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TECHNICAL STUDY REPORT ON SOLAR THERMAL TECHNOLOGY LCIA METHODS AND LCC MODELS

UNDP gef Cu ESTIF European Solar Thermal Industry Federation

UNITED NATIONS ENVIRONMENT PROGRAMME

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SUMMARY

Solar thermal suffers in the market, the media and in the policy arena, because solar thermal energy is often not accounted for, and amounts of solar thermal heat are not transparently measured and displayed. This also leads to problems/malfunctions not being spotted quickly.

This “Technical study report on solar thermal technology LCIA methods and LCC models” aims at contributing to the demonstration of the advantages of solar thermal systems, taking the lifecycle into account. This means assessing both environmental and economic benefits of the systems over their operation period. These methods allow to exemplify the diverse benefits of this technology during the lifecycle of a system, in spite of high upfront investments costs.

In order to establish reliability and comparability of life cycle assessment a comprehensive set of rules has been defined within international standards regarding life cycle assessment and life cycle costing. In Chapter ***Life cycle assessment (LCA) – Fundamentals and definitions*** of this report the fundamentals and definitions of these rules of life cycle assessment are given.

The life cycle of a product may have impact in different areas. In order to distinguish and quantify them, impact categories have been defined which are described in chapter ***Available impact categories***.

Chapter ***Available Life Cycle Impact Assessment (LCIA) methods*** gives an overview on available life cycle impact assessment methods. It is described how these methods make use of the previously described impact categories and how they differ in purpose and complexity.

Chapter ***LCIA methods applied in LCA of solar thermal systems*** is a compilation and evaluation of life cycle assessment studies of solar thermal systems with a focus on the applied life cycle impact assessment methods.

In ***Chapter Life Cycle Costing (LCC)*** analysis is described with a focus on the application on solar thermal technologies and buildings using solar thermal supply systems.

This “Technical study report on solar thermal technology LCIA methods and LCC models” was developed as part of the Global Solar Water Heating (GSWH) Market Transformation and Strengthening Initiative (GSWH Project), and as a result of a joint effort between The European Solar Thermal Industry Federation (ESTIF) and the United Nations Environment Programme (UNEP) through its Division of Technology, Industry and Economics (DTIE) and the Global Environment Fund (GEF).

Funded by the Global Environment Fund (GEF), the GSWH project’s main goal is to accelerate the global commercialization and sustainable market transformation of SWH, thereby reducing the current use of electricity and fossil fuels for hot water preparation. It will build on the encouraging market development rates already achieved in some GEF programme countries and seek to further expand the market in others where the potential and necessary prerequisites for market uptake seem to exist.

CONTENTS

INTRODUCTION

Life Cycle assessment (LCA) and Life Cycle Costing (LCC) Analysis are powerful tools to determine the impact of a product not only by its use but also its whole life cycle from cradle to grave. In order to establish reliability and comparability of life cycle assessment a comprehensive set of rules has been defined within international standards regarding life cycle assessment. During the past decades several comprehensive impact assessment methods have been developed to assess not only one single aspect of a products life cycle, e.g. its contribution to the greenhouse effect, but to assess a set of multiple aspects.

LIFE CYCLE ASSESSMENT (LCA) – FUNDAMENTALS AND DEFINITIONS

2.1 Fundamentals

The International Standards DIN EN ISO 14040 [1] and DIN EN ISO 14044 [2] describe the principles and framework for life cycle assessment (LCA). The life cycle assessment framework is structured into four main phases:

- definition of the goal and scope
- life cycle inventory analysis (LCI)
- life cycle impact assessment (LCIA)
- interpretation

Due to interactions between the phases, life cycle assessment is an iterative process. For example if it turns out in the interpretation phase, that a specific component of the investigated system has a large impact during the impact assessment phase, it may be required to investigate this component during the inventory analysis with more detail in order to meet the requirements defined in the goal and scope. The iterative structure of LCA is shown in Figure 1.

Goal and scope definition

The goal of an LCA states the intended application, the reasons for carrying out the study, the intended audience, i.e. to whom the results of the study are intended to be communicated, and whether the results are intended to be used in comparative assertions intended to be disclosed to the public.

The scope of an LCA study defines the properties of the system under investigation as well as the functional unit, the system boundary, assumptions and limitations. It should be sufficiently well defined to ensure that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal. [1]

The functional unit is the “quantified performance of a product system for use as a reference unit”. [2]

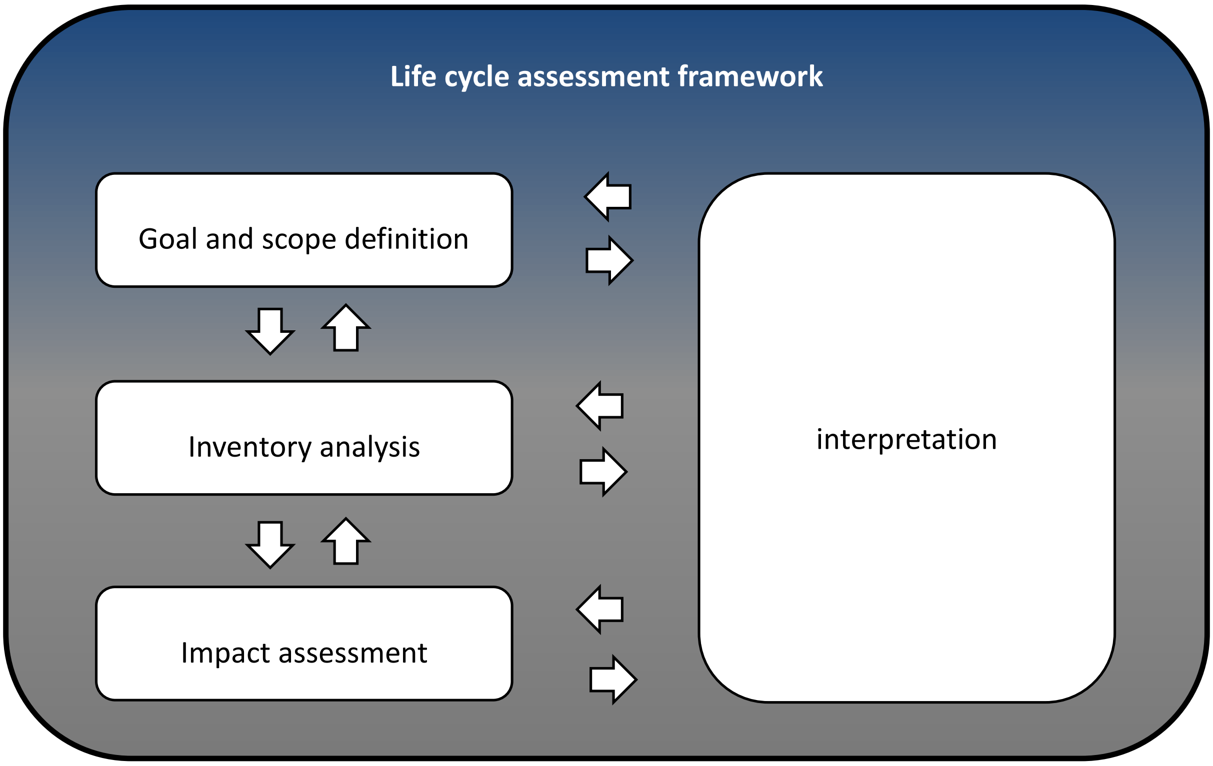

Figure 1: Life cycle assessment framework according to DIN EN ISO 14040 [1]

Inventory analysis

During the inventory analysis the investigated system is divided into its components in order to "quantify relevant inputs and outputs" [1]. Inventory analysis involves data collection, calculation procedures for validation of data and relating the data to the reference flow of the functional unit. Also, allocation of by-products and recycling is defined during this phase.

Impact Assessment

In the life cycle impact assessment phase LCI data is associated with "specific environmental impact categories and category indicators" [1] in order to evaluate and understand "the significance of potential environmental impacts" [1] of the investigated product system. For that purpose, impact categories and indicators need to be defined, which meet the objectives of the study defined in the goal and scope phase.

The scope of this study is to investigate the available life cycle impact assessment methods (LCIA methods). Hence, a closer look at this phase is provided in the following.

As shown in Figure 2 life cycle impact assessment contains mandatory elements, which provide a an LCIA result in the form of category indicator results as well as optional elements, which are intended to allow to compare and aggregate category indicator results.

Interpretation

Interpretation is the phase of LCA in which a joint consideration the LCI results and the LCIA results is carried out. In accordance with the goal and scope of the study the interpretation phase should “reach conclusions, explain limitations and provide recommendations” [1].

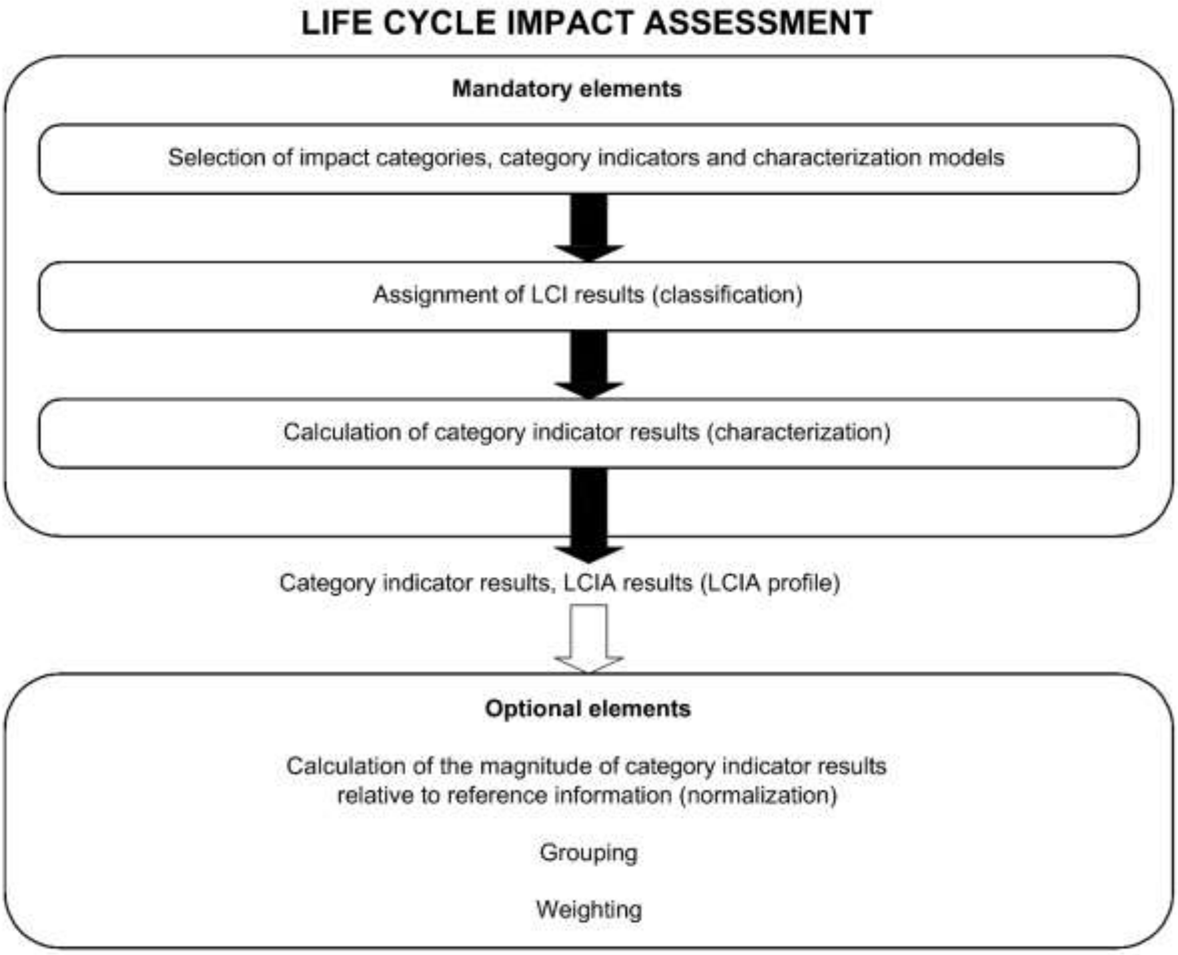

Figure 2: Elements of the LCIA phase according to DIN EN ISO 14040 [1]

2.2 Definitions

Impact category

The impact category is defined as a “class representing environmental issues of concern to which life cycle inventory analysis results may be assigned” [1]. An example for an impact category is the Global Warming Potential (GWP)

Category indicators

The category indicator is defined as a “quantifiable representation of an impact category” [1]. The category indicator of the Global Warming Potential

Characterization factor/model

A characterization factor is defined as a "factor derived from a characterization model which is applied to convert an assigned life cycle inventory analysis result to the common unit of the category indicator" [1].

Classification

Classification groups LCI results and assigns them to a specific impact category. LCI results may contribute to several impact categories. In the case of impact categories which have independent effects LCI results are assigned to all impact categories to which they contribute. In this case of impact categories with dependent effects LCI results are portioned and assigned to the impact categories to which they contribute. The distribution is defined by the classification.

Characterization

Characterization is the calculation step of converting "LCI results to indicator results to common units and aggregation of the converted results within the same impact category" [2]. This conversion is done by applying characterization factors which are derived from a characterization model. Characterization models reflect the environmental mechanism behind an environmental impact.

Midpoint and Endpoint

The available LCIA methods address different points in the cause-effect chain which defines the impact of a product system. There are LCIA methods which use a problem-oriented approach (midpoint level) and others which use a damage-oriented approach (endpoint level).

The generally used endpoints of the cause-effect chain are the human health, the natural environment and the natural resources. LCIA methods which give results as impacts on or more of these endpoints are called damage-oriented methods.

"Midpoints are considered to be a point in the cause-effect chain of a particular impact category, prior to the endpoint, at which characterization factors can be calculated to reflect the relative importance of an emission or extraction in a Life Cycle Inventory (LCI) (e.g., global warming potentials defined in terms of radiative forcing and atmospheric half-life differences)." [3]

Hence, "impacts at the endpoint […] may occur as a result of climate change, ozone depletion, as well as other categories traditionally addressed using midpoint category indicators." [3]

Most comprehensive damage-oriented LCIA methods make use of the optional elements normalization, grouping and weighing in order to provide an aggregated single category indicator.

Normalization

Normalization is defined as "the calculation of the magnitude of the category indicator results relative to some reference information" [2]. It is used to allow comparison across different impact categories and as preparation for further procedures like grouping and weighing. "Normalization transforms an indicator result by dividing it by a selected reference value." [2] Such reference values are often defined by total inputs and outputs of given area and a given period in time.

The normalized result for a given impact category and region is obtained by multiplying the characterization factors by their respective emissions. The sum of these products in every impact category gives the normalization factor.

Grouping

Grouping is defined as “the assignment of impact categories into one or more sets as predefined in the goal and scope definition” [2]. By Grouping impact categories can be sorted on a nominal basis, e.g. categories with local or global impact or categories with impact on resources or human health. Apart from this they can be ranked by grouping, e.g. impact categories with high or low priority.

Weighting

Weighting is used in order to convert indicator results according to their relative importance and aggregate these converted indicator results. The main intention of weighting an aggregating indicator results is to decrease the variety of result values given by a set of impact categories to only a few or just one result value.

AVAILABLE IMPACT CATEGORIES

In 2011 the Institute for Environment and Sustainability (IES) of the Joint Research Centre (JRC) of the European Commission released a comprehensive guidance handbook [4] with recommendations on LCIA methods. This document was used as a basis for the investigation. Further information on available LCIA methods was gathered from LCA-database and LCA-Software providers. A main source is the ecoinvent database.

Due to the large variety of available characterization models, the characterization models recommended in the ILCD Handbook are assigned to the impact categories. In cases where the ILCD Handbook makes no recommendation, the commonly used characterization model – most often represented by the characterization models in ecoinvent – are assigned. The sources are marked within the table.

A very comprehensive overview of potential characterization models for each impact category is given in [5]. Table 1 presents a set of common impact categories which are used in most comprehensive multi-dimensional LCIA methods.

