3.45E-5	1	5.08	(3,2,1,1,3,4,22)
	Cobalt			kg	1.06E-5	1	5.08	(3,2,1,1,3,4,22)
	Chromium			kg	3.54E-7	1	1.59	(3,2,1,1,3,4,31)
air, unspecified	Carbon dioxide, fossil			kg	2.06E-1	1	1.58	(4,2,1,1,4,4,14); excluding stdev of lime addition
water, river	Aluminum			kg	6.91E-7	1	10	reported values
	Arsenic, ion			kg	1.53E-7	1	10	reported values
	BOD5, Biological Oxygen Demand			kg	8.34E-5	1	10	reported values
	Cadmium, ion			kg	2.13E-8	1	10	reported values
	Calcium, ion			kg	5.49E-3	1	10	reported values
	Chromium, ion			kg	2.02E-7	1	10	reported values
	Cobalt			kg	6.25E-9	1	10	reported values
	COD, Chemical Oxygen Demand			kg	8.34E-5	1	10	reported values
	Copper, ion			kg	4.27E-7	1	10	reported values
	DOC, Dissolved Organic Carbon			kg	3.26E-5	1	10	reported values
	Iron, ion			kg	2.32E-6	1	10	reported values
	Lead			kg	1.33E-7	1	10	reported values
	Manganese			kg	1.97E-7	1	10	reported values
	Mercury			kg	2.27E-9	1	10	reported values
	Nickel, ion			kg	3.41E-7	1	10	reported values
	Nitrogen, organic bound			kg	1.82E-4	1	10	reported values
	Solved solids			kg	4.14E-5	1	10	reported values
	Sulfate			kg	1.89E-2	1	10	reported values
	Tin, ion			kg	1.97E-7	1	10	reported values
	TOC, Total Organic Carbon			kg	3.26E-5	1	10	reported values
	Zinc, ion			kg	1.19E-6	1	10	reported values
Outputs	ferronickel, 25% Ni, at plant	GLO	0	kg	1.00E+0			

Tab. 5.14 Unit process data of 1 kg of flat glass, uncoated, at plant, scenario REAL, corresponding to the NEEDS scenario realistic-optimistic (Frischknecht et al. 2008)

Explanations	Name	Location	Infrastructure-Process	Unit	flat glass, uncoated, at plant	uncertaintyType	StandardDeviation 95%	GeneralComment
	Location				RER			
	InfrastructureProcess				0			
	Unit				kg			
Technosphere	hydrogen, liquid, at plant	RER	0	kg	3.60E-6	1	5.00	(3,5,1,1,n.a.,5);
	nitrogen, liquid, at plant	RER	0	kg	4.95E-3	1	5.00	Estimation of standard deviation
	soda, powder, at plant	RER	0	kg	2.29E-1	1	1.62	(1,5,5,1,1,5);
	silica sand, at plant	DE	0	kg	5.78E-1	1	1.62	(1,5,5,1,1,5);
	refractory, fireclay, packed, at plant	DE	0	kg	1.07E-3	1	10.00	Estimation of standard deviation
	limestone, milled, packed, at plant	CH	0	kg	4.00E-1	1	1.62	(1,5,5,1,1,5);
	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	1.00E-1	1	1.32	(3,5,1,1,n.a.,5);
	flat glass plant	RER	1	unit	2.41E-10	1	3.14	(4,5,1,3,1,5);
	steel, converter, unalloyed, at plant	RER	0	kg	1.37E-5	1	1.26	(3,4,1,3,1,5);
	tin, at regional storage	RER	0	kg	9.16E-6	1	12.00	Estimation of standard deviation
	natural gas, high pressure, at consumer	RER	0	MJ	5.04E+0	1	1.32	(3,5,1,1,n.a.,5);
	heavy fuel oil, at regional storage	RER	0	kg	4.37E-2	1	1.32	(3,5,1,1,n.a.,5);
	transport, lorry 32t	RER	0	tkm	6.03E-2	1	2.09	(4,5,n.a,n.a,n.a,n.a);
	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	0	kg	1.10E-3	1	1.22	(1,3,1,1,3,1);
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	3.50E-4	1	5.00	Calculation of standard deviation based on min. and max. values
resource, in water	Water, cooling, unspecified natural origin			m3	7.00E-4	1	2.10	(2,5,3,n.a.,n.a.,n.a.);
air, unspecified	Carbon dioxide, fossil			kg	6.26E-1	1	1.38	(4,5,1,1,n.a.,5);
	Carbon monoxide, fossil			kg	5.00E-5	1	5.00	Calculation of standard deviation based on min. and max. values
	Hydrogen chloride			kg	4.50E-5	1	2.38	Calculation of standard deviation based on min. and max. values
	Hydrogen fluoride			kg	6.00E-6	1	3.33	Calculation of standard deviation based on min. and max. values
	Lead			kg	1.38E-5	1	5.38	(1,5,2,5,4,5);
	Nitrogen oxides			kg	2.00E-3	1	2.26	Calculation of standard deviation based on min. and max. values
	NMVOC, non-methane volatile organic compounds, unspecified origin			kg	5.00E-5	1	2.00	Calculation of standard deviation based on min. and max. values
	Particulates, < 2.5 um			kg	4.80E-5	1	52.60	Calculation of standard deviation based on min. and max. values
	Particulates, > 10 um			kg	6.00E-6	1	2.61	Calculation of standard deviation based on min. and max. values
	Particulates, > 2.5 um, and < 10um			kg	6.00E-6	1	2.61	Calculation of standard deviation based on min. and max. values
	Sulfur dioxide			kg	2.27E-3	1	2.63	Calculation of standard deviation based on min. and max. values
	Tin			kg	9.13E-6	1	12.00	Estimation of standard deviation
Outputs	flat glass, uncoated, at plant	RER	0	kg	1.00E+0			

Tab. 5.15 Unit process data of 1 kg of metallurgical-grade silicon, at plant, scenario REAL, corresponding to the NEEDS scenario realistic-optimistic (Frischknecht et al. 2008)

Explanations	Name	Location	Infrastructure-Process	Unit	MG-silicon, at plant	uncertaintyType	StandardDeviation 95%	GeneralComment
	Location				NO			
	InfrastructureProcess				0			
	Unit				kg			
Technosphere	oxygen, liquid, at plant	RER	0	kg	2.00E-2	1	1.29	(3,4,3,3,1,5); Literature
	silicone plant	RER	1	unit	1.00E-11	1	3.05	(1,2,1,1,3,3); Estimation
	silica sand, at plant	DE	0	kg	2.70E+0	1	1.09	(2,2,1,1,1,3); Literature
	electricity, medium voltage, at grid	NO	0	kWh	9.50E+0	1	1.09	(2,2,1,1,1,3); Literature, lower range to account for heat recovery
	hard coal coke, at plant	RER	0	MJ	2.60E+1	1	1.09	(2,2,1,1,1,3); Literature
	petroleum coke, at refinery	RER	0	kg	5.00E-1	1	1.09	(2,2,1,1,1,3); Literature
	transport, lorry 32t	RER	0	tkm	1.56E-1	1	2.10	(4,5,na,na,na,na); Standard distance 50km, 20km for sand
	transport, transoceanic freight ship	OCE	0	tkm	2.55E+0	1	2.10	(4,5,na,na,na,na); Charcoal from Asia 15000km
	transport, freight, rail	RER	0	tkm	6.90E-2	1	2.10	(4,5,na,na,na,na); Standard distance 100km
	disposal, slag from MG silicon production, 0% water, to inert material landfill	CH	0	kg	2.50E-2	1	1.09	(2,2,1,1,1,3); Literature
	charcoal, at plant	GLO	0	kg	1.70E-1	1	1.09	(2,2,1,1,1,3); Literature
	wood chips, mixed, u=120%, at forest	RER	0	m3	3.25E-3	1	1.09	(2,2,1,1,1,3); Literature
air, low population density	Aluminum			kg	1.20E-7	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Antimony			kg	6.08E-10	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Arsenic			kg	7.29E-10	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Boron			kg	2.16E-8	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Cadmium			kg	2.43E-11	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Calcium			kg	6.00E-8	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Carbon dioxide, biogenic			kg	1.61E+0	1	1.09	(2,2,1,1,1,3); Calculation
	Carbon dioxide, fossil			kg	3.61E+0	1	1.09	(2,2,1,1,1,3); Calculation
	Carbon monoxide, biogenic			kg	6.17E-4	1	5.09	(3,4,3,3,1,5); Literature
	Carbon monoxide, fossil			kg	1.38E-3	1	5.09	(3,4,3,3,1,5); Literature
	Chlorine			kg	6.08E-9	1	1.61	(3,4,3,3,1,5); Literature
	Chromium			kg	6.08E-10	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Cyanide			kg	5.32E-7	1	1.61	(3,4,3,3,1,5); Estimation
	Fluorine			kg	3.00E-9	1	1.61	(3,4,3,3,1,5); Literature, in dust
	Heat, waste			MJ	7.42E+1	1	1.09	(2,2,1,1,1,3); Literature
	Hydrogen fluoride			kg	5.00E-4	1	1.61	(3,4,3,3,1,5); Estimation
	Hydrogen sulfide			kg	5.00E-4	1	1.61	(3,4,3,3,1,5); Estimation
	Iron			kg	3.00E-7	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Lead			kg	2.66E-8	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Mercury			kg	6.08E-10	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Nitrogen oxides			kg	9.82E-3	1	1.52	(3,2,1,1,1,3); Calculation based on environmental report
	NMVOC, non-methane volatile organic compounds, unspecified origin			kg	9.60E-5	1	1.61	(3,4,3,3,1,5); Literature
	Particulates, > 10 um			kg	6.00E-4	1	1.52	(3,2,1,1,1,3); Calculation based on environmental report
	Potassium			kg	6.25E-5	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Silicon			kg	5.81E-4	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Sodium			kg	6.00E-8	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Sulfur dioxide			kg	1.23E-2	1	1.13	(3,2,1,1,1,3); Calculation based on environmental report
	Tin			kg	6.08E-10	1	5.09	(3,4,3,3,1,5); Literature, in dust
Outputs	MG-silicon, at plant	NO	0	kg	1.00E+0			

Tab. 5.16 Unit process data of 1 kg of nickel, 99.5 %, at plant, scenario REAL, corresponding to the NEEDS scenario realistic-optimistic (Frischknecht et al. 2008)

Explanations	Name	Location	Infrastructure-Process	Unit	nickel, 99.5%, at plant	uncertaintyType	StandardDeviation 95%	GeneralComment
	Location				GLO			
	InfrastructureProcess				0			
	Unit				kg			
Technosphere	limestone, milled, packed, at plant	CH	0	kg	1.93E+0	1	1.51	(5,2,2,3,1,3,4)
	blasting	RER	0	kg	1.20E-1	1	1.13	(2,2,2,1,1,4,4)
	conveyor belt, at plant	RER	1	m	3.05E-6	1	1.26	(3,2,2,1,3,4,4)
	diesel, burned in building machine	GLO	0	MJ	8.13E+0	1	1.13	(2,2,2,1,1,4,4)
	electricity, high voltage, production UCTE, at grid	UCTE	0	kWh	3.36E+0	1	1.1	(2,2,2,3,1,3,2)
	electricity, hydropower, at run-of-river power plant	RER	0	kWh	7.90E+0	1	1.14	(2,3,2,1,1,4,2)
	non-ferrous metal smelter	GLO	1	unit	3.35E-11	1	3.3	(4,2,1,5,4,4,9)
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	1.30E+1	1	1.25	(3,2,2,3,3,3,1)
	heavy fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	2.04E+1	1	1.1	(2,2,2,3,1,3,1)
	disposal, nickel smelter slag, 0% water, to residual material landfill	CH	0	kg	9.56E+0	1	2.15	(4,5,1,3,5,5,6)
	ammonia, liquid, at regional storehouse	RER	0	kg	8.37E-2	1	1.1	(2,2,2,3,1,3,4)
	chemicals inorganic, at plant	GLO	0	kg	6.15E-2	1	2	reported values
	hydrogen, liquid, at plant	RER	0	kg	4.56E-3	1	1.51	(5,2,2,3,1,3,4)
	chemicals organic, at plant	GLO	0	kg	1.80E-2	1	2	reported values
	hydrogen cyanide, at plant	RER	0	kg	2.79E-3	1	2	reported values
	sand, at mine	CH	0	kg	3.31E+1	1	1.13	(2,2,2,1,1,4,4)
	silica sand, at plant	DE	0	kg	1.89E+0	1	1.51	(5,2,2,3,1,3,4)
	portland calcareous cement, at plant	CH	0	kg	2.63E+0	1	1.13	(2,2,2,1,1,4,4)
	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	1.14E+0	1	1.14	(2,3,2,1,1,4,2)
	heat, at hard coal industrial furnace 1-10MW	RER	0	MJ	1.68E+0	1	1.1	(2,2,2,3,1,3,2)
	aluminium hydroxide, plant	RER	1	unit	6.71E-10	1	3.07	(3,2,2,1,3,4,9)
	non-ferrous metal mine, underground	GLO	1	unit	3.99E-9	1	3.07	(3,2,2,1,3,4,9)
	transport, lorry 32t	RER	0	tkm	1.80E+0	1	2.11	(3,2,2,1,3,5,5)
	disposal, sulfidic tailings, off-site	GLO	0	kg	5.36E+1	1	1.1	(2,2,2,3,1,3,6); reported values
	Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground			kg	1.26E+0	1	1.13	(2,2,2,1,1,4,12)
resource, in water	Water, river			m3	2.77E-2	1	1.13	(2,2,2,1,1,4,12)
	Water, well, in ground			m3	1.60E-1	1	1.13	(2,2,1,1,1,4,12)
	Arsenic			kg	1.86E-6	1	5.08	(3,2,1,1,3,4,22)
	Sulfur dioxide			kg	4.75E-1	1	1.64	(5,4,1,3,3,5,15)
	Silver			kg	4.42E-8	1	1.59	(3,2,1,1,3,4,31)
	NMVOC, non-methane volatile organic compounds, unspecified origin			kg	1.82E-4	1	1.59	(3,2,1,1,3,4,16)
	Magnesium			kg	8.78E-4	1	1.59	(3,2,1,1,3,4,31)
	Carbon disulfide			kg	7.98E-3	1	2.31	(4,2,2,5,4,4,23)
	Calcium			kg	1.03E-3	1	1.59	(3,2,1,1,3,4,31)
	Aluminum			kg	5.13E-4	1	1.59	(3,2,1,1,3,4,31)
	Zinc			kg	3.23E-5	1	5.08	(3,2,1,1,3,4,22)
	Tin			kg	2.09E-6	1	5.08	(3,2,1,1,3,4,22)
	Particulates, > 2.5 um, and < 10um			kg	4.64E-3	1	3.69	(3,2,1,1,5,4,20)
	Particulates, > 10 um			kg	5.37E-4	1	2.69	(3,2,1,1,5,4,19)
	Particulates, < 2.5 um			kg	5.23E-3	1	2.31	(4,2,2,5,4,4,23)
	Nickel			kg	1.36E-4	1	5.08	(3,2,1,1,3,4,22)
	Lead			kg	1.10E-5	1	5.08	(3,2,1,1,3,4,22)
	Heat, waste			MJ	5.27E+1	1	1.1	(2,2,2,3,1,3,2)
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin			kg	9.12E-12	1	3.07	(3,2,1,1,3,4,21)
	Copper			kg	1.16E-4	1	5.08	(3,2,1,1,3,4,22)
	Cobalt			kg	3.89E-4	1	5.08	(3,2,1,1,3,4,22)
air, unspecified	Carbon dioxide, fossil			kg	9.08E-1	1	1.58	(4,2,1,1,4,4,14); excluding stdev of lime addition
water, river	Aluminum			kg	1.38E-5	1	10	reported values
	Arsenic, ion			kg	6.87E-7	1	10	reported values
	BOD5, Biological Oxygen Demand			kg	1.67E-3	1	10	reported values
	Cadmium, ion			kg	8.19E-8	1	10	reported values
	Calcium, ion			kg	3.38E-2	1	10	reported values
	Chromium, ion			kg	4.17E-7	1	10	reported values
	Cobalt			kg	1.25E-7	1	10	reported values
	COD, Chemical Oxygen Demand			kg	1.67E-3	1	10	reported values
	Copper, ion			kg	1.87E-6	1	10	reported values
	DOC, Dissolved Organic Carbon			kg	6.51E-4	1	10	reported values
	Iron, ion			kg	4.64E-5	1	10	reported values
	Lead			kg	6.31E-7	1	10	reported values
	Manganese			kg	3.94E-6	1	10	reported values
	Mercury			kg	9.31E-9	1	10	reported values
	Nickel, ion			kg	4.14E-6	1	10	reported values
	Nitrogen, organic bound			kg	3.64E-3	1	10	reported values
	Solved solids			kg	8.27E-4	1	10	reported values
	Sulfate			kg	3.77E-1	1	10	reported values
	Tin, ion			kg	3.29E-7	1	10	reported values
	TOC, Total Organic Carbon			kg	6.51E-4	1	10	reported values
	Zinc, ion			kg	1.31E-5	1	10	reported values
water, lake	Calcium, ion			kg	7.55E-2	1	10	reported values
water, river	Cyanide			kg	2.99E-4	1	1.84	(4,2,2,3,4,4,33)
	nickel, 99.5%, at plant	GLO	0	kg	1.00E+0			

Tab. 5.17 Unit process data of 1 kg of pig iron, at plant, scenario REAL, corresponding to the NEEDS scenario realistic-optimistic (Frischknecht et al. 2008)

Explanations	Name	Location	Infrastructure-Process	Unit	pig iron, at plant	uncertaintyType	StandardDeviation 95%	GeneralComment
	Location				GLO			
	InfrastructureProcess				0			
	Unit				kg			
Technosphere	limestone, at mine	CH	0	kg	1.00E-2	1	1.10	(1,2,1,3,1,1);
	refractory, fireclay, packed, at plant	DE	0	kg	2.00E-3	1	1.10	(1,2,1,3,1,1);
	hard coal coke, at plant	RER	0	MJ	7.72E+0	1	1.10	(1,2,1,3,1,1);
	hard coal mix, at regional storage	UCTE	0	kg	2.10E-1	1	1.10	(1,2,1,3,1,1);
	blast furnace	RER	1	unit	1.33E-11	1	3.20	(5,nA,nA,nA,nA,nA);
	iron ore, 65% Fe, at beneficiation	GLO	0	kg	1.50E-1	1	1.10	(1,2,1,1,1,1);
	pellets, iron, at plant	GLO	0	kg	4.00E-1	1	1.10	(1,2,1,1,1,1);
	sinter, iron, at plant	GLO	0	kg	1.05E+0	1	1.10	(1,2,1,1,1,1);
	transport, lorry 32t	RER	0	tkm	3.48E-3	1	2.10	(4,5,nA,nA,nA,nA);
	transport, barge	RER	0	tkm	1.65E-2	1	2.00	(2,nA,1,3,1,3);
	transport, transoceanic freight ship	OCE	0	tkm	1.48E+0	1	2.00	(2,nA,1,1,1,3);
	transport, freight, rail	RER	0	tkm	1.86E-1	1	2.10	(4,5,nA,nA,nA,nA);
	disposal, inert waste, 5% water, to inert material landfill	CH	0	kg	2.07E-2	1	1.10	(2,3,2,3,1,3);
	disposal, sludge, pig iron production, 8.6% water, to residual material landfill	CH	0	kg	1.50E-3	1	3.00	(2,3,2,3,1,3);
	treatment, pig iron production effluent, to wastewater treatment, class 3	CH	0	m3	1.81E-6	1	1.10	(2,3,2,3,1,3);
resource, in water	Water, unspecified natural origin			m3	6.00E-3	1	1.10	(1,2,1,1,1,1);
air, unspecified	Carbon dioxide, fossil			kg	3.61E-1	1	1.10	(2,3,2,3,1,3);
	Carbon monoxide, fossil			kg	1.17E-3	1	5.00	(2,3,2,3,1,3);
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin			kg	1.06E-15	1	3.00	(2,3,2,3,1,3);
	Heat, waste			MJ	4.90E-1	1	1.10	(1,2,1,3,1,1);
	Hydrogen sulfide			kg	2.13E-7	1	1.50	(2,3,2,3,1,3);
	Lead			kg	1.06E-8	1	5.00	(2,3,2,3,1,3);
	Manganese			kg	1.06E-8	1	5.00	(2,3,2,3,1,3);
	Nickel			kg	1.06E-8	1	5.00	(2,3,2,3,1,3);
	Nitrogen oxides			kg	3.19E-5	1	1.50	(2,3,2,3,1,3);
	Particulates, < 2.5 um			kg	9.57E-6	1	3.00	(2,3,2,3,1,3);
	Particulates, > 10 um			kg	5.32E-7	1	1.50	(2,3,2,3,1,3);
	Particulates, > 2.5 um, and < 10um			kg	5.32E-7	1	2.00	(2,3,2,3,1,3);
	Sulfur dioxide			kg	2.13E-5	1	1.10	(2,3,2,3,1,3);
Outputs	pig iron, at plant	GLO	0	kg	1.00E+0			

Tab. 5.18 Unit process data of 1 kg of sinter, iron, at plant, scenario REAL, corresponding to the NEEDS scenario realistic-optimistic (Frischknecht et al. 2008)

