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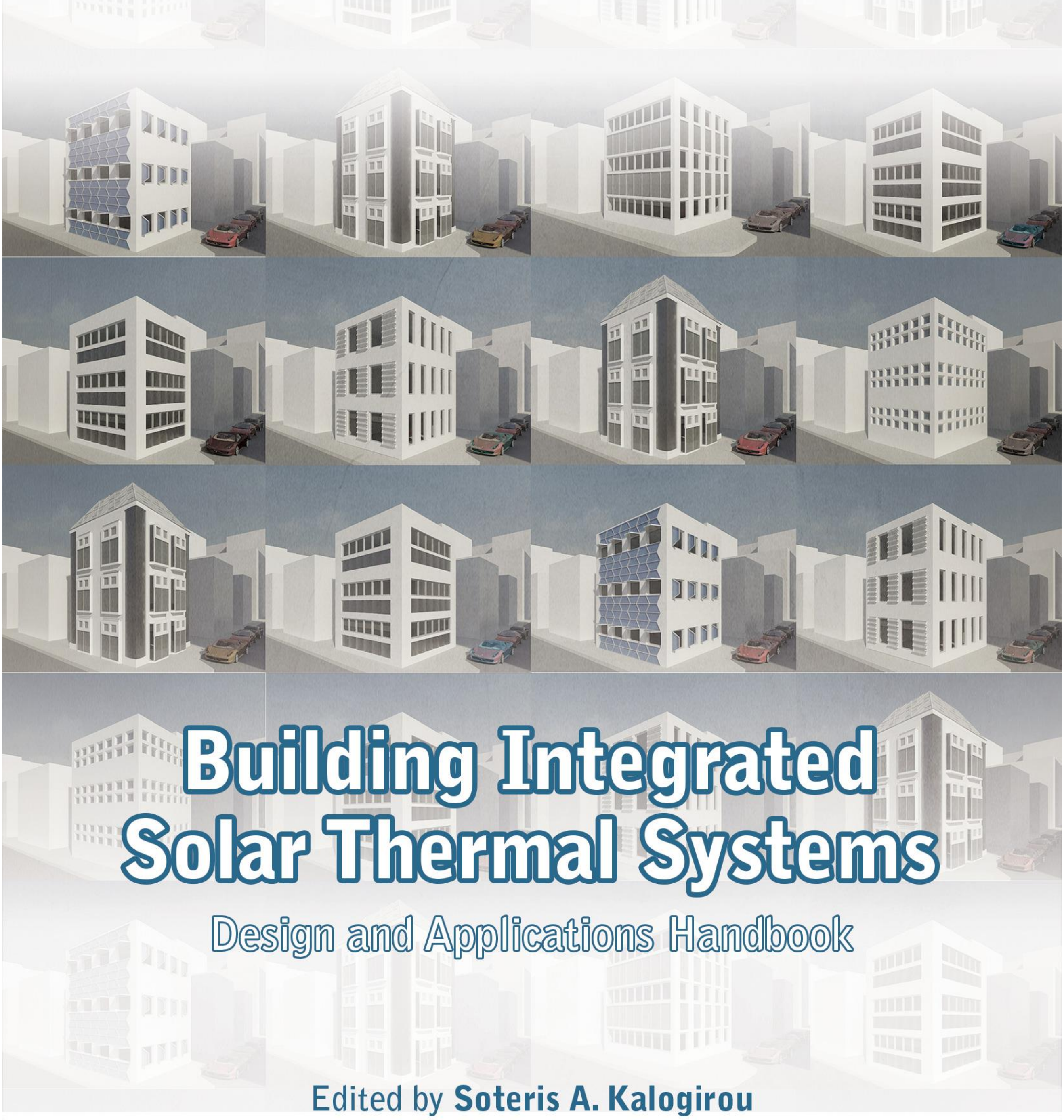

Building Integrated Solar Thermal Systems

Design and Applications Handbook

Edited by **Soteris A. Kalogirou**

CYPRUS UNIVERSITY OF TECHNOLOGY
2004

COST Action TU1205 (BISTS)

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Building Integration of Solar Thermal Systems

DESIGN AND APPLICATIONS HANDBOOK

Edited by Soteris A. Kalogirou

***Notice**: The compilation of the various chapters contained within this handbook have been produced by COST Action TU1205 members having sole responsibility of the material presented therein.*

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PREFACE

This handbook produced by the members of the COST Action TU1205 – Building Integrated Solar Thermal Systems (BISTS), funded by COST, 2013-2017. It covers introductory subjects on the presentation of the Action, the classification and characterisation of BISTS and basic resource (solar radiation) analysis. Following on, Section 2 details the basic BISTS design, including architectural planning, thermal and optical design of BISTS, modelling of the systems, installation, testing, commissioning and maintenance as well as life cycle analysis, economics and legal issues. Section 3 presents new options with respect to emerging architectural design concepts, system and application options, materials, retrofitting BISTS and thermal storage integration. Section 4 presents five different innovative BISTS designs developed by various Action members, a building erected in Israel where BISTS are applied extensively, as well as the modelling of novel solar thermal collectors suitable for building integration. The last two sections deal with the outlook of the technology and basic conclusions obtained from this Action with supporting material, including journals that publish material relevant to BISTS, participant research and testing centres and infrastructures, international activities, networks and projects and a comprehensive database of BISTS applications, presented in a connected publication produced by this Action. Many more details can be found in the Action website: http://www.tu1205-bists.eu/.

We hope that the material presented in this handbook will be of interest to architects, solar engineers, building services engineers, government bodies and anyone who has an interest in this subject. Many thanks to the Action members and non-members who participated in the writing of the various chapters and of course to the COST Office for funding this Action.

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2.10 ENVIRONMENTAL LIFE-CYCLE ANALYSIS OF SOLAR SYSTEMS

Ricardo Mateus, Sandra M. Silva and Manuela G. Almeida

2.10.1 Introduction

The reduction of energy consumption and the use of energy from renewable sources in the buildings sector are important measures needed to reduce European Union (EU) energy dependency and carbon emissions. The potential of emissions mitigation in this sector is relevant as much as 80% of the operational costs of standard new buildings can be saved through integrated design principles, often at no (or little) extra cost over the lifetime of the measure (Boermans et al., 2015).

Buildings require energy both in the form of heat (e.g. for the domestic hot water preparation, space heating and even space cooling) and electricity (e.g. for lighting, electric appliances, heating and cooling). Therefore, solar thermal (STC), photovoltaic (PV) and hybrid photovoltaic-thermal (PVT) systems are necessary technologies for building applications since they can be used to replace non-renewable energy systems in proving renewable heat, electricity and cooling energy sources.

In the feasibility studies regarding the benefits of using solar systems, it is also necessary to consider the potential environmental impacts related to their manufacture, transportation and maintenance and the environmental benefits related to the energy savings (Lamnatou et al., 2015a).

The challenge is thus to develop and select cost-effective strategies for increased efficiency and deployment of renewable energy to achieve the best building performance (e.g. less energy use, fewer carbon emissions and higher co-benefits related with indoor environmental quality) at the lowest possible effort (e.g. initial costs, life cycle costs and occupant's disturbance in the case of building renovation).

The assessment of the life-cycle performance of a new building or of an energy renovation scenario can be based on several indicators, such as cost, operational energy consumption or environmental impacts of building materials and energy consumption. Whatever the indicators used the generic pattern of its time evolution and payback time can be schematised as shown in Figure 2.10.1.

Nevertheless, recent studies (e.g. (Mateus & Bragança, 2011; Lamnatou, et al., 2015a)) concluded that most assessments are not based on a comprehensive LCA methodology, since they are only focused on a small number of environmental indicators. The reasoning for this is the simplification of the LCA method for practical use, considering only the indicators that express the commitment of the building design with the EU energy targets. Two popular indicators generally used to assess and compare the environmental life-cycle performance both at buildings and energy systems level are the energy payback time (EPBT) and carbon emissions payback time (GPBT). Other studies state that there is a lack of findings based on the use of comprehensive life-cycle analysis methods to assess the benefits of using solar systems (e.g. (Tiago Filho et al., 2016)).