Table 1: Impact categories

Resource depletion
abiotic resource depletion
mineral resource depletion
fossil resource depletion
water resource depletion
biotic resource depletion
Land use
Land occupation
Land transformation
Climate change
Stratospheric Ozone (layer) depletion
Human toxicity
Human toxicity, cancer effects
Human toxicity, non-cancer effects
Ecotoxicity
freshwater aquatic ecotoxicity
marine ecotoxicity
terrestrial ecotoxicity
Freshwater sediment ecotoxicity
Marine sediment ecotoxicity
Photochemical oxidant formation (Photochemical ozone creation potential)
Acidification
Eutrophication
terrestrial eutrophication
aquatic eutrophication
Ionising radiation

Ionizing Radiation, human health
Ionizing Radiation, ecosystems
Particulate matter formation (Respiratory inorganics)
Others
Waste heat
malodorous air
malodorous water
noise
Loss of biodiversity
Loss of life support function
Desiccation
odour
casualties

3.1 Resource Depletion

Resource depletion represents a very broad impact category. Hence there is a "lack of consensus on what is the main issue for this impact category" [5]. In a first step the earth's resources may be categorized into renewable and non-renewable resources or into biotic and abiotic resources. Available characterization differ in complexity – there are models describing simple resource extraction to models determining the scarcity of a resource by taking into account regionally differentiated deposit stocks, extraction rates, regeneration rates and recovery fractions of a resource.

The depletion of abiotic resources is mainly expressed in kg of the resource or in equivalents of another material. The depletion of resources used as fuels is often expressed by MJ of primary energy or fossil fuel.

3.2 Land Use

Human activities such as settlement, resource extraction or agriculture cause transformation and/or occupation of land. "Occupation leads to positive, or negative, impacts in terms of the stress on surrounding ecosystems, and can prevent restoration processes relative to some equilibrium or baseline. Transformation leads to net positive, or negative, impacts on the transformed area itself. The sign of the impact depends on the baseline, or on the land use just before transformation, respectively." [5] Occupation is expressed as an area occupied for a period of time in m^2a. Transformation is expressed as an area of transformed land in m^2.

In order to take into account the quality of different types of land transformation processes, Weidema and Lindeijer [6] proposed a mathematical description which multiplies the plain land use with a quality indicator.

3.3 Climate Change

A large portion of solar radiation at spectral frequencies of visible light passes the earth's atmosphere and warms the earth's surface. The surface of the earth emits radiation in the infrared spectrum of light, which is to a large part absorbed by the earth's atmosphere. This mechanism called "greenhouse effect" induced by the presence of the atmosphere leads to a higher temperature of the earth than without the atmosphere. The concentration of so called "greenhouse gases", e.g. carbon dioxide, methane and nitrous oxide, influences the portion of absorbed infrared light and by this the temperature of the atmosphere and the earth.

The most commonly used characterization model is based on factors for different chemical emissions released by the Intergovernmental Panel on Climate Change (IPCC) of the United Nations (UN). The factors express the Global Warming Potential (GWP) of an emitted chemical referenced to 1 kg of carbon dioxide. They are given for different time horizons whereas the time horizon of 100 years is proposed by the IPCC.

3.4 Stratospheric ozone (layer) depletion

The ozone in the earth's stratosphere – the so called ozone layer – absorbs a large portion of the ultraviolet light coming mainly from the sun. Atmospheric ozone is mainly destroyed by a catalytic reaction with atomic halogens. Reactive halogen gases originate from natural or man-made emissions, at Earth's surface, of source gases containing the halogens chlorine and bromine. [7] The decrease of the portion of ozone in the stratosphere leads to an increase in ultraviolet radiation at the Earth's surface. An increased exposure to UV light is suspected to cause skin cancer, cataracts damage to plants and plankton.

The most commonly used characterization model is based on factors for different chemical emissions released by the World Meteorological Organization (WMO) [7]. The factors express the Ozone Depletion Potentials (GWPs) emitted chemicals referenced to 1 kg of CFC-11.

3.5 Human toxicity

The impact category human toxicity accounts for adverse effects of chemicals on human health. "Toxicological characterization factors for human health are calculated by taking into account the time integrated fate, exposure of a unit mass of chemical released into the environment (including, in many cases, the size of the exposed population), toxicological potency (a quantitative measure related to the dose–response of a chemical, such as the LOEL – the Lowest Observable Effect Level in a test) and toxicological severity (a measure or description, qualitative or quantitative, of the effect incurred, such as bladder cancer or skin irritation)." [8] The category is further divided into cancer effects and non-cancer effects. Carcinogens are commonly expressed in terms of 1,4-dichlorobenzene equivalents. For Non-Carcinogens the chemical toluene may be used as a reference substance.

3.6 Ecotoxicity

Ecotoxicity or Environmental toxicity is similar to human toxicity except for the Area of Protection. The impact category accounts for adverse effects of chemicals on the natural environment. The toxicological characterization factors are also calculated by taking into account fate, exposure, potency and severity of a chemical released into the environment. The category is further divided into the areas freshwater ecotoxicity, marine ecotoxicity and terrestrial ecotoxicity. Within freshwater and marine ecotoxicity there are further subcategories for the water and the sediment ecotoxicity. Depending on the model used for characterization the ecotoxicity of substances is either expressed in mass equivalents of reference substance, e.g. 1,4-dichlorobenzene or by the effect on species in a Potentially Disappeared Fraction of species (PDF) or Potentially Affected Fraction of species (PAF).

3.7 Photochemical oxidant formation

Photochemical oxidant formation accounts for photochemically generated pollutants such as ozone and other reactive oxygen compounds. They are mainly "formed by the reaction of volatile organic compounds and nitrogen oxides in the presence of heat and sunlight" [9]. These compounds can harm humans, animals and plants by oxidizing organic molecules. "The heterogeneous spatial distribution of VOC and NOx sources […] and the hundreds of chemical species involved, makes the photochemical formation of ozone on a regional scale highly non-linear and dynamic. It is influenced by meteorological conditions and interaction between the different VOCs – both from anthropogenic and natural sources, such as forests.” Individual characterization factors for many different VOCs are provided in the models based on the POCP (Photochemical Ozone Creation Potential) or MIR (Maximum Incremental Reactivity) concept. Apart from these “regionally differentiated models […] attempt to capture the non-linear nature of the ozone formation with its spatially and temporally determined differences”. [10] The POCP is often expressed in mass equivalents of ethylene.

3.8 Acidification

An increase of the hydrogen ion concentration in water or soil is called acidification. It may be caused direct by introducing acidic chemicals into the water or soil e.g. through fertilizer use or indirectly through emissions of acidic gases, which react with water forming “acid rain”. Emission of the acidic gases and the acid deposition by “acid rain” often take place at different locations due to atmospheric transport. A major challenge in developing appropriate models therefore represents the consideration of the spatial difference between emission and deposition.

Most commonly acidification is calculated at midpoint level in kg SO2-equivalents with sulphur dioxide as reference acidic substance. Some LCIA methods calculate it at endpoint level indication the decrease in biodiversity as a damage to the ecosystem.

3.9 Eutrophication

Eutrophication describes the ecosystem’s reaction on nutrient enrichment. Under natural conditions, the supply of nutrients is in balance with the growth of biomass. An anthropogenic addition of nutrients often increases the competitive advantage of nutrient-demanding species at the expense of more nutrient-efficient species and by this changes the plant community. [5, 10] An example is algae bloom.

The category Eutrophication is further divided into terrestrial and aquatic eutrophication. The most important nutrients to be considered are nitrogen and phosphorus. Eutrophication is therefore expressed in mass equivalents of the reference substances PO43- and N. “Airborne spreading of phosphorus is not prevalent, and terrestrial eutrophication is therefore mainly associated with nitrogen compounds.” [10]

3.10 Ionizing radiation

Ionizing radiation is radiation with enough energy to free electrons from atoms or molecules in the body tissue. “In living organisms, this energy transfer may disturb or destroy cellular functions (somatic effect: i.e., fatal and nonfatal cancer) or it may change the genetic code of cells (hereditary effect).” [11]

Similar to human toxicity and ecotoxicity the characterization of ionizing radiation takes into account fate, exposure, potency and severity of the impact of radioactive substances for human health and the ecosystem. Hence the impact category Ionizing radiation is further divided into ionizing radiation affecting human health and ionizing radiation affecting the ecosystem. In general Ionizing radiation is given in mass equivalents of Uranium 235. On an endpoint level the expression in DALY regarding the damage on human health and PAF regarding damage on the ecosystem are common.

3.11 Particulate matter formation (Respiratory inorganics)

This impact category accounts for particulate matter that is released directly into the environment (primary particulate matter) and for particulate matter that is formed by precursor substances such as NOx, SOx, NH3, etc. (secondary particulate matter). The concerned size of respiratory particles is 10 micrometers or less.

Apart from negative effects on human health and the health of other organisms particulate matter also effects the climate. At the moment only the effect on human health is considered by the characterization models of the impact category.

“The characterization factor for particulate matter/respiratory inorganics accounts for the environmental fate, exposure, dose-response of a pollutant for midpoint factors, and of severity for endpoint factors.” [10] Particulate matter formation is expressed in mass equivalents of particles with a size of 10 micrometers (PM10) on the midpoint level or DALY on the endpoint level.

3.12 Others

Other impact categories which are noted in the literature but are not commonly applied in LCA are waste heat, malodorous air, odour, malodorous water, noise, desiccation, loss of biodiversity, loss of life support function and casualties.

AVAILABLE LIFE CYCLE IMPACT ASSESSMENT (LCIA) METHODS

The endpoint of a LCIA is the point where damage is caused. It is therefore categorized into three main "areas of protection" (AOP), which are the ecosystem, human health and resources.

4.1 CML 2001

System boundary:	**cradle-to-grave**
Orientation:	**midpoint or endpoint**
Type:	**quantitative method**
Dimensions:	**multi-dimensional**

Description

The CML 2001 impact assessment method was published in 2001 by the Center of Environmental Science (CML) of Leiden University as an operational guide to the ISO standards. It is defined by a set of impact categories and characterization methods for the impact assessment within a life cycle assessment. The methodology principles are given in [4]. The method can be applied with a problem oriented approach (midpoint method) or a damage oriented approach (endpoint method). The damage approaches are equal to the Eco-indicator 99 and the EPS method. Hence, only the unique problem oriented approach is presented. The subcategories of CML 2001 are listed for three configurations/sets: 'baseline' impact categories (A) which are used in most LCAs, 'study-specific' impact categories (B) which are not often used in LCAs and 'other' impact categories for which no operational characterization factors are available.

For most of impact categories alternative characterization factors are available e.g. for different time horizons and geographic dependencies. The following table represents the complete set of impact categories in CML 2001. A complete characterization is only given for the baseline configuration and the study-specific.

Table 2: Impact categories of CML 2001

impact category		set	LCI results	characterisation model	category indicator	Characteri-sation factor	unit
Resource depletion							
	Depletion of abiotic resources	A	extraction of minerals and fossil fuels (in kg)	concentration-based reserves and rate of de-accumulation approach	depletion of the ultimate reserve in relation to annual use	ADP	kg antimony-eq.
	Depletion of biotic resources	C	-	-	-	-	-
Land use							
	Land competition	A	land use (in m² a)	unweighted aggregation	land occupation	1 for all types of land use	m2a
	Loss of biodiversity	C	-	-	-	-	-
	Loss of life support function	C	-	-	-	-	-
Desiccation		C	-	-	-	-	-
Climate change		A	emissions of greenhouse gases to the air (in kg)	IPCC model	infrared radiative forcing (W/m^2)	GWP 100	kg CO_2-Eq
Stratospheric ozone depletion		A	emissions of ozone-depleting gases to the air	WMO model	stratospheric ozone breakdown	ODP steady state	kg CFC-11-eq./kg emission
Human toxicity		A	emissions of toxic substances to air, water and soil (in kg)	USES 2.0 model (RIVM)	acceptable daily intake / predicted daily intake	HTP steady state	kg 1,4-DCB-eq.
Ecotoxicity							
	freshwater aquatic ecotoxicity	A	emissions of toxic substances to air, water and soil (in kg)	USES 2.0 model (RIVM)	predicted environmental concentration/predicted no-effect concentration	FAETP steady state	kg 1,4-DCB-eq.
	marine aquatic ecotoxicity	A	emissions of toxic substances to air, water and soil (in kg)	USES 2.0 model (RIVM)	predicted environmental concentration/predicted no-effect concentration	MAETP steady state	kg 1,4-DCB-eq.
	Terrestrial ecotoxicity	A	emissions of toxic substances to air, water and soil (in kg)	USES 2.0 model (RIVM)	predicted environmental concentration/predicted no-effect concentration	TAETP steady state	kg 1,4-DCB-eq.
	Freshwater sediment ecotoxicity	B	emissions of toxic substances to air, water and soil (in kg)	USES 2.0 model (RIVM)	predicted environmental concentration/predicted no-effect concentration	FSETP steady state	kg 1,4-DCB-eq.
	Marine sediment ecotoxicity	B	emissions of toxic substances to air, water and soil (in kg)	USES 2.0 model (RIVM)	predicted environmental concentration/predicted no-effect concentration	MSETP steady state	kg 1,4-DCB-eq.
Photo-oxidant formation		A	emissions of substances (VOC, CO) to air (in kg)	UNECE Trajectory model	tropospheric ozone formation	POCP high NOx	kg ethylene-eq.
Acidification		A	emissions of acidifying substances to the air (in kg)	RAINS10 model (IIASA)	deposition/acidification critical load	AP European average	kg SO_2-Eq
Eutrophication		A	emissions of nutrients to air, water and soil (in kg)	stochiometric procedure, which identifies the equivalence between N and P for both terrestrial and aquatic systems	deposition/N/P equivalents in biomass	EP generic	kg PO_4-eq.
Waste heat		B	emissions of heat (in MJ) to water	unweighted aggregation	heat released	1	MJ
Odour							

	malodorous air	B	emisssions of odorous substances (in kg) to the air	reciprocal of odour threshold value in the air	volume of air filled to the odour threshold value	1/OTV	m3 air
	malodorous water	C	-	-	-	-	-
noise		B	emissions of sound (in Pa² s)	unweighted aggregation	sound	1	Pa² s (sound)
ionising radiation		B	emissions of ionising radiation to air, water and soil (in kBq)	fate and exposure models combined with epidemiological studies and the concept of DALY	DALY	ionising radiation damage factors	yr
casualities		B	number of victims	unweighted aggregation	number of victims	1	-

Characterization

An Excel spreadsheet with characterization factors for over 1900 flows is available for download on the CML website [12].

Normalization & Weighting

Available normalization sets [13]:

- World 1990, 1995, 2000
- EU28 2000
- EU25 2000
- West Europe 1995
- Netherlands 1997

Scaled or interpolated normalization factors for other countries are available in several LCA databases like GaBi5, ecoinvent 3.1.

Literature

[4] Guinée, J.B.; Gorrée, M.; Heijungs, R.; Huppes, G.; Kleijn, R.; Koning, A. de; Oers, L. van; Wegener Sleeswijk, A.; Suh, S.; Udo de Haes, H.A.; Bruijn, H. de; Duin, R. van; Huijbregts, M.A.J. Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background. Kluwer Academic Publishers, ISBN 1-4020-0228-9, Dordrecht, 2002, 692 pp.

http://cml.leiden.edu/research/industrialecology/researchprojects/finished/new-dutch-lca-guide.html

[12] http://cml.leiden.edu/software/data-cmlia.html

[13] Huijbregts et al LCA normalisation data for the Netherlands (1997/1998), Western Europe (1995) and the World (1990 and 1995).

4.2 Cumulative Energy Demand (CED)

System boundary: cradle-to-gate
Orientation: midpoint
Type: quantitative method
Dimensions: one-dimensional

Description

The Cumulated Energy Demand (CED) states the entire demand, valued as primary energy, which arises in connection with the production, use and disposal of an economic good (product or service) or which may be attributed respectively to it in a causal relation. [14]

The CED is among other in the ecological balance or LCA one possible important characteristic value for an ecological assessment. [14] But the CED does not replace an assessment with the help of comprehensive impact assessment methods such as Eco-indicator 99 or ecological scarcity. It makes only sense in combination with other methods. [15]

The purpose of solar thermal systems is to provide thermal energy as energy. Hence it is self-evident to apply this impact assessment method to solar thermal systems in order to compare the end energy delivered by the system with the cumulated energy demand during its life cycle.

