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LIFE CYCLE ASSESSMENT OF PHOTOVOLTAIC TECHNOLOGIES: A CASE STUDY OF A SOLAR FARM IN NEW ORLEANS

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« You can’t connect the dots looking forward,
you can only connect them looking backwards. »

Steve Jobs

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Abstract

Il presente lavoro di tesi è stato svolto in parte negli Stati Uniti, per la precisione a New Orleans, ove si è studiata una Solar Farm di proprietà della Entergy Inc. e si è svolto uno studio Life Cycle Assessment di tipo *cradle-to-gate*. Lo scopo è quello di analizzare in dettaglio ogni forma di inquinamento generato dalla produzione di tutti gli elementi che costituiscono la Solar Farm, per capire se realmente si tratta di un tipo di energia "green" e sostenibile dal punto di vista ambientale.

Nel primo capitolo si raggruppano e si confrontano le attuali politiche energetiche internazionali, europee e americane, e si evidenziano gli obiettivi che si intendono raggiungere entro determinate scadenze in termini di emissioni di gas serra, utilizzo delle energie rinnovabili, efficienza energetica, etc.

Nel secondo capitolo segue uno studio approfondito sul metodo del Life Cycle Assessment, con una breve introduzione storica per poi passare nel dettaglio alle fasi di studio, metodi e normativa di riferimento.

Nel terzo capitolo si analizzano le tecnologie fotovoltaiche attualmente presenti sul mercato, la loro storia e le possibili evoluzioni, con le caratteristiche dettagliate di ciascun tipo di tecnologia.

Nel quarto capitolo viene presentata la Solar Farm in analisi, spiegato il suo funzionamento, e si introduce il software utilizzato per lo studio, SimaPro 7.3.3. Infine si illustrano i risultati ottenuti dallo studio LCA.

Infine, nel quinto capitolo si discutono criticamente i risultati ottenuti e si confronta un kWh prodotto dalla Solar Farm oggetto di studio con un kWh prodotto da fonti di energia non rinnovabili, quali il carbone, il petrolio, il gas e il nucleare, per capire quanto è conveniente in termini ambientali il passaggio da fonti di energia fossili a fonti rinnovabili.

Introduction

Most of the world's current energy is produced from fossil fuels such as coal, oil and natural gas, now the disadvantages related to the dependence on imports from a limited number of countries, rising prices and especially the considerable impact on climate change have reached the public opinion.
Consequently, governments, businesses and consumers are progressively supporting the development of renewable energy sources, which are basically unlimited in availability, although they have a few drawbacks. A way to ensure the efficient development of these sources is to create and implement energy policies, and work together to establish a sustainable and responsible future for our planet.

Solar power generation has come up as one of the most rapidly growing alternative sources of electricity, and as a result there is a fierce competition on the market, which expands at very high rates because of technology cost reduction and market development, reflecting the increasing recognition of the versatility, reliability, and economy of photovoltaic (PV) supply systems. Major market segments served by this industry involve consumer applications, remote industrial systems, developing countries, and grid-connected systems. Over the years this technology has changed a lot and it is supposed to evolve even more.

In the present thesis, an accurate study was conducted on the photovoltaic technologies and the damages that their manufacturing process produces to the environment.

Part of the present thesis has been written at the University of New Orleans, with the collaboration of Entergy Inc., that kindly provided data of their solar farm pilot project, known as Entergy Solar Power Plant.

In the first chapter it is analyzed the present status of the renewable market, the main trends and the policies fostered by some countries.
One of the major support to the PV market is the incentive, financial or non-financial, which in some cases comes from the local government, or else from the regional or country government, as it is analyzed in Chapter 1 of the present thesis. The most important boost that drives the incentives, are the guidelines from the major bodies, such as European Union or United States government, and also international non-governmental organizations, such as IEA and REN21.

Chapter 2 describes in detail how to make a LCA, which ones are the standards to follow and the software and the databases used for the study.
As previously mentioned, it is important to avoid as much as possible the pollution, and photovoltaic technologies help a lot with this issue, but even they have some environmental costs, especially in terms of emissions and waste. Therefore, it is necessary to compile a Life Cycle Assessment (LCA), to evaluate the damage to the environment caused by the manufacturing process of PV panels.

Before analyzing the solar farm subject of the research, in Chapter 3 there is a synthetic summary of the existing solar technologies, and it is illustrated the principles of operation, as well as the history of photovoltaic technologies, from their very beginning until present days.

Chapter 4 briefly presents the solar farm subject of the study, Entergy Solar Power Plant, and the methodologies used for this analysis. Therefore, the LCA is described in detail.

In Chapter 5 the results previously exposed are discussed and critically analyzed, then a comparison is provided between 1 kWh of electricity produced by the solar farm subject of the study and 1 kWh produced with other sources of energy, to better understand how convenient is, in terms of environmental damages avoided, the transition from traditional energy sources to renewable ones, such as photovoltaic.

Finally, the conclusions summarize the main achievements of this work, illustrates the lacks that have been encountered and discuss future development on the topic.

Chapter 1

Energy policy: an international overview

1.1 The need of energy policies

In the past few years, the rise of the global temperature, the ozone layer depletion and the air pollution have driven a world-wide awareness that it is no longer possible to procrastinate a concrete and resolute act to curb the climate change and to build climate resilience.

The awareness mentioned above resulted in several energy efficiency policies from different parts of the world, led by a few international organizations.

One of these is **REN21** (Renewable Energy Policy Network for the 21st Century), a multi-stakeholder policy network provided by United Nations Environment Programme, in which governments, nongovernmental organizations, research and academic institutions, work together to encourage the development of renewable energy. To support policy decision making, REN21 produces every year the Renewables Global Status Report (GSR), which is a thorough overview of worldwide renewable energy market, industry, investment and policy development.

Another important organization is **IEA** (International Energy Agency), established in the framework of the Organization for Economic Co-operation and Development (OECD). As opposed to REN21, IEA reviews all forms of venergy, and deals with its related issues, such as oil, gas and coal stock and demand, renewable energy technologies, energy efficiency, access to energy, etc.

1.2 The Paris Agreement

From November 30th to December 12th 2015, the 21st annual session of Conference of Parties was held in Paris, arranged by United Nation Framework Convention of Climate Change. The conference, known as **COP21**, negotiated the Paris Agreement, an important milestone in the effort of containing the global warming. As for 2017, 148 countries have ratified this agreement, on a total of 197 signatories.
The main objective of the Paris Agreement, is to *"Holding the increase in the global average temperature to contain the global temperature rise well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels."*, as specified in par. 1a of the art. 2.

In order to achieve this goal, the parties aim to reach global peaking of greenhouse gas (GHG) emissions as soon as possible, although clearly this will take longer for developing countries, and immediately afterwards the parties will put into effect rapid reductions in accordance with the best available science.
To supervise the short-term results and assess the collective progress towards the goal, COP21 plans to undertake a stock-take every five years, the first of which will be in 2023, as specified in par. 2 of art. 14 of mentioned agree-

ment, and to publish the results, in accordance with the transparency and consistency general guidelines of the accord.

Another key point of the Paris Agreement is the international cooperation among countries, in order to enhance understanding, action and support in many different areas, such as: early warning systems, emergency preparedness, slow onset events and risk insurance facilities, as indicated in Par. 4 of art. 8.

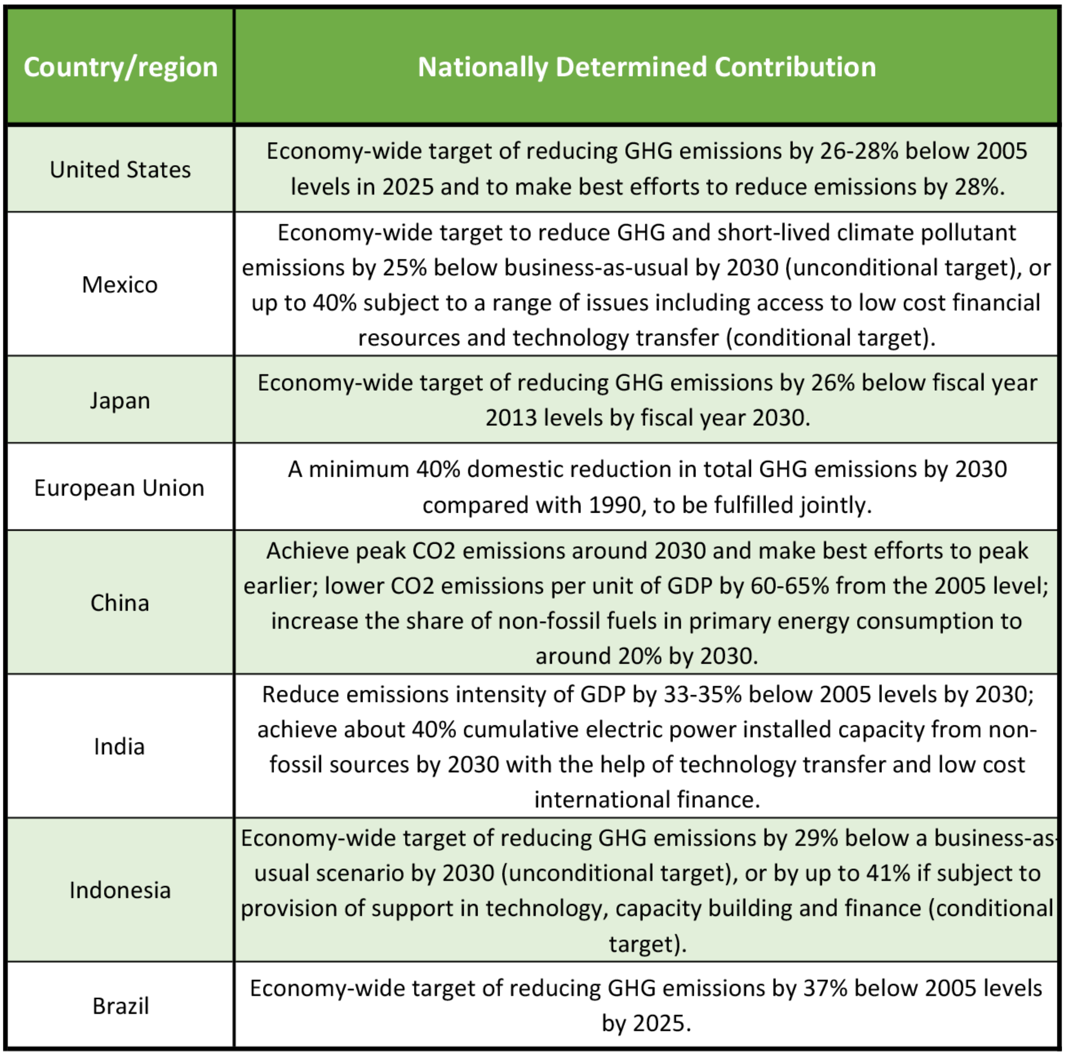
To reach the ambitious objective to contain the global temperature rise, it is important that every country, including the developing ones, put efforts in the reducing of anthropogenic emissions. The convention recognized that some countries, such as those that are particularly vulnerable to the effects of climate change and have significant capacity limitations, might need support in order not to threaten their economic growth in the pursuing of the objective. Therefore, the developed countries will provide financial resources to mentioned developing countries, as stated in par. 1 of art. 9.

A new feature introduced in par. 13 of art. 4, is the **Nationally Determined Contribution (NDC)**, in which countries determine their contributions based on of their national priorities, circumstances and capabilities, in the context of a global framework under the Paris Agreement. NDCs reflect each country's effort for reducing emissions, and how they will build resilience to climate change impacts.

Most of the NDCs resulted to be GHG goals, different for each country. They include absolute GHG emissions targets, emissions intensity targets (i.e. GHG emissions per unit of economic output), or reductions or limitations in per-capita emissions. In some cases, the target was conditional on other factors, e.g. the economic availability in developing countries.

Therefore, a few countries introduced other energy sector measures to help reducing energy-related GHG emissions in the short term, such as cut down the use of inefficient coal-fired power plants, decrease methane emissions from oil and gas production, fossil-fuel subsidy reform and carbon pricing. Table 1.1 shows as an example the NDCs of some countries (adapted from IEA, 2016).

Table 1.1: Greenhouse-gas emissions reduction goals in selected NDC.



Country/region	**Nationally Determined Contribution**
United States	Economy-wide target of reducing GHG emissions by 26-28% below 2005 levels in 2025 and to make best efforts to reduce emissions by 28%.
Mexico	Economy-wide target to reduce GHG and short-lived climate pollutant emissions by 25% below business-as-usual by 2030 (unconditional target), or up to 40% subject to a range of issues including access to low cost financial resources and technology transfer (conditional target).
Japan	Economy-wide target of reducing GHG emissions by 26% below fiscal year 2013 levels by fiscal year 2030.
European Union	A minimum 40% domestic reduction in total GHG emissions by 2030 compared with 1990, to be fulfilled jointly.
China	Achieve peak CO2 emissions around 2030 and make best efforts to peak earlier; lower CO2 emissions per unit of GDP by 60-65% from the 2005 level; increase the share of non-fossil fuels in primary energy consumption to around 20% by 2030.
India	Reduce emissions intensity of GDP by 33-35% below 2005 levels by 2030; achieve about 40% cumulative electric power installed capacity from non-fossil sources by 2030 with the help of technology transfer and low cost international finance.
Indonesia	Economy-wide target of reducing GHG emissions by 29% below a business-as-usual scenario by 2030 (unconditional target), or by up to 41% if subject to provision of support in technology, capacity building and finance (conditional target).
Brazil	Economy-wide target of reducing GHG emissions by 37% below 2005 levels by 2025.

1.3 Present market and future trend

Although the scale of capacity additions oscillates from year to year, REN21 and IEA agree that renewable energies are experiencing a very high growth, in fact the trend of deployment of wind, solar PV and hydro over the last few years is rapidly incrementing and perhaps one of the clearest signs of an energy transition taking place.

According to IEA (2016), the renewables industry passed an important milestone in 2015, with capacity additions exceeding those of fossil fuels and nuclear for the first time. In 2015, in fact, Europe used renewable energy for the most of its production of power, such as 28.8%, followed by nuclear for 26.8%, 15.6% of hard coal, and 10.4% of lignite, 15.1% of gas, and 3.2% of oil and other conventional sources, according to Agora Energiewende (2016). In USA, the main sources of new power capacity in 2015 were wind (8.6 GW) and solar (7.4 GW, solar PV and CSP), surpassing natural gas capacity additions (about 6 GW), according to FERC, Federal Energy Regulatory Commission (2015).

1.3.1 New capacity additions

For what concerns the power generation, the coal-based generation capacity of 1950 GW was overtaken by the one of renewable energies, around 1985, although the latter provides around 40% less electricity than from coal. Hence, new renewables-based capacity additions in 2015, accounting for 147.2 GW, established a new record, nearly quadruple the level achieved a decade earlier (REN21, 2016).

Of these 147.2 GW, 50 GW of capacity addition in 2015 were only solar PV-based. In United States, solar PV additions rose significantly (up to 7.3 GW) which, for the first time, was more than total natural gas capacity additions, a notable achievement given the low natural gas prices and that gas has been a leader in US capacity additions (IEA, 2016).

Japan's government target led to the addition of 11 GW of solar PV capacity; In EU, United Kingdom in 2015 saw the highest growth of solar PV capacity additions (3.7 GW), while Germany had a downtrend and was overtaken by China as the country with the largest installed solar PV capacity.

The 50 GW of new solar PV-based capacity additions installed in 2015, made the total share in the world rise to 227 GW.

Of these 227 GW, 95 GW are generated in EU (of which 40 GW are produced in Germany, while 18.9 GW in Italy and 5.4 GW in Spain) and 50 GW are from BRICS countries (Brazil, Russia, India, China and South Africa), of which almost the totality is shared between China, indisputable leader with its 44 GW, of which 15 GW of new capacity, and India with 5.2 GW (IEA, 2016), as displayed in Fig. 1.1.

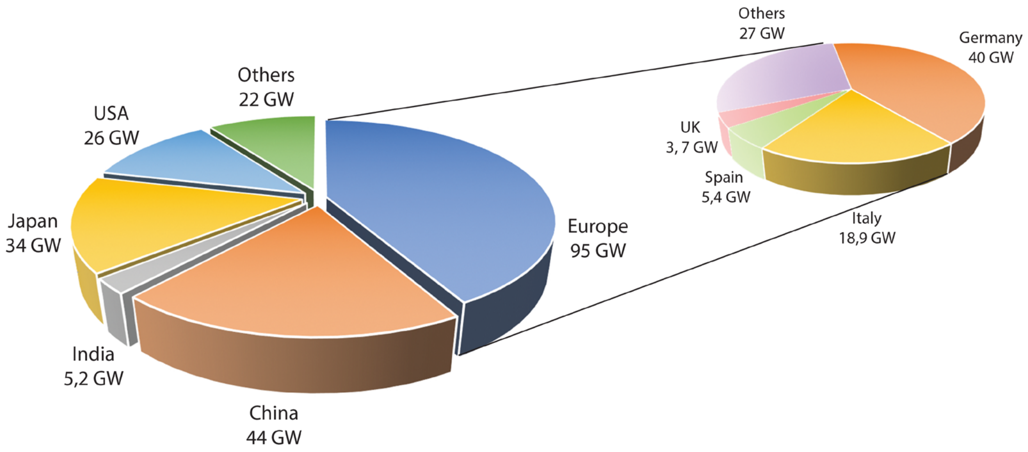


Fig. 1.1: Global share of solar PV capacity at end 2015 (227 GW).

Renewables-based power capacity additions in 2015 were led by wind, which were nearly 35% higher than the previous year and established another record high (65 GW). China (half of all additions), the European Union (led by

Germany) and the United States together accounted for more than 80% of the global total for wind power capacity additions.
Renewables contributed 23% of global electricity supply in 2014, of which more than 70% was from hydropower and 17% from variable renewables. China and the European Union are the leaders today in terms of total renewables-based electricity generation, while Iceland, Norway, Brazil, Canada, Austria and Sweden are in a league of their own when it comes to the share of electricity generated from renewable sources. The European Union (EU) has the highest share of variable renewables, meeting 11% of overall electricity demand from projects harnessing wind or solar resources, but there is considerable variation across individual EU member states (IEA, 2016).

For what concerns the heating and cooling sector, in REN21's GSR 2016, renewable energy accounted for an estimated 18% of the Europe's total heating and cooling consumption; therefore, EU has experienced the strongest growth in renewable energy use for heat of any region, with average annual increases of almost 5% since 2008.
Meanwhile, in United States the renewable energies used for heat and cooling are growing relatively slower (0,6%), partly due to the downsize of industrial output. 2015 also saw the decrease of residential heating with wood pellets, and the drop-in oil prices caused the reduction of the competitiveness of renewable heat in US (REN21, 2016).

1.4 Environmental labels

The first step is to balance all the many different regulations in all the countries across the world, in order to make effort together in the same direction and with the same strategy. ISO (International Organization for Standardization) made several codes and labels that are transposed in each country. In particular, there are three environmental labels:

- Type I (ISO 14024): e.g. Ecolabel, they are issued only to products that meet certain minimum requirements (established environmental criteria) and are certified by an independent body;
- Type II (ISO 14021): or environmental self-declarations, for which there is no certification of an independent body or a minimum acceptable level, the manufacturer merely declares the environmental aspects of his product, which he considers useful to highlight;
- Type III (ISO 14025): EPD, (Environmental Product Declaration) which provide quantitative data on the environmental profile of a product calculated according to LCA procedures established in ISO 14040.

1.4.1 Ecolabel

In 1993, the European Union, in the context of the activities of the Fifth Action Program, in order to harmonize spontaneous procedures within the various countries and to build a single market reference system, introduced the Ecolabel Europe as a European environmental label of European Recognition; thus, this did not actually erase the national trademarks.

The Ecolabel's purpose is, on the one hand, to encourage companies to follow environmentally sustainable production processes and, on the other hand, to offer consumers the opportunity to make informed choices in their purchases, because products labeled with this brand are goods that have passed strict selection criteria and reward environmental and performance excellence.

The requirements for the award of the Ecolabel (by the European Commission and an appropriate body called the European Union Ecolabel Board, EUEB) clearly follow the approach "from cradle to grave", pursuing the reduction of impacts on natural habitats and Resources, reducing emissions of polluting and dangerous substances, consumer information, etc.

1.4.2 EPD

The EPD (Environmental Product Declaration) is a technical document arose by the manufacturer's will and, after a process of verification of content by a certification body, it accompanies the marketing of the product. The assessment method is the Life Cycle Assessment, but the EPD differs from the latter because the system guarantees an objective, verifiable, comparable procedure as it is based on data provided directly by the manufacturer and not from databases.

In order to make the data contained in the statement comparable, the common parameters for each product category must be defined: the PSR (Product Specific Requirements) recently renamed as PCR, (Product Category Rules), describe in a harmonized manner, by product category or service, what data are to be collected for the realization of the Life Cycle Assessment, methods, calculations and results to be presented. These criteria are defined in a shared way and help to make EPDs comparable.

All products can access to the product environmental statement: there are no thresholds as for type I labels, but it is simply a declaration of impacts that the product generates over the life cycle; this system gains the advantage of starting a fierce environmental competition among manufacturers.

The purpose of these product declarations may be to send information from the manufacturer to the consumer (business to consumer, B2C) or to the professional broker (business to business, B2B). Anyway, the target is to encourage the demand for the supply of those goods that cause less environmental impact during their life cycle.

1.5 Energy Policy in Europe

The European Commission established different targets to achieve before 2050, in order to lead the Member States towards a more sustainable future. The first milestone will be 2020, on which all the short-term policies are focusing. The second is 2030, which presupposes the achievement of all 2020 targets, and the last is 2050, still far away from our time, and for this reason is important to take important decisions since now, to increase the chances to achieve those targets.

1.5.1 2020 Energy Strategy

In 2010 European Commission drew up the energy objectives to accomplish before 2020, in the paper “Energy 2020: A strategy for competitive, sustainable and secure energy”.

The most important target to be achieved before 2020 is to **reduce greenhouse gas emissions by 20%** (relative to data from 1990), to **increase the share of renewable energy to 20%** in gross final energy consumption, and to **make a 20% improvement in energy efficiency**, compared to 2005 peak. The main priorities are summarized in Fig. 1.2.

2020 targets

1. Achieving an energy efficient Europe;
2. Building a truly pan-European integrated energy market;
3. Empowering consumers and achieving the highest level of safety and security;
4. Extending Europe's leadership in energy technology and innovation;
5. Strengthening the external dimension of the EU energy market.

Fig. 1.2: Targets expected by 2020, as established by the European Commission.

1. <u>Achieving an energy efficient Europe:</u> is to encourage the transition to renewable by giving more financial incentives at European, national and local levels. Energy efficiency is one of the central objectives for 2020 as well as a key factor in achieving our long-term energy and climate goals. Also, the public authorities should lead by example, support clean urban mobility and energy efficiency-standards for all vehicles, and make energy efficiency a mandatory condition for allocating financial support. Another important key point is to boost industrial competitiveness by making industry more efficient and spread energy labelling in order to provide more comprehensive comparison between products.
2. <u>Building a truly pan-European integrated energy market</u>: the second

priority is to integrate and implement about time the internal market legislation, and about this, also important is to enforce strategic infrastructure priorities in the next two decades, because Europe is still lacking the grid infrastructure which will enable renewables to develop and compete on an equal footing with traditional sources, to provide environmental sustainability and access to renewables as well as security of supply. The present grid is most likely unable to sustain the volumes of renewable power required by 2020 targets (33% of gross electricity generation). The legal framework must be properly enforced to give investors the confidence to invest in new production, transport and storage options for renewable sources.

3. Empowering consumers and achieving the highest level of safety and security: citizens appear to be unaware of their rights under EU legislation, or reluctant to exercise them, and this lead to a lack of savings in utility bills. More efforts are needed to inform consumers about their rights and involve them in the internal market. The international market for oil supplies could become very tight before 2020, which means that it is important for EU consumers to reduce oil demand, which at the moment of the paper was not happening, so the strategy is to provide affordable but cost-reflective and reliable alternative supplies. Energy, in particular electricity, constitutes a substantial part of the total production costs of key European industries, including from small to medium and large enterprises.
4. Extending Europe’s leadership in energy technology and innovation: it is important for EU to make a technology shift, otherwise it will not be able to achieve all the targets for 2050 to decarbonize the electricity and transport sectors. 2050 can appear far away from our time, but it is the right moment to bring in the European mar-

ket new high performance low-carbon technologies. Europe-wide coordination and collaboration should include the pooling of different funding sources, with the cooperation of all stakeholders. The Commission will seek to leverage the EU budget to raise further the overall level of funding. The competition in international technology markets among Europe and countries such as China, Japan, South Korea and the USA is very intense, because its competitors are pursuing an ambitious industrial strategy in solar, wind and nuclear markets. EU research laboratories need to increase their efforts to remain at the forefront of the booming international market for energy technology.

5. <u>Strengthening the external dimension of the European energy market</u>: with its more than 500 million consumers, EU energy market is the world's largest regional market and largest energy importer, but Europe is facing global warming like the rest of the world, and so the solution to this challenge relies on the international collaboration, and this lead push Europe's efforts for decarbonization and energy efficiency with our main partners and in international negotiations and frameworks. As a frontrunner in policy development, the EU has more scope to influence standard-setting environmental issues and to promote respect for transparent and competitive markets. Another key point is the presence of synergies between energy objectives and other policies and instruments including trade, bilateral agreements and development cooperation instruments.

In 2014, the European Commission made an overview on the progress towards these objectives, in the paper "A policy framework for climate and energy in the period from 2020 to 2030".

They noted that in 2012 greenhouse gas emissions decreased by 18% relative to emissions in 1990, and are expected to reduce further to levels 24% and 32% by 2020 and 2030 respectively based on current policies.

The share of renewable energy sources has increased to 13% in 2012 as a proportion of final energy consumed, and is expected to rise further to 21% in 2020 and 24% in 2030.

The carbon intensity of the EU economy fell by 28% between 1995 and 2010.

1.5.2 2030 Energy Strategy

As mentioned in the previous paragraph, it can be stated that the 2020 targets are on the good track to be achieved, so the policies carried out in order to accomplish this objective are effectively working.

While renewable energy technologies have matured and costs have fallen substantially, the rapid development of renewable energy sources now brings new challenges for the whole energy system. Many energy using products are more efficient at the moment, and consumers are benefitting from real energy and financial savings.

The 2030 is a decisive step in achieving the goals of 2050. It is therefore time to reflect on these developments and the policy framework Europe needs for 2030. It is necessary to continue towards the transition to a low-carbon economy that provides consumers with competitive and reasonably priced energy, creates new opportunities for growth and employment, assures greater security of energy supply and reduces dependence on imports for the EU as a whole.

An important key factor is to strengthen regional cooperation between Member States in order to help them tackle common energy and climate challenges more cost-effectively and at the same time continue to integrate markets.

The Commission proposes to set the target, by 2030, to reduce in EU greenhouse gas emissions by 40% compared to 1990. The policies and measures implemented and envisaged by the Member States regarding their respective current GHG reduction obligations, will continue to apply after 2020. The mentioned measures should allow emissions to be reduced by 32% compared to 1990.

The pursuit of this objective will require a constant effort, but the reduction percentage will show that the proposed target for 2030 is feasible. However, it is important to carry out continuous assessment to take account of the international dimension and to ensure that Europe continues to follow the least cost path to move to a low-carbon economy.

Therefore, in the implementation of a framework for 2030, the Commission believes indispensable to set the target for greenhouse gas reduction in each Member State, continuing to take account of these distribution factors but at the same time guaranteeing the integrity of the internal market.

The transition to a sustainable, secure and competitive energy system will not be possible without a significant increase in the share of renewable energy, which will therefore have to continue to play a key role in this step. In addition, the Union may reduce its trade deficit on energy products and be less exposed to supply disruption and volatility of fossil fuel prices.

Renewable energies can also be a driving force for growth in the field of innovative technologies, create jobs in emerging sectors and help reducing air pollution. Their rapid diffusion brings challenges, especially for the power system, which has to adapt to more and more decentralized and diversified production, especially from wind and solar power. Besides, the development of most renewable energy in the EU depends on national support schemes which, while taking into account national and regional specificities, may hinder market integration and reduce cost efficiency.

In the next future, exploitation of the benefits of renewable energy will have to be as market-oriented as possible. The aim of decreasing greenhouse gas emissions by 40% should help by itself to increase the share of renewable energy in the EU, bringing it to at least 27%, as proposed by the Commission. The EU-level target will encourage more investment in renewable energy, which will, for example, increase its share in the electricity sector, moving from the current 21% to at least 45% in 2030.

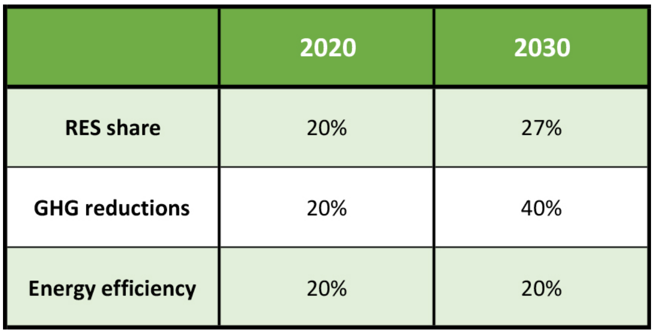
A greater energy efficiency can contribute substantially to achieving all the main objectives of EU climate and energy policies: greater competitiveness, security of supply, sustainability and also transition to an economy low carbon emissions.

