Ca' Foscari University of Venice

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Final Thesis

"Development of a tool-CF: a decision-support calculator to assess the impact of different suppliers."

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SUMMARY

Climate change arising from anthropogenic activity has been identified as one of the greatest challenges facing the world and will continue to affect business and citizens over future decades. Climate change has implications for both human and natural systems and could lead to significant impacts on resource availability, economic activity and human wellbeing. The growing environmental impacts of the last century brought communities and governments to start considering the protection of the environment and its goods and services in world policies with the goal of achieving a sustainable way of life. It is indeed fundamental to focus on the next generation way of living to ensure that current generation reduce as more as possible their environmental impacts: the complex relationships between environment and society have evolved over time, but only in recent decades they become increasingly relevant, due to the persisting influence of human activities on the surrounding environment. This has been the starting point of the development of a series of environmental indicators measuring the concrete impact of the human's activities and the Carbon Footprint (CF) represents a method used to measure the impact, in terms of CO2eq, of anthropogenic activities on the environment. In this thesis, which is based on the analysis of a project developed by a customer company of Ambiente Italia Srl, the Carbon Footprint is used to measure the impact of choosing material suppliers to produce a specific type of photovoltaic panel. Specifically, the carbon footprint method has been implemented through a calculator, namely tool-CF, built in an Excel workbook, able to calculate the amount of emissions generated, in kgCO2eq, by the suppliers involved in providing materials for the module production. The elaboration is indeed based on the "cradle to gate" Life Cycle Assessment approach which means considering the process till the factory "gate": the analysis comprehends the activities from the extraction of raw materials to the production of the photovoltaic module. The Excel file is organised specifying all the steps considered and to fulfil this approach it is divided in three sheets, specifically "Data Entry", "Impacts" and "Results", all linked and built in an easily way to fill in. A user procedure document has been then developed for the proper use of this tool-CF in which all the steps for calculating the carbon footprint are described in detail.

SOMMARIO

I cambiamenti climatici derivanti dall'attività antropica sono stati identificati come una delle maggiori sfide che il mondo deve affrontare ed è riconosciuto che continueranno ad influenzare aziende e la popolazione nei decenni futuri. I cambiamenti climatici hanno implicazioni sia per i sistemi umani che per quelli naturali e potrebbero avere un impatto significativo sulla disponibilità delle risorse, sull'attività economica e sul benessere umano. I crescenti impatti ambientali del secolo scorso hanno portato comunità e governi ad iniziare a considerare la protezione dell'ambiente e dei suoi beni e servizi nelle politiche mondiali per raggiungere uno stile di vita sostenibile. È infatti fondamentale concentrarsi sullo stile di vita della prossima generazione per garantire che quella attuale riduca il più possibile il proprio impatto ambientale: le complesse relazioni tra ambiente e società si sono evolute nel tempo, ma solo negli ultimi decenni sono diventate sempre più rilevanti, a causa della persistente influenza delle attività umane sull'ambiente circostante. Questo è stato il punto di partenza per lo sviluppo di una serie di indicatori ambientali che misurano l'impatto concreto delle attività umane e l'Impronta di Carbonio (Carbon Footprint) rappresenta un metodo utilizzato per misurare l'impatto, in termini di CO_2eq, delle attività antropiche sull'ambiente. In questa tesi, che si basa sull'analisi di un progetto sviluppato da un'azienda cliente di Ambiente Italia Srl, la Carbon Footprint viene utilizzata per misurare l'impatto della scelta dei fornitori del materiale necessario per la produzione di una specifica tipologia di pannello fotovoltaico. In particolare, il metodo dell'Impronta di Carbonio è stato implementato in un calcolatore, il tool-CF, costruito in un foglio di lavoro Excel, in grado di calcolare la quantità di emissioni generate, in kgCO2eq, dai fornitori coinvolti nella fornitura dei materiali per la produzione dei moduli. L'elaborazione è infatti basata sull'approccio Life Cycle Assessment "dalla culla al cancello" (cradle to gate), ovvero considerando il processo fino al "cancello" della fabbrica: l'analisi comprende le attività dall'estrazione delle materie prime alla produzione del modulo fotovoltaico. Il file Excel è organizzato specificando tutte le fasi considerate e per adempiere a questo approccio è suddiviso in tre fogli, nello specifico "Data Entry", "Impatti" e "Risultati", tutti collegati e costruiti in modo da essere facilmente compilabili. Per un utilizzo corretto di questo tool-CF è poi stato sviluppato un documento di procedura di utilizzo in cui sono descritti in dettaglio tutti i passaggi per il calcolo dell'Impronta di Carbonio.

RATIONALE AND GOALS

In a world threatened by climate change, the need to safeguard the environment and build an environment-friendly society has emerged from several decades now. In order to achieve this, the concepts of sustainability and sustainable development have become pillars of today's way of thinking and they find their application in the society, in the economy and in the environmental protection. Thus, sustainable development and concern for the environment represent two issues that must be considered by companies. From here, the necessity to assess a company's impact becomes increasingly important. Indeed, assessing the greenhouse gas emissions is nowadays a fundamental method included in the strategy of the companies which want to pursue the path of sustainability and be competitive on the market. Moving in this direction means, indeed, assessing the life cycle of products, organizations, and services, estimating their impact in CO_2eq and developing effective strategies to reduce it since this is necessary not only to offer quality products, but also to demonstrate care for the environment. In this context, the most valid and widely applied mean of obtaining a products' impact is the Carbon Footprint (CF) method. This allows companies not only to calculate their impacts but also, as a result, to improve their business strategy.

In this sense, the case-study requires the need to create a logical calculator, namely a tool-CF, that could guide the customer company in choosing its suppliers based on their different impacts. This thesis work aims firstly to describe the LCA method in its generality and then to deepen and dwell on the Carbon Footprint method. Subsequently, the explanation of what is the main focus of this thesis work, namely the tool-CF, will take place. The aim is to design a tool that can guide the customer company in a flexible but accurate way in the process of objectively and strategically choosing suppliers. This will be allowed using different tools and methodologies implemented within the thesis work through a structured and logical roadmap. In particular, the decision-making framework aims at helping the company in the assessment of suppliers' impacts and in the adoption and implementation of different sustainability strategies in the selection of suppliers. It is not possible to apply the tool with data provided by the customer company since they represent intern and private data, therefore they cannot be used. Thus, the tool's explanation will be followed by an example of the tool application, with data true to reality, which will be implemented to verify the functionality and possible limits of the calculator.

STRUCTURE

This thesis project has been structured in 5 chapters: Introduction of LCA and CF method (chapter 1), Materials and methods (chapter 2), Results and discussion: example of tool-CF application (chapter 3), and Conclusions (chapter 4).

In the first chapter, the LCA methodology is presented, including its origins, the history of ISO standards and the 4 phases from which it is composed. Then, an accurate explanation of the Carbon Footprint and especially the Carbon Footprint of product is given.

The second chapter covers materials and methods and includes an explanation of all the work done at Ambiente Italia Srl to develop the tool-CF for the case study.

The third chapter describes an example of the tool application using data that are true to reality and not data of the customer company for privacy reasons. Moreover, it includes the explanation of the results obtained and the relative discussion.

Finally, the fourth chapter presents conclusions regarding the entire thesis work.

1. INTRODUCTION OF LCA AND CF METHODS

In the first chapter of this thesis, an introduction of the LCA and CF methods will be developed. Starting from explaining what a Life Cycle Assessment is and how it is structured, the Carbon Footprint of the product, an assessment tool based on the LCA methodology, is analysed in detail. Indeed, the Carbon Footprint will be the impact assessment tool for the case study of this thesis work.

1.1 Framing of the Life Cycle Assessment (LCA) method

In a time when it is increasingly necessary to adopt a pro-sustainability lifestyle, the circular economy (CE) is a key concept in making the most of resources and minimizing waste, recovering as many materials as possible to put them back into the production cycle: the core defining element of the CE is the "restorative use" of resources (Geisendorf S., 2017). Here, then, is how switching from the linear economy concept to the circular one, which is based on the life cycle thinking, benefits the environment, society, and the economy. The main operational tool of the life cycle thinking is the Life Cycle Assessment (LCA) (Toniolo R. J., 2020) which represents one of the fundamental tools for the implementation of an Integrated Product Policy, policy which wants to reduce the environmental impact of products and services throughout their life cycle (https://www.isprambiente.gov.it): life cycle perspective is intrinsically inherent to the greening of the product development process (Zanni S. et al, 2020). LCA is defined by ISO (International Standard Organisation) 14040:2006, standard last reviewed and confirmed in 2022, as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (Fig. 1) (ISO, 2006).

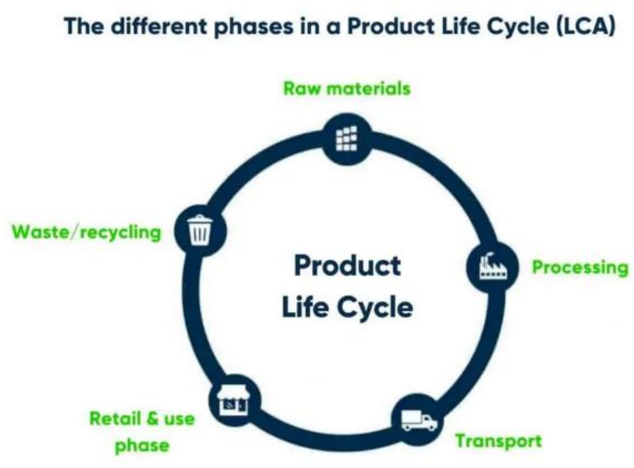


Fig. 1 Product life cycle (www.ecochain.com)

Internationally, the LCA methodology is governed by ISO 14040 and ISO 14044 standards under which a life cycle assessment study involves, as described by Figure 2: defining the objective and scope of the analysis, compiling an inventory of the inputs and outputs of a given system, assessing the potential environmental impact related to those inputs and outputs, and finally interpreting the results.

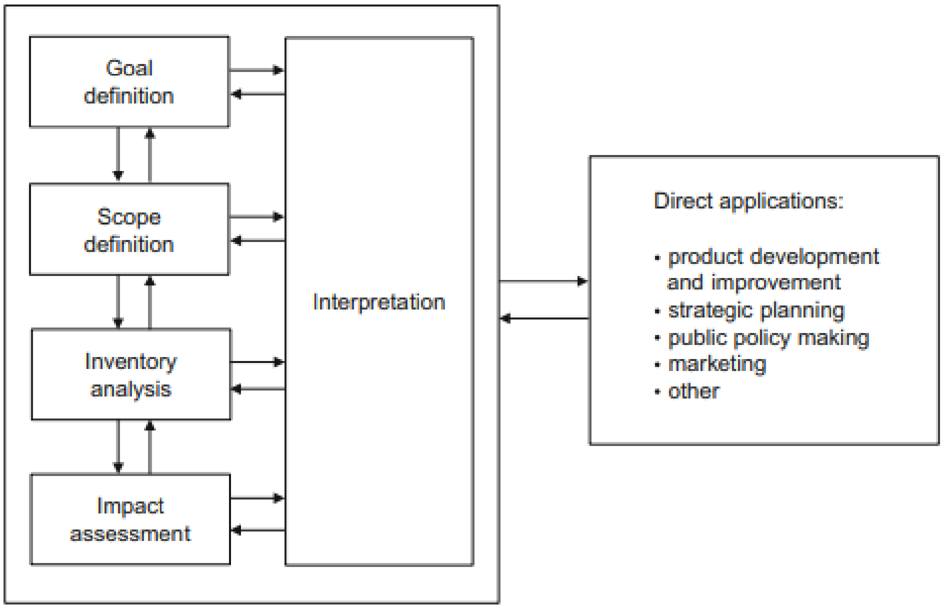


Fig. 2 Framework of LCA modified from the ISO 14040 standard (Rosenbaum R. K., 2018)

Thanks to its characteristics, LCA is used to improve production and service processes as well as to support the decision-making process in industry, government, or nongovernment organizations; to select indicators of environmental performance; and to implement eco-labelling and make environmental claims (Ren J., 2020). Furthermore, in LCA, the comprehensive coverage of processes over the life cycle is complemented by a comprehensive coverage of environmental issues: it does not focus exclusively on climate change, which generally receives most attention, but it covers a broad range of environmental issues, considering additionally (Bjorn et al., 2018):

- Stratospheric ozone depletion
- Acidification (terrestrial, freshwater)
- Eutrophication (terrestrial, freshwater, marine)
- Photochemical ozone formation
- Ecotoxicity (terrestrial, freshwater, marine)
- Human toxicity (cancer, non-cancer)
- Particulate matter formation

- Ionising radiation (human health, aquatic and terrestrial ecosystems)
- Land Use (biotic productivity, aquifer recharge, carbon sequestration, albedo, erosion, mechanical and chemical filtration capacity, biodiversity)
- Water use (human health, aquatic ecosystems, terrestrial ecosystems, ecosystem services)
- Abiotic resource use (fossil and mineral)
- Biotic resource use (e.g., fishing or wood logging)
- Pathogens

Another important aspect of LCA is that it is a quantitative tool: it can be used to compare environmental impacts of different product systems and processes. Thus, this allows to judge which products or systems are better for the environment or to point to the processes that contribute the most to the overall impact and therefore should receive attention (Klopffer W., Grahl B., 2014). Generally, quantifications aim for the "best estimate", meaning that average values of parameters involved in the modelling are consistently chosen. Finally, the quantification of potential impacts in LCA is rooted in natural science: the models of the relationships between emission (or resource consumption) and impact are based on proven causalities (Bjorn et al, 2018).

1.1.1 Origins of the LCA method

The scientific community started to place greater interest on environmental care in the second half of the past century when after the second world war the economic regrowth became essential and environmental degradation and in particular the limited access to resources started becoming a concern. The first concrete step towards environmental safeguard was taken in 1987 when the Brundtland Commission published the Brundtland report also known as "Our Common Future" where the 'sustainable development' was firstly defined. This step marked the beginning of the sustainability era since the report stated that "humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs" as the definition of sustainable development (WCED, 1987): from now on, the three pillars such as environment, society and economy represent the triple bottom line of the sustainability approach. To ensure what the Brundtland report stated, switch from a linear economy to a circular one developing sustainable production and consumption systems through a life cycle thinking has become the right action to implement in a too much waste world. However, the precursors of today's LCA, the life-cycle-oriented methods, were developed in the 1960s when scientists were concerned about the rapid depletion of fossil fuels. They were designed in US and Northern Europe in collaboration between universities and industry, and they were known as *Resource and Environmental Profile Analysis (REPA)* or Ecobalances: they could be characterised as material and energy accounting and were inspired by material flow accounting, as they were focused on inventorying energy and resource use (crude oil, steel, etc.), emissions and generation of solid waste, from each industrial process in the life cycle of product systems (Bjorn A. et al, 2018). In the early 1970s, LCA was focused mainly on energy and raw materials, later on emissions, air emissions, water emissions and solid waste were included in the calculation. Then, in the late 1970s and early 1980s, the "environmental problem" shifted to issues related to hazardous waste management. In 1990 during the SETAC (Society of Environmental Toxicology and Chemistry) conference in Vermont there was the first LCA analysis divided into three main phases: inventory, in which data describing the system are collected and converted into a standard format to provide a description of the physical characteristics of the system of interest; interpretation, in which physical inventory data are linked to observable environmental problems and improvement in which the system is modified in some way to reduce or improve observed environmental impacts (Ren J., 2020). Through the rest of the 1990s SETAC working groups in Europe and North America further discussed the methodological elements with particular focus on inventory modelling and life cycle impact assessment, regularly publishing their recommendations in SETAC working group reports presenting the agreed state of the art and delivering recommendations for further research. The working groups helped coordinate the method development and strengthen the collaboration between the different research teams developing the LCA methods and they played an important role in the strong developments in LCA methodology through the 1990s.

Thus, a series of international organizations have played and are playing a fundamental role in the development and application of LCA:

- SETAC (Society of Environmental Toxicology and Chemistry). SETAC is the international scientific forum for LCA;

- ISO (International Standardization Organization). ISO has produced standards for LCA (ISO 14040-14044) that have increased the credibility of this tool;

- UNEP (United Nations Environmental Program). UNEP has always promoted the development and application of LCA, for example through the life cycle initiative;

- EC (European Commission). The EC stimulates the harmonization of LCA through the "European Platform on LCA" which is part of the JRC in Ispra.

Considering the historical analysis just performed, it can be said that the Life Cycle Assessment (LCA) methodology was born to face the need for methods for understanding and addressing environmental protection and the impacts of products. In other words, it was born to provide information to show the effects of an activity on the environment and to identify opportunities for making changes to reduce the environmental impacts (Ren J., 2020).

1.1.2 History of ISO standards

ISO (International Organization for Standardization) is an independent, non-governmental international organization with a membership of 16 national standard bodies (https://www.iso.org). Through its members, it brings together experts to share knowledge and develop voluntary, consensus-based, market relevant International Standards that support innovation and provide solutions to global challenges.

Firstly, LCA methodology was defined by four original standards 14040–43: ISO 14040:1997, ISO 14041:1999, ISO 14042:2000, ISO 14043:2000, which were an important step to consolidate procedures and methods of LCA (Finkbeiner et al. 2006). At that time, ISO 14040:1997 defined LCA as the "study of the environmental aspects and potential impacts throughout a product's life (i.e. cradle-to-grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences".

However, a task force of the responsible subcommittee 5 (Life Cycle Assessment) of the ISO Technical Committee 207 (Environmental Management) was formed in July 2001 to identify the areas for improvements; a consensus was achieved on the following 4 key objectives:

- increase readability by compiling only two documents / merging different documents /reorganising the current standards but keeping technical content, consensus and requirements

- address applications of LCA

- links of economic and social aspects should be addressed

- give guidance / training for application in industry, government etc., especially in developing countries though translating LCA language for experts coming from other fields, facilitating the use of LCA standards, and collecting case studies using ISO standards showing their applicability.

In this sense, most of these issues could be solved by a revision of the standards. To explore this possibility and with a focus to improve the readability of the ISO 14040 series, a new ad-hoc group, consisting of 21 international experts, was created in June 2002 to review the ISO 14040/41/42/43 standards: the group then achieved a consensus on a possible way of revision of the standards. The revision had the final goal to improve readability, while leaving the requirements and technical content unaffected. As a result, the publication in 2006 of the ISO 14040 standard ('Environmental Management - Life Cycle Assessment - Principles and Framework') and the new standard 14044 containing all requirements ('Environmental management - Life cycle assessment - Requirements and Guidelines'), cancels and replaces ISO 14040:1997, ISO 14041:1998, ISO 14042:2000 and ISO 14043:2000, which have been technically revised (ISO, 2006).

This step has brought some changes in the new standards: errors and inconsistencies were removed and the readability was improved; the added technical content is in line with the previous requirements and serves mainly as a clarification of the technical content. It includes e.g., the addition of several definitions (product, process, etc.), the addition of principles for LCA (life cycle perspective, environmental focus, relative approach and functional unit etc), clarifications concerning LCA intended to be used in comparative assertions intended to be disclosed to the public, clarifications concerning system boundary, clarifications concerning the critical review panel and the addition of an annex about applications.

Overall, a standard is reviewed every 5 years and the last amendments of ISO 14040:2006 was published in 2021. Thus, the family of ISO 14040 standards, being an Environmental Management Systems (EMS) frames the requirements for conducting Life Cycle Assessments (LCA) while leaving the actual mechanics of analysis – data collection, normalization, calculation, interpretation, etc. – to the practitioner (Pryshlakivsky J. et al, 2013).