Characterization

The CED accounts for primary energy which may be present in different form from different resources. Characterization factors are given for the energy resources divided in up to 8 impact categories:

Table 3: Impact categories of CED

impact category	LCI results	characterisation model	category indicator	characterisation factor	unit
Non renewable					
fossil	fossil energy resources extracted	upper heating value of the fossil energy resources extracted.	Primary energy	CED	MJ-Eq.
nuclear	Fissile Uranium	fissile Uranium resource with the amount of energy that can be generated in a modern light water nuclear power plant. Uranium resource demand due to losses along the fuel chain (depleted Uranium, fissile Uranium remains in burnt-up fuel) is characterised with 0 MJ/kg	Primary energy	CED	MJ-Eq.
primary forest	biomass harvested	upper heating value of the biomass harvested	Primary energy	CED	MJ-Eq.
Renewable					
wind	Wind energy	amount of kinetic energy converted to mechanical energy on the rotor of the wind power plant.	Primary energy	CED	MJ-Eq.
water	Hydro energy	For hydro energy the electricity production by the turbine is taken into account. Losses in the system are included. Hydro energy from pumping storage hydro power is excluded in the inventory, if the pumping energy comes from a non-hydro source	Primary energy	CED	MJ-Eq.
geothermal	Geothermal energy	amount of geothermal energy delivered to the geothermal power plant or to the heat pump.	Primary energy	CED	MJ-Eq.
solar	Solar energy	amount of solar energy converted by the photovoltaic cell to electricity, and by the solar collector to heat	Primary energy	CED	MJ-Eq.
biomass	Biomass harvested	upper heating value of the biomass harvested	Primary energy	CED	MJ-Eq.

Normalisation & Weighting

Normalisation and Weighting is not a part of this method.

Literature

[14] VDI Guideline 4600: Cumulative Energy Demand – Terms, Definitions, Methods of Calculation, 1997

[15] Frischknecht et al.: Implementation of Life Cycle Impact Assessment Methods, Data v2.0 (2007)

4.3 Cumulative Exergy Demand (CExD)

System boundary:	**cradle-to-gate**
Orientation:	**midpoint**
Type:	**quantitative method**
Dimensions:	**one-dimensional**

Description

Bösch et al. [16] implemented the Cumulative Exergy Demand (CExD) in the ecoinvent database in 2007 as a logical consequence of the existing CED: "Energy and matter used in a society are not destroyed but only transformed. What is consumed and eventually depleted is usable energy and usable matter. Exergy is a measure of such useful energy. Therefore, CExD is a suitable energy based indicator for the quality of resources that are removed from nature. Similar to CED, CExD assesses energy use, but regards the quality of the energy and incorporates non-energetic materials like minerals and metals. However, it can be observed for non-renewable energy-intensive products that CExD is very similar to CED. Since CExD considers energetic and non-energetic resources on the basis of exhaustible exergy, the measure is comparable to resource indicators like the resource use category of Eco-indicator 99 and the resource depletion category of CML 2001. An advantage of CExD in comparison to these methods is that exergy is an inherent property of the resource. Therefore less assumptions and subjective choices need to be made in setting up characterization factors. However, CExD does not cover societal demand (distinguishing between basic demand and luxury), availability or scarcity of the resource. As a consequence of the different weighting approach, CExD may differ considerably from the resource category indicators in Eco-indicator 99 and CML 2001." [16]

The indicator Cumulative Exergy Demand (CExD) is introduced to depict total exergy removal from nature to provide a product, summing up the exergy of all resources required. CExD assesses the quality of energy demand and includes the chemical, kinetic, hydro-potential, nuclear, solar-radiative and thermal exergies of energy carriers as well as of non-energetic materials. [16]

Characterisation

In the original publication by [16] the CExD has been grouped in eight resource categories: fossil exergy; nuclear exergy; wind, solar and geothermal exergy; hydroexergy; biomass exergy; water exergy; metal ore exergy; mineral exergy.

In later implementations of the CExD in ecoinvent slightly different categories have been chosen as shown in Table 4.

Table 4: Impact categories of CExD

impact category		LCI results	characterisation model	category indicator	characterisation factor	unit
Non renewable energy resource						
	fossil	fossil energy resources extracted	Model of Boesch et al. for chemical removal from nature summing up	exergy	CExD	MJ-Eq.
	nuclear	Fissile Uranium	Model of Boesch et al. for nuclear exergy removal from nature	exergy	CExD	MJ-Eq.
	primary forest	biomass harvested	Model of Boesch et al. for chemical exergy removal from nature	exergy	CExD	MJ-Eq.
Renewable energy resource						
	wind (kinetic)	Wind energy	Model of Boesch et al. for kinetic exergy removal from nature	exergy	CExD	MJ-Eq.
	water (potential)	Hydro energy	Model of Boesch et al. for potential exergy removal from nature	exergy	CExD	MJ-Eq.
	water	Geothermal energy	Model of Boesch et al. for chemical and thermal exergy removal from nature	exergy	CExD	MJ-Eq.
	solar	Solar energy	Model of Boesch et al. for radiative exergy removal from nature	exergy	CExD	MJ-Eq.
	biomass	Biomass harvested	Model of Boesch et al. for chemical exergy removal from nature	exergy	CExD	MJ-Eq.
Non renewable material resource						
	metals	metals	Model of Boesch et al. for chemical exergy removal from nature	exergy	CExD	MJ-Eq.
	minerals	minerals	Model of Boesch et al. for chemical exergy removal from nature	exergy	CExD	MJ-Eq.

Normalisation & Weighting

Normalisation and weighting is not a part of this method.

Literature

[15] Frischknecht et al.: Implementation of Life Cycle Impact Assessment Methods, Data v2.0, 2007

[16] Bösch, M.E., Hellweg, S., Huijbregts, M.A.J., Frischknecht, R.: Applying Cumulative Energy Demand (CExD) Indicators to the ecoinvent Database. Int J LCA 12 (3) 181–190, 2007

4.4 Eco-Indicator 99

System boundary: cradle-to-gate

Orientation: endpoint

Type: quantitative method

Dimensions: multi-dimensional, aggregated

Description

Eco-Indicator 99 was developed by PRé Consultants as an update of the Eco-Indicator 95. The method was developed using a top-down methodology to provide a single indicator. This indicator is retrieved by weighing damages to the following Areas of Protection: Human health, ecosystem quality and resources.

Table 5: Impact categories of Eco-indicator 99

impact category	LCI results	characterisation model	category indicator	characterisation factor	unit
Human health					
Carcinogenic substances	Emissions of carcinogenic substances	Carcinogenicities from IARC, Fate factors from EUSES, Unit-risk concept from WHO, Survival rate by Murray et al [17]	Damage by carcinogenic substances	Damage factors for emissions of carcinogenics	DALY/kg
Respiratory effects	Emissions of CO, TSP, PM10, PM2.5, Sox, NH3, NOx to air	Based on Hoffstetter [18]	Damage by particulate matter emission and formation	Damage factor for emissions causing respiratory effects	DALY/kg
Photo-oxidant formation	emissions of VOCs to air (in kg)	Tropospheric chemistry model by Jenkin et. al. [19]	Damage by tropospheric ozone formation	Damage factors for emissions causing ozone formation	DALY/kg
Climate change	emissions of greenhouse gases to the air (in kg)	FUND 2.0 model [20], [21] (modified IPCC equivalence factors)	Damage by climate change due to increase of CO_2 concentration	Damage factors for emissions of greenhouse gases	DALY/kg
ionising radiation	emissions of ionising radiation to air, water and soil (in Bq)	Fate model by Dreicer et al. [22] and exposure models combined with epidemiological studies and the concept of DALY	Damage by ionizing radiation	Damage factors of ionising radiation	DALY/Bq
ozone layer depletion	emissions of ozone-depleting gases to the air (in kg)	Based on ODP (probably WMO model) Damage assessment by Murray et al. [17] and Hofstetter [18]	Damage by increase of UV radiation due to stratospheric ozone breakdown	Damage factors for emissions of ozone-depleting gases	DALY/kg
Ecosystem quality					
Ecotoxic substances (Ecotoxicity)	Emissions of toxic substances to air, water and soil	Fate factors from EUSES Toxic stress by PAF algorithm of Hamers et al. [23] Damage assessment by Meent et al [not published] Assumption: PDF = PAF/10	Damage by disappearance of species due to emissions of toxic substances	PDF	PDF*m2*a/kg
Acidification by airborne emissions	Airborne emissions of NH3, NOx and SOx to the air (in kg)	Nature Planner consisting of soil model (SMART) and vegetation response model (MOVE) [24]	Damage by disappearance of species due acidifying and eutrophic emissions	PDF	PDF*m2*a/kg
Eutrophication by airborne emissions	Airborne emissions of NH3, NOx and SOx to the air (in kg)	Nature Planner consisting of soil model (SMART) and vegetation response model (MOVE) [24]	Damage by disappearance of species due acidifying and eutrophic emissions	PDF	PDF*m2*a/kg
Land use	land use in terms of land occupation in m² a) and land conversion (in m²)	CORINE classification model [25], Aggregation by applying 30 a as a default restoration time to land occupation	Damage by disappearance of species due to land occupation	PDF	PDF*m2*a/m²
Resources					
Depletion of minerals and fossil fuels (abiotic resources)	extraction of minerals and fossil fuels (in kg)	Geostatistical Quality-(concentration)-based models combined with Damage assessment by surplus energy model of Müller-Wenk [26]	Damage in form of surplus energy for extraction due to decreasing quality (concentration) of resources	Surplus energy for extraction	MJ/kg MJ/m³ gas

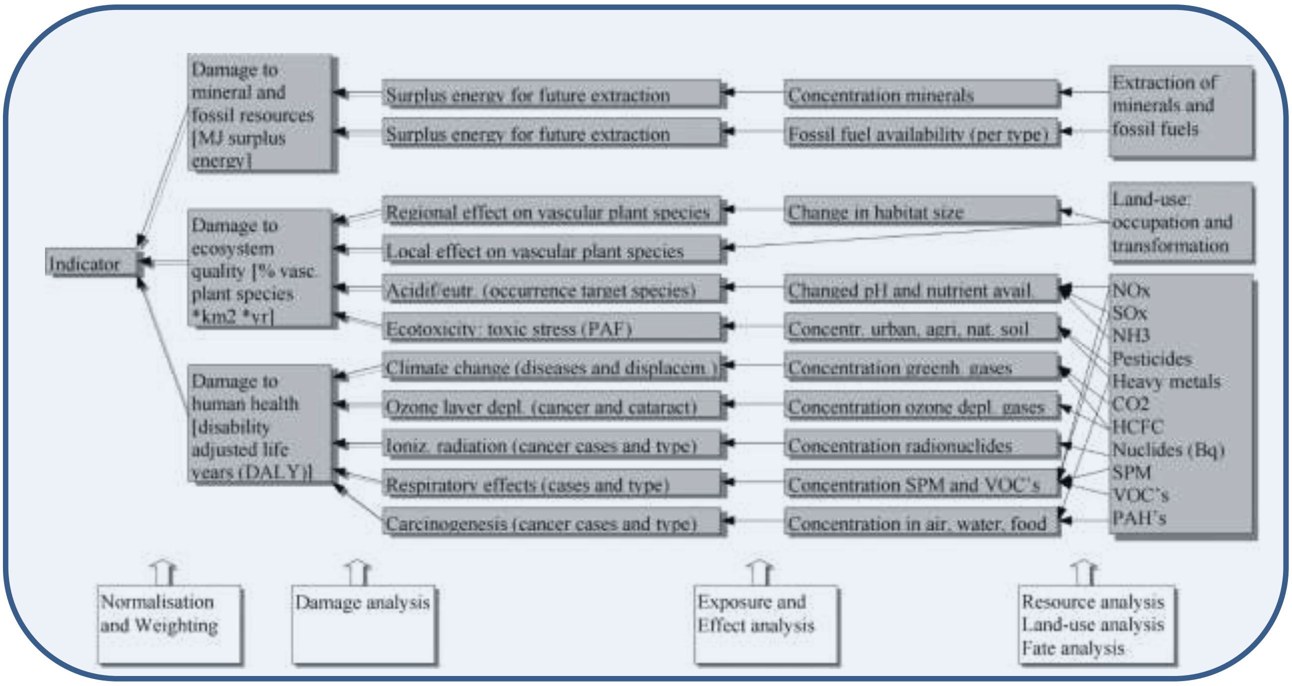

Figure 3: General representation of the methodology used in Eco-indicator 99. The white boxes refer to procedures; the grey boxes refer to (intermediate) results [27]

Characterisation

In order to cope with the inherent uncertainties of the model, it has been set up in three different configurations:

- "Egalitarian: Long time perspective: even a minimum of scientific proof justifies inclusion [of effects]
- Individualist: Short time perspective: only proven effects are included
- Hierarchist: Balanced time perspective: consensus among scientist determines inclusion of effects" [27]

Damage to human health is expressed in DALYs, damage to the ecosystem quality is given "as the loss of species over a certain area, during a certain time [28]. Damage to resources is "expressed as the surplus energy needed for future extractions of minerals and fossil fuels" [28].

Normalisation & Weighting

The damage factors are normalized on the damage category level (Area of Protection) by dividing them by the reference values given in Table 6. This allows to provide damage indicators for the three different areas of protection in the same unit (1000 Eco-indicator points) representing values per inhabitant for Europe.

Table 6: Reference values for normalization of Eco-indicator 99 [27], [29]

	Individualist	Egalitarian	Hierarchist
Human Health	0.00825 DALYs	0.0155 DALYs	0.0154 DALYs
Ecosystem Quality	4510 PDF m² a	5130 PDF m² a	5130 PDF m² a
Resources	150 MJ	5940 MJ	8410 MJ

In a second step these normalized damage indicators are weight by multiplying them with the weighting factors given in Table 7. The determination of the factors has been done through a questionnaire which has been send out to a panel of 365 members of the Swiss discussion platform on LCA.

Table 7: Weighting factors of Eco-indicator 99 [27]

	Average	Individualist	Egalitarian	Hierarchist
Human Health	40%	55%	30%	30%
Ecosystem Quality	40%	25%	50%	40%
Resources	20%	20%	20%	30%

Instead of these Hierarchist weighting factors the ecoinvent database uses the average weighting factors as hierarchic weighting factors.

Literature

[17] Murray, C.J.L., Lopez, A.D.: The global burden of disease – A comprehehnsive assessment of mortality and disability from diseases, injuries, and risk factors in 1990 and projected to 2020. Published by the Harvard School of Public Health on behalf of the World Health Organization and the World Bank, 1996

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[20] Tol, R.S.J.: Estimates of the Damage Costs of Climate Change. Part 1: Benchmark Estimates, in Environmental and Resource Economics, , Volume 21, Issue 1, pp 47-73, January 2002

[21] Tol, R.S.J.: Estimates of the Damage Costs of Climate Change, Part II. Dynamic Estimates, in Environmental and Resource Economics, Volume 21, Issue 2, pp 135-160, February 2002

[22] Dreicer, M., Tort, V., Manen, P.: ExternE: External costs of energy. Vol. No. 5: Nuclear; published by the European Commission, Directorate-General XII, Science, Research and Development (Luxembourg), 1995

[23] Hamers, T., Aldenberg, T., van de Meent, D.: Definition Report -Indicator Effects Toxic Substances (Itox), in RIVM report no. 607128001, 1996

[24] Latour, J.B., Staritsky, I.G., Alkemade, J.R.M., Wiertz, J.: The Natureplanner; Decision support system for nature and environment. Version 1.1, RIVM Report 711901019, 1997

[25] Commission of the European Communities: CORINE biotopes - The design, compilation and use of an inventory of sites of major importance for nature conservation in the European Community, Office for Official Publications of the European Communities, Luxembourg, 1991

[26] Müller-Wenk, R.: Depletion of abiotic resources weighted on base of "virtual" impacts of Power grade deposits used in future, IWÖ-Diskussionsbeitrag Nr. 57,Universität St. Gallen, 1998

[27] Goedkoop M. and Spriensma R.: The Eco-indicator 99: A damage oriented method for life cycle impact assessment. PRé Consultants, Amersfoort, The Netherlands, 1999

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[29] Goedkoop M. and Spriensma R.: The Eco-indicator 99: A damage oriented method for life cycle impact assessment. PRé Consultants, Amersfoort, The Netherlands, 2000, retrieved from: www.pre.nl/eco-indicator99/

[30] Goedkoop M. and Spriensma R.: Methodology Annex: The Eco-indicator 99: A damage oriented method for life cycle impact assessment. PRé Consultants, Amersfoort, The Netherlands, 1999

[31] Goedkoop M. and Spriensma R.: Methodology Annex: The Eco-indicator 99: A damage oriented method for life cycle impact assessment. PRé Consultants, Amersfoort, The Netherlands, 2000, retrieved from: www.pre.nl/eco-indicator99/

4.5 Ecosystem Damage Potential (EDP)

System boundary:	**cradle-to-gate**
Orientation:	**endpoint**
Type:	**quantitative**
Dimensions:	**one-dimensional**

Description

The Ecosystem Damage Potential (EDP) indicates the “damages from complex series of land transformation, land occupation, and land restoration” [32]. The method takes into account the restoration time. In this way damage is not only assessed by the area of transformed or occupied land but also by the difficulty of restoration of a transformation.