Energy saving should complement the use of renewable energy by Member States within their respective greenhouse gas emission reduction plans, which should also advise national measures to be taken to improve energy efficiency. The Commission's analysis shows that a target of 40% reduction in greenhouse gas emissions would require greater energy savings (around 25%) in 2030.

In some sectors, such as industry and passenger transport vehicles, Europe will have to continue on the path of improvements observed in recent years, while in other areas, such as the housing sector, other modes of transport and electrical equipment, it is necessary to significantly intensify current efforts, in order to exploit the strong potential that is still unused. To this end, investment in construction (which would have a positive impact on management costs), general conditions and availability of information to encourage consumers to switch to innovative products and services as well as adequate financial instruments to ensure that the benefits of change consequently come to all consumers of energy.

The European Union's energy efficiency goal is not binding and the progress made in this area depends on specific policy measures taken at EU and national level, which include, inter alia, domestic and industrial equipment, vehicles and building. At present, it is predicted that the target of 20% will not be fully achieved. At the end of the review process, the Commission will evaluate any need to propose amendments to the Energy Efficiency Directive. 2020 and 2030 targets are summarized in Table 1.2.

Table 1.2: 2020 and 2030 EU's energy targets.



	2020	2030
RES share	20%	27%
GHG reductions	20%	40%
Energy efficiency	20%	20%

1.5.3 2050 Energy Roadmap

Although it is not possible to predict the long-term future, the scenarios illustrated in the Energy Roadmap for 2050 examine some of the ways towards decarbonization of the energy system, which involve all major changes, such as carbon prices, technology, and networks.

Several scenarios aimed at achieving an 80% reduction in greenhouse gas emissions, involving 85% of energy-related CO2 emissions, including those in the transport sector, have been examined. The Commission also observed the scenarios foreseen by Member States and interested parties and their comments. Because of the long-term horizon, these results present a certain degree of uncertainty, mainly because uncertain are the hypotheses on which they are based on.

Scenario analysis is illustrative and looks at the effects, challenges and opportunities of possible ways to modernize the energy system. They are not mutually exclusive options, but focus on common elements and aim to support long-term investment approaches.

One of the main obstacles to investment is uncertainty. The analysis of the projections carried out by the Commission, the Member States and interested parties shows a series of clear trends, challenges, opportunities and structural changes that must be taken into account in drawing up the strategic measures needed to define an appropriate framework for investors.

Based on this analysis, this Energy Roadmap identifies key conclusions on "no regrets" options in the European energy system. This makes it also important to achieve a European approach, where all Member States share common understanding of the key features for a transition to a low-carbon energy system, and which provides the certainty and stability which are needed.

The 2050 Roadmap made by the European Commission is not supposed to replace national, regional and local initiatives aimed at modernizing energy supply, but it is proposed to develop a long-term and neutral European framework in the technological field where these policies are more effective.

The **decarbonization scenarios** examined in the 2050 Roadmap are the following:

High Energy Efficiency: focuses on political commitment to achieve high energy savings; it includes, among others, stricter minimum requirements for appliances and new buildings; high renovation rates of existing buildings; establishment of energy savings obligations on energy utilities. This leads to a decrease in energy demand of 41% by 2050, as compared to the peaks in 2005-2006.

Diversified supply technologies: all energy sources can race in the market without specific support measures. Decarbonization is triggered by a carbon price fixing that requires public acceptance of both nuclear and Carbon Capture and Storage (CCS).

High Renewable Energy Sources: robust support measures for RES in order to achieve a very high share of RES in gross final energy consumption (75% in 2050) and a share of RES in electricity consumption reaching 97%.

Delayed CCS: like the previous scenario but it assumes that CCS is delayed, leading to higher shares for nuclear energy with decarbonization driven in the first place by carbon prices rather than technology push.

Low nuclear: Similar to Diversified supply technologies scenario, but it assumes that no new nuclear (other than reactors currently under construction) is being built resulting in a higher penetration of CCS (around 32% in power generation).

By combining the different scenarios, it is possible to extract some conclusions which can help to shape decarbonization strategies today, which will deliver their full effects by 2020, 2030 and beyond. They are:

1. Decarbonization is possible, and in the long run may be less expensive than current policies. The costs of transforming the energy system do not differ substantially from the Current Policy Initiatives (CPI) scenario. In the latter case, the total cost of the energy system (including fuels, electricity and capital costs, investment in equipment, energy efficient products, etc.) could represent slightly less than 14.6% of European GDP in 2050, compared to the level of 10.5% in 2005.
2. Higher capital expenditure and lower fuel costs. In all the decarbonization scenarios, the EU bill for fossil fuel imports in 2050 would significantly drop, if compared with the one of today. The analysis

also indicates that between 2011 and 2050 the only cumulative investment costs in the network could range from 1.5 to 2.2 trillion euros, where the higher amount reflects a larger investment in support of renewable energy. The average capital costs of the energy system will increase significantly, thus bringing a widespread impact on the European economy and jobs in manufacturing, services, construction, transport and agricultural sectors.

3. Electricity plays an increasing role. In all scenarios, it can be noted that electricity will play a much greater role than the current situation - almost doubling its share in final energy demand and it will probably reach 36-39% in 2050 - and it will contribute to the decarbonization of transport and heating and cooling. In the 2050 Roadmap, it is estimated that electricity could provide approximately 65% of the transport energy demand. In order to achieve this goal, the energy production system should be subject to structural change and to reach a significant level of decarbonization (57-65% in 2030 and 96-99% in 2050) by 2030.
4. Electricity prices will rise until 2030 and then decline. Most of these increases is already happening in the reference scenario, and is linked to the replacement of obsolete production facilities that have already been fully depreciated over the next 20 years. In the High Renewables scenario, which implies a 97% share for renewable sources in electricity consumption, the modelled electricity prices continue to rise but at a decelerated rate because of high capital costs and hypothesis about high needs for balancing capacity, storage and grid investments in this "near 100% RES power" scenario.
5. Household expenditure will increase. In all scenarios, including the one based on current trends, energy expenditure and related products

(including transport) will probably have a greater impact on household spending, rising to about 16% in 2030 and drop off to more than 15% in 2050. However, if regulation, standards or innovative mechanisms are used to accelerate the introduction of energy efficient products and services, this would reduce costs.

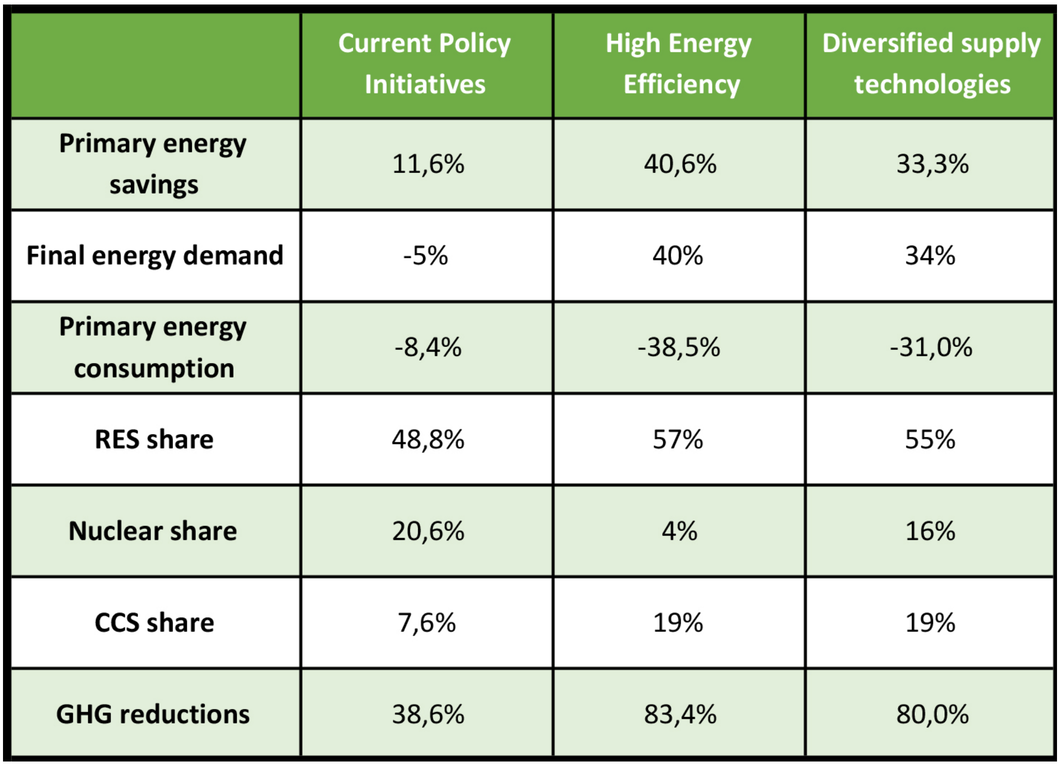
6. Energy savings throughout the system are crucial. Compared to the peaks in 2005-2006, primary energy demand will fall between 16% and 20% by 2030 and between 32% and 41% by 2050. In order to achieve significant energy savings, it will be necessary to free up the economic growth from the energy consumption, and strengthen the relevant measures in all Member States and in all economic sectors.
7. Renewables rise substantially. RES will achieve at least 55% in gross final energy consumption in 2050, which is very high compared to the current level of 10%. The share of renewables in electricity consumption reaches 64% in the High Energy Efficiency scenario and 97% in the High Renewables Scenario, which includes significant electricity storage to accommodate varying RES supply even at times of low demand.
8. CCS has to play a critical role in system transformation. If commercialized, Carbon Capture and Storage will have to contribute remarkably in most scenarios, guaranteeing up to 32% of energy production, in the case of limited nuclear production, and a share of 19 to 24% in other scenarios, with the exception of the High RES scenario.
9. Nuclear energy provides an important contribution. Nuclear is still a key source of low carbon electricity generation, and thus it will provide a major contribution in the energy transformation process in those Member States where it is pursued. The highest penetration of nuclear comes in Delayed CCS scenario, in which will be 18% in primary

energy, and Diversified supply technologies scenario (15% in primary energy), which show the lowest total energy costs.

10. Decentralization and centralized systems increasingly interact. Large-scale centralized systems, such as nuclear and gas stations and decentralized systems, will progressively need to work in synergy. The new energy system will have to promote and boost a new configuration of decentralized and centralized large-scale plants, which will depend on each other, for example, if local resources would not be sufficient or varied over time.

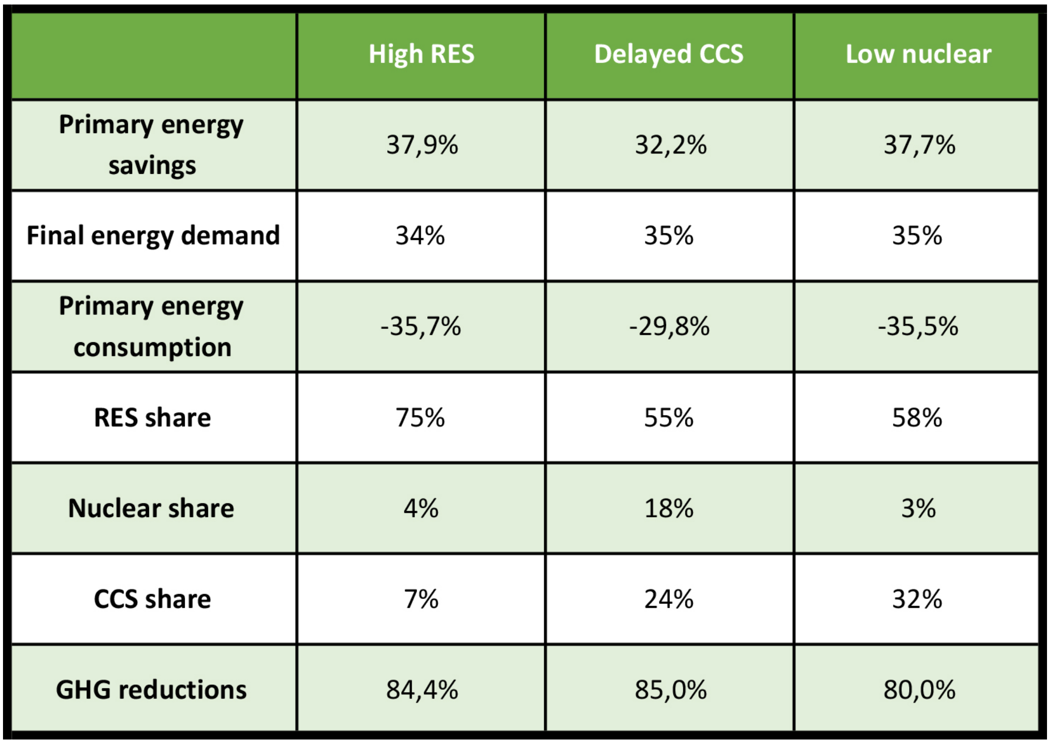
It's hard to compare 2050 targets to the 2020 and 2030 ones, since the Roadmap shows different scenarios and the projections may significantly vary from one to another. In Table 1.3 and 1.4 the analyzed scenarios are summarized in a general overview.

Table 1.3: CPI, High Energy Efficiency and Diversified supply technologies scenarios.



	Current Policy Initiatives	High Energy Efficiency	Diversified supply technologies
Primary energy savings	11,6%	40,6%	33,3%
Final energy demand	-5%	40%	34%
Primary energy consumption	-8,4%	-38,5%	-31,0%
RES share	48,8%	57%	55%
Nuclear share	20,6%	4%	16%
CCS share	7,6%	19%	19%
GHG reductions	38,6%	83,4%	80,0%

Table 1.4: High RES, Delayed CCS and low nuclear scenarios.



	High RES	Delayed CCS	Low nuclear
Primary energy savings	37,9%	32,2%	37,7%
Final energy demand	34%	35%	35%
Primary energy consumption	-35,7%	-29,8%	-35,5%
RES share	75%	55%	58%
Nuclear share	4%	18%	3%
CCS share	7%	24%	32%
GHG reductions	84,4%	85,0%	80,0%

1.6 Energy policy in United States

NREL (National Renewable Energy Laboratory), authority of the U.S. Department of Energy, made a technical report in 2009 in which it studies by sector (buildings, transportation, industrial, and power) energy consumption and thus the energy efficiency policies at the federal, state, and local levels. The report found out that buildings consume 40% of U.S. primary energy, including 72% of U.S. electricity consumption and 36% of natural gas consumption. The building sector drives the growth for new power plants; 87% of the growth in electricity sales between 1985 and 2006 is attributable to building sector demand (EERE, Office of Energy Efficiency and Renewable Energies, 2008).

In order to decrease such demand, the authors suggest to undertake a focused legislation that aims at building efficiency performance.

NREL highlighted that the policy types most frequently employed to increase the use of energy-efficient technologies in buildings, are the following:

1. **Building codes**, which affect long-term energy demands;
2. **Appliance standards**, which establish minimum levels of efficiency of appliances;
3. **Labels and consumer information**, which provide information on long-term energy consumption of appliances and buildings;
4. **Incentives**, both financial and non-financial, which include programs such as tax credits and expedited permitting for efficient buildings;
5. **Research and development**, e.g., on technologies needed to achieve cost-competitive zero-energy buildings.

At the federal level, the Energy Policy Act of 2005, expanded under the Energy Independence and Security Act of 2007, requires that existing buildings must reduce energy consumption 30% by 2015, compared with 2003 levels, through building upgrades and efficient appliances, as stated in section 431 of Energy Independence and Security Act of 2007.

In section 433 of the same paper, it is affirmed that the buildings shall be designed in order to reduce the fossil fuel-generated energy consumption of 80% by 2020, compared with 2003 levels (measured by Energy Information Agency, EIA).

In 2015, the US government released Executive Order 13693, in which were established the sustainable objectives for the next decade.

In section 3 it is stated that the total share of electric energy must come from renewable or alternative sources in a raising amount from fiscal year 2016 to fiscal year 2025, as showed in Table 1.5.

Table 1.5: Target share of renewable and alternative energy.

Fiscal year	Amount
2017	4%
2021	15%
2025	30%

For what concerns the GHG emissions, the objective is to reduce them progressively compared to 2014 data, as shown in Table 1.6.

Table 1.6: GHG reduction target.

Fiscal year	Amount
2016-2017	10%
2018-2019	13%
2020-2021	16%
2022-2023	20%
2025	25%

American and European objectives are not directly comparable, because of the different time reference and the fragmented American legislation, but we can still have a glance of the medium-term targets:

Europe, as we saw in the previous paragraph, has set the objective of **renewable energy sources share** at 20% by 2020 and 30% by 2030, while America has established the same target at 16% by 2020 and 25% by 2025.

In Europe, the **GHG emission reduction** is meant to be decreased at 20% by 2020 and 40% by 2030, and in United States is 15% by 2021 and 30% by 2030.

To achieve this target, U.S. government relies on Building Codes, an essential part of government efforts to transform the long-term market for energy efficiency. They contribute to save energy and money over a building's lifetime by regulating aspects of the building envelope, lighting, and heating, ventilation, and air conditioning (HVAC) system.
Building codes fall primarily within state and local jurisdiction, and since United States are a very wide country with many different climate areas, codes vary extensively across the nation, in order to meet the different needs.

At the state level, most of them have adopted codes based on model codes developed by the International Energy Conservation Code (IECC) and the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE). The strictness of the codes adopted depends on the states' climate and interests of local stakeholders.
Some states that do have statewide mandates adopt harsh codes to drastically reduce energy demand; e.g. in California, per capita building-related energy demand has remained distinctively constant over the last three decades, after passage in the 1970s of both a statewide building code and appliance standards.

At the local level, in order to promote high energy efficiency of both public and private buildings, the U.S. Green Building Council's introduced the Leadership in Energy and Environmental Design (LEED), a certification system for every kind of building.

LEED is a voluntary system for buildings at a high level of performance; it concerns the entire lifecycle of the building itself, from the design to the construction and management.

This certification promotes a sustainable approach, recognizing the performance of buildings in key areas such as energy and water saving, CO2 emission reduction, improved ecological quality of the interior, materials and resources used, the project and the choice of site.

130 jurisdictions require that buildings owned or supported by government must be LEED certified, and a few even mandate LEED certification for new private buildings, but since local jurisdictions have little regulatory power over the private sector, a widely accepted option is to make available financial and non-financial incentives, in order to encourage certification.

Sometimes, in states without mandatory building codes, local governments can provide their own codes. For example, Illinois has a statewide commercial building code, but most localities institute their own residential codes; some have adopted IECC 2003, others have implemented IECC 2006 and still others have codes that date back to IECC 2000 and 1998.

One of the most critical activities in ensuring energy savings resulting from building codes is local enforcement. Each jurisdiction varies in its procedures for enforcing compliance, including training and resources available to code officials.

1.6.1 Financial incentives

One of the biggest hindrance to the sustainable develop is the economic issue, since energy efficient technologies, especially in the initial investment, can have high up-front capital costs compared to traditional alternatives.

To help reduce this cost gap and stimulate environmental-friendly development, some policies offer financial incentives, such as grants, loans, rebates, subsidies, and tax incentives.

Said incentives aim to reduce both the investment capital and installation costs, but they also have different goals depending on the sector.

In the **industrial** and **manufacturing** sectors, the objective is to target efficiency improvements early in the commercialization process, in order to reduce program implementation costs.

In the **commercial**, **residential**, and **end-user** sectors, the goal is to use the financial incentives to educate the public on benefits of energy efficiency and increase market penetration of existing efficient technologies.

At the federal level, the government set two important key-points: the Business Energy Investment Tax Credit (ITC), which mainly supports solar PV, and the Renewable Energy Production Tax Credit (PTC), which mainly supports wind power (see Table 2.1 below).

Relative to standards and labeling, federal financial incentives for efficiency are rather new. The most recent economic support for energy efficiency are the grants and loans offered to small agricultural residents and businesses through the Rural Energy for America Program (REAP), which U.S. Department of Agriculture enacted in the Farm Security and Rural Investment Act of 2002.

United States Department of Agriculture (USDA) provided $23 million each fiscal year in grants, loans, and loan guarantees, to help small agricultural producers to make energy efficient improvements and install renewable energy technologies.

REAP aims to enhance the energy independence in United States, by boosting the private sector allocation of renewable energy, and also reducing the demand for power through energy efficiency improvements. In the long term, these investments are supposed to help lower the energy costs for small businesses and agricultural producers. REAP was included in Agricultural Act of 2014, in which funds of $20 million were renewed until 2018 (Agricultural Act of 2014, Section 9007).

According to the report by NREL, in the period 2002-2005, energy efficiency projects represented 38% of total REAP awards, and resulted in approximate energy savings of 75,000 MWh.

Based on program popularity and impact, as well as the increasing focus on energy and rural development issues more broadly in the United States, USDA announced that REAP was included in Agricultural Act of 2014, in which funds of $20 million were renewed until 2018 (Agricultural Act of 2014, Section 9007). Subsequently, the Food, Conservation and Energy Act of 2008 (HR 2419) allocated $60-$70 million annually from 2009-2012 for the program's continuation.

The most recent federal efforts to establish financial tax incentives target upstream efforts for the purposes of optimizing intervention costs (i.e., approaching a small number of appliance manufacturers instead of many consumers). There is, however, one end-user investment tax credit for primary residences and high-efficiency home equipment, including windows, doors, insulation, heat pumps and heat pump water heaters, central air conditioners.

A lot of states have also been provided financial incentives to subsidize energy efficiency.

Oregon, as for example, has offered a Business Energy Tax Credit (BETC) since 1979, which involves a tax credit of 35% for the purchase of conservation technologies, and also incorporates a Pass-through Option, which allows entities that do not pay a sufficient amount in taxes to obtain a one-off payment. The main feature of this program is that instead of being based on

costs, as is common for tax credits, this financial incentive is based on performance as measured by square footage and level of achieved sustainability, which involves at least reductions in energy use of 10% for building retrofits or new home construction and 25% reductions for lighting upgrades. In the same state, a tax credit is also available to developers of sustainable buildings with LEED-certifications of at least Silver.
Other examples include, but are not limited to, the California Energy Commission, which offers loans at a fixed rate of 3% to schools, hospitals, and local governments for energy audits and the implementation of efficiency measures.
New York provides financial incentives and technical assistance to owners of multifamily buildings to improve building energy performance. Utilities across most states offer rebates toward the purchase of energy-efficient appliances (DSIRE 2009).

Several states have established to fund energy efficiency programs, including financial incentives, by adding a utility charge to each customer bill, called system benefits charge (SBC). SBCs are meant to fund incentives, education programs, and demonstration projects; usually they are raised as a $/kWh charge on consumer utility bills, and thus they do not affect the general state budget. This is the reason why such funds have remained stable despite severe cuts in public spending across most states.

Local governments provide both financial and non-financial incentives. A popular new trend is a tax-credit policy meant to finance residential energy efficiency improvements, through municipal bonds that are repaid through property taxes. The financing is provided in exchange for a lien on the property.

The mentioned program has been successful because residents are not requested to have necessarily a good credit to get a loan, because the loan is secured against their property, and since the property serves as collateral, it is also ensured that the lender's risk is eliminated, because energy efficiency retrofits cannot be removed in the case of non-payment, unlike solar panels.
Another important benefit of this program is that homeowners do not have to regain their investment through home sale price if home ownership changes hands, since the loan lies in the property owner and not in the purchaser. This is a very valuable feature, because energy efficiency improvements, such as insulation, are usually invisible to prospective home buyers.
Another kind of local financing is through the Weatherization Assistance Program (WAP), which benefited from an expansion in funding by the federal American Recovery and Reinvestment Act of 2009.
The main target of WAP is to permanently reduce the utility bills of low-income residents by helping them pay for one-time energy efficiency improvements to their residence, rather than simply contributing to their bills, solution that can only work in the short term.
The main target of WAP is simple: instead of contribute month-to-month to the utility bills, this program is meant to be a long-lasting help to the low-income residents, by supporting the payment for one-time energy efficiency upgrades to their houses.
A secondary goal is to extend the number of jobs related with the renewable energies, known as "green jobs", by basically expanding the market for energy audits and efficiency retrofits.

Local governments can also influence building efficiency through non-financial incentives. In states with building codes that do not authorize local alterations, localities can encourage energy efficiency in the private sector by providing both financial disbursements and, more frequently, zero-cost incentives, such as expedited permitting.

For example one locality, Arlington (Virginia), grants density and/or height bonuses to buildings that achieve LEED-certification. The effectiveness of this small group of geographically dispersed incentives has not been evaluated in the NREL report.

Louisiana provides many incentives in several sectors to help people and corporations moving to renewable, most of them are aimed at supporting the purchase of efficient household appliances and also at contributing to the payment of the utility bills.

New Orleans City Council established in 2010 a rebate program called "Energy Smart Program", in cooperation with Entergy Inc., which provides energy audits and cash rebates to who invest in qualifying energy efficiency improvements, through energy assessments and valuable cash rebates on a variety of energy efficiency improvements.

In Appendix A are listed some of the financial incentives that are available in New Orleans, from the federal to the state to the local level.

1.7 Policy development in the rest of the world

Over 150 countries have adopted specific policies for renewables-based power, 75 have policies for renewables-based heat and 72 for renewables in transport (IEA, 2016).

Power sector policies are evolving, as the status of renewables matures: initial policies were targeted at bridging a large cost gap, but recent initiatives have moved towards reducing the risks of capital-intensive investments.

In May 2016, Japan amended the terms of its feed-in tariff to require authorized projects to have connection contracts with power companies by no later than end-March 2017 or they will be cancelled. Over 100 GW of solar PV projects have been approved to date, with around 30 GW having been installed by the end of 2015, so the remaining 70 GW are subject to the new deadline (IEA, 2016).

In February 2016, India released state-specific targets consistent with its national aim of a 17% Renewable Purchase Obligation (RPO) level by 2022. The government has also accelerated the approval of large-scale solar PV projects through its Solar Park initiative, which aims to support the creation of the necessary infrastructure to enable the establishment of concentrated zones of development of solar power generation projects (around 20 GW of new capacity has been approved so far) (SECI, 2016).

Chapter 2

Life Cycle Assessment method

2.1 Origin and development of the LCA

Life Cycle Assessment (LCA) have had different names before assuming this title. This methodology was in fact known with other words, such as life cycle analysis, cradle to grave analysis, resource and environmental profile analysis, eco balance, energy and environmental analysis, etc.

When this approach was created, it represented an absolute newness, since until then to reach the efficiency improvements, the researchers had been focused on the single components of the manufacturing process, and they did not consider that often the improvements obtained analyzing separately the single processes could be only apparent.

For instance, a single industrial operation can be made more efficient or cleaner at the expenses of others, simply moving the pollution in the space or time, overlooking the fact that the benefits obtained locally can offset the issues that therefore are generated elsewhere (or later in the timeline), with the final result to obtain no real improvement or even worsen the total balance.

Moreover, the LCA approach distance itself from the model typically preferred by economists, which used to consider the partition of the industry in sectors (mining, building, machinery, etc.); the new approach, instead, was based on the analysis of the compliance of specific purposes for each manufacturing and services sector; for example, in the case of milk distribution are included: food industry, packaging industry, paper industry, and so on.

Since 70's there are the first examples of application of the Life Cycle Thinking theory, used as backing by big American companies, such as EPA (Environmental Protection Agency); the purpose was to compare different materials for the same uses, and this was the opportunity which increased the number of LCA analysis applied to the manufacturing processes: compare corresponding performances with different solutions and materials, from an environmental point of view.

This method, more than introducing the idea of valuate the environmental consequences during the whole life cycle of the process, presented the evaluation of the energy consumption, intended as belonging to the category of natural resources, and thus stimulate the attention to the concept of the shortage of natural supplies.

Some studies of global models were published in the book "The Limits to Growth" (Meadows et al., 1972), in which the authors tried to foresee in what way the population growth could influence the raw materials and energy demand. The outlook of a quick depletion of fossil fuels and eventual climate change, due to the excess of heat released in the air by the combustion processes, pushed towards calculation of energy consumption and towards industrial waste. In that period the oil crisis had not exploded yet, but despite, the awareness that they were exploiting limited energetic resources, was already sufficiently developed that induced researchers from the academic and industrial world to face those issues.

Afterwards, the increasing levels of pollution, the pressure from the environmental movement, the issues due to the end use of waist, contributed to push the common effort to the tuning of new methodologies and tools which could modify the typical approach of the classic economic theory to this kind of phenomenon.

In the late ‘80s, this brought to the achievement and diffusion of the concept of “sustainable development”, defined for the first time in the document “Our Common Future”, by the World Commission on Environment and Development (1987), as the “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”.

Given that there are no cost-effective production processes at an energy and environmental point of view, the approach to be taken is to understand the dynamics of operation of the different processes in order to be able to propose corrective improvement actions.

In the same period, in Europe, Boustead and Hancock published the Handbook of industrial energy analysis (1979), which, from the experience of some bottle manufacturer, could offer for the first time an operating description of the analytical process that is a fundamental part of the present LCA. This handbook is still considered as a milestone in the history of the method, in which we can find the first signals of the need of an integrated approach to the life cycle.

The word LCA was created only during the SETAC congress (Society of Environmental Toxicology and Chemistry) in Smuggler Notch (Vermont) in 1990, to better characterize the target of the analysis until then made with other names.