1.1.3 LCA phases

A Life Cycle Assessment study comprehend a series of definite phases that must be applied, and which are specified by ISO norms of 14040 series. There are four fixed phases, but in terms of life cycle stages considered, there exist possible variants based on the case-study analysed:

- Cradle-to-grave. The cradle-to-grave model represents the life cycle thinking as a whole since it assesses the environmental footprint of the product's full life cycle, including all 5 life cycle stages (https://ecochain.com/blog/cradle-to-grave-in-lca/): from the time natural resources are extracted from the ground and processed through each subsequent stage of manufacturing, transportation, product use, and ultimately, disposal (https://www.eea.europa.eu) (Fig. 3). As a result, this approach shows the complete environmental footprint of a product. Thus, it demonstrates where all the product's environmental impacts come from and this allows to implement the most effective measures to reduce them. To perform a Life Cycle Assessment, specific data need to be collected such as data related to the raw materials and production phase of the product: energy carriers, utilities, process emissions, production waste, transport, and raw materials (a list of all the materials required to manufacture a product is usually presented trough a BOM – Bill of materials); data on the use phase of the product, this includes the transport to stores, and the average use & maintenance of the product by consumers (e.g. electricity use, maintenance, cleaning, etc.); data on the end of life phase, so waste-disposal method and its processes, emissions connected to waste disposal method, possible energy recovery in the disposal processes and possible recycling processes of (part) of the materials.

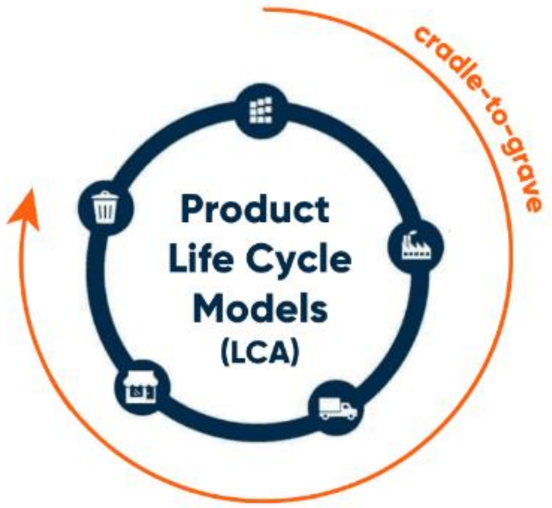


Fig. 3 Cradle-to-grave approach
(https://ecochain.com/blog/cradle-to-grave-in-lca/)

- Cradle-to-gate. Cradle-to-gate is an assessment of a product's partial life cycle, from resource extraction (cradle) to the factory gate (i.e., before being transported to the consumer) (Fig. 4). Here, the use and disposal phases of the product are omitted. Indeed, doing an LCA according to cradle-to-gate model it means collecting data and gaining insight only into the first two stages in the product life cycle: raw materials, transport of the raw materials, and production processes. It stops assessing before the finished product is transported anywhere, so before it leaves the factory gate (https://ecochain.com/blog/cradle-to-grave-in-lca/). Cradle-to-gate assessments are sometimes the basis for environmental product declarations (EPDs) also called EPDs business-to-business. Moreover, cradle-to-gate is used when post-factory-gate processes are uncertain and to compare products that have identical post-factory-gate processes.

  This product life cycle model is the adopted approach for the case-study of this thesis.

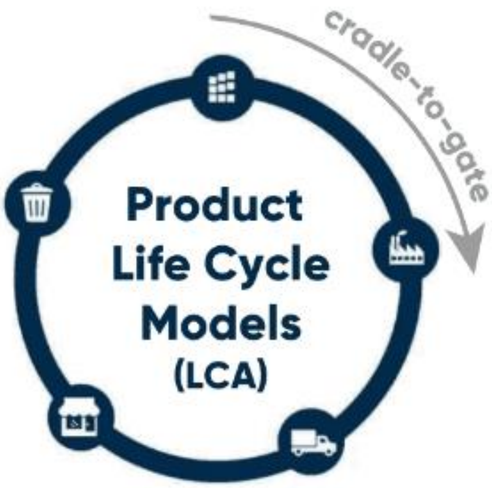


Fig. 4 Cradle-to-gate approach (https://ecochain.com/blog/cradle-to-grave-in-lca/)

- Cradle-to-cradle (closed loop production). Cradle-to-cradle is a specific type of Cradle-to-grave assessment, in which the end-of-life disposal phase of the product is a recycling process (Cao C., 2017). It is a method used to minimize the environmental impact of products by using sustainable production, operation, and disposal systems; it aims to incorporate responsible social responsibility in product development.

- Gate-to-gate. Gate-to-gate is a partial LCA covering only one value-added process in the entire production chain. Gate-to-gate modules can subsequently be linked in their appropriate supply chain to form a complete cradle-to-gate assessment (Cao C., 2017).

- Well-to-wheel. Well-to-wheel is a specific LCA used for transportation fuels and vehicles. The analysis is often divided into phases entitled "well-to-station," or "well-to-tank," and the "station-to-wheel," or "tank-to-wheel," or "plug-to-wheel." The first phase, which incorporates the raw material or production fuel and the transformation and delivery of fuel or transmission energy, is called the "upstream" phase, while the phase that deals with operation of the vehicle is called the "downstream" phase (Cao C., 2017).

Here, the phases to obey to produce a life cycle assessment (Fig. 5), will be analyzed:

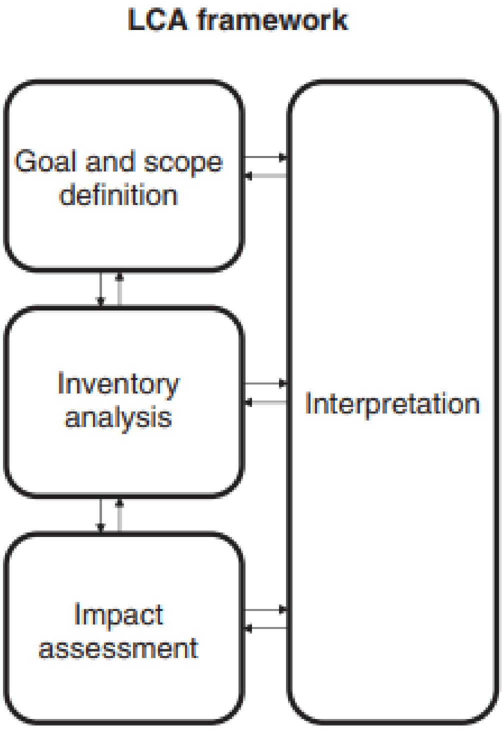


Fig. 5 LCA phases according to ISO 14040 (Klopffer W., 2014)

1. <u>Goal and scope definition</u>: it is the first phase in a life cycle assessment, and it represents central importance to each LCA. At this stage, the objectives and purposes of the study need to be made explicit. Indeed, these steps must be clear and concise because this is a critical part due to its strong influence on the result of the LCA (EEA, 1997). The goal definition must establish the identification of the intended application (e.g. product development/improvement, environmental management systems, marketing, etc), the reasons for carrying out the study (e.g. eco-labeling, eco-design), the stakeholders involved, and the type of audience for which it is intended (to whom the results are intended to be reported, i.e., if they are intended to be used in comparative assertion or if they are intended to be disclosed to the general public). Instead, the scope defines the dimension and detail of the study to reach the goal. In the scope, the following items must be defined (Ren J., 2020):
   - function of the product system: it is necessary to exactly define the product system whose LCA study is being carried out by reporting as much information as possible that will correctly identify the product system, its distinguishing features, and supported functionality.
   - functional unit: from the outset, a reference unit of measurement, called the "functional unit," with which to treat and display the data and information of an LCA must be defined. It is the main item, and it:

    - is a measure of the “functional outflow performance of the system's product”.
    - is decisive, as this is the reference unit of measurement to which input and output flows can be linked.
    - allows for comparability of the results of an LCA (i.e., comparison on the basis of an equivalent function).
- system boundary: it is necessary to define and delimit the physical environments, operations and production processes that will be considered for the analysis. To define the boundaries of the system, one must describe the system under investigation in all its components/phases and construct a flowchart of the process/system under investigation.
- data quality requirements: there are two data categories. Primary data that are directly collected in the field (interviews, forms, data collection, etc.) and secondary data that can be obtained from the literature or from specific databases, i.e. databases specially prepared such as the Ecoinvent database. In all studies, the following additional indicators of data quality should be considered in a level of detail consonant with the objectives and scope of the study: accuracy, completeness, representativeness, consistency, and reproducibility.
- limitation and assumptions: all assumptions and limitations necessary to make up for the lack of information must be reported and justified. Variations in assumptions and limitations can be used in the sensitivity analysis stage to understand how these affect the final result.
- type and format of the final report: all the information collected and generated during the scoping and goal-setting phase must be clearly stated in the final report. There is no standard template for LCA reports, but certification requires that all procedures, assumptions, data gaps, etc. are accurately described.

2. **Life Cycle Inventory (LCI):** Inventory analysis is the second phase in a life cycle and it represents the central, best developed and most scientific component of LCA (Klopffer W., 1997). This phase involves compiling and quantifying all inputs and outputs of matter and energy for a given system/product, consisting of several processes, through its life cycle (various stages). This LCA's phase includes:
    - construct a flowchart of the system to analyze: it must graphically represent the various process units that combine to form the system under consideration, and link them together through the various flows (inputs and outputs) of matter and energy. It is necessary to identify significant components, any subsystems and justify the exclusion of one or more units (Bjorn et al, 2018).

- prepare for data collection;
- collect all the data: the data to be used in the inventory phase should, as far as possible, be collected directly in the field (primary data). In case it is not possible to obtain data directly in the field, it is necessary to make use of data obtained from literature/databases (secondary data). Data may be collected in different ways such as preparing data collection forms followed by interviews, with measurements in the field and by annual reports. However, there are no standard ISO methods for assessing the quality of the available data, it is necessary to cite source, reference period, etc., transparency is required. To collect secondary data there are different databases which may be used. There exist paid global databases (e.g., Ecoinvent), open global databases (e.g., ELCD -European Life Cycle DB) and sectoral databases (such as those of the Plastics Europe - Association of Plastic Manufacturers) and they aim to simplify the search for information, but it is necessary to always verify their reliability (Bjorn et al, 2018).
- adopt allocation procedures if necessary: allocation of the input or output flows of a unit process belonging to the studied system-product. That is, to attribute the load of energy, materials and emissions corresponding to an output of the production system under study. Attribution can be made based on physical (mass, volume, energy, ...) or economic quantities.

3. **Life Cycle Impact Assessment (LCIA):** a stand-alone Life Cycle Inventory (LCI: goal definition and scoping + inventory analysis) can provide useful information for product improvements, benchmarking, energy savings, and emission reduction. The LCI is, however, not sufficient for the comparative assessment of product systems. For this important application as well as for a deeper understanding of the systems investigated, an impact assessment must be performed (Klopffer W., 1997). It is, indeed, aimed at understanding and assessing the magnitude and significance of the potential impacts of a product or system. In contrast to the three other LCA phases, LCIA is in practice largely automated by LCA software, but the underlying principles, models and factors should still be well understood by practitioners to ensure the insight that is needed for a qualified interpretation of the results. At this third stage, the life cycle inventory's information on elementary flows is translated into environmental impact scores (Rosenbaum R. K. et al, 2018). The idea of this phase is to compress the long list of inventory results into a shorter list of impact categories, characterized by appropriate indicators.

The ISO 14040/14044 standards distinguish mandatory and optional steps for the LCIA phase, which will be briefly explained further in this chapter (Rosenbaum R. K. et al, 2018):

- The **mandatory steps** require the selection of *impact categories* (according to ISO is a class that represents an environmental problem, to which class the LCIA results should be assigned. E.g. climate change, acidification, eutrophication and ecotoxicity etc.), *category indicators* (according to ISO, the category indicator represents and quantifies the impact category. E.g. radiative forcing, H+ proton release etc.), *characterisation models* (are not defined according to ISO. They are mathematical models of the impact of elementary flows, with respect to a particular category indicator. E.g. IPCC model for substances that cause climate change (CO_2, CH_4, …), and the *characterization factor* which is, according to ISO, a factor derived from the characterization model, and it is applied to convert the assigned LCI results into the common unit of the category indicator. The common unit allows the results to be grouped into the indicator of the category.

  Examples:

  - GWP (Global Warming Potential). Greenhouse gases warm the earth by absorbing energy and decreasing the rate at which the energy escapes the atmosphere. These gases differ in their ability to absorb energy. GWP is used to indicate the extent to which a greenhouse gas is capable of warming the atmosphere. Each greenhouse gas has a specific GWP which allows comparison of the amount of energy the emissions of 1 ton of gas will absorb over a given time period, usually a 100-year averaging time, compared with the emissions of 1 ton of CO_2 (Vallero D. A., 2019).
  - AP (Acidification Potential)
  - ODP (Ozone Depletion Potential)

  Then, through *classification* the elementary flows of the LCI are assigned to the impact categories to which they contribute according to their known potential effects: e.g., an emission of CO_2 into air is assigned to climate change (Rosenbaum R. K. et al, 2018). Finally, the *characterisation*: apply the appropriate characterization factor to transform the LCI results into the result of a category indicator.
- The **optional steps** are the *normalisation* which aim is to clarify the relative importance of the indicator results: values are divided with reference to a standard value. The normalisation is followed by the *weighting*: the categories results are assigned numerical factors in accordance with their importance, then multiplied by these factors and finally aggregated in a single impact score (Ren J. et al, 2020).

4. **Life Cycle Interpretation:** it is the fourth and last phase of LCA methodology.
   It is defined as the stage where the results of the inventory and impact analysis are consistently combined to propose useful recommendations in accordance with the aims and objectives of the study. The interpretation is comprised of several elements (Ren J. et al, 2020):

- Identification of the significant issues based on the results of the LCI and LCIA phases. The objective of this step is to analyze the results from the LCI or LCIA phases in order to help determining the significant issues, in accordance with the goal and scope definition.
- Final assessments: an evaluation that considers completeness, sensitivity, and consistency checks. The results of uncertainty analysis and data quality analysis should supplement these checks. The completeness check is performed to control that all the needed data and information are available and complete; the sensitivity check is performed to evaluate the reliability of the results; and the consistency check is conducted to determine whether assumptions, methods, and data are coherent with the goal and scope defined.
- Conclusions, limitations and recommendations: the last stage where final conclusions and suggested recommendations are reported.

1.2 The roadmap to the Carbon Footprint (CF) analysis

In the first decade of this century, the scientific consensus on climate change was that: “the climate is changing and that these changes are in large part caused by human activities” (Wilbanks T. J. et al., 2010). This statement has been largely confirmed nowadays by the United Nations body for assessing the science related to climate change “IPCC” (Intergovernmental Panel of Climate Change), which in its 6th Assessment Report (AR6), 6th of a series of reports prepared by the IPCC about knowledge on climate change, its causes, potential impacts and response options, states that “human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global surface temperature reaching 1.1°C above 1850–1900 in 2011–2020” (IPCC, 2023). Thus, the main contributing factor to climate change is the level of greenhouse gases (because they are able to absorb heat) – such as carbon dioxide – in the atmosphere and, in turn, the rate at which human activity is releasing further greenhouse gases into the atmosphere.

Starting from the last decades of the past century, many steps towards lowering the greenhouse gases emissions have been made. Firstly, in the 1992 Rio de Janeiro United Nations Conference on Environment and Development (UNCED), the need to create an instrument that could measure the effects of anthropogenic pressure in terms of the greenhouse effect started to spread. Subsequently, further negotiations between the various nations began, culminating in the signing of the Kyoto Protocol, a legally binding agreement ratified in 1997 and not entering into force until 2005, to which almost all the world's nations adhere, except for the United States. Under the Protocol, 37 industrialized countries and the European Community have committed to reducing their emissions by an average of 5 % against 1990 levels over the five-year period 2008-2012 (UNFCCC, 2011). In addition, with the Europe 2020 strategy, the European Union sets a target for 2020 to reduce greenhouse gas emissions by 20% or 30% compared to 1990 (Savova I., 2012).

In December 2010, to avoid the most severe impacts of climate change, at the 16th Conference of the Parties (COP 16), the annual meeting of the countries that have ratified the United Nations Framework Convention on Climate Change (UNFCCC), the parties agreed on a common commitment to limit the maximum temperature increase to within 2°C above pre-industrial levels and to consider lowering this maximum threshold to 1.5°C in the near future. The implications of the results produced by the IPCC 5th Assessment Report (AR5), in 2014, are such that limiting global temperature rise to within 2°C of pre-industrial times requires concrete and substantial global reductions in greenhouse gas emissions (IPCC, 2014). Achieving the 2°C target, on which there is international agreement, means spending what is left of the carbon budget in a thoughtful way (Friedlingstein P. et al, 2020).

After more than two decades of negotiations, in December 2015 governments adopted the first universal agreement to tackle climate change at the 21st Conference of the Parties (COP 21) in Paris. The Paris Agreement states to hold the increase in the global average temperature to “well below” 2 °C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change; (UNFCCC, 2015). To achieve this goal, the parties aim to stabilize global greenhouse gas emissions as soon as possible and achieve the goal of net zero emissions in the second half of the century. For the first time, all parties must make ambitious efforts to reduce greenhouse gas emissions. All countries, every five years, must renew and update their climate action plans ("nationally determined planned contributions") and communicate them transparently to enable assessment of collective progress ("global stocktaking"). The agreement entered into force in November 2016 after being ratified by the minimum number of 55 governments representing at least 55% of global greenhouse gas emissions.

Despite all of these treaties and agreements and the further COP, the last one was COP27 in Egypt, the future scenarios do not bode well since the global average temperature is continuing to rise: to date, there is a net absorption of solar energy by the Earth system, which means that more energy is entering the Earth system than is being sent back into space resulting in rising temperatures. About that, the IPCC's projections in its AR5, known as Representative Concentration Pathways (RCPs) because they are expressed in terms of greenhouse gas concentrations (the result of emissions) rather than in terms of emission levels, describe different scenarios. Each scenario implies a different magnitude of climate change produced by human activities (e.g., each RCP shows a different amount of additional heat stored in the Earth system because of GHG emissions). The number associated with each RCP indicates the strength of climate change generated by human activity by 2100 compared to the pre-industrial period. There exist four different RCP scenarios (IPCC, 2014) (Fig 6):

-RCP 2.6: it is unlikely to exceed 2°C. This includes an ‘aggressive’ mitigation with emissions halved within 2050.

-RCP 4.5: it is very likely to not exceed 2°C. Strong mitigation: emissions stabilize at half of today's levels by 2080.

-RCP 6.0: it is likely to exceed 2°C. Few mitigation: emissions grow until 2080 and then decrease.

-RCP 8.5: it is likely to exceed 2°C. Business-as-usual: between likely and unlikely to exceed 4 degrees.