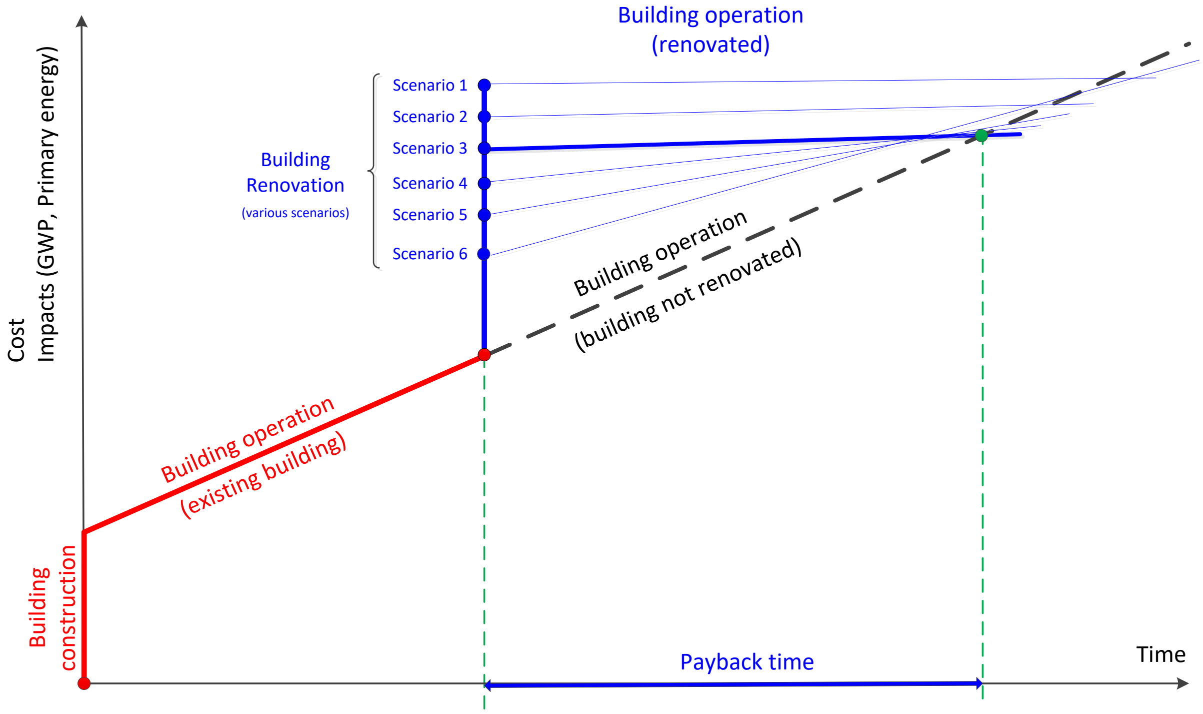

Figure 2.10.1. Schematic representation of the payback time of renovation operations (Ott et al., 2014).

Based on this context, the main goals of this section are: to define sustainable construction and to present the new standards in the context; to discuss the importance of the Life Cycle Assessment (LCA) method in the assessment of the environmental benefits resulting from the use of solar systems; to present the method to perform a life-cycle analysis to a building integrated or added Solar Thermal System for domestic hot water preparation; and to present the indicators used in the assessment of the environmental performance. At the end, a case study of an energy renovation project is presented in order to show the practical application of the LCA method in the assessment of the environmental benefits of using a Solar Thermal Collector (STC). In order to present the differences and discuss the results of using generic or specific Life-cycle Inventory (LCI) data in the early design stage, two renovation scenarios are presented.

2.10.2 The concept of sustainable building

Sustainable building is aimed at promoting the design, construction, renovation and operation of buildings that are more balanced at environmental, social and economic aspects.

As presented in Figure 2.10.2, sustainable building is the shift from the old paradigm where buildings were designed to meet only three aspects of competiveness (time, cost and quality) to a new paradigm where the human satisfaction, the minimal potential environmental impacts and the reduction of raw-material and energy’s consumption are in the centre of the design options.

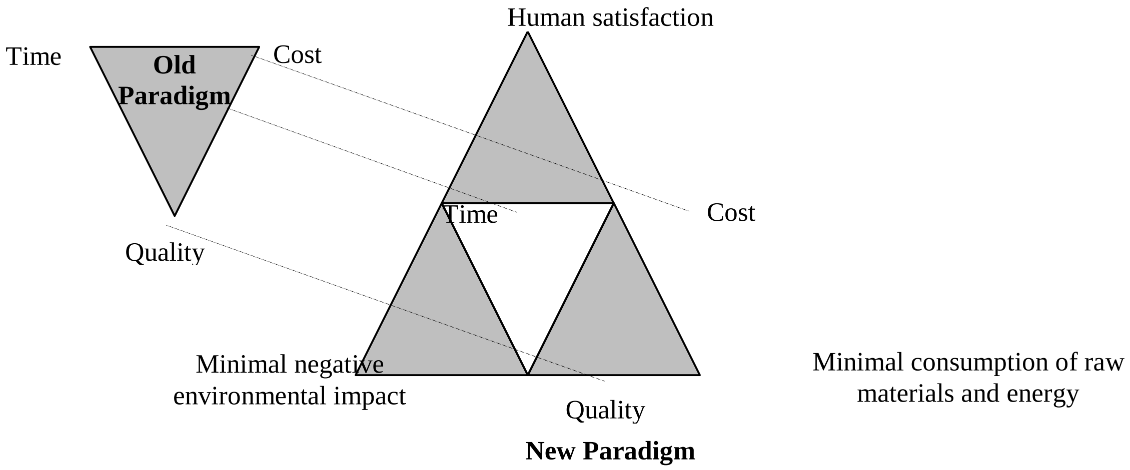

Figure 2.10.2. Holistic approach to building sustainability analysis.

Optimizing building sustainability involves various relations between built, natural and social systems. Therefore, it comprises hundreds of parameters, most of them interrelated and partly contradictory. This way, this process is only possible through a systematic approach.

Sustainability assessment tools are useful to gather and report information for decision-making during different phases of construction, design and use of a building (holistic approach).

In order to standardize and promote the interpretation and comparison of results from different assessment methods developed in Europe, the European Committee for Standardization (CEN) created the Technical Committee 350 (CEN/TC 350). The CEN/TC 350 is divided in five Working Groups (WG) (Figure 2.10.3): WG1 – Environmental Performance of Buildings; WG2 – Building Life-cycle Description; WG3: Products Level; WG4: Economical Performance of Buildings; and WG5 – Social Performance of Buildings.

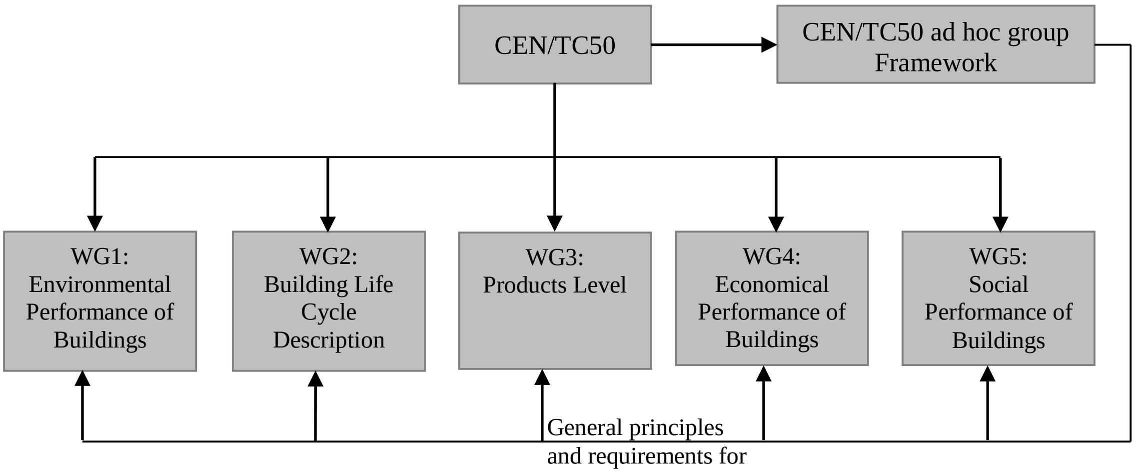

Figure 2.10.3. Organization of CEN Technical Committee 350.

This technical committee is providing the rules to assess the sustainability of the construction works, including buildings, to be applied in the different life-cycle stages of a building (Figure 2.10.4): pre-operation phase, operation phase and end-of-life phase. It also allows the quantification of the environmental benefits beyond the system boundaries, that result, for instance, from the recycling of materials to be used in a new life-cycle.