Moreover, in this occasion was proposed a framework divided in 3 main phases supposed to be executed cyclically (see Fig. 2.1), which represented the first structure of the LCA, and it still form the essential configuration of the method, except for an additional first step introduced afterward.

The first one is an inventory phase, in which the information and data collected are organized and converted into a standard form in order to describe in detail the physical characteristics of the system studied (that is the analogical model of the system); the next phase involves the interpretation of inventory data, which are related and linked to environmental issues; in the end there's the improving phase, in which the manufacturing system is subject to analysis and simulations in order to try and improve the overall efficiency.

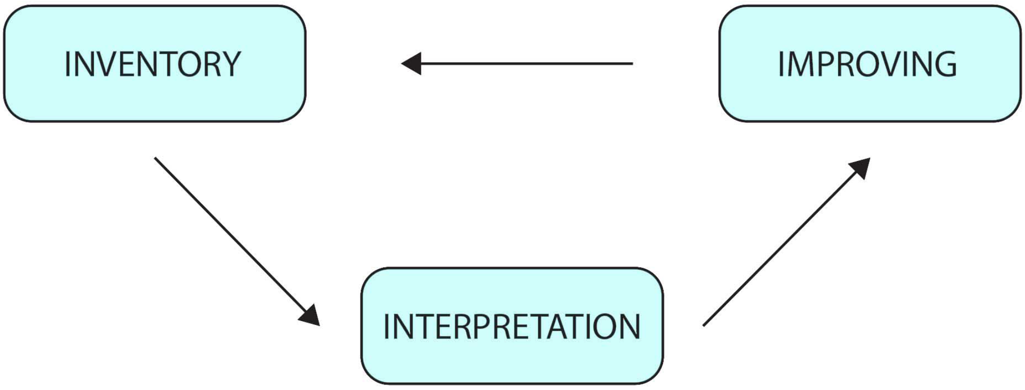


Fig. 2.1: The three main phases of an LCA, as proposed during the SETAC congress (1990).

In early '90s many proposals were actualized, in order to find a standardization of the LCA method through the publication of handbooks and specific papers, computing tools and database for a practical use; these tools nowadays are widespread and used by most researchers and operators in the industry.

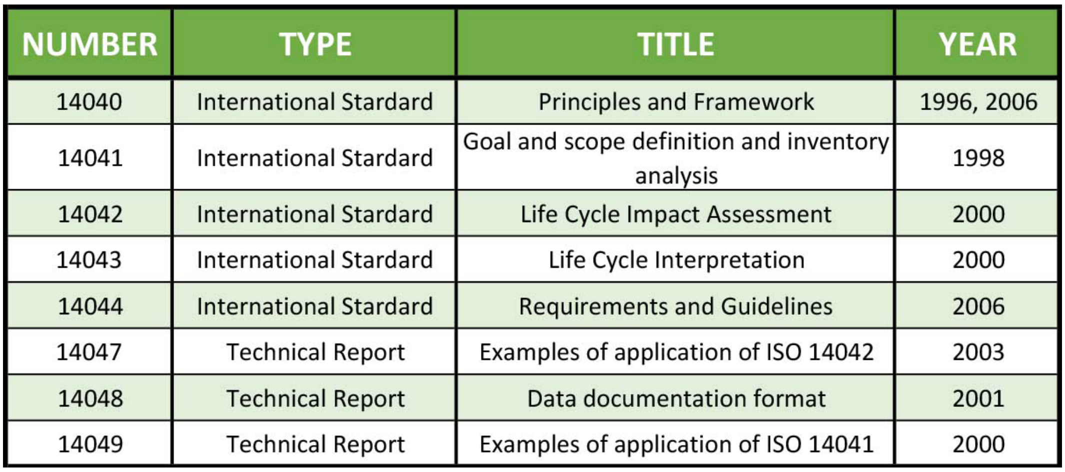
To the present day, the LCA is increasingly acclaimed and it is becoming an essential tool for calculating the environmental load of production systems, enabling, thanks to the many applications and experiences, to increase the degree of diffusion of the topics dealt with.
The European Commission considers this approach as the only one able to provide a scientific and reliable basis to evaluate the environmental impacts

of products and processes in a global perspective.

The maturity and unification of the methodology are evidenced by the release, by ISO and its Technical Committee 207 (TC207), of the technical regulation of the ISO 14040 “Environmental management - Life cycle assessment - Principles and framework”, which concerns several issues related to many aspects of business environment management, meeting the needs expressed by companies, governments, non-governmental organization (NGO), manufacturers, who started drafting voluntary certification for their products, and by consumers themselves.

ISO published more standards and technical reports concerning the environmental labels and the Life Cycle Analysis method, as illustrated in Table 2.1.

Table 2.1: ISO publications on Life Cycle Analysis.



NUMBER	TYPE	TITLE	YEAR
14040	International Stardard	Principles and Framework	1996, 2006
14041	International Stardard	Goal and scope definition and inventory analysis	1998
14042	International Stardard	Life Cycle Impact Assessment	2000
14043	International Stardard	Life Cycle Interpretation	2000
14044	International Stardard	Requirements and Guidelines	2006
14047	Technical Report	Examples of application of ISO 14042	2003
14048	Technical Report	Data documentation format	2001
14049	Technical Report	Examples of application of ISO 14041	2000

ISO 14041, ISO 14042 and ISO 14043 were updated in 2006 and merged into ISO 14044.

At the manufacturing level, the most important industry associations in Europe and the world have already made public or are developing databases to provide lifecycle data and information about the materials and processes they represent.

In United States, The U.S. Department of Energy and NREL (National Re-

newable Energy Laboratory) developed the U.S. Life Cycle Inventory (LCI) Database in 2003 with input from a variety of partners, to help LCA manufacturers, building designers, and developers to answer questions about environmental impact and select energy-efficient and environmentally friendly materials, products, and processes for their projects.
This LCI Database Project was initiated on May 1, 2001, and gained national prominence at a meeting of interests hosted by the Ford Motor Company. Funding agencies and representatives of industrial, academic, and consulting communities voiced strong support for the project. As a result, an advisory group with 45 representatives from manufacturing, government, and non-government organizations, as well as LCA experts, worked together to create the U.S. LCI Database Project Development Guidelines. NREL maintains and updates the database with support from the Building Technologies Office, which funds ongoing research in life cycle assessments to expand the available data (NREL, 2012).

In Italy, after Anpa's experience (Agenzia nazionale per la protezione dell'ambiente, then Apat, now Ispra) the Italian I-LCA database was published in 2000, an indicator of intense activity both at the company level and in research projects funded largely by the European Commission, although currently it is no longer compatible since its structure and content does not conform anymore to the standards of publicly available databases and would need to be up-to-date.
The availability of a national LCA database, up-to-date, publicly available and usable, can be a major asset for the application of sustainability policies in Italy. For these reasons, in February 2014, the Ministry of the Environment, with the technical and scientific support of ENEA, created a demonstration of an Italian database, which is currently the agri-food sector, which

is the first national nucleus of Life Cycle Data Network, a system that aims to network European and non-European databases using similar quality criteria and methodological coherence.

2.2 Definition

It is suitable, before describing in detail the framework of a LCA, to report a few definitions in order to better contextualize the topic.

ISO 14040 describes the LCA as “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle”

A LCA applied to an industrial system therefore addresses the efficiency study of the system in question to the protection of the environment and human beings, as well as to the saving of resources. The essential point of the theory is the definition of this “industrial system” that the ISO standard identifies with a “product system”; furthermore, it is necessary to specify that the life cycle analysis does not coincide with a product life cycle analysis.

A LCA describes the system that generates these products or, in other words, the function of the system itself: ISO norms regard a product system to indicate precisely “collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product”.

Ultimately, it should be highlighted that an LCA is always a simplification of real processes because, as a model, it does not include a complete representation of all interactions and exchanges with the environment but only of those considered to be more significant by those conducting the study, in order to make comparisons between different choices.

2.3 Framework

The modern LCA framework provided by ISO 14040 can be summarized in four main phases, as shown in Fig. 2.2, which are:

- Goal and Scope Definition;
- Life Cycle Inventory Analysis, LCI;
- Life Cycle Impact Assessment, LCIA;
- Life Cycle Interpretation.

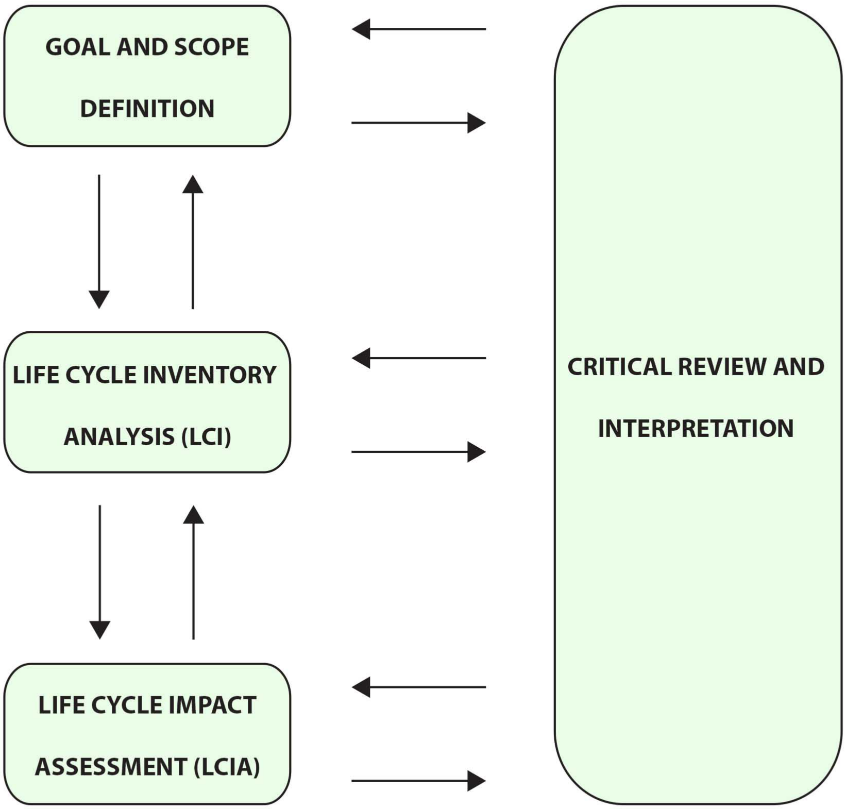


Fig. 2.2: Stages of an LCA, according to ISO 14040.

Before explaining in detail the various phases, it should be pointed out that the methodological approach is of a dynamic and iterative type, because the availability of data and information necessary for its development, which is a fundamental part of the analysis, is often not complete; but as the study goes into more detail new data can be added, replaced or updated the older ones, requiring an on-going review.

2.3.1 Goal and scope definition

Standard ISO 14040, in section 5.2, states that the goal of an LCA establishes: the intended application, the reasons for conducting the study, the designed audience, and whether the results are meant to be used in comparative assertions intended to be disclosed to the public.

Also, ISO 14040 continues: "The scope should be sufficiently well defined to ensure that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal".

Therefore, the goals and scope of the study significantly influences the choices and the starting hypotheses, leading to very different scenarios from time to time.

Several variables depend on the purposes of an LCA, such as the definition of life cycle breadth, the options to consider, the quality and reliability of the data available, the level of detail to be achieved, etc. In general, however, the scope can have one of the following purposes: research and development, green marketing (ecological labeling, environmental communication, etc.), support in environmental management systems, eco-design.

Although often, at the beginning of an LCA analysis, it is not possible to bring the case back to one of these categories, finding a preliminary strategy is effective because it helps to define the boundaries of the research; then at every moment it is possible to go back and extend the scope and expanding the study scenario.

At this point, the system is defined as the set of devices that perform one or more precise operations having a certain function, bordered by physical boundaries from the environment system and having input-output exchange relationships with it.

The flows of materials, energy and end products that form such systems, come together in many operations connected to each other, often in a complex way. In this articulated scenario, it is useful to define the individual operations that make up the process, that is the unit processes, each of which receives input from the previous ones and, with their own output, go to the following (see Fig. 2.3).

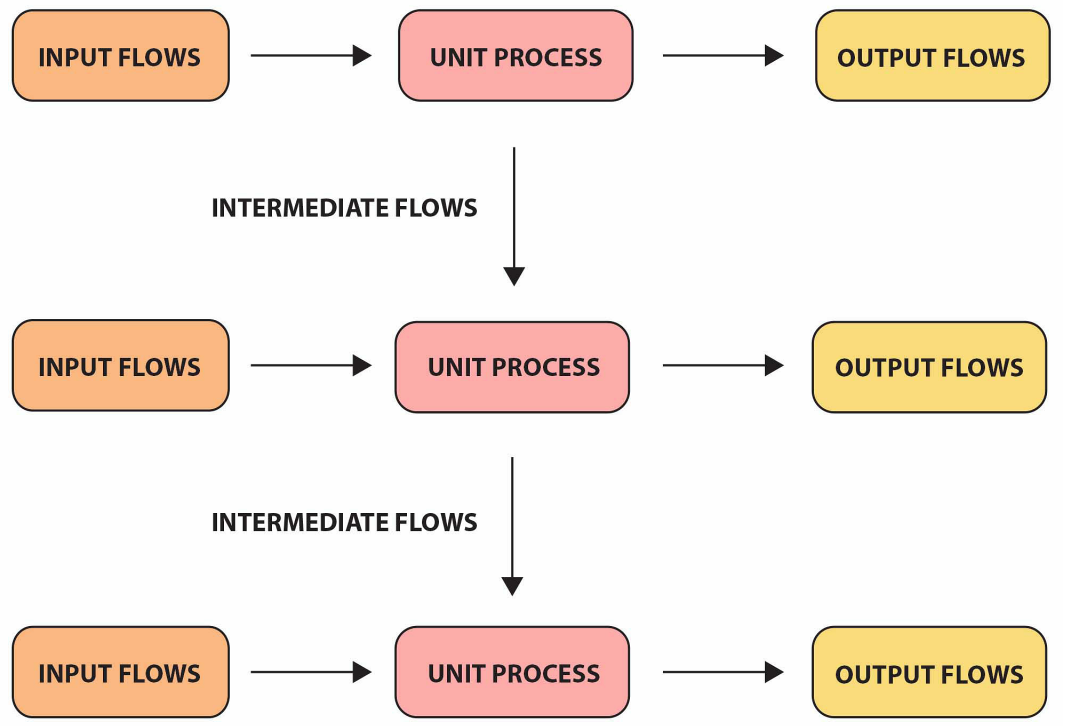


Fig 2.3: A set of unit processes within a product system.

It is also possible to consider the behavior of a unitary operation under stationary conditions, regardless of the other, and thus limit the analysis to system parts, i.e. to sub-productions.
It is important to specify from the beginning what the reference measurement unit is, i.e. the **functional unit**, with whom refer data and information, as defined by ISO 14040: “quantified performance of a product system for use as a reference unit. […] The functional unit shall be consistent with the goal and scope of the study. One of the primary purposes of a functional unit is to provide a reference to which the input and output data are normalized (in a mathematical sense). Therefore the functional unit shall be clearly defined and measurable.”
This choice is totally arbitrary and it depends on the purposes of the study, as well as binding for its success. To better clarify this concept, it is possible to refer to a paintwork of a wall: the functional unit will be the square meter of surface protected by painting for a minimum period of time and not, for example, the kilogram of paint.

The next step, of great importance, is the definition of the **system boundaries**, following a detailed description of the process under consideration. Basically, the relationship between product system (or management system) and the environmental system are investigated, or rather the effects of the first on the second; it is therefore necessary to define the boundaries between these two systems.
A first definition is made based on geographical, technological and physical boundaries of production processes; continuing with the study, it is possible to exclude non-relevant processes or to include others that were initially not considered.

An effective solution is to disaggregate the various phases that make up the entire process, each of which may be articulated into sub-phases: the level of detail depends extremely on data availability.
In Fig. 2.4 the first phase of the LCA is displayed.

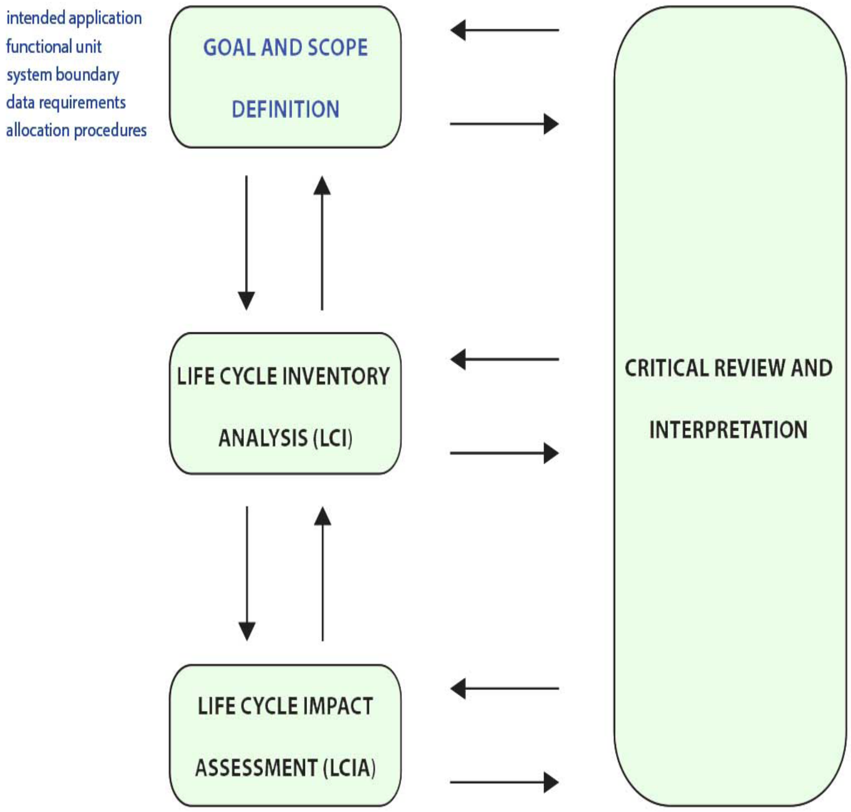


Fig. 2.4: The first phase of the LCA.

2.3.2 Inventory Analysis

Inventory analysis is the time of an LCA in which an analogue model of reality is constructed in order to represent, as faithfully as possible, all the exchanges between the individual operations of the system. The main requirement of a lifecycle inventory is to ensure reliability of its data, so its editing must follow a well-defined code, provided objectively by ISO 14040.

The inventory is divided into four modules:

1. Process flow-chart: consists of a graphical and qualitative representation of all the relevant phases and of all the processes involved in the life cycle of the analyzed system. It consists of process sequences (boxes) connected by material flows (arrows). Its fundamental feature is to divide a system into several sub-systems, to perform interconnection actions (the outputs of a sub-system upstream are the inputs of a downstream sub-system) and to identify the parts of the process that are of major importance, especially in environmental matters, in order not to give the same level of attention indiscriminately at all stages;
2. Data collection: requires a very large amount of time and resources due to the amount of information needed, including all stages of the production process, often difficult to find. The reliability of the data collected during this phase is critical, even though it is practically impossible to ensure the same level of accuracy for all the information used. Therefore, the data to be used should, as far as possible, be primary data, i.e. collected directly on the field. In the absence of such data, secondary data can be used, obtained from literature or from predefined databases (citing the source). In addition to impacts related to the process, data on impacts and consumption of electricity imported into the system should also be defined by clarifying the reference context (countrywide, statewide, local) to assess the mixing of fuels that contribute to the production of the exploited electric kW, the overall system efficiency and its impacts on the environment and the impacts and consumption of the transport system;
3. System boundaries: the boundary points between the studied system and the environment are defined (i.e. the load on the environ-

ment must be specified, represented by all the extractions occurring throughout the life cycle) and also the boundary between the processes considered relevant and irrelevant is stated. At this point, the practitioners decide the extension of the study, setting what is to be included and what, instead, must be overlooked. Therefore, the purpose of the study, previously defined, depends on practical considerations, based on the opportunity not to involve elements that, in fact, do not have a substantial relevance to the final results;

4. Data processing: after collecting the data, these are related to all process units that contribute to the production of the functional unit in the study (e.g. the amount of electricity used in production, the kg x km of product and the co-product that need to be transported, how many kg of raw materials are used, etc.) where, for each process unit, an appropriate unit of measurement for the reference flow (e.g. 1 kg of material or 1 MJ of energy) will be determined.

Next, the environmental impact data is processed and referred to the functional product unit by defining a contributing factor: it expresses the contribution of each process to the production of a functional unit, expressed through the unit of chosen size (e.g. 175 kWh / 1000 kg). This procedure must be performed for all the substances present in each process.

A problem that may arise during this phase, if different products are generated from the same production process, is the distribution of consumption and impacts related to these products. In this case, it is important to try to understand in detail the manufacturing process, so each product can get its share of raw material, consumed energy and therefore also their respective impacts on air, water and solid waste.

Moreover, most industrial systems produce, in addition to the main ones, "any of two or more products coming from the same unit process or product system", as defined by ISO 14040, known as co-products or sub-products; thus, it is useful and necessary to subdivide the system into sub-systems, each of which generates or uses a single product that, once recomposed, brings to the starting system.

The operation that correctly assigns inputs and outputs to individual subsystems is called allocation or partitioning, and allows to match energy and environmental loads with the different co-products and sub-products generated by a process. The most commonly used allocation method that involves using the physical characteristics of products, such as mass, volume, energy, etc.
The issue of the allocation is also significant when it is necessary to allocate the right energy and environmental load to a recycled material that becomes raw material in a production system, or to a co-product that replaces another; in this way, it is possible to avoid some environmental impacts that would arise with the whole production of the material, by relieving the energy and environmental loads of the final product. In conclusion, in the absence of detailed specifications, the mass allocation method is preferable.

To continue in the inventory analysis, it seems useful to briefly note that the management of the end of life of materials should be treated as waste; this is because although waste is one of the central problems of production systems, through an LCA approach it is possible to define and identify, already in the early stages of design, the best choices for effectively reducing environmental and economic impacts linked to the end of life of the product.
When a good comes to the end of its useful life, after harvesting, there are three alternatives: matter recovery, energy recovery, disposal at landfill. Each of these possibilities presents aspects that need to be analyzed and compared

in order to choose the best environmental way.

For the first option, it is necessary to distinguish between reuse and recycling: the reuse consists of reusing a product that has come to its end for the same function it had carried out over the useful life cycle without making any substantial changes; recycling allows to retrieve the material contained in the product at the end of life after appropriate treatments, in order to manufacture the same or another product.

Energy recovery is possible through waste-to-energy processes that allow to produce electricity or heat from the feedstock energy present in waste materials.

The last option is represented by the controlled landfill, in which all the materials that have not undergone recovery/recycling and which, in some cases, may involve a partial recovery of energy through the combustion of biogas produced.

Given this, one of the most interesting aspects from the point of view of the method involves quantifying the positive aspects of recovering some types of waste; one way is to evaluate the impacts avoided, that is subtract, from the impacts generated, those associated with recovered flows that are therefore considered to be beneficial. A second approach considers CO2 emissions in the atmosphere, mainly through computers that can measure the contribution of a product to the greenhouse effect in terms of CO2 equivalent.

One last method aims to account the amount of feedstock energy, i.e. potentially combustible energy; such analysis is carried out when, for a material, it is possible to choose between recovery of matter or energy: in this case the material in question is associated with a quantity of feedstock energy equal to its calorific power.

The results of a lifecycle inventory are normally presented in six main parameter categories: primary fuels and feedstocks (grouped in “energy outcomes”), raw materials, solid waste, water and air emissions (grouped in “environmental”). It is essential to appropriately classifying solid waste in order to identify its destiny, disposal or recovery, to correctly evaluate end-of-life impacts.

This paragraph ends with some observations regarding the precision level of an LCA study; by its own nature, this methodology is not “accurate”, especially when the system analyzed includes a long and complex chain or when secondary data is widely used.

The mistake made is however function of the resources employed in the study and its complexity; in spite of this, the LCA is a methodology that offers the highest support in terms of comparison and analysis of the life cycle phases considered.

In Fig. 2.5 the second phase of the LCA is displayed.

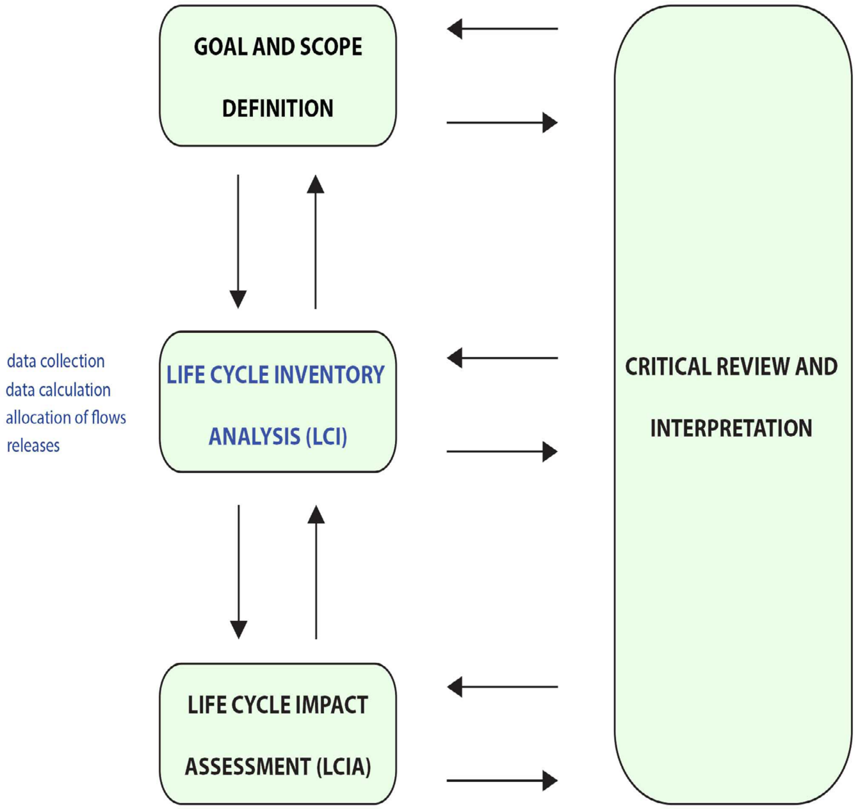


Fig. 2.5: The second phase of the LCA.

2.3.3 Life Cycle Impact Assessment

The information obtained from the inventory analysis is the starting point for environmental assessments to which the LCA Life Cycle Impact Assessment (LCIA) phase is dedicated, regulated by the ISO 14040 and ISO 14044 standards.

The goal of the study is to identify the extent of environmental changes that arises as a result of releases into the environment (emissions or waste) and the consumption of resources associated to a manufacturing activity.

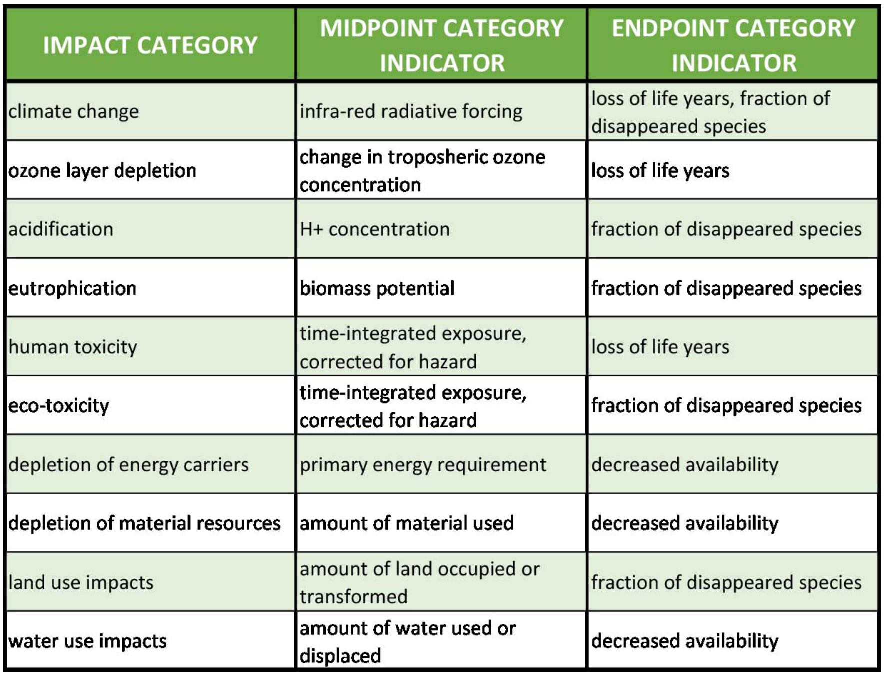
This task is far from simple, especially regarding the scientifically acceptable correlation between the emissions and the environmental effects.

As the standard ISO 14001 says, an is “a change to the environment that is caused either partly or entirely by one or more environmental aspects. An environmental aspect can have either a direct and decisive impact on the environment or contribute only partially or indirectly to a larger environmental change.” That is to say, the impact is what originates an effect, without claiming to be able to unambiguously quantify the effect on the basis of the impact, but trying to estimate it through hypotheses and conventions.

Moreover, these effects are subdivided globally, regionally and locally according to the scale of action; hence, depending on the level of analysis the study is supposed to achieve, it is possible to set the evaluation step with a global or specific approach for a particular site (Curran, 2012).

Table 2.2 shows the main environmental effects and their influence scale (for details of the effects listed below see par. 2.4.3).