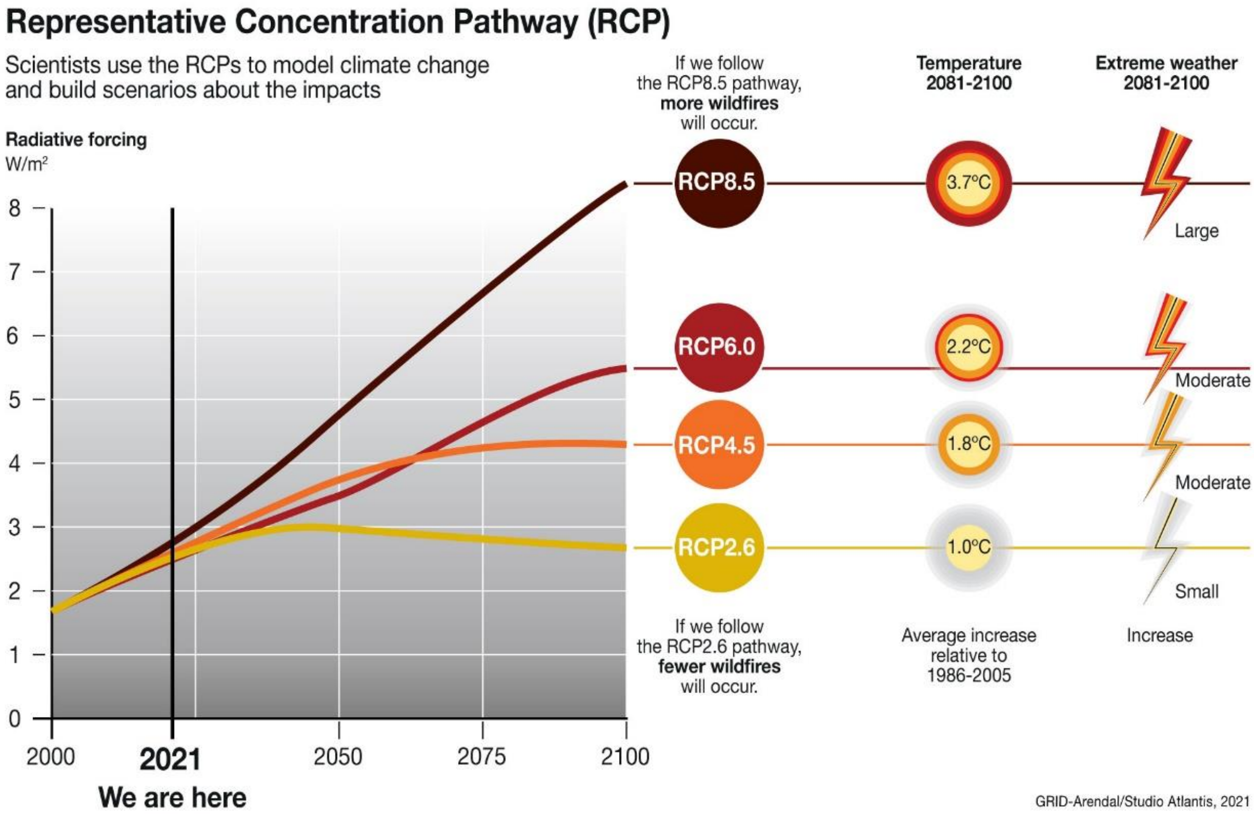


Fig. 6 RCP Scenarios developed by IPCC in AR5 (graph developed in 2022 by GRID-Arendal, a non-profit environmental communications centre. Graph shows the 2021 situation)

In every RCP scenario, except RCP 2.6, global mean surface temperature rise at the surface of the oceans and land is likely to exceed 1.5°C by the end of the 21st century compared to the pre-industrial period and the warming will continue beyond 2100.

The results published in the AR5 have been updated with the 2021 IPCC 6th Assessment Report on Climate Change according to which "global GHG emissions in 2030 associated with the implementation of NDCs (Nationally Determined Contributions) announced prior to COP26 would make it *likely* that warming will exceed 1.5°C during the 21st century and would make it harder to limit warming below 2°C – if no additional commitments are made or actions taken" (IPCC, 2023). Moreover, new scenarios named SSP, Shared Socioeconomic Pathways, that are a collection of climate scenarios which provide narratives describing alternative socio-economic developments, appeared for the first time in the AR6. Factoring socioeconomic elements into future climate scenarios is essential as these are known to be fundamental drivers of both climate change and advances in mitigation and adaptation: indeed, each SSP includes projections of population and economic growth, as well as technological and geopolitical trends (https://www.ipcc.ch). The cornerstone of the SSPs is a set of baselines that describe the world in the absence of new climate policies, and mitigation scenarios that address the effects of mitigation policies (https://www.climateforesight.eu/seeds/shared-socioeconomic-pathways/). The 5 scenarios are (Fig.7):

- a world of sustainability-focused growth and equality (SSP1);
- a "middle of the road" world where trends broadly follow their historical patterns (SSP2);
- a fragmented world of "resurgent nationalism" (SSP3);
- a world of ever-increasing inequality (SSP4);
- a world of rapid and unconstrained growth in economic output and energy use (SSP5).

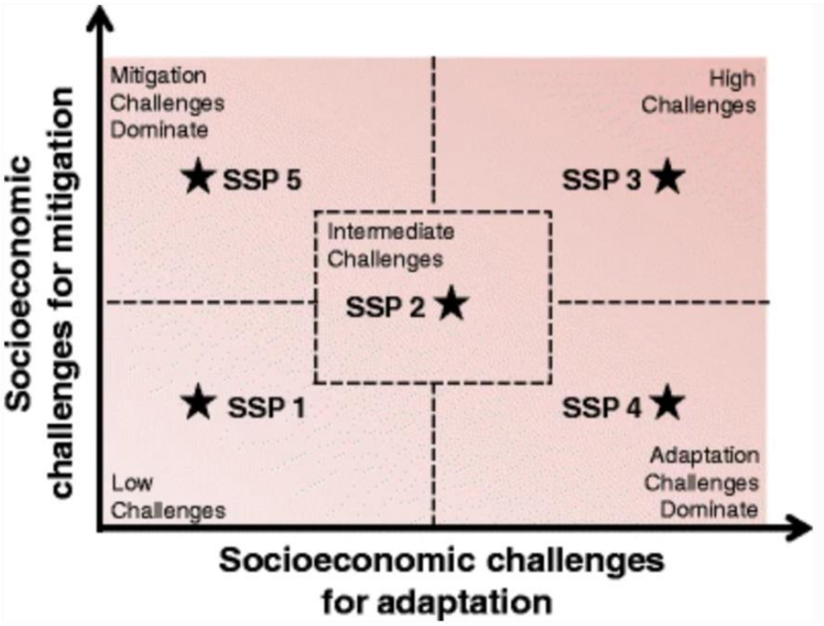


Fig. 7 SSP scenarios developed by IPCC in AR6

Still in AR6, these SSPs are combined with RCPs of AR5 in a scenario matrix architecture that shows how socioeconomic choices will affect climate change in the 21st century (https://www.climateforesight.eu/seeds/shared-socioeconomic-pathways/).

These further scenarios are developed by the WG1 (Working Group 1) of IPCC, which addresses the most up-to-date physical understanding of the climate system and climate change bringing together the latest advances in climate science (https://www.ipcc.ch). WG1 assessed the climate response to the five illustrative scenarios based on Shared Socio-economic Pathways (SSPs) that cover the range of possible future development of anthropogenic drivers of climate change (IPCC, 2023). These scenarios are:

- SSP3-7.0 and SSP5-8.5: high and very high GHG emissions scenarios have CO2 emissions that roughly double from current levels by 2100 and 2050, respectively.
- SSP2-4.5: the intermediate GHG emissions scenario has CO2 emissions remaining around current levels until the middle of the century (IPCC, 2023).
- SSP1-1.9 and SSP1-2.6: the very low and low GHG emissions scenarios have CO2 emissions declining to net zero around 2050 and 2070, respectively, followed by varying levels of net negative CO2 emissions.

1.3 The Carbon Footprint (CF) analysis

To limit the increase of the global average temperature and to avoid the worst effects, robust approaches for the measurement and management of GHG emissions are required in order to target setting and assessing the success of climate change mitigation measures. Selecting a 'Carbon Footprint' to quantify GHG emissions is straightforward and allows the source of "carbon" to be identified, which can be used in mitigation actions. Today, the carbon footprint has become a primary focus for all aspects of society, and it is widely used to explore the responses to global change in all areas of life (Chen K. et al, 2021). However, carbon footprinting when has begun to be framed at the end of the first decade of the 2000s was a relatively new field: it was indeed preceded by the *ecological footprinting*, a measure of resource use, that determines how much land area is required to maintain a given population indefinitely (Barnett A. et al, 2013). The term 'carbon footprint' did not appear in literature until 2007 when Wiedmann and Minx in their report "A definition of 'Carbon Footprint'" define it as a "measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product" (Wiedmann T. & Minx J., 2007). This definition included activities of individuals, populations, governments, companies, organisations, processes, industry sectors etc.; products include goods and services. In any case, all direct (on-site, internal) and indirect emissions (off-site, external, embodied, upstream, downstream) need to be considered. Wright L. A. et al in "'Carbon footprinting': towards a universally accepted definition", wrote that the term was driven largely by media, government, industry and nongovernmental organizations, captivating the interest of business, consumers and policy makers, although it was only recently adopted by the academic community: this brought confusion and little consensus over what the term actually would mean or what the process would measure (Wright L. A. et al, 2011). However, after a critical review of the definition of carbon footprint from the 'grey literature' and the academic literature, they proposed the CF as a "A measure of the total amount of CO_2 and CH_4 emissions of a defined population, system or activity, considering all relevant sources, sinks and storage within the spatial and temporal boundary of the population, system or activity of interest, calculated as CO_2 and using the relevant 100-year global warming (GWP100)". Focusing on CF as a measure of CO_2 and CH_4 emissions, they exclude other GHGs since carbon dioxide and methane are by far the most emitted GHGs. The definition has later undergone some other modifications: Barnett et al. in 2013 in their report "A history of product carbon footprinting" define it as "a measure which expresses in CO_2 equivalent the total amount of greenhouse gases that are directly or indirectly caused by an activity or accumulated over the life cycle of a product. Each greenhouse gas is scaled by its global warming potential".

A series of approaches of Carbon Footprint have been developed in time. Selecting a Carbon Footprint to quantify GHG emissions is straightforward and allows the source of "carbon" to be identified, which can be used in mitigation actions. Today, the Carbon Footprint has become a primary focus for all aspects of society, and it is widely used to explore the responses to global change in all areas of life: it is developed by companies, individuals, organizations, nations and cities. The emergence of the carbon footprint facilitates the identification of major emission sources, enabling the prioritization of areas to reduce emissions and improve efficiency (Chen K. et al, 2022). Indeed, Carbon Footprinting can exist for:

- Products and services: in principle, the ISO LCA standards 14040 and 14044 provided a tool for the calculation of GHGs associated with a product. However, the standards did not explicitly document the process or boundaries required to calculate a carbon footprint: in response, ISO14067 has been developed. The product Carbon Footprint (CFP) is expressed as the sum of GHG emissions and GHG removals in a product system, expressed as CO_2 equivalents and based on a Life Cycle Assessment (LCA) using the single impact category of climate change (ISO, 2018).

- Organisations and sectors: reporting of GHG emissions in an organizational context (e.g., business units or municipal organizations) has become increasingly important. Carbon Footprint of organisations (CFO) is expressed in CO_2eq, and it is used as a tool for sustainable management of different business areas, thus translating into a competitiveness tool. There exist two standards for the CFO: GHG Protocol Initiative and ISO 14064-1. The GHG protocol, developed in 1998 by the World Resource Institute and the World Business Council for Sustainable Development, has the mission to develop internationally accepted greenhouse gas (GHG) accounting and reporting standards for business and to promote their broad adoption (WBCSD & WRI, 2015). The GHG Protocol Initiative comprises two separate but linked standards: GHG Protocol Corporate Accounting and Reporting Standard (GHG Protocol Corporate Standard) and GHG Protocol Project Quantification Standard. The revised edition of the GHG Protocol Corporate Standard provides standards and guidance for companies and other types of organizations preparing a GHG emissions inventory. It covers the accounting and reporting of the six greenhouse gases covered by the Kyoto Protocol — carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF6) (WBCSD & WRI, 2015). The ISO 14064-1 specifies principles and requirements at the organization level for the quantification and reporting of greenhouse gas (GHG) emissions and removals. It includes requirements for the design, development, management, reporting and verification of an organization's GHG inventory (ISO, 2018). Furthermore, according to the standard, the organization shall establish a historical base year for GHG emissions and removals for comparative purposes or to meet GHG programme requirements or other intended uses of the GHG inventory. Base-year emissions or removals may be quantified based on a specific period (e.g. a year or part of a year) or averaged from several periods (e.g. several years) (ISO, 2018).

- Nations, regions and cities: this approach is less considered comparatively to the footprint of products and organisations. Moreover, issues regarding the fairness in the emissions' allocation are closely linked to the carbon footprints of nations. Carbon footprints can also be used at the subnational level, most importantly for cities. Their concentration of people, wealth and resources makes cities centres for economic activities, innovation, and culture. However, urban activities also lead to negative impacts on the environment that often manifest themselves beyond city boundaries. Attributing to cities the carbon emissions associated with the production of goods and services they consume, urban areas covering only 2% of the Earth's land are responsible for approximately 80% of global greenhouse gas emissions (Sun X. et al, 2022). Local and regional governments are responsible for many decisions that affect GHG emissions, such as transport and land-use planning, zoning, and setting building standards as well as the management of their own activities. The development of city carbon footprinting models is of potential importance in providing accurate data to allow for evidence-based strategic decisions (Wright L. A. et al, 2011).

- Personal: this approach considers the increasing awareness of studying the individual impact on the environment as a source of GHG emissions. The amount of GHG, like CO_2, produced by a person's activities is defined as personal carbon footprint. A software application used to calculate the contribution a particular operation or activity makes to the total CO_2 output of an individual is called carbon footprint 'calculator'. One such calculator is meant to help users estimate their total carbon emissions and then motivate them to adopt low-carbon behaviours. (Lin S., 2015).

Considering the analysed historical path of the Carbon Footprint method, it can be said that it calculates and measures the total amount of greenhouse gases emissions generated, expressed in terms of carbon dioxide equivalents (CO_2eq), by a particular product, service, or organization. For the case-study of this thesis, a photovoltaic panel, the Product Carbon Footprint (CFP) has been computed.

1.3.1 Product Carbon Footprint (CFP) calculation method

The standard which guides the CFP composition is the ISO 14067:2018.

The standard was firstly proposed in the first ISO/TC (Technical Committee) 207/WG2 (Working Group 2) meeting in April 2008. It was developed by over 100 experts from more than 30 countries, including developing countries such as China, Argentina, Indonesia, etc., and received many comments from international involvement (Wu P. et al, 2015). It offers a valid standardized way for any type of company to calculate the climate footprint of its products and understand, at the same time, how to reduce it.

ISO 14067 defines some key points:

- Reference Principles.

- Methodology for quantifying the Product Carbon Footprint (CFP)

- Report on the CFP study

- Communication of the CFP

Through the activity of auditing made by a third party (CFP verification), it is possible to:

- Conduct a critical review of the CFP study: if the study is approved then the next step regards the certification.

- Certify that the CFP study complies with ISO 14067.

It is important to note it is not mandatory to certificate the study: a company may not ask for a revision of the CFP study. The certification is a powerful step since it requires, in addition of the payment of a consultant to do the CFP calculation, the payment of a third independent part which critically revise the CFP to see if it is compliant to ISO 14067. A company, however, may end the process to the CFP calculation, which is mandatory, without the certification of the product or service that often is a great effort for a company since it requires time, money, and human resources. In this case, the CFP calculation study may be used as an internal decision-making tool to evaluate in which processes to direct strategic efforts to reduce the environmental impact. Thus, the certification of the product represents a step of certain significance and in particular kind of relationships such as in case of international relationships, public administrations or with public government, the certification may represent an important requirement which gives strength, reliability and greater authority to the technical Carbon Footprint assessments also in view of possible participation in public calls and tenders.

The indication on the product of the value of the Carbon Footprint and possibly the voluntary offsetting of related emissions is a green marketing tool that has been successfully tested in many European countries. For Italian exporters, particularly in some commodity sectors, qualifying their products with a carbon free or carbon neutral indication or with a wording that makes explicit the company's position in relation to CO_2eq emissions has already become a requirement; for others, however, it constitutes a point of qualification and an element of competitiveness, on which is also relied on in advertising.

Specifically, the first reference standard for the Product Carbon Footprint ISO/TS 14067:2013 specified principles, requirements and guidelines for the quantification and communication of the carbon footprint of a product (CFP), based on International Standards on life cycle assessment (ISO 14040 and ISO 14044) for quantification and on environmental labels and declarations (ISO 14020, ISO 14024 and ISO 14025) for communication (ISO, 2013). For the quantification part, a lot of ISO 14044 content is copied into ISO 14067: ISO 14067 did not bring neither much news nor a broad range of specific requirements (Finkbeiner M., 2013). Then the ISO 14067:2013 was technically revised and in 2018 was replaced by the new revised standard: "ISO 14067:2018. Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification" which has come to represent the standard for quantifying the carbon footprint of products. The revision of the document covered the part of the quantification of the climate footprint, a scope that was too broad in ISO 14067:2013 (https://www.accredia.it/2018/12/20/carbon-footprint-le-novita-per-lambiente-con-la-norma-internazionale-iso-14067/,). Further evolution has occurred with the development of Minimum Environmental Criteria (CAM), which establish specific environmental requirements for many products and the (accredited) certifications by which to confirm that these requirements are met.

The ISO 14067:2018 specifies principles, requirements and guidelines for the quantification and reporting of the carbon footprint of a product (CFP), in a manner consistent with International Standards on life cycle assessment (LCA) (ISO 14040 and ISO 14044) (ISO, 2018). However, it is important to note that carbon offsetting and communication of CFP or partial CFP information are outside the scope of the document. The document does not address any social, economic or other environmental aspects or impacts potentially arising from a product's life cycle: it addresses only a single impact category, the climate change. The method of calculating the Product Carbon Footprint according to ISO 14067 involves several processing steps, entirely similar to those of the LCA methodology:

- Definition of goals and objectives: defining the functional unit and boundaries of the product system to be analyzed is part of this phase.
- GHG inventory analysis: quantification of all greenhouse gas (GHG) emissions throughout the product life cycle, from raw material extraction to final product disposal.
- Allocation of collected data: creation of databases divided by sector and process, after identification of system boundaries.
- Characterization: the amount of each GHG gas is converted to tCO_2eq, using the appropriate Global Warming Potential (GWP).
- Carbon Footprint Assessment: the data obtained are analyzed, identifying the most impactful steps to guide management and design choices toward greater product sustainability.

In all these phases, ISO 14067 requires reference at all these stages to the Product Category Rules (PCRs), where available. PCRs are shared guidelines and rules to be followed in developing LCA and are specific to each type of product or service.

1.3.2 Product Category Rules (PCR)

Common life cycle-based quantitative claims exist in two forms: multi-criteria claims called environmental product declarations (EPDs) and single criteria claims such as product carbon footprints (CFPs) (Subramanian V. et al, 2012). The PCRs, "Product Category Rules", as defined in the ISO 14025:2006 standard which is last reviewed and confirmed in 2020 (https://www.iso.org), are a requirement for the creation of Type III Environmental Product Declarations (EPDs) (Ingwersen W. W., 2013): an EPD is a standardized (ISO 14025) and LCA-based tool to communicate the environmental performance of a product (Grahl B. & Schmincke E., 2007). Furthermore, product category rules exist even for other types of LCA-based product claims, such as product carbon footprints (CFPs) or other forms of quantitative product environmental footprints (Ingwersen W. W., et al, 2013).

EPDs, CFPs and other forms of product claims based on an ISO 14044 life cycle assessment (LCA) are used as a basis for labels and reports that inform purchasers in the supply chain and final consumers. That's why PCRs are fundamental instructions (Subramanian V. et al, 2012). These Product Category Rules (PCRs) provide product category specific rules, requirements, and guidelines for calculating and reporting environmental data across the full life cycle of a product or service Data that need to be considered for the GHG calculation in the CFP are: "primary data" or "foreground data", such as the consumption of energy and materials, i.e., the steps that are directly involved in the life cycle of products (production, use, transportation, disposal, etc.), and "secondary data" or "background data", that are data indirectly involved such as the production of materials and energy used in the processes of primary data, and they are searched generally in the LCA databases or the literature and the statistics (Subramanian V. et al, 2012).