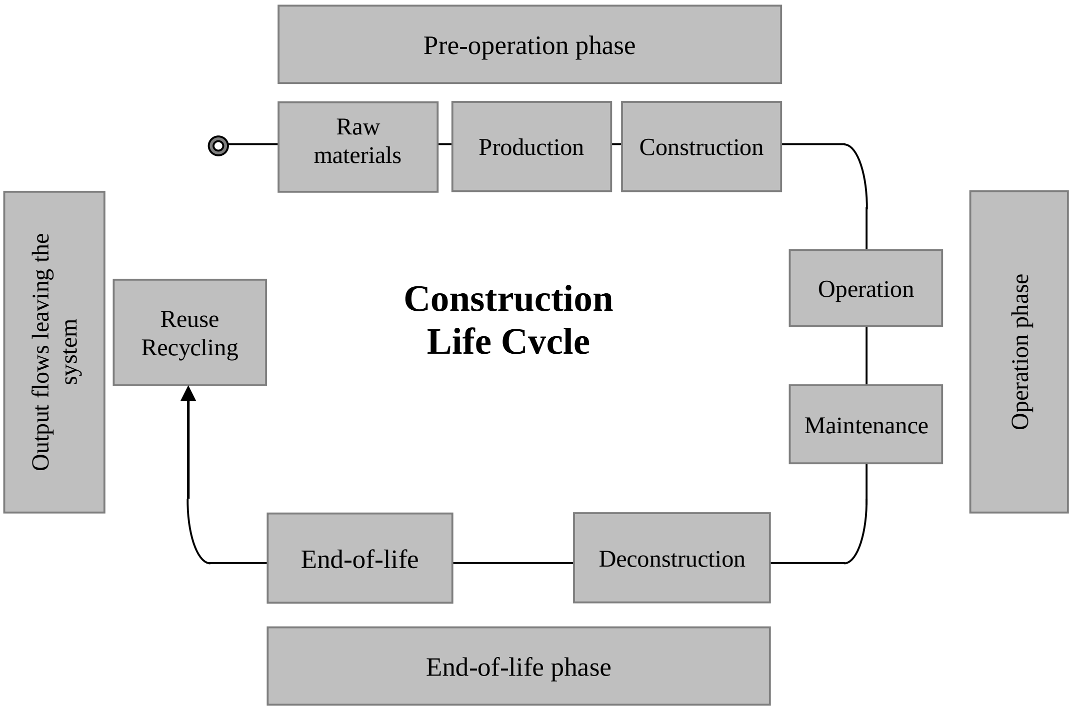

Figure 2.10.4. Life-cycle phases of a construction.

As a result of the work carried out to date the following main standards have been produced to support the evaluation of the environmental, social and economic performance of a building (CEN, 2010; CEN, 2011a,b; CEN, 2011a,b; CEN, 2014; CEN, 2015):

- EN 15643-1:2010, Sustainability of construction works - Sustainability assessment of buildings - Part 1: General framework;

- EN 15643-2:2011, Sustainability of construction works - Assessment of buildings - Part 2: Framework for the assessment of environmental performance;

  EN 15643-3:2012, Sustainability of Construction Works - Assessment of Buildings - Part 3: Framework for the assessment of social performance;

- EN 15643-4:2012, Sustainability of Construction Works - Assessment of Buildings - Part 4: Framework for the assessment of economic performance;

- EN 15978:2011, Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method;

- EN 16309:2014, Sustainability of construction works - Assessment of the social performance of buildings - Calculation method;

- EN 16627:2015, Sustainability of construction works - Assessment of the economic performance of buildings - Calculation method;

As discussed by several authors, the use of STC can have positive impacts in the different dimensions of sustainable development, mainly at environment and economic levels. In a study developed for the Portuguese context (Monteiro da Silva et al., 2016), authors concluded that the Greenhouse Gas Payback Time (GPBT) is under 19 months and the Economic Payback Time (EPBT) under 16 months. In other location, Kalogirou (2010) investigated a domestic, thermosiphon solar water heater (for the climate conditions of Nicosia, Cyprus) and concluded that the energy spent for manufacture/installation was recouped in approximately 13 months. At the level of PVs, for example, Lu and Yang (2010) studied the sustainability of a roof-mounted 22 kW building integrated PV system in Hong Kong and concluded a GPBT ranging from 3.6 to 5.3 years (depending on the considered energy mix) and an EPBT of 7.3 years.

2.10.3 Methodology to quantify the environmental benefits of using solar thermal systems in buildings

2.10.3.1 Steps of LCA at the building scale

Life-cycle analysis (LCA) is an analytical methodology that is aimed to assess the resources content and the environmental impacts associated with the life-cycle of a manufactured product. The LCA method is standardized by the International Organisation for Standardisation (ISO 14040:2006) (ISO, 2006). It has several applications, including: i) analysis of the contribution of the various life-cycle stages to the global environmental impact; ii) comparison between products; and iii) internal and external communication. Currently there are two specific rules for defining the framework and requirements of an LCA: ISO/FDIS 14040:2006 (ISO, 2006a), Environmental Management – Life Cycle Assessment – Principles and framework; and the ISO/FDIS 14044:2006 (ISO, 2006b), Environmental Management – Life Cycle Assessment – Requirements and guidelines.

According to ISO 14040:2006 (ISO, 2006a) and ISO 14044:2006 (ISO, 2006b), and as shown in Figure 2.10.5, the implementation of an LCA analysis is essentially an iterative process that is accomplished in four phases (ISO, 2006a; ISO, 2006b):

- Definition of Goals and Scope;
- Life-Cycle Inventory;
- Life-Cycle Impact Assessment;
- Interpretation.

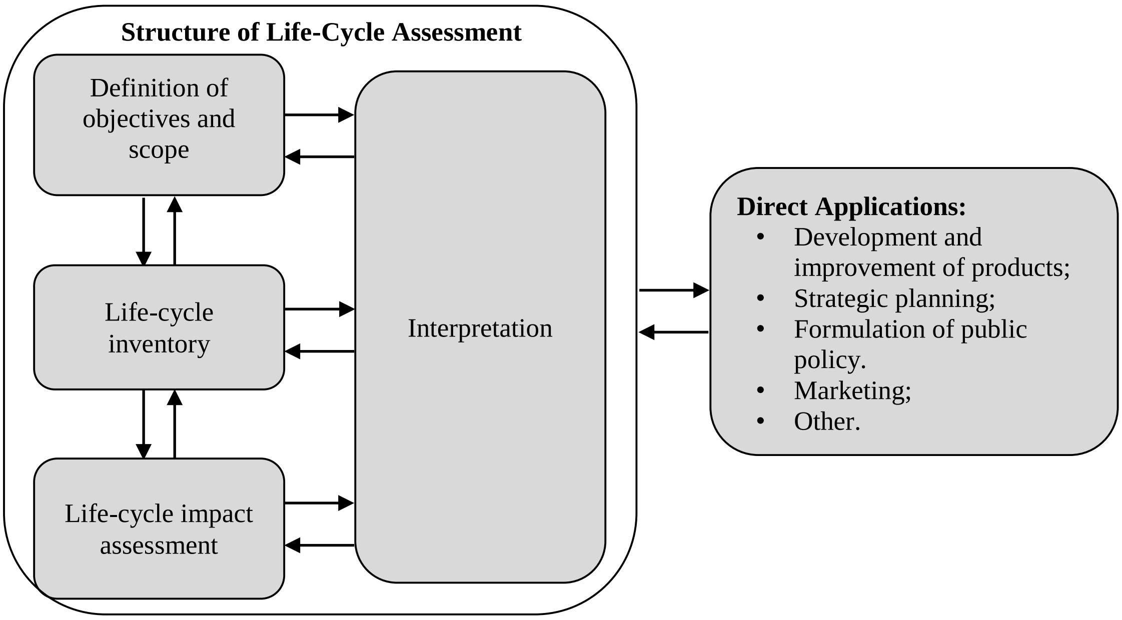

Figure 2.10.5. Stages of LCA (according to standard ISO 14040:2006).

As presented in Figure 2.10.6, according to EN 15978:2011 (CEN, 2011b) a typical life cycle of a building can be separated into four distinct stages (product, construction, use and end-of-life) each consisting of one or several life cycle modules. The product stage refers to the collection of raw materials through resource extraction, the transportation of raw materials and the manufacture of these raw materials into products. The construction stage includes the transportation of the building materials to the construction site and the construction-installation processes. The use stage refers to heating, cooling and electricity requirements, water services and other services including maintenance, repair, material replacement and refurbishment. The last stage, end-of-life, includes the decommissioning, deconstruction and demolition of the building, the waste processing of building products and assemblies, intermediate transportation steps and the disposal of demolition waste. The building assessment information also includes supplementary information beyond building life cycle. This includes the benefits and loads beyond the system boundary resulting from reuse/recovery/recycling potential and from in-situ production of energy that it is exported outside the system boundary. In the next subsections, each phase of the LCA method is briefly introduced.

i) Goal and scope

In this phase the objectives of the study are formulated and specified according to the intended application and the following aspects are identified: the objectives; the target audience of the evaluation; the various stages that compose the building life-cycle and its relevance to the purpose of the study; the functional unit that will be assessed; the boundary conditions; and the methodology for the allocation of impacts and consumption of raw materials in the various processes. In defining the Goals and Scope, the object of study is described in the form of functional unit. When comparing, for example, two different solar systems the functional unit may be "one solar system to heat the hot water of a three occupant’s dwelling".