Table 2.2: Main environmental effects and scale of influence.



IMPACT CATEGORY	MIDPOINT CATEGORY INDICATOR	ENDPOINT CATEGORY INDICATOR
climate change	infra-red radiative forcing	loss of life years, fraction of disappeared species
ozone layer depletion	change in troposheric ozone concentration	loss of life years
acidification	H+ concentration	fraction of disappeared species
eutrophication	biomass potential	fraction of disappeared species
human toxicity	time-integrated exposure, corrected for hazard	loss of life years
eco-toxicity	time-integrated exposure, corrected for hazard	fraction of disappeared species
depletion of energy carriers	primary energy requirement	decreased availability
depletion of material resources	amount of material used	decreased availability
land use impacts	amount of land occupied or transformed	fraction of disappeared species
water use impacts	amount of water used or displaced	decreased availability

Many of these later impacts are even conditional on our future activities, including future emission scenarios and mitigating actions. The result of this phase will be an environmental profile of the study system that can be used to compare the behavior of different production processes, and to define how and where to intervene in order to achieve a minimization of impacts.

To be able to quantitatively model the emissions of different causes of global warming into impact indicators, it is important to choose a certain point in the causal mechanism. This can be at the front-end (e.g. change in radiation balance), at the back-end (e.g. change of bio-diversity), or somewhere in between (e.g. change in temperature).

In LCA, two main schools are followed (Curran, 2012):

- the **midpoint** approach, focused on the front-end;
- the **endpoint** approach, focused on the back-end.

Midpoint methods measure damage basing on the missing natural substances and the emissions produced; midpoint indicators are expressed by impact categories with their characterization, and their unit is the equivalent unit of the emissions that produce the damage. This approach has the advantage of including fewer disputable assumptions and more objective facts.

Endpoint methods measure damage basing on the effects that emissions or missing natural substances produce on humans, the quality of the ecosystem, resource depletion, and climate change; in this case substances and emissions are characterized, impact categories are aggregated into categories of damage, which are normalized and evaluated. This approach has the advantage that it provides more intuitive metrics (like loss of life years instead of kg CO2-equivalents).

Regardless of the choice between midpoint and endpoint, the indicator chosen is referred to as the impact category indicator, or category indicator for short.

Next, a way must be found to convert the emission data into the selected impact indicator. Researchers in chemistry, meteorology, ecology, etc., have developed model fragments to estimate the atmospheric span life of greenhouse gases, their effect on the radiation balance and the formation of clouds, the effects of temperature on the distribution of species, etc. These fragments have been combined by workgroups from the UN-based International Panel on Climate Change (IPCC) into quantitative models of the impacts of greenhouse gas emissions. Part of this is the global warming potentials (GWPs), which are quantitative measures of the strength of different greenhouse gases. Many midpoint LCIA methods apply GWPs for climate change. GWPs provide one example of a set of characterization factors, and the IPCC-model from which they are derived is an example of a characterization model. It is important to highlight that characterization factors are often tabulated in LCA guidebooks and are implemented in many LCA software packages, while the characterization models often require supercomputers and expert knowledge (Curran, 2012). The selection of impact categories to be addressed is needed before selecting a category indicator and a characterization model with associated characterization factors.

Some LCA studies focus on just one impact category, e.g., the carbon footprint is considered a form of LCA that addresses just climate change at the midpoint level through GWPs; on the other hand, some LCA studies can include fifteen or more impact categories.
In practice, the choice of impact categories often is among "IMPACT2002+", "IPCC", "CML", "ReCiPe", "ILCD", etc. The mentioned methods comprise a suggested set of impact categories with a category indicator and a set of characterization factors. ISO leaves freedom of choice in these matters.
Table 2.3 gives a summary of the most used impact categories and category indicators. As we can see, the column with endpoint indicators contains many times the same term (e.g., "loss of life years"): this indicates that impact categories can be aggregated into fewer endpoint indicators than midpoint indicators (Curran, 2012).

Table 2.3: Overview of widely-used impact categories.

IMPACT CATEGORY	MIDPOINT CATEGORY INDICATOR	ENDPOINT CATEGORY INDICATOR
climate change	infra-red radiative forcing	loss of life years, fraction of disappeared species
ozone layer depletion	**change in troposheric ozone concentration**	**loss of life years**
acidification	H+ concentration	fraction of disappeared species
eutrophication	**biomass potential**	**fraction of disappeared species**
human toxicity	time-integrated exposure, corrected for hazard	loss of life years
eco-toxicity	**time-integrated exposure, corrected for hazard**	**fraction of disappeared species**
depletion of energy carriers	primary energy requirement	decreased availability
depletion of material resources	**amount of material used**	**decreased availability**
land use impacts	amount of land occupied or transformed	fraction of disappeared species
water use impacts	**amount of water used or displaced**	**decreased availability**

With this in mind, the ISO 14040 and ISO 14044 standards indicate, in the general structure of an LCIA, mandatory elements that convert the inventory results into appropriate indicators.

To conform with the standard, it is mandatory for a study to complete:

- selection of impact categories, category indicators effects to be considered, and characterization models;
- assignment of LCI results to the selected environmental effects (**classification**);
- comparison of environmental indicators calculated with reference values (**characterization**);
- determination of the importance of individual environmental effects (**evaluation**).

There are also optional elements, which can help developing this phase:

- calculation of the magnitude of category indicator results relative to reference information (**normalization**);
- sorting (on a nominal basis, like global/regional/local) and ranking (on an ordinal basis, like high/medium/low priority) the impact categories (**grouping**);
- multiplying the normalized results of each of the impact categories with a factor which expresses the relative importance of the impact category (**weighting**).

The first action in the LCIA phase is thus the choice of environmental effects to base the analysis on. The calculation of final indicators is, like in other applications where a mathematical model is used, of boundary conditions, hypotheses made, data quality, and scientific knowledge.

As mentioned before, in the specific context of an LCA, the greatest uncertainties lie in the characterization factors of the various waste water placed in the environment; this is why LCA practitioners only use internationally acknowledged factors, whose scientific validity is widely established, so as to limit as much as possible the subjectivity component.

This science is based on good knowledge of the phenomena that underpin the dynamics of pollutants that originate in greenhouse-related problems and atmospheric ozone depletion. As for other phenomena, such as eutrophication, acidification, etc. further uncertainties should be considered, as to the fact that these impacts mainly occur at regional and local levels, so the weather factors of the place become indispensable.

For these reasons, it is important to keep in mind that the significance of the results decreases as global effects move to those at the local scale.

The impact assessment categories should link the potential impacts and effects to the entities that we aim to protect.

The commonly-accepted areas of protection (AoP) are (Curran, 2012):

- Human Health;
- Natural Environment;
- Natural Resources.

Fig. 2.6 describes the relationship between midpoints and areas of protection.

After identifying which categories of impact to consider, the following phase is the **classification**, that consists in distributing the values of all the emissions (gaseous, liquid and solid) caused directly and indirectly by the various process operations.

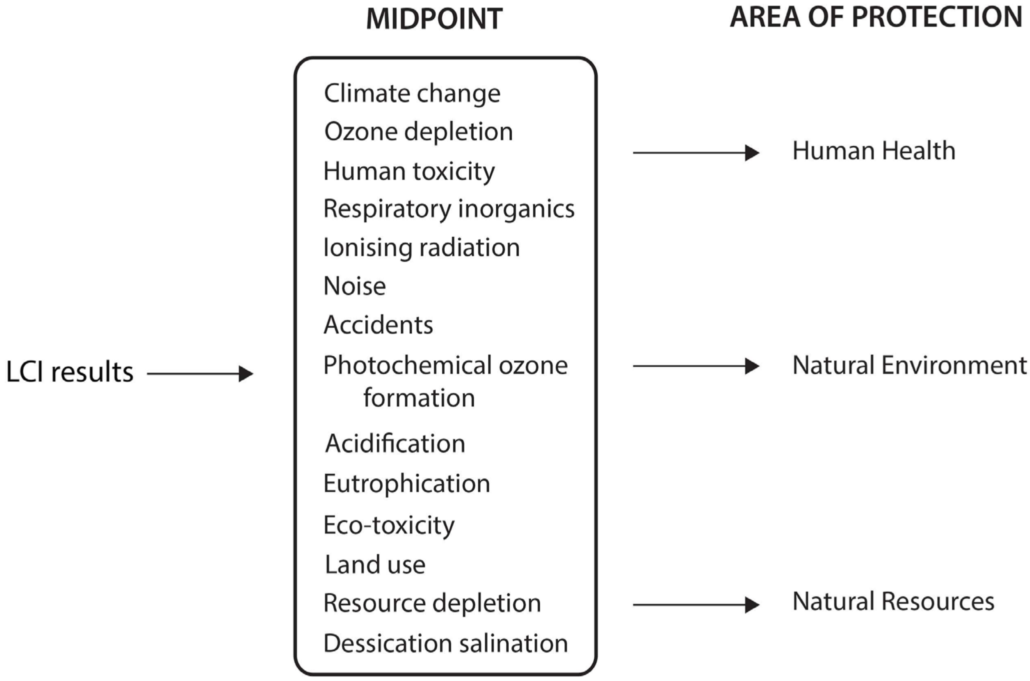


Fig. 2.6: The relationship between midpoints and areas of protection.

Frequently, the same substance constituting an emission is likely to contribute to multiple phenomena of impact, triggering chain effects of difficult interpretation.

It is important to highlight that the effects of impact identified should be considered as potential because this phase represents a first general approach to the assessment; for a more accurate evaluation it is necessary to proceed with the identification of those parts of the system that are most responsible for the identified impacts and by deepening through more sophisticated control techniques.

The impact analysis follows the criterion of "less is better", which in this case means if all kinds of emissions are relevant based on their intrinsic risk level, regardless of the resulting concentration level of the emission itself.

This simplification may seem coarse, but it is justified by the fact that this aggregation process of inventory results in impact categories does not aim to give absolute but fair value judgments between two or more comparing production processes.

Ultimately, the characterization phase allows the homogeneous and quantitative determination of the contribution of individual emissions, expressed it in a suitable unit of measure. This phase transforms, through a series of calculations, the substances present in the inventory and previously classified into numeric indicators, determining the relative contribution of each single substance or source used.

This operation is carried out by multiplying the weights of the substances emitted or consumed in each process for the relative weight factors of each impact category. As ISO 140140 defines, a characterization factor is "derived from a characterization model which is applied to convert an assigned life cycle inventory analysis result to the common unit of the category indicator".

In summary, the characterization factor measures the intensity of the effect of the substance on the environmental problem considered and is determined by an Authority based on purely scientific considerations.

For example, greenhouse gas quantities are expressed in kilograms of CO2 equivalent through a standardization operation based on GWPs, Global Warming Potentials. These potentials are calculated for each of these gases based on their radiation absorption capacity and the time of stay in the atmosphere.

Since the first applications of the life cycle analysis methodology, it has become desirable to express the results with equivalent and synthetic numerical parameters. This operation is known as normalization and allows to process data and aggregate them into a single value in order to facilitate comparison operations.

At this phase, the values obtained by the characterization are normalized, i.e. divided for a "reference value" or "normal effect" generally represented by global, regional, European or American average data, referring to a given time interval. The most common choices are: the total value of the size in question for a given global, regional, national or local area; the total value for a given area and per person; the value of the size in question in a reference scenario.

Through normalization, it is possible to determine the magnitude of the environmental impact of the system studied, and compare it to the one produced in the chosen geographic area as a reference.

The final phase is the evaluation, whose goal is to be able to express, through a final environmental index, the environmental impact associated with the product over its whole lifecycle.

The values of normalized effects are therefore multiplied by "weight factors" of the evaluation, concerning to the various categories of damage and often reported in technical guides, which express the importance of criticality attributed to each environmental problem. By this procedure, the relative importance of a category of impact is compared to that of the other categories. There are several evaluation models, they can be divided into:

- Inclusive models: include a large number of different parameters, often giving up high accuracy and quantification of effects;
- Quantitative models: handle impact data with great precision, limited to a restricted number of parameters;
- Pragmatic models: place as intermediate between the previous two, defining with precision the parameters that allow a correct evaluation of the product, considering the relative costs and execution times.

Based on the calculation of these factors, whichever model followed, there is the principle of **distance-to-target**: it states that the greater the gap between the present state and the ideal one, the greater the gravity of an effect (Curran, 2012). It is obvious how subjective this judgment is, which can vary by geographical areas, sensibilities and different thinking schools.
By adding the values of the effects thus obtained, a single dimensional value is obtained, called eco-indicator, the final environmental index, which quantifies the environmental impact associated with the product.

As mentioned above, the Impact Assessment phase, unlike the Inventory phase that has achieved a good degree of standardization, is still characterized by controversial aspects that require further scientific insights. Moreover, subjectivity linked to the choice of Impact Assessment methods will not easily reach international consensus.
An attempt to meet these standardization requirements is the “Environmental Product Declaration”, based on ISO 14025, which is a report that states the ways in which a product, throughout its lifecycle, affects the environment;

and thus said standard describes the requirements for performing all stages of a Life Cycle Assessment, and a number of predetermined impact categories are identified in order to standardize the contents of LCA studies.

Fig. 2.7 summarizes the third phase of an LCA.

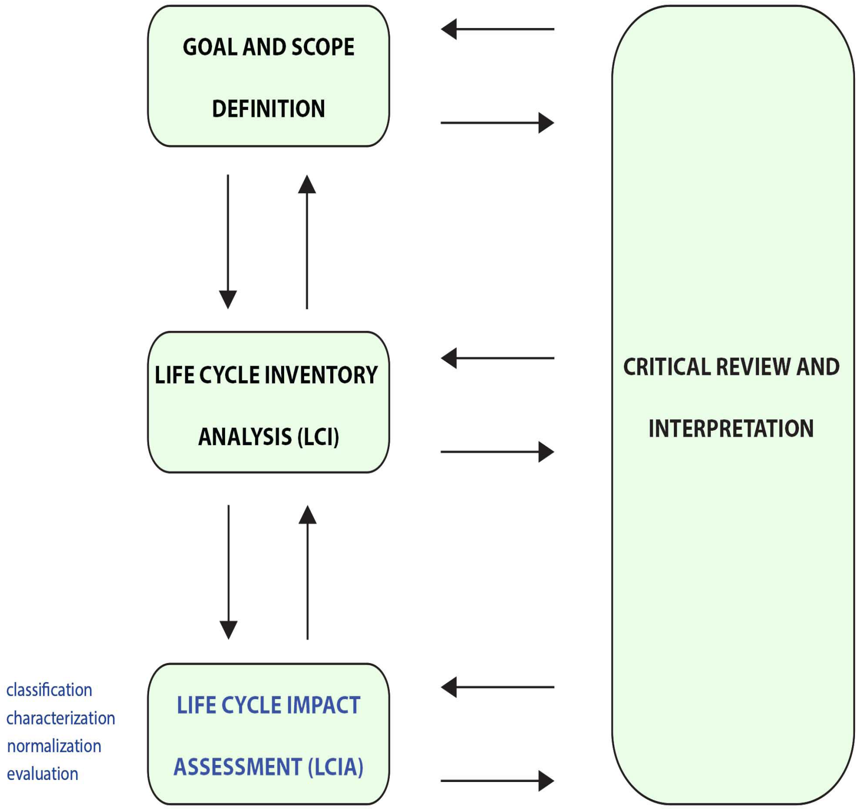


Fig. 2.7: The third phase of the LCA.

2.3.4 Critical review and interpretation

Life cycle analysis can be used for a variety of purposes, from process improvement to product innovation to new standards of sustainable production, to the development of environmental policy and communication strategies.

ISO 14040 defines this last phase as the time to achieve a good correlation between inventory and impact analysis results, in order to propose useful recommendations in accordance with the goals of the study.

The text of ISO on interpretation is very concise, and no details are given on procedures and techniques to be employed. The same applies to most guidebooks on LCA, they mention carrying out an uncertainty analysis, but give no clear guidance on how this should be done (Curran, 2012).

The improvement of production, i.e. the choice between the alternatives applicable to the manufacturing system to maximize energy-environmental efficiency, requires a certain effort at the planning and organizational level; there is no reference code for this step: the designer's experience and the competence of the Life Cycle practitioner are the basis for the assessment.

The standard recommends to respect the following steps:

- identification of the significant issues based on the results of the LCI and LCIA phases of LCA;
- evaluation that considers completeness, sensitivity and consistency checks;
- conclusions, limitations, and recommendations.

If the interpretation of the LCA assessment is used for comparative purposes between alternative products, it is not easy to make, since a product or activity may have a reduced environmental burden compared to some indicators, and a high one compared to others. In confronting alternatives, this can make it difficult to find a better solution from an environmental point of view, and thus make ambiguous choices.

Moreover, the result of evaluation is an outcome that must remain open to different reading possibilities, and in this lies the wealth of information it can provide.

However, the approach remains of an iterative type, since every step developed during this phase should be re-examined in an LCA view.

Ultimately, it should be noted that the environmental impact assessment as a decision-support tool must be supplemented by an economical assessment, Life Cycle Costing, which allows to highlight costs in a global vision of the entire life cycle.

Fig. 2.8 shows the relationship of the interpretation phase to other phases of LCA.

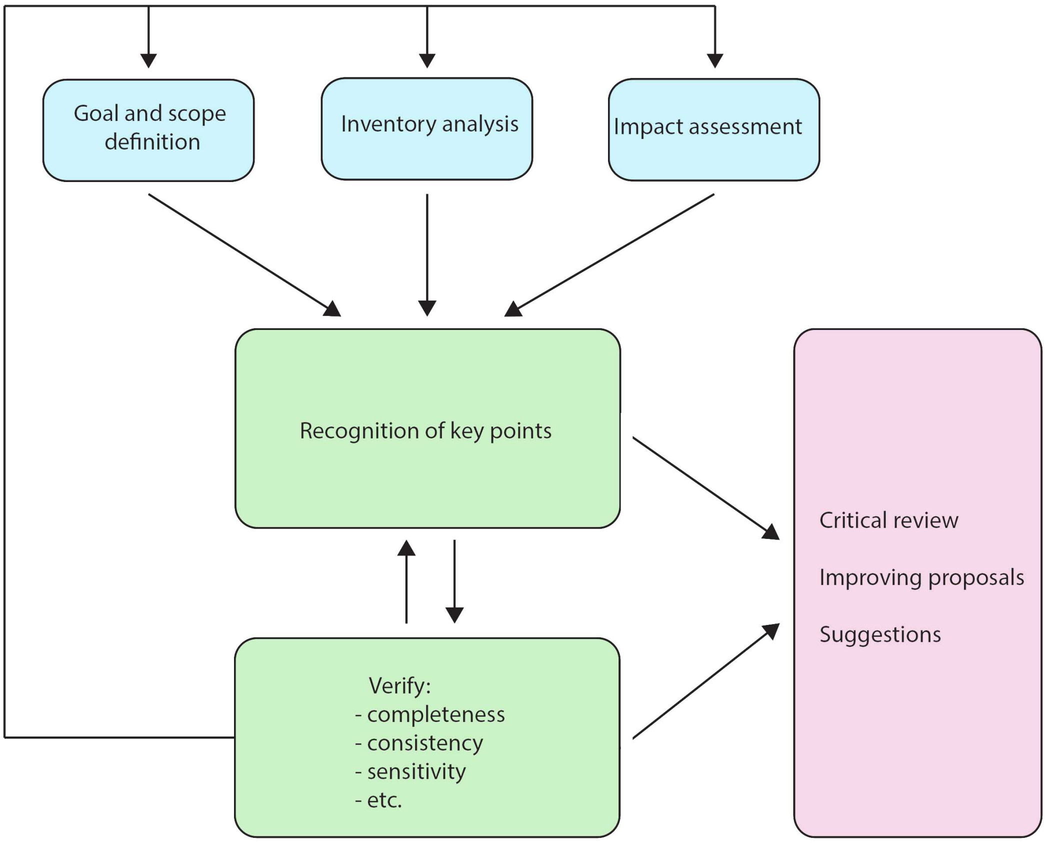


Fig. 2.8: The relationship between the fourth phase of the LCA and the other three.

2.4 Calculation methods

The environmental impact assessment, unlike the inventory stage that has achieved a good level of standardization, as mentioned above, is still characterized by controversial aspects that require further scientific insights, despite considerable efforts to harmonize. In addition, subjectivity linked to the criteria for assessing or weighing the damage makes it more difficult to achieve international consensus.

Following there are a few different methods that can be used to conduct a LCA.

2.4.1 IPCC 2007 GWP 100a

IPCC 2007 GWP 100a is a midpoint method, developed by IPCC (International Panel on Climate Change), which calculates the damage caused by the greenhouse effect.

The only category of impact considered is Global Warming 100a, which contributes to the greenhouse effect of a greenhouse gas relative to the CO2 effect, whose reference potential is 1. Each GWP value can be calculated for a specific span (typically 20, 100 or 500 years) (Hauschild and Huijbregts; 2015).

2.4.2 Cumulative Energy Demand (CED)

CED method was developed by Boustead and Hancock in 1979; it quantifies the part of energy extracted from nature and stored in the manufacture of a product, expressed in MJ.

It is a midpoint method that aims to analyze the use of energy throughout the entire life cycle of a product or service, this means that it considers both the direct uses of energy and the indirect costs due, for example, to the use of building materials or raw materials.

This method allows to identify the most energetic phases in the whole system, in order to base on these ones an environmental balance and to make comparisons with analysis in which only direct energy is considered (Hauschild and Huijbregts; 2015). Two categories of impact (renewable and non-renewable resources) are identified in eight subcategories:

- non-renewable energy, fossil;
- non-renewable energy, nuclear;
- non-renewable energy, primary forest;
- renewable energy, biomass;
- renewable energy, wind;
- renewable energy, geothermal;
- renewable energy, solar;
- renewable energy, water.

In this way, it is possible to calculate the direct energy, i.e., the one involved in the production process; and also, the indirect energy, which is the part of energy stored in the product and ready to be consumed.

2.4.3 CML 2002

A group of researchers led by CML, the Center of Environmental Science of Leiden University, proposed different impact categories and characterization methods for assessing environmental impacts. This is a midpoint method, it has the normalization phase but not the weighting.

CML 2002 includes nine "baseline" impact categories that are used in almost all LCA studies, and twelve "study-specific impact categories" that may merit inclusion, if appropriate to the goal and scope (Curran, 2012).

The most frequent impact categories are:

- **Acidification**, cause of multiple impacts on soil, water, organisms, ecosystems, etc. The Acidification Potential value (AP) is calculated considering an infinite time horizon expressed in kg of SO2 equivalent / kg;

- **Eutrophication** which includes all the impacts due to the excessive amount of macro-nutrients in the environment, particularly related to the overabundance of nitrates and sulphates. The nitrification potential (NP) is expressed as kg of PO4 equivalent / kg emitted in an infinite time span;
- **Ozone layer depletion**, that allows to a larger fraction of UV rays to reach the Earth’s surface, which have harmful effects on human and animal health, on terrestrial and aquatic ecosystems, on materials, etc. This category refers to the global scale, at an infinite time, and defines the potential for ozone depletion expressed in kg of CFC equivalent / kg emitted;
- **Human toxicity**, which refers to the effects of toxic substances on human health. The human toxicity potential (HTP) describes the fate, exposure, and effects of these substances in an infinite time horizon and is expressed as kg of 1,4 dichlorobenzene / kg;
- **Terrestrial eco-toxicity,** which refers to the effects of toxic substances on air, water and soil. Eco-toxicity potential (FAETP) describes the fate, exposure, and effects of these substances in an infinite time horizon and is expressed as kg of 1,4 dichlorobenzene / kg emitted.

One of the main features introduced by CML, is the midpoint category Human toxicity: through a new model of calculation, Human toxicity meets the need to estimate the cumulative toxicological risk, and the potential impacts associated to a certain substance released in the environment.

2.4.4 Eco-indicator 99

Developed by PRé Consultants in the Netherlands, Eco-indicator 99 is a damage-oriented approach that characterizes elementary flows into eleven midpoint categories as an intermediary modeling step toward damage modeling of three endpoint categories: human health, ecosystem quality and resource depletion.

The standard unit given in all the categories is point (Pt) or millipoint (mPt). Since the aim of this method is the comparison of products or components, the value itself is not most relevant but rather a comparison of values.

This method can include different aspects, especially in terms of assessment, depending on the attitudes and beliefs of each person. To obtain a detailed representation of the results, it has been conceived in three distinct versions, each of which represents a certain cultural perspective. They are:

- **Hierarchist** has a strong attachment to the group, but not to its impositions; he does not recognize role differences, makes ambiguous relationships within the group often triggering conflicts;
- **Individualist** is a person free from any bond; in his vision, everything is provisional and subject to negotiation;
- **Egalitarian** has a strong attachment to the group, but not to its impositions; he does not recognize role differences, makes ambiguous relationships within the group often triggering conflicts.

The hierarchist version is chosen as the default, while the other two versions are suggested for use in a robustness analysis.

The classification and evaluation of the three archetypes have strong implications for the methodology; the most obvious effect is that there is no longer a single model, but three distinct versions of the same model. This may seem an obstacle for the user of the method, but actually it reflects the fact that judgment on environmental issues is affected by the cultural background.

By presenting three different perspectives, it leaves freedom to choose the more appropriate for each particular case.

A subsequent weighting step might be performed to view results in a single score applying weighting factors specific to each cultural perspective, as shown in Table 2.4 (Curran, 2012).

Table 2.4: Weighting sets for hierarchist, egalitarian, and individualist perspectives.

	HIERARCHIST	EGALITARIAN	INDIVIDUALIST
Human Health	40%	30%	55%
Ecosystem Quality	40%	50%	25%
Resources	20%	20%	20%

2.4.5 IMPACT 2002+

Implemented by the Swiss Federal Institute of Technology in Lausanne, the environmental assessment method called IMPACT 2002+ offers an intermediate solution as the impact categories are measured as midpoint (equivalent emission units) and the damage categories are measured as endpoints (effects on ecosystem, human health and resource depletion).

The results are transmitted to 14 categories of impact, which in turn can be traced back to four categories of damage that are (Owsianiak et al., 2014):

- Global warming (kg CO2 equivalent to air);
- Ozone layer depletion (kg CFC-11 eq to air);
- Photochemical oxidation (kg C2H4 eq to air);
- Terrestrial acidification/nitrification (kg SO2 eq to air);
- Aquatic eutrophication (kg PO43- eq to water);

- Aquatic eco-toxicity (kg TEG eq to water);
- Terrestrial eco-toxicity (kg TEG eq to soil);
- Ionizing radiations (Bq C-14 eq to air);
- Respiratory effects (kg PM2.5 eq to air);
- Carcinogens (kg C2H3Cl eq to air);
- Non-carcinogens (kg C2H3Cl eq to air);
- Land occupation (m2 y);
- Non-renewable energy (MJ);
- Mineral extraction (MJ surplus).

The characterization factors for the different impact categories are based on an equivalence principle, i.e. the scores assigned to the different substances are expressed in kg of a reference substance. The characterization, standardization and weighing phases are similar to those indicated in the Eco-indicator 99 method and the total damage is expressed in points (Pt).

2.4.6 ReCiPe

ReCiPe was created under a joint effort of the RIVM (Rijksinstituut voor Volksgezonheid en Milieu), CML, PRé Consultants, Radboud Universiteit Nijmegen and CE Delft.

The ReCiPe approach combines the midpoint approach of CML with the damage approach of Eco-indicator 99, in order to allow users to choose which level, midpoint or endpoint, is desired for reporting indicators.

The user can choose between eighteen rather accurate, but not very easy to interpret, midpoints versus three easy to understand, but more uncertain, endpoints (Curran, 2012):

- Damage to Human Health;
- Damage to Ecosystems;
- Damage to Resource Availability.

The midpoint indicators are:

- Climate Change (kg CO2 eq);
- Ozone Depletion (kg CFC-11 eq);
- Photochemical Ozone Formation (kg NMVOC eq);
- Terrestrial Acidification (kg SO2 eq);
- Freshwater Eutrophication (kg P eq);
- Marine Eutrophication (kg N eq);
- Freshwater Ecotoxicity (kg 1,4 DB eq);
- Marine Ecotoxicity (kg 1,4 DB eq);
- Terrestrial Ecotoxicity (kg 1,4 DB eq);
- Ionising Radiation (kBq U235 eq);
- Particulate Matter Formation (kg PM10 eq);
- Human Toxicity (kg 1,4 DB eq);
- Agricultural Land Occupation (m2 y);
- Urban Land Occupation (m2 y);
- Natural Land Transformation (m2);
- Metal Depletion (kg Fe eq);
- Fossil Fuel Depletion (kq oil eq).

CHAPTER 3

Technical review of existing solar technologies

3.1 Photovoltaic systems

All solar cells require a light absorbing material which is present within the cell structure to absorb photons and generate power via the photovoltaic effect. These cells comprise a p-type and an n-type of semiconductors that are joined together to generate a p-n junction.

When sunlight of a determinate wavelength strikes on these cells, energy from the photon is transferred to an atom of the semiconducting material in the p-n junction. This effect induces the electrons to jump to the conduction band, which is a higher energy state. As a result, a hole is created in the valence band that the electron jumped up from, and this creates two charge carriers, an electron-hole pair. The hole can also move, but in the opposite direction to the n-side. Thus, an electric field is created in the region of the junction as electrons move to the positive p-side and holes move to the negative n-side, and it causes negatively charged particles to move in one direction and positively charged particles in the other direction. It is this process which creates a current in the cell (GSE, 2011).