The CFP is one of the tools of the "CO_2 visualization", showing the GHGs of the daily goods and foods, through wordings and symbols in labels, to the consumers in the supermarket, making the consumers purchase them and then moving to the sustainable society (Inaba A. et al, 2016). However, the comparison of the emissions between products is not the main aim of Product Carbon Footprint, since it is easy for the consumers to ascertain which product has less emissions produced. The CFPs, indeed, are expected to make the producers develop the new products with less environmental impacts and then move to the sustainable production. Therefore, it is necessary for the implementation procedure of CFPs to be fair and transparent. According to ISO 14025:2006, the implementation of CFP began precisely with the creation of PCR, when not already available (Inaba A. et al, 2016).

The program holder of the CFP shall establish and manage the PCRs. When the CFP is implemented in a variety of products, it becomes necessary to consider the consistency and the relevance of each PCR. In addition, the program holder shall provide the secondary data to the practitioner of the CFP. When the CFP is trusted by the consumers and the practitioner can carry out the CFP conveniently, the maintenance of secondary data and the disclosure of the PCR are indispensable. These are the most important issues in the implementation of the CFP (Inaba A., et al, 2016).
The use of PCRs ensures homogeneity and comparability between the results of Carbon Footprint calculations performed by different companies for similar products. Clearly define the scope of the PCR is important so that users can appropriately apply specific rules to guide the life cycle assessment.

2. MATERIALS AND METHODS

The subject of this thesis consists of a project developed at Ambiente Italia Srl, a consulting society based in Carbonera (TV). The development of this project required the use of specific materials and methods which will be described in detail in the further chapters. The main objective of this thesis consists in showing each step that were necessary for the construction of an Excel calculator, named tool-CF (Carbon Footprint), which will be helpful for a specific customer company to choose the more sustainable suppliers from the environmental point of view, measuring their impact in kgCO2eq.

Generally, regarding the materials used, the development of the project has seen different kind of data: data provided by the customer company, which in this thesis will be hided or not quantitatively mentioned since they are private data, data which have been extracted from the database Ecoinvent v3.8, and testing data, which are data chosen by Ambiente Italia Srl personnel that have been used to test the formulas.

Instead, concerning the methods used, the work consisted in using Excel worksheets, SimaPro software and Word writing sheets.

2.1 Case-study analysis

The study developed at Ambiente Italia Srl consisted in assessing the different climate change impacts, in terms of $kgCO_2eq$, of the various suppliers of materials necessary to build a specific Utility Scale module of photovoltaic (PV) panel. There are two typologies of solar panels: Utility Scale (US) and Distributed Generation (DG). Utility Scale refers to medium-to large-scale solar energy installations, often placed far from population centres and demand in large expanses of non-sloping vacant land and designed to generate large amounts of electricity to be place directly onto the large-scale regional grid at a specific point; they are characterized by high transmission costs (Hernandez R. R. et al, 2013). Distributed Generation refers to very small-to medium-scale solar energy installations designed close to population centre to generate moderate amounts of electricity to be placed onto the local electrical distribution system at the point of both generation and use; typically integrated into pre-existing infrastructure or new ones, they are designed as stand-alone facilities or could be used to generate greater electrical energy in conjunction with other similar nearby installations (Hernandez R. R. et al, 2013).

The thesis project is about an innovative bifacial photovoltaic panel of the utility scale format.

2.1.1 Case-study PCR

The PCR (Product Category Rules) used for the case-study is "PCR EPDItaly014 – Photovoltaic modules - Electricity produced by photovoltaic modules". This document has been prepared for use within the EPDItaly Program. The main aim of the EPDItaly Program is to provide a tool to enhance the value of the commitment made by an organisation, whether in Italy or abroad, working in any market sector, to reduce the environmental impact associated with the products or services they supply (EPDItaly, 2020). This is achieved through the Environmental Product Declaration (EPD), which enables the organisation to communicate, in a clear and transparent way, the environmental performance of its products to the market in an understandable and credible way, gaining national and international visibility (EPDItaly, 2020).

The PCR document represents a Core PCR that can be used as part of the EPDItaly Program to prepare, assess and validate an internationally valid Environmental Product Declaration (EPD) through the timely verification of the environmental performance of products falling in the category "Photovoltaic modules" (EPDItaly, 2020). The PCR includes photovoltaic plants for domestic/residential or industrial applications of any size, stand-alone or grid-connected, consisting of one or more modules and/or strings. It is fundamental to specify the functional unit, which is the product category unit to be referred to when determining environmental impacts. If the product's "function" is not determined or cannot be specified, the declared unit (UD) may be used. This is the case for those products that end at the manufacturing facility's gates and whose use is not known (EPDItaly, 2020): the declared unit is the reference for the cradle-to-gate analysis. In the case-study, since up to the gate the module has not yet performed its function of producing energy, the piece produced (the PV module) has been considered as UD. According to EN 15804, the declared unit shall be applied in place of a functional unit when an EPD is based on a cradle-to-gate LCA (BRE Global, 2018). However, since it is important to the customer company knowing the impact per kWh produced, even if it is a cradle-to-gate analysis, the functional unit has been defined: it is the quantified performance of the product system under study and in this case, it is the kWh produced by the module in 30 years. In the case-study, the results of the climate change impact of the PV production are reported per declared unit and then specified per functional unit, the kWh produced in 30 years.

PCRs define a set of rules to ensure, for each individual product belonging to a given category, a uniform approach is taken when performing the LCA and the subsequent EPD is created. However, in the case-study, the PCR is followed solely to accomplish the LCA since the creation of an EPD is not required.

2.2 CF analysis for the case-study: LCA "cradle to gate"

The LCA methodology used for this case-study is a "cradle-to-gate" approach. Life Cycle Assessments (LCA) following cradle-to-gate measure a photovoltaic module's environmental footprint up to the point where it leaves the factory gate. This means the environmental footprint results don't include the footprint of product use by customers and its end-of-life processes (waste/recycling/upcycling). Thus, this approach means collecting data and gain insight only into the first two stages in the product life cycle: upstream stage and core stage, downstream is indeed not considered. According to the case-study PCR, the upstream stage considers the following aspects (EPDItaly, 2020):

- extraction of raw materials, production of semi-finished products, production and disposal of waste associated with the processes;

- transportation of raw materials and semi-finished products from suppliers to the company manufacturing/assembling the photovoltaic module

Moreover, the core stage contains most of the environmental impacts related to the production of electricity by photovoltaic modules. Two types of impact related to the Core stage can be identified (EPDItaly, 2020):

- core – process: section reporting the environmental impacts associated with the operation of the photovoltaic module or solar park;

- core – infrastructure: section reporting the environmental impacts associated with the construction of the photovoltaic module (or solar park) and all the auxiliary and infrastructure equipment needed to ensure that electricity is properly generated and fed into the grid.

However, in the case-study, when organizing the tool it was decided to consider only the production of components, auxiliaries and packaging in the upstream stage. Thus, inbound transports have been included in the core stage. The case-study core stage therefore includes transports and only part of the core-infrastructure's impacts but not the core-process' ones since there is no consideration of the impacts associated with the installation and operation of the photovoltaic module, but only impacts associated with the construction of the photovoltaic module.

The assessment lasts before the finished product is transported anywhere, so before it leaves the factory gate.

Specifically, in the case-study the following stages have been analysed (EPDItaly, 2020), for the upstream stage:

1. Extraction of raw materials, processing, production of the materials necessary for the realization of the photovoltaic module.
2. Extraction of auxiliary materials, processing, production of the materials necessary for the realization of the photovoltaic module.
3. Extraction, production and processing of primary, secondary and tertiary packaging materials necessary for the packaging of the finished product.

for the core stage:

4. Transportation of raw materials, auxiliaries and packaging from the supplier to the manufacturer of the photovoltaic module.
5. Production: this phase includes all the assembly operations of the photovoltaic modules (core-infrastructure).

2.2.1 Tool-CF workbook

The calculator, named tool-CF, of the case study consists in an Excel workbook divided into three worksheets: "Data Entry", "Impacts" and "Results". The order in which these sheets were first created and then compiled is "Data Entry" as the first one, "Impacts" as the second one and "Results" as the last one. These worksheets present different types of data but are not stand-alone since one sheet is linked to the other through the reporting of some data. Indeed, "Data Entry", which consists in the input worksheet where the personnel of the customer company will insert their data in the appropriate cells, consists of a worksheet setting that is re-presented in the "Impacts" sheet. The "Impacts" sheet, in fact, for the first half is the same as the "Data Entry", such that the cells are a copy and paste of the cells of the "Data Entry", and for the other half presents specific data and formulas necessary to develop certain calculations. The third worksheet, "Results", in turn consists of a summary of the results obtained in the "Impacts" worksheet: again, the results were reported by copying and pasting the appropriate cells. It is important to note that the second worksheet, "Impacts", will not be made visible to the customer company because it contains formulas setting and data extracted by Ambiente Italia Srl which are necessary for the calculations to work properly and therefore must not be modified: this sheet is private, and the access is allowed only to Ambiente Italia's personnel.

2.3 Worksheets and typology of data involved

2.3.1 Data Entry worksheet

The project started with setting the “Data Entry” worksheet: since it is a cradle-to-gate approach the system boundaries have been chosen and then the processes included in them have been reported in the worksheet as sections one below the other in the first column on the left part of the worksheet (Fig.8). Thus, “Data Entry” constitutes the sheet into which input data are entered. “Data Entry” allows for the creation of the life cycle inventory related to the specific product, the photovoltaic panel. Furthermore, above the worksheet façade another sequence has been created: it referred to informations such as “unità di misura” (unit of measure), “dati” (data), “km trasporto su strada” (km road transport), “km trasporto navale” (km ship transport), “km trasporto aereo” (km air transport) (Fig. 8). These five columns have been fixed in a way that scrolling down the worksheet they must be compiled for every system boundary.

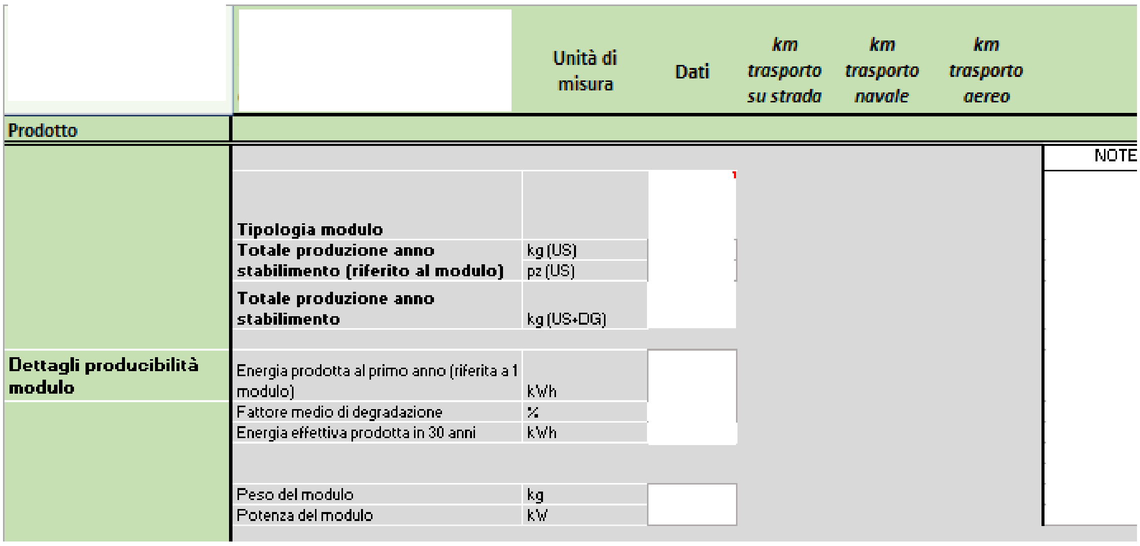


Fig. 8 Data Entry setting: system boundary description on the left, specific data description above and data cells in the centre

The white cells cover private data, collected by the client company, referring to the last production year of the PV panel. Initially, in the construction of this worksheet, the cells were blank, then, once the construction of the sheet was completed, they have been filled with such data.

In the case-study, the processes included in the system boundaries are:

- “Prodotto” (Product) (Fig.9): in this section all the characteristics of the product has been highlighted. A concise description of the product is followed by the details regarding the module manufacturability, its weight (kg) and its power (kW). All of these data were given by the customer company.

Prodotto		
	Tipologia modulo	
	Totale produzione anno	kg (US)
	stabilimento (riferito al modulo)	pz (US)
	Totale produzione anno stabilimento	kg (US+DG)
Dettagli producibilità modulo	Energia prodotta al primo anno (riferita a 1 modulo)	kWh
	Fattore medio di degradazione	%
	Energia effettiva prodotta in 30 anni	kWh
	Peso del modulo	kg
	Potenza del modulo	kW

Fig. 9 “Prodotto” (product) section

- “Energia Elettrica” (Electric Energy) (Fig. 10): the total consumption of the electric energy measured in terms of kWh/year and the self-production of electricity, which have been provided by the client company, have been reported. At the manufacturing plant, energy consumption measurement is possible on the assembly line dedicated to photovoltaic modules, through an end-of-process meter that considers all machinery. The total consumption of electric energy considers the energy withdrawn from the various types of grids added to the self-generated electricity. The total self-generated electricity was given by the customer company as well as the total consumption, instead the total energy from the grid has been calculated through a subtraction between total consumption and self-generated electricity. The different amounts of electric energy withdrawn from the various grids have been calculated multiplying the total from the grid by the specific percentage of each grid, which have been given by the company.

Energia Elettrica			
	CONSUMI TOTALI DI ENERGIA ELETTRICA	**kWh/anno**	
	E.E. Prelevata da rete mix standard	kWh/anno	
	E.E. Prelevata da rete rinnovabile - idroelettrico	kWh/anno	
	E.E Prelevata da rete rinnovabile fotovoltaico	kWh/anno	
	E.E Prelevata da rete rinnovabile eolico	kWh/anno	
	E.E Prelevata da rete geotermico	kWh/anno	
	Totale da rete	kWh/anno	
	AUTOPRODUZIONE DI ENERGIA ELETTRICA		
	Fotovoltaico		
	Energia elettrica prodotta e autoconsumata	kWh/anno	
	Trigenerazione		
	Energia elettrica prodotta e autoconsumata	kWh/anno	

Fig. 10 “Energia Elettrica” (electric energy) section

- “Combustibili” (Fuels) (Fig. 11): the typology (natural gas) and the quantity of fuel consumed has been reported. These data were given by the company.

Combustibili			
	Tipologia di combustibile		**Quantità consumata**
	Gas Naturale (non utilizzato nel trigeneratore)	Sm3/anno	

Fig. 11 “Combustibili” (fuels) section

- “Componenti modulo” (Module components) (Fig. 12): in this section, each component of the module has been reported. In Figure 12, as examples, front and back glass are reported. Each component’s weight is placed at the first line measured in kg/module. Then, the percentage refers to how much each supplier contributed to supplying that component. Specifically, data regarding component’s weight and the distances covered by land, sea and air have been reported. Quantities have been reported thanks to the Bills of Materials (BOM) given by the customer company. Instead, distances between the suppliers and the production site of the PV modules have been computed since the customer company provided a list of suppliers.

Componenti modulo						
	COMPONENTI E/O SEMILAVORATI IN ENTRATA		**Peso del componente**	**Da fornitore componente a**		
				Km via terra	**Km via nave**	**Km via aerec**
	Vetro anteriore	kg/modulo				
	Vetro anteriore -	%				
	Vetro anteriore -	%				
	Vetro anteriore - fornitore 3	%				
	Vetro anteriore - fornitore 4	%				
	Vetro anteriore - fornitore 5	%				
	Vetro anteriore - fornitore 6	%				
	Vetro posteriore	kg/modulo				
	Vetro posteriore -	%				
	Vetro posteriore -	%				
	Vetro posteriore - fornitore 3	%				
	Vetro posteriore - fornitore 4	%				
	Vetro posteriore - fornitore 5	%				
	Vetro posteriore - fornitore 6	%				

Fig. 12 “Componenti modulo” (components) section

- “Ausiliari” (Auxiliaries) (Fig.13): in addition to the components, auxiliaries have been reported too: figure 10 shows some of them. Specifically, all the ones being part of the cell line and the module line for the Utility Scale module have been described in terms of quantity (kg/year) and distances covered by land, sea and air. Quantities have been given by the company through the compilation of a checklist; real distances will be compiled by the company based on their suppliers because, in contrast to the components, the customer company did not provide a list of suppliers of the auxiliaries, so hypothetical values have been entered.

Ausiliari						
			Quantità	Km via terra	Km via nave	Km via aereo
CELL LINE	Azoto	kg/anno				
	Silano	kg/anno				
	Idrogeno	kg/anno				
	Fosfina	kg/anno				
	Borano	kg/anno				
	Anidride Carbonica	kg/anno				
	Metano	kg/anno				
MODULE LINE - US product	Module-Glass Transparent Label	kg/anno				
	Module-Glass Label Ink	kg/anno				
	Screens ECA printing US	kg/anno				
	Squeegee ECA US	kg/anno				
	Flux for Interconnection	kg/anno				

Fig. 13 "Ausiliari" (auxiliaries) section

- "Emissioni di gas effetto serra" (Greenhouse gases emissions) (Fig. 14): the discharged quantity, in terms of kg/year, and the typology of pollutants produced have been described for each facility/activity involved in GHGs emissions. Both quantities and pollutants produced have been communicated by the company.

- "F-Gas" (F-Gas) (Fig. 14): topped-up quantity, in kg/year, and gas typology for each process unit. Both have been communicated by the company.

- "Acqua" (Water) (Fig. 14): quantity, in m^3/year, of water, used in the production process of the photovoltaic panel, entered in the building from the industrial waterwork. The amount of incoming water and the percentage of water actually used are reported.

Emissioni di gas effetto serra	Impianto/Attività		Quantità scaricate	Inquinanti prodotti
	Produzione del modulo (fase di deposizione) -	kg/anno		
		kg/anno		
	Assemblaggio modulo	kg/anno		
	Produzione del modulo -	kg/anno		
	EVENTUALE CAMINO AGGIUNTIVO	kg/anno		
		kg/anno		
		kg/anno		
F-Gas	**Unità di processo**		**Quantità rabboccata**	**Tipologia di gas**
	Unità di refrigerazione	kg/anno		
	Apparecchiature elettriche (PECVD)	kg/anno		
		kg/anno		
Acqua	**Acqua in entrata allo stabilimento**		**Quantità**	
	Fonte: acquedotto industriale	m3/anno		
	per usi produttivi	%		

Fig. 14 “Emissioni di gas effetto serra” (greenhouse gases emissions), “F-Gas” (F-Gas), “Acqua” (water) sections

- “Rifiuti” (Wastes) (Fig. 15): the quantities, in kg/year, of each type of waste specified in terms of CER code and waste’s name. The quantities of waste, communicated by the customer company, have been divided based on their destination: landfill, incineration and recovery.

Rifiuti			Quantità per destinazione finale		
Codice CER	**Nome del rifiuto**		**Discarica**	**Incenerimento**	**Recupero**
160306	rifiuti organici, diversi da quelli di cui alla voce 16 03 05	kg/anno			
160505	gas in contenitori a pressione, diversi da quelli di cui alla voce 16 05 04	kg/anno			
060103*	acido fluoridrico	kg/anno			
060204*	idrossido di sodio e di potassio	kg/anno			
080410	adesivi e sigillanti di scarto, diversi da quelli di cui alla voce	kg/anno			

Fig. 15 “Rifiuti” (wastes) section

- “Imballaggi” (Packaging) (Fig. 16): the packaging typology of the PV panels consists of a structure named bi-pack which is formed by two pallets, one on top of the other, and in each of them the packaged structures containing modules are placed. Thus, quantities of realized bi-pack and modules for each bi-pack, have been specified. Then, the materials from which a bi-pack is made (wood, paper, plastic, etc.) have been specified, and for each material the type and quantity of material used has been specifically described (e.g., for wood the pallet, for paper the label, cardboard kit, etc.). Similarly to the auxiliaries, hypothetical values regarding the distance, by sea, ship and land in km, from the supplier to the manufacturing company, have been entered since the customer company did not provide a list of suppliers of the packaging. The quantities of bi-packs and of the various materials have been reported by the customer company in the appropriate checklist.