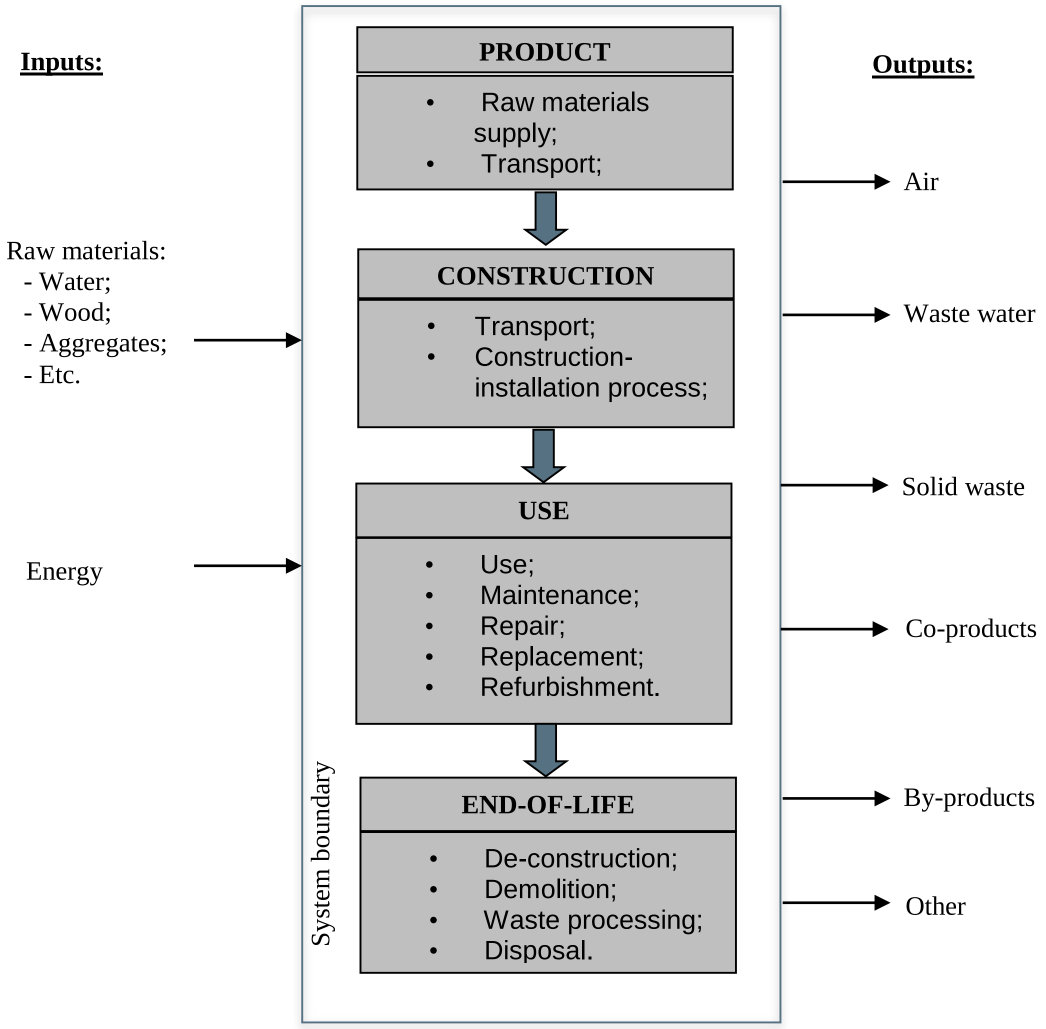

Figure 2.10.6. Schematic representation of building life cycle breakdown into elementary stages (CEN, 2011b).

ii) Inventory assessment

The life-cycle inventory entails the quantification of the flows for and from a product system. In traditional life-cycle environmental analysis, the inventory flows include inputs of water, energy and raw materials, and releases to air, land and water (Figure 2.10.7).

This phase is very time consuming, since it is often necessary to collect, from the companies, data associated with the production system. However, approximately 80% of the data that is needed for a common LCA analysis is already published (Pré-consultants, 2008).

One of the sources of information more accepted by the experts in LCA is the Ecoinvent database (Weidema et al., 2013). The latest version available of Ecoinvent (v3.1) contains life-cycle inventory data for over 4000 industrial processes, including energy supply, resource extraction, materials supply, chemicals, metals, waste management systems and transport services. Gabi datasets (Gabi, 2015) are another important source of average LCI data that is used in LCIA, namely at the European scale.

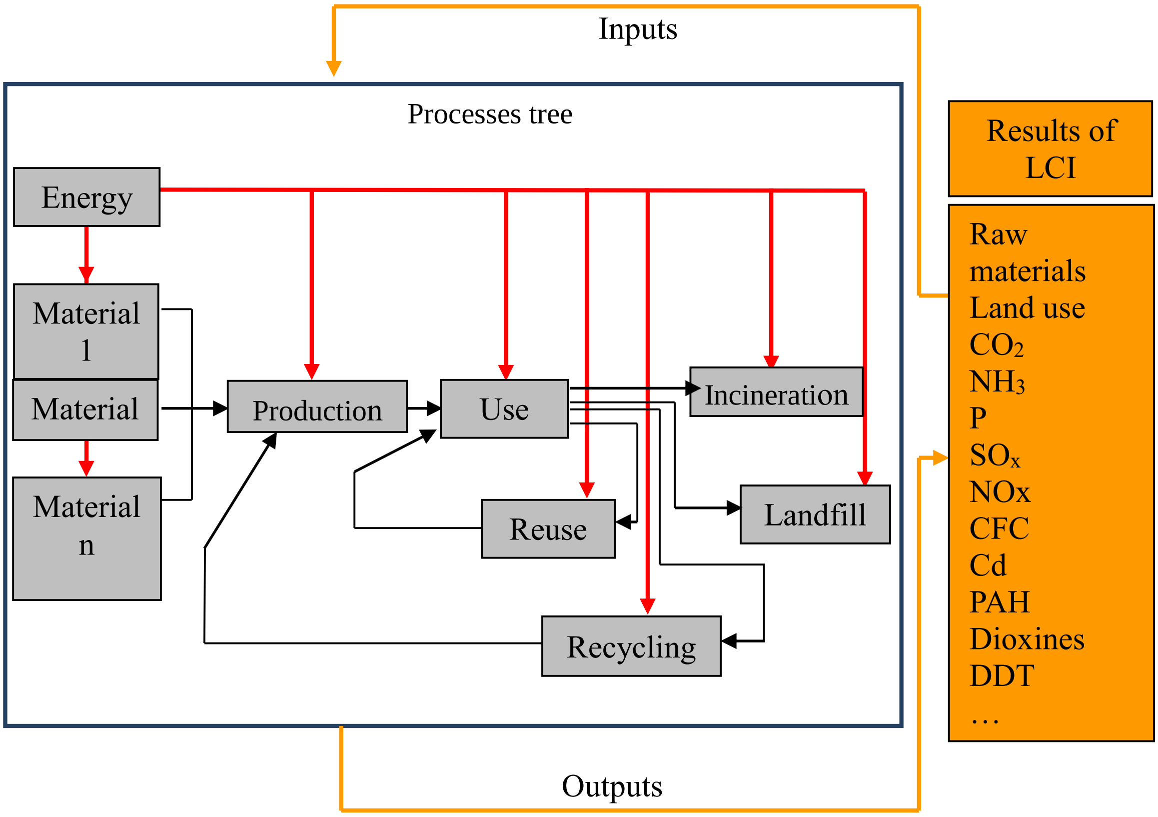

Figure 2.10.7. Schematic representation of the inventory stage of a LCA.

Besides the common building products, Ecoinvent datasets include average LCI data about solar thermal collectors and PVs, namely at the level of building-added systems and components. At this level, this database covers building-added solar thermal systems plus both building-added and building-integrated photovoltaic systems, but there is no data related to hybrid photovoltaic/thermal systems.

An analysis regarding the available LCI data related with solar systems can be found in the publication of Lamnatou et al. (2015a).

The Ecoinvent 3.1 database includes, for the several types of solar thermal collectors and systems (Figure 2.10.8): LCI data for system components; LCI data for complete systems and LCI data for delivered heat. The LCI data includes the production (i.e. materials, heat exchange fluid, copper pipes used in the installation of the system, water and energy used during production), delivery of the system parts with a van, mounting processes in the roof and disposal, but excludes auxiliary heating. The presented values are not from a specific installation or from a specific building-added STCs producer, but are based on the average LCI of the collectors and complete systems sold in Switzerland during a year and therefore they intended to represent the average technology that is currently available on the market. Although the context of the LCI data is Switzerland, since there are only slightly differences between the technologies used within the European countries it is possible to assume that these figures are valid at the European scale.