Characterisation

The characterization of different land use types within this method is based on the CORINE Plus classification [34].

Normalisation & Weighting

No further normalization or weighting is performed.

Literature

[32] Koellner, T., Scholz, R.W.: Assessment of Land Use Impacts on the Natural Environment Part 1: An Analytical Framework for Pure Land Occupation and Land Use Change. In Int J LCA 12 (1) 16–23, 2007

[33] Koellner, T., Scholz RW.: Assessment of Land Use Impacts on the Natural Environment. Part 2: Generic Characterization Factors for Local Species Diversity in Central Europe. Int J LCA 13 (1) 32–48, 2008

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4.6 Ecological Footprint

System boundary: n/a
Orientation: n/a
Type: quantitative
Dimensions: one-dimensional

Description

The ecological footprint is defined according to Huijbregts et al. [35] as the biologically productive land and water a population requires to produce the resources it consumes and to absorb part of the waste generated by fossil and nuclear fuel consumption.

The ecological footprint takes into account direct land occupation as well as indirect land occupation related to nuclear energy use and to CO2 emissions from fossil energy use and cement production. The total ecological footprint is the sum of the accounted direct and indirect land occupations:

$$EF = EF_{direct} + EF_{CO_2} + EF_{nuclear}$$

Table 8: impact categories of the ecological footprint

impact category	LCI results	category indicator	characterisation factor	unit
Ecological footprint of land occupation	Land use (in m²a)	occupation (in m² a)	EF_{direct}	m²a
Ecological footprint of nuclear energy use	Nuclear energy use (in MJ)	Additional biologically productive area required to sequester the CO_2 emissions by afforestation of equal fossil energy use (in m²a)	$EF_{nuclear}$	m²a
Ecological footprint of CO_2 emissions	emissions of CO_2 from fossil energy use and cement production (in kg)	Additional biologically productive area required to sequester the CO_2 emissions by afforestation (in m²a)	EF_{CO2}	m²a
Ecological footprint, total	Combination of the LCI results above	-	EF	m²a

Characterisation

Different characterization factors are given in [35] for different types of occupied land. The ecological footprint of nuclear energy use “is calculated as if it were fossil energy” [35]. Waste management for nuclear waste is not considered by the method.

Normalization & Weighting

No further normalization or weighting is applied.

Literature

[35] Huijbregts, M.A.J., Hellweg, S., Frischknecht, R., Hungerbühler, K. and Hendriks, A. J.: Ecological Footprint Accounting in the Life Cycle Assessment of Products. In: accepted for publication in Ecological Economics, 2006

4.7 Ecological Scarcity Method 2006

System boundary:	**cradle-to-grave**
Orientation:	**endpoint (distance-to-target)**
Type:	**quantitative method**
Dimensions:	**multi-dimensional, aggregated**

Description

The impact assessment of the ecological scarcity method accounts for emission of pollutants and extraction of resources and quantifies the impact in form of eco-points by using eco-factors. These eco-factors base on the “distance-to-target” of a specific emission or resource extraction. The “distance-to-target” is determined by “the current emission situation, and […] Swiss national policy targets as well as international targets supported by Switzerland” [36]. Hence, eco-factors are intended to change with change in political settings of Switzerland and knowledge base.

Table 9: impact categories of the Ecological Scarcity Method 2006

impact category	LCI results	category indicator	characterisation factor	unit
Ecological scarcity of emissions to air	CO_2 and further greenhouse gases, Ozone-depleting substances, NMVOCs and further substances with photochemical ozone creation potential, Nitrogen oxides (NOx), Ammonia (NH_3), SO_2 and further acidifying substances, Particulate matter (PM10, PM2.5 + PM2.5–10, Diesel soot), Carbon monoxide (CO), Benzene, Dioxins and furans (PCDD/PCDF), Lead (Pb), Cadmium (Cd), Mercury (Hg) and Zinc (Zn)	Various, depending on substance	UBP/EP	Umweltbelastungspunkte / Eco-points
Ecological scarcity of emissions to surface water	Nitrogen, Phosphorus, Organic matter (BOD, COD, DOC, TOC), Heavy metals and arsenic, Radioactive emissions to seas, AOX, Chloroform, PAHs (polycyclic aromatic hydrocarbons), Benzo(a)pyrene, Endocrine disruptors	Various, depending on substance	UBP/EP	Umweltbelastungspunkte / Eco-points
Ecological scarcity of emissions to groundwater	Nitrate in groundwater	Nitrate in groundwater (in g)	UBP/EP	Umweltbelastungspunkte / Eco-points
Ecological scarcity of emissions to soil	Heavy metals in soils and Plant protection products (PPPs)	Various, depending on substance	UBP/EP	Umweltbelastungspunkte / Eco-points
Ecological scarcity of resources	Energy resources, Land use, Gravel extraction and Freshwater consumption	Various, depending on substance	UBP/EP	Umweltbelastungspunkte / Eco-points

Ecological scarcity of waste	Carbon in material consigned to bioreactive landfills, Hazardous wastes in underground repositories and Radioactive wastes in final repositories	Various, depending on substance	UBP/EP	Umweltbelastungspunkte / Eco-points
Ecological Scarcity, total	Combination of the LCI results above	Various, depending on substance	UBP/EP	Umweltbelastungspunkte / Eco-points

Characterisation

Characterisation is mainly performed following Swiss regulations. In case of greenhouse gases and ozone-depleting substances the IPCC 2001 report [37] and the Montreal protocol of 2000 [38] are used for characterization. The characterization of land use is based on the Ecosystem Damage Potential (EDP).

Normalisation & Weighting

Normalisation is based on the region of whole Switzerland, weighting is determined by "the difference between the current pollutant emission or resource consumption and the politically determined emission or consumption targets" [36].

Literature

[36] Frischknecht, R., Steiner, R., Jungbluth, N.: The Ecological Scarcity Method – Eco-Factors 2006. A method for impact assessment in LCA. Environmental studies no. 0906. Federal Office for the Environment, Bern: 188 pp., 2009

[37] Houghton et al.: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp., 2001

[38] The Montreal Protocol on Substances that Deplete the Ozone Layer. United Nations Environment Programme.

4.8 EDIP 2003

System boundary: -

Orientation: midpoint

Type: quantitative method

Dimensions: multi-dimensional

Description

The method for Environmental Development of Industrial Products (EDIP) [39], [40] was developed by the Institute for Product Development (IPU) at the Technical University of Denmark in Lyngby. EDIP 2003 is a further development of EDIP 97 and 2003 aims on providing a site-dependent impact assessment method by spatial differentiation in characterization and normalization.

Table 10: impact categories of EDIP 2003

impact category	LCI results	category indicator	characterisation factor	unit
Global Warming Potential	emissions of greenhouse gases to the air (in kg)	infrared radiative forcing (W/m^2)	GWP	g CO_2-Eq.
Stratospheric ozone depletion	emissions of ozone-depleting substances	Stratospheric ozone concentration (in ppt a)	ODP	g CFC-11-eq.
Acidification	Emissions of acidifying substances	area of ecosystem brought to exceed the critical load of acidification (in m^2)	AP	0.01 m2 unprotected ecosystem
Terrestrial eutrophication	emissions of P and N compounds	area of ecosystem brought to exceed the critical load of eutrophication (in m^2)	TEP	0.01 m2 unprotected ecosystem
Aquatic eutrophication	emissions of P and N compounds	Nitrogen or phosphorus concentration	AEP	g N-Eq. or g P-Eq.
Photochemical ozone exposure of plants	VOC, NOx, CO, CH4	accumulated exposure above the threshold of 40 ppb (AOT40) times the area	POFPplants	m2·ppm·h
Photochemical ozone exposure of human beings	VOC, NOx, CO, CH4	accumulated exposure above the threshold of 60 ppb (AOT60) times number of persons	POCPhumans	pers·ppm·h
Human toxicity via air exposure	Emissions human toxic substances	exposure of humans in the deposition area as product of concentration increase and number of people	HTP	Pers.·$\mu g/m^3$
ecotoxicity	ecotoxic substances	Volume of exposed compartment	ETP	m^3

Characterisation

For the characterization of the global impact categories global warming and stratospheric ozone depletion factors from IPCC and WMO/UNEP are used.

Normalisation & Weighting

Normalisation is performed in terms of “person equivalents”. Weighting factors “are based on political reduction targets” [39]

Literature

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[40] Potting, J. and Hauschild, M.: Background for spatial differentiation in life cycle impact assessment – the EDIP2003 methodology. Danish Environmental Protection Agency, Copenhagen, 2004

4.9 EPS 2000

System boundary: n/a

Orientation: n/a

Type: quantitative method

Dimensions: multi-dimensional

Description

The EPS system (Environmental Priority Strategies in product design) was developed with a focus on commercial product development processes. It is based on the willingness to pay (WTP) to avoid or restore changes. "The WTP is measured in today's OECD population and applied to all those, who are affected by a change." [41] The endpoint categories are human health, ecosystem production, abiotic resources. Also cultural values are defined as endpoint category with the confinement: "Changes in cultural and recreational values are difficult to describe by general indicators, as they are highly specific and qualitative in nature. Indicators are therefore defined when needed. and abiotic resources." [41]

Table 11: impact categories of EPS 2000

impact category	LCI results	category indicator	characterisation factor	unit
Human health				
Life expectancy	various (see [42])	Years of life lost (YOLL)	various (see [42])	pers. a
Severe morbidity	various (see [42])	Severe morbidity	various (see [42])	pers. a
Morbidity	various (see [42])	morbidity	various (see [42])	pers. a
Severe Nuisance	various (see [42])	Severe nuisance	various (see [42])	pers. a
Nuisance	various (see [42])	nuisance	various (see [42])	pers. a
Ecosystem production				
Crop growth capacity	various (see [42])	crop	various (see [42])	kg
Wood growth capacity	various (see [42])	wood	various (see [42])	kg
Fish and meat production capacity	various (see [42])	Fish and meat	various (see [42])	kg
Soil acidification	various (see [42])	Base cation capacity of soils	various (see [42])	H+ mole equivalents
Production capacity for irrigation water	various (see [42])	Irrigation water	various (see [42])	kg
Production capacity for drinking water	various (see [42])	Drinking water	various (see [42])	kg
Abiotic resource				
Depletion of element reserves	various (see [42])	"Element name" reseves	various (see [42])	kg
Depletion of fossil reserves	various (see [42])	Natural gas reserves	various (see [42])	kg
Depletion of fossil reserves	various (see [42])	Oil reserves	various (see [42])	kg
Depletion of fossil reserves	various (see [42])	Coal reserves	various (see [42])	kg
Depletion of mineral reserves	various (see [42])	"Mineral name" reserves	various (see [42])	kg
Biodiversity				
Species extinction	various (see [42])	Normalized extinction of species (NEX)	various (see [42])	-

Characterisation

Three different methods for characterization are used, 'empirical', 'equivalency' and 'mechanistic':

"For the empirical method, the system borders in time and space is defined, and the characterisation factor for a substance is determined by dividing a category indicator value allocated to the system with an emission of the substance allocated to the system.

The equivalency method use traditional equivalency factors like the global warming potential to calculate characterisation factors. For example to calculate CO's impacts on severe morbidity via global warming, the characterisation factor for CO2 with respect to severe morbidity is used and just multiplied by the GWP for CO relative CO2.

The mechanistic method typically estimates the portion of an emitted amount of a substance that will reach a sensitive target and use dose-response information to calculate the response per mass of the emitted substance." [41]

Normalisation & Weighting

"The default-weighting indicator is the willingness to pay (WTP) to restore impacts on the safeguard subjects, as measured amongst today's OECD inhabitants." [41] The willingness to pay is expressed in Environmental Load Units (ELU). Normalisation of extinction of species "is made with respect to the species extinct during 1990" [41].

Literature

[41] Steen, B.: A systematic approach to environmental priority strategies in product development (EPS). Version 2000 – General system characteristics. CPM Report 1999:4. Centre for Environmental Assessment of Products and Material Systems, Göteborg 1999.

[42] Steen, B.: A systematic approach to environmental priority strategies in product development (EPS). Version 2000 – Models and data of the default method. Centre for Environmental Assessment of Products and Material Systems, Göteborg 1999

4.10 ReCiPe (2008)

System boundary:	**Cradle-to-grave**
Orientation:	**Midpoint or Endpoint**
Type:	**quantitative method**
Dimensions:	**multi-dimensional**

Description

ReCiPe 2008 is a comprehensive live cycle impact assessment method that has been developed by RIVM, CML, PRé Consultants, and Radboud Universiteit Nijmegen. It builds on the Eco-indicator 99 and the CML Handbook on LCA (2002). The ReCiPe method is implemented both on the midpoint level and the endpoint level. On the midpoint level LCI results are assigned to 18 different impact categories shown in Table 12.

Table 12: Midpoint-categories of ReCiPe 2008

impact category	LCI results	category indicator	characterisation factor	unit
Climate change (CC)	emissions of greenhouse gases to the air (in kg)	Infra-red radiative forcing (in W a/m²)	GWP	kg CO_2-Eq to air
ozone depletion (OD)	emissions of ozone-depleting substances	Stratospheric ozone concentration (in ppt a)	ODP	kg CFC-11-eq. to air
Terrestrial Acidification (TA)	emissions of NOx, NH_3 and SO_2 to the air (in kg)	Base saturation (in a m²)	TAP	kg SO_2-eq. to air
Freshwater Eutrophication (FE)	emissions of P and N compounds to air, water and soil (in kg)	Phosphorus concentration (in a kg/m³)	FEP	kg P-Eq. to freshwater
Marine Eutrophication (ME)	emissions of P and N compounds to air, water and soil (in kg)	Nitrogen concentration (in a kg/m³)	MEP	kg N-Eq. to freshwater
Human toxicity (HT)	human toxic and ecotoxic substances (very many)	Hazard-weighted dose	HTP	kg 1,4-DCB-eq. to urban air
Photochemical oxidant formation (POF)	emissions of substances (NMVOC, CO) to air (in kg)	Photochemical ozone concentration (in kg)	POFP	kg NMVOC to air
Particulate matter formation (PMF)	emissions of PM10 particles and SO_2 NH_3 and NOx to air (in kg)	PM10 intake	PMFP	kg PM10-Eq. to air
Terrestrial ecotoxicity (TET)	human toxic and ecotoxic substances (very many)	Hazard-weighted concentration (in m² a)	TETP	kg 1,4-DCB-eq. to industrial soil
freshwater ecotoxicity (FET)	human toxic and ecotoxic substances (very many)	Hazard-weighted concentration (in m² a)	FETP	kg 1,4-DCB-eq. to freshwater
marine ecotoxicity (MET)	human toxic and ecotoxic substances (very many)	Hazard-weighted concentration (in m² a)	METP	kg 1,4-DCB-eq. to marine water
ionising radiation (IR)	Emissions of radionuclides (in Bq)	Absorbed dose	IRP	kg U235-Eq. to air
Agricultural land occupation (ALO)	land occupation (in m² a)	occupation (in m² a)	ALOP	m2a
Urban land occupation (ULO)	land occupation (in m² a)	occupation (in m² a)	ULOP	m2a
Natural land transformation (NLT)	land transformation (in m²)	Transformation (in m²)	NLTP	m²
water depletion (WD)	Freshwater use (in m³)	Amount of water (in m³)	WDP	m³
Mineral resource depletion (MRD)	extraction of minerals (in kg)	Grade decrease (in 1/kg)	MDP	kg Fe-Eq.
Fossil fuel depletion (FD)	extraction of fossil fuel resources (in kg)	Lower heating value (in MJ)	FDP	kg Oil-Eq.