Imballaggi						
		Quantità				
Tipologia di imballaggio	Bi-pack realizzati	n/anno				
	Moduli per Bi-pack	n/bi-pack				
				Da fornitore imballaggio a		
Composizione bi-pack	**Tipologia**	**Quantità unitaria**	**Numero per Bi-pack**	**km via terra**	**km via nave**	**km via aereo**
Legno	Pallet in legno (inferiore)					
	Pallet in legno (superiore)					
Carta	Cornice angolare in cartone					
	Etichetta del pallet in legno					
	Kit di cartone (inferiore)					
	Kit di cartone (superiore)					
	Scatola di cartone - Etichetta					
	Schede tecniche in formato A4					
	Manuale di installazione					

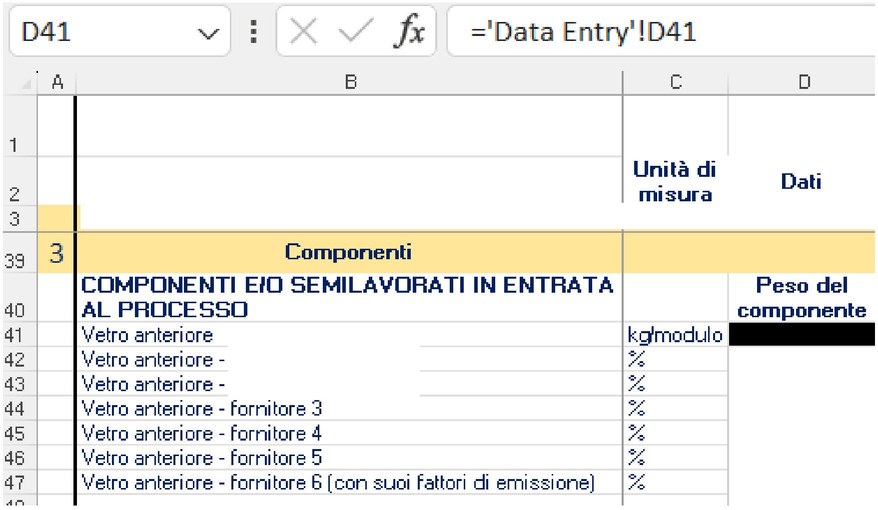
Fig. 16 “Imballaggi” (packaging) section

On the right side of each section, a column named “Note” has been created in order to give more specific informations about values, activities, materials properties and other information.

2.3.2 Impacts worksheet

The "Impacts" worksheet is organised the same way of "Data Entry" regarding the processes sections included in the system boundaries and the columns of unit of measure, data and km by car, sea and air: the cells in the "Impacts" worksheet are linked to the same cells, in terms of position, of the "Data entry" worksheet so when a value is entered on a "Data Entry" cell it is at the same time visible in the same cell on the "Impacts" worksheet.

The only modified parameter from the "Data Entry" to the "Impacts" worksheet is the unit of measure. Indeed, in the "Data Entry" sheet the data entered concerning quantities must be referred to one year of operations while in the "Impacts" worksheet these data will be made explicit for the declared unit, the module. The only difference concerns the "Componenti" (components) (Fig. 17) for which, in both worksheets, relevant data are referred to the UD.


D41 ='Data Entry'!D41

	A	B	C	D
1				
2			Unità di misura	Dati
3				
39	3	Componenti		
40		COMPONENTI E/O SEMILAVORATI IN ENTRATA AL PROCESSO		Peso del componente
41		Vetro anteriore	kg/modulo	[redacted]
42		Vetro anteriore -	%	
43		Vetro anteriore -	%	
44		Vetro anteriore - fornitore 3	%	
45		Vetro anteriore - fornitore 4	%	
46		Vetro anteriore - fornitore 5	%	
47		Vetro anteriore - fornitore 6 (con suoi fattori di emissione)	%	

Fig. 17 D41 cell has the same value of the D41 "Data Entry" cell

However, since in the "Impacts" worksheet the calculations take place, in some processes of the system boundaries, specific tables, which represent the novelty in respect to the Data Entry, are included. These tables are the following:

- "Composizione del mix" (Mix composition) (Fig. 18): the electricity taken from the different types of grids i.e., standard mix grid, hydroelectric renewable grid, photovoltaic renewable grid, wind renewable grid and geothermal grid, sum up with the self-generated electricity must be equal to the total consumptions of electric energy. The table shows the different percentage of withdrawns from the various grids and the percentage related to the type of self-generated electricity. The table is set up with a formula that if the sum of the percentages gives 100%, the check gives as output "ok", otherwise it gives "check".

Energia Elettrica			
CONSUMI TOTALI DI ENERGIA ELETTRICA			
			COMPOSIZIONE DEL MIX
			%
E.E. Prelevata da rete mix standard			
E.E. Prelevata da rete rinnovabile - idroelettrico			
E.E Prelevata da rete rinnovabile fotovoltaico			
E.E Prelevata da rete rinnovabile eolico			
E.E Prelevata da rete geotermico			
Totale da rete			
AUTOPRODUZIONE DI ENERGIA ELETTRICA			
Fotovoltaico			
Energia elettrica prodotta e autoconsumata			
Trigenerazione			
Energia elettrica prodotta e autoconsumata			
		Check composizione mix	ok

Fig. 18 “Composizione del mix” (mix composition) table

- “Modulo fotovoltaico” (Photovoltaic module) (Fig. 19): this specific type of PV panel has an estimated 30 years of life (EPDItaly, 2020), as an example figure 16 shows the firsts 10 years. In this table, given a module power decay of 0,25% per year, the module power considering the decay and the annual production in kWh/year is computed.

In the “module power considering decay” column, in each cell the module power of one year is multiplied for 1-0,25% so that the value of the successive year is computed.

In the “annual production” column, the annual production of one year has been divided by the “module power considering decay” value of the same year. Then, the result has been multiplied for the “module power considering decay” of the successive year to find the final value. This procedure has been replicated for each cell.

Modulo - 30 anni di vita, producibilità max, decadimento=	0,25%	**decadimento potenza modulo %**	**potenza modulo considerando decadimento**	**produzione annua [kWh/anno]**
anno 0	**0**	0,00%		
anno 1	**1**	0,25%		
anno 2	**2**	0,25%		
anno 3	**3**	0,25%		
anno 4	**4**	0,25%		
anno 5	**5**	0,25%		
anno 6	**6**	0,25%		
anno 7	**7**	0,25%		
anno 8	**8**	0,25%		
anno 9	**9**	0,25%		
anno 10	**10**	0,25%		

Fig. 19 “Modulo fotovoltaico” (photovoltaic module) table

To provide a clearer visualization for the reader, the columns of the Excel worksheet “Impacts” described so far run from “A” to “N” column. Furthermore, the second part of the “Impacts” worksheet, which will now be described, extends to the right continuing into the adjacent columns, so from column “O” onwards. This second part of the worksheet has been set in a way to compute the total GWP (Global Warming Potential) of activities and transports. The Total GWP comprehends (https://www.environdec.com):

- Fossil-GWP: resulting from the use of fossil resources;
- Biogenic-GWP: arising from the use of biogenic sources;
- LULUC-GWP: referring to land use and its modifications

This second part of the worksheet has been set up highlighting three different column sections: emission factors of activities, emission factors of transports and total impacts. According to EPA (United States Environmental Protection Agency), an emissions factor, which is expressed in $kgCO_2eq$ terms, is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (e.g., kilograms of particulate emitted per megagram of coal burned). Such factors facilitate estimation of emissions from various sources of air pollution. In most cases, these factors are simply averages of all available data of acceptable quality and are generally assumed to be representative of long-term averages for all facilities in the source category (i.e., a population average). Moreover, these data are updated whenever a new study or report about it is published. Thus, emission factors are an integral part of the Carbon Footprint calculation: in the Ecoinvent v3.8 database they are already made explicit in $kgCO_2eq$, a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP) (https://www.ec.europa.eu).

Firstly, the emission factors of activities have been defined: in the sheet the relative section covers columns from “O” to “Q”. They have been extracted from the Ecoinvent v3.8 database based on the specific boundary system considered: each material, process or activity of the boundary system has a value for each of the three typologies of emission factors. Figures 20 and 21 shows two examples.

Figure 20 shows the emission factors considered for the electric energy: emission factors of the electric energy withdrawals activities and emission factors of the self-producing electric energy activities.

Figure 21 shows the emission factors considered for the waste: emission factors of landfilling, incineration, and recovery activities i.e., the three possible destinations for waste.

A	B	O	P	Q
		FATTORI DI EMISSIONE ATTIVITA' (da database)		
		FOSSILE	BIOGENICA	LULUC
		kg CO2 eq	kg CO2 eq	kg CO2 eq
1	**Energia Elettrica**			
	CONSUMI TOTALI DI ENERGIA ELETTRICA			
	E.E. Prelevata da rete mix standard	5,61E-01	2,52E-03	1,82E-05
	E.E. Prelevata da rete rinnovabile - idroelettrico	0,022896	0,0005402	1,80E-06
	E.E Prelevata da rete rinnovabile fotovoltaico	1,08E-08	3,82E-10	2,06E-11
	E.E Prelevata da rete rinnovabile eolico	0,00016	0,0000001	0,000000036
	E.E Prelevata da rete geotermico	5,83E-06	5,65E-09	2,57E-10
	Totale da rete			
	AUTOPRODUZIONE DI ENERGIA ELETTRICA			
	Fotovoltaico			
	Energia elettrica prodotta e autoconsumata	2,058E-06	7,27E-08	3,92E-09
	Trigenerazione			
	Energia elettrica prodotta e autoconsumata	0,771207	0,000137	8,64E-06

Fig. 20 "Energia Elettrica" (Electric Energy) emission factors

A	B	O	P	Q
		FATTORI DI EMISSIONE ATTIVITA' (da database)		
		FOSSILE	BIOGENICA	LULUC
		kg CO2 eq	kg CO2 eq	kg CO2 eq
8	**Rifiuti**			
		0,313685	0,0004124	0,00015712
Codice EWC	**Nome del rifiuto**	0,259621	3,377E-05	5,58001E-06
160306	rifiuti organici, diversi da quelli di cui alla voce 16 03 05	0,006802	3,29E-07	5,56E-08
160505	gas in contenitori a pressione, diversi da quelli di cui alla voce 16 05 04			

Fig. 21 "Rifiuti" (Wastes) emission factors

The extraction of emission factors also covered the remaining processes of the system boundaries.

Adjacent to the columns of emission factors, a section regarding the transport emission factors has been created (columns from "S" to "AA"). However, this section has been specifically created for the materials which require transportation from the supplier to the company site where the PV panel production takes place. Reference is made to components, auxiliaries, and packaging. Furthermore, for each of these three materials, three typologies of transportation, which constitutes the three possible materials' ways of transport, have been identified: by vehicle, by ship and by aircraft. Even in this case, the emission factors of these ways of transportation have been extracted from the Ecoinvent v3.8 database.

B	S	T	U	V	W	X	Y	Z	AA
	FATTORE DI EMISSIONE - AUTOMEZZO			FATTORE DI EMISSIONE - NAVE			FATTORE DI EMISSIONE - AEREO		
	FOSSILE	BIOGENICA	LULUC	FOSSILE	BIOGENICA	LULUC	FOSSILE	BIOGENICA	LULUC
	kg CO2 eq	kg CO2 eq	kg CO2 eq	kg CO2 eq	kg CO2 eq	kg CO2 eq	kg CO2 eq	kg CO2 eq	kg CO2 eq
Componenti									
COMPONENTI E/O SEMILAVORATI IN ENTRATA AL PROCESSO									
Vetro anteriore									
Vetro anteriore -	0,000139496	1,024E-08	2,361E-09	8,79E-06	5,224E-10	1,43E-10	0,0007122	4,42E-08	8,7E-09
Vetro anteriore -	0,000139496	1,024E-08	2,361E-09	8,79E-06	5,224E-10	1,43E-10	0,0007122	4,42E-08	8,7E-09
Vetro anteriore - fornitore 3	0,000139496	1,024E-08	2,361E-09	8,79E-06	5,224E-10	1,43E-10	0,0007122	4,42E-08	8,7E-09
Vetro anteriore - fornitore 4	0,000139496	1,024E-08	2,361E-09	8,79E-06	5,224E-10	1,43E-10	0,0007122	4,42E-08	8,7E-09
Vetro anteriore - fornitore 5	0,000139496	1,024E-08	2,361E-09	8,79E-06	5,224E-10	1,43E-10	0,0007122	4,42E-08	8,7E-09
Vetro anteriore - fornitore 6	0,000139496	1,024E-08	2,361E-09	8,79E-06	5,224E-10	1,43E-10	0,0007122	4,42E-08	8,7E-09
Vetro posteriore									
Vetro posteriore -	0,000139496	1,024E-08	2,361E-09	8,79E-06	5,224E-10	1,43E-10	0,0007122	4,42E-08	8,7E-09
Vetro posteriore -	0,000139496	1,024E-08	2,361E-09	8,79E-06	5,224E-10	1,43E-10	0,0007122	4,42E-08	8,7E-09
Vetro posteriore - fornitore 3	0,000139496	1,024E-08	2,361E-09	8,79E-06	5,224E-10	1,43E-10	0,0007122	4,42E-08	8,7E-09
Vetro posteriore - fornitore 4	0,000139496	1,024E-08	2,361E-09	8,79E-06	5,224E-10	1,43E-10	0,0007122	4,42E-08	8,7E-09
Vetro posteriore - fornitore 5	0,000139496	1,024E-08	2,361E-09	8,79E-06	5,224E-10	1,43E-10	0,0007122	4,42E-08	8,7E-09
Vetro posteriore - fornitore 6	0,000139496	1,024E-08	2,361E-09	8,79E-06	5,224E-10	1,43E-10	0,0007122	4,42E-08	8,7E-09

Fig. 22 Transport emission factors of “componenti” (components)

Figure 22 shows the emission factors extracted for the three typologies of transports of components. Focusing on “FATTORI DI EMISSIONE – AUTOMEZZO” (Emission Factors- Vehicle), as it is possible to note the three values of emission factors are the same for every material, regardless of where the supplier is located. This also occurs for ship and aircraft emission factors. Thus, these values will be identical even for the other materials which necessitate of transports: auxiliaries and packaging. The reason why the values are the same is that since an emission factor is related to the mean of transport, it does not vary as the type of material transported and the location of departure and arrival of the supplier change. Standard means (standard vehicle, standard ship, standard aircraft) are considered for each type of transport.

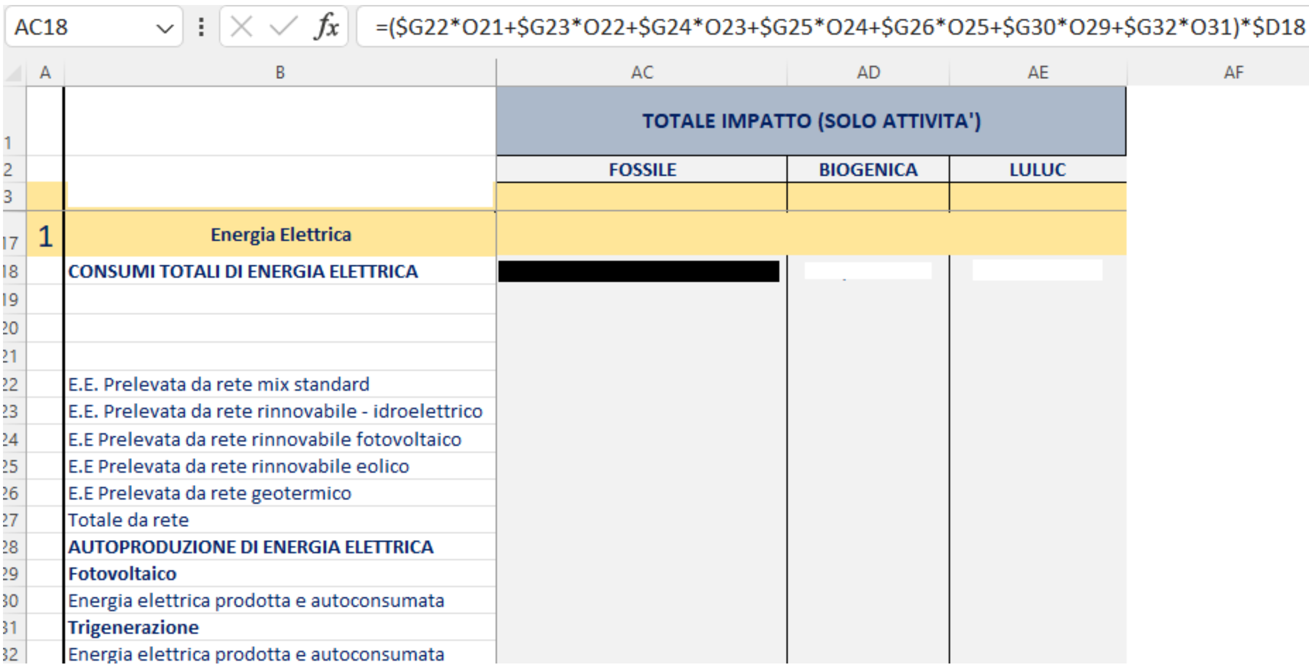
These columns of emission factors of activities and transportations did not involve any type of calculation: it is in fact only a matter of entering data extracted from the Ecoinvent v3.8 database in the appropriate cells.

Adjacent to the first two sections of emission factors, a third section has been created. This is the section where calculations take place: specifically, the computation of the total impact of activities and transports has been made. This part is organised in a way to compute the total impact of activities and transports, considering both the data of the very first columns (from “A” to “N”) and the emission factors values of the successive two sections, through formulas. This third section is divided in three sub-sections, covering the columns from “AC” to “AK” (Fig. 23): one calculates the impact of activities, one the impact of transports and the third summarizes the results of the first two.

AC	AD	AE	AF	AG	AH	AI	AJ	AK
TOTALE IMPATTO (SOLO ATTIVITA')			TOTALE IMPATTO (SOLO TRASPORTO FORNITORI)			TOTALE IMPATTI		
FOSSILE	BIOGENICA	LULUC	FOSSILE	BIOGENICA	LULUC	totale impatto fossile	totale impatto biogenica	totale impatto luluc
kg CO2 eq/UD	kg CO2 eq/UD	kg CO2 eq/UD	kg CO2 eq/UD	kg CO2 eq/UD	kg CO2 eq/UD	kg CO2 eq/UD	kg CO2 eq/UD	kg CO2 eq/UD

Fig. 23 Organisation of the third section

In the "TOTALE IMPATTO (SOLO ATTIVITA')" columns, the impact value originated by electric energy consumption has been calculated by multiplying the mix composition of the total consumptions of electric energy with the respective emission factor reported in the first section: i.e for the fossil column the fossil emission factor, for the biogenic column the biogenic emission factor and for the luluc column the luluc emission factor. In Figure 24, an example regarding the total impact of electric energy for the fossil GWP is reported.