There are substantially two generations in solar cells on the current market for housing applications: the first includes monocrystalline (c-Si) and polycrystalline (pc-Si) cells, mostly made by silicon; the second sees the birth of thin film cells and other materials are used, e.g. cadmium telluride (CdTe), amorphous silicon (a-Si), copper indium gallium diselenide (CIGS). A third generation is ready to join the market, but due to its expensive cost it may happen in a few years (Lee and Ebong, 2016).

Fig. 3.1 shows arrays of first generation PV panels.

Fig. 3.1: Entergy Solar Power Plant in New Orleans (courtesy of Entergy Inc.).

3.1.1 First generation

Silicon is the most common material used in manufacturing solar cells, because of its abundance on earth, low contamination rate, high durability, and the wide experience of the microelectronics industry (Camargo Nogueira et al., 2015).

Most commercial Si solar cells have used boron-doped single-crystal wafers (around 400 μm thick) grown by the Czochralski (CZ) process, which is the standard process used for the usages of microelectronics. CZ Si is free from lattice defects; nevertheless it contains residual impurities such as oxygen, carbon, and transition-metal ions. Oxygen introduced from a quartz crucible is beneficial for microelectronics, because the oxygen reinforces the wafers and can also be used for guttering defects from wafer surfaces. Oxygen reacts with the boron to form an electronically active defect that limits the quality loss of the material after illumination. Magnetic confinement is used to decrease the amount of oxygen by transferring material from the crucible within the melt. Si grown by the float-zone (FZ) process is the preferable method for solar cells of highest efficiencies because it has the lowest recombination losses. (Petter Jelle et al., 2015).

Polycrystalline material in the form of fragments obtained from highly purified polysilicon is placed in a quartz crucible which itself is located in a graphite pot and melted under inert gases by induction heating. A seed crystal is immersed and slowly withdrawn under rotation.

Although polycrystalline and multicrystalline are often used as synonyms, multicrystalline usually refers to crystals larger than one millimeter. Multicrystalline solar photovoltaic cells are the most common type of solar cells in the fast-growing PV market and consume most of the worldwide produced polycrystalline.

The advantages in multicrystalline silicon are lower capital cost for wafers production, higher silicon utilization and square wafers, which give a higher packing density in the module than round or pseudo-square monocrystalline wafers. It is also easier to produce large wafers with sizes of 150×150 mm and 200×200 mm. Considerable progress has been made recently in improving solar-cell efficiencies on multicrystalline wafers (Petter Jelle et al., 2015).

3.1.2 Second generation

Amorphous silicon (a-Si) solar PV cells belong to the category of a-Si thin-film, where one or several layers of photovoltaic solar cell materials are deposited onto a substrate. a-Si solar photovoltaic modules are formed by vapor depositing a thin layer of silicon material about 1 μm thick on a substrate material such as glass or metal. a-Si thin film can also be deposited at very low temperatures, as low as 75 °C (Kumar Shukla et al., 2015).

In its simplest form the a-Si thin film cell structure has a single sequence of p-i-n layers. However, single layer a-Si thin film cells suffer from significant degradation in their power output when exposed to the sun. The mechanism of degradation is known as Staebler-Wronski Effect, after its discoverers. Better stability requires the use of thinner layers in order to increase the electric field strength across the material. However, this reduces light absorption, hence solar PV cell efficiency. This has led the industry to develop tandem and even triple layer devices that contain p-i-n cells stacked one on top of the other. One of the pioneers of developing PV solar cells using a-Si thin film is Uni-Solar. They use a triple layer system that is optimized to capture light from the full solar spectrum (Hussin et al. 2016).

Cadmium telluride photovoltaic solar cells are based on CdTe thin film layers as semiconductor to transform absorbed solar light and generate electricity. In cadmium telluride PV solar cells the lower electrode is made from copper-doped carbon paste, while the upper layer is made of tin oxide (SnO2) or cadmium-based stannous oxide (Cd2SnO4). Between the upper layer and the semiconductor cadmium telluride, cadmium sulphide (CdS) is placed. CdTe PV solar cells are the second most abundant solar photovoltaic technology in the world market place after pc-Si, currently representing 7% of the 2014 world market. CdTe thin-film photovoltaic solar cells can be manufactured quickly and providing a lower-cost alternative to conventional silicon-based photovoltaic technologies. The record efficiency for a laboratory CdTe solar PV cell is 21.5% by First Solar, while the same company recently reported its average commercial solar cell efficiency to be 14.7% (Kim et al., 2014).

Copper indium gallium diselenide photovoltaic solar cells (CIGS) have the highest energy production of any thin film photovoltaic solar technology. Their power conversion efficiency on a glass substrate is now approaching 20%. Recent developments in the field of this material have pointed to flexible PV devices, with polyamide or metal foil substrates. CIGS photovoltaic solar cells have a very high absorption coefficient at their band gap of 1.5 eV, resulting in a very strong absorption of the solar light spectrum. Due to its expensive cost, most of the usages of this material remain in space applications (Heriche et al., 2016).

Thin-film solar cells have the following important advantages in comparison to crystalline cells: (i) the thickness of Si can be highly reduced up to 50 μm; (ii) thin films can be deposited on low-cost substrates; (iii) thin films can be produced on module-sized substrates and in integrally interconnected structures.

Moreover thin film solar cells have good performance in diffused light conditions because of their good absorbance in the UV visible and IR region. Thus, compared to first generation solar cells, second generation solar cells are cheaper and have better performance in condition of diffused light (Lokhande et al., 2016).

3.1.3 Third generation

In first and second generation panels silicon of PV cells is not able to capture all the solar spectrum, since it has different sensitivity: in blue it is sensitive only in a part, in red it has low sensitivity, in infrared it is not sensitive at all, while it is sensitive only in green-yellow. For this reason solar absorption is strictly reduced and a considerable amount of energy is misplaced. The solution is to use different materials with different rates of absorption of solar radiations, in order to capture the whole solar spectrum, which is the final purpose of the current research in concentrator panels of third generation (Kandilli et al., 2017).

The substantial difference between the first two generations and the third lies in the technology and methodology of absorption of solar radiations: concentrator PV uses Fresnel lenses and curved mirrors to concentrate sunlight on small multi-junction solar cells and transform heat directly in electric power. Above these solar cells several layer of different thin-film are put on top to better absorb solar spectrum and the frequency bands of various colors.

Current research and development is rapidly improving their competitiveness in the utility-scale segment and in areas of high insolation. This sort of solar technology can be thus used in smaller areas.

The principal flaw of concentrator PV systems is that they can only convert direct sunlight into energy, missing out on the large fraction of sunlight diffracted by clouds and the atmosphere, so they often use solar trackers to increase their efficiency.

This is a reason why concentrator PVs have not reached yet the mass production, and also the manufacturing cost is still expensive (Kandilli and Külahli, 2017).

The third generation of solar panels also includes a new technology that can offer high rates of performance at lower cost: Dye-sensitized solar cell (DSSC). The materials of whom these panels are made such as titanium oxide (TiO2) are plentiful, inexpensive and innocuous to the people and to the environment.

Dye-sensitized solar cells are growing very fast due to their easy fabrication process (they are insensitive to environment contaminants and processable at ambient temperature), indeed they are becoming popular as cost-effective photovoltaic device. In addition, DSSCs work better even during darker conditions, such as in the dawn and dusk or in cloudy weather (Richhariyaa et al., 2017).

The mentioned cells are composed of titanium oxide (TiO2) semiconductor which is commonly used as a paint base in pigment industry, and the dye sensitizer that can be extracted from several natural resources with very low costs.

DSSCs cover a variety of basic components and multiple possible combinations. Current researches are focusing on refining each material and identifying ideal conditions in order to optimize their overall performance in assembled devices. The development of models that could quantitatively identify the promising semiconductors, dyes, and electrolytes, as well as their assembly, could substantially save experimental time and resources (Gong et al., 2017).

3.2 Types of photovoltaic systems

There are substantially three principal classifications, according to their functional and operational requirements and how the equipment is connected to other electric sources and electrical loads:

- grid-connected systems
- stand-alone systems
- building-integrated photovoltaic systems (BIPV)

3.2.1 Grid-connected systems

A grid-connected PV system is a plant permanently linked to the electric utility grid. As shown in Fig. 3.2, during the day time the PV panel produces DC power, and in order to be used by the domestic devices it goes through an inverter, which transforms DC in AC power, and then can feed the housing requirements. If the PV panel produces more energy than needed, the power goes to the electricity supplier, which works as a storage system, thanks to a meter with the task of keeping the accounting of the energy generated by the PV panels. At night time (or when the sun is covered) the power goes back from the utility grid to fulfill the energy requirements. It is not required to install batteries, hence these systems allow more effective utilization of generated power because of the absence of storage losses (Rodrigo et al., 2016).

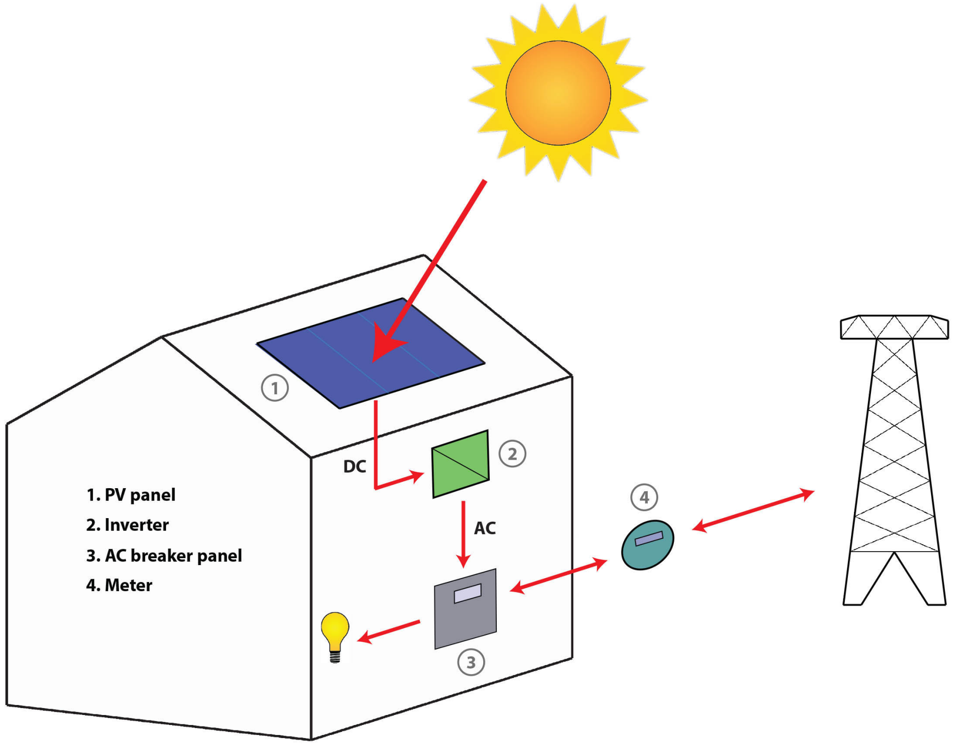


Fig. 3.2: A grid-connected PV system.

The essential component in grid-connected PV systems is the inverter, also known as power conditioning unit (PCU). The PCU converts the DC power of the PV array into AC power with proper voltage magnitude, frequency and phase to be connected to the utility grid, and automatically stops supplying power to the grid when the utility grid is not energized.

It is very important to design the correct size of the inverter, because it will affect the system efficiency. The losses in the power switches incorporated in the inverters are function of the DC input voltage and therefore, the inverter conversion efficiency is voltage dependent. For this reason, it is important to remember that low array-to-inverter power sizing ratios (oversized inverters) will increase the amount of time the inverter operates at low loads in which the instantaneous efficiency is lower, and on the other hand, high array-to-inverter power sizing ratios (undersized inverters) will increase the amount of time the inverter is clipped, i.e. it limits the output power to the inverter nominal power, causing maximum power point losses and reducing the overall efficiency (Rodrigo et al., 2016).

There are various kinds of grid-connected PV inverters:

Line-commutated inverter: in which the utility grid dictates the commutation process started by reversal of the AC voltage polarity, using power switching devices like commutating thyristors. The gate terminal of the device controls the turn-on operation, while the turn-off cannot be controlled by the same. Turn-off of such device is performed with the help of an add-on circuit to the device.

Self-commutated inverter: the current is transferred from one switching device to another in a controlled manner; differs from the previous because it uses a power switching device, the potential at the gate terminal can control both the turn-on and the turn-off operation, such as Metal Oxide Semiconductor Field Effect Transistor (MOSFET). Power MOSFETs are used for low power typically less than 10 kW and high-frequency switching operation (20–800 kHz), a feature required to reduce an inverter's output-current harmonics, size of the magnetic filter used, and weight of the inverter (Jana et al., 2016).

The self-commutated inverters may be voltage source inverter (VSI) or current source inverter (CSI) based on voltage or current waveforms at their input DC side.

In VSI, the input side is a DC voltage source, the input voltage holds the same polarity, the average power flow direction through the inverter is determined by the polarity of the input DC current; at the output side, an AC voltage waveform of the constant amplitude and variable width can be obtained. The input DC side terminals of a VSI are typically connected in parallel with a relatively large capacitor that resembles a voltage source.

In CSI, the input side is a DC current source, the input current holds the same polarity, and therefore the average power flow direction through the inverter is determined by the polarity of the input voltage; at the output side, an AC current waveform of the constant amplitude and variable width can be obtained. The input DC side of the CSI is typically connected in series with a relatively large inductor that maintains the current continuity.
A VSI can be operated in voltage control mode as well as in current-control mode and in many times, VSI with current control mode is preferred for grid-connected PV system (Jana et al., 2016).

A bi-directional interface is established between the PV system AC output circuits and the electric utility network, usually at an on-site distribution panel or service entrance. This allows the AC power produced by the PV system to either supply on-site electrical loads, or to back-feed the grid when the PV system output is greater than the on-site load demand. In night hours and cloudy whether when the electrical loads are greater than the PV system output, the amount of power required is received from the electric utility grid, to ensure that the PV system will not continue to operate and feed back into the utility grid when the grid is down for service or repair (Allouhi et al., 2016).

3.2.2 Stand-alone systems

Generally stand-alone systems are used to serve poorly accessible areas or zones characterized by low energy consumption that does not make suitable the connection to the utility grid.
Different from grid-connected type, stand-alone systems are not connected to electric utility grid, which can provide the cover of the energy requirement even in absence of solar irradiation, thus in order to keep supply power in

every whether condition and at night time it must be equipped with a storage system, usually electric batteries. These types of systems may be powered by a PV array only, or may use wind or an engine-generator as an auxiliary power source in what is called a PV-hybrid system (Wai Chong et al., 2016). The core of stand-alone PV system is the battery storage, which is used to compensate the inherent power fluctuations (excess or shortage) and to regulate the overall system operation based on a power management strategy. There are substantially two different types of battery: lead-acid and lithium-ion battery. Anuphappharadorn et al. (2014) made a study where they analyzed these two kind of batteries from different points of view, and they found out that lead-acid batteries (the first to be used) are preferable for the economic side, but on the other hand lithium-ion batteries have many advantages when compared with lead-acid battery technology, such as high energy density, low maintenance and a higher number of lifecycle.

As shown in Fig. 3.3, charge controller regulates the output from the solar array to prevent the batteries from being over charged (or over discharged) by dissipating the excess power into a load. It has the function of preserving batteries efficiency and extend their lifetime through various features, such as a maximum power point tracker (MPPT) to help better utilize the available array maximum power output, and automatic turn off in case of full charge of the batteries to safeguard them (Scudo et al., 2013).

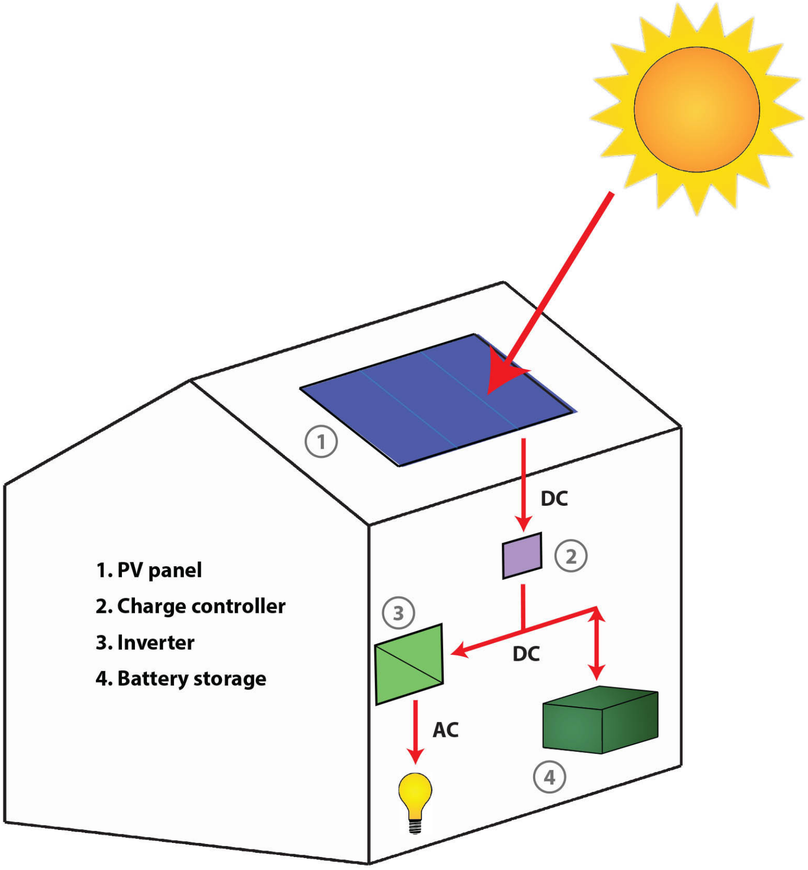


Fig. 3.2: A stand-alone PV system.

3.2.3 Building-Integrated photovoltaic systems (BIPV)

Usually building-integrated PV systems are combined with a thermic solar system, and they comprise a group of technologies in which the solar panels can be used in replacement of traditional architectural elements, e.g. modules for roofing, facades, windows, etc. Their ideal position is connected to the yield, inversely proportional to the surface temperature of panels during the activity: non-shady zones, SE or SO facing, covered by railings or parapet. It is possible to use such PV modules for brise-soleil or the shading of large areas in case of the roofing, (Yang and Athienitis, 2016).

BIPV/T in turn are divided into air-based and water-based, according to the media used to cool the panels.

Air-based BIPV/Ts can either be active (open-loop) or passive (based on buoyancy force).

Generally an active BIPV/T system is often installed in an open-loop configuration, because it is able to run at a lower temperature than the close-loop air system, so it is possible to achieve a higher efficiency and thus better PV performance and durability, not to mention that open-loop systems have the potential for supplying pre-heated fresh air to a building. The working operation is simple: outdoor air is driven by a fan and passes through the channel behind the PV panels.

In a passive system moving parts are not required because the heated air is either fed into the indoor space or exhausted into the ambient. This kind of system usually is combined with the building environment in regard to heating, cooling and lighting loads, and electricity production (Yang and Athienitis, 2014).

In water-based systems, also combined BIPV/T, a typical water collector is constructed by attaching PV to the thermal absorber using thermal paste with high conductivity, welding, or mechanical force. Thermal efficiencies of the BIPV/T system under natural and forced water circulation modes were similar, and so were electrical efficiencies. The natural circulation mode was found more favorable since the forced circulation mode incurred extra fan power consumption.

The thermal performance is enhanced using a selective coating that ensures maximum solar absorption while maintains low emissivity in the infrared region. The annual performance of a roof-mounted single-glazed PV/T water system was simulated to match the electrical and hot water consumption profiles of a typical UK house (Herrando et al., 2014). Simulation results identified that PV packing factor significantly influences electrical output, and that water flow rate affected hot water production to a greater extent.

In Fig. 3.4 are summarized the two main BIPV systems.

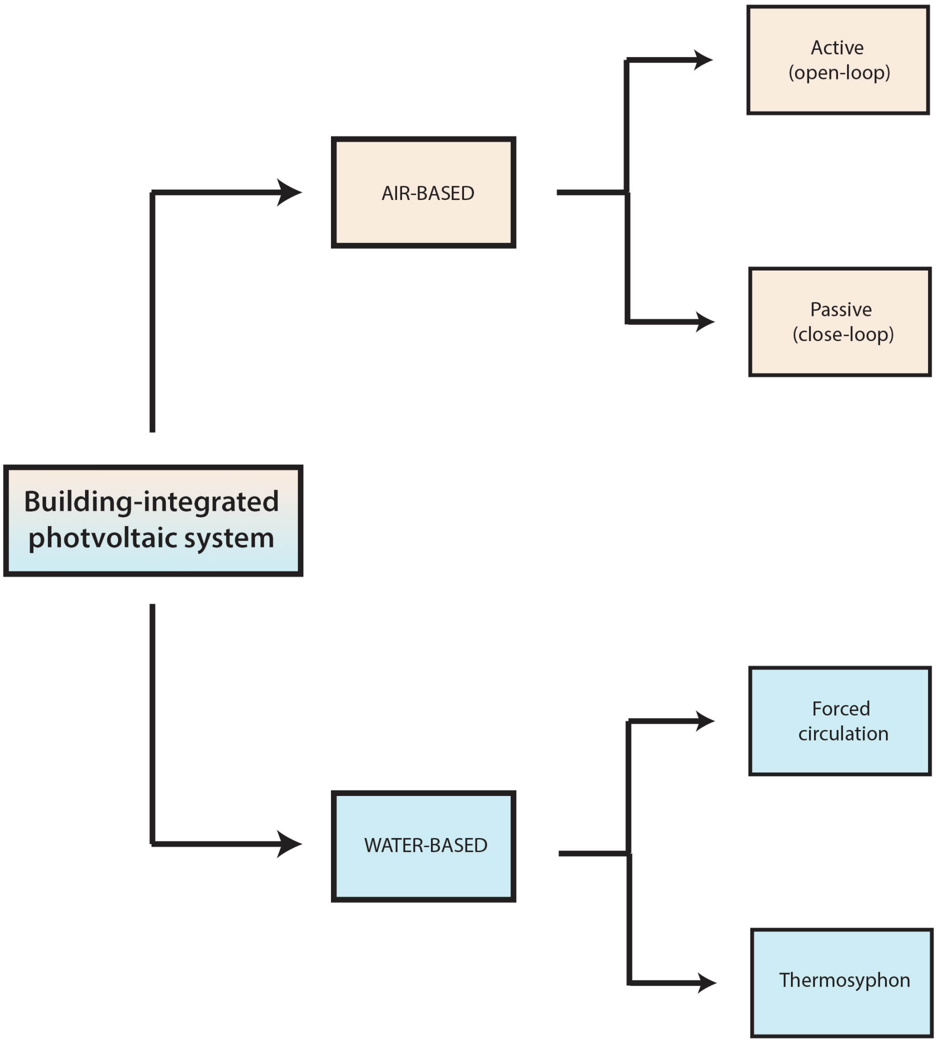


Fig. 3.4: Different types of building-integrated photovoltaic systems

The main difference between a BIPV and a PV system added to an existent building is that the first one not only works as an energy provider, but it also influences building energy performance.

The entrance of PV products in the field of building construction has undoubtedly brought a revolution but there's still need of further researches. In fact, when a PV module is fully integrated in the building skin its electrical and thermal performance will change significantly in comparison to traditional PV installations. The prediction of this performance is of great importance for the designing of a BIPV projects as well as for the future projections of the system's behavior (Chatzipanagi et al., 2016). The main parameters affecting the performance are the degree and nature of ventilation (Agathokleous and Kalogirou, 2016), the mounting structure, the inclination/orientation and, generally the presence of shadows (Sánchez and Izard; 2015).

In the first place an amount of the incident solar energy is directly converted into power by the PV module before transmitting through the envelope, then part of the absorbed solar energy is removed in the form of heat when a cooling medium is utilized. Furthermore, the use of semi-transparent PV modules changes the visible transmittance of light and subsequently the artificial lighting energy consumption profile, hence the solar absorptivity of a building envelope is changed when replacing conventional building structures, e.g. the reflective roof, with PV modules (Yang and Athienitis, 2016).

The operating temperatures of BIPV modules affect impressively their performance and therefore a lot of researches has been based on this specific issue. In terms of experimental research, the impact of the operating temperatures on the performance of BIPV modules has been investigated under Standard Test Conditions (STC) and compared with outdoor conditions measurements (Park et al., 2010).

Some researchers are concentrating on special cases, such as tropical regions where the temperatures are significantly high. They focus on the indoor thermal comfort and how the operating temperatures of the modules depend on that, and even how the electrical performance of the system is affected (Pillai et al., 2014).

An experimental framework has been examined by other research groups; specifically, their research was oriented towards the effect of ventilation on the cell temperature and on the module performance (Han et al., 2013).
Some other researches incorporate the temperature in other parameters, and therefore do not directly relate it to the performance of the module but focus instead on meteorological parameters and real operating conditions (Olivieri et al., 2014).

3.3 Solar thermal systems

Solar thermal systems are devices that are able to capture solar energy, stock it and use it in many different ways, in particular to heat domestic hot water (DHW).
Occasionally electric photovoltaic systems and solar thermal systems are combined together to produce directly DHW and save the energy gained from PV cells to feed only the electric needs of the house.

Solar thermal collectors can be categorized based on the temperature of collectors as low (until 120 °C), medium (app. 500 °C), or high-temperature (app. 1000 °C). Low and medium-temperature collectors are usually flat plates and are used for heating water or air for residential and commercial use (Iparraguirre et al., 2016). High-temperature collectors concentrate sunlight using mirrors or lenses and are generally used for fulfilling heat requirements in large industrial plants.
A thermal solar system is composed of the following units: a storage medium, a heat exchanger and a storage tank. The storage medium can be sensible, latent heat or thermochemical storage material. The purpose of the heat exchanger is to supply or extract heat from the storage medium. The storage

tank holds the storage medium and insulates the system from the surroundings.

Sensible heat storage is based on the material’s specific heat capacity. According to Alva et al. (2017), sensible heat storage systems can be:

- **Steam accumulators**: the panels convert water into steam and the excess steam is stored at high pressure up to 100 bar in steam accumulators during off-peak hours. The high pressure allows the steam to be stored in liquid phase with a high volumetric heat capacity of water up to 1.2 kW h m-3 (Medrano et al., 2010). The drawback is that this system has issues like increased piping cost due to high vapor pressure, instability of two phase flow inside receiver tubes and a need for auxiliary protective heating system during start up.
- **Two tanks direct active system**: a heat transfer fluid like mineral oil acts as both fluid itself and thermal storage medium, hence an intermediate heat exchanger is not required. In this system there are two tanks, one at high temperature and the other at low temperature. The heat transfer fluid flows from hot tank to power block where it discharges the heat energy to generate steam, and then flows back to cold tank. During the day time the heat transfer fluid from cold storage tank flows to the solar collector system and gets heated and flows back in to the hot tank.
- **Two tanks indirect active system**: a heat transfer fluid like steam or mineral oil works as fluid itself and molten salt acts as thermal storage medium, which is stored in two large tanks, at two different temperature levels and at ambient pressure, providing a definite temperature gradient in order to charge or discharge sensible heat. The heat transfer from the thermal fluid to the molten salt and vice versa, is accomplished via the use of a fluid-to-molten-salt heat exchanger

(Zaverskya et al., 2014). The typical heat exchanger setup used at commercial collector plants is a counter flow shell-and-tube heat exchanger design, where the thermal fluid flows on the tube-side and the molten salt flows on the shell-side (Herrmann et al., 2004). This fluid setup is mainly due to the rather high system pressure of the thermal fluid circuit. Thus, taking the piping and solar field pressure drop into account, the maximum system pressure of the thermal fluid circuit is usually around 25 to 30 bar. On the other hand, the molten salt features a very low vapor pressure, so it can be stored in the tanks at ambient air pressure, and is thus placed on the heat exchanger's shell-side.

- **Single tank thermocline system**: the storage tank is comprised of a vertical cylindrical tank containing the solid filler material, and inlet and outlet ports at the top and bottom, respectively. During the charging process, hot fluid enters through the top of the storage tank, displacing cold fluid which exits through the bottom. A distributor ensures that the incoming flow is uniformly distributed over the area of the tank. During the discharging process, the flow direction is reversed. (Bonanos and Votyakov; 2016). To reduce the quite expensive liquid storage medium requirement, a low cost solid filler material is used to fill most of the volume in the thermocline tank and it works as primary thermal storage material. This kind of system where the solid filler is used as primary thermal storage material is a passive system.
- **Packed bed passive system**: this is a passive system used very often for temperatures up to 100 °C in conjunction with solar air heaters. The system will have lightly packed solid material like quartzite rock and silica sand, through which the heat transfer fluid (usually air) is

circulated. During the charging phase, air gets heated at solar collectors and then flows into a bed of graded particles. Then during the heating the bed air gets cooled, and after it returns to the collectors for reheating and the cycle restarts. At the beginning, only the particles near the entrance of the bed are heated while the temperature near the exit remains unchanged and the air comes out of the bed almost at ambient temperature. The exit air temperature begins to rise only after many cycles, and when the bed is fully charged, its temperature becomes uniform. When energy is needed from storage, discharge process starts, and thus the airflow direction gets reversed: air at ambient temperature enters the bed and gets heated, ready to be delivered to the building. After heating the space, cold air from room flows back to the bed and the cycle is repeated. In order to avoid heat losses, the storage system is generally well insulated and installed close to the solar collectors (Alva et al., 2017).