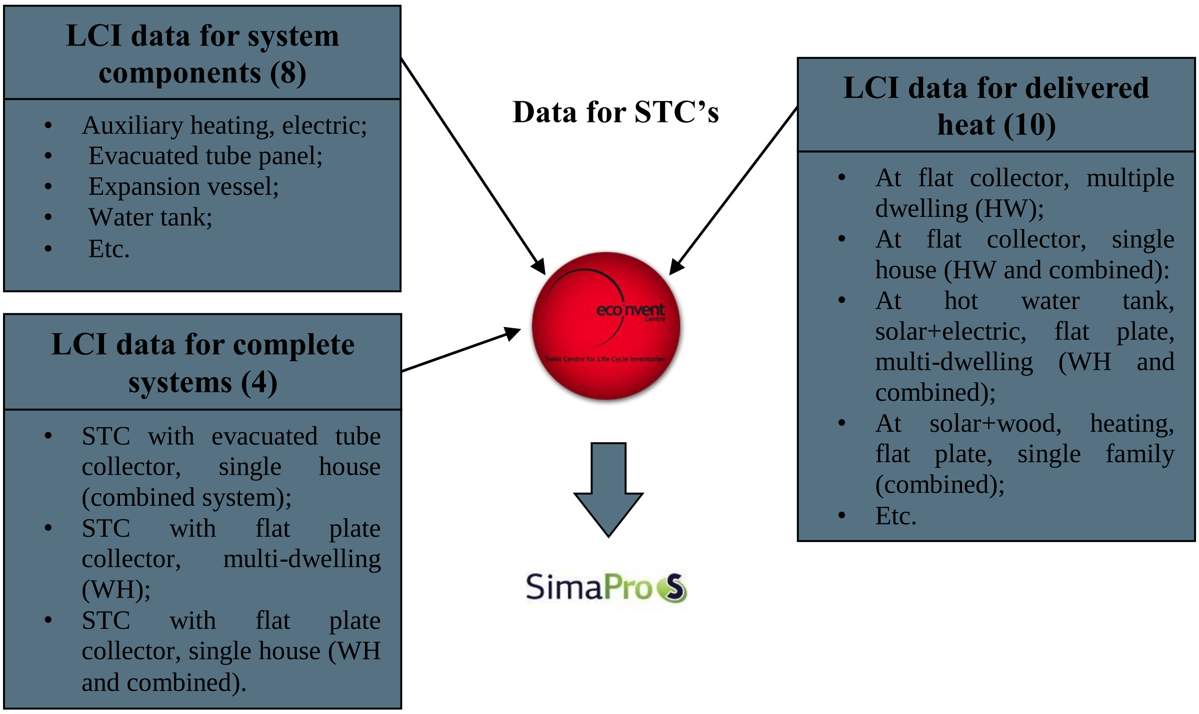

Figure 2.10.8. Schematic representation of the inventory stage of a LCA.

Regarding the inventory data related with the consumed energy, Ecoinvent also presents, for each energy vector, the inventory for each Mega Joule (MJ) of consumed energy.

iii) Life-cycle impact assessment

The Environmental Impact Assessment Methods (EIAM) comprise the analysis of the input and output of materials, of energy consumption and of emissions to the environment of a product over its life cycle and therefore are based on the life-cycle inventory. According to EN15978:2011 (CEN, 2011b) the results are expressed as indicators that represent the quantified environmental impacts and aspects caused by the building during its whole life cycle. This standard states that the assessment of the environmental performance of a building is based in 22 indicators, subdivided in the following four types (Table 2.10.1): i) indicators describing environmental impacts (7 indicators); ii) indicators describing resource use (8); iii) indicators describing waste categories (3); and iv) indicators describing the output flows leaving the system (4).

Analysing the current state-of-art in the field of life-cycle analysis of design alternatives at the scale of buildings (e.g. (Mateus & Bragança, 2011; Abd Rashid & Yusoff, 2015)), building components (e.g. (Pargana, 2014; Mateus et al., 2013)) or building technical systems (e.g. (Lamnatou, et al., 2015a; Lamnatou, et al., 2015b; Belussi et al. 2015)) it is possible to verify that for practicality most studies consider a limited set of indicators in the analysis rather than considering the complete list of the EN 15804:2012 (CEN, 2012c) environmental indicators.

Table 2.10.1. Indicators to be considered in the assessment of the environmental performance according to EN 15978:2011 (CEN, 2011b).

Type of indicators	**Indicator**	**Unit**
Indicators describing environmental impacts	Global warming potential, GWP	kg CO_2 equiv
	Depletion potential of the stratospheric ozone layer, ODP	kg CFC 11 equiv
	Acidification potential of land and water; AP	kg SO_2^- equiv
	Eutrophication potential, EP	kg $(PO_4)^{3-}$ equiv
	Formation potential of tropospheric ozone photochemical oxidants, POCP	kg Ethene equiv
	Abiotic Resource Depletion Potential for elements; ADP_elements	kg Sb equiv
	Abiotic Resource Depletion Potential of fossil fuels ADP_fossil fuels	MJ, net calorific value
Indicators describing resource use	Use of renewable primary energy excluding energy resources used as raw material	MJ, net calorific value
	Use of renewable primary energy resources used as raw material	MJ, net calorific value
	Use of non-renewable primary energy excluding primary energy resources used as raw material	MJ, net calorific value
	Use of non-renewable primary energy resources used as raw material	MJ, net calorific value
	Use of secondary material	kg
	Use of renewable secondary fuels	MJ
	Use of non-renewable secondary fuels	MJ
	Net use of fresh water	m^3
Indicators describing waste categories	Hazardous waste disposed	kg
	Non-hazardous waste disposed	kg
	Radioactive waste disposed	kg
Indicators describing the output flows leaving the system	Components for re-use	kg
	Materials for recycling	kg
	Materials for energy recovery (not being waste incineration)	kg
	Exported energy	MJ for each energy carrier

As already concluded by other authors (e.g. (Ortiz et al., 2009; Khasreen, 2009)) commonly used environmental impact categories in this type of studies are global warming potential, acidification, ozone depletion and eutrophication. Therefore, in the comparative analysis of the potential environmental impacts resulting from the implementation of STC, it is recommending that only type 1 group of indicators of this standard are considered. According to the EN 15978:2011 (CEN, 2011b), the impact assessment should involve seven midpoint environmental impact categories, i.e. global warming, ozone depletion, acidification of soil and water, eutrophication, photochemical ozone creation and depletion of abiotic resources (elements and fossil, separately). These environmental impact categories are assessed using the characterization factors of the CML-IA life-cycle impact assessment method (developed in the Netherlands by the Institute of Environmental Sciences (CML) of Leiden University).

In addition to these indicators, two additional environmental categories are normally considered (Table 2.10.2). These categories are calculated based on a single issue method, the Cumulative Energy Demand (CED) (Frischknecht et al., 2007). This method expresses the depletion of energy resources based on the higher heating value and, in fact this provides the calculation of six environmental categories (Monteiro & Freire, 2012) (non-renewable, fossil; non-renewable, nuclear; non-renewable, biomass; renewable, biomass; renewable, wind, solar, geothermal; renewable, water) which were grouped and presented in a simplified form in only two categories with the same unit (mega Joule—MJ): Non-renewable Cumulative Energy Demand (CEDNRE) and Total Cumulative Energy Demand (CEDTOT). According to several authors (e.g. (Ferreira et al., 2014)) these two indicators that describe the life-cycle energy consumption are of most importance in the comparison between different energy targets in building renovation.

Table 2.10.2. LCA method and declared unit that was used to quantify the environmental indicators.

Indicators	**Units**	**Methods**
Global warming potential (GWP)	[Kg CO2 $_{\text{equiv.}}$]	CML-IA baseline (v3.02)
Depletion of the stratospheric ozone layer (ODP)	[KgCFC-11 $_{\text{equiv.}}$]	CML-IA baseline (v3.02)
Acidification potential (AP)	[Kg SO2 $_{\text{equiv.}}$]	CML-IA baseline (v3.02)
Eutrophication potential (EP)	[Kg PO4 $_{\text{equiv.}}$]	CML-IA baseline (v3.02)
Formation potential of tropospheric ozone (POCP)		
Abiotic deplet. potential of fossil resources (ADP_{FF})	[Kg C2H4 $_{\text{equiv.}}$]	CML-IA baseline (v3.02)
Deplet. of abiotic resources-elements ($\text{ADP}_{\text{elements}}$)	[MJ $_{\text{equiv.}}$]	CML-IA baseline (v3.02)
Cumulative Energy Demand – non renewable (CED_{NRE})	[kg.SB $_{\text{equiv.}}$]	CML-IA baseline (v3.02)
Cumulative Energy Demand – total ($\text{CED}_{\text{TOTAL}}$)	[MJ $_{\text{equiv.}}$]	Cumulative Energy Demand (v1.09)
	[MJ $_{\text{equiv.}}$]	Cumulative Energy Demand (v1.09)

To facilitate the quantification of the environmental impacts, a life cycle analysis software (e.g. SimaPro or Gabi) is used to modulate the life cycle of the analysed renovation scenarios and to assess the abovementioned life cycle impact categories.