AC18 =($G22*O21+$G23*O22+$G24*O23+$G25*O24+$G26*O25+$G30*O29+$G32*O31)*$D18

	A	B	AC	AD	AE
1			TOTALE IMPATTO (SOLO ATTIVITA')		
2			FOSSILE	BIOGENICA	LULUC
3					
17	1	Energia Elettrica			
18		CONSUMI TOTALI DI ENERGIA ELETTRICA	[redacted]		
19					
20					
21					
22		E.E. Prelevata da rete mix standard			
23		E.E. Prelevata da rete rinnovabile - idroelettrico			
24		E.E Prelevata da rete rinnovabile fotovoltaico			
25		E.E Prelevata da rete rinnovabile eolico			
26		E.E Prelevata da rete geotermico			
27		Totale da rete			
28		AUTOPRODUZIONE DI ENERGIA ELETTRICA			
29		Fotovoltaico			
30		Energia elettrica prodotta e autoconsumata			
31		Trigenerazione			
32		Energia elettrica prodotta e autoconsumata			

Fig. 24 Covered values of the electric energy total impact

In addition to the electric energy, other specific formulas were set up for:

- Water, the values of the three impacts have been computed multiplying the consumed quantity of water by the percentage for productive use and by the relative emission factor.
- Wastes impacts have been calculated multiplying the total amount of waste of one typology of waste disposal, calculated in kg waste/UD, by the relative emission factor.
- Packaging impacts have been computed multiplying the weight (in kg/UD) of each Bi-pack component with the respective emission factor.

In the “TOTALE IMPATTO (SOLO ATTIVITA’)” sub-section, apart from the specific calculation required by the electric energy and water, the remaining processes’ elements impact values have been calculated simply multiplying the respective quantity, whose values are in the first part of the “Impacts” worksheet specifically in the “D” column, with the respective emission factor of fossil, biogenic and LULUC.

In the “TOTALE IMPATTO (SOLO TRASPORTO FORNITORI)” sub-section, formulas have been created only for the materials which require transports. The formula performed to compute the fossil, biogenic and LULUC impact values consists in three addends (an example in Figure 25):

1- weight of the component multiplied by the product between the distance covered by land and the relative emission factor.

2- weight of the component multiplied by the product between the distance covered by sea and the relative emission factor.

3- weight of the component multiplied by the product between the distance covered by air and the relative emission factor.

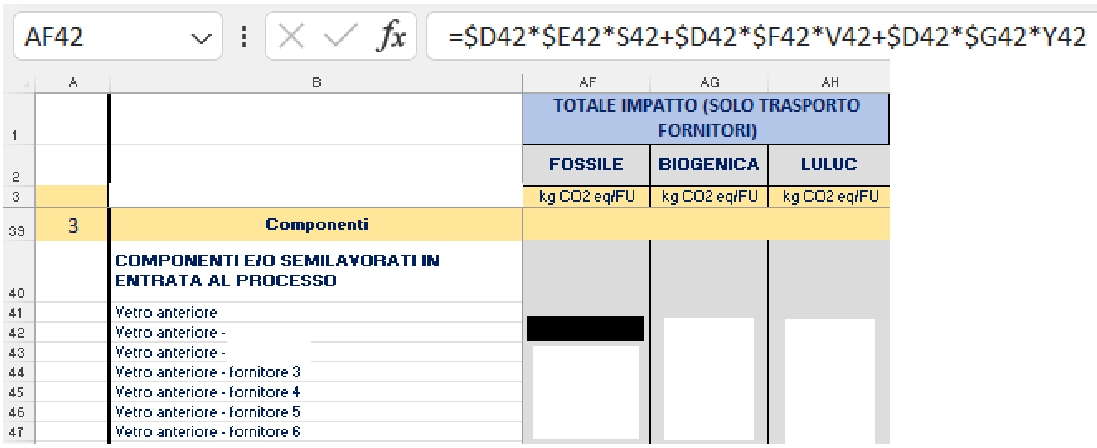


Fig. 25 The three addends of the formula calculating the fossil transport impact

The same formula structure with the three addends has been applied even for the auxiliaries but with the respective quantities, distances, and emission factors values. Instead, for the packaging, the formula performed to compute the fossil, biogenic and LULUC impact values consists in these three addends:

1- weight (in kg/UD) of each Bi-pack component multiplied by the product between the distance covered by land and the relative emission factor.

2- weight (in kg/UD) of each Bi-pack component multiplied by the product between the distance covered by sea and the relative emission factor.

3- weight (in kg/UD) of each Bi-pack component multiplied by the product between the distance covered by air and the relative emission factor.

Both for "TOTALE IMPATTO (SOLO ATTIVITA')" and "TOTALE IMPATTO (SOLO TRASPORTO FORNITORI)", at the end of each list of calculations, one cell was always dedicated to report the totals derived from summing up all the values computed above, as Figure 26 shows as an example.

	TOTALE IMPATTO (SOLO ATTIVITA')		
	FOSSILE	BIOGENICA	LULUC
Wafer - fornitore 2	0,00E+00	0,00E+00	0,00E+00
Wafer - fornitore 3	0,00E+00	0,00E+00	0,00E+00
Wafer - fornitore 4	0,00E+00	0,00E+00	0,00E+00
Wafer - fornitore 5	0,00E+00	0,00E+00	0,00E+00
Incapsulante			
Incapsulante -			
Incapsulante - fornitore 2	0,00E+00	0,00E+00	0,00E+00
Incapsulante - fornitore 3	0,00E+00	0,00E+00	0,00E+00
Incapsulante - fornitore 4	0,00E+00	0,00E+00	0,00E+00
Incapsulante - fornitore 5	0,00E+00	0,00E+00	0,00E+00
Telaio			
Telaio -			
Telaio - fornitore 2	0,00E+00	0,00E+00	0,00E+00
Telaio - fornitore 3	0,00E+00	0,00E+00	0,00E+00
Telaio - fornitore 4	0,00E+00	0,00E+00	0,00E+00
Telaio - fornitore 5	0,00E+00	0,00E+00	0,00E+00
	[redacted]	[redacted]	[redacted]

Fig. 26 The black cells cover the values representing the sum of all the above values

As totals of the "TOTALE IMPATTO (SOLO ATTIVITA')" and "TOTALE IMPATTO (SOLO TRASPORTO FORNITORI)" sub-sections were obtained, they have been reported in the third sub-section, the "TOTALE IMPATTI" sub-section, as Figure 27 shows. In case where transports were not considered, only the results of the activities have been reported.

A	B	AI	AJ	AK
		TOTALE IMPATTI		
		totale impatto fossile	totale impatto biogenica	totale impatto luluc
		kg CO2 eq/FU	kg CO2 eq/FU	kg CO2 eq/FU
3	Componenti			
	COMPONENTI E/O SEMILAVORATI IN ENTRATA AL PROCESSO	TRASPORTO COMPONENTI DEL MODULO FOTOVOLTAICO		
	Vetro anteriore			
	Vetro anteriore -			
	Vetro anteriore -	PRODUZIONE COMPONENTI DEL MODULO FOTOVOLTAICO		
	Vetro anteriore - fornitore 3			
	Vetro anteriore - fornitore 4			
	Vetro anteriore - fornitore 5			
	Vetro anteriore - fornitore 6			

Fig. 27 Part of the "TOTALE IMPATTI" sub-section

For each of the nine processes included in the system boundaries, the results obtained on the “TOTALE IMPATTI” sub-section were then again summed up to end with a unique number of total GWP related to that system boundary (from columns “AL” to “AN”): Figure 28 shows the total of components’ production as the sum of the three impacts. This happens even for transports. In case where transports were not considered, only the results of the activities were reported.

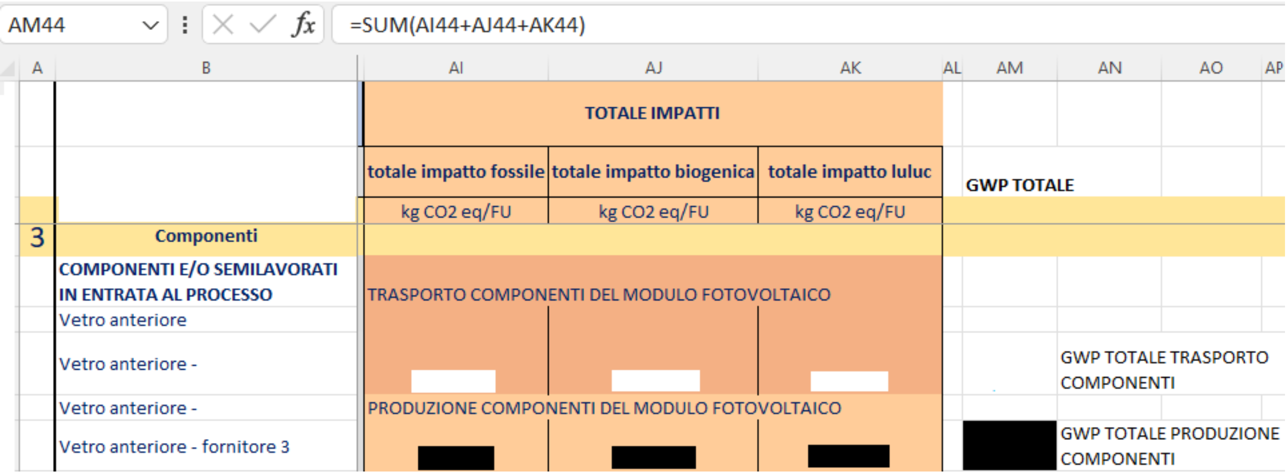


Fig. 28 Example of total GWP calculation

2.3.3 Results worksheet

The third worksheet, the "Results" one, reports the product CF results (from cradle to gate): results indicators per declared unit (one module) (Fig. 29) and results indicators per functional unit (kWh produced by a module in 30 years) (Fig. 30).

In Fig. 29 the table showing results indicators per declared unit (one module) has been reported. Specifically, upstream and core phases results have been divided in fossil, biogenic and LULUC GWP firstly and then summed up in a total GWP. For the upstream phase the impact of the production of all components, auxiliaries and packaging for the photovoltaic module have been reported. The core phase, considering inbound transportation and all the contributions (electric energy, fuel consumption, atmospheric emissions, wastes and F-Gas) to photovoltaic module assembly has been reported. Furthermore, the table showing results indicators per functional unit (Fig. 30) has also been made explicit both for the upstream and core phase: however, in this table the values are derived from the division between the values of the table per declared unit divided by the effective energy produced in 30 years, data present in the "Data Entry" sheet.

RISULTATI LCA DI PRODOTTO (dalla-culla-al-cancello)				
	Risultati indicatori per unità dichiarata (1 modulo)			
	GWP Fossile	GWP Biogenica	GWP Uso del suolo	GWP TOTALE
UPSTREAM	kg CO_2 eq/UD	kg CO_2 eq/UD	kg CO_2 eq/UD	**kg CO_2 eq/UD**
Produzione componenti del modulo fotovoltaico	[redacted]	[redacted]	[redacted]	[redacted]
Vetro anteriore - Malaysia	[redacted]	[redacted]	[redacted]	[redacted]
Vetro anteriore - Vietnam	[redacted]	[redacted]	[redacted]	[redacted]
Vetro posteriore - Malaysia	[redacted]	[redacted]	[redacted]	[redacted]
Vetro posteriore - Vietnam	[redacted]	[redacted]	[redacted]	[redacted]
ECA (Ag) - Belgium	[redacted]	[redacted]	[redacted]	[redacted]
Pasta d'argento (Ag) - Giappone	[redacted]	[redacted]	[redacted]	[redacted]
Interconnessione a nastro - Austria	[redacted]	[redacted]	[redacted]	[redacted]
Silicone - Germania	[redacted]	[redacted]	[redacted]	[redacted]
Stringi nastro - Austria	[redacted]	[redacted]	[redacted]	[redacted]
Scatola di giunzione - Cina (Jiangsu)	[redacted]	[redacted]	[redacted]	[redacted]
Wafer - Cina (Shaanxi)	[redacted]	[redacted]	[redacted]	[redacted]
Wafer - Cina (Tianjin)	[redacted]	[redacted]	[redacted]	[redacted]
Incapsulante - Cina (Zhejiang)	[redacted]	[redacted]	[redacted]	[redacted]
Telaio - Cina (Jiangsu)	[redacted]	[redacted]	[redacted]	[redacted]
Produzione ausiliari	[redacted]	[redacted]	[redacted]	[redacted]
Produzione imballaggi del modulo fotovoltaico	[redacted]	[redacted]	[redacted]	[redacted]
TOTALE UPSTREAM	[redacted]	[redacted]	[redacted]	[redacted]
CORE				
TRASPORTI IN ENTRATA	[redacted]	[redacted]	[redacted]	[redacted]
ASSEMBLAGGIO M. FOTOVOLTAICO - en.elettrica	[redacted]	[redacted]	[redacted]	[redacted]
ASSEMBLAGGIO M. FOTOVOLTAICO - consumo combustibili	[redacted]	[redacted]	[redacted]	[redacted]
ASSEMBLAGGIO M. FOTOVOLTAICO - acqua	[redacted]	[redacted]	[redacted]	[redacted]
ASSEMBLAGGIO M. FOTOVOLTAICO - emissioni in atmosfera	[redacted]	[redacted]	[redacted]	[redacted]
ASSEMBLAGGIO M. FOTOVOLTAICO - rifiuti	[redacted]	[redacted]	[redacted]	[redacted]
ASSEMBLAGGIO M. FOTOVOLTAICO - F Gas	[redacted]	[redacted]	[redacted]	[redacted]
TOTALE CORE	[redacted]	[redacted]	[redacted]	[redacted]
TOTALE	[redacted]	[redacted]	[redacted]	[redacted]

Fig. 29 Results indicators for declared unit

Risultati indicatori per unità funzionale (kWh prodotto da 1 modulo, in 30 anni)				
	GWP Fossile	GWP Biogenica	GWP Uso del suolo	GWP TOTALE
UPSTREAM	kg CO2 eq/FU	kg CO2 eq/FU	kg CO2 eq/FU	kg CO2 eq/FU
Produzione componenti del modulo fotovoltaico	[redacted]	[redacted]	[redacted]	[redacted]
Produzione ausiliari	[redacted]	[redacted]	[redacted]	[redacted]
Produzione imballaggi del modulo fotovoltaico	[redacted]	[redacted]	[redacted]	[redacted]
TOTALE UPSTREAM	[redacted]	[redacted]	[redacted]	[redacted]
CORE				
TRASPORTI IN ENTRATA	[redacted]	[redacted]	[redacted]	[redacted]
ASSEMBLAGGIO M. FOTOVOLTAICO - en.elettrica	[redacted]	[redacted]	[redacted]	[redacted]
ASSEMBLAGGIO M. FOTOVOLTAICO - consumo combustibili	[redacted]	[redacted]	[redacted]	[redacted]
ASSEMBLAGGIO M. FOTOVOLTAICO - acqua	[redacted]	[redacted]	[redacted]	[redacted]
ASSEMBLAGGIO M. FOTOVOLTAICO - emissioni in atmosfera	[redacted]	[redacted]	[redacted]	[redacted]
ASSEMBLAGGIO M. FOTOVOLTAICO - rifiuti	[redacted]	[redacted]	[redacted]	[redacted]
ASSEMBLAGGIO M. FOTOVOLTAICO - F Gas	[redacted]	[redacted]	[redacted]	[redacted]
TOTALE CORE	[redacted]	[redacted]	[redacted]	[redacted]
TOTALE	[redacted]	[redacted]	[redacted]	[redacted]

Fig. 30 Results indicators for functional unit

2.3.4 Data settings for checking

Data described in the last chapter referred to all the data involved in filling in the tool-CF. "Data Entry" is the worksheet where the personal customer company must insert data. The total GWP of the different activities involved in producing this PV panel is reported in the "Results" worksheet: it is especially useful for the customer company since it shows the impact value based on data entered in "Data entry". These worksheets setting indeed allows the customer company to study which activity is the most impactful and it allows to consider changing the strategy regarding the choice of the type of materials and their supplier. Values in the "Results" worksheet are the result of applying the formulas set in the "Impacts" worksheet: once changed by the customer company a value in the "Data Entry" sheet, being the "Impacts" worksheet linked to it, the formulas work with the new value reporting a final value in the "Results" worksheet that will be different.

Once the "Data Entry" and "Impacts" worksheets have been built up in detail with the recognition of the processes included in the system boundaries, units of measure and quantities, formulas in the "Impacts" sheet have been set up. Initially, the formulas related empty cells with no numeric values inside: at this stage, in fact, both worksheets are set but in the cells where there should be numeric values there is no value. After having set the formulas, the value "1" was then placed, as a test, in all the cells corresponding to quantities to verify the correct functioning of formulas and that they would not give as a result wordings such as "DIV/0!" or "#VALUE" because this would have meant no value and so no information. This test involved both the "Data Entry" sheet, entering the value "1" in all those cells where the customer company will have to enter their quantities, and "Impacts", where the value "1" besides that being automatically reported by cells that are linked to the Data Entry, it has also been entered in the cells corresponding to the emission factors which were not extracted yet from Ecoinvent 3.8 (Fig. 31).

		FATTORI DI EMISSIONE ATTIVITA' (da database)		
		FOSSILE	BIOGENICA	LULUC
		kg CO2 eq	kg CO2 eq	kg CO2 eq
3	**Componenti**			
	COMPONENTI E/O SEMILAVORATI IN ENTRATA AL PROCESSO			
	Vetro anteriore			
	Vetro anteriore -			
	Vetro anteriore -			
	Vetro anteriore - fornitore 3	1	1	1
	Vetro anteriore - fornitore 4	1	1	1
	Vetro anteriore - fornitore 5	1	1	1
	Vetro anteriore - fornitore 6 (con suoi fattori di emissione)	1	1	1
	Vetro posteriore			
	Vetro posteriore -			
	Vetro posteriore -			
	Vetro posteriore - fornitore 3	1	1	1
	Vetro posteriore - fornitore 4	1	1	1
	Vetro posteriore - fornitore 5	1	1	1
	Vetro posteriore - fornitore 6 (con suoi fattori di emissione)	1	1	1
	ECA (Ag)			
	ECA (Ag) -			
	Eca (Ag) - fornitore 2	1	1	1
	Eca (Ag) - fornitore 3	1	1	1
	Eca (Ag) - fornitore 4	1	1	1
	Eca (Ag) -fornitore 5 (con suoi fattori di emissione)	1	1	1

Fig. 31 Example of entering “1” value as a test in “Impacts” emission factor table

Once the test was passed and the correct functioning of the formulas checked, data were subsequently entered. In the “Data Entry” instead of the “1” values, some data provided by the customer company have been entered, where available. In the “Impacts” worksheet, instead, the “1” values at the level of the emission factors have been replaced by the real emission factors extracted from the Ecoinvent v3.8 database.

2.3.5 BOM (Bill of materials)

A BOM (Bill of Materials), is a comprehensive list of all the materials, components, and subassemblies required to manufacture a product. A BOM essentially provides a structure for making a product repeatably every time, thereby introducing a degree of standardization to the production process. BOMs are a company’s guide and recipe for building their product. (Lauri K. H., 2023). A bill of materials contains the quantity or volume of each item used and it may also contain information such as cost, lead time, waste factors, and other work-centre data required to produce the finished item. In the case-study, the BOM provided by the customer company includes:

- material: component of the PV panel. At the end of the components’ list, the total weight of the module, derived from the sum of each component, was shown;

- part weight: how much that part weights, in terms of kg/module;

- percentage of total part weight: how much each part weights, in percentage, respect to the total weight of the module;

- supplier: the name of the supplier which provides the materials;

- country of origin: the country where that shop is located;

- country of origin – main component: the country of origin of the material's main component.

- main component: typology of the material used for that kind of component;

- recyclable: if that component could be recyclable;

- recycled: if that component is recycled

The customer company provided the BOMs through an Excel file. Not having a BOM, or having an inaccurate BOM, can lead to waste, inefficiency, and errors in the manufacturing process (Lauri K. H., 2023).