Explanations	Name	Location	Infrastructure-Process	Unit	sinter, iron, at plant			
	Location				GLO			
	InfrastructureProcess				0			
	Unit				kg			
Technosphere	quicklime, in pieces, loose, at plant	CH	0	kg	5.00E-2	1	1.10	(1,2,1,3,1,1);
	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	1.00E-2	1	1.10	(1,2,1,3,1,1);
	hard coal coke, at plant	RER	0	MJ	1.14E+0	1	1.10	(1,2,1,3,1,1);
	aluminium oxide, plant	RER	1	unit	2.50E-11	1	5.00	rough estimation
	iron ore, 65% Fe, at beneficiation	GLO	0	kg	1.05E+0	1	1.10	(1,2,1,1,1,1);
	natural gas, high pressure, at consumer	RER	0	MJ	2.90E-2	1	1.10	(1,2,1,3,1,1);
	transport, lorry 32t	RER	0	tkm	2.00E-3	1	2.10	(4,5,nA,nA,nA,nA);
	transport, barge	RER	0	tkm	3.15E-2	1	2.00	(2,nA,1,3,1,3);
	transport, transoceanic freight ship	OCE	0	tkm	2.84E+0	1	2.00	(2,nA,1,1,1,3);
	transport, freight, rail	RER	0	tkm	3.09E-1	1	2.10	(4,5,nA,nA,nA,nA);
resource, in water	Water, unspecified natural origin			m3	5.00E-4	1	1.10	(1,2,1,1,1,1);
air, unspecified	Cadmium			kg	1.83E-9	1	5.00	(2,3,2,3,1,3);
	Carbon dioxide, fossil			kg	1.55E-1	1	1.10	(2,3,2,3,1,3);
	Carbon monoxide, fossil			kg	1.95E-2	1	5.00	(2,3,2,3,1,3);
	Chromium			kg	4.59E-9	1	5.00	(2,3,2,3,1,3);
	Copper			kg	6.42E-9	1	5.00	(2,3,2,3,1,3);
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin			kg	4.59E-13	1	3.00	(1,3,2,3,1,2);
	Heat, waste			MJ	1.54E+0	1	1.10	(1,2,1,3,1,1);
	Hydrocarbons, aliphatic, alkanes, unspecified			kg	1.37E-4	1	1.50	(2,3,2,3,1,3);
	Hydrogen chloride			kg	1.56E-5	1	1.50	(2,3,2,3,1,3);
	Hydrogen fluoride			kg	1.28E-6	1	1.50	(2,3,2,3,1,3);
	Lead			kg	3.67E-8	1	5.00	(2,3,2,3,1,3);
	Manganese			kg	1.83E-8	1	5.00	(2,3,2,3,1,3);
	Mercury			kg	1.47E-8	1	5.00	(2,3,2,3,1,3);
	Nickel			kg	1.83E-9	1	5.00	(2,3,2,3,1,3);
	Nitrogen oxides			kg	4.04E-4	1	1.50	(2,3,2,3,1,3);
	PAH, polycyclic aromatic hydrocarbons			kg	1.05E-7	1	3.00	(2,3,2,3,1,3);
	Particulates, < 2.5 um			kg	2.10E-5	1	3.00	(2,3,2,3,1,3);
	Polychlorinated biphenyls			kg	9.17E-10	1	3.00	(2,3,2,3,1,3);
	Sulfur dioxide			kg	8.25E-4	1	1.10	(2,3,2,3,1,3);
	Titanium			kg	4.59E-9	1	5.00	(2,3,2,3,1,3);
	Vanadium			kg	4.59E-9	1	5.00	(2,3,2,3,1,3);
	Zinc			kg	1.83E-9	1	5.00	(2,3,2,3,1,3);
	Aluminium	-	-	kg	1.80E-11	1	5.00	(2,3,2,3,1,3);
	Arsenic, ion	-	-	kg	6.00E-14	1	5.00	(2,3,2,3,1,3);
	Cadmium, ion	-	-	kg	1.30E-13	1	5.00	(2,3,2,3,1,3);
	Chloride	-	-	kg	3.10E-7	1	5.00	(2,3,2,3,1,3);
	Chromium, ion	-	-	kg	6.00E-13	1	5.00	(2,3,2,3,1,3);
	Copper, ion	-	-	kg	4.00E-12	1	5.00	(2,3,2,3,1,3);
	Cyanide	-	-	kg	1.30E-12	1	5.00	(2,3,2,3,1,3);
	Iron, ion	-	-	kg	1.40E-11	1	5.00	(2,3,2,3,1,3);
	Mercury	-	-	kg	9.00E-14	1	5.00	(2,3,2,3,1,3);
	Nickel, ion	-	-	kg	3.00E-12	1	5.00	(2,3,2,3,1,3);
	Lead	-	-	kg	4.00E-12	1	5.00	(2,3,2,3,1,3);
	Zinc, ion	-	-	kg	1.60E-12	1	5.00	(2,3,2,3,1,3);
	Sulfate	-	-	kg	1.60E-7	1	5.00	(2,3,2,3,1,3);
	Fluoride	-	-	kg	4.30E-10	1	5.00	(2,3,2,3,1,3);
	Sulfide	-	-	kg	4.00E-12	1	5.00	(2,3,2,3,1,3);
	Ammonium, ion	-	-	kg	9.13E-9	1	5.00	(2,3,2,3,1,3);
	Nitrate	-	-	kg	4.87E-9	1	5.00	(2,3,2,3,1,3);
	Nitrite	-	-	kg	1.31E-10	1	5.00	(2,3,2,3,1,3);
	TOC, Total Organic Carbon	-	-	kg	1.10E-9	1	5.00	(2,3,2,3,1,3);
	sinter, iron, at plant	GLO	0	kg	1.00E+0			

Tab. 5.19 Unit process data of 1 kg of zinc, primary, at regional storage, scenario REAL, corresponding to the NEEDS scenario realistic-optimistic (Frischknecht et al. 2008)

Explanations	Name	Location	Infrastructure-Process	Unit	zinc, primary, at regional storage	uncertaintyType	StandardDeviation 95%	GeneralComment
	Location				RER			
	InfrastructureProcess				0			
	Unit				kg			
Technosphere	oxygen, liquid, at plant	RER	0	kg	1.08E-1	1	1.25	(3,3,2,1,3,3,4)
	diesel, burned in building machine	GLO	0	MJ	4.19E-2	1	1.25	(3,3,2,1,3,3,2)
	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	1.23E+0	1	1.31	(4,3,2,1,3,3,2)
	hard coal, burned in industrial furnace 1-10MW	RER	0	MJ	4.46E+0	1	1.25	(3,3,2,1,3,3,1)
	electricity, hydropower, at run-of-river power plant	RER	0	kWh	1.85E+0	1	1.31	(4,3,2,1,3,3,2)
	iron ore, 46% Fe, at mine	GLO	0	kg	2.80E-1	1	1.25	(3,3,2,1,3,3,4)
	zinc concentrate, at beneficiation	GLO	0	kg	2.53E+0	1	1.33	(3,3,2,1,3,5,4)
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	1.04E+0	1	1.25	(3,3,2,1,3,3,1)
	transport, lorry 32t	RER	0	tkm	4.06E-1	1	1.31	(4,3,1,1,3,3,2)
	transport, transoceanic freight ship	OCE	0	tkm	9.47E+0	1	2.10	(4,3,2,1,3,3,5)
	transport, freight, rail	RER	0	tkm	2.25E+0	1	1.31	(4,3,1,1,3,3,2)
	steam, for chemical processes, at plant	RER	0	kg	1.09E+0	1	1.25	(3,3,2,1,3,3,1)
	disposal, inert waste, 5% water, to inert material landfill	CH	0	kg	3.75E-1	1	1.25	(3,3,2,1,3,3,6)
	treatment, sewage, unpolluted, to wastewater treatment, class 3	CH	0	m3	3.90E-2	1	1.25	(3,3,2,1,3,3,6)
resource, in water	Water, river			m3	3.90E-2	1	1.25	(3,3,2,1,3,3,2)
air, low population density	Arsenic			kg	1.26E-5	1	5.04	(3,4,2,1,1,4,22)
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin			kg	1.00E-11	1	3.04	(3,4,2,1,1,4,21)
	Lead			kg	2.68E-5	1	5.04	(3,4,2,1,1,4,22)
	Mercury			kg	1.00E-6	1	5.04	(3,4,2,1,1,4,22)
	Particulates, < 2.5 um			kg	9.30E-5	1	3.04	(3,4,2,1,1,4,27)
	Particulates, > 10 um			kg	1.85E-5	1	1.46	(3,4,2,1,1,4,29)
	Particulates, > 2.5 um, and < 10um			kg	1.85E-5	1	1.28	(3,4,2,1,1,4,28)
	Sulfur dioxide			kg	8.86E-3	1	1.19	(3,4,2,1,1,4,15)
	Zinc			kg	5.20E-4	1	5.04	(3,4,2,1,1,4,22)
water, river	Arsenic, ion			kg	1.18E-6	1	5.02	(1,3,1,3,1,4,35)
	BOD5, Biological Oxygen Demand			kg	3.11E-4	1	1.65	(3,5,1,3,3,4,32)
	Cadmium, ion			kg	3.68E-6	1	5.02	(1,3,1,3,1,4,35)
	COD, Chemical Oxygen Demand			kg	4.66E-4	1	1.60	(3,3,1,3,3,4,32)
	Copper, ion			kg	4.00E-6	1	5.02	(1,3,1,3,1,4,35)
	DOC, Dissolved Organic Carbon			kg	1.82E-4	1	1.65	(3,5,1,3,3,4,32)
	Fluoride			kg	2.98E-5	1	1.58	(1,3,1,3,3,4,32)
	Lead			kg	4.20E-5	1	5.02	(1,3,1,3,1,4,35)
	Mercury			kg	1.72E-7	1	5.02	(1,3,1,3,1,4,35)
	TOC, Total Organic Carbon			kg	1.82E-4	1	1.65	(3,5,1,3,3,4,32)
	Zinc, ion			kg	4.58E-5	1	5.02	(1,3,1,3,1,4,35)
Outputs	zinc, primary, at regional storage	RER	0	kg	1.00E+0			

Tab. 5.20 through Tab. 5.29 show the unit process data of 1 kg of the production of materials in the scenario OPT, which corresponds to the very optimistic scenario defined in the NEEDS project.

Tab. 5.20 Unit process data of 1 kg of clinker, at plant, scenario OPT, corresponding to the NEEDS scenario very optimistic (Frischknecht et al. 2008)

Explanations	Name	Location	Infrastructure-Process	Unit	clinker, at plant	uncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				kg			
Technosphere	ammonia, liquid, at regional storehouse	CH	0	kg	9.08E-4	1	1.22	(2,1,1,1,1,5);
	lubricating oil, at plant	RER	0	kg	4.71E-5	1	1.22	(2,1,1,2,1,5);
	calcareous marl, at plant	CH	0	kg	4.66E-1	1	1.22	(2,1,1,1,1,5);
	clay, at mine	CH	0	kg	3.31E-1	1	1.22	(2,1,1,2,1,5);
	limestone, milled, loose, at plant	CH	0	kg	8.41E-1	1	1.22	(2,1,1,1,1,5);
	sand, at mine	CH	0	kg	9.26E-3	1	1.22	(2,1,1,1,1,5);
	lime, hydrated, loose, at plant	CH	0	kg	3.92E-3	1	1.22	(2,1,1,1,1,5);
	refractory, basic, packed, at plant	DE	0	kg	1.90E-4	1	1.22	(2,1,1,1,1,5);
	refractory, fireclay, packed, at plant	DE	0	kg	8.21E-5	1	1.22	(2,1,1,1,1,5);
	refractory, high aluminium oxide, packed, at plant	DE	0	kg	1.37E-4	1	1.22	(2,1,1,1,1,5);
	cement plant	CH	1	unit	6.27E-12	1	3.05	(2,1,1,1,1,5);
	diesel, burned in building machine	GLO	0	MJ	1.34E-2	1	1.22	(2,1,1,2,1,5);
	Industrial machine, heavy, unspecified, at plant	RER	1	kg	3.76E-5	1	3.10	(4,4,1,1,1,5);
	electricity, medium voltage, at grid	CH	0	kWh	5.80E-2	1	1.22	(2,1,1,1,1,5);
technology	hard coal, at regional storage	WEU	0	kg	6.14E-3	1	1.22	(2,1,1,2,1,5);
	bauxite, at mine	GLO	0	kg	1.20E-4	1	1.22	(2,1,1,2,1,5);
	chromium steel 18/8, at plant	RER	0	kg	5.86E-5	1	1.22	(2,1,1,2,1,5);
	natural gas, high pressure, at consumer	CH	0	MJ	4.38E-2	1	1.22	(2,1,1,1,1,5);
	heavy fuel oil, at regional storage	CH	0	kg	4.41E-3	1	1.22	(2,1,1,1,1,5);
	light fuel oil, at regional storage	CH	0	kg	7.26E-5	1	1.22	(2,1,1,1,1,5);
	petroleum coke, at refinery	RER	0	kg	7.58E-4	1	1.22	(2,1,1,2,1,5);
	charcoal, at plant	GLO	0	kg	0			
	transport, lorry 16t	CH	0	tkm	8.61E-5	1	2.06	(3,3,1,1,1,5);
	transport, lorry 28t	CH	0	tkm	2.68E-3	1	2.05	(2,1,1,1,1,5);
	transport, lorry 40t	CH	0	tkm	2.11E-3	1	2.05	(2,1,1,1,1,5);
	transport, van <3.5t	CH	0	tkm	7.09E-5	1	2.05	(2,1,1,2,1,5);
	transport, barge	RER	0	tkm	7.22E-3	1	2.05	(2,1,1,2,1,5);
	transport, freight, rail	RER	0	tkm	7.09E-3	1	2.05	(2,1,1,2,1,5);
	transport, freight, rail	CH	0	tkm	1.77E-2	1	2.06	(3,3,1,1,1,5);
	disposal, inert waste, 5% water, to inert material landfill	CH	0	kg	8.00E-5	1	1.22	(2,1,1,1,1,5);
	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	0	kg	4.50E-5	1	1.22	(2,1,1,1,1,5);
	tap water, at user	RER	0	kg	3.40E-1	1	1.22	(2,1,1,2,1,5);
resource, in water	Water, unspecified natural origin			m3	1.62E-3	1	1.22	(2,1,1,1,1,5);
air, unspecified	Ammonia			kg	2.28E-5	1	1.56	(2,1,1,1,1,5);
	Antimony			kg	2.00E-9	1	5.06	(2,1,1,1,1,5);
	Arsenic			kg	1.20E-8	1	1.56	(2,1,1,1,1,5);
	Beryllium			kg	3.00E-9	1	1.56	(2,1,1,1,1,5);
	Cadmium			kg	7.00E-9	1	1.56	(2,1,1,1,1,5);
	Carbon dioxide, biogenic			kg	1.57E-2	1	1.22	(2,1,1,1,1,5);
Air, unspecified	Carbon dioxide, fossil			kg	6.59E-1	1	1.22	(2,1,1,1,1,5);
	Carbon monoxide, fossil			kg	1.00E-4	1	2.05	(2,1,1,1,1,5);
	Chromium			kg	1.45E-9	1	1.56	(2,1,1,1,1,5);
	Chromium VI			kg	5.50E-10	1	1.56	(2,1,1,1,1,5);
	Cobalt			kg	4.00E-9	1	1.56	(2,1,1,1,1,5);
	Copper			kg	1.40E-8	1	1.56	(2,1,1,1,1,5);
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin			kg	9.60E-13	1	2.05	(2,1,1,1,1,5);
	Heat, waste			MJ	3.62E+0	1	1.22	(2,1,1,1,1,5);
	Hydrogen chloride			kg	6.31E-6	1	1.56	(2,1,1,1,1,5);
	Lead			kg	8.50E-8	1	5.06	(2,1,1,1,1,5);
	Mercury			kg	3.30E-8	1	1.56	(2,1,1,1,1,5);
	Methane, fossil			kg	8.88E-6	1	2.05	(2,1,1,1,1,5);
	Nickel			kg	5.00E-9	1	1.56	(2,1,1,1,1,5);
	Nitrogen oxides			kg	1.60E-4	1	1.56	(2,1,1,1,1,5);
	NMVOC, non-methane volatile organic compounds, unspecified origin			kg	5.64E-5	1	2.05	(2,1,1,1,1,5);
	Zinc			kg	6.00E-8	1	1.56	(2,1,1,1,1,5);
	Vanadium			kg	5.00E-9	1	1.56	(2,1,1,1,1,5);
	Tin			kg	9.00E-9	1	5.06	(2,1,1,1,1,5);
	Thallium			kg	1.30E-8	1	1.56	(2,1,1,1,1,5);
	Sulfur dioxide			kg	1.00E-5	1	1.56	(2,1,1,1,1,5);
	Selenium			kg	2.00E-9	1	5.06	(2,1,1,1,1,5);
air, low population density	Particulates, < 2.5 um			kg	6.40E-6	1	3.05	(2,1,1,1,1,5);
	Particulates, > 10 um			kg	1.50E-6	1	1.56	(2,1,1,1,1,5);
	Particulates, > 2.5 um, and < 10um			kg	2.10E-6	1	2.05	(2,1,1,1,1,5);
Outputs	clinker, at plant	CH	0	kg	1.00E+0			

Tab. 5.21 Unit process data of 1 kg of copper, primary, at refinery RER, scenario OPT, corresponding to the NEEDS scenario very optimistic (Frischknecht et al. 2008)

Explanations	Name	Location	Infrastructure-Process	Unit	copper, primary, at refinery	uncertaintyType	StandardDeviation 95%	GeneralComment
	Location				RER			
	InfrastructureProcess				0			
	Unit				kg			
Technosphere	limestone, milled, packed, at plant	CH	0	kg	2.50E-1	1	1.51	(5,2,2,3,1,3,4)
	electricity, hydropower, at run-of-river power plant	RER	0	kWh	2.62E-1	1	1.10	(2,2,2,3,1,3,2)
	oxygen, liquid, at plant	RER	0	kg	3.00E-1	1	1.10	(2,2,2,3,1,3,4)
	silica sand, at plant	DE	0	kg	7.50E-1	1	1.51	(5,2,2,3,1,3,4)
	electricity, high voltage, production UCTE, at grid	UCTE	0	kWh	1.75E-1	1	1.10	(2,2,2,3,1,3,2)
	anode, aluminium electrolysis	RER	0	kg	1.00E-3	1	2.07	(5,5,5,6,4,6,4)
	non-ferrous metal smelter	GLO	1	unit	1.14E-11	1	3.07	(3,2,2,1,3,4,9)
	natural gas, burned in industrial furnace >100kW	RER	-	MJ	6.62E+0	1	1.10	(2,2,2,3,1,3,1)
	heavy fuel oil, burned in industrial furnace 1MW, non-modulating	RER	-	MJ	0	1	1.10	(2,2,2,3,1,3,1)
	disposal, nickel smelter slag, 0% water, to residual material landfill	CH	-	kg	9.25E-1	1	1.10	(2,2,2,3,1,3,6)
	treatment, sewage, unpolluted, to wastewater treatment, class 3	CH	-	m3	5.80E-3	1	1.13	(2,2,1,1,1,4,13)
	copper concentrate, at beneficiation	RER	-	kg	4.14E+0	1	1.10	(2,2,2,3,1,3,4)
resource, in water	Water, river			m3	5.80E-3	1	1.13	(2,2,1,1,1,4,12)
air, low population density	Antimony			kg	1.00E-6	1	5.08	(3,2,1,1,3,4,22)
	Arsenic			kg	1.50E-5	1	5.08	(3,2,1,1,3,4,22)
	Cadmium			kg	3.00E-6	1	5.08	(3,2,1,1,3,4,22)
	Carbon dioxide, fossil			kg	1.10E-1	1	1.89	(5,4,1,3,3,5,7)
	Chromium			kg	5.00E-8	1	5.08	(3,2,1,1,3,4,22)
	Copper			kg	2.00E-4	1	5.08	(3,2,1,1,3,4,22)
	Heat, waste			MJ	1.97E+0	1	1.14	(2,3,2,1,1,4,13)
	Lead			kg	5.00E-5	1	5.08	(3,2,1,1,3,4,22)
	Manganese			kg	5.00E-6	1	5.08	(3,2,1,1,3,4,22)
	Mercury			kg	1.00E-7	1	5.08	(3,2,1,1,3,4,22)
	Nickel			kg	1.00E-5	1	5.08	(3,2,1,1,3,4,22)
	Particulates, < 2.5 um			kg	2.00E-7	1	3.07	(3,2,1,1,3,4,27)
	Particulates, > 10 um			kg	4.01E-5	1	1.50	(3,2,1,1,3,4,29)
	Particulates, > 2.5 um, and < 10um			kg	1.20E-4	1	1.34	(3,2,1,1,3,4,28)
	Selenium			kg	1.00E-6	1	5.08	(3,2,1,1,3,4,22)
	Zinc			kg	1.50E-4	1	5.08	(3,2,1,1,3,4,22)
	Vanadium			kg	2.50E-7	1	5.08	(3,2,1,1,3,4,22)
	Tin			kg	2.50E-6	1	5.08	(3,2,1,1,3,4,22)
	Sulfur dioxide			kg	6.00E-3	1	1.64	(5,4,1,3,3,5,15)
	NMVOC, non-methane volatile organic compounds, unspecified origin			kg	1.50E-5	1	1.59	(3,2,1,1,3,4,16)
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin			kg	2.50E-13	1	3.07	(3,2,1,1,3,4,21)
	Carbon monoxide, fossil			kg	3.00E-5	1	5.08	(3,2,1,1,3,4,22)
water, river	Arsenic, ion			kg	1.08E-7	1	10.00	reported values
	Cadmium, ion			kg	1.58E-8	1	10.00	reported values
	Chromium, ion			kg	1.66E-7	1	10.00	reported values
	Copper, ion			kg	3.05E-7	1	10	reported values
	Lead			kg	9.26E-8	1	10	reported values
	Mercury			kg	1.66E-9	1	10	reported values
	Nickel, ion			kg	1.23E-7	1	10	reported values
	Zinc, ion			kg	4.91E-7	1	10	reported values
	Tin, ion			kg	1.66E-7	1	10	reported values
Outputs	copper, primary, at refinery	RER	0	kg	1.00E+0			

Tab. 5.22 Unit process data of 1 kg of copper, primary, at refinery RLA, scenario OPT, corresponding to the NEEDS scenario very optimistic (Frischknecht et al. 2008)