As an example, Table 2.10.3 presents the life-cycle impact assessment of building-added solar thermal collectors. Figures presented in this Table are not from a specific installation or building-added STCs producer. The values are based in the average LCI of the collectors and complete systems sold in the Switzerland during a year and therefore they intended to represent the average technology that is currently available on the market. Although the context of the LCI data is Switzerland, since there are only slightly differences between the technologies used within the European countries it is possible to assume that these figures are valid at the European scale. The functional unit of the values presented in Table 2.10.3 is 1 m^2 for the collectors and one piece for the solar thermal systems and they represent the typical system technology available in the Swiss market. A combined system is the one that is used at the same time for domestic hot water and for indoor spaces heating.

Table 2.10.3. Life-cycle impact assessment of Building-Added solar thermal collectors (Infrastructure) (source: Lamnatou, et al., 2015a).

Solar thermal collectors (Infrastru-cture)	**Life-cycle impact category**						**Embodied energy**	
	ADP	**GWP**	**ODP**	**AP**	**POCP**	**EP**	**ADP_FF**	**ERE**
Evacuated tube collector	6.74 E-01	9.03 E+01	8.42 E-06	7.81 E-01	3.26 E-02	6.55 E-01	1.48 E+03	1.38 E+02
Flat plate collector	6.81 E-01	1.02 E+02	9.69 E-06	9.76 E-01	5.00 E-02	6.65 E-01	1.52 E+03	2.56 E+02
Solar system, flat plate collector, multiple dwelling, hot water	7.00 E+01	1.02 E+04	1.47 E-03	8.44 E+01	5.21 E+00	6.24 E+01	1.60 E+05	1.85 E+04
Solar system, flat plate collector, one-family house, hot water	9.83 E+00	1.33 E+03	1.35 E-04	8.77 E+00	6.24 E-01	5.93 E+00	2.13 E+04	2.65 E+03
Solar system, flat plate collector, one-family house, combined system	1.95 E+01	2.84 E+03	3.52 E-04	1.98 E+01	1.34 E+00	1.39 E+01	4.35 E+04	5.29 E+03
Solar system with evacuated tube collector, one-family house, combined system	1.77 E+01	2.35 E+03	3.06 E-04	1.58 E+01	1.03 E+00	1.25 E+01	3.90 E+04	3.68 E+03

2.10.3.2 Modelling the life-cycle of buildings with added or integrated solar thermal collectors

Modelling the life-cycle of a solar thermal collector is a process that is normally integrated in the whole life-cycle assessment of a building. The whole life-cycle analysis is based in the quantification of the materials and energy flows and the physical boundary includes, as presented in Figure 2.10.9 (Lamnatou, et al., 2015a):

- Construction element: It includes the materials used for the external (roof, windows, etc.) and the internal (internal wall, etc.) building fabrics. A construction element is made of one or more materials. Each material corresponds to a material layer. Examples of a construction element: roof, external wall, window, internal partition.

- Building Integrated (BI) solar thermal systems: BI solar thermal systems are made of different systems, such as the heating or the ventilation systems. Each system is made of components (boiler, pump, etc.) and each component is made of materials and may consume energy. Solar thermal collectors and also PV systems are included in this context.

- Other building systems: It includes, besides the BI solar thermal system, the installed technical equipment to support the operation of a building, as defined in EN 15978:2011 (CEN, 2011b) (e.g. artificial lighting, elevators, etc.).

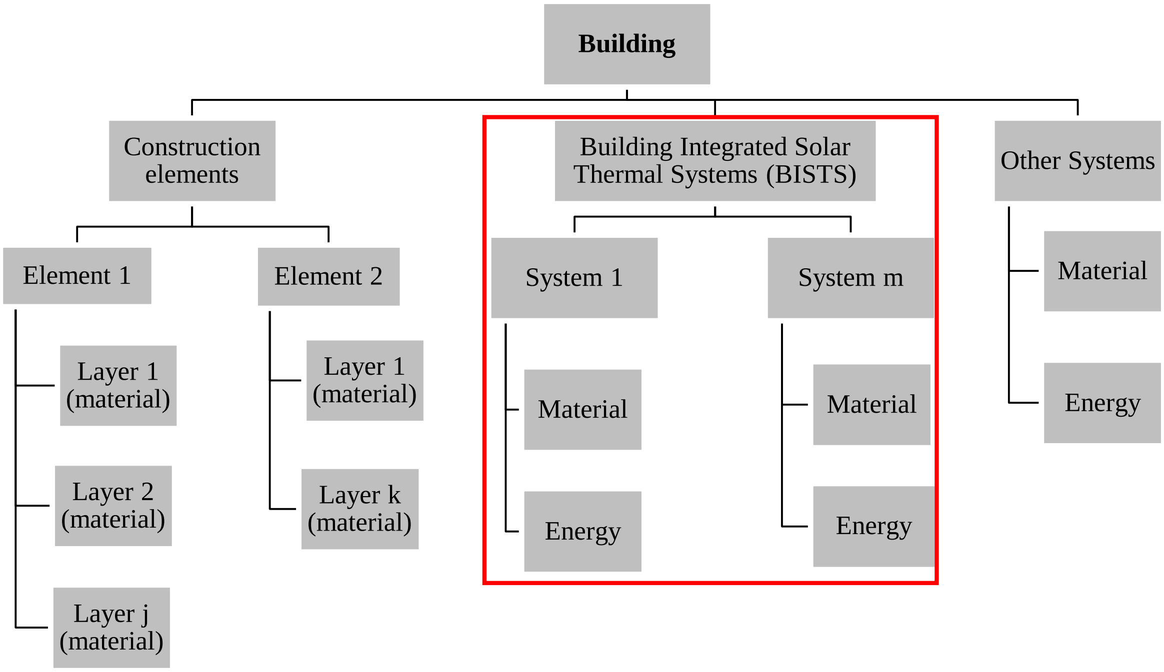

Figure 2.10.9. Structure of the building model used for LCIA.

In order to assess the whole life-cycle environmental impacts and the contribution of the BI solar thermal system to the environmental impacts and benefits, the following processes must be included in the LCIA (Lamnatou, et al., 2015a):

- Materials used for construction elements and BI solar thermal system components. It should include the materials added (or replaced) during the construction or renovation of a building. The stages corresponding to the manufacturing, maintenance replacement and elimination of these materials must be included in the calculation. It also includes materials added for energy generation or harvesting (e. g. solar collectors, PVs, heat pump). The LCIA is influenced by the service life of the construction materials and the BI solar thermal component and therefore it should be defined. A longer service life can compensate a higher environmental impact;

- Energy consumed by BI solar thermal system: This includes the energy used by the BI solar thermal system to fulfill its requirements (heating, cooling, domestic hot water production, etc.) during building operation stage;
- The energy delivered inside and outside the building system and produced at the building scale by the BI solar thermal system: necessary to calculate the benefits and loadings both at and beyond the system boundary. The benefits and loadings beyond the system boundary are calculated when the building integrates a system for in-situ energy production that produces energy that it is exported outside the system boundary.

As presented in Figure 2.10.10, a typical LCA study about BI solar thermal system includes the following stages: extraction of raw materials, production of the components, system assembling, system operation (including energy delivery inside and outside the building boundary) and maintenance, system disposal and all transportations that take place in the different life-cycle stages.