In addition to the BOM, the consulting company needed more data to build the tool-CF. Indeed, the consulting company, in this case Ambiente Italia Srl, prepared a data collection checklist which consists of an Excel workbook, where each sheet has certain data to be entered (energy, fuels, water, emissions, auxiliaries, packaging, waste, etc.). The customer company had entered in the data collection checklist the data requested and then sent it to the consulting company. Then, once the "Data Entry" sheet was set up, those data have been entered.

"Data Entry" is the only open sheet to the customer company: once the tool-CF was set up and entered all the above data , the consulting society will give the tool to the customer company which will focus on entering their providers of materials and on the analysis the relative impacts.

2.3.6 Calculation software, databases, and methodologies

In an ever-changing world, where companies no longer look only at profit, but also engage in social protection and aim to be more sustainable, many of them struggle to find out how to embed sustainability into their daily operations, how to make their sustainability efforts measurable and how to turn their sustainability initiatives into a competitive advantage. In this sense, LCA is recognized as the leading method to measure product sustainability, as it is able to quantify a wide range of environmental themes and provide a deep understanding of impacts, from cradle to grave (https://network.simapro.com/). There exist computational software such as SimaPro, open LCA and Gabi (Ganzheitliche Bilanzierung) which simplify analysis in LCA studies, enabling the creation of the life cycle model of the analysed product and facilitating the visualization and evaluation of potential environmental impacts. ***SimaPro*** is the leading LCA software and through it, complex life cycles can be modelled and analysed transparently and systematically, environmental hotspots can be identified, and different strategies for impact reduction can be evaluated (https://to-be.it/strumenti/simapro.com/). ***Open LCA*** is world-wide the only free, open source LCA software that can be used for professional ecological, social and economical life cycle assessments. Among other things, openLCA can be used for LCAs, carbon & water footprints, eco-design, environmental product declarations, life cycle costing and social life cycle assessment. Sphera's product sustainability software, ***GaBi***, combines the industry's best life cycle assessment (LCA) software, with modelling and reporting capabilities, with reliable and consistent environmental data. With more than 20 industry-specific databases, Sphera's analysis tools enable companies to understand the environmental impact of their entire product life cycle and make fact-based decisions.

The data, regardless of the software used, are processed by choosing among multiple methods of impact assessment, which may have more or less articulated structures and include several steps, of which only the characterization, the first one, is mandatory. Eco-Indicator 99 and ReCiPe are amongst the most used impact assessment methods. Eco-Indicator 99 method, developed in 1999 by PRé Consultants B.V., helps designers to make an environmental assessment of a product by calculating eco-indicator scores for materials and processes used. The resulting scores provide an indication of areas for product improvements (Mannan S., 2012). ReCiPe, developed in 2008, through cooperation between RIVM, Radboud University Nijmegen, Leiden University and PRé Sustainability, has as the main objective to transform the long list of life cycle inventory results into a limited number of indicator scores which express the relative severity on an environmental impact category (pre-sustainability.com). Within the software are numerous European and international databases, which are periodically updated. The databases are inventory datasets and are an indispensable support for LCA studies: from these are derived the numerous input and output data of matter and energy that allow the analysis of the system or product under study to be completed. There are some databases that contain information related to multiple industry sectors, such as Ecoinvent which is recognized as the largest and most consistent LCI database on the market, while others cover specific areas, such as for agribusiness. The Ecoinvent LCI data can be used for e.g. life cycle assessment, life cycle management, carbon footprint assessment, water footprint assessment, environmental performance monitoring, product design and eco-design (DfE) or Environmental Product Declarations (EPD). Ecoinvent is one of the most extensive international LCI databases with more than 15,000 LCI datasets in a large variety of areas from energy supply to transports to construction materials, metal processing and many more. The databases appear to be more or less integrated with specific software, for example Ecoinvent with SimaPro, or to be more generic in nature, including the ELCD (European Reference Life Cycle Data System) database, which supports multiple calculation software. For the case-study, the Ecoinvent v3.8 database is used, integrated in SimaPro, and data are elaborated with the IPCC (2013) method.

2.3.7 Tool dataset

SimaPro, developed by the Dutch company PRè (Product Ecology Consultant), has been the world's leading LCA software for 30 years, used by companies, universities, research institutes in more than 80 countries (https://network.simapro.com/). SimaPro is a professional tool for collecting, analyzing and monitoring the environmental performance of products and services. It helps effectively to apply the sustainability expertise to empower informed decision-making, change product life cycles for the better, and increase company's positive impact. It gives the possibility to turn sustainability objectives of a company into action through life cycle assessment (LCA) and helps make sustainability efforts measurable. Rely on sustainability data to measure, analyse and compare the environmental performance of products and services and let the data drive the decision-making process. This software can be used for various applications: sustainability reporting, carbon, environmental, social and water footprinting, biodiversity assessments, sustainable product design, and more. In the Fig. 32 an example of the SimaPro worksheet is visible: to easily find the required material/process from the large inventory database, determine the material/process type and search it accordingly under the respective categories (PRè Sustainability, 2023).

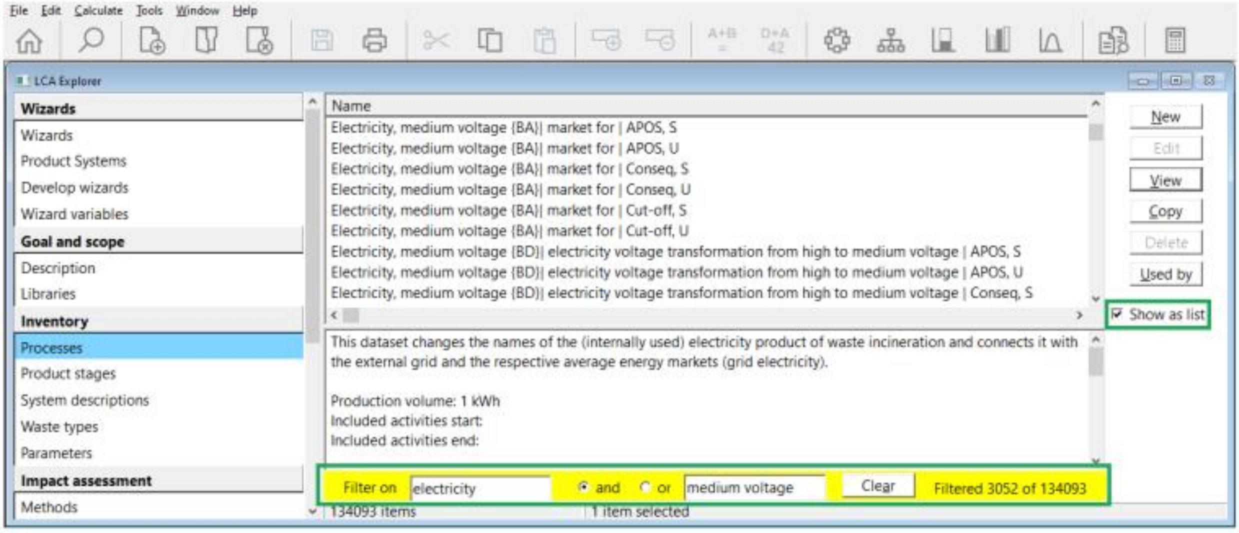


Fig. 32 Example of SimaPro sheet (PRè Sustainability, 2023)

In the case-study, data were extracted from the Ecoinvent v3.8 database. The Ecoinvent Database enables users to gain a deeper understanding of the environmental impacts of their products and services. It is a repository covering a diverse range of sectors on global and regional level. It currently contains more than 18.000 activities, modelling human activities or processes. Ecoinvent datasets contain information on the industrial or agricultural process they model, measuring the natural resources withdrawn from the environment, the emissions released to the water, soil and air, the products demanded from other processes (electricity), and of course, the products, co-products and wastes produced (https://ecoinvent.org/the-ecoinvent-association/software-tools/).

In the data entry phase, the starting point was the extraction of data from the database, specifically data concerning the emission factors of different components and activities. Emissions factors have long been the fundamental tool in developing national, regional, state, and local emissions inventories for air quality management decisions and in developing emissions control strategies.

Besides SimaPro, two kinds of sites have been used:

- Searates has been used to calculate the trajectory and the distances in terms of km of the suppliers which transport goods by ship. The customer company provided a list of suppliers and some of them require the transportation by ship. Specifically, "Shipping Distance & Time Calculator" tool of Searates has been used. It's a logistics application created to estimate distances and times between sea routes under particular parameters (https://www.searates.com/it/). It works entering the origin and destination port and then the system displays data about distances and time estimates from SeaRates database. The involved calculations are based on Open sources combined with information from various shipping lines and nautical agencies. This information has been collected for over ten years and is regularly updated (https://www.searates.com/it/).

- Google Maps. It was firstly named "Where 2 Technologies" by its founders Lars and Jens Eilstrup Rasmussen and later acquired by Google Inc. in 2004 which renamed this web-application to Google Maps (Mehta H. et al, 2019). This tool enables people to navigate and find the shortest and most convenient route to their desired destination. According to a recent survey, Google Maps has acquired almost 64 million users. Moreover, it has included new features like street-view, location of hospitals, cafes, police-stations and many more helpful features. The algorithms, techniques and technology used by Google Maps is cutting-edge and highly advanced (Mehta H. et al, 2019). The team of engineers at Google, preserve and analyze myriad datasets including historic and real-time data, which is what makes Google Maps so progressive and accurate. Indeed, in the case-study project the precise characteristics of this tool allow to compute in the most accurate way possible the distances of the known suppliers present in the BOM the customer company provided.

- Regarding the aircraft shipment method, no indication was given in reference to possible suppliers whose route had to be done by air so no type of site or shipment by air software were used.

2.4 Tool-CF using procedure

Preparing the document regarding the procedure for using the tool-CF has been the last phase of the project. Indeed, providing to the customer company the calculator alone is not useful since it does not include a concrete and detailed explanation for its correct use. In this sense, a proper document named "Management procedure of the tool-CF calculator for the photovoltaic panel" has been created. It consists in 6 sections where firstly an overview of the case-study product is given and subsequently the management of data entries in the calculator is explained. The 6 sections of the document are the following:

- Scope of the procedure: it defines the practices to be implemented for the correct use of the tool meeting the requirements of ISO norms and EPD Italy programme.
- Generality: it explains to whom the procedure is shared thus the customer company.
- Application field: it gives a general description of the customer company. It explains what the company stands for, what it is involved in, and what sectors it operates in.
- Data collection: it defines that for the compilation of the tool, the reference PCR must be used. Moreover, it states that primary data for the module fabrication stage should be

privileged, but in case they are not available, generic data could be useful as well. In addition, it defines the two types of data which may be entered in the calculator i.e site-specific data, provided by the company through the checklist and non-site-specific data, not directly related to the specific product and coming from the Ecoinvent v3.8 database.

- Variable data: data which constitute the set of information that is needed to feed the Data Entry are different and represent the variable data, which can also be characterized as primary data such that characterize each photovoltaic module and therefore differentiate one product from another and those which refer to the production in the plant related to a specific year
- Product system boundaries: it covers the processes from "cradle to gate" in the factory where PV module production takes place
- Identification and collection of site-specific and non-site-specific data
- Data relating to components, auxiliary materials and packaging
- Assembly data
- Data relating to emissions, F-Gas and water

➢ Entering data in the tool-CF: information regarding data entries in the tool-CF are briefly explained, the details are in Annex A.

➢ Output data of the tool-CF: which output data gives the tool (values), especially information about what to do when there are statements such as "DIV/0!" or "#VALORE".

➢ Annex A: tool-CF compilation instructions

➢ Annex B: self-monitoring checklist

3. RESULTS AND DISCUSSION: EXAMPLE OF TOOL-CF APPLICATION

This chapter shows how the tool-CF works through an example application. It is important to note that data in this chapter are for demonstration purposes only with the ultimate aim of verifying that the tool works properly. Indeed, any type of data used are true to reality, they are not the data provided by the customer company since they cannot be used being private data which cannot be published. However, only three typologies of data have not been modified:

- emission factors in the "Impacts" worksheet, which are data extracted from the Ecoinvent v3.8 database

- the component suppliers' location: Malaysia, Vietnam, Belgium, Japan, Germany, Austria and China. The transports' emission factors refer to the standard mean of transportation used (vehicle, ship, aircraft), not to the location of the supplier.

- productive site location: a city in South-Italy which will not be specifically mentioned for privacy reasons

The PV module is assumed to weigh 37 kg.

The Data Entry sheet filled with example data is reported in Appendix A. Accordingly, the results obtained are those reported in Figure 33 and 34. Figure 33 shows the results per declared unit while Figure 34 shows the results per functional unit.

RISULTATI LCA DI PRODOTTO (dalla-culla-al-cancello)				
	Risultati indicatori per unità dichiarata (1 modulo)			
	GWP Fossile	GWP Biogenica	GWP Uso del suolo	GWP TOTALE
UPSTREAM	kg CO_2 eq/UD	kg CO_2 eq/UD	kg CO_2 eq/UD	**kg CO_2 eq/UD**
Produzione componenti del modulo fotovoltaico	**3,36E+02**	**2,29E+00**	**8,81E-01**	**3,39E+02**
Vetro anteriore - Malaysia	1,92E+01	1,81E-01	4,93E-02	**1,94E+01**
Vetro anteriore - Vietnam	4,32E+00	2,88E-02	3,12E-03	**4,35E+00**
Vetro posteriore - Malaysia	1,92E+01	1,81E-01	4,93E-02	**1,94E+01**
Vetro posteriore - Vietnam	4,32E+00	2,88E-02	3,12E-03	**4,35E+00**
ECA (Ag) - Belgium	1,86E+00	8,67E-03	5,55E-04	**1,87E+00**
Pasta d'argento (Ag) - Giappone	7,31E+00	2,63E-02	1,10E-02	**7,34E+00**
Interconnessione a nastro - Austria	3,62E-01	2,77E-03	1,53E-03	**3,67E-01**
Silicone - Germania	1,06E+00	1,51E-02	7,13E-04	**1,08E+00**
Stringi nastro - Austria	3,50E-01	3,50E-01	3,50E-01	**1,05E+00**
Scatola di giunzione - Cina (Jiangsu)	2,54E+00	7,40E-03	4,34E-03	**2,55E+00**
Wafer - Cina (Shaanxi)	1,21E+02	6,66E-01	1,76E-01	**1,21E+02**
Wafer - Cina (Tianjin)	1,21E+02	6,66E-01	1,76E-01	**1,21E+02**
Incapsulante - Cina (Zhejiang)	8,06E+00	1,35E-02	3,97E-03	**8,08E+00**
Telaio - Cina (Jiangsu)	2,58E+01	1,13E-01	5,29E-02	**2,60E+01**
Produzione ausiliari	**1,23E+01**	**5,31E-02**	**3,18E-02**	**1,24E+01**
Produzione imballaggi del modulo fotovoltaico	**1,48E+00**	**6,18E-03**	**1,66E-02**	**1,51E+00**
TOTALE UPSTREAM	**3,49E+02**	**2,35E+00**	**9,30E-01**	**3,53E+02**
CORE				
TRASPORTI IN ENTRATA	3,83E+00	2,43E-04	6,30E-05	**3,83E+00**
ASSEMBLAGGIO M. FOTOVOLTAICO - en.elettrica	1,58E+01	4,89E-03	1,83E-04	**1,58E+01**
ASSEMBLAGGIO M. FOTOVOLTAICO - consumo combustibili	3,46E-01	4,87E-05	7,29E-06	**3,46E-01**
ASSEMBLAGGIO M. FOTOVOLTAICO - acqua	5,48E-05	6,73E-06	7,64E-08	**6,16E-05**
ASSEMBLAGGIO M. FOTOVOLTAICO - emissioni in atmosfera	2,86E-01	0,00E+00	0,00E+00	**2,86E-01**
ASSEMBLAGGIO M. FOTOVOLTAICO - rifiuti	1,25E-08	1,35E-11	5,10E-12	**1,25E-08**
ASSEMBLAGGIO M. FOTOVOLTAICO - F Gas	0,00E+00	0,00E+00	0,00E+00	**0,00E+00**
TOTALE CORE	**2,02E+01**	**5,19E-03**	**2,53E-04**	**2,03E+01**
TOTALE	369,60	2,35	0,93	**372,88**

Fig. 33 Results per declared unit of the tool-CF example application

	Risultati indicatori per unità funzionale (kWh prodotto da 1 modulo, in 30 anni)			
	GWP Fossile	GWP Biogenica	GWP Uso del suolo	GWP TOTALE
UPSTREAM	kg CO2 eq/FU	kg CO2 eq/FU	kg CO2 eq/FU	**kg CO2 eq/FU**
Produzione componenti del modulo fotovoltaico	9,37E-03	6,39E-05	2,46E-05	9,46E-03
Produzione ausiliari	3,44E-04	1,48E-06	8,89E-07	3,47E-04
Produzione imballaggi del modulo fotovoltaico	4,14E-05	1,73E-07	4,62E-07	4,21E-05
TOTALE UPSTREAM	9,75E-03	6,56E-05	2,60E-05	**9,85E-03**
CORE				
TRASPORTI IN ENTRATA	1,07E-04	6,80E-09	1,76E-09	**1,07E-04**
ASSEMBLAGGIO M. FOTOVOLTAICO - en.elettrica	4,41E-04	1,37E-07	5,11E-09	**4,41E-04**
ASSEMBLAGGIO M. FOTOVOLTAICO - consumo combustibili	9,66E-06	1,36E-09	2,04E-10	**9,66E-06**
ASSEMBLAGGIO M. FOTOVOLTAICO - acqua	1,53E-09	1,88E-10	2,13E-12	**1,72E-09**
ASSEMBLAGGIO M. FOTOVOLTAICO - emissioni in atmosfera	7,98E-06	0,00E+00	0,00E+00	**7,98E-06**
ASSEMBLAGGIO M. FOTOVOLTAICO - rifiuti	3,49E-13	3,76E-16	1,42E-16	**3,49E-13**
ASSEMBLAGGIO M. FOTOVOLTAICO - F Gas	0,00E+00	0,00E+00	0,00E+00	**0,00E+00**
TOTALE CORE	5,65E-04	1,45E-07	7,08E-09	**5,66E-04**
TOTALE	0,01032	0,00007	0,00003	**0,01041**

Fig. 34 Results per functional unit of the tool-CF example application

The results obtained in the example of the tool's application demonstrate the correct procedure followed to build it. Indeed, the customer company can observe the different impacts of the considered phases and choose to continue or modify their strategy.

The results per declared unit (Fig.33) show that the total GWP of the upstream phase corresponds to 3,53E+02 $kgCO_2eq$/UD while the total GWP of the core phase is 2,03E+01 $kgCO_2eq$/UD. Thus, the total GWP sum up between the two phases is 372,88 $kgCO_2eq$/UD.

The results per functional unit (Fig. 34) show that the total GWP of the upstream phase corresponds to 9,85E-03 $kgCO_2eq$/FU while the total GWP of the core phase is 5,66E-04 $kgCO_2eq$/FU. In this case, the total GWP sum up between the two phases is 0,01041 $kgCO_2eq$/FU.

It is important to note that the tables of Figures 33 and 34 do not consider different input data: indeed, table in Figure 34 simply reports the results per UD (Fig. 33) but divided by the FU, the kWh produced by the module in 30 years.

3.1 Upstream phase

Accordingly with the results obtained, it can be seen that the upstream phase is the most impactful phase and therefore the production of components, auxiliaries and packaging weights more on the climate change impact category, in terms of $kgCO_2eq$ released, than the transportation and assembly activities. This occurs both for the results per declared unit and per functional unit.