Explanations	Name	Location	Infrastructure-Process	Unit	copper, primary, at refinery	uncertaintyType	StandardDeviation 95%	GeneralComment
	Location				RLA			
	InfrastructureProcess				0			
	Unit				kg			
Technosphere	oxygen, liquid, at plant	RER	0	kg	9.86E-2	1	1.10	(2,2,2,3,1,3,4)
	silica sand, at plant	DE	0	kg	4.88E-1	1	1.51	(5,2,2,3,1,3,4)
	limestone, milled, packed, at plant	CH	0	kg	1.63E-1	1	1.51	(5,2,2,3,1,3,4)
	electricity, high voltage, production UCTE, at grid	UCTE	0	kWh	1.21E-1	1	1.10	(2,2,2,3,1,3,2)
	electricity, hydropower, at run-of-river power plant	RER	0	kWh	1.82E-1	1	1.10	(2,2,2,3,1,3,2)
	anode, aluminium electrolysis	RER	0	kg	6.50E-5	1	2.07	(5,5,5,6,4,6,4)
	copper concentrate, at beneficiation	RLA	0	kg	2.07E+0	1	1.10	(2,2,2,3,1,3,4)
	copper, SX-EW, at refinery	GLO	0	kg	1.39E-1	1	1.10	(2,2,2,3,1,3,1)
	non-ferrous metal smelter	GLO	1	unit	8.75E-12	1	3.07	(3,2,2,1,3,4,9)
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	1.74E+0	1	1.10	(2,2,2,3,1,3,1)
	heavy fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	4.96E+0	1	1.10	(2,2,2,3,1,3,1)
	disposal, nickel smelter slag, 0% water, to residual material landfill	CH	0	kg	5.70E-1	1	1.10	(2,2,2,3,1,3,6)
	treatment, sewage, unpolluted, to wastewater treatment, class 3	CH	0	m3	2.90E-3	1	1.13	(2,2,1,1,1,4,13)
resource, in water	Water, river			m3	2.90E-3	1	1.13	(2,2,1,1,1,4,12)
air, low population density	Antimony			kg	6.50E-7	1	5.08	(3,2,1,1,3,4,22)
	Arsenic			kg	9.75E-6	1	5.08	(3,2,1,1,3,4,22)
	Cadmium			kg	1.95E-6	1	5.08	(3,2,1,1,3,4,22)
	Carbon dioxide, fossil			kg	9.07E-2	1	1.89	(5,4,1,3,3,5,7)
	Carbon monoxide, fossil			kg	2.47E-5	1	5.08	(3,2,1,1,3,4,22)
	Chromium			kg	3.25E-8	1	5.08	(3,2,1,1,3,4,22)
	Copper			kg	1.30E-4	1	5.08	(3,2,1,1,3,4,22)
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin			kg	1.65E-12	1	3.07	(3,2,1,1,3,4,21)
	Heat, waste			MJ	1.39E+0	1	1.14	(2,3,2,1,1,4,13)
	Lead			kg	3.25E-5	1	5.08	(3,2,1,1,3,4,22)
	Manganese			kg	3.25E-6	1	5.08	(3,2,1,1,3,4,22)
	Mercury			kg	6.50E-8	1	5.08	(3,2,1,1,3,4,22)
	Nickel			kg	6.50E-6	1	5.08	(3,2,1,1,3,4,22)
	NMVOC, non-methane volatile organic compounds, unspecified origin			kg	1.24E-5	1	1.59	(3,2,1,1,3,4,16)
	Particulates, < 2.5 um			kg	4.19E-7	1	3.07	(3,2,1,1,3,4,27)
	Particulates, > 10 um			kg	8.38E-5	1	1.50	(3,2,1,1,3,4,29)
	Particulates, > 2.5 um, and < 10um			kg	2.51E-4	1	1.34	(3,2,1,1,3,4,28)
	Selenium			kg	6.50E-7	1	5.08	(3,2,1,1,3,4,22)
	Sulfur dioxide			kg	4.88E-3	1	1.64	(5,4,1,3,3,5,15)
	Tin			kg	1.63E-6	1	5.08	(3,2,1,1,3,4,22)
	Vanadium			kg	1.63E-7	1	5.08	(3,2,1,1,3,4,22)
	Zinc			kg	6.50E-5	1	5.08	(3,2,1,1,3,4,22)
water, river	Arsenic, ion			kg	6.86E-8	1	10.00	reported values
	Cadmium, ion			kg	1.00E-8	1	10.00	reported values
	Chromium, ion			kg	1.05E-7	1	10.00	reported values
	Copper, ion			kg	1.93E-7	1	10.00	reported values
	Lead			kg	5.86E-8	1	10.00	reported values
	Mercury			kg	1.05E-9	1	10.00	reported values
	Nickel, ion			kg	7.80E-8	1	10.00	reported values
	Tin, ion			kg	1.05E-7	1	10.00	reported values
	Zinc, ion			kg	3.11E-7	1	10.00	reported values
Outputs	copper, primary, at refinery	RLA	0	kg	1.00E+0			

Tab. 5.23 Unit process data of 1 kg of ferronickel, 25 % Ni, at plant, scenario OPT, corresponding to the NEEDS scenario very optimistic (Frischknecht et al. 2008)

Explanations	Name	Location	Infrastructure-Process	Unit	ferronickel, 25% Ni, at plant	uncertaintyType	StandardDeviation 95%	GeneralComment
	Location				GLO			
	InfrastructureProcess				0			
	Unit				kg			
Technosphere	limestone, milled, packed, at plant	CH	0	kg	4.69E-1	1	1.51	(5,2,2,3,1,3,4)
	blasting	RER	0	kg	1.20E-3	1	1.13	(2,2,2,1,1,4,4)
	conveyor belt, at plant	RER	1	m	8.00E-7	1	1.26	(3,2,2,1,3,4,4)
	diesel, burned in building machine	GLO	0	MJ	1.91E+0	1	1.13	(2,2,2,1,1,4,4)
	electricity, high voltage, production UCTE, at grid	UCTE	0	kWh	6.23E+0	1	1.10	(2,2,2,3,1,3,2)
	hard coal, burned in industrial furnace 1-10MW	RER	0	MJ	1.60E+1	1	1.10	(2,2,2,3,1,3,1)
	wood chips, from industry, mixed, burned in furnace 1000kW	CH	0	MJ	1.45E+1	1	2.00	
	electricity, hydropower, at run-of-river power plant	RER	0	kWh	1.19E+0	1	1.10	(2,2,2,3,1,3,2)
	non-ferrous metal smelter	GLO	1	unit	6.48E-11	1	3.07	(3,2,2,1,3,4,9)
	non-ferrous metal mine, surface	GLO	1	unit	2.00E-9	1	3.07	(3,2,2,1,3,4,9)
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	2.70E+1	1	1.10	(2,2,2,3,1,3,1)
	heavy fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	1.50E+0	1	1.10	(2,2,2,3,1,3,1)
	disposal, nickel smelter slag, 0% water, to residual material landfill	CH	0	kg	1.27E+1	1	2.15	(4,5,1,3,5,5,6)
resource, in ground	Nickel, 1.98% in silicates, 1.04% in crude ore, in ground			kg	1.74E+0	1	1.13	(2,2,2,1,1,4,12)
resource, land	Occupation, mineral extraction site			m2a	1.65E-3	1	1.59	(3,2,2,1,3,4,7)
	Transformation, from unknown			m2	5.49E-5	1	3.07	(3,2,2,1,3,4,9)
	Transformation, to mineral extraction site			m2	5.49E-5	1	2.08	(3,2,2,1,3,4,8)
air, low population density	Antimony			kg	3.54E-10	1	1.59	(3,2,1,1,3,4,31)
	Arsenic			kg	2.52E-6	1	5.08	(3,2,1,1,3,4,22)
	Beryllium			kg	4.60E-9	1	1.59	(3,2,1,1,3,4,31)
	Boron			kg	1.77E-8	1	1.59	(3,2,1,1,3,4,31)
	Cadmium			kg	1.94E-10	1	1.59	(3,2,1,1,3,4,31)
	Zinc			kg	4.38E-5	1	5.08	(3,2,1,1,3,4,22)
	Tin			kg	2.82E-6	1	5.08	(3,2,1,1,3,4,22)
	Selenium			kg	8.84E-11	1	1.59	(3,2,1,1,3,4,31)
	Particulates, > 2.5 um, and < 10um			kg	9.14E-4	1	3.69	(3,2,1,1,5,4,20)
	Particulates, > 10 um			kg	1.31E-4	1	2.69	(3,2,1,1,5,4,19)
	Particulates, < 2.5 um			kg	9.00E-4	1	2.31	(4,2,2,5,4,4,23)
	Nickel			kg	5.57E-6	1	5.08	(3,2,1,1,3,4,22)
	Mercury			kg	8.84E-11	1	1.59	(3,2,1,1,3,4,31)
	Manganese			kg	1.68E-6	1	1.59	(3,2,1,1,3,4,31)
	Lead			kg	1.34E-5	1	5.08	(3,2,1,1,3,4,22)
	Heat, waste			MJ	3.34E+1	1	1.10	(2,2,2,3,1,3,2)
	Fluorine			kg	9.60E-6	1	1.59	(3,2,1,1,3,4,31)
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin			kg	1.00E-11	1	3.07	(3,2,1,1,3,4,21)
	Copper			kg	1.73E-5	1	5.08	(3,2,1,1,3,4,22)
	Cobalt			kg	5.29E-6	1	5.08	(3,2,1,1,3,4,22)
	Chromium			kg	1.77E-7	1	1.59	(3,2,1,1,3,4,31)
air, unspecified	Carbon dioxide, fossil			kg	2.06E-1	1	1.58	(4,2,1,1,4,4,14); excluding stdev of lime addition
water, river	Aluminum			kg	6.91E-7	1	10.00	reported values
	Arsenic, ion			kg	1.53E-7	1	10.00	reported values
	BOD5, Biological Oxygen Demand			kg	8.34E-5	1	10.00	reported values
	Cadmium, ion			kg	2.13E-8	1	10.00	reported values
	Calcium, ion			kg	5.49E-3	1	10.00	reported values
	Chromium, ion			kg	2.02E-7	1	10.00	reported values
	Cobalt			kg	6.25E-9	1	10.00	reported values
	COD, Chemical Oxygen Demand			kg	8.34E-5	1	10.00	reported values
	Copper, ion			kg	4.27E-7	1	10.00	reported values
	DOC, Dissolved Organic Carbon			kg	3.26E-5	1	10	reported values
	Iron, ion			kg	2.32E-6	1	10	reported values
	Lead			kg	1.33E-7	1	10	reported values
	Manganese			kg	1.97E-7	1	10	reported values
	Mercury			kg	2.27E-9	1	10	reported values
	Nickel, ion			kg	3.41E-7	1	10	reported values
	Nitrogen, organic bound			kg	1.82E-4	1	10	reported values
	Solved solids			kg	4.14E-5	1	10	reported values
	Sulfate			kg	1.89E-2	1	10	reported values
	Tin, ion			kg	1.97E-7	1	10	reported values
	TOC, Total Organic Carbon			kg	3.26E-5	1	10	reported values
	Zinc, ion			kg	1.19E-6	1	10	reported values
Outputs	ferronickel, 25% Ni, at plant	GLO	0	kg	1.00E+0			

Tab. 5.24 Unit process data of 1 kg of flat glass, uncoated, at plant, scenario OPT, corresponding to the NEEDS scenario very optimistic (Frischknecht et al. 2008)

Explanations	Name	Location	Infrastructure-Process	Unit	flat glass, uncoated, at plant	uncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER			
	InfrastructureProcess				0			
	Unit				kg			
Technosphere	hydrogen, liquid, at plant	RER	0	kg	3.60E-6	1	5.00	(3,5,1,1,n.a.,5);
	nitrogen, liquid, at plant	RER	0	kg	4.95E-3	1	5.00	Estimation of standard deviation
	soda, powder, at plant	RER	0	kg	2.29E-1	1	1.62	(1,5,5,1,1,5);
	silica sand, at plant	DE	0	kg	5.78E-1	1	1.62	(1,5,5,1,1,5);
	refractory, fireclay, packed, at plant	DE	0	kg	1.07E-3	1	10.00	Estimation of standard deviation
	limestone, milled, packed, at plant	CH	0	kg	4.00E-1	1	1.62	(1,5,5,1,1,5);
	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	8.89E-2	1	1.32	(3,5,1,1,n.a.,5);
	flat glass plant	RER	1	unit	2.41E-10	1	3.14	(4,5,1,3,1,5);
	steel, converter, unalloyed, at plant	RER	0	kg	1.37E-5	1	1.26	(3,4,1,3,1,5);
	tin, at regional storage	RER	0	kg	9.16E-6	1	12.00	Estimation of standard deviation
	natural gas, high pressure, at consumer	RER	0	MJ	5.44E+0	1	1.32	(3,5,1,1,n.a.,5);
	heavy fuel oil, at regional storage	RER	0	kg	0	1	1.32	(3,5,1,1,n.a.,5);
	transport, lorry 32t	RER	0	tkm	6.03E-2	1	2.09	(4,5,n.a,n.a,n.a,n.a);
	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	0	kg	1.10E-3	1	1.22	(1,3,1,1,3,1);
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	3.50E-4	1	5.00	Calculation of standard deviation based on min. and max. values
resource, in water	Water, cooling, unspecified natural origin			m3	7.00E-4	1	2.10	(2,5,3,n.a.,n.a.,n.a.);
air, unspecified	Carbon dioxide, fossil			kg	5.12E-1	1	1.38	(4,5,1,1,n.a.,5);
	Carbon monoxide, fossil			kg	5.00E-5	1	5.00	Calculation of standard deviation based on min. and max. values
	Hydrogen chloride			kg	4.50E-5	1	2.38	Calculation of standard deviation based on min. and max. values
	Hydrogen fluoride			kg	6.00E-6	1	3.33	Calculation of standard deviation based on min. and max. values
	Lead			kg	1.38E-5	1	5.38	(1,5,2,5,4,5);
	Nitrogen oxides			kg	2.00E-3	1	2.26	Calculation of standard deviation based on min. and max. values
	NMVOC, non-methane volatile organic compounds, unspecified origin			kg	5.00E-5	1	2.00	Calculation of standard deviation based on min. and max. values
	Particulates, < 2.5 um			kg	4.80E-5	1	52.60	Calculation of standard deviation based on min. and max. values
	Particulates, > 10 um			kg	6.00E-6	1	2.61	Calculation of standard deviation based on min. and max. values
	Particulates, > 2.5 um, and < 10um			kg	6.00E-6	1	2.61	Calculation of standard deviation based on min. and max. values
	Sulfur dioxide			kg	2.27E-3	1	2.63	Calculation of standard deviation based on min. and max. values
	Tin			kg	9.13E-6	1	12.00	Estimation of standard deviation
Outputs	flat glass, uncoated, at plant	RER	0	kg	1.00E+0			

Tab. 5.25 Unit process data of 1 kg of metallurgical-grade silicon, at plant, scenario OPT, corresponding to the NEEDS scenario very optimistic (Frischknecht et al. 2008)

Explanations	Name	Location	Infrastructure-Process	Unit	MG-silicon, at plant	uncertaintyType	StandardDeviation 95%	GeneralComment
	Location				NO			
	InfrastructureProcess				0			
	Unit				kg			
Technosphere	oxygen, liquid, at plant	RER	0	kg	2.00E-2	1	1.29	(3,4,3,3,1,5); Literature
	silicone plant	RER	1	unit	1.00E-11	1	3.05	(1,2,1,1,3,3); Estimation
	silica sand, at plant	DE	0	kg	2.70E+0	1	1.09	(2,2,1,1,1,3); Literature
	electricity, medium voltage, at grid	NO	0	kWh	9.50E+0	1	1.09	(2,2,1,1,1,3); Literature, lower range to account for heat recovery
	hard coal coke, at plant	RER	0	MJ	1.39E+1	1	1.09	(2,2,1,1,1,3); Literature
	petroleum coke, at refinery	RER	0	kg	5.00E-1	1	1.09	(2,2,1,1,1,3); Literature
	transport, lorry 32t	RER	0	tkm	1.77E-1	1	2.10	(4,5,na,na,na,na); Standard distance 50km, 20km for sand
	transport, freight, rail	RER	0	tkm	1.11E-1	1	2.10	(4,5,na,na,na,na); Standard distance 100km
	disposal, slag from MG silicon production, 0% water, to inert material landfill	CH	0	kg	2.50E-2	1	1.09	(2,2,1,1,1,3); Literature
	charcoal, at plant	GLO	0	kg	5.88E-1	1	1.09	(2,2,1,1,1,3); Literature
	wood chips, mixed, u=120%, at forest	RER	0	m3	3.25E-3	1	1.09	(2,2,1,1,1,3); Literature
air, low population density	Aluminum			kg	1.20E-7	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Antimony			kg	6.08E-10	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Arsenic			kg	7.29E-10	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Boron			kg	2.16E-8	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Cadmium			kg	2.43E-11	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Calcium			kg	6.00E-8	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Carbon dioxide, biogenic			kg	2.83E+0	1	1.09	(2,2,1,1,1,3); Calculation
	Carbon dioxide, fossil			kg	2.49E+0	1	1.09	(2,2,1,1,1,3); Calculation
	Carbon monoxide, biogenic			kg	1.06E-3	1	5.09	(3,4,3,3,1,5); Literature
	Carbon monoxide, fossil			kg	9.35E-4	1	5.09	(3,4,3,3,1,5); Literature
	Chlorine			kg	6.08E-9	1	1.61	(3,4,3,3,1,5); Literature
	Chromium			kg	6.08E-10	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Cyanide			kg	5.32E-7	1	1.61	(3,4,3,3,1,5); Estimation
	Fluorine			kg	3.00E-9	1	1.61	(3,4,3,3,1,5); Literature, in dust
	Heat, waste			MJ	7.42E+1	1	1.09	(2,2,1,1,1,3); Literature
	Hydrogen fluoride			kg	5.00E-4	1	1.61	(3,4,3,3,1,5); Estimation
	Hydrogen sulfide			kg	5.00E-4	1	1.61	(3,4,3,3,1,5); Estimation
	Iron			kg	3.00E-7	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Lead			kg	2.66E-8	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Mercury			kg	6.08E-10	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Nitrogen oxides			kg	9.82E-3	1	1.52	(3,2,1,1,1,3); Calculation based on environmental report
	NMVOC, non-methane volatile organic compounds, unspecified origin			kg	9.60E-5	1	1.61	(3,4,3,3,1,5); Literature
	Particulates, > 10 um			kg	6.00E-4	1	1.52	(3,2,1,1,1,3); Calculation based on environmental report
	Potassium			kg	6.25E-5	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Silicon			kg	5.81E-4	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Sodium			kg	6.00E-8	1	5.09	(3,4,3,3,1,5); Literature, in dust
	Sulfur dioxide			kg	1.23E-2	1	1.13	(3,2,1,1,1,3); Calculation based on environmental report
	Tin			kg	6.08E-10	1	5.09	(3,4,3,3,1,5); Literature, in dust
Outputs	MG-silicon, at plant	NO	0	kg	1.00E+0			

Tab. 5.26 Unit process data of 1 kg of nickel 99.5 %, at plant, scenario OPT, corresponding to the NEEDS scenario very optimistic (Frischknecht et al. 2008)