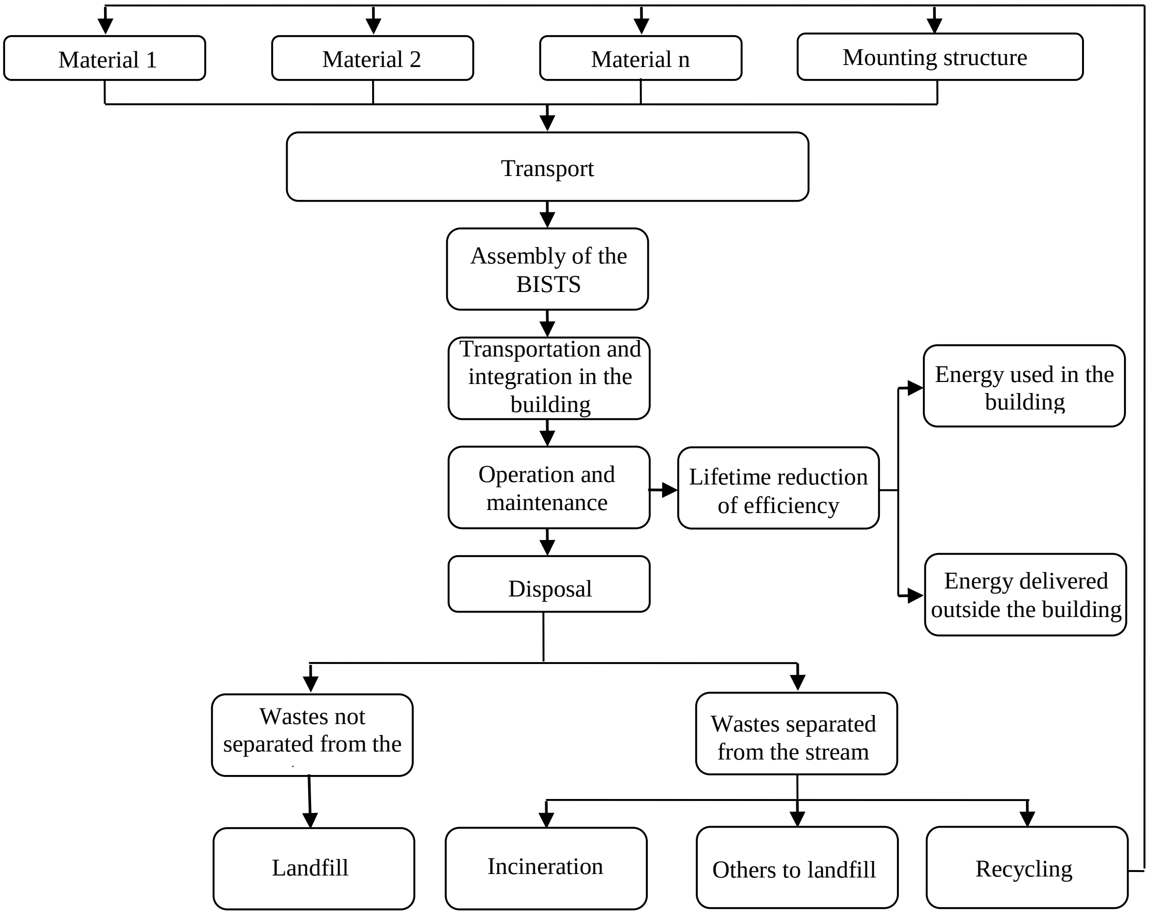

Figure 2.10.10. Structure of the building model used for LCIA.

2.10.4 Case study

2.10.4.1 Goal and scope

In order to present the environmental benefits resulting from the implementation of a Solar Thermal Collector (STC) in an energy renovation of a dwelling, two renovation scenarios will be presented. This study is also aimed to present the differences in the results from using data for the average European STC technology and for a tailored (specific) STC. This study is intended at assessing the contribution of the STC in the energy balance to produce the Domestic Hot Water (DHW) and therefore the effect of other active and passive energy renovation principles will not be considered.

The lifetime considered for the renovation project is 40 years and therefore the cumulative environmental impacts for this operation period will be considered together with the embodied impacts of the used equipment. Following the recommendations from other studies (e.g. (Monteiro da Silva et al., 2016)), a lifetime of 20 years is considered for the equipment used (STC, heat pump and light oil boiler).

2.10.4.2 Methodology

i) Life–cycle impact assessment

The methodology used in this study uses it is according to the EN 15978:2011 (CEN. 2011b). Nevertheless, rather than considering all indicators presented in this standard, this is focused in the three main environmental indicators are considered in this study: Total Cumulative Energy Demand (CED_{TOT}), non-Renewable Cumulative Energy Demand (CED_{nRE}) and Global Warming Potential (GWP). Table 2.10.4 presents the LCA method and the declared unit that was used to quantify the environmental indicators.

Table 2.10.4. LCA method and declared unit that was used to quantify the environmental indicators.

Indicators	Units	Methods
Global warming potential (GWP)	[Kg $CO_{2\ equiv.}$]	CML-IA baseline (v3.02)
Cumulative Energy Demand – non-ren. (CED_{NRE})	[MJ $_{equiv.}$]	Cumulative Energy Demand (v1.09)
Cumulative Energy Demand – total (CED_{TOTAL})	[MJ $_{equiv.}$]	Cumulative Energy Demand (v1.09)

The impacts resulting from the end-of-life stage are simulated using a scenario were: i) materials resulting from the dismantling of the systems are transported for an average distance of 50km; ii) 95% of the aluminium and glass are recycled and the remaining materials are placed in a landfill; iii) and the glycol is incinerated. In order to facilitate the life-cycle assessment process, a life-cycle analysis software (SimaPro 8.0.5) was used to modulate the life-cycle of the analysed renovation scenarios and to assess the abovementioned life-cycle impact categories.

ii) Quantification of the energy needs for DHW

The calculations of the energy needs followed the methodology of the Portuguese regulation for the thermal performance of residential buildings (Portugal, 2013) which is based on the quasi-steady state method presented in ISO 13790:2008 (ISO, 2008). The Portuguese thermal regulation provides the values of the degree-days and uses the envelope heat balance method for the calculation of heating needs. With regard to cooling needs, it uses the average difference between indoor-outdoor temperature and the envelope heat balance during the cooling period. The energy used for Domestic Hot Water (DHW) preparation is calculated according to the reference DHW consumption: 40 litres per person and per day, heated at 60ºC.

The primary energy was calculated considering the conversion factors of 2.6 kWhPE/kWh for electricity and 1 kWhPE/kWh for natural gas, biomass and thermal energy from solar systems. For the calculation of the non-renewable primary energy, the contribution of the on-site renewable energy systems (solar thermal) is deducted from the total amount of primary energy use, which is according to Portuguese regulation.

2.10.4.3 Description of the building and energy renovation scenarios

i) Existing scenario

The building is a four-bedroom single-family dwelling located in the city of Porto, North of Portugal (Figure 2.10.11). According to the Köppen classification, this building is located in a Warm-summer Mediterranean climate (Csb). In this city, the average annual sum of the horizontal solar irradiation is around 1600 kWh/m^2 (Figure 2.10.12). The dwelling does not have any obstacles nearby to obstruct the access of the sun, which highlights the location's high potential to harvest solar radiation.

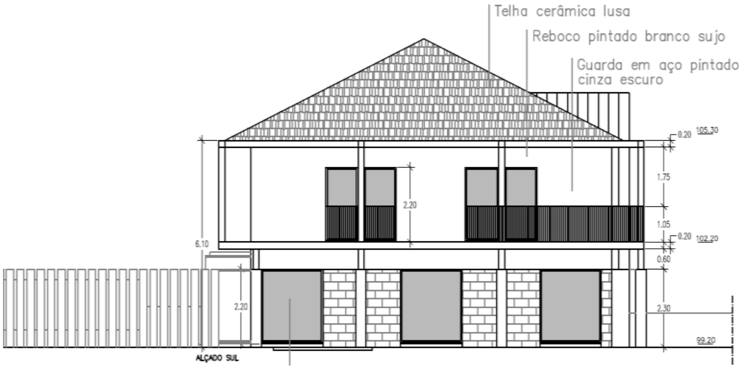

Figure 2.10.11. Main facade of the case study (facing south).

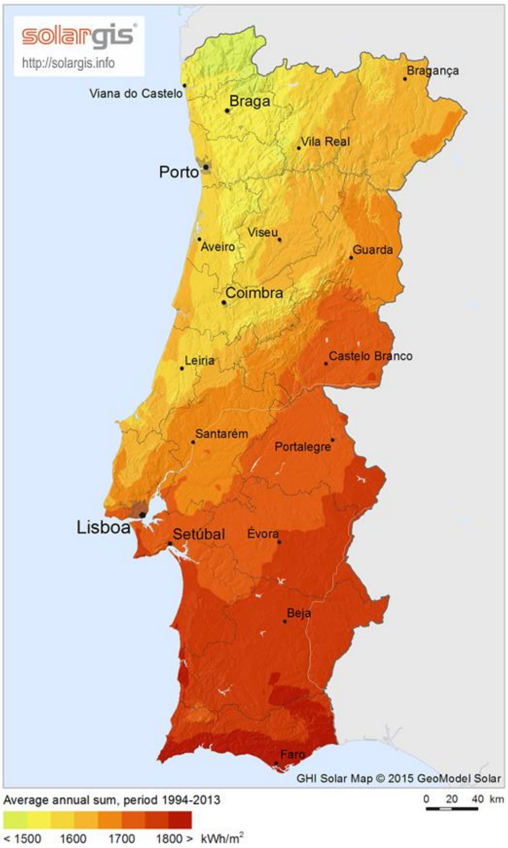

Figure 2.10.12. Global Horizontal Irradiation (GHI) in Portugal (source: solargis.com).

Before the renovation, the building used a non-modulating and non-condensating light oil boiler with an efficiency of 94% as a DHW heating system. The delivered energy to heat the hot water is 1912 kWh/m^2.

ii) Implementation of a conventional STC – Scenario 1

In this scenario, the light oil boiler is replaced by a conventional solar thermo-symphonic flat plate collector, assisted by an auxiliary heat pump. Conventional means that the used STC is built up with the average technology used across Europe. Therefore, the inventory data for a system like this was extracted from the Ecoinvent 3.1 database.