- **Solid medium passive system**: the heat exchanger for the heat transfer fluid is embedded in a solid matrix. A high cycling stability is essential for a long lifetime of the storage; in fact ordinary concrete develops cracks after repeated thermal cycles, and current researches are developing new resistant concrete. The leading focusing area is: improvements in the solid storage material’s thermophysical properties, cycling stability and economic factors like availability, cost and production methods.

Fig. 3.5 summarizes the different types of solar thermal systems, based on the storage material used.

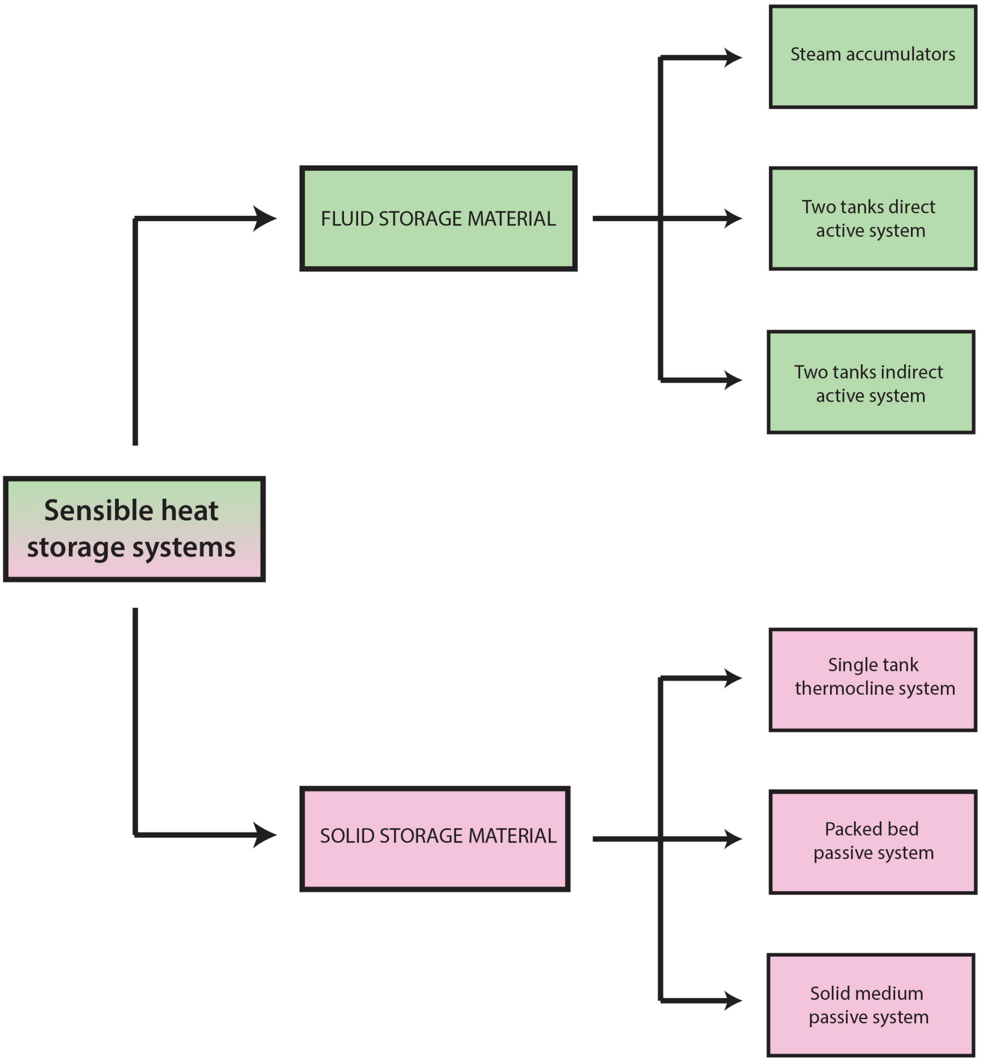


Fig. 3.5: Different types of solar thermal systems.

On the other side, latent heat storage systems (LHTESS) rely on the material's phase change enthalpy to store heat within a narrow temperature range, providing greater energy density. LHTESS employs Phase Change Materials (PCMs) to store and release heat by reversible liquid/solid phase transformation (Lei et al., 2016).

According to Pereira da Cunha and Eames (2016) PCMs can be:

Organic (saturated fatty acids, sugar alcohols, carboxylic acids, amides and alkanes), generally have very low thermal conductivity (from 0.1 to 0.7 W/mK), hence needing mechanisms to increase their heat transfer in order to reach reasonable rates of heat output;

- Salt hydrates created by water absorption by the anhydrous salt at ambient temperatures, have a phase change enthalpy depending on the bond strength between the water molecules and the salt;
- Eutectic, also known as ionic liquids. The main components used to create medium temperature eutectic mixtures are: nitrate, chloride and sulphate salts of alkali and alkaline metals, such as magnesium, potassium, lithium and calcium. Due to their higher density and stability in their liquid state, these PCMs have been used widely as ionic liquids in high temperature sensible thermal storage systems (thermonuclear energy, concentrated solar thermal power.

LHTESS is believed to be one of the most promising energy storage methods, owing to its high energy storage density and its ability to provide constant temperature output.

LHTESS are conditioned by factors like geometry of the container, daily insolation at the location and its thermal parameters. This system uses a latent heat storage material based on temperature range and other requirement specifications of the system. Usually the geometries of LHTESS are pipe model, cylinder model, shell and tube model, rectangular slab model. The model that can reduce heat loss at minimum are the shell and tube system.

LHTESS are mainly used in industrial applications (Xu et al., 2017), e.g. a typical LHTESS coupled industrial refrigeration system can charge with excess waste heat from industrial processes, store energy overnight, and discharge it during peak electrical tariff period or for backup application.

Chapter 4

Case study: LCA of a solar farm in New Orleans

The subject of this thesis is the Life Cycle Assessment of a solar farm located in New Orleans, Louisiana, owned by Entergy Corporation, shown in Fig. 4.1.

Although its headquarter is in New Orleans, Entergy is one of the main energy companies for electric power production and distribution not just in Louisiana, but also in Texas, Mississippi and Arkansas.

Fig. 4.1: Entergy Solar Farm in New Orleans (courtesy of Entergy Inc.)

Entergy started a pilot project in June 2016, by installing a Solar Power Plant with an overall generation capacity of 1,08 MW, on a land area of 11 acres, that has a horizontal global irradiation of 1659,3 kWh/m^{2}y, that makes a power production of 1,79 GWh per year.

Since the mentioned solar farm is a pilot project, some lack of information was encountered, especially on the economic side, due to the confidentiality of the investment. However, Entergy staff provided all the necessary information for the LCA, summarized below.

4.1 Description of the solar farm

There are overall 4254 PV panels, produced by a Chinese company named Jinko Solar, model JKM 315P-72, which has an efficiency of 16,23%. They are made in polycrystalline silicon and organized in arrays (for details see Par. 4.6). Each array tilts slowly on one axis in order to follow the path of the sun during the day, and the energy necessary to make this movement derives from one small PV panel, specific for this purpose, assembled on each row, as shown in Fig. 4.2.

Fig. 4.2: A detail of the PV panel dedicated to the tilt of the whole row of panels (courtesy of Entergy Inc.)

The PV panels transform the incident sunlight in direct energy and then the electric current is sent to the inverter, model GP Tech PV 500WD, that transform direct current in alternate current. There are 3 in total, as a precaution measure of a breakdown, and they have an efficiency of 97,32%; this means that only the 2,68% of energy produced is loss due to the inverter.

The power generated is fed directly into the grid and in order to supply a constant amount of electricity for a better performance, there are 196 batteries LG Chem M4860 P2B (Fig 4.3), in 14 rows of 14 batteries each, that are charged by the PV panels in DC every day, so in case of a sudden rain or bad weather, the batteries can still feed the grid with the collected power. In case the power accumulated in the batteries is not needed, the batteries send their stored energy to the inverter and then feed the grid anyway.

Fig. 4.3: Detail of two rows of batteries (courtesy of Entergy Inc.)

The degradation rate of the solar farm has been calculated as 0,7% per year, thus the span life estimated for Entergy Solar Power Plant is 25 years.

In Fig. 4.4 there is a framework that may help to understand how the solar farm works.

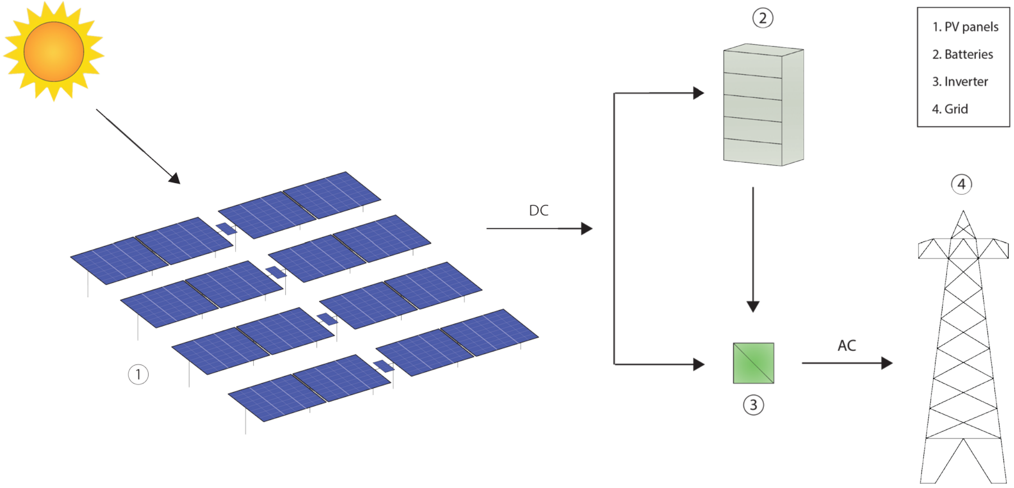


Fig. 4.4: Functional diagram of Entergy Solar Power Plant.

4.2 The software used for the LCA: SimaPro 7.3.3

The software used for the LCA of the mentioned solar farm is SimaPro 7.3.3, developed by the Dutch company PRé (Product Ecology) Consultants, leader in the assessment of the environmental impacts and the creation of strategies aimed to the sustainability. It is a tool that assess the environmental loads of industrial products and processes, and subsequently the impact of services such as integrated waste management.

Fig. 4.5 shows the software interface.

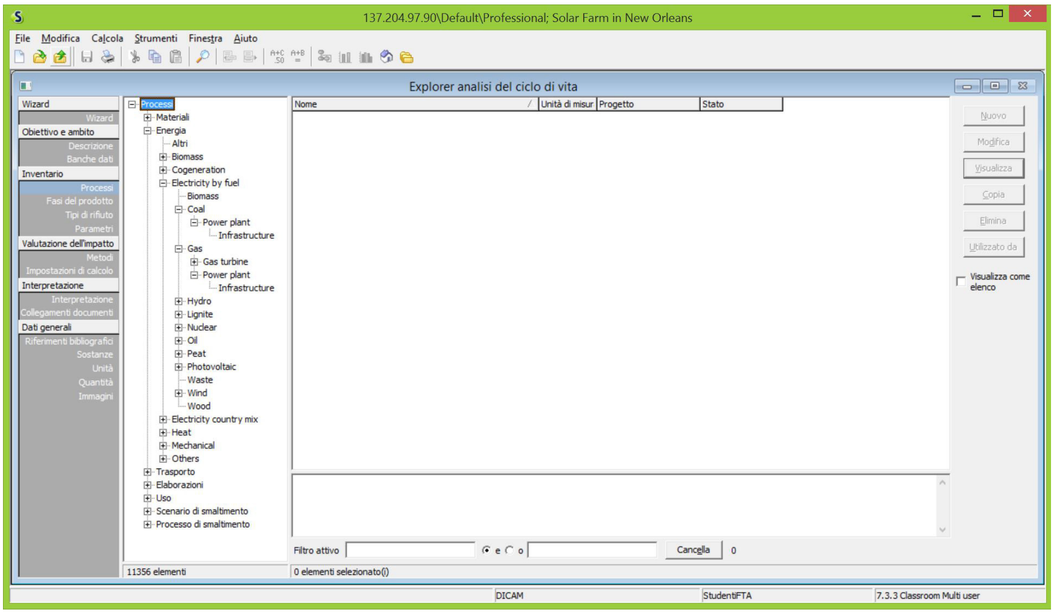


Fig. 4.5: SimaPro 7.3.3 interface.

SimaPro can analyze the environmental data of complex products and processes, from raw material extraction to disposal, and also complies with the ISO14040 series and contains a reference database that can be modified as needed, including the most frequently requested data on materials, production processes, power generation, distribution and product disposal.

The **databases** provide the basic elements for conducting the study, and in SimaPro there are 11: Ecoinvent System Processes, Ecoinvent Unit Processes, ELCD, EU & DK Input Output Database, Industry Data, LCA Food DK, Methods, Swiss Input Output Database, USA Input Output Database, USA Input Output Database System Expansion, USLCI.

The fundamental unit of which the whole structure of the system is based on is the **process**. Processes are subdivided into the domain from which they originate, and are subdivided into 7 categories: materials, energy, transport, ongoing process, use, disposal scenario and disposal process, each of which further subdivided into subcategories. Each process can be connected to another process by creating networks, thus forming a tree structure of an entire production system.

The software interface has, on the left, a column named LCA Explorer that allows to access to all the different functions, and is structured as a checklist closely following the typical procedure followed in an LCA analysis:

1. Goal and scope
2. Inventory
3. Impact assessment
4. Interpretation

The goal and scope section is further subdivided into:

- Description: where one can enter information such as project name, date, author, buyer, type of life cycle analysis, targets, etc., fields that refer to the indications provided by ISO 14041. It is very important to indicate to whom the analysis is to be made, in particular it is necessary to specify whether it will be used for internal purposes of a company or if it will serve to compare two products. In fact, in the latter case, ISO standards state that it is not possible to perform the weighing phase and that a process review by a subject of the same level is necessary.
- Libraries: where one can select the databases that it is necessary use, and which can be changed if the project so requests.

In the inventory section, one can enter all the analysis data, and thus the final result, the "core" of the LCI, is a tree graph that contains all the processes related to the product.

The two main sub-categories that make up the inventory are:

- Processes: articulated in turn in Documentation, Input / Output, Parameters, System Description. Specifically, the Input / Output label allows you to access the compilation of a sheet with data such as:
  - Known inputs from nature (resources);
  - Known inputs from technosphere (materials and fuels);
  - Known inputs from technosphere (electricity and heat);
  - Known outputs to technoshpere – products and co-products;
  - Known outputs to technoshpere – avoided products;
  - Emission to air/soil/water;
  - Final waste flows;
  - Non-material emissions (radiation, noise, etc.)
  - Social issues;
  - Economic issues;
  - Waste and emissions to treatment.
- Product stages: useful for describing the composition, assembly, phase of use, and the end-of-life scenario of the product. Each product stage refers to processes; for example, if a given product contains 1 kg of steel, it is possible to make a connection with the process that describes the steel production and specify the amount of 1 kg.

A LCA can refer to:

- An assembly (which can be connected to other sub-assemblies);
- One or more processes;
- One or more auxiliary product life cycles. These auxiliary life cycles are constructed in the same way as any other life cycle, which includes the assembly and end-of-life stages;
- A disposal/end-of-life scenario.

One of the most complex and interesting steps of an LCA is the modeling of waste scenarios and product end-of-life. However, it is necessary to make a point at a glance: "waste scenario" means all processes referring to material flows, without considering any other feature or information concerning the disassembling stages of the product in the various parts forming it (subassemblies); In the "disposal scenario", this information is maintained, thus allowing to model the subassembly and (partial) reuse of product components. For a better clarification of this difference, one can think, for example, of glass recycling: throwing a bottle into the glass compartment container is an operation that falls into the first type of analysis, i.e. in waste management; bottles that are washed and reused, are treated in a product disposal scenario. In a waste scenario analysis, the generic waste stream is subdivided according to the different types of waste it is composed of and for each of them a precise treatment is planned to detect the emissions and impacts that occur, from disposal to the landfill, incineration, recycling, composting, etc.

In the case of an incinerator, for example, different emissions originate and it is interesting to know which material is responsible for each of them, and specifically to bind the composition of the material to the emissions. SimaPro allows to do this by dividing the generic waste stream into different types of waste, such as paper, plastic, PVC, metal, etc., specifying which material belongs to each type of waste.

These emissions depend on the composition of the product. For example, given 2 kg of material classified as "PVC waste" and assuming that 50% of the waste is destined for an incinerator, this treatment will receive as input 1 kg of material.

Waste scenario in SimaPro also provides very useful outputs such as heat or materials that can be reused in recycling or incineration processes; this means that if 1 kWh of electricity is generated by the incineration of a certain waste, the environmental load that would normally be generating such electricity is subtracted: this also explains why, often, negative environmental loads are obtained in stages of end-of-life products.

For what concerns the disposal scenario, however, the flow of the available products is subdivided in three different ways:

- Products that are disassembled;
- Products that are reused;
- Products treated with waste scenario (seen above).

Once these steps are done, the impact assessment method is selected and the program returns, through tables and graphs (even by tree), the impact of all process units considered.

For what concerns the impacts, SimaPro provides a wide range of assessment method, such as: CML 2002, Eco-Indicator 99, EPS 2000, EDIP 2003, IMPACT 2002, Cumulative Energy Demand, IPCC 2007 GWP, etc.

The choice of the method is entirely arbitrary and depends on the starting points of the study and therefore the categories of environmental impact that it is considered appropriate to analyze in a specific way.

4.3 Goal definition

The goal of this study is to evaluate the damage to the environment caused by the whole life cycle of the solar farm described in the previous paragraph. Such results identify the manufacturing impacts and can be therefore used to prioritize eventual improvements correctly.

4.4 Functional unit

The functional unit chosen for this study is 1 kWh of electricity produced from converted solar irradiation.

4.5 System boundaries

The present study is a LCA “from cradle to gate”, thus the system boundaries range from collecting raw materials, processing them from semi-finished products to the manufacturing of component products, such as the batteries, the inverter and the PV panels.

4.6 Inventory analysis

The inventory analysis is the most important and challenging phase of the LCA; in fact, all the processes and individual operations related to each stage of the production had to be re-constructed in detail, determining materials used each time, with their respective quantities, packaging and transport from the supplier.

The 4254 PV panels are organized in 19 arrays of 222 panels each, plus 36 in the last row, that makes a total of 20 arrays. Each array, except the last, is divided in two rows (one of 90 panels and the other one of 132), as there is a space in between for the maintenance.

The support of the panels is made by two different beams: W8x15 and W14x26, deep in the soil respectively 38,1 cm (15 inches) and 76,2 cm (30 inches), depending on the position.

The W8x15 beam supports a block of six panels, and every six blocks there is W14x26. In the last row there are six blocks, so there are two W14x26 and six W8x15. In total, there are: 135 W14x26 and 576 W8x15 beams.

At the moment of the study, it was possible to model the single panel and its packaging (made of boxes of 3-layer and 7-layer cardboard and wooden pallets) because all the data needed has been kindly provided by Jinko Solar; unfortunately, there is a lack of data for the inverters and the batteries, but since they both are listed in SimaPro 7.3.3, it has been chosen to simply select the inverter and the battery from the database, instead of modeling the single components. For a detailed inventory, see Appendix C.

A significant limit to the study is that it was not possible to retrieve any data for what concerns the consumption of water, electricity and gas in the factories for any of the products, except for the power required for the assembly of panels.

4.7 Results

The present LCA study was conducted with the following methodologies:

- CML 2 baseline 2000;
- Eco-Indicator 99;
- IMPACT 2002+;
- EPD, for the following components:
    - JKM 315P (PV panel);
    - LG Chem M4860 P2B (battery);
    - GP Tech PV 500WD (inverter).

For more details on the chosen methods, see. par. 2.4.

In the next four paragraphs the results of the LCA are simply exposed for each methodology used; since CML 2 baseline 2000 does not have the weighting phase, it has been chosen to observe only the normalization phase in all the methods, for a better comparison.

For a critical review and discussion of such results and comparison with other sources of energy, see Chapter 5.

All the results are available in detail in Appendix D.

4.7.1 CML 2 baseline 2000 analysis

The study conducted with CML 2 baseline 2000 shows that the most affected impact category is Marine Aquatic Ecotoxicity, and all the other categories are much less significant, except for Fresh Water Aquatic Ecotoxicity (see Fig. 4.6).

As it can be noticed from Fig. 4.7, the study reveals that in the sum of all the categories, the company that produces the elements with the most harmful impacts is Jinko Solar (40%), precisely, divided into:

- PV panel (33,92%);
- Road transport (3,66%);
- Pallet (1,96%);
- Ship transport (0,28%).

The Box and the energy used for the production of the panels (Natural gas) are not showed in the graphic because their percentage are lower than 0%.

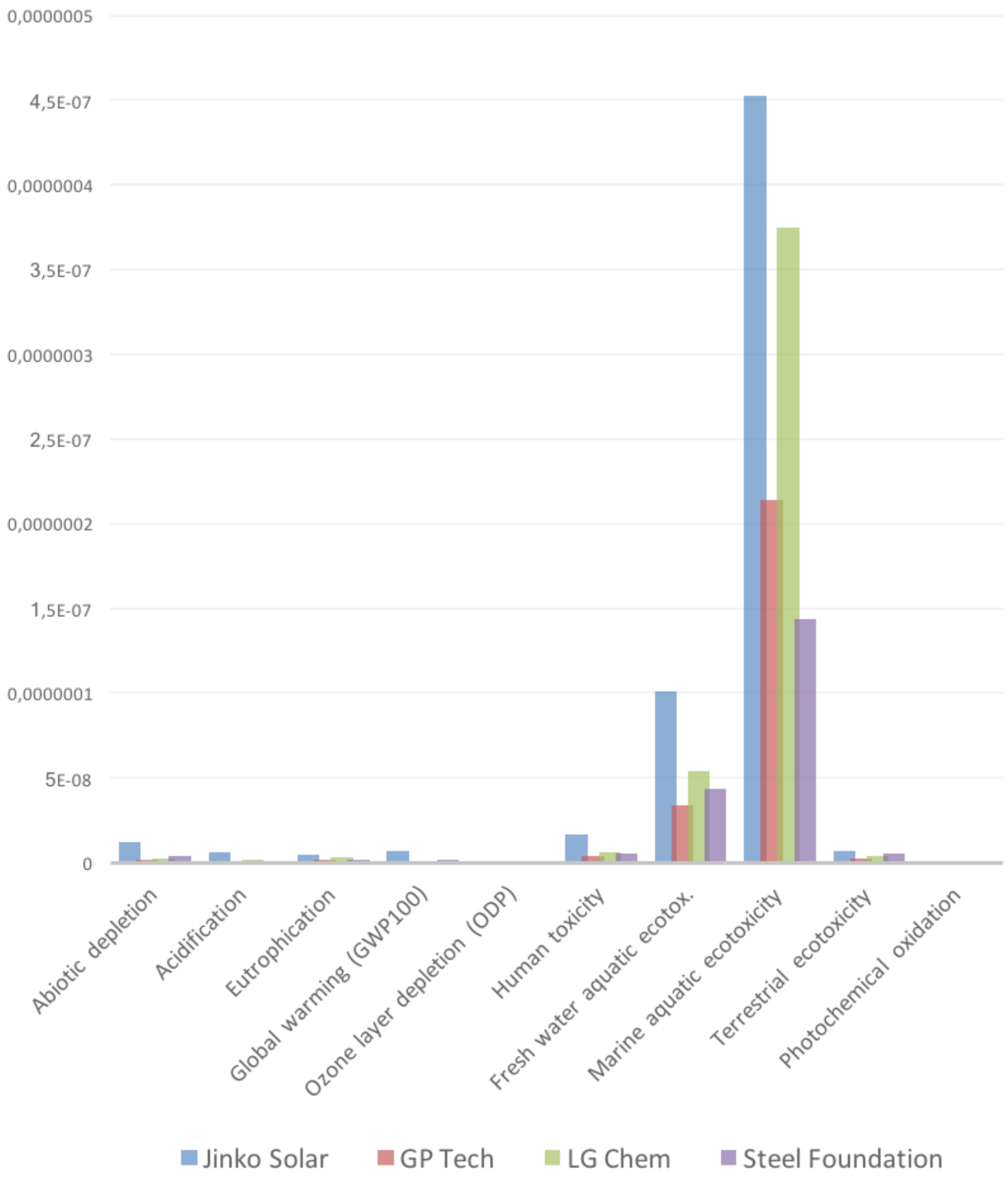


Fig. 4.6: Impact categories with CML 2 baseline 2000.

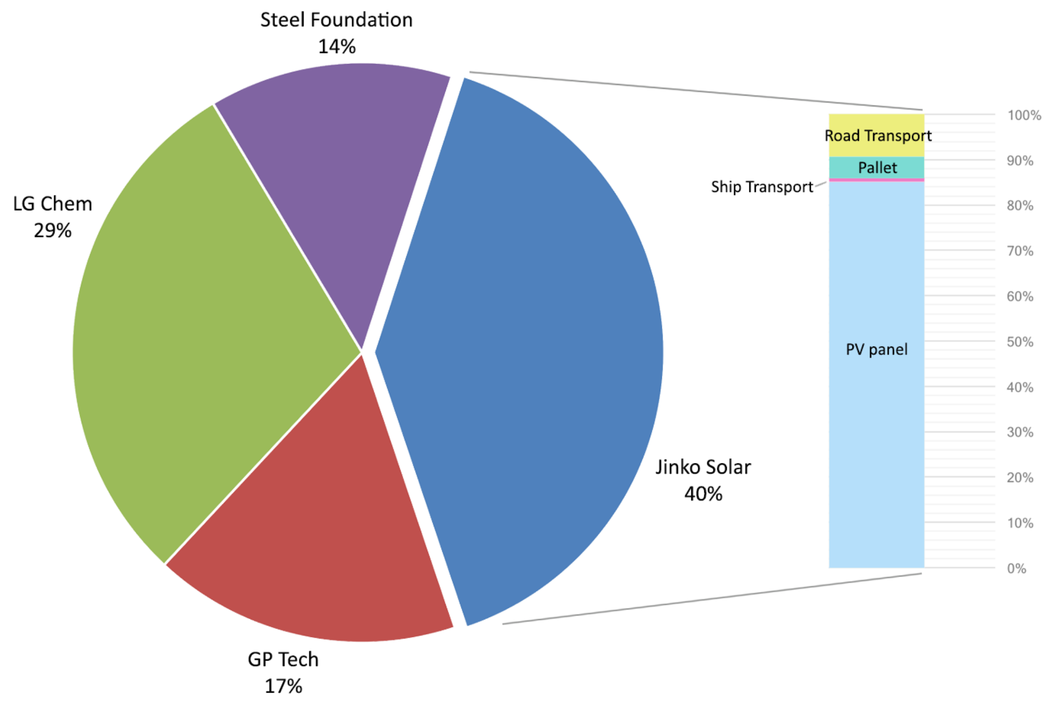


Fig. 4.7: Contribution of the single components to the total of the damages in CML.

4.7.2 Ecoindicator 99 analysis

For the study with Ecoindicator 99, it has been chosen the Hierarchist profile, as the default setting in SimaPro 7.3.3.

As represented in Fig. 4.8, the results show that the most affected categories are:

- Carcinogens (94,2 points);
- Fossil fuels (74,54 points);
- Respiratory inorganics (61,31 points),

while the less relevant categories are:

- Ozone layer depletion (0,003 points);
- Respiratory organics (0,06 points);
- Radiation (0,19 points).