On the endpoint level three categories exist which are formed by transformation and aggregation of most of the midpoint categories. A rough overview of this process is given by

Figure 4.

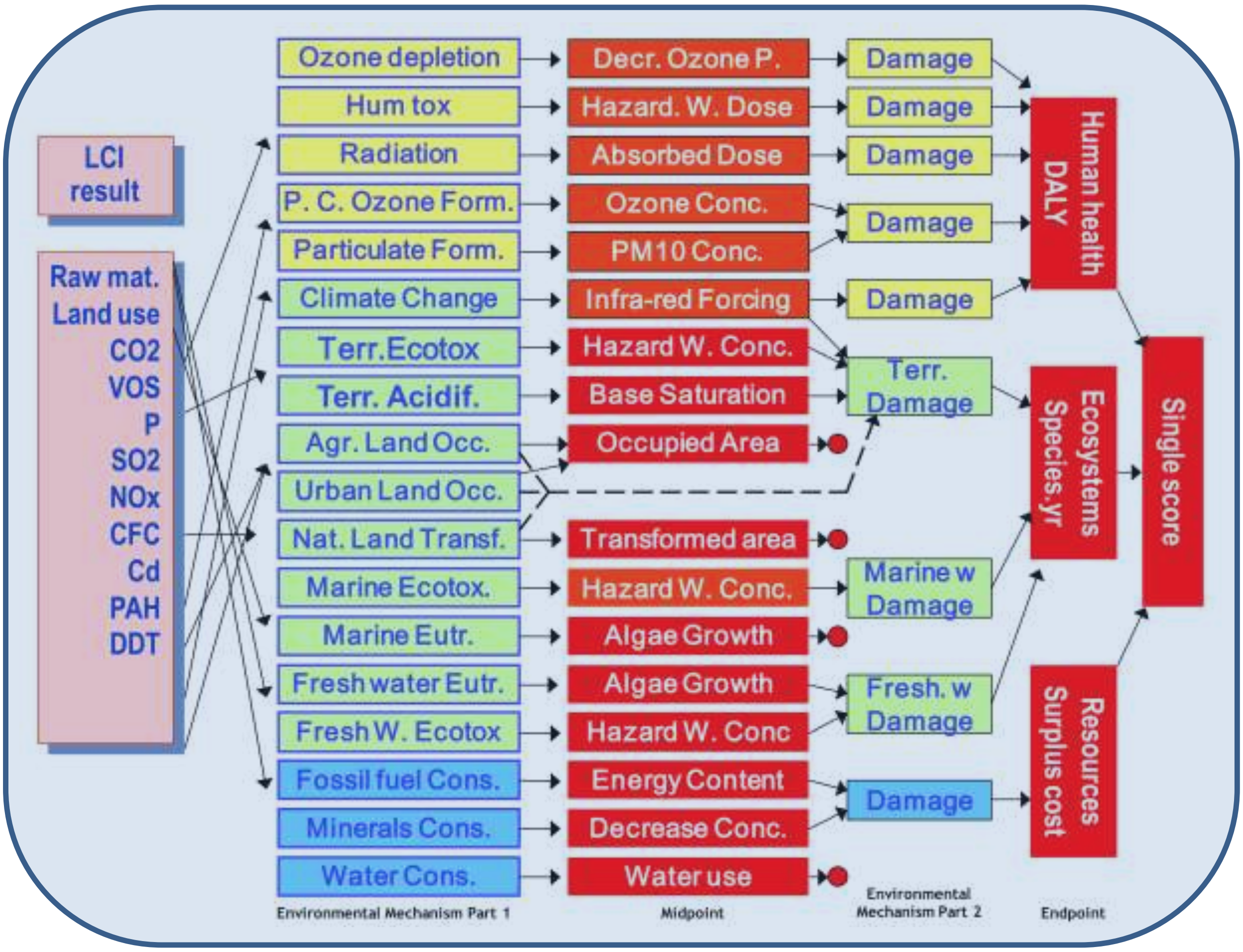

Figure 4: Allocations, transformations and aggregations from LCI results over midpoint indicators to endpoint indicators in ReCiPe 2008 [43]

The three endpoint categories are listed in Table 13

Table 13: Endpoint categories of ReCiPe 2008

impact category	category indicator	unit
Damage to human health (HH)	Disability-adjusted loss of life years (DALY)	DALY
Damage to ecosystem diversity (ED)	Loss of species during a year	Species a
Damage to resource availability (RA)	Increased cost	$

Characterisation

ReCiPe 2008 contains three characterisation perspectives: individualist (I), hierarchist (H) and egalitarian (E). Each of these three perspectives applies a different set of multiplication factors during the transformation from midpoint to endpoint results. The sets differ only for the midpoint categories CC, OD, TA and FD. Individualist is a short-term rather optimistic perspective, hierarchist a perspective based on most common policy principles and Egalitarian is a precautionary long-term perspective.

Normalisation & Weighting

There are comprehensive normalization sets available in [44] and online in Excel-format. These sets distinguish between the three mentioned perspectives and as well as two regions – Europe and World. Weighting factors are shown in Table 14. By multiplication with normalization and weighting factors the units of the three endpoint indicators can be converted to a common unit in order to create a single result value.

Table 14: Set of weighting factors for ReCiPe 2008

	Individualist	Hierarchist	Egalitarian	Average
Ecosystems	250	400	500	400
Human health	550	300	300	400
Resources	200	300	200	200
Total	1000	1000	1000	1000

Literature

[43] Goedkoop, M. et.al.: ReCiPe 2008 – A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. 2013 <http://www.leidenuniv.nl/cml/ssp/publications/recipe_characterisation.pdf>

[44] Wegener, S. et al.: Normalisation in product life cycle assessment: An LCA of the global and European economic systems in the year 2000. Science of the Total Environment, 390 (1): 227-240, 2008

4.11 Others

Other LCIA methods which have not been studied in detail are TRACI, USETOX, LIME, CML 2002, MEEuP, Ecosense, RiskPoll, BEES+, ILCD, IMPACT 2002+, IPCC2007, IPCC2001, EDIP 97.

4.12 Comparative Table of available LCIA methods

Table 15 allows the comparison of the presented LCIA methods with regard to System boundary, orientation and dimensions. All presented methods are quantitative methods. In some cases a definite information for system boundary or orientation cannot be given. This is marked by “n/a”.

In table 16 the impact categories are listed for the investigated LCIA methods and some of the other LCIA methods mentioned in 4.11. The intention of this table is to give a comparative overview of the comprehensiveness of the different methods. One has to keep in mind that definitions of categories for similar impacts vary between LCIA methods to a certain degree. Also some LCIA methods have special impact categories which are not mentioned in this table.

Table 15: system boundary, orientation and dimensions of different LCIA methods

	CML 2001	Cumulative Energy Demand (CED)	Cumulative Exergy Demand (CExD)	Eco-Indicator 99	Ecosystem Damage Potential (EDP)	Ecological Footprint	Ecological Scarcity Method 2006	EDIP 2003	EPS 2000	IMPACT 2002+	IPCC 2001	IPCC 2007	ReCiPe	TRACI	LIME
cradle-to-gate		X	X			n/a			n/a		X	X		n/a	
gate-to-grave						n/a			n/a					n/a	
cradle-to-grave	X			X	X	n/a	X	X	n/a	X			X	n/a	X
Midpoint	X	X	X			n/a		X	n/a	X	X	X	X	X	
Endpoint	X			X	X	n/a	X		n/a	X			X		X
one-dimensional		X	X		X	X					X	X		X	
multi-dimensional, aggregated				X			X		X	X			X		X
multi-dimensional	X							X							

Table 16: impact categories of different LCIA methods

	CML 2001	Cumulative Energy Demand (CED)	Cumulative Exergy Demand (CExD)	Eco-Indicator 99	Ecosystem Damage Potential (EDP)	Ecological Footprint	Ecological Scarcity Method 2006	EDIP 2003	EPS 2000	IMPACT 2002+	IPCC 2001	IPCC 2007	ReCiPe	TRACI	LIME
Resource depletion	X													X	X
abiotic resource depletion	X			X					X						
mineral resource depletion									X	X			X		X
fossil resource depletion									X	X			X		X
water resource depletion													X		
biotic resource depletion	X														X
Land use	X			X	X	X									X
Land occupation					X	X				X			X		X
Land transformation					X								X		X
Climate change	X			X			X	X		X	X	X	X	X	X
Stratospheric Ozone depletion	X			X			X	X		X			X	X	X
Human toxicity	X							X	X	X			X		X
Human toxicity, cancer effects				X			X			X				X	X
Human toxicity, non-cancer eff.							X			X				X	X
Ecotoxicity	X			X				X						X	X
freshwater aquatic ecotoxicity	X									X			X		X
marine ecotoxicity	X									X			X		X
terrestrial ecotoxicity	X									X			X		X
Freshwater sediment ecotoxicity	X														
Marine sediment ecotoxicity	X														
Photochemical oxidant formation	X			X			X	X		X			X	X	X
Acidification	X			X			X	X	X	X				X	X
terrestrial acidification										X					
aquatic acidification										X					
Eutrophication	X			X			X							X	X
terrestrial eutrophication								X		X			X		
aquatic eutrophication								X		X			X		
Ionising radiation	X			X									X		
Ionizing Radiation, human health										X					
Ionizing Radiation, ecosystems															
Particulate matter formation				X			X			X			X	X	

LCIA METHODS APPLIED IN LCA OF SOLAR THERMAL SYSTEMS

The following selection of published studies provides an overview on the environmental impacts of the life cycle of solar thermal systems and products related to solar thermal energy and gives an analysis of the methods used to determine these impacts.

5.1 Environmental Impacts of Solar Thermal Systems with Life Cycle Assessment

System boundary:	cradle-to-use
Functional unit:	Production of DHW for a four-person household, (assessed to be 140 litres of 60°C) in temperate climate and 20 years of life expectancy. Production of DHW for a four-person household, (assessed to be 200 litres of 50°C) in tropical climate and 20 years of life expectancy.
Scenarios:	Solar thermal + gas solar thermal + electricity gas heater electric heater thermosiphon
geographic reference:	Lyon, France Le Lamentin, Martinique
data time reference:	n/a
LCIA-methods:	Impact 2002+ (v 2.04)
Derivatives:	energy payback time
software:	SimaPro 7.1 PhD and the database ecoinvent 2.0

“This study clearly shows that solar thermal systems are a very interesting solution to reduce the environmental impacts of domestic hot water production. The impact assessment results for temperate climate systems highlight the backup energy as the major factor on environmental impacts. However, this study does not end with a clear-cut energy. This is mainly due to characteristics of the French electricity mix that has a low CO2 content but an important primary energy ratio. For all SWH, regardless of backup energy, solar panels, water tank and pipes emerge as the key environmental components.

Therefore, considering those results, technical improvement related to the main impacting components can be realized to lower the environmental impacts of the solar thermal part of SWH. This project has been followed by a LCA on larger solar thermal installations to determine their related environmental impacts and compare with domestic solar systems.”

Source:

[45] de Laborderie, A. et al.: Environmental Impacts of Solar Thermal Systems with Life Cycle Assessment, in Proceedings of World Renewable Energy Congress 2011 – Sweden, 8-13, Lingköping, Sweden, p. 3678-3685, May 2011

5.2 Life cycle assessment of a solar thermal collector: sensitivity analysis, energy and environmental balances

System boundary:	cradle-to-grave
Functional unit:	solar collector for domestic warm water demand including the absorbing collector, the water tank (180 l capacity) and the support for the roof fastening
Scenarios:	solar collector (thermosiphon system)
geographic reference:	Palermo, Italy
data time reference:	n/a
LCIA-methods:	Embodied Energy GWP
Derivatives:	Emission payback time (considering CO_2 emissions) energy payback time
software:	-

"The primary energy consumption and the main air emissions (CO2, CO, SOx, NOx, dust) have been the two criteria to compare the different scenarios" with different electricity mixes. "The global warming potential (GWP) related to the collector life cycle is 721 kg-eq. CO2. Considering a domestic gas boiler, it is assumed a specific global warming factor of 65:7 _ 10_3 kg-eq. CO2 per MJ of useful heat. The yearly CO2-eq. emission saving is estimated to be 407 kg-eq. CO2. Similar to the energy payback time, even the CO2-payback time resulted lower than 2 years."

"The LCA studies have generally an intrinsic uncertainty related to various factors (i.e. difficulty in the survey of data, lack of detailed information sources, data quality, etc.). Consequently, it is more important for the experts to evaluate the order of magnitude of input–output flows ascribable to the product than to trace an ''exact'' eco-profile of products.

This problem, commonly noticed in every LCA, has been strongly noticed in our case study. Regarding the solar thermal collector, we have observed a strong dependence of the FU eco-profile on the input materials. They globally imply about 70–80% of the environmental impacts. The environmental impacts of material have been supposed to be enclosed within a variation range. These intervals have been realized on the basis of data coming from environmental databases, LCA tools and, in general, from European environmental studies. The analysis of data quality has been based on many parameters such as geographical coverage, technological level, representativeness, etc. Results have shown a great uncertainty regarding aluminium, copper, thermal fluid and galvanized steel, the dominant material.

Even the other life cycle steps (transports, installation and maintenance) cause large impacts. The production process affects the eco-profile for about 5 % of impacts (excepting some air pollutants released during cutting and welding steps). The LCA results have been synthesized into two indexes: the energy and environmental payback times. The great energy and environmental convenience of this equipment are shown by very low values of payback times (lower than 2 years).

Including the variability related to raw material eco-profiles and the uncertainties due to the other life cycle steps, it has been estimated that the variation range can be extended as following: energy consumption from 8 to 15 GJ, CO2 emission from 500 to 900 kg. Joining concepts of durability and supposing a loss of efficiency up to 40%, it has been estimated that, even in pessimistic scenarios, the energy and emission payback times are lower than 4 years. These results permit to state a positive qualitative judgement regarding the environmental performances of the collector that is not sensibly influenced by all the study uncertainties."

Source:

[46] Ardente, F., Beccali, G., Cellura, M., Lo Brano, V.: Life cycle assessment of a solar thermal collector: sensitivity analysis, energy and environmental balances, in Renewable Energy 30, p. 109–130, 2005

5.3 Role of Alternative Energy Sources: Solar Thermal Technology Assessment

System boundary:	cradle-to-gate
Functional unit:	1 MWH electricity at end-user
Scenarios:	250 MW net parabolic solar thermal power plant
geographic reference:	USA
data time reference:	n/a
LCIA-methods:	GWP 100 of IPCC 2007
Derivatives:	-
software:	GaBi 4.0

"The environmental profile of this analysis focuses on the LC GHG emissions of solar thermal power. The LC GHG emissions for solar thermal power from a 250 MW net power plant are 44.6 kg CO2e/MWh, based on 2007 IPCC 100-year GWP factors (Forster, et al., 2007). The majority of LC GHG emissions are from CO2 at 82.3 percent, with the remainder split between CH4, N2O, and SF6 at 5.6 percent, 4.5 percent, and 7.6 percent, respectively. Solar collector construction accounts for 48 percent of the LC GHG emissions for solar thermal power, while plant operation accounts for 38 percent. The construction of the plant and the trunkline contribute a combined 6 percent, while T&D accounts for 8 percent.