Explanations	Name	Location	Infrastructure-Process	Unit	nickel, 99.5%, at plant	uncertaintyType	StandardDeviation 95%	GeneralComment
	Location				GLO			
	InfrastructureProcess				0			
	Unit				kg			
Technosphere	limestone, milled, packed, at plant	CH	0	kg	1.93E+0	1	1.51	(5,2,2,3,1,3,4)
	blasting	RER	0	kg	1.20E-1	1	1.13	(2,2,2,1,1,4,4)
	conveyor belt, at plant	RER	1	m	3.05E-6	1	1.26	(3,2,2,1,3,4,4)
	diesel, burned in building machine	GLO	0	MJ	8.13E+0	1	1.13	(2,2,2,1,1,4,4)
	electricity, high voltage, production UCTE, at grid	UCTE	0	kWh	2.98E+0	1	1.1	(2,2,2,3,1,3,2)
	electricity, hydropower, at run-of-river power plant	RER	0	kWh	7.02E+0	1	1.14	(2,3,2,1,1,4,2)
	non-ferrous metal smelter	GLO	1	unit	3.35E-11	1	3.3	(4,2,1,5,4,4,9)
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	1.65E+1	1	1.25	(3,2,2,3,3,3,1)
	heavy fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	9.07E+0	1	1.1	(2,2,2,3,1,3,1)
	wood chips, from industry, mixed, burned in furnace 1000kW	CH	0	MJ	4.91E+0	0	0	0
	disposal, nickel smelter slag, 0% water, to residual material landfill	CH	0	kg	9.56E+0	1	2.15	(4,5,1,3,5,5,6)
	ammonia, liquid, at regional storehouse	RER	0	kg	8.37E-2	1	1.1	(2,2,2,3,1,3,4)
	chemicals inorganic, at plant	GLO	0	kg	6.15E-2	1	2	reported values
	hydrogen, liquid, at plant	RER	0	kg	4.56E-3	1	1.51	(5,2,2,3,1,3,4)
	chemicals organic, at plant	GLO	0	kg	1.80E-2	1	2	reported values
	hydrogen cyanide, at plant	RER	0	kg	2.79E-3	1	2	reported values
	sand, at mine	CH	0	kg	3.31E+1	1	1.13	(2,2,2,1,1,4,4)
	silica sand, at plant	DE	0	kg	1.89E+0	1	1.51	(5,2,2,3,1,3,4)
	portland calcareous cement, at plant	CH	0	kg	2.63E+0	1	1.13	(2,2,2,1,1,4,4)
	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	1.01E+0	1	1.14	(2,3,2,1,1,4,2)
	heat, at hard coal industrial furnace 1-10MW	RER	0	MJ	7.48E-1	1	1.1	(2,2,2,3,1,3,2)
	aluminium hydroxide, plant	RER	1	unit	6.71E-10	1	3.07	(3,2,2,1,3,4,9)
	non-ferrous metal mine, underground	GLO	1	unit	3.99E-9	1	3.07	(3,2,2,1,3,4,9)
	transport, lorry 32t	RER	0	tkm	1.80E+0	1	2.11	(3,2,2,1,3,5,5)
	disposal, sulfidic tailings, off-site	GLO	0	kg	5.36E+1	1	1.1	(2,2,2,3,1,3,6); reported values
	Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground			kg	1.26E+0	1	1.13	(2,2,2,1,1,4,12)
resource, in water	Water, river			m3	2.77E-2	1	1.13	(2,2,2,1,1,4,12)
	Water, well, in ground			m3	1.60E-1	1	1.13	(2,2,1,1,1,4,12)
	Arsenic			kg	9.31E-7	1	5.08	(3,2,1,1,3,4,22)
	Sulfur dioxide			kg	2.38E-1	1	1.64	(5,4,1,3,3,5,15)
	Silver			kg	2.21E-8	1	1.59	(3,2,1,1,3,4,31)
	NMVOC, non-methane volatile organic compounds, unspecified origin			kg	1.82E-4	1	1.59	(3,2,1,1,3,4,16)
	Magnesium			kg	8.78E-4	1	1.59	(3,2,1,1,3,4,31)
	Carbon disulfide			kg	7.98E-3	1	2.31	(4,2,2,5,4,4,23)
	Calcium			kg	1.03E-3	1	1.59	(3,2,1,1,3,4,31)
	Aluminum			kg	2.57E-4	1	1.59	(3,2,1,1,3,4,31)
	Zinc			kg	1.61E-5	1	5.08	(3,2,1,1,3,4,22)
	Tin			kg	1.04E-6	1	5.08	(3,2,1,1,3,4,22)
	Particulates, > 2.5 um, and < 10um			kg	2.32E-3	1	3.69	(3,2,1,1,5,4,20)
	Particulates, > 10 um			kg	2.69E-4	1	2.69	(3,2,1,1,5,4,19)
	Particulates, < 2.5 um			kg	2.62E-3	1	2.31	(4,2,2,5,4,4,23)
	Nickel			kg	6.82E-5	1	5.08	(3,2,1,1,3,4,22)
	Lead			kg	5.49E-6	1	5.08	(3,2,1,1,3,4,22)
	Heat, waste			MJ	5.27E+1	1	1.1	(2,2,2,3,1,3,2)
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin			kg	9.12E-12	1	3.07	(3,2,1,1,3,4,21)
	Copper			kg	5.78E-5	1	5.08	(3,2,1,1,3,4,22)
	Cobalt			kg	1.94E-4	1	5.08	(3,2,1,1,3,4,22)
air, unspecified	Carbon dioxide, fossil			kg	9.08E-1	1	1.58	(4,2,1,1,4,4,14); excluding stdev of lime addition
water, river	Aluminum			kg	1.38E-5	1	10	reported values
	Arsenic, ion			kg	6.87E-7	1	10	reported values
	BOD5, Biological Oxygen Demand			kg	1.67E-3	1	10	reported values
	Cadmium, ion			kg	8.19E-8	1	10	reported values
	Calcium, ion			kg	3.38E-2	1	10	reported values
	Chromium, ion			kg	4.17E-7	1	10	reported values
	Cobalt			kg	1.25E-7	1	10	reported values
	COD, Chemical Oxygen Demand			kg	1.67E-3	1	10	reported values
	Copper, ion			kg	1.87E-6	1	10	reported values
	DOC, Dissolved Organic Carbon			kg	6.51E-4	1	10	reported values
	Iron, ion			kg	4.64E-5	1	10	reported values
	Lead			kg	6.31E-7	1	10	reported values
	Manganese			kg	3.94E-6	1	10	reported values
	Mercury			kg	9.31E-9	1	10	reported values
	Nickel, ion			kg	4.14E-6	1	10	reported values
	Nitrogen, organic bound			kg	3.64E-3	1	10	reported values
	Solved solids			kg	8.27E-4	1	10	reported values
	Sulfate			kg	3.77E-1	1	10	reported values
	Tin, ion			kg	3.29E-7	1	10	reported values
	TOC, Total Organic Carbon			kg	6.51E-4	1	10	reported values
	Zinc, ion			kg	1.31E-5	1	10	reported values
water, lake	Calcium, ion			kg	7.55E-2	1	10	reported values
water, river	Cyanide			kg	2.99E-4	1	1.84	(4,2,2,3,4,4,33)
	nickel, 99.5%, at plant	GLO	0	kg	1.00E+0			

Tab. 5.27 Unit process data of 1 kg of pig iron, at plant, scenario OPT, corresponding to the NEEDS scenario very optimistic (Frischknecht et al. 2008)

Explanations	Name	Location	Infrastructure-Process	Unit	pig iron, at plant	uncertaintyType	StandardDeviation 95%	GeneralComment
	Location				GLO			
	InfrastructureProcess				0			
	Unit				kg			
Technosphere	limestone, at mine	CH	0	kg	1.00E-2	1	1.10	(1,2,1,3,1,1);
	refractory, fireclay, packed, at plant	DE	0	kg	2.00E-3	1	1.10	(1,2,1,3,1,1);
	hard coal coke, at plant	RER	0	MJ	5.72E+0	1	1.10	(1,2,1,3,1,1);
	hard coal mix, at regional storage	UCTE	0	kg	2.70E-1	1	1.10	(1,2,1,3,1,1);
	blast furnace	RER	1	unit	1.33E-11	1	3.20	(5,nA,nA,nA,nA,nA);
	iron ore, 65% Fe, at beneficiation	GLO	0	kg	1.50E-1	1	1.10	(1,2,1,1,1,1);
	pellets, iron, at plant	GLO	0	kg	4.00E-1	1	1.10	(1,2,1,1,1,1);
	sinter, iron, at plant	GLO	0	kg	1.05E+0	1	1.10	(1,2,1,1,1,1);
	transport, lorry 32t	RER	0	tkm	3.48E-3	1	2.10	(4,5,nA,nA,nA,nA);
	transport, barge	RER	0	tkm	1.65E-2	1	2.00	(2,nA,1,3,1,3);
	transport, transoceanic freight ship	OCE	0	tkm	1.48E+0	1	2.00	(2,nA,1,1,1,3);
	transport, freight, rail	RER	0	tkm	1.86E-1	1	2.10	(4,5,nA,nA,nA,nA);
	disposal, inert waste, 5% water, to inert material landfill	CH	0	kg	2.07E-2	1	1.10	(2,3,2,3,1,3);
	disposal, sludge, pig iron production, 8.6% water, to residual material landfill	CH	0	kg	2.00E-4	1	3.00	(2,3,2,3,1,3);
	treatment, pig iron production effluent, to wastewater treatment, class 3	CH	0	m3	1.81E-6	1	1.10	(2,3,2,3,1,3);
resource, in water	Water, unspecified natural origin			m3	6.00E-3	1	1.10	(1,2,1,1,1,1);
air, unspecified	Carbon dioxide, fossil			kg	3.06E-1	1	1.10	(2,3,2,3,1,3);
	Carbon monoxide, fossil			kg	9.90E-4	1	5.00	(2,3,2,3,1,3);
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin			kg	5.32E-16	1	3.00	(2,3,2,3,1,3);
	Heat, waste			MJ	4.90E-1	1	1.10	(1,2,1,3,1,1);
	Hydrogen sulfide			kg	1.06E-7	1	1.50	(2,3,2,3,1,3);
	Lead			kg	5.32E-9	1	5.00	(2,3,2,3,1,3);
	Manganese			kg	5.32E-9	1	5.00	(2,3,2,3,1,3);
	Nickel			kg	5.32E-9	1	5.00	(2,3,2,3,1,3);
	Nitrogen oxides			kg	1.60E-5	1	1.50	(2,3,2,3,1,3);
	Particulates, < 2.5 um			kg	4.79E-6	1	3.00	(2,3,2,3,1,3);
	Particulates, > 10 um			kg	2.66E-7	1	1.50	(2,3,2,3,1,3);
	Particulates, > 2.5 um, and < 10um			kg	2.66E-7	1	2.00	(2,3,2,3,1,3);
	Sulfur dioxide			kg	1.06E-5	1	1.10	(2,3,2,3,1,3);
Outputs	pig iron, at plant	GLO	0	kg	1.00E+0			

Tab. 5.28 Unit process data of 1 kg of sinter, iron, at plant, scenario OPT, corresponding to the NEEDS scenario very optimistic (Frischknecht et al. 2008)

Explanations	Name	Location	Infrastructure-Process	Unit	sinter, iron, at plant	uncertaintyType	StandardDeviation 95%	GeneralComment
	Location				GLO			
	InfrastructureProcess				0			
	Unit				kg			
Technosphere	quicklime, in pieces, loose, at plant	CH	0	kg	5.00E-2	1	1.10	(1,2,1,3,1,1);
	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	1.00E-2	1	1.10	(1,2,1,3,1,1);
	hard coal coke, at plant	RER	0	MJ	1.00E+0	1	1.10	(1,2,1,3,1,1);
	aluminium oxide, plant	RER	1	unit	2.50E-11	1	5.00	rough estimation
	iron ore, 65% Fe, at beneficiation	GLO	0	kg	1.05E+0	1	1.10	(1,2,1,1,1,1);
	natural gas, high pressure, at consumer	RER	0	MJ	2.54E-2	1	1.10	(1,2,1,3,1,1);
	transport, lorry 32t	RER	0	tkm	2.00E-3	1	2.10	(4,5,nA,nA,nA,nA);
	transport, barge	RER	0	tkm	3.15E-2	1	2.00	(2,nA,1,3,1,3);
	transport, transoceanic freight ship	OCE	0	tkm	2.84E+0	1	2.00	(2,nA,1,1,1,3);
	transport, freight, rail	RER	0	tkm	3.09E-1	1	2.10	(4,5,nA,nA,nA,nA);
resource, in water	Water, unspecified natural origin			m3	5.00E-4	1	1.10	(1,2,1,1,1,1);
air, unspecified	Cadmium			kg	9.17E-10	1	5.00	(2,3,2,3,1,3);
	Carbon dioxide, fossil			kg	1.42E-1	1	1.10	(2,3,2,3,1,3);
	Carbon monoxide, fossil			kg	1.79E-2	1	5.00	(2,3,2,3,1,3);
	Chromium			kg	2.29E-9	1	5.00	(2,3,2,3,1,3);
	Copper			kg	3.21E-9	1	5.00	(2,3,2,3,1,3);
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin			kg	2.29E-13	1	3.00	(1,3,2,3,1,2);
	Heat, waste			MJ	1.54E+0	1	1.10	(1,2,1,3,1,1);
	Hydrocarbons, aliphatic, alkanes, unspecified			kg	6.87E-5	1	1.50	(2,3,2,3,1,3);
	Hydrogen chloride			kg	7.80E-6	1	1.50	(2,3,2,3,1,3);
	Hydrogen fluoride			kg	6.42E-7	1	1.50	(2,3,2,3,1,3);
	Lead			kg	1.83E-8	1	5.00	(2,3,2,3,1,3);
	Manganese			kg	9.17E-9	1	5.00	(2,3,2,3,1,3);
	Mercury			kg	7.34E-9	1	5.00	(2,3,2,3,1,3);
	Nickel			kg	9.17E-10	1	5.00	(2,3,2,3,1,3);
	Nitrogen oxides			kg	2.02E-4	1	1.50	(2,3,2,3,1,3);
	PAH, polycyclic aromatic hydrocarbons			kg	5.27E-8	1	3.00	(2,3,2,3,1,3);
	Particulates, < 2.5 um			kg	1.05E-5	1	3.00	(2,3,2,3,1,3);
	Polychlorinated biphenyls			kg	4.59E-10	1	3.00	(2,3,2,3,1,3);
	Sulfur dioxide			kg	4.13E-4	1	1.10	(2,3,2,3,1,3);
	Titanium			kg	2.29E-9	1	5.00	(2,3,2,3,1,3);
	Vanadium			kg	2.29E-9	1	5.00	(2,3,2,3,1,3);
	Zinc			kg	9.17E-10	1	5.00	(2,3,2,3,1,3);
	Aluminium	-	-	kg	9.00E-12	1	5.00	(2,3,2,3,1,3);
	Arsenic, ion	-	-	kg	3.00E-14	1	5.00	(2,3,2,3,1,3);
	Cadmium, ion	-	-	kg	6.50E-14	1	5.00	(2,3,2,3,1,3);
	Chloride	-	-	kg	1.55E-7	1	5.00	(2,3,2,3,1,3);
	Chromium, ion	-	-	kg	3.00E-13	1	5.00	(2,3,2,3,1,3);
	Copper, ion	-	-	kg	2.00E-12	1	5.00	(2,3,2,3,1,3);
	Cyanide	-	-	kg	6.50E-13	1	5.00	(2,3,2,3,1,3);
	Iron, ion	-	-	kg	7.00E-12	1	5.00	(2,3,2,3,1,3);
	Mercury	-	-	kg	4.50E-14	1	5.00	(2,3,2,3,1,3);
	Nickel, ion	-	-	kg	1.50E-12	1	5.00	(2,3,2,3,1,3);
	Lead	-	-	kg	2.00E-12	1	5.00	(2,3,2,3,1,3);
	Zinc, ion	-	-	kg	8.00E-13	1	5.00	(2,3,2,3,1,3);
	Sulfate	-	-	kg	8.00E-8	1	5.00	(2,3,2,3,1,3);
	Fluoride	-	-	kg	2.15E-10	1	5.00	(2,3,2,3,1,3);
	Sulfide	-	-	kg	2.00E-12	1	5.00	(2,3,2,3,1,3);
	Ammonium, ion	-	-	kg	4.56E-9	1	5.00	(2,3,2,3,1,3);
	Nitrate	-	-	kg	2.44E-9	1	5.00	(2,3,2,3,1,3);
	Nitrite	-	-	kg	6.57E-11	1	5.00	(2,3,2,3,1,3);
	TOC, Total Organic Carbon	-	-	kg	5.50E-10	1	5.00	(2,3,2,3,1,3);
	sinter, iron, at plant	GLO	0	kg	1.00E+0			

Tab. 5.29 Unit process data of 1 kg of zinc, primary, at regional storage, scenario OPT, corresponding to the NEEDS scenario very optimistic (Frischknecht et al. 2008)

Explanations	Name	Location	Infrastructure-Process	Unit	zinc, primary, at regional storage	uncertaintyType	StandardDeviation 95%	GeneralComment
	Location				RER			
	InfrastructureProcess				0			
	Unit				kg			
Technosphere	oxygen, liquid, at plant	RER	0	kg	1.08E-1	1	1.25	(3,3,2,1,3,3,4)
	diesel, burned in building machine	GLO	0	MJ	4.19E-2	1	1.25	(3,3,2,1,3,3,2)
	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	1.10E+0	1	1.31	(4,3,2,1,3,3,2)
	hard coal, burned in industrial furnace 1-10MW	RER	0	MJ	2.44E+0	1	1.25	(3,3,2,1,3,3,1)
	electricity, hydropower, at run-of-river power plant	RER	0	kWh	1.65E+0	1	1.31	(4,3,2,1,3,3,2)
	iron ore, 46% Fe, at mine	GLO	0	kg	2.80E-1	1	1.25	(3,3,2,1,3,3,4)
	zinc concentrate, at beneficiation	GLO	0	kg	2.53E+0	1	1.33	(3,3,2,1,3,5,4)
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	2.44E+0	1	1.25	(3,3,2,1,3,3,1)
	transport, lorry 32t	RER	0	tkm	4.06E-1	1	1.31	(4,3,1,1,3,3,2)
	transport, transoceanic freight ship	OCE	0	tkm	9.47E+0	1	2.10	(4,3,2,1,3,3,5)
	transport, freight, rail	RER	0	tkm	2.25E+0	1	1.31	(4,3,1,1,3,3,2)
	steam, for chemical processes, at plant	RER	0	kg	1.09E+0	1	1.25	(3,3,2,1,3,3,1)
	disposal, inert waste, 5% water, to inert material landfill	CH	0	kg	3.75E-1	1	1.25	(3,3,2,1,3,3,6)
	treatment, sewage, unpolluted, to wastewater treatment, class 3	CH	0	m3	3.90E-2	1	1.25	(3,3,2,1,3,3,6)
resource, in water	Water, river			m3	3.90E-2	1	1.25	(3,3,2,1,3,3,2)
air, low population density	Arsenic			kg	1.26E-5	1	5.04	(3,4,2,1,1,4,22)
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin			kg	1.00E-11	1	3.04	(3,4,2,1,1,4,21)
	Lead			kg	8.04E-6	1	5.04	(3,4,2,1,1,4,22)
	Mercury			kg	1.00E-6	1	5.04	(3,4,2,1,1,4,22)
	Particulates, < 2.5 um			kg	9.30E-5	1	3.04	(3,4,2,1,1,4,27)
	Particulates, > 10 um			kg	1.85E-5	1	1.46	(3,4,2,1,1,4,29)
	Particulates, > 2.5 um, and < 10um			kg	1.85E-5	1	1.28	(3,4,2,1,1,4,28)
	Sulfur dioxide			kg	8.86E-3	1	1.19	(3,4,2,1,1,4,15)
	Zinc			kg	2.88E-5	1	5.04	(3,4,2,1,1,4,22)
water, river	Arsenic, ion			kg	1.18E-6	1	5.02	(1,3,1,3,1,4,35)
	BOD5, Biological Oxygen Demand			kg	3.11E-4	1	1.65	(3,5,1,3,3,4,32)
	Cadmium, ion			kg	3.68E-6	1	5.02	(1,3,1,3,1,4,35)
	COD, Chemical Oxygen Demand			kg	4.66E-4	1	1.60	(3,3,1,3,3,4,32)
	Copper, ion			kg	4.00E-6	1	5.02	(1,3,1,3,1,4,35)
	DOC, Dissolved Organic Carbon			kg	1.82E-4	1	1.65	(3,5,1,3,3,4,32)
	Fluoride			kg	2.98E-5	1	1.58	(1,3,1,3,3,4,32)
	Lead			kg	4.20E-5	1	5.02	(1,3,1,3,1,4,35)
	Mercury			kg	1.72E-7	1	5.02	(1,3,1,3,1,4,35)
	TOC, Total Organic Carbon			kg	1.82E-4	1	1.65	(3,5,1,3,3,4,32)
	Zinc, ion			kg	4.58E-5	1	5.02	(1,3,1,3,1,4,35)
Outputs	zinc, primary, at regional storage	RER	0	kg	1.00E+0			

5.7 Aluminium

The life cycle inventory data of the supply chain of aluminium in ecoinvent data v2.2 are rather outdated. The aluminium industry recently published new data and thus the life cycle inventories of the supply chain of aluminium representing the current situation were updated. The updated life cycle inventory data are described in this Subchapter.

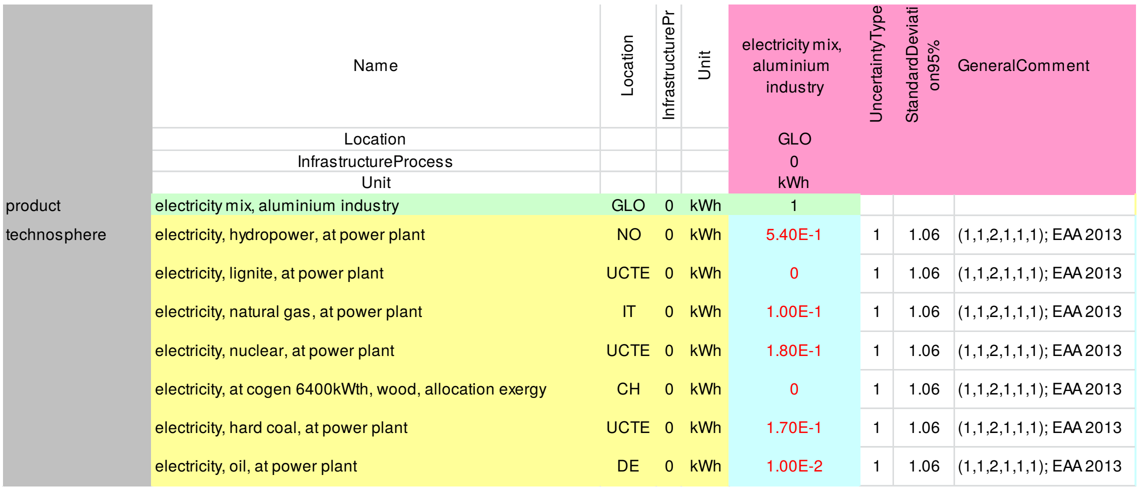
Inventory data representing the production of primary aluminium are mainly based on the European Aluminium Association (EAA) (2013), and they refer to the year 2010. The inventory data are used in the BAU scenario.

Scenario-dependent developments in the aluminium electricity mix and in the production of liquid aluminium are used to approximate possible situations in 2050.

5.7.1 Electricity Mix of the Aluminium Industry

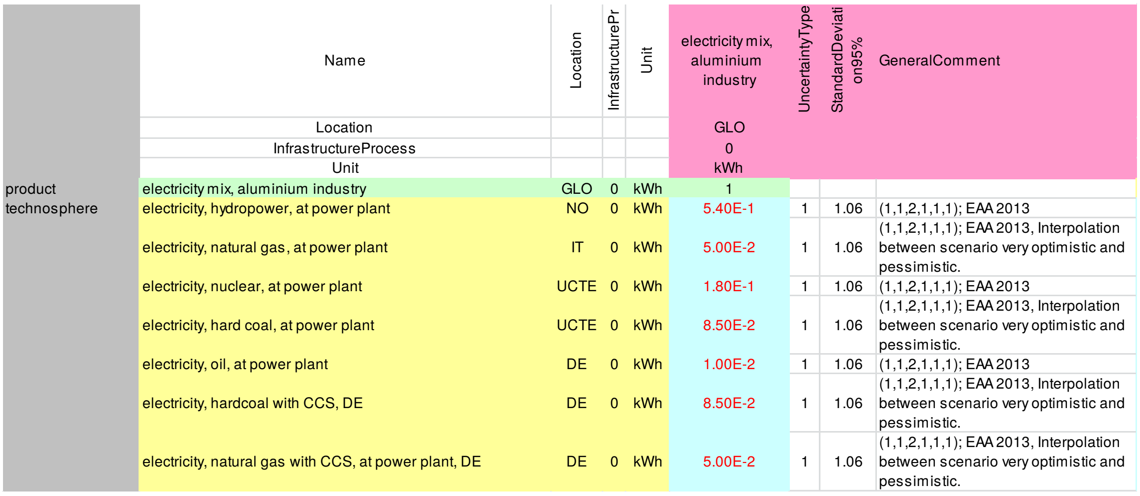
In the scenario BAU, the present electricity mix is used to model the 2050 electricity mix of the aluminium industry. In the scenario OPT, natural gas and hard coal are assumed to have CCS technologies installed to substantially reduce CO_2 emissions. The electricity mix applied in the scenario REAL is an interpolation between the electricity mixes used in the other two scenarios (see Tab. 5.30 through Tab. 5.32).