The input data of the results obtained in the upstream phase are reported in Figures A2 (components), A3, A4 and A7: they referred to components', auxiliaries', and packaging data. In the list of components in Figures A2 and A3, front and back glasses represent the 80% of the total PV weight panel: despite that, front and back glasses productive processes are not the main responsible of the high total GWP value of the components production. In fact, wafer and frame production processes have a value, on the total components production GWP, higher than the glass production process, with a value of 1,21E+02 kgCO2eq and 2,60E+01 kgCO2eq respectively. It should be noted then that on a total components production GWP of 3,39E+02 $kgCO_2eq$/UD, 3,16E+02 $kgCO_2eq$/UD, the 93%, comes from the productive processes of glasses, wafer and frame. Production processes of auxiliaries have a smaller impact than components, despite being numerically more: Figure A4 shows the quantities (in kg) per year of some auxiliaries, but making the data explicit for the UD, operation done in the "Impacts" sheet, it results in much smaller quantities per module than data for the components, and thus the auxiliaries' productive processes impact per module results to be less than for components, specifically 1.24E+01 kgCO2eq/UD. Concerning the materials used to compose the packaging (Fig.A7), these are in a lower number of components and auxiliaries. Moreover, some of them are in very low quantities (kg) per UD (labels, foils, ink, PET band, and plastic films) and the production processes required for these materials have an impact on the total GWP once lower than the components and auxiliaries one: 1.51E+00 kgCO2eq/UD.

Regarding the analysis of the three GWP, the fossil GWP is the highest one and the LULUC GWP the lowest: it means that the processes considered contribute more on the use of fossil fuels resources than the use of biogenic sources or the change deriving from the land use.

3.2 Core phase

On the other hand, the core phase is less impactful than the upstream phase. The processes included in the core phase correspond to the assembly of the PV panel and the inbound transport of materials: to understand the impact of these processes data of all the recognized sections, and found in all the Figures in Appendix A, must be considered. However, for components', auxiliaries', and packaging sections, only the transport data count. Considering the results per UD, the total GWP of inbound transports is 3,83E+00 kgCO_2eq/UD: in the case-study, only road and ship transportation means have been considered (Fig. A2, A3, A4, A7). In the module assembly operations on the productive site, the electric energy consumptions' impact amounts to 1,58E+01 kgCO_2eq/UD which is the largest amount compared to the other operations concerning the module assembly: indeed, consumption of the natural gas (Fig. A2) amounts to 3,46E-01 kgCO_2eq/UD, consumption of water (Fig. A5) to 6,16E-05 kgCO_2eq/UD, atmospheric emissions (Fig. A5) (CO_2, NOx, VOC) of the plant involved to 2,86E-01 kgCO_2eq/UD (the discharged quantities are very low), wastes (some of them in Fig. A6) produced during the productive process to 1,25E-08 kgCO_2eq/UD and F-Gas to 0,00E+00 kgCO_2eq/UD since there are not the use of F-Gas (Fig. A5). These results show that in the assembly activity of the PV panel, the consumption of electricity used to produce the module has the greatest impact: this is due to the amount of electricity taken from the different grids and the part of self-generation. Indeed, electric energy consumed in the module assembly amounts to more or less the 78% of the total core phase GWP (2,03E+01 kgCO_2eq/UD), even larger than the transports impact which amounts at 19%. The other impacts coming from GHG emissions, fossil fuel consumption, water consumption, wastes production and F-Gas use, have a quantity per UD value much lower and so less impactful.

If the customer company wants to consider the airfreight than the ocean freight, thereby reducing the time of supplying the materials, some different calculations must be made. Considering the use of aircrafts for suppliers that are far away, e.g., Vietnam, Malaysia, China, and Japan in this case, the distances between suppliers and the production site have been calculated by modifying the input data and entering the air distances in the appropriate column of the Data Entry sheet removing the distances by ship. When there is no specific indication of the supplier site location, the capital of the country where the supplier is located is considered: this is a consideration that has made for all the components apart from jbox ("scatola di giunzione"), wafer, encapsulant and frame, where the BOM indicates specific locations. Thus, airfreight results in an inbound transport value of 1,72E+02 kgCO2eq/UD from a previous value of 3,83E+00 kgCO2eq/UD thus increasing the total GWP from 372,88 to 540,61 kgCO2eq/UD.

Analysing the three GWP, the fossil GWP is the higher one and the LULUC GWP have much lower values: it means that the processes considered contribute more on the use of fossil fuels resources than the use of biogenic sources or the change deriving from the land use.

3.3 Interpretation of the results and discussion

The results obtained in the above analysis show the impacts of the various activities: in this section interpretation of results and suggestions on how to intervene to reduce the impacts will be reported. Overall, both in the results per UD and per FU, the upstream phase is more impactful than the core phase: however, for the companies it is crucial to include both the phases in the sustainability strategy to try to reduce the impact wherever possible. Regarding the upstream phase, it is suggested to act on the choice of supplier, especially for glasses, wafer and frame, with a low-impact production process: the impact of production processes depends on the technological, geographical and economic characteristics of different suppliers. The more impactful the production process is, the more it will weigh on the total GWP of the upstream phase. Therefore, in order to reduce the climate change impact, the customer company should first inquire about how the suppliers' production processes are and thus choose the more sustainable. Instead, concerning the core phase, based on the results obtained, acting on modifying the ways of transports and the consumption of electric energy could be useful. Since some suppliers are far from the productive site, it might be thought on substituting the ship with the aircraft and this could prove to be a strategy for the customer company. However, using the aircraft do not represent a sustainable strategy: as results in the Core phase show, total GWP increases when using airfreight since it leaves the most significant carbon footprint for large items compared to ocean freight. Flights emit 500 grams of carbon dioxide/metric tons of cargo per kilometre of transportation. However, ships emit only between 10 to 40 grams of carbon dioxide per kilometre (Kilgore G., 2023). The Carbon Footprint of airplanes is 20 to 30 times more than ships. For this reason, air freight produces a more carbon footprint for more significant items than the ocean freight. Thus, it is not suggested to consider the aircraft as a mean to the materials' transport although the distance covered is much less than by ship. It is suggested to continue preferring road and ship transports although the time-delivery is higher. Moreover, it is fundamental to act on the electricity consumption being the most impactful activity: the suggestion is to take action by trying to acquire as much energy as possible from renewable generation sources grid such as hydroelectric, photovoltaic and wind power, which have consistently low emission factors.

To do simulations in the tool, the customer company must rely on the consulting society to extract the appropriate EFs from Ecoinvent v3.8 because EFs for manufacturing processes can be country-specific and are updated over time. Indeed, even though the material is the same the emission factor is different for each country supplier because the productive process may be different from country to country. Thus, in case of new suppliers coming from new countries, since the productive process will be different, the tool-CF must be updated with the new supplier and the relative emission factor. If the consulting society provides data regarding emission factors to the customer company, the latter may works autonomously, otherwise the customer company has to rely on the consulting society which will update the tool-CF. On the other hand, transportation FEs are not country-specific but based on the mean of transports typology and even these one are updated over time.

Since the databases are constantly updated, the customer company must remain in contact with the consulting society in order to keep the emission factors, and so the results, updated, since temporal, geographical, technological and transport informations may be modified through new studies and reports.

Moreover, observing the three parts of the total GWP, fossil, biogenic and LULUC, it was noted that the fossil GWP is always greater than the other two.

4. CONCLUSIONS

The thesis project consisted of developing a practical calculator to comprehend the climate change impact a product could generate based on the choice of the different materials' suppliers. This calculator, namely tool-CF, was developed in the context of the need for companies to assess their impact and implement sustainability strategies. Specifically, the final version of the tool-CF applied to an example of the case-study has shown that through the construction of an Excel workbook characterised by appropriate details in terms of sheets organisation, sections recognition and data selection, it is a powerful tool: the link between each worksheet has been proven to work and this gives to the customer company the opportunity to check which is the most affordable solution in terms of material purchase and thus to develop different market strategies in order to lowering pollution to meet environmental requirements. Each step of the tool construction was fundamental and it was necessary to be done precisely and with consciousness: in fact, each part of the tool was previously studied according to the requests of the customer company.

The choice of suppliers, and thus of their materials processing, is crucial when considering the assembly of a product. In case of the production of a photovoltaic panel, impacts from the manufacturing processes and transport of components, auxiliaries, and packaging, in addition to all those resulting from the operations for its assembly, which however are productive site-specific and do not depend on the suppliers' choice, must be considered. Thus, best solution led to the choice of which is the best supplier to meet the materials' requirements maintaining a limited climate change impact. In this sense, this tool gives the possibility to the customer company to try to insert data of some suppliers, see the impact related and consequently decide if pursuing the path or change strategy and so suppliers. However, the final version of the tool-CF pointed out some limitations. The main limitation is that the client company cannot use the tool independently because it needs the various EFs to be always appropriate in terms of technological, geographic and temporal representativeness. This means that the customer company needs a consulting company, such as Ambiente Italia Srl, to rely on by extracting the appropriate info (EF) from the appropriate databases available from time to time.

Considering the requests of the customer company and the work done at Ambiente Italia Srl to develop the calculator, it can be said that, by analysing the final version of the tool, it meets the customer company's demand. Additionally, it is possible to comprehend how important a tool that measures the Carbon Footprint is on the strategies of a company. It is fundamental to note that this final version of the tool-CF is not the definitive one which will be delivered to the customer company since some corrections and updates by Ambiente Italia are expected, but it is very close to it. The development of this tool would also allow the company itself that produced it, Ambiente Italia Srl, to be able to use it as the basis for any other future projects involving the production of a calculator.

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APPENDIX A – EXAMPLE OF THE TOOL-CF APPLICATION

Data Entry example sheet

		Unità di misura	Dati	km trasporto su strada	km trasporto navale	km trasporto aereo
Prodotto						
	Tipologia modulo		pannello fotovoltaico			
	Totale produzione anno stabilimento (riferito al	kg (US)	104636000			
		pz (US)	2828000			
	Totale produzione anno stabilimento	kg (US+DG)	149106000			
Dettagli producibilità modulo	Energia prodotta al primo anno (riferita a 1 modulo)	kWh	1220,6			
	Fattore medio di degradazione	%	0,25%			
	Energia effettiva prodotta in 30 anni	kWh	35.812			
	Peso del modulo	kg	37,0000			
	Potenza del modulo	kW	0,700			
Energia Elettrica						
	CONSUMI TOTALI DI ENERGIA ELETTRICA	**kWh/anno**	203055000			
	E.E. Prelevata da rete mix standard	kWh/anno	0			
	E.E. Prelevata da rete rinnovabile - idroelettrico	kWh/anno	15699795,9			
	E.E Prelevata da rete rinnovabile fotovoltaico	kWh/anno	74443905			
	E.E Prelevata da rete rinnovabile	kWh/anno	26557711,8			
	E.E Prelevata da rete geotermico	kWh/anno	4345587,3			
	Totale da rete	kWh/anno	121.047.000			
	AUTOPRODUZIONE DI ENERGIA ELETTRICA					
	Fotovoltaico					
	Energia elettrica prodotta e autoconsumata	kWh/anno	0			
	Trigenerazione					
	Energia elettrica prodotta e autoconsumata	kWh/anno	82008000			

Fig. A1 “Prodotto” (Product) and “Energia Elettrica”(Electric Energy) filled with example data

Combustibili

Tipologia di combustibile		Quantità consumata
Gas Naturale (non utilizzato nel trigeneratore)	Sm3/anno	573110

Componenti modulo

COMPONENTI E/O SEMILAVORATI IN ENTRATA AL PROCESSO		Peso del componente	Da fornitore componente a Km via terra	Km via nave	Km via aereo
Vetro anteriore	kg/modulo	14,750			
Vetro anteriore - Malaysia	%	80%	213,44	10615,47	
Vetro anteriore - Vietnam	%	20%	162,54	13341,42	
Vetro anteriore - fornitore 3	%	0%			
Vetro anteriore - fornitore 4	%	0%			
Vetro anteriore - fornitore 5	%	0%			
Vetro anteriore - fornitore 6 (con suoi fattori di emissione)	%	0%			
Vetro posteriore	kg/modulo	14,750			
Vetro anteriore - Malaysia	%	80%	213,44	10615,47	
Vetro anteriore - Vietnam	%	20%	162,54	13341,42	
Vetro posteriore - fornitore 3	%	0%			
Vetro posteriore - fornitore 4	%	0%			
Vetro posteriore - fornitore 5	%	0%			
Vetro posteriore - fornitore 6 (con suoi fattori di emissione)	%	0%			
ECA (Ag)	kg/modulo	0,014			
ECA (Ag) - Belgium	%	100%	2267		
Eca (Ag) - fornitore 2	%	0%			
Eca (Ag) - fornitore 3	%	0%			
Eca (Ag) - fornitore 4	%	0%			
Eca (Ag) -fornitore 5 (con suoi fattori di emissione)	%	0%			
Pasta d'argento (Ag)	kg/modulo	0,020			
Pasta d'argento (Ag) - Giappone	%	100%	485,12	16302,75	
Pasta d'argento (Ag) - fornitore 2	%	0%			
Pasta d'argento (Ag) - fornitore 3	%	0%			
Pasta d'argento (Ag) - fornitore 4	%	0%			
Pasta d'argento (Ag) - fornitore 5	%	0%			

Fig. A2 “Combustibili” (Fuels) and some “Componenti modulo” (Module components) filled with example data about quantities

Interconnessione a nastro	kg/modulo	0,072			
Interconnessione a nastro - Austria	%	100%	1878		
Ribbon interconnection - fornitore 2	%	0%			
Ribbon interconnection - fornitore 3	%	0%			
Ribbon interconnection - fornitore 4	%	0%			
Ribbon interconnection - fornitore 5	%	0%			
Silicone	kg/modulo	0,350			
Silicone - Germania	%	100%	1928		
Silicone - fornitore 2	%	0%			
Silicone - fornitore 3	%	0%			
Silicone - fornitore 4	%	0%			
Silicone - fornitore 5	%	0%			
Stringi nastro	kg/modulo	0,350			
Stringi nastro - Austria	%	100%	1878		
Ribbon stringer - fornitore 2	%	0%			
Ribbon stringer - fornitore 3	%	0%			
Ribbon stringer - fornitore 4	%	0%			
Ribbon stringer - fornitore 5	%	0%			
Scatola di giunzione	kg/modulo	0,360			
Scatola di giunzione - Cina (Jiangsu)	%	100%	130,1	14884,37	
Scatola di giunzione - fornitore 2	%	0%			
Scatola di giunzione - fornitore 3	%	0%			
Scatola di giunzione - fornitore 4	%	0%			
Scatola di giunzione - fornitore 5	%	0%			
Wafer	kg/modulo	1,080			
Wafer - Cina (Shaanxi)	%	50%	1404,1	14884,37	
Wafer - Cina (Tianjin)	%	50%	81,1	16033,51	
Wafer - fornitore 2	%	0%			
Wafer - fornitore 3	%	0%			
Wafer - fornitore 4	%	0%			
Wafer - fornitore 5	%	0%			
Incapsulante	kg/modulo	2,400			
Incapsulante - Cina (Zhejiang)	%	100%	192,1	14884,37	
Incapsulante - fornitore 2	%	0%			
Incapsulante - fornitore 3	%	0%			
Incapsulante - fornitore 4	%	0%			
Incapsulante - fornitore 5	%	0%			
Telaio	kg/modulo	2,854			
Telaio - Cina (Jiangsu)	%	100%	225,1	14884,37	
Telaio - fornitore 2	%	0%			
Telaio - fornitore 3	%	0%			
Telaio - fornitore 4	%	0%			
Telaio - fornitore 5	%	0%			

Fig. A3 Remaining "Componenti modulo" (Module components)

Ausiliari						
			Quantità	Km via terra	Km via nave	Km via aereo
CELL LINE	Azoto	kg/anno	420.202	350	0	0
	Silano	kg/anno	7.666	70	16000	0
	Idrogeno	kg/anno	16.871	20	0	0
	Fosfina	kg/anno	12.050	50	0	0
	Borano	kg/anno	5.680	350	0	0
	Anidride Carbonica	kg/anno	3.151	70	0	0
	Metano	kg/anno	1.661	20	0	0
MODULE LINE - US product	Module-Glass Transparent Label	kg/anno	380,82	500	0	0
	Module-Glass Label Ink	kg/anno	3,60	75	0	0
	Screens ECA printing US	kg/anno	3725,09	20	0	0
	Squeegee ECA US	kg/anno	1231,06	50	0	0
	Flux for Interconnection	kg/anno	18,48	500	0	0

Fig. A4 Some "Ausiliari" (auxiliaries) filled with example data

Emissioni di gas effetto serra				
	Impianto/Attività		**Quantità scaricate**	**Inquinanti prodotti**
	Produzione del modulo (fase di deposizione) - PECVD	kg/anno	950000	CO_2
		kg/anno	653,54	NOx
	Assemblaggio modulo	kg/anno	75711,87	VOC
F-Gas				
	Unità di processo		**Quantità rabboccata**	**Tipologia di gas**
	Unità di refrigerazione	kg/anno	0	R134A
	Apparecchiature elettriche	kg/anno	0	SF_6
Acqua				
	Acqua in entrata allo stabilimento		**Quantità**	
	Fonte: acquedotto industriale	m3/anno	2536000	
	per usi produttivi	%	65%	

Fig. A5 Some "Emissioni di gas effetto serra" (Greenhouse gases emissions), some "F-Gas" (F-Gas) and "Acqua" (water) filled with example data

Rifiuti					
			Quantità per destinazione finale		
Codice CER	Nome del rifiuto		Discarica	Incenerimento	Recupero
160306	rifiuti organici, diversi da quelli di cui alla voce 16 03 05	kg/anno			6.100
160505	gas in contenitori a pressione, diversi da quelli di cui alla voce 16 05 04	kg/anno	250		
060103*	acido fluoridrico	kg/anno	3.500		
060204*	idrossido di sodio e di potassio	kg/anno	3.500		
080410	adesivi e sigillanti di scarto, diversi da quelli di cui alla voce 08 04 09	kg/anno	318.000		
100118*	rifiuti prodotti dalla depurazione dei fumi, contenenti sostanze pericolose	kg/anno	37.000		
161001*	soluzioni acquose di scarto, contenenti sostanze pericolose	kg/anno	23.000		
161002	soluzioni acquose di scarto, diverse da quelle di cui alla voce 16 10 01	kg/anno			44.000
170203	plastica	kg/anno			2.800
190801	vaglio	kg/anno			1.250
190806*	resine a scambio ionico saturate o esaurite	kg/anno			2.500
190814	fanghi prodotti da altri trattamenti delle acque reflue industriali, diversi da quelli di cui alla voce 19 08 13	kg/anno			1.880.000
190901	rifiuti solidi prodotti dai processi di filtrazione e vaglio primari	kg/anno	1.200		1.500
CER	DESCRIZIONE	kg/anno			
CER	DESCRIZIONE	kg/anno			
CER	DESCRIZIONE	kg/anno			

Fig. A6 Some “Rifiuti” (wastes) filled with example data

Imballaggi						
			Quantità			
Tipologia di imballaggio	Bi-pack realizzati	n/anno	41814			
	Moduli per Bi-pack	n/bi-pack	70			
				Da fornitore imballaggio a		
Composizione bi-pack	Tipologia	Quantità unitaria (kg)	Numero per Bi-pack	km via terra	km via nave	km via aereo
Legno	Pallet in legno (inferiore)	52	1	350	0	0
	Pallet in legno (superiore)	52	1	70	0	0
Carta	Cornice angolare in cartone	0,07	280	350	0	0
	Etichetta del pallet in legno	0,008	2	70	0	0
	Kit di cartone (inferiore)	25,05	1	20	0	0
	Kit di cartone (superiore)	22,45	1	50	0	0
Plastica	Banda in PET	0,86	1	350	0	0
	Copertura in film plastico	2,2	1	70	0	0
Altro	Pallet di legno - Inchiostro per etichette	0,006	2	350	0	0
	Scatola di cartone - Inchiostro per etichette	0,01	4	70	0	0

Fig. A7 “Imballaggi” (packaging) filled with example data

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