The results above do not account for the GHG emissions from land use change. The GHG emissions from direct land use change are an additional 4.4 kg CO2e/MWh. There was no indirect land use change since no agricultural land was displaced by the solar thermal facility modeled in this study. Thus, the land use GHG emissions solar thermal power increases the total LC GHG emissions from 44.6 to 49.0 kg CO2e/MWh. This study was not performed as a comparative analysis, so there are no reference values for the emissions to other power generation technologies. The majority of lead and mercury emissions results from the fabrication processes to make steel for the facility and collectors. Glass manufacturing accounts for a significant portion of the ammonia, PM, SO2, and VOC emissions. Fuels combustion in support of the operation of the solar thermal facility comprises most of the CO and NOx emissions. The EROI was also calculated for solar thermal. EROI is defined as the ratio of usable, acquired energy to energy expended. For solar thermal power generation the value is 8.21."

Source:

[47] Skone, T.J., P.E. of National Energy Technology Laboratory for U.S. Department of Energy, Office of fossil energy: Role of Alternative Energy Sources: Solar Thermal Technology Assessment, August 28, 2012

5.4 Dynamic life cycle assessment (LCA) of renewable energy technologies

System boundary:	cradle-to-grave
Functional unit:	1 kWh electric energy at the power plant
Scenarios:	different renewable electricity and heat producing systems (wind power, solar thermal power plants, geothermal energy, PV, solar thermal collectors, biogas, hydro power, waste and wood incineration)
geographic reference:	Germany
data time reference:	2010 2030
LCIA-methods:	Energy resources (CED) Global Warming (GWP) Acidification (AP) Eutrophication (EP)
Derivatives:	-
software:	Umberto

"From the LCA results it follows that for all renewable energy chains the inputs of finite energy resources and emissions of greenhouse gases are extremely low compared with the conventional system. The relevant environmental impacts of the renewable energy systems amount to a maximum of 20% of an expected future German mix for electricity, a maximum of 15% of the reference mix for heat, and a maximum of 55% of the future diesel car in the case of fuels. LCA results for renewable energy systems reveals that the use made of the material resources investigated (iron ore, bauxite) is less than or similar to that made by conventional systems with some exceptions. It should be noted that the other environmental impacts associated with the provision of the materials are of course taken into account, and that the input of materials in particular depends heavily on the local situation. The findings do not reveal any clear verdict for or against renewable energies in the case of other environmental impacts. The comparison depends more on a large number of context-dependent parameters, e.g.

- the technology configuration examined (e.g. polycrystalline, monocrystalline or amorphous silicon or thin-film solar cells, steam turbine or combustion engine CHP units, etc.);
- the type of energy source used, especially in the case of biomass, and its specific properties (fuel inventory, transport distances, etc.);
- the geographical location, topographical situation and local conditions of the plant (crucial for solar radiation, full-load hours, expenditure on barrages for hydropower, etc.) and integration into the local infrastructure.

Future development will enable a further reduction of environmental impacts that are caused by regenerative energy systems. Different factors are responsible:

- Progress with respect to technical parameters of the energy converters, in particular improved efficiency, emissions characteristics, increased lifetime, etc.
- Advances with regard to the production process of the energy converters or fuels, e.g. reduced sawing losses or wafer thickness for solar cells, decreased fertilizer input, and higher yields for biomass cultivation, etc.

- Advances with regard to ‘external’ services originating from conventional energy and transport systems, for instance improved electricity or process heat supply for system production, ecologically optimized transport systems for the biomass transportation, etc.

On the other hand, the last aspect could potentially lead to higher ecological impacts, because the attainable credits for by-products (‘avoided burden’), e.g. glycerin in bio diesel production, are also lower. Nevertheless, the combined effect of the three progress (advance) factors will allow substantial reduction of environmental impacts.”

Source:

[48] Pehnt, M.: Dynamic life cycle assessment (LCA) of renewable energy technologies, Renewable Energy 31, p. 55–71, 2006

5.5 Life Cycle Assessment (LCA) of various solar heat technologies

System boundary:	cradle-to-grave
Functional unit:	17650 GWh electric energy at the power plant
Scenarios:	100 MW Solar Power Tower (25 years lifetime)
geographic reference:	mostly Germany
data time reference:	n/a
LCIA-methods:	Global Warming (GWP) Acidification (AP) Eutrophication (EP)
Derivatives:	-
software:	GaBI Education, 2011

“In this final year project a life cycle assessment (LCA) model was developed in GaBi to determine the impact of a heliostat field for a 100 MW power tower. In the field of energy generation, it is important to considered sustainability and cleanliness of the technology.

Hence; the LCA that was done on the heliostats needed to fuel the power tower can be used to see the magnitude of the environmental impact that implementation of this technology will have. However, the results obtained are mostly based on data from Germany because of the lack of other data sources in GaBi. In this LCA it can be seen that carbon dioxide, sulphur dioxide and nitrogen oxides are the emissions that have the greatest environmental impact in their different environmental impact categories respectively. The manufacturing of the heliostats contribute to more than 80% of the emissions. This creates the opportunity to look at the improvement of this process. This LCA forms a basis on which further research and assessments can be done. The assessment can be more in-depth than the current LCA by breaking the three main processes down into their most basic processes. Each process can then be individually assessed to determine the root cause of the majority of emissions. Reliable data is recommended, because some of the data in this LCA was assumed because of proprietary rights and inaccessibility of data. Taking all of these factors into account, the conclusion that is made is that the use of solar power towers is one of the cleanest methods of generating energy, relative to other technologies. It is more sustainable and helpful towards the environment. Thus it is indeed a “green” technology.“

Source:

[49] Winterbach, F.: Life Cycle Assessment (LCA) ofvarious solar heat technologies, Bachelor thesis at Stellenbosch University, December 2011

5.6 Life cycle environmental impact assessment of a solar water heater

System boundary:	cradle-to-grave
Functional unit:	1 MW of hot water from a solar thermal system
Scenarios:	solar thermal system comprising of a flat plate collector panel with a gross area of 4 m2 and a 200 lt. hot water cylinder
geographic reference:	Thessaloniki, Greece
data time reference:	n/a
LCIA-methods:	Eco-Indicator 99
Derivatives:	-
software:	GEMIS

"The technical and environmental performance of a solar water heater (SWH) is examined using the method of life cycle assessment (LCA). The present LCA study quantifies the environmental benefits of the installation of a SWH with electricity as auxiliary for domestic use in the city of Thessaloniki. Solar thermal heating produces no emissions during operation but some small levels of emissions are produced during the manufacture and installation of components and systems. This work examines the manufacturing stages of the SWH and records resource consumption and waste streams to the environment.

The system boundary includes the production of raw materials such as steel, glass, copper, aluminium, glass fibber and polyurethane insulators, the manufacturing of the various parts of the SWH such as the solar collector and the heat storage tank, and finally the assembly process. The functional unit chosen is 1 MW of produced hot water. The environmental impacts taken into consideration in the study, are the greenhouse effect, ozone depletion, acidification, eutrophication, heavy metals, carcinogens, winter smog and summer smog. The system can provide 1702 kWh/year and the solar contribution is 58.5%. The financial characteristics of the system investigated give life cycle savings equal to 4280.0 € and pay-back time equal to 5 years."

Within the assessment according to Eco-indicator 99 the environmental impact results in the following distribution on the impact categories: Acidification 54%, winter smog 25%, glowbal warming 12%, others 9%.

Source:

[50] Koroneos, C.J., Evanthia A. Nanaki: Life cycle environmental impact assessment of a solar water heater, in Journal of Cleaner Production 37, p. 154-161, 2012

5.7 Comparative LCA of Two Thermal Energy Storage Systems for Shams-1 Concentrated Solar Power Plant: Molten Salt vs. Concrete

System boundary:	cradle-to-grave
Functional unit:	800 MWH of electric energy at a Concentrated Solar Power Plant
Scenarios:	molten salt thermal energy store concrete thermal energy store
geographic reference:	United Arab Emirates
data time reference:	n/a

LCIA-methods:	Eco-Indicator 99
Derivatives:	-
software:	SimaPro

"Thermal energy storage (TES) for concentrated solar power (CSP) is gaining popularity because it has the potential to increase the hours of electricity production from the CSP technology. In this Study, we conducted a comparative life cycle assessment (LCA) of two TES technologies (concrete and molten salt) for Shams-1 CSP plant in United Arab Emirates. Eco-Indicator 99 was employed to model the environmental impact per 800MWhe produced. Results obtained show that concrete TES has a greater environmental impact than molten salt TES, with fossil fuel being the largest impact contributor in both cases. A sensitivity analysis in which different scenarios were considered showed a reduction in environmental impact when waste recycling and transportation changes are incorporated. Based on the results obtained, incorporating molten salt TES in Shams-1 will have a lower environmental impact than the use of concrete TES."

"The results show that the concrete TES has a greater environmental impact than the molten salt TES. The biggest impact contributors in both cases were fossil fuel and respiratory inorganics."

Source:

[51] Adeoye, J.T. et al: Comparative LCA of Two Thermal Energy Storage Systems for Shams1 Concentrated Solar Power Plant: Molten Salt vs. Concrete, in Journal of Clean Energy Technologies, Vol. 2, No. 3, July 2014

5.8 A Life Cycle Assessment (LCA) of a Paraboloidal-Dish Solar Thermal Power Generation System

System boundary:	cradle-to-grave
Functional unit:	1 kWh of electric energy
Scenarios:	paraboloidal dish solar thermal power plant (30 years lifetime) Fossil fuel power station (30 years lifetime)
geographic reference:	Sicily
data time reference:	n/a
LCIA-methods:	Eco-Indicator 99
Derivatives:	-
software:	SimaPro

"The overall environmental impact arising from the entire life cycle of a thermal solar power plant that uses linear parabolic concentrators is extremely limited and almost insignificant compared to the impact produced by traditional fossil fuel power stations. The C02 eq. emissions are just 13g/kWh of electricity produced (without recycling) and the energy balance also appears favourable. The results obtained are rather encouraging and deserve to be studied further in particular to develop a comparative study with other thermodynamic solar technologies that use solar concentrators."

Source:

[52] Cavallaro, F., Ciraolo, L.: A Life Cycle Assessment (LCA) of a Paraboloidal-Dish Solar Thermal Power Generation System, in Environment Identities and Mediterranean Area, ISEIMA '06. First international Symposium on, p. 260-265, 2006

5.9 Life-cycle assessment of a 100% solar fraction thermal supply to a European apartment building using water-based sensible heat storage

System boundary:	cradle-to-grave
Functional unit:	1 MJ of heat energy output
Scenarios:	solar thermal system air-source heat-pump ground-source heat pump natural gas furnace oil furnace wood-pellet furnace storage tank lifetimes (40, 50, 60 and 75 years) solar collector lifetimes (20, 25 and 30 years)
geographic reference:	Switzerland, European Climate
data time reference:	2005
LCIA-methods:	CML 2001 CED IPCC2007 Eco-Indicator 99
Derivatives:	-
software:	SimaPro

Table 17: damage categories, impact indicators and LCIA methods used in [53]

Damage category	Impact indicator	Unit	methodology
Consumption of resources	Primary energy use	MJ/MJ	CED
	Abiotic resources	kg (Sb eq.)/MJ	CML 2001
Climate change	GHG emissions	kg (CO_2 eq.)/MJ	IPCC 2007
Ecosystem quality	Land use	PDF m²a/MJ	Eco-indicator 99
	Ecotoxicity		
	acidification		
	Eutrophication		
Human health	Carcinogens	DALY/MJ	Eco-indicator 99
	Respiratory organics		
	Respiratory inorganics		
	Climate change		
	radiation		
	Ozone layer depletion		

"Providing 100% of a building's heating and hot water using a solar thermal system in a European climate has been shown to be both practically feasible and functionally successful for a new apartment building in Switzerland. The research conducted a life cycle assessment of the solar thermal system and compared the results with an air-source heat-pump, ground-source heat pump, natural gas furnace, oil furnace and a wood-pellet furnace. Using a range of lifetime scenarios it was found that the solar thermal system displays potentially significant advantages over all other systems in terms of reductions for purchased primary energy (from 84 to

93%) and reductions in GHG emissions (from 59 to 97%). However, due to the heavy industrial processes and the particular metals used in manufacturing, the solar thermal system was shown to have a higher demand for resources which, in relation to the natural gas system, can be by a factor of almost 38. Potential impacts on ecosystem quality were marginally worse than for the heat-pump and fossil fuel systems due to resource use impacts whilst potential human health impacts were similar to the heat pump systems but better than the fossil and biomass fuelled systems."

Source:

[53] Simonsa, A., Firth, S.K.: Life-cycle assessment of a 100% solar fraction thermal supply to a European apartment building using water-based sensible heat storage in Energy and Buildings 43, p. 1231–1240, 2011

5.10 Life Cycle Assessment of Solar Thermal Power Technology in China

System boundary:	cradle-to-grave
Functional unit:	1 kWh electric energy produced at the power plant
Scenarios:	300 MW plant coal-fired power generation plant
geographic reference:	Hami, China
data time reference:	2008
LCIA-methods:	Acidification (AP) Climate change (GWP) CED
Derivatives:	energy balance factor (EBF): ratio of energy output to input energy payback time (EPT) is the index that accounts, by energy production, for the number of years required to recover the total energy input into the system over an entire life cycle
software:	AGP (Assessment for Green-Product) developed by the Research Center for Eco-Environmental Sciences, Chinese Academy of Science (CAS), based on Chinese product and environmental data.

"Results: solar tower power technology shows an environmental profile much better than the current mix of technologies used to produce electricity in China.

The cumulative energy demand of the life cycle of solar thermal power plant is much lower than the energy produced.

CO2 value of global warming emissions is around 31.6 g/kWh, which is much lower than the value of 738 g/kWh for competing fossil technologies.

Other impacts calculated are much lower than those produced by the current Chinese electricity generation system, and most of them are produced in the operation of the fossil-fired plant due to the consumption of natural gas or coal."

Source:

[54] The Power of Renewables: Opportunities and Challenges for China and the United States / Appendix B: Life Cycle Assessment of Solar Thermal Power Technology in China, p.217-226, 2010

5.11 Life cycle assessment of a solar thermal collector

System boundary:	cradle-to-grave
Functional unit:	1 solar thermal collector (thermosiphon including store and installation material) with a total net surface of 2.13 m^2
Scenarios:	solar thermal collector (thermosiphon including store and installation material)
geographic reference:	Italy
data time reference:	n/a
LCIA-methods:	eco-profile Energy consumption Environmental impacts: – Resources consumption – Air emissions – Water emissions – Wastes and solid pollutants – Global warming potential (GWP) – acidification potential (AP) – ozone depleting potential (ODP) – nutrification potential (NP) – photochemical ozone creation potential (POPC)
Derivatives:	Energy payback time, CO_2 payback time

Source:

[55] Ardente, F. et al.: Life cycle assessment of a solar thermal collector, in Renewable Energy 30, p. 1031–1054, 2005

5.12 The environmental performance of a building-integrated solar thermal collector, based on multiple approaches and life-cycle impact assessment methodologies

System boundary:	cradle to grave
Functional unit:	solar thermal system including 14 solar collectors, storage tank, pump, external insulated tubes, glycol
Scenarios:	building-integrated solar thermal system (30 years lifetime) in 3 different configurations recycling, no recycling electricity mixes (France and Spain) comparison with conventional boiler comparison with LCAs of other collector types from literature sources.

geographic reference:	n/a
data time reference:	n/a
LCIA-methods:	Eco-indicator 99, IMPACT 2002+, embodied energy (EE), embodied carbon (EC)
Derivatives:	energy payback time

Abstract:

"In continuation of authors' previous study, the present investigation regards the comprehensive evaluation of the environmental profile of a patented building-integrated solar thermal collector, based on multiple Life Cycle Impact Assessment (LCIA) methodologies. The system has been developed and experimentally tested at the University of Corsica, in France and it consists of collectors integrated into building gutters. Three alternative configurations are examined by means of the LCIA methodologies Eco-Indicator 99 (EI99) and IMPACT 2002þ along with embodied energy and embodied carbon. Multiple approaches and scenarios are examined in order to evaluate the effect of several parameters on system environmental performance. The results, based on all the LCIA methodologies used, reveal that the configuration with collectors in parallel connection can considerably improve the environmental profile of the reference system (collectors in series). This impact can be further reduced by using systems with double absorber surface/output and/or recycling. On the other hand, the present investigation provides a critical comparison of the proposed system with other types of solar thermal and conventional heating systems. The primary energy and CO2 savings (per month) related with the production of energy by the proposed BI solar thermal systems, instead of using a conventional heating system, are also presented."