Tab. 5.30 Unit process data of 1 kWh electricity mix for the aluminium industry, according to NEEDS scenario pessimistic (Frischknecht et al. 2008)



	Name	Location	InfrastructurePr	Unit	electricity mix, aluminium industry	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				GLO			
	InfrastructureProcess				0			
	Unit				kWh			
product	electricity mix, aluminium industry	GLO	0	kWh	1			
technosphere	electricity, hydropower, at power plant	NO	0	kWh	5.40E-1	1	1.06	(1,1,2,1,1,1); EAA 2013
	electricity, lignite, at power plant	UCTE	0	kWh	0	1	1.06	(1,1,2,1,1,1); EAA 2013
	electricity, natural gas, at power plant	IT	0	kWh	1.00E-1	1	1.06	(1,1,2,1,1,1); EAA 2013
	electricity, nuclear, at power plant	UCTE	0	kWh	1.80E-1	1	1.06	(1,1,2,1,1,1); EAA 2013
	electricity, at cogen 6400kWth, wood, allocation exergy	CH	0	kWh	0	1	1.06	(1,1,2,1,1,1); EAA 2013
	electricity, hard coal, at power plant	UCTE	0	kWh	1.70E-1	1	1.06	(1,1,2,1,1,1); EAA 2013
	electricity, oil, at power plant	DE	0	kWh	1.00E-2	1	1.06	(1,1,2,1,1,1); EAA 2013

Tab. 5.31 Unit process data of 1 kWh electricity mix for the aluminium industry, according to NEEDS scenario optimistic-realistic (Frischknecht et al. 2008)



	Name	Location	InfrastructurePr	Unit	electricity mix, aluminium industry	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				GLO			
	InfrastructureProcess				0			
	Unit				kWh			
product	electricity mix, aluminium industry	GLO	0	kWh	1			
technosphere	electricity, hydropower, at power plant	NO	0	kWh	5.40E-1	1	1.06	(1,1,2,1,1,1); EAA 2013
	electricity, natural gas, at power plant	IT	0	kWh	5.00E-2	1	1.06	(1,1,2,1,1,1); EAA 2013, Interpolation between scenario very optimistic and pessimistic.
	electricity, nuclear, at power plant	UCTE	0	kWh	1.80E-1	1	1.06	(1,1,2,1,1,1); EAA 2013
	electricity, hard coal, at power plant	UCTE	0	kWh	8.50E-2	1	1.06	(1,1,2,1,1,1); EAA 2013, Interpolation between scenario very optimistic and pessimistic.
	electricity, oil, at power plant	DE	0	kWh	1.00E-2	1	1.06	(1,1,2,1,1,1); EAA 2013
	electricity, hardcoal with CCS, DE	DE	0	kWh	8.50E-2	1	1.06	(1,1,2,1,1,1); EAA 2013, Interpolation between scenario very optimistic and pessimistic.
	electricity, natural gas with CCS, at power plant, DE	DE	0	kWh	5.00E-2	1	1.06	(1,1,2,1,1,1); EAA 2013, Interpolation between scenario very optimistic and pessimistic.

Tab. 5.32 Unit process data of 1 kWh electricity mix for the aluminium industry, according to NEEDS scenario very optimistic (Frischknecht et al. 2008)

	Name	Location	InfrastructurePr	Unit	electricity mix, aluminium industry	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				GLO			
	InfrastructureProcess				0			
	Unit				kWh			
product	electricity mix, aluminium industry	GLO	0	kWh	1			
technosphere	electricity, hydropower, at power plant	NO	0	kWh	5.40E-1	1	1.06	(1,1,2,1,1,1); EAA 2013
	electricity, nuclear, at power plant	UCTE	0	kWh	1.80E-1	1	1.06	(1,1,2,1,1,1); EAA 2013
	electricity, oil, at power plant	DE	0	kWh	1.00E-2	1	1.06	(1,1,2,1,1,1); EAA 2013
	electricity, hardcoal with CCS, DE	DE	0	kWh	1.70E-1	1	1.06	(1,1,2,1,1,1); EAA 2013, assumption all hard coal with CCS technology
	electricity, natural gas with CCS, at power plant, DE	DE	0	kWh	1.00E-1	1	1.06	(1,1,2,1,1,1); EAA 2013, assumption all natural gas with CCS technology

5.7.2 Bauxite Mining

LCI data are based on the European Aluminium Association report (EAA 2013). Water consumption and CO_2 emissions data are added according to information from the EAA (2013) (see Tab. 5.33).

Tab. 5.33 Unit process data of 1 kg bauxite mining

Explanations	Name	Location	InfrastructurePr	Unit	bauxite, at mine	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				GLO			
	InfrastructureProcess				0			
	Unit				kg			
product	bauxite, at mine	GLO	0	kg	1			
Technosphere	blasting	RER	0	kg	1.56E-4	1	1.06	(1,2,2,1,1,1); ecoinvent
	diesel, burned in building machine	GLO	0	MJ	1.28E-2	1	2.00	(1,1,2,1,1,1); EAA 2013
	electricity, medium voltage, production ENTSO, at grid	ENTSO	0	kWh	9.00E-4	1	1.06	(1,1,2,1,1,1); EAA 2013
	heavy fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	8.24E-3	1	1.06	(1,1,2,1,1,1); EAA 2013
	mine, bauxite	GLO	1	unit	8.33E-13	1	3.00	(1,2,2,1,1,1); ecoinvent
	recultivation, bauxite mine	GLO	0	m2	1.67E-4	1	2.00	(1,2,2,1,1,1); ecoinvent
resource, in ground	Aluminium, 24% in bauxite, 11% in crude ore, in ground	-	-	kg	2.81E-1	1	1.06	(1,2,2,1,1,1); ecoinvent
	Water, salt, ocean	-	-	m3	7.00E-4	1	1.06	(1,1,2,1,1,1); EAA 2013
resource, land	Occupation, mineral extraction site	-	-	m2a	3.35E-4	1	1.50	(1,1,2,1,1,1); EAA 2005
	Transformation, from arable	-	-	m2	1.07E-4	1	2.00	(1,1,2,1,1,1); EAA 2005
	Transformation, from arable, non-irrigated, fallow	-	-	m2	3.41E-5	1	2.00	(1,1,2,1,1,1); EAA 2005
	Transformation, from forest, extensive	-	-	m2	2.67E-5	1	2.00	(1,1,2,1,1,1); EAA 2005
	Transformation, to mineral extraction site	-	-	m2	1.67E-4	1	2.00	(1,1,2,1,1,1); EAA 2005
resource, in water	Water, cooling, unspecified natural origin	-	-	m3	5.00E-4	1	1.06	(1,1,2,1,1,1); EAA 2013
air, low population density	Heat, waste	-	-	MJ	3.24E-3	1	1.08	(1,1,2,1,1,1); EAA 2005
	Particulates, < 2.5 um	-	-	kg	8.50E-6	1	3.01	(2,1,2,1,1,1); EAA 2005
	Particulates, > 10 um	-	-	kg	8.50E-5	1	1.51	(2,1,2,1,1,1); EAA 2005
	Particulates, > 2.5 um, and < 10um	-	-	kg	7.65E-5	1	2.01	(2,1,2,1,1,1); EAA 2005
	treatment, sewage, to wastewater treatment, class 3	CH	0	m3	7.50E-4	1	1.08	(2,1,2,1,1,1); EAA 2005
	Carbon dioxide, fossil	-	-	kg	2.00E-3	1	1.08	(2,1,2,1,1,1); EAA 2013
	Water, Europe	-	-	kg	3.80E-1	1	1.51	(2,1,2,1,1,1); EAA 2013

5.7.3 Aluminium Oxide Production

Aluminium oxide is produced by calcination of the aluminium hydroxide at approx.1000° C. The calcination is done in a circulating fluidised bed calciner and removes the water of crystallisation from the hydroxide.

LCI data are based on EAA report (2013). Water consumption data are added according to information from EAA (see Tab. 5.34).

Tab. 5.34 Unit process data of 1 kg aluminium oxide production

	Name	Location	InfrastructurePr	Unit	aluminium oxide, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER			
	InfrastructureProcess				0			
	Unit				kg			
product	aluminium oxide, at plant	RER	0	kg	1			
technosphere	aluminium hydroxide, plant	RER	1	unit	2.51E-11	1	3.23	(5,na,na,na,na,na); ecoinvent
technosphere	bauxite, at mine	GLO	0	kg	2.25E+0	1	1.06	(1,1,2,1,1,1); EAA 2013
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	1.06E-1	1	1.06	(1,1,2,1,1,1); EAA 2013
	quicklime, milled, loose, at plant	CH	0	kg	4.20E-2	1	1.06	(1,1,2,1,1,1); EAA 2013
resource, in water	Water, well, in ground	-	-	m3	3.60E-3	1	1.06	(1,1,2,1,1,1); EAA 2013
	heavy fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	5.82E+0	1	1.06	(1,1,2,1,1,1); EAA 2013
technosphere	diesel, burned in building machine	GLO	0	MJ	1.00E-3	1	1.06	(1,1,2,1,1,1); EAA 2013
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	4.30E+0	1	1.06	(1,1,2,1,1,1); EAA 2013
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	0	1	1.22	(2,1,2,1,3,1); EAA 2013
	electricity, medium voltage, production ENTSO, at grid	ENTSO	0	kWh	1.81E-1	1	1.06	(1,1,2,1,1,1); EAA 2013
	treatment, sewage, to wastewater treatment, class 3	CH	0	m3	3.10E-3	1	1.06	(1,1,2,1,1,1); EAA 2013
emission soil, unspecified	Heat, waste	-	-	MJ	6.52E-1	1	1.06	(1,1,2,1,1,1); EAA 2013
emission water, unspecified	Suspended solids, unspecified	-	-	kg	2.30E-4	1	1.50	(1,1,2,1,1,1); EAA 2013
emission water, unspecified	Mercury	-	-	kg	1.26E-10	1	5.00	(1,1,2,1,1,1); EAA 2013
	COD, Chemical Oxygen Demand	-	-	kg	2.46E-4	1	1.51	(2,1,2,1,1,1); EAA 2005 and ecoinvent, assumption for oil/grease
	BOD5, Biological Oxygen Demand	-	-	kg	2.46E-4	1	1.51	(2,1,2,1,1,1); EAA 2005 and ecoinvent, assumption for oil/grease
	DOC, Dissolved Organic Carbon	-	-	kg	6.75E-5	1	1.51	(2,1,2,1,1,1); EAA 2005 and ecoinvent, assumption for oil/grease
	TOC, Total Organic Carbon	-	-	kg	6.75E-5	1	1.51	(2,1,2,1,1,1); EAA 2005 and ecoinvent, assumption for oil/grease
emission air, unspecified	Mercury	-	-	kg	6.00E-8	1	5.01	(2,1,2,1,1,1); EAA 2013
emission air, unspecified	Nitrogen oxides	-	-	kg	1.11E-3	1	1.51	(2,1,2,1,1,1); EAA 2013
	Sulfur dioxide	-	-	kg	2.68E-3	1	1.08	(2,1,2,1,1,1); EAA 2013
	Carbon dioxide, fossil	-	-	kg	8.43E-1	1	1.08	(2,1,2,1,1,1); EAA 2013
technosphere	disposal, inert waste, 5% water, to inert material landfill	CH	0	kg	4.80E-2	1	1.06	(1,1,2,1,1,1); EAA 2013
technosphere	disposal, redmud from bauxite digestion, 0% water, to residual material landfill	CH	0	kg	6.71E-1	1	1.06	(1,1,2,1,1,1); EAA 2013
	disposal, inert material, 0% water, to sanitary landfill	CH	0	kg	6.90E-3	1	1.06	(1,1,2,1,1,1); EAA 2013
	disposal, hazardous waste, 0% water, to underground deposit	DE	0	kg	2.00E-4	1	1.06	(1,1,2,1,1,1); EAA 2013
emission air, low population density	Particulates, < 2.5 um	-	-	kg	7.00E-6	1	3.00	(1,1,2,1,1,1); EAA 2013
emission air, low population density	Particulates, > 2.5 um, and < 10um	-	-	kg	6.30E-5	1	2.00	(1,1,2,1,1,1); EAA 2013
	Particulates, > 10 um	-	-	kg	7.00E-5	1	1.50	(1,1,2,1,1,1); EAA 2013
emission air, unspecified	Water, Europe	-	-	kg	5.00E-1	1	1.50	(1,1,2,1,1,1); EAA 2013

5.7.4 Anode Production

Pre-baked or self-baking anodes are used in the production of primary aluminium. They consist of carbon, which stems from Petroleum-coke and/or Coal/tar pitch. LCI data are based on the European Aluminium Association report (EAA 2013) (see Tab. 5.35).

Tab. 5.35 Unit process data of 1 kg anode, aluminium electrolysis

	Name	Location	Infrastructur	Unit	anode, aluminium electrolysis	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER			
	InfrastructureProcess				0			
	Unit				kg			
product	anode, aluminium electrolysis	RER	0	kg	1			
technosphere	anode plant	RER	1	unit	2.50E-10	1	3.20	(5,na,na,na,na,na); ecoinvent
	bitumen, at refinery	RER	0	kg	1.52E-1	1	1.10	(1,1,2,1,1,3); EAA 2013
	cast iron, at plant	RER	0	kg	4.10E-3	1	1.10	(1,1,2,1,1,1); EAA 2013
	electricity, medium voltage, production ENTSO, at grid	ENTSO	0	kWh	1.08E-1	1	1.10	(1,1,2,1,1,1); EAA 2013
	heavy fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	5.20E-1	1	1.10	(1,1,2,1,1,1); EAA 2013
	heat, natural gas, at industrial furnace >100kW	RER	0	MJ	2.23E+0	1	1.10	(1,1,2,1,1,1); EAA 2013
technosphere	diesel, burned in building machine	GLO	0	MJ	1.55E-2	1	1.06	(1,1,2,1,1,1); EAA 2013
technosphere	petroleum coke, at refinery	RER	0	kg	7.20E-1	1	1.10	(1,1,2,1,1,1); EAA 2013
	refractory, fireclay, packed, at plant	DE	0	kg	5.90E-3	1	1.10	(1,1,2,1,1,1); EAA 2013
	disposal, asphalt, 0.1% water, to sanitary landfill	CH	0	kg	9.60E-3	1	1.10	(1,1,2,1,1,1); EAA 2013
	disposal, inert waste, 5% water, to inert material landfill	CH	0	kg	4.70E-3	1	1.10	(1,1,2,1,1,1); EAA 2013
	disposal, refractory SPL, Al elec.lysis, 0% water, to residual material landfill	CH	0	kg	3.00E-3	1	1.10	(1,1,2,1,1,1); EAA 2013
technosphere	disposal, hazardous waste, 0% water, to underground deposit	DE	0	kg	1.40E-3	1	6.00	(1,1,2,1,1,3); EAA 2013
resource, in water	Water, cooling, unspecified natural origin	-	-	m3	5.60E-3	1	1.10	(1,1,2,1,1,1); EAA 2013
emission air, unspecified	Benzo(a)pyrene	-	-	kg	6.00E-8	1	3.00	(1,1,2,1,1,1); EAA 2013
	Carbon dioxide, fossil	-	-	kg	1.99E-1	1	1.10	(1,1,2,1,1,3); EAA 2013
	Carbon monoxide, fossil	-	-	kg	1.04E-3	1	5.00	(1,1,2,1,1,3); ecoinvent v2.0
emission air, low population density	Heat, waste	-	-	MJ	3.89E-1	1	1.10	(1,1,2,1,1,1); EAA 2013
emission air, unspecified	Hydrogen fluoride	-	-	kg	1.23E-5	1	1.50	(1,1,2,1,1,1); EAA 2013
	Nitrogen oxides	-	-	kg	4.50E-4	1	1.50	(1,1,2,1,1,1); EAA 2013
emission air, unspecified	PAH, polycyclic aromatic hydrocarbons	-	-	kg	6.00E-5	1	3.00	(1,1,2,1,1,1); EAA 2013
emission air, low population density	Particulates, < 2.5 um	-	-	kg	6.03E-05	1	3.00	(1,1,2,1,1,1); EAA 2013
	Particulates, > 10 um	-	-	kg	9.03E-05	1	1.50	(1,1,2,1,1,1); EAA 2013
	Particulates, > 2.5 um, and < 10um	-	-	kg	9.94E-05	1	2.00	(1,1,2,1,1,1); EAA 2013
emission air, unspecified	Sulfur dioxide	-	-	kg	7.70E-4	1	1.10	(1,1,2,1,1,1); EAA 2013
emission water, unspecified	PAH, polycyclic aromatic hydrocarbons	-	-	kg	9.60E-7	1	3.00	(1,1,2,1,1,1); EAA 2013
	Suspended solids, unspecified	-	-	kg	1.40E-4	1	1.50	(1,1,2,1,1,1); EAA 2013
technosphere	treatment, sewage, to wastewater treatment, class 3	CH	0	m3	2.20E-3	1	1.06	(1,1,2,1,1,1); EAA 2013
emission air, unspecified	Water, Europe	-	-	kg	3.40E+0	1	1.50	(1,1,2,1,1,1); EAA 2013
technosphere	transport, freight, rail	RER	0	tkm	1.66E-1	1	2.09	(4,5,na,na,na,na); ecoinvent, standard distances for all sub-processes
	transport, lorry >16t, fleet average	RER	0	tkm	8.31E-2	1	2.09	(4,5,na,na,na,na); ecoinvent, standard distances for all sub-processes

5.7.5 Liquid Aluminium Production

Aluminium oxide is processed to liquid aluminium using electrolysis (Hall Heroult process). This process requires relatively large amounts of electricity.

Data about resource consumption and emissions are based on the World Aluminium LCI 2010 (WorldAluminium 2013), see Tab. 5.36 to Tab. 5.38. Scenario-dependent LCIs are derived from these unit process raw data. Emission factors of the airborne pollutants (Benzo(a)pyrene, Carbon Dioxide (fossil), HFC 116, fluoride, hydrogen fluoride, CFC-14, nitrogen oxides, polycyclic aromatic hydrocarbons, particulate matter and sulphur dioxide), used in the REAL and OPT scenarios are based on expert judgements[9]. The remaining inputs and outputs remain unchanged.