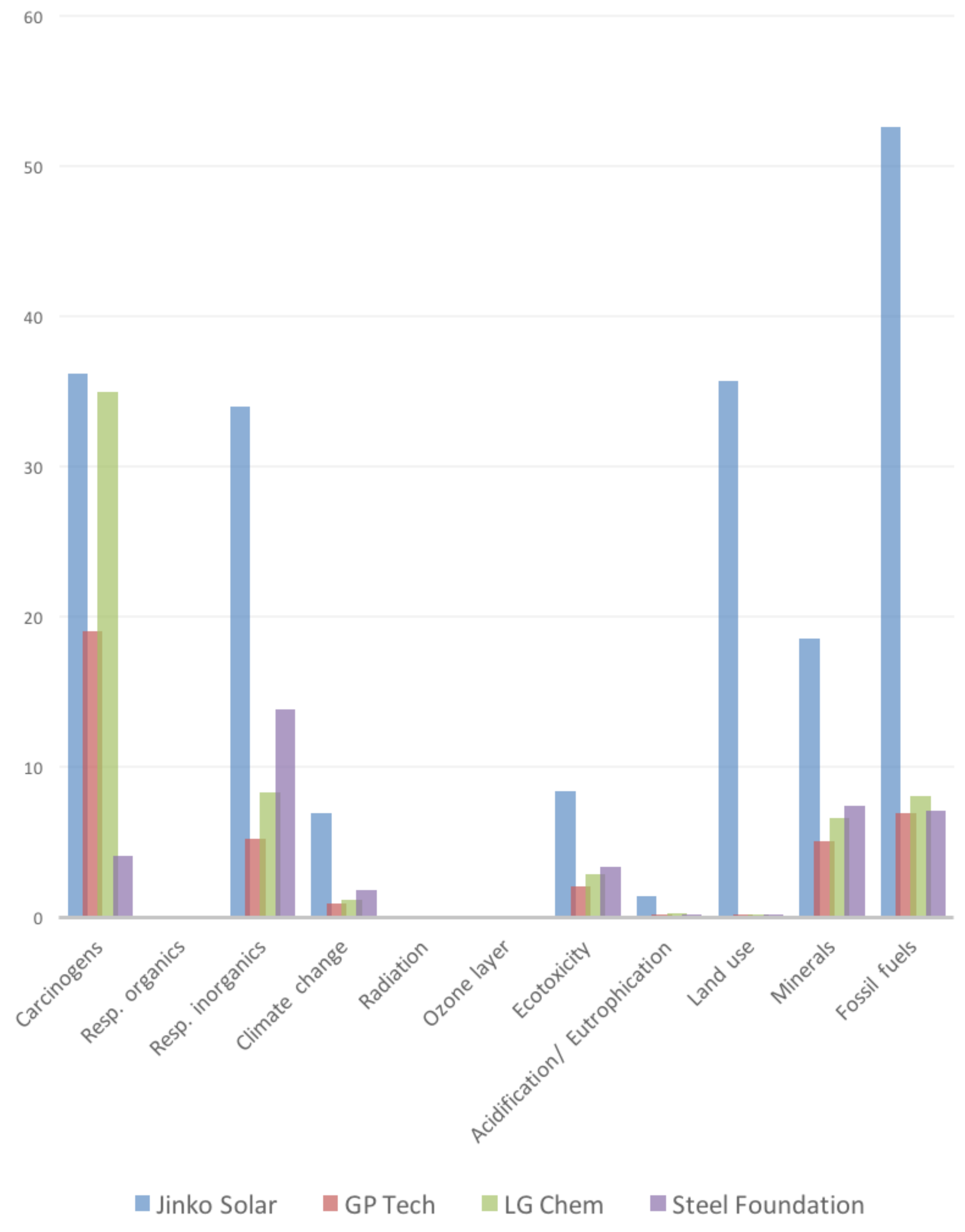


Fig. 4.6: Impact categories with Ecoindicator 99.

The components that affect the environment the most are the Jinko Solar (58%), in turn divided into;

- PV panel (40%);
- Road transport (3,7%);
- Pallet (13,05%);
- Ship transport (1,02%).

The Box and the Natural gas are lower than 0%, as displayed in the graphic in Fig. 4.9.

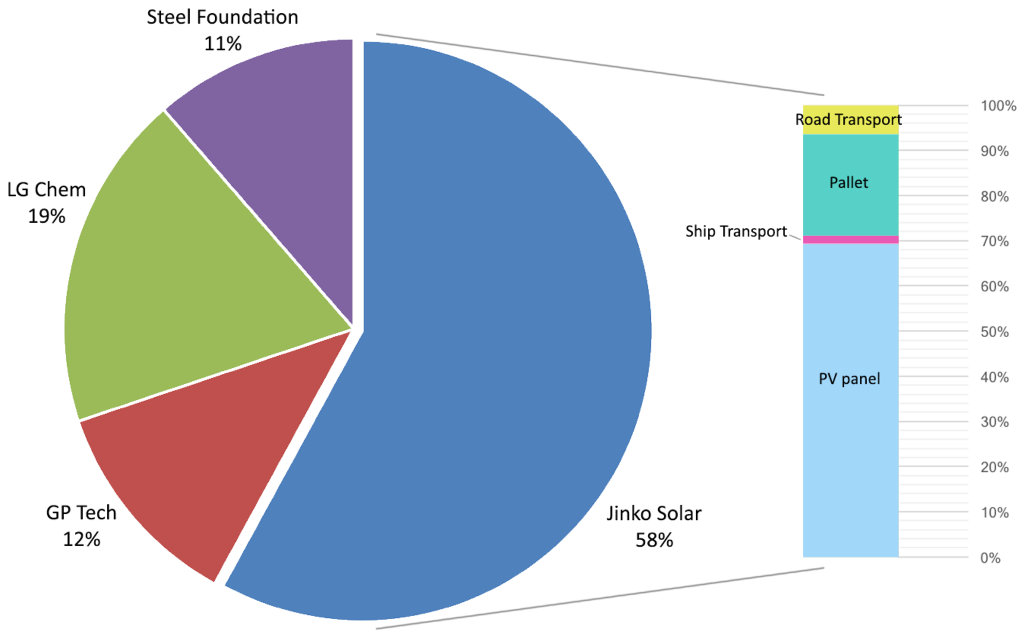


Fig. 4.9: Contribution of the single components to the total of the damages in Ecoindicator.

4.7.3 IMPACT 2002+ analysis

The analysis conducted with IMPACT 2002+ displays that the most affected impact categories are Respiratory inorganics, Non-renewable energy and Global warming, as presented in Fig. 4.10.

When the single components where analyzed, also in this case it came upon that the component that contribute for two thirds of the damages is the Jinko Solar (66%), but the second one is the Foundation (15%) and the LG Chem is the third (12%), as showed in Fig. 4.11. In the graphic, the Box and the Natural gas were excluded since their percentage is lower than 0%.

Specifically, the element of the panel that is responsible for most of the pollutants is the tempered glass, as shown in Appendix D.

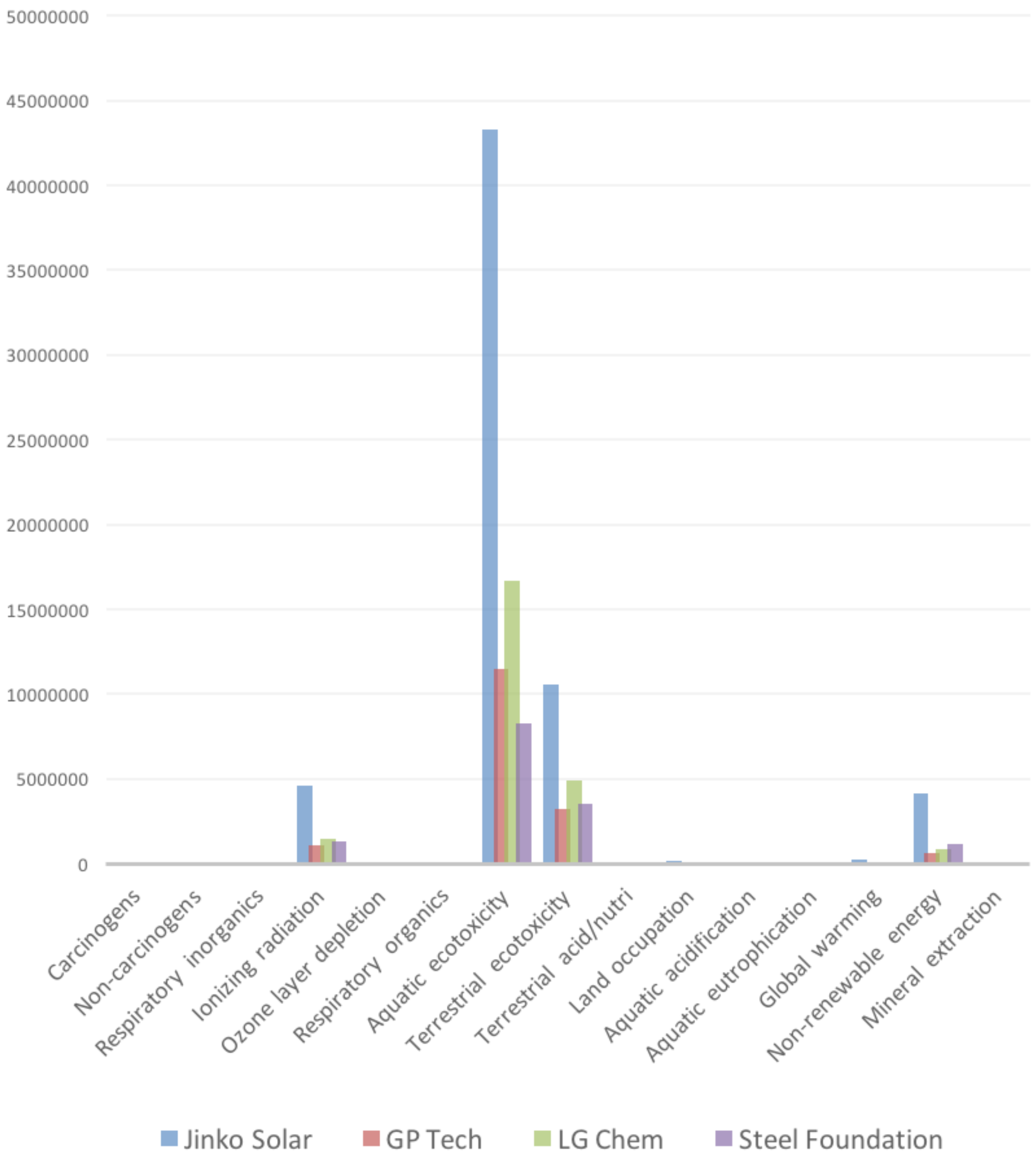


Fig. 4.10: Results of the analysis with IMPACT 2002+.

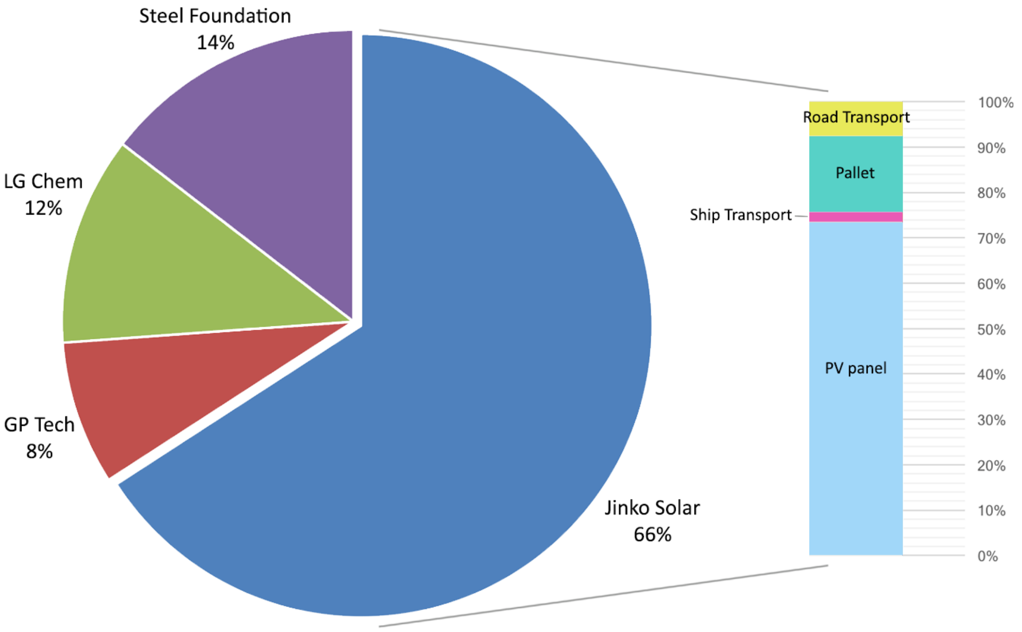


Fig. 4.11: Contribution of the single components to the total of the damages in IMPACT.

4.7.4 EPD analysis

In the EPD analysis the single main components were considered separately, and since there isn't the phase of normalization but only the characterization, all the impact categories have different units, so instead of graphics it has been chosen to show in Table 4.1 the comparison among JKM 315P-72 (PV panel), GP Tech PV 500 WD (inverter) and LG Chem M4860 P2B (battery), each of them taken singularly.

Table 4.1: EPD results for the PV panel, the inverter and the battery.

Impact category	Unit	JKM 315 P-72	GP Tech PV 500 WD	LG Chem M4860 P2B
Global warming (GWP100)	kg CO2 eq	51,33973897	12715,0766	251,7810954
Ozone layer depletion	kg CFC-11 eq	5,80455E-06	0,001063266	2,82159E-05
Photochemical oxidation	kg C2H4 eq	0,036523242	219837,4399	0,375264443
Acidification	kg SO2 eq	0,302227091	80,48267212	2,331858206
Eutrophication	kg PO4 eq	0,106323936	82,95637655	2,223825149
Non renewable, fossil	MJ eq	728,5583108	19,92191827	4386,007311

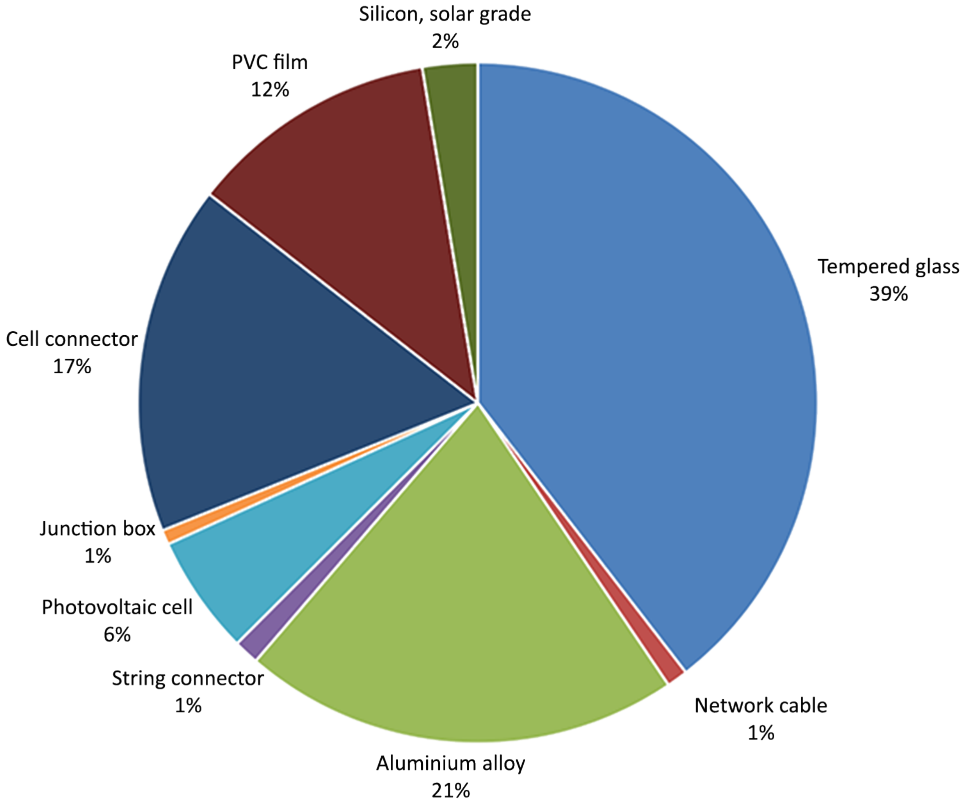


Fig. 4.12: Contribution of the single elements of the PV panel to the Global Warming Potential category in EPD.

As mentioned before, only the PV panel has been modeled, thus only for this component it is possible to show how the single elements are responsible for the environmental impacts.

As an example, it has been chosen to show in Fig. 4.12 only the contribution for the impact category Global Warming Potential (measured in kg of CO2-eq).

In Fig. 4.13 it is showed in percentage how each component contributes to all the impact categories.

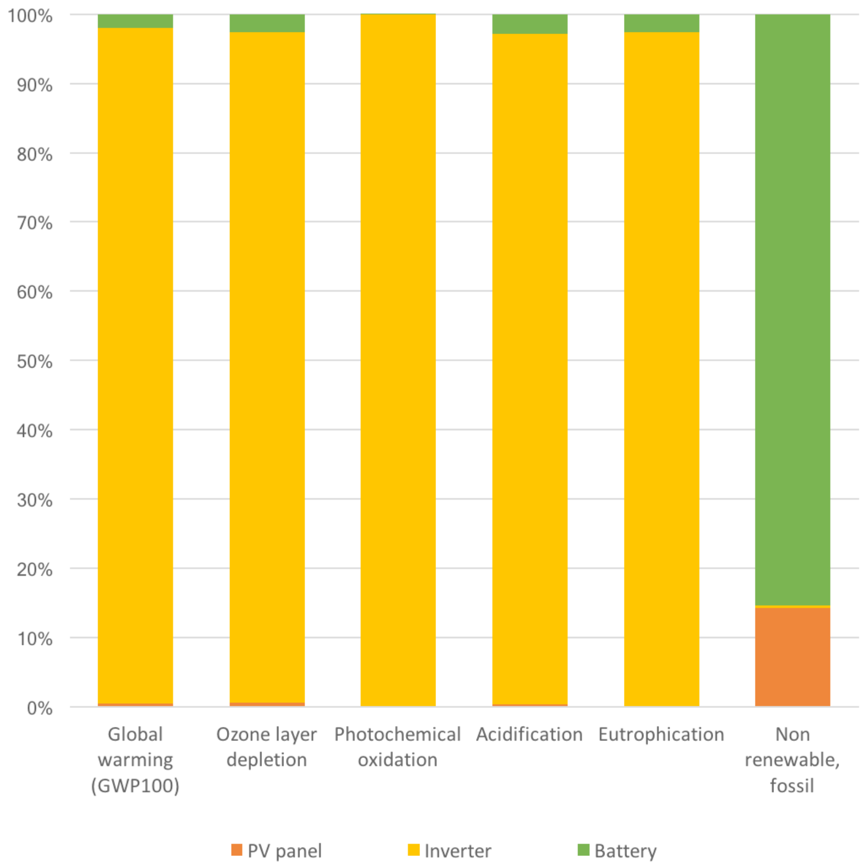


Fig. 4.13: Contribution of PV panel, inverter and battery to each category.

CHAPTER 5

Interpretation of the results

In the previous chapter the results of the LCA have been exposed and it was possible to observe very different data, due the differences among the methods used.

In this chapter, the results are interpreted for each methodology, then a comparison is provided between the functional unit chosen for this study, 1 kWh of energy produced by Entergy Solar Power Plant, and 1 kWh produced by other sources of energy, including non-renewable.

5.1 CML results

CML is a midpoint method, thus it analyzes objective damages as Global Warming Potential, expressed in quantitative unit like kg of CO2 eq., and therefore it does not have the weighting phase, which typically belongs to the endpoint methods.

The results of the normalization phase show that the Marine Aquatic Ecotoxicity is the category that affects the most the total damages to the environment (score 1,185×10-6 on an overall of 1,518×10-6), while the second one is Fresh Water Marine Ecotoxicity, with a score of 2,312×10-7, and the third one is Human Toxicity (score 3,112×10-8). The category that impact the less is Ozone Layer Depletion (2,732×10-11).

The difference of 2 orders of magnitude, makes all the categories but the Marine and Freshwater Ecotoxicity, not relevant to the purpose of the present study. For a detail of the complete score see Appendix E.

There is coherence in these two categories, since the elements considered are placed in the same order in both of them.

The PV panel is the single element that contribute the most, with 33,92%. The study reveals also that the energy needed for the manufacturing process of the panels (Natural gas) is negligible respect all the other elements (share lower than 10-5), and, although the distance covered by ship is longer than the one covered on the road, the latter transportation produces more damages (3,66% vs 0,28% of the total score).

5.2 Ecoindicator results

Ecoindicator is an intermediary method, as it models both midpoint and end-point categories, so it gives an intermediary view between the quantity and quality.

Regard to the precedent study with CML, in the Ecoindicator study there are less categories that are negligible, in fact only Ozone Layer Depletion (0,003 points), Respiratory organics (0,06 points) and Radiation (1,19 points) are non-relevant respect the main one, which is Carcinogens, with 94,2 points on an overall of 333,43.

As seen in CML, in all the impact categories the elements contribute in the same order, even though not always at the same percentage; for example, in Carcinogens the first three elements per score are: PV panel (35,23 points), Battery (34,96 points) and inverter (19,04 points), while in Fossil fuels the first three are: PV panel (38,53 points), Battery (8,01 points) and inverter (6,89 points). The only exception is Land use, in which the Pallet is almost the only one component present in the category, with 34,95 points on an overall score of 36,21, probably because it is made of wood, the most responsible object in the impact category Land use.

Like the precedent study, the results show that the PV panel contributes the most to the damages (40%), and the Box and the Natural gas are negligible, as they contribute for just 0,35% and 0,0001%, respectively.

5.3 IMPACT results

Impact 2002+ is similar to Ecoindicator, as it combines midpoint and endpoint categories in order to give a well-balanced point of view between objective facts and intuitive but ambiguous statements.

In this study, there are two impact categories that made an overall score of absolute zero, and they are: Aquatic acidification and Aquatic eutrophication, while other six categories made a score lower than 0, and they are: Ozone layer depletion, Respiratory organics, Ionizing radiation, Aquatic ecotoxicity, Terrestrial acidification, Mineral extraction. The highest category is Respiratory inorganics, which has 60,54 points.

IMPACT reveals that like in CML and Ecoindicator analysis, in all the impact categories the PV panel is the most affective element, and the battery contribute to damages more than the inverter.

Also here, the category Land occupation is the only exception, in which the Pallet has the highest score, specifically 14,41 points on 14,75 overall.

Again, the Box and the Natural gas contributes are negligible, as they made an overall score of 1,03 and 0,0004 points respectively, on an overall of 217,95.

5.4 EPD results

The EPD study shows different results than the ones reported in the previous analysis, as here the order of the share of the single components is reversed, in fact the PV panel has the lowest score and the inverter has the highest; the only exception in this case is the impact category Non-renewable, in which the inverter has the lowest share and the battery the highest.

The impact categories have different units, and since the EPD does not comprise the normalization phase, they are not directly comparable among each other. Since the PV panel, as already mentioned, is the only component that was modeled, the EPD for this component can thus be compared to the results of the previous analysis with the other methodologies.

Among all the elements that constitute the PV panel, the one that impact the environment the most is the Tempered glass, coherently with the precedent studies, except for the category Eutrophication, in which the highest is the Cell connector.

5.5 Comparison with non-renewable sources of energy

In order to give further information about how to interpret these results, once completed the LCA study with the mentioned methodologies, it is possible to proceed to the analysis which compare the energy from the solar farm subject of the study with non-renewable sources of energy, such as:

- Oil;
- Hard coal;
- Nuclear;
- Natural gas.

The functional unit chosen in the previous chapter, 1 kWh of electric energy, will be used as unit of comparison for this purpose.

For this purpose, all the emissions resulted from the precedent LCA analysis have been divided for the annual production of Entergy Solar Power Plant, mentioned in Chapter 5.

The results of the weighting phase, with the methodology IMPACT 2002+, are presented in Fig. 5.1.

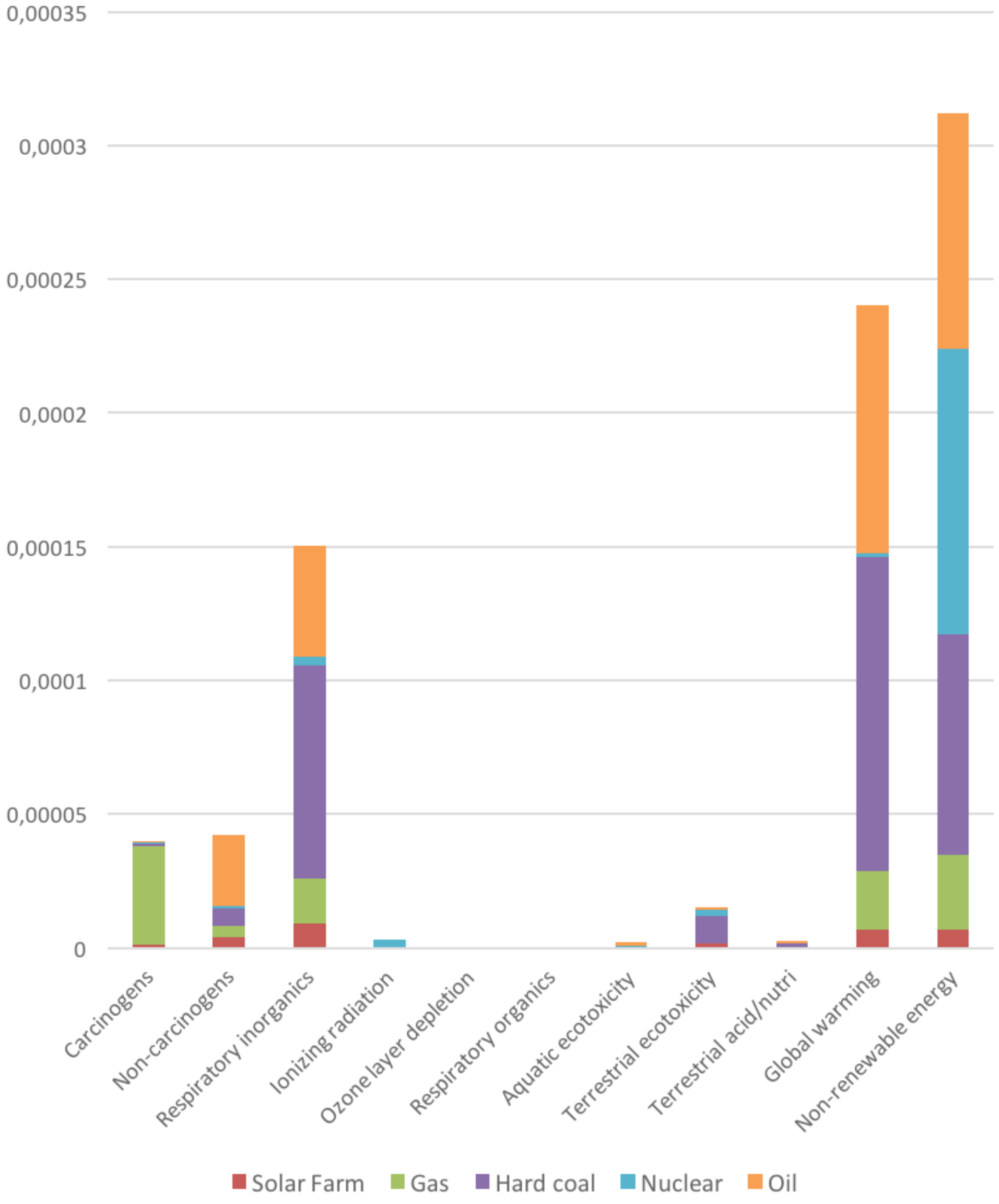


Fig. 5.1: Comparison between Entergy Solar Power Plant and other sources of energy.

The results show that the Solar Farm, in most of the impact categories (especially Respiratory inorganics, Terrestrial ecotoxicity, Global warming and Non-renewable energy) produces less pollution and harmful emissions compared with Natural gas, Hard coal, Nuclear and Oil.

The analysis also reveals that some impact categories, like Ionizing radiation, Ozone layer depletion and Respiratory organics, are not directly comparable in the same scale of the others, thus for some of them we can't see how much the single sources of energy damage the environment; therefore, in Fig. 5.2 is reported the percentage of the impacts for each source.

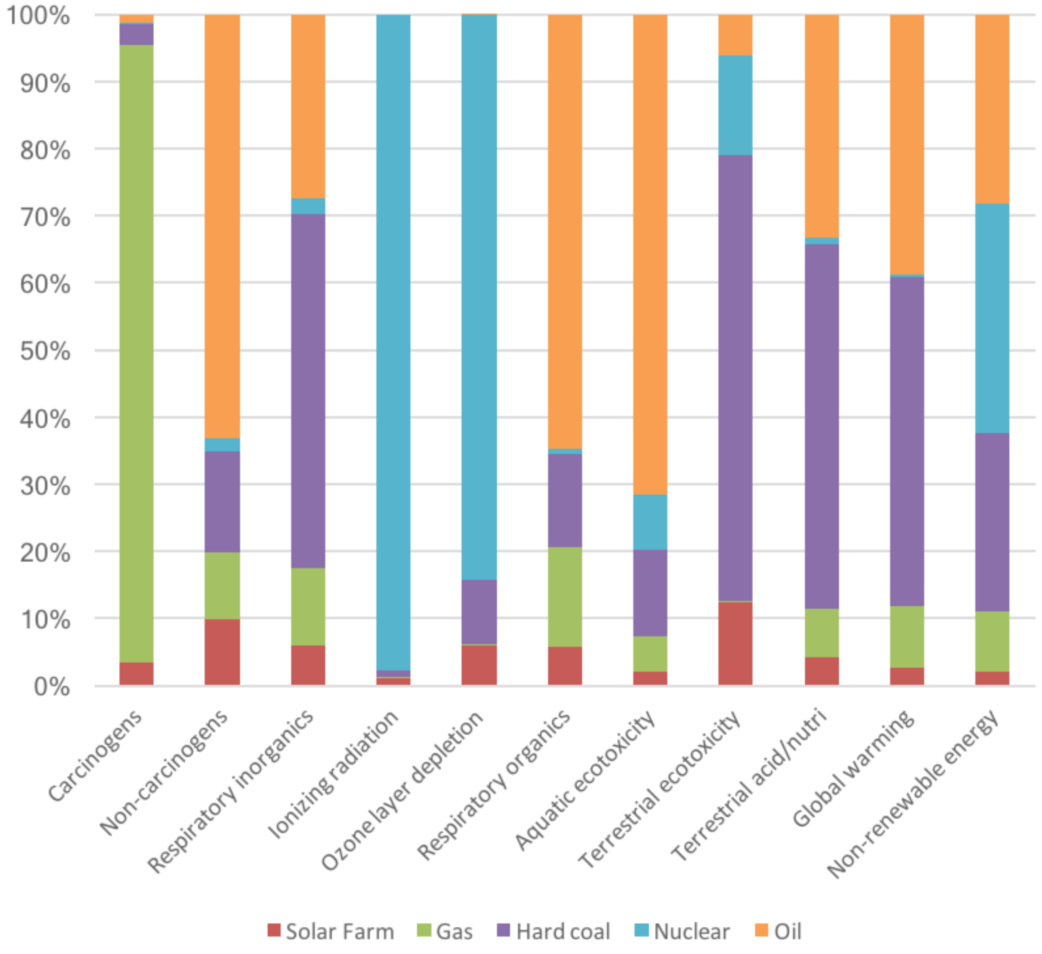


Fig. 5.2: Percentage of the damages for each source of energy.