Source:

[56] Lamnatou, C., Notton, G., Chemisana, D., Cristofari, C.: The environmental performance of a building-integrated solar thermal collector, based on multiple approaches and life-cycle impact assessment methodologies, in Building and Environment 87, p. 45 – 58, 2015

5.13 Life Cycle Assessment of solar energy systems: Comparison of photovoltaic and water thermal heater at domestic scale

System boundary:	cradle-to-grave
Functional unit:	1 m² of roof
Scenarios:	comparison of 4 different photovoltaic systems and solar thermal water heater at domestic scale over a lifetime of 25 years with performance reduction of PV, with and without recycling
geographic reference:	Italy
data time reference:	present
LCIA-methods:	Eco-indicator 95 (ecoinvent 2.2)
Derivatives:	energy payback time CO_2-eq. payback time

Abstract:

“This study is concerned with the results of a Life Cycle Assessment comparison between photovoltaic silicon based modules and thin film modules e and solar thermal systems, as technologies which are usually installed for partially covering household energy demand.

Several studies focused on energy and environmental performances of photovoltaic and solar thermal collectors, however they have been always analysed separately. This study proposes the comparison of different systems to exploit the solar energy, producing different energy types. The comparison was done referring to one square meter of roof surface occupied by the equipment.

The environmental burdens were calculated according to the indicators proposed by Eco-indicator'95 method. The results showed that the system based on thermal solar collector obtained the major number of more favourable indicators: eight out of ten, in the case of no-recycling of materials after dismantling phase, and six out of ten in the case of recycling of materials after dismantling phase. The thin film modules and solar thermal collector showed the lowest values of energy payback time and CO2eq payback time.

Results clearly show that photovoltaic and solar thermal collector can effectively provide comparable environmental and energy benefits as regard to domestic scale installation.”

“In conclusion, photovoltaic installations actually provide benefits from the environmental and energy point of view; nevertheless similar advantages, or even better, could be achieved by means of solar thermal collector installation.“

Source:

[57] Carnevale, E., Lombardi, L., Zanchi, L.: Life Cycle Assessment of solar energy systems: Comparison of photovoltaic and water thermal heater at domestic scale, Energy 77, p. 434 – 446, 2014

5.14 Life cycle assessment (LCA) optimization of solar-assisted hybrid CCHP system

System boundary:	cradle-to-grave
Functional unit:	n/a
Scenarios:	hybrid combined cooling heating and power (CCHP) system incorporating with solar energy and natural gas
geographic reference:	n/a
data time reference:	n/a
LCIA-methods:	global warming potential (GWP) acidification potential (AP) and respiratory effect potential (REP)
Derivatives:	-

Abstract:

“This work aims at optimizing life cycle performance of a hybrid combined cooling heating and power (CCHP) system incorporating with solar energy and natural gas. A basic natural gas CCHP system containing power generation unit, heat recovery system, hybrid cooling system and storage tank, is integrated with solar

photovoltaic (PV) and/or heat collector. LCA optimization methodology is proposed to optimize the configuration and variable load operation of the solar-assisted CCHP system to minimize the life cycle environmental impact. CCHP schemes in following electrical load (FEL) and following thermal load (FTL) strategies are optimized by different objectives respectively. Analysis and comparison are performed on life cycle environmental impacts caused by global warming potential, acidification potential and respiratory effect potential. The influences of main independent decision variables are discussed to discover the generic configuration rules for hybrid CCHP system. The results indicate that FTL strategy is superior to FEL strategy at taking the environmental compensation of surplus products from the hybrid CCHP system into consideration."

Source:

[58] Wang, J. et al.: Life cycle assessment (LCA) optimization of solar-assisted hybrid CCHP System, in Applied Energy 146, p. 38–52, 2015

5.15 Life cycle performance assessment of small solar thermal cooling systems and conventional plants assisted with photovoltaics

System boundary:	cradle-to-grave
Functional unit:	1 system
Scenarios:	conventional compression chiller, conventional compression chiller + PV (grid, stand-alone, partial), solar thermal + absorption chiller with hot back-up or cold back-up. lifetime of 25 years, except for batteries, charge regulators and inverters
geographic reference:	Rio de Janeiro, Palermo, Zurich
data time reference:	n/a
LCIA-methods:	CED GWP (From EPD 2008)
Derivatives:	Energy Payback time (EPT) Emission Payback time (EmPT)
Software:	SimaPro with ecoinvent database

Abstract:

"Starting from the results of a Life Cycle Assessment of small solar assisted heat driven chillers, the application of such methodology has been extended to systems with a conventional compression chiller assisted by a photovoltaic plant (PV). This study aims to provide a comprehensive compared investigation of these two families of solar assisted cooling systems (with solar thermal or PV). Results indicate that, in many cases, the systems with the PV grid connected plant performed best. In addition, two more configurations were investigated to further define the PV assisted systems, which minimise their interaction with the grid through the use of electricity storages. These systems performed worse than the PV grid connected systems and the solar thermal assisted systems in nearly all the analysed cases."

"Results are very sensitive to climate conditions affecting the energy performance in the operation phase, and to the national electricity mix."

Source:

[59] Beccali, M. et al.: Life cycle performance assessment of small solar thermal cooling systems and conventional plants assisted with photovoltaics, in Solar Energy 104, p. 93–102, 2014

5.16 Life cycle analysis of a building-integrated solar thermal collector, based on embodied energy and embodied carbon methodologies

System boundary:	cradle-to-grave
Functional unit:	1 solar thermal system consisting of 14 solar collectors; storage tank, pump, external insulated tubes, glycol
Scenarios:	lifetime of 20 and 30 years
geographic reference:	n/a
data time reference:	n/a
LCIA-methods:	embodied energy (EE) embodied carbon (EC) GWP
Derivatives:	Energy Payback Time (EPT)

Abstract:

"The present study is a life cycle analysis of a patented building-integrated solar thermal collector which was developed / experimentally tested at the University of Corsica, in France, with the concept "integration into gutters / no visual impact". Three configurations (reference and two alternatives) are evaluated. The life-cycle impact assessment methodologies of embodied energy (EE) / embodied carbon (EC),two databases and multiple scenarios are adopted. The results reveal that the reference system can considerably improve its environmental performance by utilizing collectors connected in parallel. The Energy Payback Time of the reference system decreases to less than 2 years by parallel connection while it is around 0.5years if recycling is also adopted. The EE of the systems is around 3 GJprim/m2 and it is reduced to around 0.4–0.5 GJprim/m2 by recycling. The EC of the configurations is approximately 0.16 t CO2.eq/m2 without recycling and around 0.02 – 0.03 t CO2.eq/m2 with recycling.CO2.eq emissions are strongly related with electricity mix. A reduction 28 – 96% in CO2.eq emissions of the systems is achieved by adopting configurations with "double collector surface / output". Concerning indicator of sustainability, the system with parallel connection shows a value of 0.78. The findings of the present investigation could be utilized for the design of building-integrated solar thermal systems as well as for research purposes."

Source:

[60] Lamnatou, C., Notton, G., Chemisana, D., Cristofari, C.: Life cycle analysis of a building-integrated solar thermal collector, based on embodied energy and embodied carbon methodologies, in Energy and Buildings 84, p. 378–387, 2014

5.17 Environmental benefits of domestic solar energy systems

System boundary:	cradle-to-grave
Functional unit:	1 kWh 1 kg of collector
Scenarios:	solar water heating system and solar space and water heating system using flat plate collectors with diesel or electrical pack-up, lifespan of 20 years
geographic reference:	Nicosia, Cyprus
data time reference:	n/a
LCIA-methods:	Acidification Ozone layer depletion global climate change
Derivatives:	payback time

Abstract:

"All nations of the world depend on fossil fuels for their energy needs. However the obligation to reduce CO2 and other gaseous emissions in order to be in conformity with the Kyoto agreement is the reason behind which countries turn to non-polluting renewable energy sources. In this paper the pollution caused by the burning of fossil fuels is initially presented followed by a study on the environmental protection offered by the two most widely used renewable energy systems, i.e. solar water heating and solar space heating. The results presented in this paper show that by using solar energy, considerable amounts of greenhouse polluting gasses are avoided. For the case of a domestic water heating system, the saving, compared to a conventional system, is about 80% with electricity or Diesel backup and is about 75% with both electricity and Diesel backup. In the case of space heating and hot water system the saving is about 40%. It should be noted, however, that in the latter, much greater quantities of pollutant gasses are avoided.

Additionally, all systems investigated give positive and very promising financial characteristics. With respect to life cycle assessment of the systems, the energy spent for manufacture and installation of the solar systems is recouped in about 1.2 years, whereas the payback time with respect to emissions produced from the embodied energy required for the manufacture and installation of the systems varies from a few months to 9.5 years according to the fuel and the particular pollutant considered. Moreover, due to the higher solar contribution, solar water heating systems have much shorter payback times than solar space heating systems.

It can, therefore, be concluded that solar energy systems offer significant protection to the environment and should be employed whenever possible in order to achieve a sustainable future."

Source:

[61] Kalogirou, S.A.: Environmental benefits of domestic solar energy systems, in Energy Conversion and Management 45, p. 3075–3092, 2004

5.18 A total cost perspective on use of polymeric materials in solar collectors – Importance of environmental performance on suitability

System boundary:	cradle-to-grave, but end-of-life impact of the systems is not considered
Functional unit:	1 m² collector area 1 solar heating system
Scenarios:	3 solar heating systems which “could produce the same quantity of solar heat to the reference building“, over a lifetime of 25 years, one with polymeric flat plate solar collectors, one with flat plate collectors with copper absorbers and one with evacuated tube collectors
geographic reference:	Stockholm
data time reference:	n/a
LCIA-methods:	Eco-indicator 99 GWP 100 CED
Derivatives:	Energy Payback time

Abstract:

“To assess the suitability of solar collector systems in which polymeric materials are used versus those in which more traditional materials are used, a case study was undertaken. In this case study a solar heating system with polymeric solar collectors was compared with two equivalent but more traditional solar heating systems: one with flat plate solar collectors and one with evacuated tube solar collectors. To make the comparison, a total cost accounting approach was adopted. The life cycle assessment (LCA) results clearly indicated that the polymeric solar collector system is the best as regards climatic and environmental performance when they are expressed in terms of the IPPC 100 a indicator and the Ecoindicator 99, H/A indicator, respectively. In terms of climatic and environmental costs per amount of solar heat collected, the differences between the three kinds of collector systems were small when compared with existing energy prices. With the present tax rates, it seems unlikely that the differences in environmental and climatic costs will have any significant influence on which system is the most favoured, from a total cost point of view. In the choice between a renewable heat source and a heat source based on the use of a fossil fuel, the conclusion was that for climatic performance to be an important economic factor, the tax or trade rate of carbon dioxide emissions must be increased significantly, given the initial EU carbon dioxide emission trade rate. The rate would need to be at least of the same order of magnitude as the general carbon dioxide emission tax rate used in Sweden. If environmental costs took into account not only the greenhouse effect but also other mechanisms for damaging the environment as, for example, the environmental impact factor Ecoindicator 99 does, the viability of solar heating versus that of a natural gas heating system would be much higher.”

Source:

[62] Carlsson, B., Persson, H., Meir, M., Rekstad, J.: A total cost perspective on use of polymeric materials in solar collectors – Importance of environmental performance on suitability, in Applied Energy 125, p. 10–20, 2014

5.19 Comparative Environmental and Economic Analysis of Conventional and Nanofluid Solar Hot Water Technologies

System boundary:	n/a
Functional unit:	1 Solar collector
Scenarios:	two different solar hot water heaters: a conventional flat plate collector and a new nanofluid-based direct-absorption collector
geographic reference:	Phoenix, USA
data time reference:	n/a
LCIA-methods:	Embodied Energy (EE), Emissions of CO_2, SOx, NOx related to Embodied energy
Derivatives:	-

Abstract:

"This study compares environmental and economic impacts of using nanofluids to enhance solar collector efficiency as compared to conventional solar collectors for domestic hot water systems. Results show that for the current cost of nanoparticles the nanofluid based solar collector has a slightly longer payback period but at the end of its useful life has the same economic savings as a conventional solar collector. The nano fluid based collector has a lower embodied energy (~9%) and approximately 3% higher levels of pollution offsets than a conventional collector. In addition if 50% penetration of residential nanofluid based solar collector systems for hot water heating could be achieved in Phoenix, Arizona over 1 million metric tons of CO2 would be offset per year."

Source:

[63] Otanicar, T.P., Golden, J.S.: Comparative Environmental and Economic Analysis of Conventional and Nanofluid Solar Hot Water Technologies, in Environ. Sci. Technol. 43, p. 6082–6087, 2009

5.20 Economic and environmental life cycle analysis of solar hot water systems in the United States

System boundary:	cradle-to-grave
Functional unit:	hot water demand of 1 person (93,28 l/d at 60 °C)
Scenarios:	Flat plate collector (4 m²) or evacuated tube collector (2,4 m²) solar water heating systems with electrical or natural gas auxiliary heater and electricity or natural gas driven water heating systems with a lifespan of 20 years
geographic reference:	Los Angeles Atlanta Chicago

LCIA-methods:	CED GWP100
Derivatives:	payback time
Database:	ecoinvent 2.0

Abstract:

"This paper evaluates the solar water heating systems for the U.S. typical residential buildings, from the energetic, economic and environmental perspectives, and includes two different types of solar collectors (i.e. flat-plate and evacuated-tube solar collectors), two types of auxiliary systems (i.e. natural gas and electricity), and three different locations (i.e. Los Angeles, Atlanta, and Chicago). The performance of solar water heating systems is also compared with conventional systems that use either natural gas or electricity. The results showed that the flat-plate solar water heating systems using natural gas auxiliary heater has the best performance among all the types and at all locations. The energetic and environmental payback periods for solar water heating systems are less than half of a year, and the life cycle cost payback for solar water heating systems vary from 4 to 13 years for different cities and different configurations when using the conventional electrical water heating system in each city as the benchmark. For a representative case, i.e. flat-plate solar water heating system with natural gas auxiliary heater in Atlanta, sensitivity analysis shows that the daily hot water use has the most significant effects on energetic, environmental and economic performance."

Source:

[64] Hang, Y., Qu, M., Zhao, F.: Economic and environmental life cycle analysis of solar hot water systems in the United States, in Energy and Buildings 45, p. 181–188, 2012

5.21 Environmental assessment of solar thermal collectors with integrated water storage

System boundary:	cradle-to-grave
Functional unit:	1 collector
Scenarios:	heat from an ICS collector and from electrical boiler, lifespan of 15-20 years
geographic reference:	Italy
data time reference:	n/a
LCIA-methods:	Ecoindicator 95 (Greenhouse effect (GE), Ozone layer depletion, Acidification, Eutrophication, Heavy metals, Winter smog, Summer smog, Primary energy consumption (PEC), Solid waste production)
Derivatives:	payback time
Software:	SimaPro 5.0

Abstract:

"Solar thermal systems feed on a ''clean'' energy source. However, a complete analysis of the environmental performance of solar thermal collectors should take into account not only their operation phase, but also their whole life cycle. This paper reports the results of a life cycle assessment of a solar thermal collector with integrated water storage. The study, carried out by means of SimaPro 5.0 software, aims at drawing a thorough environmental profile of the collector, highlighting the most relevant contributions to the total impacts, measured by means of a set of aggregate environmental indicators. In order to evaluate the possible improvements of the system configuration, several sensitivity analyses were performed, for different phases of its life cycle.

Thanks to this optimization, the reduction of the impacts could be up to 40%. Environmental pay back times were calculated as well. Their values range from 5 to 19 months, remarkably lower than the expected lifespan of the systems (15e20 years)."