Tab. 5.36 Unit process data of 1 kg primary aluminium, liquid, scenario BAU, corresponding to the scenario pessimistic according to NEEDS (Frischknecht et al. 2008)

	Name	Location	Infrastructure	Unit	aluminium, primary, liquid, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER			
	InfrastructureProcess				0			
	Unit				kg			
product	aluminium, primary, liquid, at plant	RER	0	kg	1			
technosphere	aluminium electrolysis, plant	RER	1	unit	1.54E-10	1	3.09	(4,5,na,na,na,na); ecoinvent
	aluminium fluoride, at plant	RER	0	kg	1.62E-2	1	1.06	(1,1,2,1,1,1); World aluminum 2010
	aluminium oxide, at plant	RER	0	kg	1.93E+0	1	1.06	(1,1,2,1,1,1); World aluminum 2010
	anode, aluminium electrolysis	RER	0	kg	4.39E-1	1	1.06	(1,1,2,1,1,1); World aluminum 2010
	cathode, aluminium electrolysis	RER	0	kg	6.02E-3	1	1.06	(1,1,2,1,1,1); World aluminum 2010
	electricity mix, aluminium industry	GLO	0	kWh	1.53E+1	1	1.06	(1,1,2,1,1,1); World aluminum 2010
	transport, freight, rail	RER	0	tkm	8.74E-2	1	2.09	(4,5,na,na,na,na); World aluminum 2010
	transport, lorry >16t, fleet average	RER	0	tkm	5.77E-3	1	2.09	(4,5,na,na,na,na); World aluminum 2010
	transport, transoceanic freight ship	OCE	0	tkm	1.34E+1	1	2.09	(4,5,na,na,na,na); World aluminum 2010
	refractory, fireclay, packed, at plant	DE	0	kg	7.56E-3	1	1.08	(1,1,2,1,1,3); World aluminum 2010
	reinforcing steel, at plant	RER	0	kg	3.95E-3	1	1.06	(1,1,2,1,1,1); World aluminum 2010
resource, in water	Water, salt, ocean	-	-	m3	3.89E-3	1	1.06	(1,1,2,1,1,1); World aluminum 2010
	Water, well, in ground	-	-	m3	6.25E-3	1	1.06	(1,1,2,1,1,1); World aluminum 2010
technosphere	disposal, filter dust Al electrolysis, 0% water, to residual material landfill	CH	0	kg	4.25E-3	1	1.06	(1,1,2,1,1,1); World aluminum 2010
	disposal, inert waste, 5% water, to inert material landfill	CH	0	kg	1.23E-2	1	1.06	(1,1,2,1,1,1); World aluminum 2010
	disposal, refractory SPL, Al elec.lysis, 0% water, to residual material landfill	CH	0	kg	8.88E-3	1	1.08	(2,1,2,1,1,1); World aluminum 2010
emission air, unspecified	Benzo(a)pyrene	-	-	kg	7.35E-7	1	3.00	(1,1,2,1,1,1); World aluminum 2010
	Carbon dioxide, fossil	-	-	kg	1.54E+0	1	1.06	(1,1,2,1,1,1); World aluminum 2010
	Ethane, hexafluoro-, HFC-116	-	-	kg	7.47E-6	1	1.50	(1,1,2,1,1,1); World aluminum 2010
emission water, unspecified	Fluoride	-	-	kg	6.03E-5	1	1.50	(1,1,2,1,1,1); World aluminum 2010
emission air, low population density	Heat, waste	-	-	MJ	5.50E+1	1	1.06	(1,1,2,1,1,1); World aluminum 2010
emission air, unspecified	Hydrogen fluoride	-	-	kg	1.12E-3	1	1.50	(1,1,2,1,1,1); World aluminum 2010
	Methane, tetrafluoro-, R-14	-	-	kg	5.60E-5	1	1.50	(1,1,2,1,1,1); World aluminum 2010
	Nitrogen oxides	-	-	kg	2.52E-4	1	1.50	(1,1,2,1,1,1); World aluminum 2010
	PAH, polycyclic aromatic hydrocarbons	-	-	kg	5.40E-5	1	3.00	(1,1,2,1,1,1); World aluminum 2010
emission air, low population density	Particulates, < 2.5 um	-	-	kg	2.34E-3	1	3.00	(1,1,2,1,1,1); World aluminum 2010
	Particulates, > 2.5 um, and < 10um	-	-	kg	2.14E-4	1	2.00	(1,1,2,1,1,1); World aluminum 2010
emission air, unspecified	Sulfur dioxide	-	-	kg	1.49E-2	1	1.06	(1,1,2,1,1,1); World aluminum 2010
	Water, Europe	-	-	kg	9.46E+0	1	1.50	(1,1,2,1,1,1); World aluminum 2010
emission water, unspecified	Suspended solids, unspecified	-	-	kg	5.07E-4	1	1.50	(1,1,2,1,1,1); World aluminum 2010
	Oils, unspecified	-	-	kg	4.99E-6	1	1.50	(1,1,2,1,1,1); World aluminum 2010
	PAH, polycyclic aromatic hydrocarbons	-	-	kg	2.65E-7	1	3.00	(1,1,2,1,1,1); World aluminum 2010

---

[9] Personal communication with Chris Bayliss, World Aluminium, 18.10.2013

Tab. 5.37 Unit process data of 1 kg primary aluminium, liquid, scenario REAL, corresponding to the scenario realistic-optimistic according to NEEDS (Frischknecht et al. 2008)

	Name	Location	Infrastructure	Unit	aluminium, primary, liquid, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER			
	InfrastructureProcess				0			
	Unit				kg			
product	aluminium, primary, liquid, at plant	RER	0	kg	1			
technosphere	aluminium electrolysis, plant	RER	1	unit	1.54E-10	1	3.09	(4,5,na,na,na,na); ecoinvent
	aluminium fluoride, at plant	RER	0	kg	1.56E-2	1	1.06	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
	aluminium oxide, at plant	RER	0	kg	1.92E+0	1	1.06	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
	anode, aluminium electrolysis	RER	0	kg	4.20E-1	1	1.06	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
	cathode, aluminium electrolysis	RER	0	kg	6.02E-3	1	1.06	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
	electricity mix, aluminium industry	GLO	0	kWh	1.46E+1	1	1.06	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
	transport, freight, rail	RER	0	tkm	8.74E-2	1	2.09	(4,5,na,na,na,na); World aluminum 2010 and interpolation between scenario very optimistic and
	transport, lorry >32t, EURO4	RER	0	tkm	5.77E-3	1	2.09	(4,5,na,na,na,na); World aluminum 2010 and interpolation between scenario very optimistic and
	transport, transoceanic freight ship	OCE	0	tkm	1.34E+1	1	2.09	(4,5,na,na,na,na); World aluminum 2010 and interpolation between scenario very optimistic and
	refractory, fireclay, packed, at plant	DE	0	kg	7.56E-3	1	1.06	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
	reinforcing steel, at plant	RER	0	kg	3.95E-3	1	1.06	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
resource, in water	Water, salt, ocean	-	-	m3	3.89E-3	1	1.06	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
	Water, well, in ground	-	-	m3	6.25E-3	1	1.06	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
technosphere	disposal, filter dust Al electrolysis, 0% water, to residual material landfill	CH	0	kg	4.25E-3	1	1.06	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
	disposal, inert waste, 5% water, to inert material landfill	CH	0	kg	8.67E-3	1	1.06	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
	disposal, refractory SPL, Al elec.lysis, 0% water, to residual material landfill	CH	0	kg	5.39E-3	1	1.06	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
emission air, unspecified	Benzo(a)pyrene	-	-	kg	3.68E-7	1	3.00	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
	Carbon dioxide, fossil	-	-	kg	1.47E+0	1	1.06	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
	Ethane, hexafluoro-, HFC-116	-	-	kg	3.73E-6	1	1.50	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
emission water, unspecified	Fluoride	-	-	kg	5.43E-5	1	1.50	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
emission air, low population density	Heat, waste	-	-	MJ	5.27E+1	1	1.06	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
emission air, unspecified	Hydrogen fluoride	-	-	kg	1.06E-3	1	1.50	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
	Methane, tetrafluoro-, R-14	-	-	kg	2.80E-5	1	1.50	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
	Nitrogen oxides	-	-	kg	2.27E-4	1	1.50	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
	PAH, polycyclic aromatic hydrocarbons	-	-	kg	2.70E-5	1	3.00	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
emission air, low population density	Particulates, < 2.5 um	-	-	kg	2.11E-3	1	3.00	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
	Particulates, > 2.5 um, and < 10um	-	-	kg	1.92E-4	1	2.00	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
emission air, unspecified	Sulfur dioxide	-	-	kg	7.95E-3	1	1.06	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
	Water, Europe	-	-	kg	9.46E+0	1	1.50	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
emission water, unspecified	Suspended solids, unspecified	-	-	kg	5.07E-4	1	1.50	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
	Oils, unspecified	-	-	kg	4.99E-6	1	1.50	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic
	PAH, polycyclic aromatic hydrocarbons	-	-	kg	2.65E-7	1	3.00	(1,1,2,1,1,1); World aluminum 2010 and interpolation between scenario very optimistic and pessimistic

Tab. 5.38 Unit process data of 1 kg primary aluminium, liquid, scenario OPT, corresponding to the scenario very optimistic according to NEEDS (Frischknecht et al. 2008)

	Name	Location	Infrastructure	Unit	aluminium, primary, liquid, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER			
	InfrastructureProcess				0			
	Unit				kg			
product	aluminium, primary, liquid, at plant	RER	0	kg	1			
technosphere	aluminium electrolysis, plant	RER	1	unit	1.54E-10	1	3.09	(4,5,na,na,na,na); ecoinvent
	aluminium fluoride, at plant	RER	0	kg	1.50E-2	1	1.06	(1,1,2,1,1,1); Prebake
	aluminium oxide, at plant	RER	0	kg	1.90E+0	1	1.06	(1,1,2,1,1,1); Prebake
	anode, aluminium electrolysis	RER	0	kg	4.00E-1	1	1.06	(1,1,2,1,1,1); Prebake
	cathode, aluminium electrolysis	RER	0	kg	6.02E-3	1	1.06	(1,1,2,1,1,1); world aluminium 2010
	electricity mix, aluminium industry	GLO	0	kWh	1.40E+1	1	1.06	(1,1,2,1,1,1); Prebake
	transport, freight, rail	RER	0	tkm	8.74E-2	1	2.09	(4,5,na,na,na,na); world aluminium 2010
	transport, lorry >32t, EURO5	RER	0	tkm	5.77E-3	1	2.09	(4,5,na,na,na,na); world aluminium 2010
	transport, transoceanic freight ship	OCE	0	tkm	1.34E+1	1	2.09	(4,5,na,na,na,na); world aluminium 2010
	refractory, fireclay, packed, at plant	DE	0	kg	7.56E-3	1	1.06	(1,1,2,1,1,1); world aluminium 2010
	reinforcing steel, at plant	RER	0	kg	3.95E-3	1	1.06	(1,1,2,1,1,1); world aluminium 2010
resource, in water	Water, salt, ocean	-	-	m3	3.89E-3	1	1.06	(1,1,2,1,1,1); world aluminium 2010
	Water, well, in ground	-	-	m3	6.25E-3	1	1.06	(1,1,2,1,1,1); world aluminium 2010
technosphere	disposal, filter dust Al electrolysis, 0% water, to residual material landfill	CH	0	kg	4.25E-3	1	1.06	(1,1,2,1,1,1); world aluminium 2010
	disposal, inert waste, 5% water, to inert material landfill	CH	0	kg	5.00E-3	1	1.06	(1,1,2,1,1,1); assumption
	disposal, refractory SPL, Al elec.lysis, 0% water, to residual material landfill	CH	0	kg	1.90E-3	1	1.06	(1,1,2,1,1,1); assumption
emission air, unspecified	Benzo(a)pyrene	-	-	kg	0	1	3.00	(1,1,2,1,1,1); expert guess
	Carbon dioxide, fossil	-	-	kg	1.40E+0	1	1.06	(1,1,2,1,1,1); Prebake
	Ethane, hexafluoro-, HFC-116	-	-	kg	0	1	1.50	(1,1,2,1,1,1); expert guess
emission water, unspecified	Fluoride	-	-	kg	4.83E-5	1	1.50	(1,1,2,1,1,1); assumption
emission air, low population density	Heat, waste	-	-	MJ	5.04E+1	1	1.06	(1,1,2,1,1,1); calculation
emission air, unspecified	Hydrogen fluoride	-	-	kg	1.01E-3	1	1.50	(1,1,2,1,1,1); assumption
	Methane, tetrafluoro-, R-14	-	-	kg	0	1	1.50	(1,1,2,1,1,1); expert guess
	Nitrogen oxides	-	-	kg	2.01E-4	1	1.50	(1,1,2,1,1,1); assumption
	PAH, polycyclic aromatic hydrocarbons	-	-	kg	0	1	3.00	(1,1,2,1,1,1); expert guess
emission air, low population density	Particulates, < 2.5 um	-	-	kg	1.87E-3	1	3.00	(1,1,2,1,1,1); assumption
	Particulates, > 2.5 um, and < 10um	-	-	kg	1.71E-4	1	2.00	(1,1,2,1,1,1); assumption
emission air, unspecified	Sulfur dioxide	-	-	kg	1.00E-3	1	1.06	(1,1,2,1,1,1); prebake
	Water, Europe	-	-	kg	9.46E+0	1	1.50	(1,1,2,1,1,1); world aluminium 2010
emission water, unspecified	Suspended solids, unspecified	-	-	kg	5.07E-4	1	1.50	(1,1,2,1,1,1); world aluminium 2010
	Oils, unspecified	-	-	kg	4.99E-6	1	1.50	(1,1,2,1,1,1); world aluminium 2010
	PAH, polycyclic aromatic hydrocarbons	-	-	kg	2.65E-7	1	3.00	(1,1,2,1,1,1); world aluminium 2010

5.7.6 Primary Aluminium Production

The process "primary aluminium production" covers the processing of liquid aluminium into cast aluminium ingots. LCI data are based on EAA report (2013) (see Tab. 5.39).

Tab. 5.39 Unit process data of 1 kg primary aluminium, according to EAA (2013)

	Name	Location	InfrastructureProcess	Unit	aluminium, primary, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER			
	InfrastructureProcess				0			
	Unit				kg			
product	aluminium, primary, at plant	RER	0	kg	1			
technosphere	aluminium casting, plant	RER	1	unit	1.54E-10	1	3.23	(5,na,na,na,na,na); ecoinvent
	aluminium, primary, liquid, at plant	RER	0	kg	1.02E+0	1	1.06	(1,1,2,1,1,1); EAA 2013
	chlorine, liquid, production mix, at plant	RER	0	kg	5.00E-5	1	1.06	(1,1,2,1,1,1); EAA 2013
	argon, liquid, at plant	RER	0	kg	2.11E-3	1	1.08	(2,1,2,1,1,1); EAA 2013
	corrugated board, mixed fibre, single wall, at plant	RER	0	kg	1.80E-3	1	1.08	(1,1,2,1,1,3); ecoinvent
	palm oil, at oil mill	MY	0	kg	8.00E-5	1	1.08	(1,1,2,1,1,3); ecoinvent
	cryolite, at plant	RER	0	kg	4.00E-4	1	1.08	(1,1,2,1,1,3); ecoinvent
	nitrogen, liquid, at plant	RER	0	kg	2.20E-4	1	1.08	(1,1,2,1,1,3); EAA 2013
	rock wool, at plant	CH	0	kg	1.10E-4	1	1.08	(1,1,2,1,1,3); ecoinvent
emission resource, in water	Water, well, in ground	-	-	m3	8.30E-3	1	1.06	(1,1,2,1,1,1); EAA 2013
technosphere	electricity mix, aluminium industry	GLO	0	kWh	9.80E-2	1	1.06	(1,1,2,1,1,1); EAA 2013
	heavy fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	1.90E-1	1	1.06	(1,1,2,1,1,1); EAA 2013
	diesel, burned in building machine	GLO	0	MJ	4.60E-2	1	1.06	(1,1,2,1,1,1); EAA 2013
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	1.35E-3	1	1.06	(1,1,2,1,1,1); EAA 2013
emission air, unspecified	Heat, waste			MJ	3.53E-1	1	1.50	(1,1,2,1,1,1); EAA 2013
emission air, unspecified	Hydrogen chloride	-	-	kg	2.00E-5	1	1.50	(1,1,2,1,1,1); EAA 2013
emission air, unspecified	Nitrogen oxides			kg	2.10E-4	1	1.50	(1,1,2,1,1,1); EAA 2013
	Particulates, > 2.5 um, and < 10um			kg	4.00E-05	1	1.50	(2,1,2,1,1,1); EAA 2013 and ecoinvent
	Sulfur dioxide			kg	1.50E-4	1	1.50	(1,1,2,1,1,1); EAA 2013
	Carbon dioxide, fossil			kg	1.13E-1	1	1.50	(1,1,2,1,1,3); EAA 2013
emission water, unspecified	Suspended solids, unspecified	-	-	kg	3.40E-4	1	1.50	(1,1,2,1,1,1); EAA 2013
	disposal, filter dust Al electrolysis, 0% water, to residual material landfill	CH	0	kg	5.00E-4	1	1.06	(1,1,2,1,1,1); EAA 2013, filter dust
	disposal, inert waste, 5% water, to inert material landfill	CH	0	kg	1.10E-3	1	1.06	(1,1,2,1,1,1); EAA 2013, other landfill waste
	disposal, refractory SPL, Al elec.lysis, 0% water, to residual material landfill	CH	0	kg	6.00E-4	1	1.06	(1,1,2,1,1,1); EAA 2013, refractory material
	treatment, sewage, to wastewater treatment, class 3	CH	0	m3	8.70E-3	1	1.08	(2,1,2,1,1,1); EAA 2013

6 Cumulative Results and Interpretation

6.1 Overview

Section 6 describes the cumulative environmental impacts of future CdTe and single-crystalline silicon 3-kWp rooftop PV power plants installed and operated in Europe today and in 2050 (see Section 6.2) and of electricity produced today and in 2050 with single-Si crystalline silicon and CdTe PV (see Section 6.3). In Section 6.4, the NREPBT of single-Si and CdTe PV systems are presented and discussed. Finally, data quality aspects are described in Section 0.

6.2 Life Cycle GHG Emissions of Future 3-kWp Plants

6.2.1 Single-crystalline Silicon Photovoltaic Laminate

Tab. 6.1 and Fig. 6.1 show greenhouse gas emissions of single-crystalline silicon-based 3-kWp PV power plants according to the three scenarios (BAU, REAL and OPT) in kg CO_2-eq (according to IPCC (2013, Tab. 8.A.1, 100a)), including the relative contribution of the different non-laminate parts of the PV power plants mounted on slanted-roofs in Europe.

The highest share of the impacts is caused by the PV laminate. Due to the technical improvements in the production of PV laminates, the share of the PV laminate becomes lower in the future. Future improvements of the slanted roof construction (mounting system), the inverter and the electric installation are disregarded in this study. The reduction in impacts caused in the manufacturing of these components is due to improvements in module efficiency (less square meters of mounting system required) and within their supply chain (less impacts in the production of copper, aluminium etc.). Therefore, the contribution of these parts of the PV power plant remains more or less constant and gains more importance in 2050 compared to today.

Tab. 6.1 Greenhouse gas emissions of single-crystalline silicon-based 3-kWp photovoltaic power plants installed on slanted roofs in Europe according to the three scenarios (BAU, REAL and OPT) in kg CO_2-eq (according to IPCC (2013, Tab. 8.A.1, 100a)) showing the contribution of the different parts to the overall total.

Single-Si	Inverter	Electric installation	Slanted roof construction	Photovoltaic laminate	Transports	Total	Total emissions
today	420	120	660	5 800	58		7 000
BAU	9%	3%	9%	78%	1%	100%	4 600
REAL	16%	5%	13%	65%	2%	100%	2 500
OPT	23%	7%	16%	52%	2%	100%	1 700

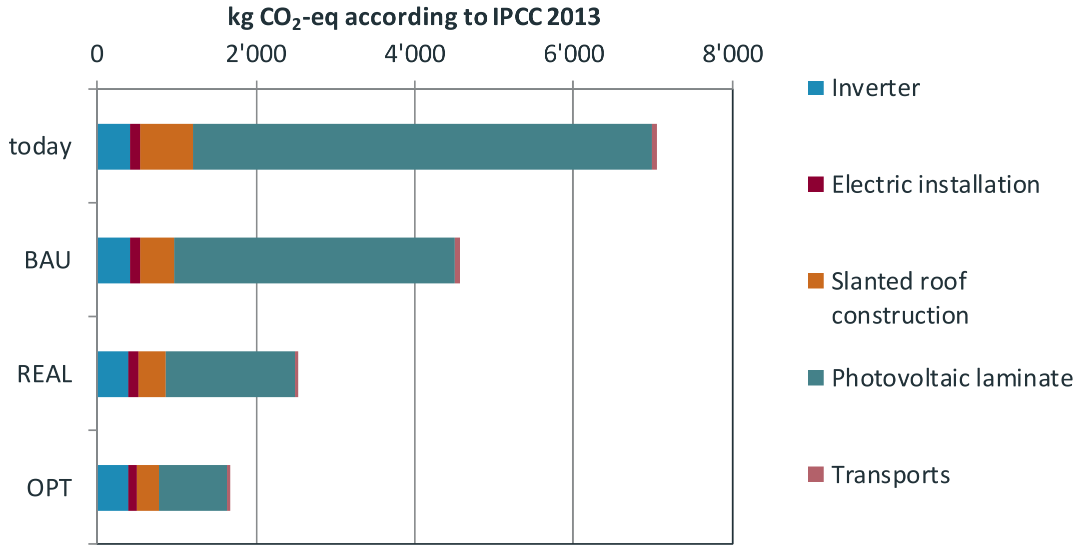


Fig. 6.1 Greenhouse gas emissions of single-crystalline silicon-based 3-kWp photovoltaic power plants installed on slanted roofs in Europe according to the three scenarios (BAU, REAL and OPT) in kg CO_2-eq (according to IPCC (2013, Tab. 8.A.1, 100a)) showing the contribution of the different parts.

6.2.2 Cadmium-telluride Photovoltaic Laminate

Tab. 6.2 and Fig. 6.2 show the greenhouse gas emissions of CdTe-based 3-kWp PV power plants installed on slanted roofs in Europe according to the three scenarios (BAU, REAL and OPT) in kg CO_2-eq (according to IPCC (2013, Tab. 8.A.1, 100a)), including the contribution of the different parts.

The relative contributions of the different non-laminate parts of the PV power plant are greater than those of the single-Si silicon based PV power plants mainly because those from the laminate are lower for CdTe than for single-Si (see Fig. 6.1).

Tab. 6.2 Greenhouse gas emissions of CdTe-based-3kWp photovoltaic power plants installed on slanted roofs in Europe according to the three scenarios (BAU, REAL and OPT) in kg CO_2-eq (according to IPCC (2013, Tab. 8.A.1, 100a)) showing the contribution of the different parts to the overall total.

CdTe	Inverter	Electric installation	Slanted roof construction	Photovoltaic laminate	Transports	Total	Total emissions
today	420	120	740	1 200	100		2 600
BAU	23%	7%	27%	39%	4%	100%	1 800
REAL	30%	9%	28%	28%	4%	100%	1 300
OPT	35%	11%	27%	24%	4%	100%	1 100

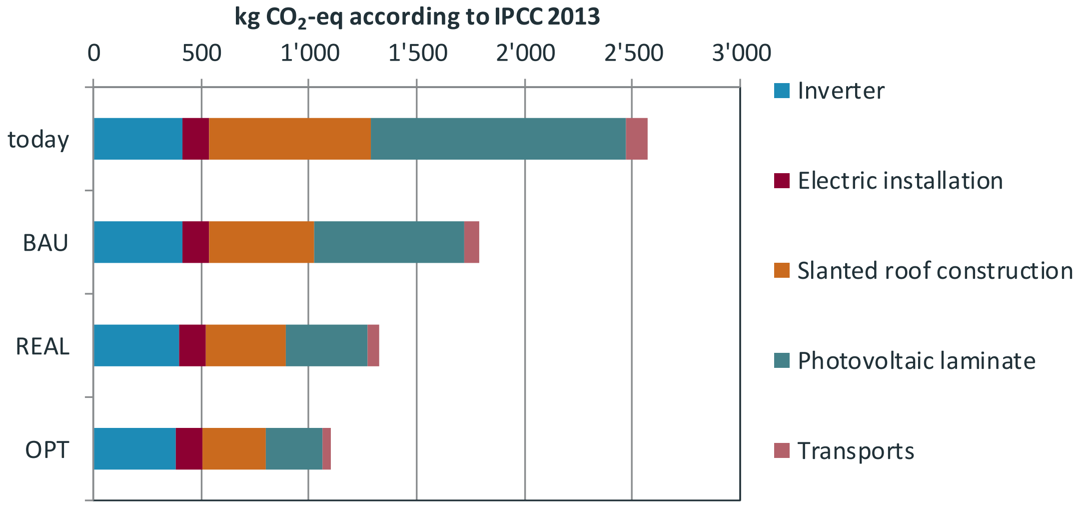


Fig. 6.2 Greenhouse gas emissions of CdTe-based 3-kWp photovoltaic power plants installed on slanted roofs in Europe according to the three scenarios (BAU, REAL and OPT) in kg CO_2-eq (according to IPCC (2013), Tab. 8.A.1, 100a) showing the contribution of the different parts.