According to the Portuguese thermal code for residential buildings (Portugal, 2013), the STCs to be considered in new buildings or major energy renovations must produce the same energy as a conventional/reference flat solar thermal system with an area equal to the number of bedrooms plus 1 m^2. Therefore, 5 m^2 of solar thermal collectors is considered in this study and the system is designed to provide 65% of the DHW's energy needs. The remaining energy is provided by an air-water heat pump with a Coefficient of Performance (COP) of 3. The flat plat collectors are connected to a water tank that has a capacity of 300 litres.

iii) Implementation of a specific STC – Scenario 2

In this scenario, it is considered that the DHW is produced by a new type of solar thermal collectors that are being designed and the auxiliary heat by an air-water heat pump with a COP of 3. The solar thermal installation has 5 m² of flat plate collectors and yearly covers

80% of the energy needs. The heat pump provides the rest of the necessary energy. In this scenario the flat plat collectors are connected to a 300 litres water tank placed inside the house that is connected to a recirculation pump.

2.10.5 Results

2.10.5.1 Life-cycle inventory

The systems in the existing and scenario 1 are considered to be conventional. Therefore, the life-cycle inventory regarding the embodied materials (type and amount of materials) and embodied energy used to manufacture both systems were based in the EcoInvent 3.1 database. In the considered lifetime, systems are replaced once, on year 20. Regarding the transportation, mounting on the building and maintenance impacts, those were considered to be the average ones defined in the used life-cycle inventory database.

Regarding the operation stage,

Table 2.10.5 presents the amount of delivered energy used for the hot water preparation and the energy vector used in the existing scenario. Table 2.10.6 presents the data considered for scenario 1.

Table 2.10.5. Amount of delivered energy used for the hot water preparation and the energy vector used in the existing scenario.

Consumer	Delivered energy (kWh/year)	Vector	Covers (%)	Efficiency (%)
Domestic hot water	1912	Light fuel oil	100	94

Table 2.10.6. Amount of delivered energy used for the hot water preparation and the energy vector used in scenario 1.

Consumer	Delivered energy (kWh/year)	Vector	Covers (%)	Efficiency (%)
Domestic hot water	1912	Electricity	35	3
		Solar thermal	65	-

In scenario 2, since it uses a new type of STC, a specific inventory related to the type and amount of materials used to manufacture the STC was carried out. The inventory of materials used to manufacture the flat plate collectors and the water tank are presented in Table 2.10.7.

Table 2.10.7. Materials used to manufacture the solar collector and the water tank implemented in scenario 2.

	Material	Quantity (kg)
Solar collector	Aluminium sheet (primary aluminium)	15.40
	Flat glass	14.20
	Copper tube	5.10
	Mineral wool	2.31
	Polyester	0.17
Water tank	Chromium steel	28.00
	Mineral wool	8.20
	Copper tube	11.30
	Tube insulation (elastomer)	3.60
	Propylene glycol	2.90

Regarding the inventory related with the assembly of materials to manufacture the new STC system, since this system is still in an early stage of development, it is not possible to use specific data related to the manufacture process. Therefore, a scenario considering these impacts equivalent to 30% of those related with the used materials was considered. This figure is similar to the one set by the EcoInvent 3.1 database for conventional STC systems and was used by other authors in similar studies (e.g. (Lamnatou, et al., 2015b)).

For the transportation stage, from the factory to the construction site, a scenario considering that the system is transported in an average distance of 50 km using a light van was used. Regarding the impacts resulting from the mounting processes in the construction site, a scenario considering it equivalent to the ones resulting from the consumption of 1 kWh of electricity was used. As an example other studies, consider these impacts equivalent to 3% of the material's embodied impacts (e.g. (Lamnatou, et al., 2015b)). Due to the lack of data, the maintenance impacts were not considered in this scenario.

Table 2.10.8. Amount of delivered energy used for the hot water preparation and the energy vector used in scenario 2.

Consumer	Delivered energy (kWh/year)	Vector	Covers (%)	Efficiency (%)
Domestic hot water	1912	Electricity	20	3
		Solar thermal	80	-

2.10.5.2 Life-cycle impact assessment

Table 2.10.9 presents for each considered scenario the results from the quantification of the environmental indicators. Figure 2.10.13 and Figure 2.10.14 present, respectively, the life-cycle cumulative energy demand and global warming potential of each renovation scenario.

Table 2.10.9. Results from the quantification of the environmental indicators.

Scenario	**CED_Tot (MJ)**	**CED_nRE (MJ)**	**GWP (Kg.eq. CO_2)**
Before renovation	404 517.50	400 800.50	26 800.00
Scenario 1	175 780.50	164 500.50	12 200.00
Scenario 2	174 982.50	146 508.60	12 600.00

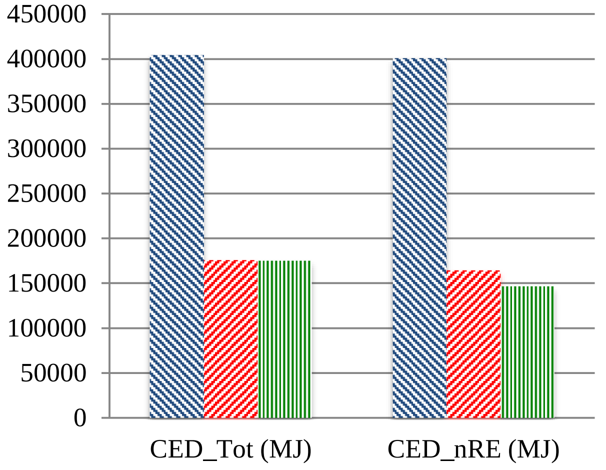

Figure 2.10.13. Life-cycle cumulative energy demand (Total – CED_Tot and non-Renewable – CED_nRE) of each scenario.

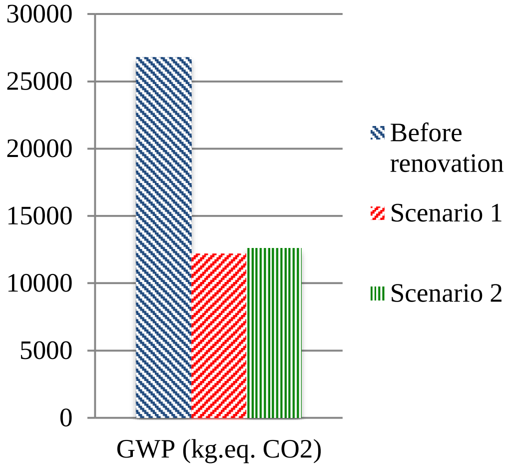

Figure 2.10.14. Life-cycle global warming potential (GWP) of each scenario.

2.10.5.3 Discussion of results

From the analysis of results obtained in section 2.10.5.2 it is possible to conclude that in the city of Porto, Portugal, the implementation of solar thermal collectors in the replacement of conventional hot water production systems is a very good option to reduce the potential life-cycle environmental impacts of a residential building. For a four-bedroom residential building, a solar system that covers around 65% of the energy needs to heat the water and that uses a heat pump as an auxiliary heating source, will have a potential to reduce both the life-cycle cumulative energy demand and CO_2 emissions in around 55%.

Results also show a very small difference from the life-cycle impact assessment results obtained from the use of generic inventory data or specific inventory of materials used in a STC system. This allows the conclusion that in an early design stage of both a new building or energy renovation scenario, it is suitable to use generic (average) European life-cycle inventory data to assess the embodied impacts of solar systems and to support decision making towards the choice of the most energy efficient solution.

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COST Action TU1205 - An Overview

Energy use in buildings represents 40% of the total primary energy used in the EU and therefore developing effective energy alternatives is imperative. Solar thermal systems (STS) will have a main role to play as they contribute directly to the heating and cooling of buildings and the provision of domestic hot water. STS are typically mounted on building roofs with no attempt to incorporate them into the building envelope, creating aesthetic challenges and space availability problems. The Action will foster and accelerate long-term development in STS through critical review, experimentation, simulation and demonstration of viable systems for full incorporation and integration into the traditional building envelope. Viable solutions will also consider economic constraints, resulting in cost effective Building Integrated STS. Additionally, factors like structural integrity, weather impact protection, fire and noise protection will be considered. The most important benefit of this Action is the increased adoption of RES in buildings. Three generic European regions are considered; Southern Mediterranean, Central Continental and Northern Maritime Europe, to fully explore the Pan-European nature of STS integration. The Action consortium presents a critical mass of European knowledge, expertise, resources, skills and R&D in the area of STS, supporting innovation and conceptual thinking.

Domain: Transport and Urban Development (TUD)

Action Webpages: http://www.tu1205-bists.eu/ & http://www.cost.eu/COST_Actions/tud/Actions/TU1205

Countries participating: Austria, Belgium, Bulgaria, Cyprus, Denmark, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Lithuania, Malta, Netherlands, Poland, Portugal, Romania, Serbia, Spain, Turkey, United Kingdom.

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