Source:

[65] Battisti, R., Corrado, A.: Environmental assessment of solar thermal collectors with integrated water storage, in Journal of Cleaner Production 13, p. 1295-1300, 2005

5.22 Net energy analysis of solar and conventional domestic hot water systems in Melbourne, Australia

System boundary:	cradle-to-gate (including 10 years of use)
Functional unit:	1 hot water system
Scenarios:	5 hot water systems: electric-boosted solar hot water system, gas-boosted solar hot water system, electric storage hot water system, gas storage hot water system and a gas instantaneous hot water system with a lifespan of 10 years
geographic reference:	Melbourne, Australia
data time reference:	1992 - 1993
LCIA-methods:	embodied energy, primary energy
Derivatives:	energy payback time

Abstract:

"It is commonly assumed that solar hot water systems save energy and reduce greenhouse gas emissions. The net energy requirement of solar hot water systems has rarely been analysed, including their embodied energy. The extent to which solar hot water systems save energy compared to conventional systems in Melbourne, Australia, is shown through a comparative net energy analysis. It was shown that the embodied energy component of the net energy requirement of solar and conventional hot water systems was insignificant. The solar hot water systems provided a net energy saving compared to the conventional systems after 0.5–2 years, for electric- and gas-boosted systems respectively."

Source:

[66] Crawford, R.H., Treloar, G.J.: Net energy analysis of solar and conventional domestic hot water systems in Melbourne, Australia, in Solar Energy 76, p. 159–163, 2004

5.23 Optimizing energy and environmental performance of passive Trombe wall

System boundary:	cradle-to-grave
Functional unit:	annual primary operating energy consumption for heating and the annualized embodied energy in the construction elements of the house.
Scenarios:	6 variants of Trombe walls with a lifespan of 50 years
geographic reference:	Lyon, France (Construction materials from UK)
data time reference:	n/a
LCIA-methods:	embodied energy, primary energy
Derivatives:	energy payback time

Abstract:

“The energy and environmental performance is compared for buildings with and without Trombe walls. The indicator for environmental performance is a sum of primary operating energy for heating during winter and the annualized embodied energy consumed by using the Trombe walls. Two Trombe walls are used at the south side of a “Mozart” house located in Lyon, France. The house satisfies the French thermal regulation. The performances of several constructions of Trombe walls are studied. The annualized lifecycle energy use by houses with Trombe walls may be lower when the core material has lower density and lower embodied energy. For heating by electricity there are much higher values of the optimum thickness of the core layer and that of the primary energy consumption than that for heating by using natural gas. When the building with Trombe walls is used, the annual final energy saving during heating is around 20%. For the electrical heating and optimum core thickness, the energy ratio is around 6 and the energy payback time is around 8 years. For the natural gas heating these values are around 3, and around 18 years, respectively.”

Source:

[67] Bojic, M., Johannes, K., Kuznik, F.: Optimizing energy and environmental performance of passive Trombe wall, in Energy and Buildings 70, p. 279–286, 2014

5.24 Thermal performance, economic and environmental life cycle analysis of thermosiphon solar water heaters

System boundary:	cradle-to-grave
Functional unit:	1 solar collector, 1 year of operation
Scenarios:	thermosiphon solar water heating system with electricity and diesel backup and conventional electrical/diesel water heating system
geographic reference:	Cyprus (European electricity mix)
data time reference:	n/a

LCIA-methods:	embodied energy, land displacement, air and water pollution, CO, CO_2, NOx, N_2O, CH_4, Hydrocarbons, SO_2 emissions, dust, cost of damage by CO, CO_2 and SO_2
Derivatives:	energy payback time

Abstract:

"In this paper, the environmental benefits or [sic] renewable energy systems are initially presented followed by a study of the thermal performance, economics and environmental protection offered by thermosiphon solar water heating systems. The system investigated is of the domestic size, suitable to satisfy most of the hot water needs of a family of four persons. The results presented in this paper show that considerable percentage of the hot water needs of the family are covered with solar energy. This is expressed as the solar contribution and its annual value is 79%. Additionally, the system investigated give positive and very promising financial characteristics with payback time of 2.7 years and life cycle savings of 2240 € with electricity backup and payback time of 4.5 years and life cycle savings of 1056 € with diesel backup. From the results it can also be shown that by using solar energy considerable amounts of greenhouse polluting gasses are avoided. The saving, compared to a conventional system, is about 70% for electricity or diesel backup. With respect to life cycle assessment of the systems, the energy spent for the manufacture and installation of the solar systems is recouped in about 13 months, whereas the payback time with respect to emissions produced from the embodied energy required for the manufacture and installation of the systems varies from a few months to 3.2 years according to the fuel and the particular pollutant considered. It can therefore be concluded that thermosiphon solar water hearting [sic] systems offer significant protection to the environment and should be employed whenever possible in order to achieve a sustainable future."

Source:

[68] Kalogirou, S.: Thermal performance, economic and environmental life cycle analysis of thermosiphon solar water heaters, in Solar Energy 83, p. 39–48, 2009

LIFE CYCLE COSTING

Life Cycle Costing (LCC) is determined by performing a Life Cycle Costing Analysis (LCCA). It is a one-dimensional method for cost management of a product in most cases, but is also applicable for projects, services, etc. It uses an easy to understand monetary unit. The method is taking into account not only development and production but the complete life cycle of a product from development to recycling or disposal. The system boundary is therefore cradle-to-grave. LCCA may be performed from a producer perspective or a customer perspective, which have to be considered both in order to create a product with sustainable success in the market.

In the past decades LCC was mainly used in the building sector [69] or mass production of automotive and electronic products.

With regard to products related to the use of solar thermal energy LCC is a useful tool to compare costs of conventional systems and solar systems for thermal energy supply. The initial costs of conventional heating devices like oil or gas burners are generally considered to be lower than those of solar thermal systems. In the long run conventional systems tend to have higher costs for maintenance and operation than solar thermal systems. LCC from a customer perspective provides customers a basis for the decision on solar thermal or conventional energy supply systems taking into account the complete costs during the life cycle.

The shortcoming of this method is its restriction to a monetary unit. [70] The issues considered in LCA like impacts on the environment, human health and resources are not represented in LCC. Yet these impacts may result in direct or indirect (with spatial and/or temporal distance and/or different distribution) monetary costs in the future, which are not accounted for by LCC. In order to attenuate the shortcomings of LCA in economics and LCC in ecology a combined use of LCC and LCA is most promising. For this purpose also LCC-oriented environmental accounting tools have been developed. A comprehensive overview on LCC-oriented environmental accounting tools can be found in [70].

6.1 Mathematical principles

In order to make monetary inputs and outputs with temporal distance comparable future payments are discounted to a net present value (NPV). Life cycle costs are therefore given as net present value. Glucha and Baumann [70] pointed out that in practice different calculations rules may be used for discounting which may lead to confusion and results which are not comparable. In the following some mathematical basics regarding the financial evaluation techniques of different methods are explained by mathematical description.

The basic NPV is defined as the sum of all payments at present value:

$$NPV = \sum_{t=0}^{LT} \frac{C_t}{(1+i)^t}$$

with LT = lifetime, t = time, i = interest rate, Ct = Cash flow

The NPV is based on the time value of money described by the following equation:

$$FV_t = PV \cdot (1+i)^t$$

with FVt = future value, PV = present value, t = time, i = interest rate

The internal rate of return r is given for NPV = 0:

$$NPV = \sum_{t=0}^{LT} \frac{C_t}{(1+r)^t} = 0$$

with LT = lifetime, t = time, r = rate of return, Ct = Cash flow

Annual cost (AC) and payback time can by determined via LCC. The payback time must be considered as a critical measure in life cycle analysis. Its purpose is to specify a time at which the object of investigation "has payed for itself". By its nature this measure neglects impacts after this point of time.

Life cycle savings (LCS) are defined as the difference of life cycle costs of two different scenarios. In the case of solar thermal technology, this is mostly a comparison of a conventional heating system and a solar thermal system.

The savings-to-investment ratio is the ratio of LCS to initial investment.

The present value of annuity is the product of a cash flow per year and the annuity factor.

The present value of annuity factor is

$$A_{t,r} = \frac{1 - \frac{1}{(1+r)^t}}{r}$$

with t = time, r = rate of return.

6.2 Methods and models

Geissdoerfer et al. [71] point out, that there is no standardized LCC model available yet. LCC and TCO (Total Cost of Ownership) models have been developed for specific case studies or branches of industry. Other than a LCC model a TCO model accounts also for transaction costs. Geissdoerfer et al. assessed 20 LCC and TCO models regarding their potential to be used as a standardized model for cost management. Most of these guidelines and models are not applicable for solar thermal technologies because they are specific for other branches of industry or focus on low value goods in large numbers.

Three guidelines or standards were found to be relevant for LCC of solar thermal technologies: DIN EN 60300-3-3, the guidelines VDI 2067:2012 and the International Standard ISO 15686-5:2008, which are presented in the following.

DIN EN 60300-3-3

"This International Standard establishes a general introduction to the concept of life cycle costing and covers all applications. Although costs incurred over the life cycle consist of many contributing elements, this international standard particularly highlights the costs associated with the dependability of an item." [72]

"The prime use of this standard is to compare one alternative system solution to another where future cost of ownership comprising maintenance, operations, enhancement and disposal actions is significant and must be balanced against the cost of acquisition and the residual unrealized risk of ownership. Such a balance is achieved by technical and monetary assessments that trade off acquisition costs against varying outcomes of availability, reliability, maintainability and supportability." [72]

The financial evaluation techniques used are:

- Discounted cash flow or NPV
- Internal rate of return (IRR)
- Depreciation and amortization
- Cost-benefit analysis
- Time value of money

Source:

[72] DIN EN 60300-3-3: Dependability management - Part 3-3: Application guide - Life cycle costing, Beuth Verlag, Berlin, September 2014

VDI 2067

The series of guidelines VDI 2067 [73] defines a structured method and calculation procedures for life cycle costing analysis. The focused area of application is building installations. Special attention is placed on the energy supply of buildings. The guidelines are divided into several parts as shown in Table 18.

Table 18: List of parts of VDI 2067

Part 1: Principles and cost calculation
Part 10: Energy demand for heating, cooling, humidification and dehumidification
Part 12: Energy demand for domestic water heating
Part 20: Water heating
Part 21: Air-conditioning technology
Part 22: Heating of domestic hot water
Part 30: Energy input in distribution
Part 40: Heat and cold generation

Part 40 [74] describes LCC calculation procedures for heat and cold generation systems including solar thermal systems. Compared to other guidelines the calculation procedures are described in more detail.

"The series of guidelines VDI 2067 deals with the calculation of the economic efficiency of building installations. It applies for all building types. Because the calculation of the power requirement is made step by step, the guideline is divided in several parts." [73]

The financial evaluation technique used is the annuity method.

Sources:

[73] VDI 2067 Part 1: Economic efficiency of building installations - Fundamentals and economic calculation, Beuth Verlag, Berlin, September 2012

[74] VDI 2067 Part 40: Economic efficiency of building services installations Energy effort for generation, Beuth Verlag, Berlin, September 2012

ISO 15686-5

ISO 15686-5:2008 "gives guidelines for performing life cycle cost (LCC) analyses of buildings and constructed assets and their parts." [75] The cost assessment described in Part 5 is to be performed in conjunction with other sub-standards of ISO 15686, like Part 1: Technical Assessment, Part 6: Environmental assessment and Part 3: Audit and review.

The cost assessment guideline also provides an extended method referred to as whole-life-cycle, which also considers further impacts like environmental cost impacts and social costs and benefits.

The financial evaluation techniques used are:

- Present Value (NPV)
- Payback period
- Net savings (NS)
- Savings-to-investment ratio (SIR)
- Internal rate of return (IRR)
- Annual cost (AC) or annual equivalent value (AEV)

Source:

[75] ISO 15686:2008 Buildings and Constructed Assets - Service Life Planning Part 5: Life Cycle Costing, June 2008

6.3 LCC analysis applied on solar thermal systems

Studies published so far focus mainly on the building sector, some in connection with different systems for energy supply. Studies on solar thermal technologies without consideration of the building are rather rare.

Botsaris et al. [76] performed an LCCA for a solar water heating system (thermosiphon system) in Thessaloniki in order to obtain life cycle costs (LCC) and life cycle savings (LCS) in comparison with an electrical heating system. Also the payback time was calculated. "The financial characteristics of the system investigated give life cycle savings equal to 4280.0 € and pay-back time equal to 5 years." [76]

Valan Arasu and Sornakumar [77] investigated the LCC of a solar thermal hot water system with a fiber reinforced parabolic trough collector that replaces an existing electric water heating system in a restaurant in Madurai, India. They determined LCS for a lifetime of 15 years. For the economic analysis a computer program was developed in MATLAB. "The LCS method and the MATLAB computer simulation program presented in this paper can be used to estimate the LCS of other renewable energy systems." [77]

Kalogirou [78] presented a detailed economic analysis of a solar energy system based on a spreadsheet computer program. He performed an exemplary calculation of the LCC for a hot water system and calculated LCS of the solar system compared to a fuel-only system.

Leckner and Zmeureanu [79] analyzed the LCC of a Net Zero Energy House in Montreal, canada which uses a solar thermal combisystem. They compared it to the LCC of "an average house that complies with the provincial code." [79]

"The Net Zero Energy House (NZEH) presented in this paper is an energy efficient house that uses available solar technologies to generate at least as much primary energy as the house uses over the course of the year. […] The life cycle cost analysis of the NZEH shows, however, that due to the high cost of the solar technologies and the low cost of electricity in Montreal, financial payback is never achieved." [79]

On a similar application but at the location of Denmark Marszal and Heiselberg [80], performed an LCCA of a multi-storey residential Net Zero Energy Building (Net ZEB) from the customer perspective.

"The study includes three levels of energy demand and three alternatives of energy supply systems: (1) photovoltaic installation with photovoltaic/solar thermal collectors and an ambient air/solar source heat pump;

(2) photovoltaic installation with a ground-source heat pump; (3) photovoltaic installation with district heating grid. The results indicate that in order to build a cost-effective Net ZEB, the energy use should be reduced to a minimum leaving just a small amount of left energy use to be covered by renewable energy generation. Moreover, from the user perspective in the Danish context, the district heating grid is a more expensive source of heat than a heat pump for the Net ZEB." [80]

In [81] the analysis was expanded to off-site options of the use of energy from windmills.

"The results indicate that in case of the on-site renewable supply options, the energy efficiency should be the first priority in order to design a cost-optimal Net ZEB. However, the results are opposite for the off-site renewable supply options, and thus it is more cost-effective to invest in renewable energy technologies than in energy efficiency." [81]

CONCLUSION

Life cycle assessment has been used successfully for the assessment of solar thermal systems and products related to solar thermal energy. During the past decades a variety of one-dimensional and multi-dimensional, comprehensive LCIA methods has been developed. This report gives an overview on the fundamental principles of LCA as well as available LCIA methods and studies related to solar thermal applications. The investigated LCIA methods differ in complexity and focus on different sets of impact categories. The choice of the LCIA method for a life cycle assessment allows to consider different impact categories or even sets of impact categories. Through characterization, normalization and weighting LCIA methods provide results from specific aspects of environment, human health or resources to single score results.

Life Cycle Costing (LCC) Analysis from a customer perspective provides customers a basis for the decision on solar thermal or conventional energy supply systems taking into account the complete costs during the lifecycle. Impacts that cannot be described in monetary units may result in direct or indirect monetary costs in the future, which are not accounted for by LCC. In order to attenuate the shortcomings of LCA in economics and LCC in ecology a combined use of LCC and LCA is most promising.

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"Technical study report on solar thermal technology LCIA methods and LCC models" aims at contributing to the demonstration of the advantages of solar thermal systems, taking the lifecycle into account. This means assessing both environmental and economic benefits of the systems over their operation period. These methods allow to exemplify the diverse benefits of this technology during the lifecycle of a system, in spite of high upfront investments costs.

This "Technical study report on solar thermal technology LCIA methods and LCC models" was developed as part of the Global Solar Water Heating (GSWH) Market Transformation and Strengthening Initiative.