6.3 Environmental Impacts of Future PV Electricity

This section reports results per kWh of electricity generated. Factors required to convert the results of the previous section, which were reported as absolute GHG emissions to install a 3-kWp PV power plant on European residential rooftops, to electricity (kWh) produced include the annual yield and lifetime of the power plant, and the efficiency of the module. These factors have been reported in Tables 2.1, 3.11 and 3.4, respectively.

Note that as a first-order approximation, results reported here can be scaled to ones based on alternative assumptions by the ratio of the given annual yield and the annual yield of another location of installation or the ratio of the given lifetime and the new lifetime of the PV power plant. A simple scaling of the results according to the module efficiency is not possible because not all the parts of the PV power system show a linear relation with the efficiency of the used modules. However, the LCI data are available for download on www.treeze.ch and the efficiencies of the PV modules can be adjusted therein for a more robust accounting.

6.3.1 Single-crystalline Silicon Photovoltaic Electricity

For single-Si, based on the assumptions and projections made here, we estimate that the greenhouse gas emissions per kWh of electricity produced from residential rooftop application in Europe are reduced from 80 g CO_2-eq today to 65 % of that value in 2050 in the scenario BAU, 31 % in 2050 in the scenario REAL and 18 % in 2050 in the scenario OPT (see Tab. 6.3 and Fig. 6.3 in relative values).

Similar scale reductions are estimated with regard to other environmental impacts (see Tab. 6.3, Tab. 6.4 and Fig. 6.3), except perhaps for human toxicity potential. Human toxicity potential is estimated to be reduced to only 85% in the BAU and 45 % in the scenario OPT. The main reason for a lower projected benefit for human toxicity than for the other indicators is that the amount of copper, the main human-toxic emission in the PV life cycle, is not projected to decrease for its main uses in module wiring and inverters[10].

---

[10] More recent impact category indicators and higher quality inventory data may significantly affect the human toxicity results and notably change the significance of copper with respect to potential toxicity impacts of PV electricity.

Tab. 6.3 Estimates of life cycle greenhouse gas emissions (using 100 year global warming potentials from IPCC (2013)), non-renewable cumulative energy demand (following Frischknecht et al. (2007c)) and acidification potential (following Goedkoop et al. (2009)) of electricity produced in 2050 with single-crystalline silicon-based photovoltaic laminates mounted on slanted roofs in Europe according to the three scenarios (BAU, REAL and OPT). Results for "today" are defined to be 100 %, with the three scenarios as fractions thereof. Key assumptions are: module efficiency: 15.1% (today), 22.9% (BAU), 25.2% (REAL), 27.6% (OPT); annual yield (electricity generated per kWp of the PV power plant and year): 975 kWh/kWp including degradation (10.5% average for lifetime); solar irradiation: 1 331 kWh/m^2. Lifetime of the PV power plant: 30 years (today and BAU), 35 years (REAL), 40 years (OPT). The system includes mounting, cabling, inverter and maintenance and considers production in different regions of the world (Europe, North America, China and Asia & Pacific) using region-specific electricity mixes. This is a prospective LCA for expected future development in the year 2050. The calculations are performed using the software SimaPro with ecoinvent v2.2+ as background database.

		Greenhouse gas emissions	Cumulative energy demand, non-renewable	Acidification
		g CO_2 eq	MJ oil-eq	kg SO_2 eq
Single-Si laminate	today	80.0	0.97	5.4E-04
	BAU	65%	66%	68%
	REAL	31%	40%	25%
	OPT	18%	28%	13%

Tab. 6.4 Estimates of life human toxicity potential, photochemical ozone creation potential, particulate matter formation potential and urban land occupation (following Goedkoop et al. (2009)) of electricity produced in 2050 with single-crystalline silicon-based photovoltaic laminates mounted on slanted roofs in Europe according to the three scenarios (BAU, REAL and OPT). Results for "today" are defined to be 100%, with the three scenarios as fractions thereof. Key assumptions are: module efficiency: 15.1% (today), 22.9% (BAU), 25.2% (REAL), 27.6% (OPT); annual yield (electricity generated per kWp of the PV power plant and year): 975 kWh/kWp including degradation (10.5% average for lifetime) ; solar irradiation: 1 331 kWh/m^2. Lifetime of the PV power plant: 30 years (today and BAU), 35 years (REAL), 40 years (OPT). The system includes mounting, cabling, inverter and maintenance and considers production in different regions of the world (Europe, North America, China and Asia & Pacific) using region-specific electricity mixes. This is a prospective LCA for expected future development in the year 2050. The calculations are performed using the software SimaPro with ecoinvent v2.2+ as background database.

		Human toxicity	Photochemical ozone creation potential	Particulate matter	Urban land occupation
		kg 1,4-DB eq	kg NMVOC eq	kg PM_{10} eq	m^2*a
Single-Si laminate	today	8.0E-02	3.2E-04	1.8E-04	3.9E-03
	BAU	85%	68%	67%	67%
	REAL	57%	34%	28%	39%
	OPT	45%	22%	16%	29%

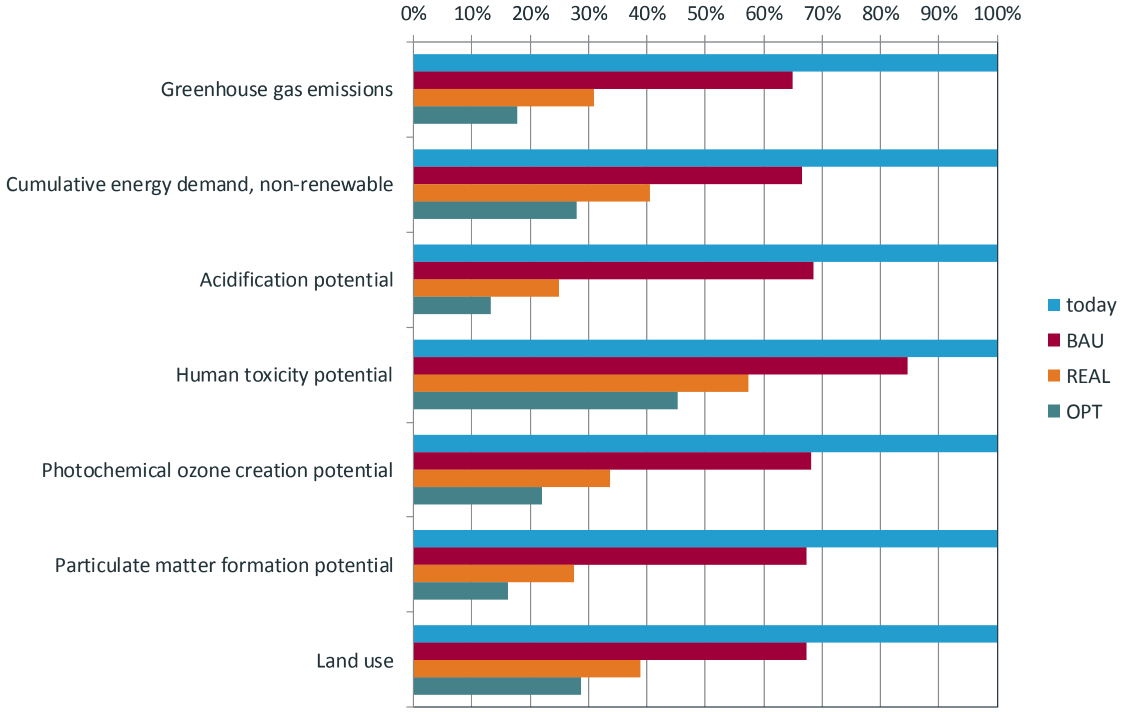


Fig. 6.3 Estimates of life cycle greenhouse gas emissions (using 100 year global warming potentials from IPCC (2013)), non-renewable cumulative energy demand (following Frischknecht et al. (2007c)), acidification potential, human toxicity potential, photochemical ozone creation potential, particulate matter formation potential and urban land use (following Goedkoop et al. (2009)) of electricity produced in 2050 with single-crystalline silicon-based photovoltaic laminates mounted on slanted roofs in Europe according to the three scenarios (BAU, REAL and OPT). Results for "today" are defined to be 100%, with the three scenarios as fractions thereof. Key assumptions are: module efficiency: 15.1% (today), 22.9% (BAU), 25.2% (REAL), 27.6% (OPT); annual yield (electricity generated per kWp of the PV power plant and year): 975 kWh/kWp including degradation (10.5% average for lifetime); solar irradiation: 1 331 kWh/m^2. Lifetime of the PV power plant: 30 years (today and BAU), 35 years (REAL), 40 years (OPT). The system includes mounting, cabling, inverter and maintenance and considers production in different regions of the world (Europe, North America, China and Asia & Pacific) using region-specific electricity mixes. This is a prospective LCA for expected future development in the year 2050. The calculations are performed using the software SimaPro with ecoinvent v2.2+ as background database.

6.3.2 Cadmium-telluride Photovoltaic Electricity

For CdTe, based on the assumptions and projections made here, we estimate that the greenhouse gas emissions per kWh of electricity produced from residential rooftop application in Europe are reduced from 29 g CO_2-eq today to 70 % in the scenario BAU, 44 % in the scenario REAL and 32% g CO_2-eq in the scenario OPT in the year 2050 (see Tab. 6.5 and Fig. 6.4).

The reductions with regard to other environmental impacts are similar to those of greenhouse gas emissions except for human toxicity, where the reduction is less pronounced (see Fig. 6.3, Tab. 6.5 and Tab. 6.6)[11].

Tab. 6.5 Estimates of life cycle greenhouse gas emissions (using 100 year global warming potentials from IPCC (2013)), non-renewable cumulative energy demand (following Frischknecht et al. (2007c)), acidification potential (following Goedkoop et al. (2009)) of electricity produced in 2050 with CdTe photovoltaic laminates mounted on slanted roofs in Europe, according to the three scenarios (BAU, REAL and OPT). Results for "today" are defined to be 100%, with the three scenarios as fractions thereof. Key assumptions are: module efficiency: 13.4% (today), 20.5% (BAU), 22.6% (REAL), 24.7% (OPT); annual yield (electricity generated per kWp of the PV power plant and year): 975 kWh/kWp including degradation (10.5% average for lifetime); solar irradiation: 1 331 kWh/m^2. Lifetime: 30 years (today and BAU), 35 years (REAL), 40 years (OPT). The system includes mounting, cabling, inverter and maintenance and considers production using region-specific electricity mixes. This is a prospective LCA for expected future development in the year 2050; the calculations are performed using the software SimaPro with ecoinvent v2.2+ as background database.

		Greenhouse gas emissions	Cumulative energy demand, non-renewable	Acidification
		g CO_2 eq	MJ oil-eq	kg SO_2 eq
CdTe laminate	today	29.0	0.43	1.7E-04
	BAU	70%	71%	83%
	REAL	44%	49%	41%
	OPT	32%	37%	29%

---

[11] More recent impact category indicators and higher quality inventory data may significantly affect the human toxicity results and notably change the significance of copper with respect to potential toxicity impacts of PV electricity

Tab. 6.6 Estimates of human toxicity potential, photochemical ozone creation potential, particulate matter formation potential and urban land occupation (following Goedkoop et al. (2009)) of electricity produced in 2050 with CdTe photovoltaic laminates mounted on slanted roofs in Europe, according to the three scenarios (BAU, REAL and OPT). Results for "today" are defined to be 100%, with the three scenarios as fractions thereof. Key assumptions are: module efficiency: 13.4% (today), 20.5% (BAU), 22.6% (REAL), 24.7% (OPT); annual yield (electricity generated per kWp of the PV power plant and year): 975 kWh/kWp including degradation (10.5% average for lifetime); solar irradiation: 1 331 kWh/m^2. Lifetime: 30 years (today and BAU), 35 years (REAL), 40 years (OPT). The system includes mounting, cabling, inverter and maintenance and considers production using region-specific electricity mixes. This is a prospective LCA for expected future development in the year 2050; the calculations are performed using the software SimaPro with ecoinvent v2.2+ as background database.

		Human toxicity	Photochemical ozone creation potential	Particulate matter	Urban land occupation
		kg 1,4-DB eq	kg NMVOC eq	kg PM_{10} eq	m^2*a
CdTe laminate	today	5.4E-02	1.1E-04	6.5E-05	1.5E-03
	BAU	94%	69%	75%	74%
	REAL	67%	45%	44%	59%
	OPT	54%	33%	34%	50%

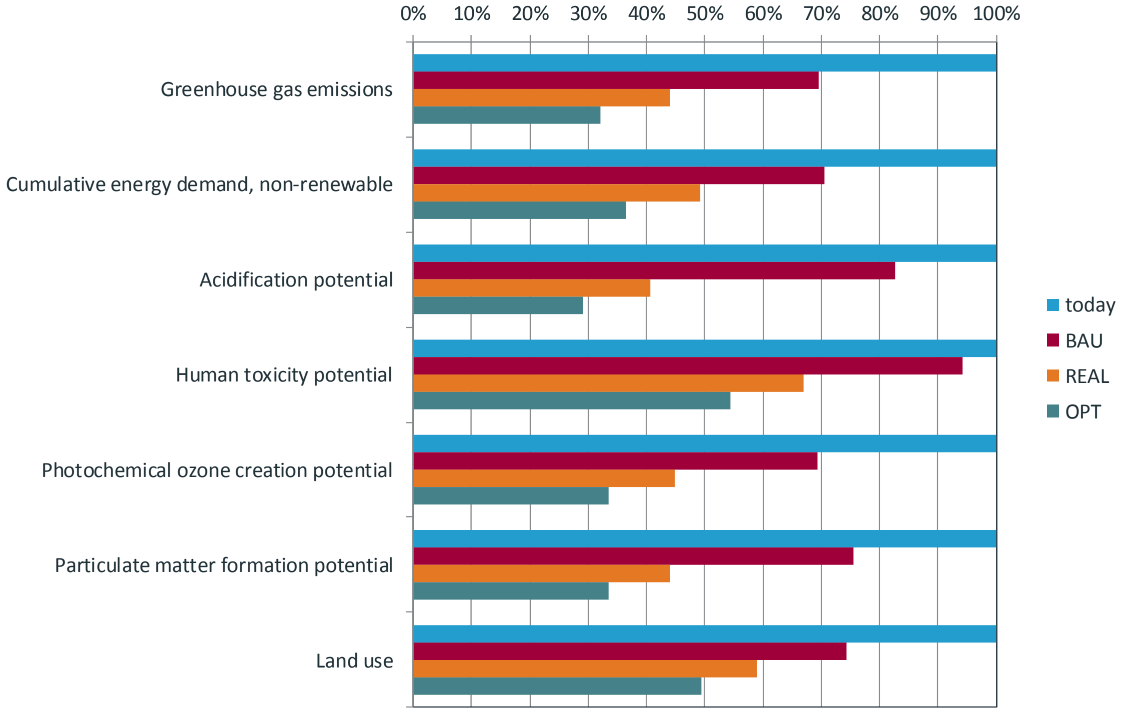


Fig. 6.4 Estimates of life cycle greenhouse gas emissions (using 100 year global warming potentials from IPCC (2013)), non-renewable cumulative energy demand (following Frischknecht et al. (2007c)), acidification potential, human toxicity potential, photochemical ozone creation potential, particulate matter formation potential and urban land occupation (following Goedkoop et al. (2009)) of electricity produced in 2050 with CdTe photovoltaic laminates mounted on slanted roofs in Europe, according to the three scenarios (BAU, REAL and OPT). Results for "today" are defined to be 100%, with the three scenarios as fractions thereof. Key assumptions are: module efficiency: 13.4% (today), 20.5% (BAU), 22.6% (REAL), 24.7% (OPT); annual yield (electricity generated per kWp of the PV power plant and year): 975 kWh/kWp including degradation (10.5% average for lifetime); solar irradiation: 1 331 kWh/m^2. Lifetime: 30 years (today and BAU), 35 years (REAL), 40 years (OPT). The system includes mounting, cabling, inverter and maintenance and considers production using region-specific electricity mixes. This is a prospective LCA for expected future development in the year 2050; the calculations are performed using the software SimaPro with ecoinvent v2.2+ as background database.

6.4 Non-renewable and Total Energy Payback Time

6.4.1 Single-crystalline Silicon Photovoltaic Power Plant

Fig. 6.5 shows the NREPBT in years according to Frischknecht et al. (Frischknecht et al. 2007c) of a 3-kWp single-crystalline silicon-based PV power plant installed on a slanted-roof in Germany, Spain or Europe with an annual yield of 838, 1 316 and

975 kWh/kWp, respectively, and a scenario-dependent lifetime of 30, 35 and 40 years (BAU, REAL, OPT, respectively).

The NREPBT is calculated with the non-renewable cumulative energy demand of the non-renewable residual electricity mix of the European network (ENTSO-E). The LCIs of the non-renewable residual electricity mixes for Europe and the scenarios are presented in Section 4.6.

The NREPBT of a 3-kWp single-Si silicon-based photovoltaic power plant varies between 0.9 and 2.7 years depending on location, lifetime and scenario. The NREPBT is the highest for PV plants installed in Germany, as the annual yield there is the lowest (838 kWh/kWp), and it is the lowest for PV plants installed in Spain because the annual yield there is the highest (1 316 kWh/kWp).

Depending on the scenario, the NREPBT is reduced from between 28% and 47% compared to today. This corresponds to a reduction of between 0.8 and 1.3 years compared to today, depending on the country of installation and the scenario. The NREPBT of a 3-kWp single-crystalline silicon-based PV power plant in the scenario OPT corresponds to 1.4, 0.9 and 1.2 years for the installation in Germany, Spain and Europe, respectively.

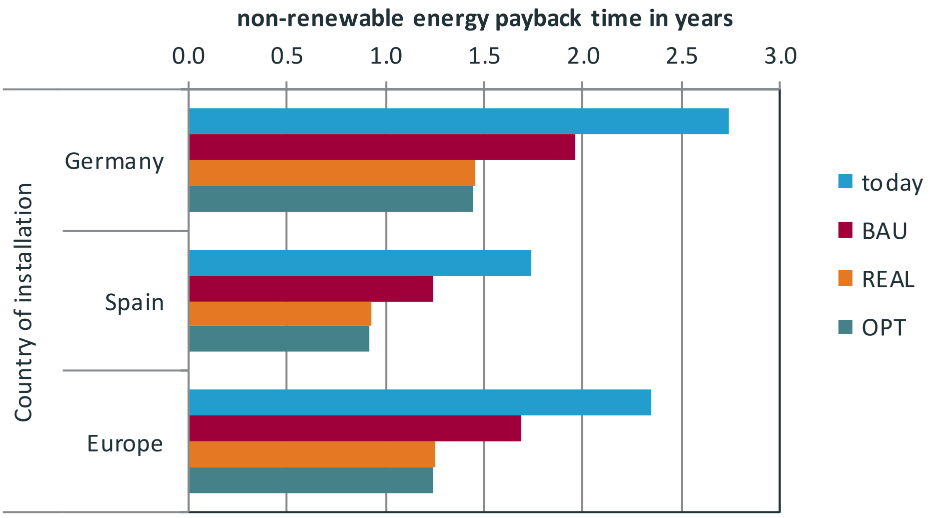


Fig. 6.5 Non-renewable energy payback time of a 3-kWp single-crystalline silicon-based photovoltaic power plant according to the three scenarios (BAU, REAL and OPT) and today in years. Key assumptions are: module efficiency: 15.1 % (today), 22.9 % (BAU), 25.2 % (REAL), 27.6 % (OPT); annual yield (electricity generated per kWp of the PV power plant and year): 975 kWh/kWp including degradation (10.5 % average for lifetime); solar irradiation: DE: 1 147 kWh/m^2, ES: 1 812 kWh/m^2, EU: 1 331 kWh/m^2. The system includes mounting, cabling, inverter and maintenance and considers production in different regions of the world (Europe, North America, China and Asia & Pacific) using region-specific electricity mixes. This is a prospective LCA for expected future development in the year 2050. The calculations are performed using the software SimaPro with ecoinvent v2.2+ as background database. (The reference for the NREPBT is the European non-renewable residual electricity mix.)

The total energy payback time EPBT is between 0.1 and 0.4 years higher compared to the NREPBT (see Fig. 6.7).

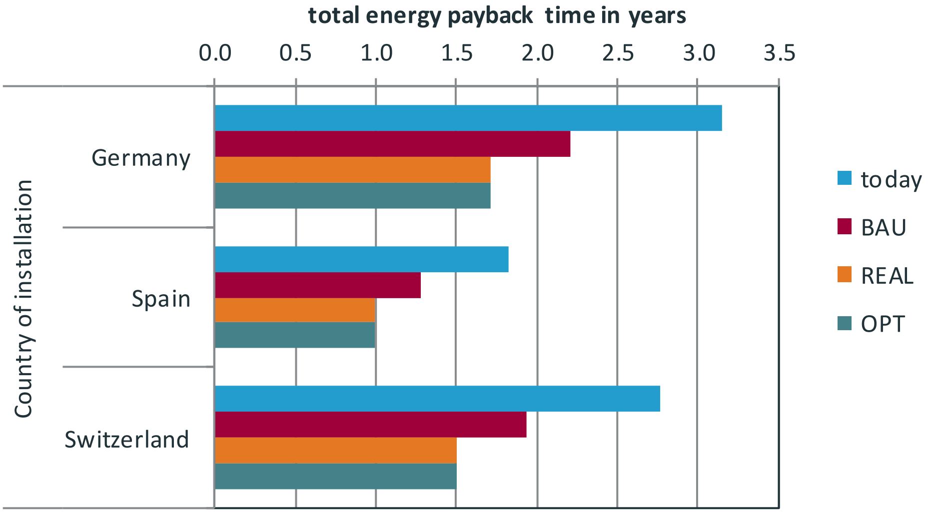


Fig. 6.6 Total energy payback time of a 3-kWp single-crystalline silicon-based photovoltaic power plant according to the three scenarios (BAU, REAL and OPT) and today in years. Key assumptions are: module efficiency: 15.1 % (today), 22.9 % (BAU), 25.2 % (REAL), 27.6 % (OPT); annual yield (electricity generated per kWp of the PV power plant and year): 975 kWh/kWp including degradation (10.5 % average for lifetime); solar irradiation: DE: 1 147 kWh/m^2, ES: 1 812 kWh/m^2, EU: 1 331 kWh/m^2. The system includes mounting, cabling, inverter and maintenance and considers production in different regions of the world (Europe, North America, China and Asia & Pacific) using region-specific electricity mixes. This is a prospective LCA for expected future development in the year 2050. The calculations are performed using the software SimaPro with ecoinvent v2.2+ as background database. (The reference for the EPBT is the European non-renewable residual electricity mix.)

6.4.2 Cadmium-telluride Photovoltaic Power Plant

Fig. 6.7 shows the NREPBT in years of a 3-kWp CdTe PV power plant installed on a slanted roof in Germany, Spain or Europe with an annual yield of 838, 1 316 and 975 kWh/kWp, respectively and a scenario-dependent lifetime of 30, 35 and 40 years (BAU, REAL, OPT, respectively).

The NREPBT is calculated with the non-renewable cumulative energy demand of the non-renewable residual electricity mix of the European network (ENTSO-E). The LCIs of the non-renewable residual electricity mixes for Europe and the scenarios are presented in Section 4.6.

The NREPBT of a 3-kWp CdTe PV power plant varies between 0.5 and 1.2 years depending on location, lifetime and scenario. The NREPBT time is reduced from between 24% and 36 % compared to today. This corresponds to a reduction of between 0.3 and 0.4 years compared to today, depending on the country of installation and the scenario. The NREPBT of CdTe PV laminates in the scenario OPT corresponds to 0.8, 0.5 and 0.7 years for the installation in Germany, Spain and Europe.

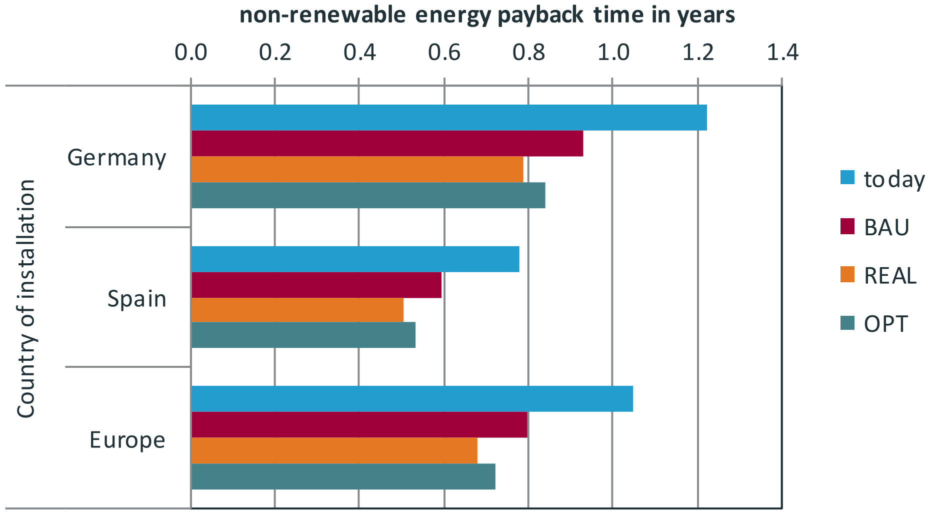


Fig. 6.7 Non-renewable energy payback time of a 3-kWp CdTe photovoltaic power plant according to the three scenarios (BAU, REAL and OPT) and today in years.
Key assumptions are: module efficiency: 13.4 % (today), 20.5 % (BAU), 22.6 % (REAL), 24.7 % (OPT); annual yield (electricity generated per kWp of the PV power plant and year): DE: 838 kWh/kWp, SP: 1 316 kWh/kWp, EU:975 kWh/kWp including degradation (10.5 % average for lifetime); solar irradiation: DE: 1 147 kWh/m^2, ES: 1 812 kWh/m^2, EU: 1 331 kWh/m^2. The system includes mounting, cabling, inverter and maintenance and considers production using region-specific electricity mixes. This is a prospective LCA for expected future development in the year 2050; the calculations are performed using the software Sima-Pro with ecoinvent v2.2+ as background database.
(The reference for the NREPBT is the European non-renewable residual electricity mix.)

The results may look anomalous in that REAL has a lower NREPBT than OPT, so an explanation is warranted. The decrease of the non-renewable cumulative energy demand of the European non-renewable residual electricity mix between the scenarios REAL and OPT is higher than the improvements based on CdTe module and manufacturing efficiency gains. (The non-renewable cumulative energy demand of the European non-renewable residual electricity mix (based on the technology shares shown in Tab. 4.7) corresponds to 12.4, 11.6, 11.0 and 8.8 MJ oil-eq/kWh for today and the scenarios BAU, REAL and OPT, respectively.) Therefore, the NREPBT in the scenario OPT for CdTe is higher than in the scenario REAL. However, the non-renewable cumulative energy demand of electricity generated by CdTe PV modules is still lower in the scenario OPT, but the replaced electricity (reference electricity mix) is an important parameter for the calculation of the NREPBT, leading to these differences between the NREPBT in the scenario REAL and the scenario OPT. This effect has extensively been discussed by Raugei (2013).

The total energy payback time EPBT is generally between 0 and 0.2 years higher compared to the NREPBT (see Fig. 6.8).

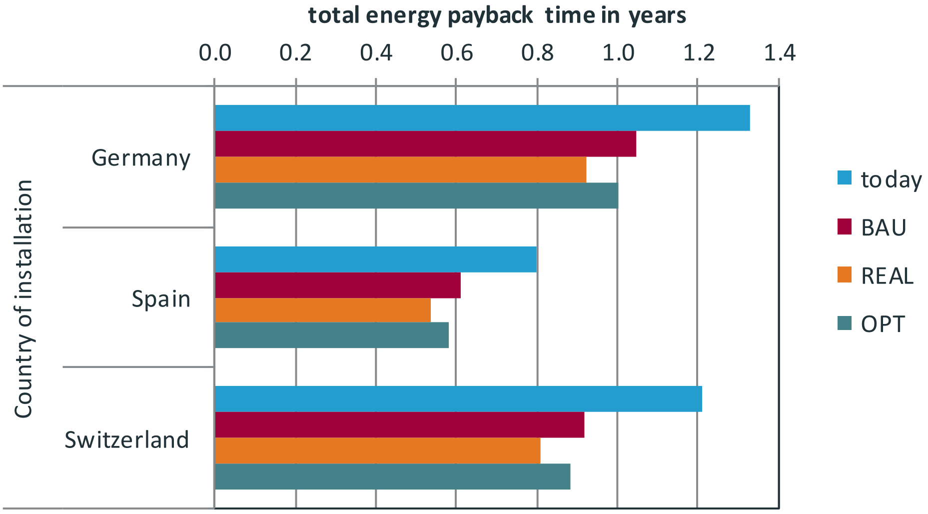


Fig. 6.8 Total energy payback time of a 3-kWp CdTe photovoltaic power plant according to the three scenarios (BAU, REAL and OPT) and today in years. Key assumptions are: module efficiency: 13.4 % (today), 20.5 % (BAU), 22.6 % (REAL), 24.7 % (OPT); annual yield (electricity generated per kWp of the PV power plant and year): DE: 838 kWh/kWp, SP: 1 316 kWh/kWp, EU:975 kWh/kWp including degradation (10.5 % average for lifetime); solar irradiation: DE: 1 147 kWh/m^2, ES: 1 812 kWh/m^2, EU: 1 331 kWh/m^2. The system includes mounting, cabling, inverter and maintenance and considers production using region-specific electricity mixes. This is a prospective LCA for expected future development in the year 2050; the calculations are performed using the software SimaPro with ecoinvent v2.2+ as background database.
(The reference for the EPBT is the European non-renewable residual electricity mix.)

6.5 Limitations

This section highlights several issues related to the quality of information used in modeling projections of environmental impacts for the fast-changing and globally-sourced PV modules, starting with the specific and moving to the general.

The predictions and scenarios related to the development of PV technologies as well as those related to the environmental efficiency of material supply and the electricity mixes used in manufacturing are uncertain. That is why three different scenarios are developed which reflect these inherent uncertainties about the future.

A potentially important characteristic of PV modules is where they were manufactured. It has been of considerable interest to researchers to develop LCIs for module manufacturing in different countries, but so far no contemporary data are available for countries outside of Europe and the US. Thus, variation in the LCI according to world region is accomplished through the simplified approach of applying region-specific electricity mixes. Development of robust, country-specific LCIs remains an area of future research.

The information about the production shares at the different levels of the supply chain of silicon based PV is reliable. However, the market shares (comprising domestic production and imports) are less reliable. The trade of polysilicon, silicon wafers and PV modules between the different regions of the world is based on assumptions, as no data were available for the traded volumes between the different world regions. It was also assumed that the global mix would not change in the future, again for lack of any reliable data source providing such a projection.

Based on differences in absolute impacts, assumptions of global module supply mix are more or less influential. Such assumptions matter more under the scenario BAU, but much less for the scenario OPT since the absolute impacts have been driven so low by 2050 already.

Possible changes in design and material usage of important parts of the PV power plants like the slanted-roof construction and the inverter are not taken into account. These balance-of-system parts of the PV system become relatively more important to the system total because the environmental impacts of the PV modules are expected to be much lower; thus, developing projections of these components to 2050 is an area of future research. Nevertheless, the different parameter sets of the three future scenarios cover a broad range of possible developments, and they can indicate the likely direction of change, even if the results so far in the future will never be known precisely.

7 Conclusions

The specfic cases analyzed were for single crystalline and cadmium telluride modules deployed in small scale power plants on residential roofs in Europe. The results of this assessment of future PV electricity production indicate significant reduction in the environmental impacts of PV electricity compared with those from today given three sets of assumptions (scenarios) of projected changes in PV module design, performance and supplying industries. This was found for all environmental impact indicator categories assessed. The greenhouse gas emissions of future crystalline silicon PV electricity are reduced by one third (BAU scenario), two third (REAL scenario) and more than 80 % (OPT scenario). The reduction in greenhouse gas emissions of future CdTe PV electricity is less pronounced. However, the emissions of current CdTe PV electricity are substantially lower than for crystalline silicon PV. The reduction in other environmental impacts is similar to the reduction in greenhouse gas emissions except for human toxicity. However in current life cycle assessment data and indicators high uncertainties are attached to human toxicity indicator results (European Commission 2010). Based on the data and impact models used in this study it is yet premature to estimate how the scenarios may affect the potential human toxicity impacts. More detailed information, higher quality life cycle inventory data and better impact assessment models are needed to reduce the uncertainty in quantifying potential human toxicity impacts.

The gains in energy and material efficiency of the PV technologies analysed and the developments in environmental efficiency of material supply lead to a significant reduction in the non renewable and total energy payback time in the future, even in the BAU scenario. The NREPBT of future crystalline silicon and CdTe PV electricity drops below 2 years and 1 year, respectively, when installed in Germany. Installations in Spain show NREPBT which are about 40 % lower than those of installations in Germany.

The results are based on a set of assumptions and projections that use the best available information. They are subject to considerable uncertainty, especially when projecting more than 30 years for the fast-evolving crystalline Si- and CdTe-PV technologies. Therefore, the results of this analysis are best interpreted as indicating the currently expected direction and approximate relative magnitude of change for the PV industry rather than as precise predictions of absolute impacts in future years. While the absolute magnitude of results will change if different locations or applications are considered, the direction and relative magnitude of projected changes in impacts compared to the current situation is likely consistent with those reported here, and therefore informative to energy decisions with long-term consequences.

Future energy planning, such as the Energy Strategy 2050 of the Swiss Federal Council (Bundesamt für Energie 2013), could benefit from the results of this and other LCAs of future PV electricity rather than LCA results representing the (recent) past. Doing so would allow technological improvement potentials—which are to be expected in rapidly developing technologies such as PV—to be taken into account.

References

Bundesamt für Energie 2013	Bundesamt für Energie (2013) Energieperspektiven 2050 - Zusammenfassung. Bundesamt für Energie (BFE), Abteilung Energiewirtschaft, Bern.
Clemmer et al. 2013	Clemmer S., Rogers J., Sattler S., Macknick J. and Mai T. (2013) Modeling low-carbon US electricity futures to explore impacts on national and regional water use. In: Environmental research letters(8), pp. 12, 10.1088/1748-9326/8/1/015004.
de Wild-Scholten & Alsema 2005	de Wild-Scholten M. J. and Alsema E. A. (2005) Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic Module Production. In proceedings from: Proceedings of the Materials Research Society Fall 2005 Meeting, Boston, USA, 28-30 November 2005, retrieved from: www.mrs.org.
de Wild-Scholten & Alsema 2007	de Wild-Scholten M. J. and Alsema E. A. (2007) Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic System Production. Energy research Center of the Netherlands, Petten, The Netherlands and Copernicus Institute for Sustainable Development and Innovation, Utrecht University, The Netherlands, retrieved from: www.ecn.nl/publicaties/default.aspx?au=44649.
de Wild-Scholten 2013	de Wild-Scholten M. J. (2013) Energy payback time and carbon footprint of commercial photovoltaic systems. In: Solar Energy Materials & Solar Cells, pp.
EAA 2013	EAA (2013) Environmental Profile Report for the European Aluminium Industry; Data for the year 2010. European Aluminium Association, EAA, Brussels, Belgium.
ecoinvent Centre 2010	ecoinvent Centre (2010) ecoinvent data v2.2, ecoinvent reports No. 1-25. Swiss Centre for Life Cycle Inventories, Duebendorf, Switzerland, retrieved from: www.ecoinvent.org.
EPIA 2012	EPIA (2012) Connecting the sun - solar photovoltaics on the road to large-scale grid integration. European Photovoltaic Industry Association (EPIA), Brussels - Belgium.
European Commission 2010	European Commission (2010) ILCD Handbook (International Reference Life Cycle Data System), Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment. European Commission, DG-JRC.
FHI-ISE 2013	FHI-ISE (2013) Photovoltaics report. Fraunhofer Institue (FHI) for Solar Energy System (ISE), Freiburg, Germany, retrieved from: www.ise.fraunhofer.de.
First Solar 2011	First Solar (2011) First Solar Corporate Overview. In, pp., retrieved from: www.firstolar.com.
First Solar 2014	First Solar (2014) Key Quarterly Financial Data. First Solar, Inc., Tempe, Arizona, USA.

Frischknecht et al. 2007a	Frischknecht R., Tuchschmid M. and Krewitt W. (2007a) Meeting the NEEDS of European Environmental Sustainability Assessment. In proceedings from: LCA of Energy - Energy in LCA; 14th SETAC Europe Case Studies Symposium, December 3 to 4, 2007, Gothenburg.
Frischknecht et al. 2007b	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Heck T., Hellweg S., Hischier R., Nemecek T., Rebitzer G. and Spielmann M. (2007b) Overview and Methodology. ecoinvent report No. 1, v2.0. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.
Frischknecht et al. 2007c	Frischknecht R., Jungbluth N., Althaus H.-J., Bauer C., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M. and Nemecek T. (2007c) Implementation of Life Cycle Impact Assessment Methods. ecoinvent report No. 3, v2.0. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.
Frischknecht & Krewitt 2008	Frischknecht R. and Krewitt W. (2008) Meeting the NEEDS of European Environmental Sustainability Assessment. In proceedings from: 8th International Conference on EcoBalance, December 10-12, 2008, Tokyo.
Frischknecht et al. 2008	Frischknecht R., Faist Emmenegger M., Steiner R., Tuchschmid M. and Gärtner S. (2008) LCA of Background processes. In: NEEDS Project, Deliverable 15.1. ESU-services and ifeu, Uster and Heidelberg, retrieved from: www.needs-project.org/RS1a/RS1a%20D15.1%20LCA%20of%20background%20processes.pdf.
Frischknecht 2010	Frischknecht R. (2010) NEEDS: Effective assessment of long-term sustainable energy policies in Europe by integrating LCA, external costs and energy planning models. In proceedings from: Der Systemblick auf Innovation – Technikfolgenabschätzung in der Technikgestaltung, NTA4 – Vierte Konferenz des Netzwerkes TA, 24.-26. November 2010, Berlin, retrieved from: http://www.itas.fzk.de/v/nta4/.
Fthenakis et al. 2011	Fthenakis V., Frischknecht R., Raugei M., Chul K. H., Alsema E., Held M. and Scholten M. d. W. (2011) Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity. Subtask 20 "LCA", IEA PVPS Task 12, retrieved from: http://www.iea-pvps-task12.org/.
Gambhir et al. 2012	Gambhir A., Hirst N., Brown T., Riahi K., Schulz N., Faist M., Foster S., Jennings M., Munuera L., Tong D. and Tse L. K. C. (2012) CHINA’S ENERGY TECHNOLOGIES TO 2050. Grantham Institute for Climate Change, London.
Garabedian 2013	Garabedian R. (2013) First Solar Technology Update. First Solar Inc.
Garabedian 2014	Garabedian R. (2014) First Solar Technology Update. First Solar Inc.

Goedkoop et al. 2009	Goedkoop M., Heijungs R., Huijbregts M. A. J., De Schryver A., Struijs J. and van Zelm R. (2009) ReCiPe 2008 - A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. First edition. Report I: Characterisation, NL, retrieved from: lcia-recipe.net/.
Goodrich et al. 2013	Goodrich A., Hacke P., Wang Q., Sopori B., Margolis R., James T. and Woodhouse M. (2013) A wafer-based monocrystalline silicon photovoltaics roadmap: Utilizing known technology improvement opportunities for further reductions in manufacturing costs. In: Solar Energy Materials & Solar Cells, 114, pp. 110-135, retrieved from: www.elsevier.com/locate/solmat.
IEA-PVPS 2013	IEA-PVPS (2013) Trends in Photovoltaic Applications - Survey report of selected IEA countries between 1992 and 2012. PVPS T1 - 23 : 2013. International Energy Agency (IEA), retrieved from: www.iea-pvps.org.
IEA 2010	IEA (2010) Technology Roadmap: Solar photovoltaic energy. International Energy Agency (IEA), retrieved from: http://www.iea.org/publications/.
IPCC 2013	IPCC (2013) The IPCC fifth Assessment Report - Climate Change 2013: the Physical Science Basis. Working Group I, IPCC Secretariat, Geneva, Switzerland.
ITRPV 2013	ITRPV (2013) International Technology Roadmap for Photovoltaics (ITRPV) - Results 2012. SEMI PV Group.
Itten et al. 2014	Itten R., Wyss F. and Frischknecht R. (2014) LCI of the global crystalline photovoltaics supply chain and of future photovoltaics electricity production. treeze Ltd., Uster, Switzerland.
Jungbluth et al. 2012	Jungbluth N., Stucki M., Flury K., Frischknecht R. and Buesser S. (2012) Life Cycle Inventories of Photovoltaics. ESU-services Ltd., Uster, CH, retrieved from: www.esu-services.ch.
LC-inventories 2012	LC-inventories (2012) Corrections, updates and extensions of ecoinvent data v2.2. treeze Ltd., retrieved from: www.lc-inventories.ch.
Marwede & Reller 2012	Marwede M. and Reller A. (2012) Future recycling flows of tellurium from cadmium telluride photovoltaic waste. In: Resources, Conservation and Recycling(69), pp. 35-49.
Payet et al. 2013	Payet J., Evon B., Sié M., Blanc I., Belon-Saint-Pierre D., Guermont C., Adra N., Puech C. and Durand Y. (2013) Methodological framework for assessing the environmental impacts of photovoltaic systems using the life cycle assessment method. ADEME.
Photon International 2013	Photon International (2013) Average module efficiencies. In: Photon International, pp.
PRé Consultants 2012	PRé Consultants (2012) SimaPro 7.3.3, Amersfoort, NL.

Raugei 2013	Raugei M. (2013) Energy pay-back time: methodological caveats and future scenarios. In: Progress in Photovoltaics: Research and Applications, 21(4), pp. 797-801.
Shockley & Queisser 1961	Shockley W. and Queisser H. J. (1961) Detailed Balance Limit of Efficiency of p-n Junction Solar Cells. In: J. Appl. Phys, 32(3), pp. 510-519.
Swanson 2005	Swanson R. M. (2005) Approaching the 29% Limit Efficiency of Silicon Solar Cells. In: 20th European Photovoltaic Solar Energy Conference Barcelona, Spain.
Woodhouse et al. 2013	Woodhouse M., Goodrich A., Margolis R., James T., Dhere R., Gessert T., Barnes T., Eggert R. and Albin D. (2013) Perspectives on the pathways for cadmiumtelluride photovoltaic module manufacturers to address expected increases in the price for tellurium. In: Solar Energy Materials & Solar Cells(115), pp. 199-212, retrieved from: www.elsevier.com/locate/solmat.
WorldAluminium 2013	WorldAluminium (2013) Global life cycle inventory data for the primary aluminium industry, data 2010. In, pp.

IEA INTERNATIONAL ENERGY AGENCY

ISBN 978-3-906042-30-5

9 783906 042305 >