The graphic in Fig. 5.2 shows how much the different sources contribute to the environmental damages.

The result is interesting because the source that produces less pollutant is not always the Solar Farm, e.g. in Terrestrial ecotoxicity the contribute of Natural gas is irrelevant (0,27%) and the share of the Solar Farm is 12,38%, but in Carcinogens Natural gas accounts for the 91,86% of the total, and the Solar Farm 3,52%.

Another example: in Respiratory organics, Nuclear impacts with the 0,88% and the Solar Farm with 5,96%, while in Ionizing radiation the share is respectively 97,76% and 1,14%.

The results demonstrate that in some impact categories photovoltaic is the source that pollutes the less, or at least the second one at a short distance; while a non-renewable source that may impact the less in one category, in other categories may be the one that impact the most, as mentioned above.

Therefore, although in this analysis photovoltaic is not always the source of energy that produces less damages, in general it is still the most convenient source, because its environmental advantages compensate its few drawbacks in some impact categories.

In conclusion, if we sum the scores obtained in all the impact categories for each source of energy, as shown in Fig. 5.3, the Solar Farm emerges as the source that has the lowest share of impacts.

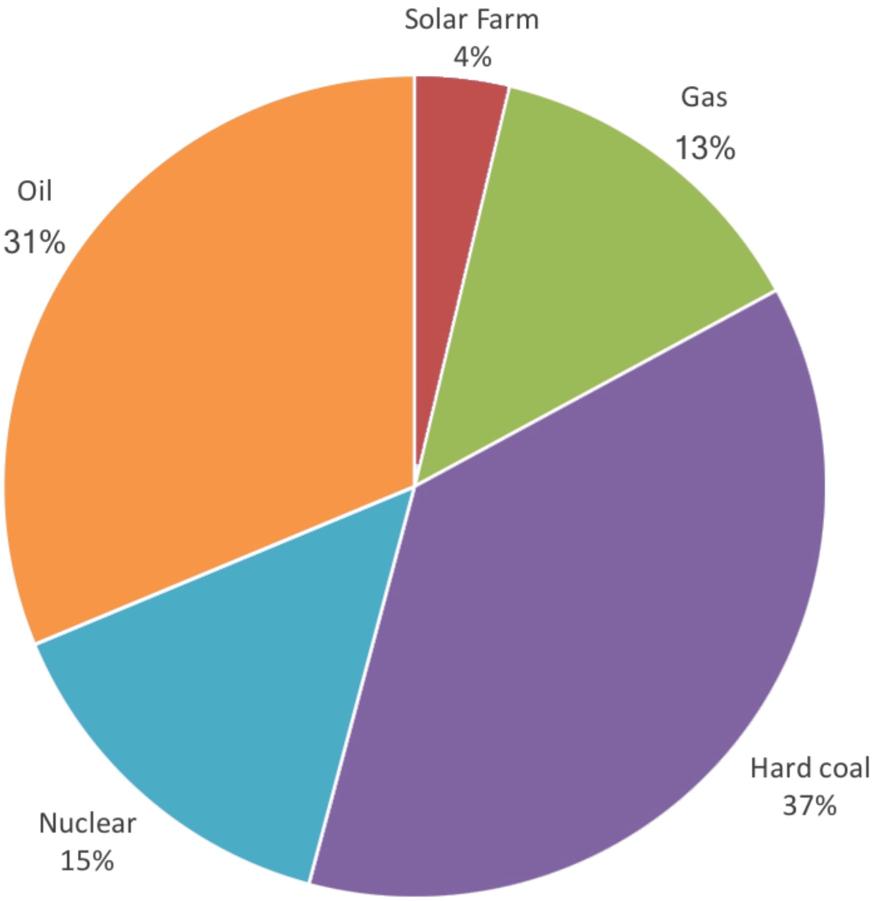


Fig. 5.3: Share of the total weighting score for each source of energy.

Conclusions

In the present thesis it has been conducted a thorough study of photovoltaic technologies, which analyzes its strengths, the aspects to be improved, the possible evolutions and the tools that the legislation provides to ensure its development, in the perspective of a sustainable future that sees renewable energy as an integral part of the world power consumption.

Thanks to the data kindly provided by Entergy Inc. and Jinko Solar, the case study considered allowed an in-depth analysis from many points of view and with different approaches, in order to give a broad overview on the subject.

The LCA conducted in the previous chapters achieved an important result: the solar farm subject of the study produces much less pollutant than non-renewable sources of energy, such as nuclear, oil, natural gas and hard coal. Therefore, this work highlights the sustainability of the transition from the non-renewable sources of energy to the photovoltaic power, in terms of damages and harmful emissions avoided to the environment.

An interesting starting point for a next study would be the waste scenario, which might give very different results, for example the Nuclear energy, which resulted to have the lowest share of damages in some impact categories, might have many issues with the radioactive waste disposal.

The scope of the present thesis was focused on the photovoltaic technology, in a next study would be interesting to make a LCA of other types of renewable energy plant, such as Wind, Geothermal, Hydro, Tidal and Wave power, and then compare them to the same non-renewable sources, as done with Solar in this thesis.

Photovoltaic technologies have probably a long way to go before reaching the mass exploitation, but so far the results are promising, and with the appropriate tools this technology will help to contain the progressive climate change and pollution derived from the human activities.

Regardless of the pollution, the non-renewable sources for their very definition will not last forever, hence it is important to rely on a long-lasting source of power. Moreover, the countries that at the present produce the most of the fossil fuels are few, while the photovoltaic is available in every region of the world, even though it can be more or less convenient in terms of hours of light and solar irradiation.

It is only a matter of time before the photovoltaic becomes a steady and trustworthy source of energy, and by then hopefully the humanity will have learned to take care of planet Earth.

Appendix A

Table A.1: Financial incentives available in New Orleans municipality.

Name	Implementing sector	Incentive type	Eligible technologies	Applicable sector	Amount
Residential Renewable Energy Tax Credit	Federal	Personal tax credit	Solar Water Heat, Solar Photovoltaics	Residential	30%
Energy-Efficient Commercial Building Tax Deduction	Federal	Corporate tax deduction	Insulation, Water Heaters, Lightning, Chillers, Furnaces, Boilers, Heat Pumps, Air Conditioners, Windows, Roof	Commercial, Construction, State Governament, Federal Government	$0.30-$1.80 per square foot
Residential Energy Efficiency Tax Credit	Federal	Personal tax credit	Biomass Stoves, Water Heaters, Furnaces, Boilers, Heat Pumps, Air Conditioners, Insulation, Windows, Roofs	Residential	$500
Energy-Efficient New Homes Tax Credit for Home Builders	Federal	Corporate tax credit	Comprehensive Measures, Whole Building	Construction	$1,000-$2,000
New Orleans City - Energy Smart Program	Local	Rebate Program	Solar Water Heat, Lightning, Heat Pumps, Air Conditioners, Insulation, Duct/Air sealing, Pool Pumps	Residential	$5,000
Tax Credit for Solar Energy Systems on Residential Property	State	Corporate tax credit	Solar Photovoltaics	Commercial, Residential, Low Income Residential, Integrators	50% (up to $10,000)
Energy-Efficient Mortgages	Federal	Loan program	Solar - Passive, Solar Water Heat, Solar Space Heat, Solar Photovoltaics, Daylighting	Residential	$8,000
Business Energy Investment Tax Credit (ITC)	Federal	Corporate tax credit	Solar Water Heat, Solar Space Heat, Solar Thermal Electric, Solar Photovoltaics, other renewable energies	Commercial, Industrial, Investor-Owned Utility, Cooperative Utilities	30%
Green Power Purchasing Goal for Federal Government	Federal	Green power purchasing	Solar Water Heat, Solar Space Heat, Solar Thermal Electric, Solar Photovoltaics, other renewable energies	Federal Government	10% in 2016-2017, 15% in 2018-2019, 20% in 2020-2021, 25% in 2022-2023
Renewable Electricity Production Tax Credit (PTC)	Federal	Corporate tax credit	Geothermal Electric, Solar Thermal Electric, Solar Photovoltaics, Wind (All), Biomass, Hydroelectric, Wave	Commercial, Industrial	$0.012/kWh
Weatherization Assistance Program (WAP)	Federal	Grant program	Furnaces, Heat pumps, Air conditioners, Caulking/Weather-stripping, Duct/Air sealing, Insulation, Other EE	Tribal Government, Low Income Residential	case-by-case

Appendix B

B.1 Investment evaluation

The LCA analysis takes into consideration all the environmental aspects of the manufacturing process of the product, but the economical side is not meant to be overlooked, as the investment must be convenient for the company, in order to support its own growth and development.

Any investment decision involves the use of economic resources for deferred benefits over time. The investment is the comparison between an initial expense to incur in order to start the investment itself, and the cash flows expected from it, only if the latters have a higher monetary value than the resources used. Another important feature of the investment is the risk, that is any factor that may endanger the remuneration or the amount of the initial outlay. Therefore, the risk must be carefully assessed by a company for the implementation of a project.

Hence, it is assumed that an investment is defined when it is known the distribution of costs and revenues over time.

The cost of an investment is the amount of financial outflows, or less incoming cash flows associated with its implementation; Similarly, the "benefits" associated with it are made of incoming cash flows, or less cash outflows. Thus, an investment operation can be represented by an estimated succession of future cash incomes and outcomes, called cash flow.

The analysis of the financial economic cycle of an investment starts with the assessment of the investment feed-back process, thus analyzing the cash outflow incurred upon the investment.

The recovery of such flows, the central feature of the problem, is the first step in terms of business goals, which must be associated with the profitability of the investment. In general, the management cycle uses financial resources (equity capital or credit) for the acquisition of the investment project, the result of which starts the process of returning on monetary resources (revenues).

Therefore, the management process recognizes two operating cycles: economic and financial, which in its temporal dynamics represents the flow of revenues and costs incurred through inbound and outbound financial operations. Within this cycle, the objective of the investment project is set, that is to achieve at the end of the management period, the economic result (revenues ▸ costs) and the financial one (inflows ▸ outflows).

B.2 Investment assessment methods

The investment assessment phase is linked to the choice of the most suitable method. Among the many methods, the following will be analyzed:

- Net Present Value (NPV);
- Internal Rate of Return (IRR);
- Return On Investment (ROI);
- Payback Time (PBT).

B.2.1 Net Present Value (NPV)

The NPV is based on the principle that an activity must be completed only if the benefits that it produces can be higher than the resources used. Therefore, the initial cost is compared with the future cash flows generated by an investment, in order to indicate the financial balance of the project; if the latter is positive, it means that the investment makes more than it costs, and thus the project can be realized.

NPV is basically the present value of all future cash flows, discounted back to the present time at the appropriate discount rate, less the cost to acquire mentioned cash flows (see Fig. 3.1). The analysis relates to the differential cash flow and not to the net accounting profit, on the assumption that the adoption of the principle of economic competence, leading to ignoring the timing of revenue and outflows, do not estimate the value of time (Berk et al., 2013).

Thus, NPV adequately evaluates the time distribution of the differentiated cash flows, which are made homogenous through a discounting process. The net present value, resulting from the difference between the present value of the incoming flows and the discounted value of the outflows:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0$$

Where

Ct = net cash inflow during the period t

C0 = total initial investment flow

r = discount rate

t = number of time periods

B.2.2 Internal Rate of Return (IRR)

Internal rate of return (IRR) is the primary metric by which sponsors estimate the attractiveness of a potential investment.

IRR measures the total return on a sponsor's equity investment, including any additional equity contributions made, or dividends received, during the investment horizon. It is defined as the discount rate that must be applied to the sponsor's cash outflows and inflows during the investment horizon in order to produce a net present value (NPV) of zero.

In general, the difference between the cost of capital and the IRR tells us the amount of estimation error in the cost of capital estimate that can exist without altering the original decision.

Similar to NPV, the internal rate of return (IRR) investment rule is based on the concept that if the return on the investment opportunity that is considered is greater than the return on other alternatives in the market with equivalent risk and maturity (i.e., the project's cost of capital), the investment opportunity is worth to undertake (Berk et al., 2013).

The IRR measures the average return of the investment and indicates the sensitivity of the NPV to estimation error in the cost of capital. Thus, knowing the IRR can be very useful, but relying on it to make investment decisions can be hazardous.

Because the IRR is a measure of the expected return of investing in the project, it could be tempting to extend the IRR investment rule to the case of mutually exclusive projects by picking the project with the highest IRR. Unfortunately, picking one project over another simply because it has a larger IRR can lead to mistakes. Problems arise when the mutually exclusive investments have differences in scale (require different initial investments) and when they have different cash flow patterns. That is why it's suitable to use

IRR rule alongside with other investment assessment methods.

To calculate IRR using the formula, it is necessary to set NPV equal to zero and solve for the discount rate r, which is here the IRR. Nevertheless, because of the nature of the formula, IRR cannot be calculated analytically, and must instead be calculated either through iterative process or using software programmed to calculate IRR (Rosenbaum and Pearl, 2013).

B.2.3 Return On Investment (ROI)

Return on investment (ROI) measures a company's ability to provide earnings (or returns) to its capital providers. ROI ratios employ a measure of profitability in the numerator and a measure of capital (e.g., invested capital, shareholders' equity, or total assets) in the denominator (Rosenbaum and Pearl, 2013).

The most commonly used ROI metrics are:

- **Return on invested capital (ROIC)**, which measures the return generated by all capital provided to a company. ROIC uses a pre-interest earnings statistic in the numerator, such as EBIT (earnings before interest and taxes) and a metric that captures both debt and equity in the denominator. The denominator is typically calculated on an average basis (e.g., average of the balances as of the prior annual and most recent periods).

$$ROIC = \frac{EBIT}{Average\ Net\ Debt + Equity}$$

- **Return on equity (ROE),** which calculates the return generated on the equity provided to a company by its shareholders. As a result, ROE incorporates an earnings metric net of interest expense, such as net income, in the numerator and average shareholders' equity in the denominator. ROE is an important indicator of performance as companies are intently focused on shareholder returns.

$$ROE = \frac{Net\ Income}{Average\ Shareholders'Equity}$$

- **<u>Return on asset (ROA)</u>**, measures the return generated by a company's asset base, thereby providing a barometer of the asset efficiency of a business. ROA typically utilizes net income in the numerator and average total assets in the denominator.

$$ROA = \frac{Net\ Income}{Average\ Total\ Assets}$$

B.2.4 Payback Period (PP)

The Payback Period method estimates the number of years it takes for a company to recover its original investment in a project, when net cash flow equals zero.

If incoming cash flows are expected to be constant over time, the period of monetary recovery is determined by the ratio between outgoing cash flows for initial investment and incoming annual cash flows.

In the case of absolute decisions, the criterion for selecting the investment is given by the comparison between the period of monetary recovery and a certain pre-established period, called cut-off period. In general, choosing the cut off period means finding the longest return time that financial managers feel acceptable for an investment. In case of a comparing decision among several investments, the company will probably choose the one with the lowest PP.

PP is among the arithmetic-accounting methods because, in addition to examining incoming cash flows, it indicates the time limits in which the cash flows generated by the investment can cover the capital invested initially (Berk et al., 2013).

If the amount of cash flows is constant, PP is obtained by dividing the initial investment for the annual cash inflows.

$$PP = \frac{Initial\ Investment}{Annual\ Cash\ Inflows}$$

If the cash flows tend to vary from period to period, the calculation of PP is made by adding the net cash flows generated by the investment, until the full recovery of the initial investment.

Despite its usefulness, the method presents some critical aspects, due primarily to a partial evaluation of the flows generated by the investment. Among incoming flows, only those generated until the time of the investment's recovery are considered, regardless of the subsequent ones. This results in the possibility to penalize investments that generate higher inflows over the medium to long term, to the benefit of the investments that generate higher inflows in the short run. Moreover, PP does not consider the time distribution of flows, their different value in relation to the years and the risk associated with the investment.

In order to overcome this limitation, a variation of this method is often used, called Discounted Payback Period, which, on the contrary, involves streamlining of flows. The mathematical calculation is similar to simple PP, with the difference that it discounts future cash flows and and recognizes the time value of money (Rosenbaum and Pearl, 2013).

Appendix C

Table C.1: Inventory of the PV panel, energy needed to produce them, the transport from the factory and its packaging.

JKM 315P-72		
Material	Quantity	Unit
Photovoltaic cell, multi-Si	0,024336	m2
Solar glass	18,592	kg
Aluminium alloy, AlMg3	1,847	kg
Network cable	1,2	m
Silicon, solar grade	0,034	kg
Copper	0,125	kg
Polyphenylene sulfide	0,035	kg
Polypropylene fibres	0,003	kg
Tin plated chromium steel sheet	0,104	kg
Silver	0,005	kg
PVC film E	1,94	m2

TRANSPORT		
Process	Quantity	Unit
Transoceanic tanker	1168880	tkm
Combination truck	376145	tkm

POWER		
Process	Quantity	Unit
Natural gas	14,67	MJ

BOX		
Material	Quantity	Unit
Corrugated board, double wall	3,9597	kg
Corrugated board, single wall	12,5733	kg

PALLET		
Material	Quantity	Unit
Industrial residue wood, hard, dried	22	kg

Table C.2: Inventory of the foundation, inverter and battery.

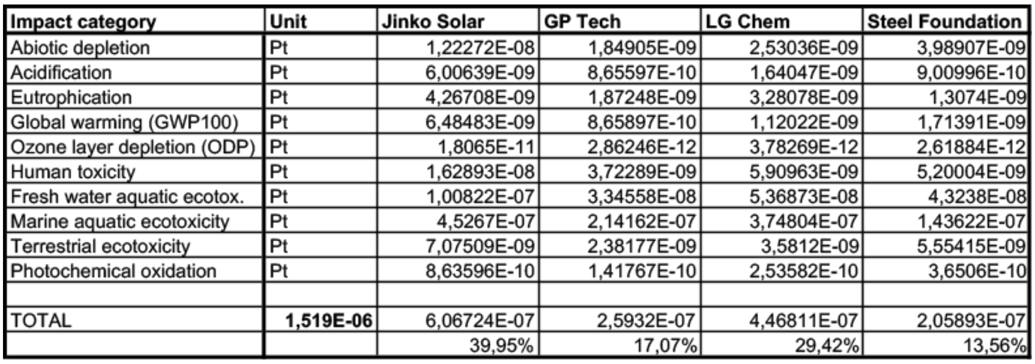
FOUNDATION		
Material	Quantity	Unit
Steel, low-alloyed	43,255	ton

LG CHEM M4860 P2B		
Material	Quantity	Unit
Battery, LiIo, rechargeble	196	p

GP TECH PV 500 WD		
Material	Quantity	Unit
Inverter, 500 kW	3	p

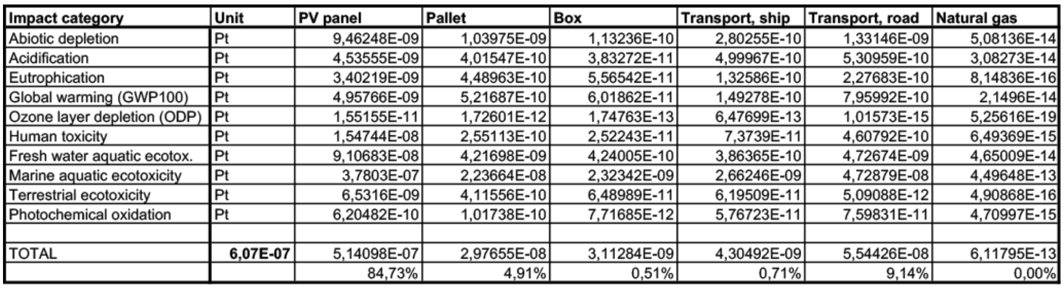
Appendix D

Table D.1: Detail of the CML results.



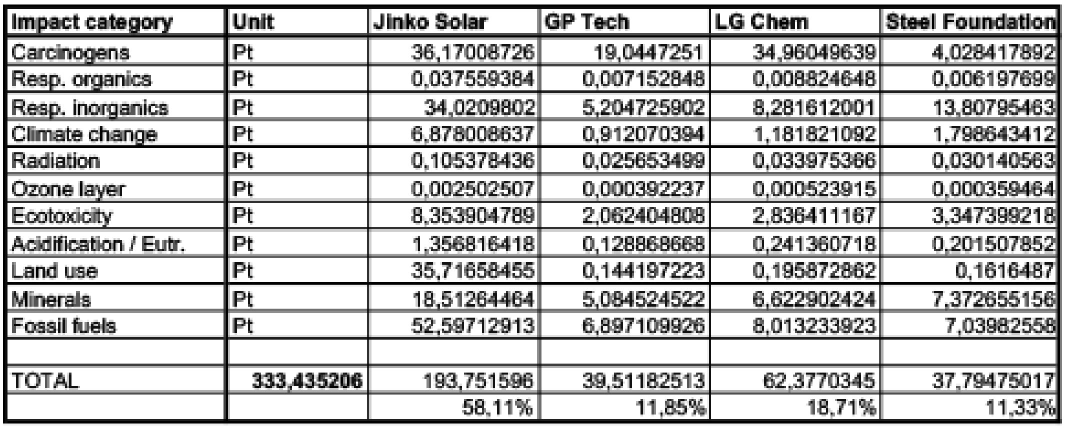
Impact category	Unit	Jinko Solar	GP Tech	LG Chem	Steel Foundation
Abiotic depletion	Pt	1,22272E-08	1,84905E-09	2,53036E-09	3,98907E-09
Acidification	Pt	6,00639E-09	8,65597E-10	1,64047E-09	9,00996E-10
Eutrophication	Pt	4,26708E-09	1,87248E-09	3,28078E-09	1,3074E-09
Global warming (GWP100)	Pt	6,48483E-09	8,65897E-10	1,12022E-09	1,71391E-09
Ozone layer depletion (ODP)	Pt	1,8065E-11	2,86246E-12	3,78269E-12	2,61884E-12
Human toxicity	Pt	1,62893E-08	3,72289E-09	5,90963E-09	5,20004E-09
Fresh water aquatic ecotox.	Pt	1,00822E-07	3,34558E-08	5,36873E-08	4,3238E-08
Marine aquatic ecotoxicity	Pt	4,5267E-07	2,14162E-07	3,74804E-07	1,43622E-07
Terrestrial ecotoxicity	Pt	7,07509E-09	2,38177E-09	3,5812E-09	5,55415E-09
Photochemical oxidation	Pt	8,63596E-10	1,41767E-10	2,53582E-10	3,6506E-10
TOTAL	**1,519E-06**	6,06724E-07	2,5932E-07	4,46811E-07	2,05893E-07
		39,95%	17,07%	29,42%	13,56%

Table D.2: Detail of the CML results. Contribution of the PV panel.



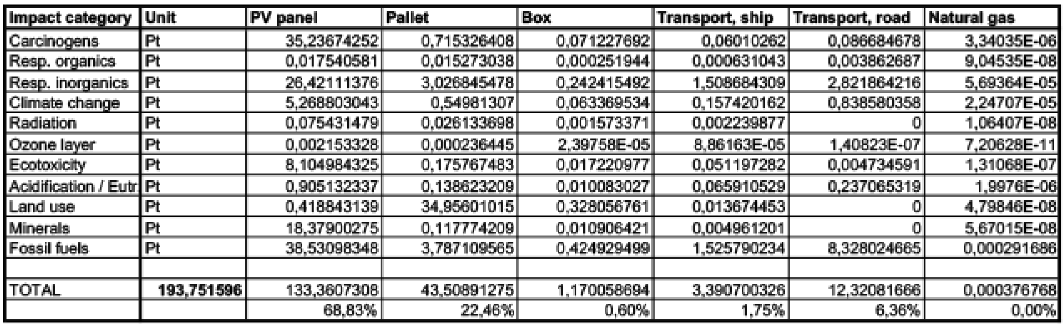
Impact category	Unit	PV panel	Pallet	Box	Transport, ship	Transport, road	Natural gas
Abiotic depletion	Pt	9,46248E-09	1,03975E-09	1,13236E-10	2,80255E-10	1,33146E-09	5,08136E-14
Acidification	Pt	4,53555E-09	4,01547E-10	3,83272E-11	4,99967E-10	5,30959E-10	3,08273E-14
Eutrophication	Pt	3,40219E-09	4,48963E-10	5,56542E-11	1,32586E-10	2,27683E-10	8,14836E-16
Global warming (GWP100)	Pt	4,95766E-09	5,21687E-10	6,01862E-11	1,49278E-10	7,95992E-10	2,1496E-14
Ozone layer depletion (ODP)	Pt	1,55155E-11	1,72601E-12	1,74763E-13	6,47699E-13	1,01573E-15	5,25616E-19
Human toxicity	Pt	1,54744E-08	2,55113E-10	2,52243E-11	7,3739E-11	4,60792E-10	6,49369E-15
Fresh water aquatic ecotox.	Pt	9,10683E-08	4,21698E-09	4,24005E-10	3,86365E-10	4,72674E-09	4,65009E-14
Marine aquatic ecotoxicity	Pt	3,7803E-07	2,23664E-08	2,32342E-09	2,66246E-09	4,72879E-08	4,49648E-13
Terrestrial ecotoxicity	Pt	6,5316E-09	4,11556E-10	6,48989E-11	6,19509E-11	5,09088E-12	4,90868E-16
Photochemical oxidation	Pt	6,20482E-10	1,01738E-10	7,71685E-12	5,76723E-11	7,59831E-11	4,70997E-15
TOTAL	**6,07E-07**	5,14098E-07	2,97655E-08	3,11284E-09	4,30492E-09	5,54426E-08	6,11795E-13
		84,73%	4,91%	0,51%	0,71%	9,14%	0,00%

Table D.3: Detail of the Ecoindicator results.



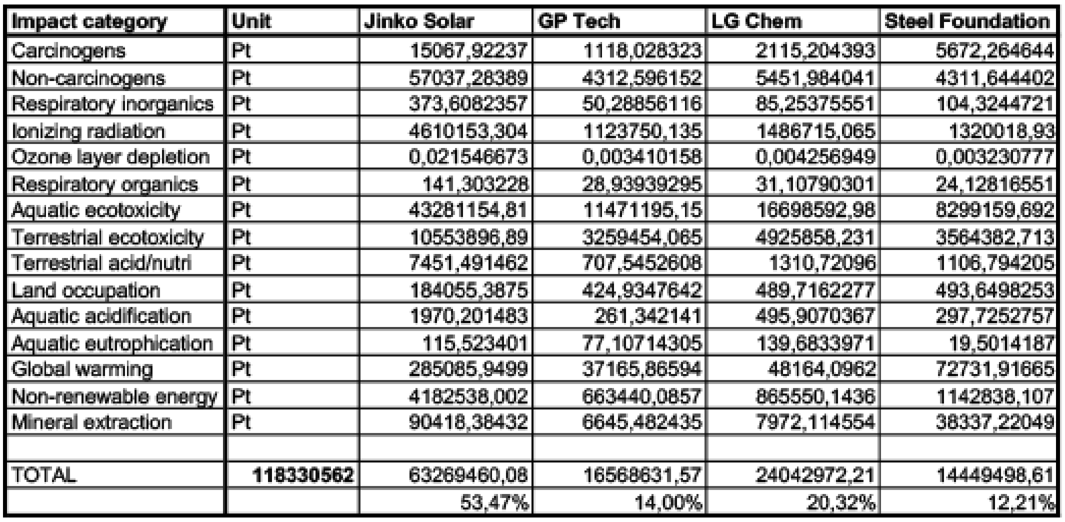
Impact category	Unit	Jinko Solar	GP Tech	LG Chem	Steel Foundation
Carcinogens	Pt	36,17008726	19,0447251	34,96049639	4,028417892
Resp. organics	Pt	0,037559384	0,007152848	0,008824648	0,006197699
Resp. inorganics	Pt	34,0209802	5,204725902	8,281612001	13,80795463
Climate change	Pt	6,878008637	0,912070394	1,181821092	1,798643412
Radiation	Pt	0,105378436	0,025653499	0,033975366	0,030140563
Ozone layer	Pt	0,002502507	0,000392237	0,000523915	0,000359464
Ecotoxicity	Pt	8,353904789	2,062404808	2,836411167	3,347399218
Acidification / Eutr.	Pt	1,356816418	0,128868668	0,241360718	0,201507852
Land use	Pt	35,71658455	0,144197223	0,195872862	0,1616487
Minerals	Pt	18,51264464	5,084524522	6,622902424	7,372655156
Fossil fuels	Pt	52,59712913	6,897109926	8,013233923	7,03982558
TOTAL	**333,435206**	193,751596	39,51182513	62,3770345	37,79475017
		58,11%	11,85%	18,71%	11,33%

Table D.4: Detail of the Ecoindicator results. Contribution of the PV panel.



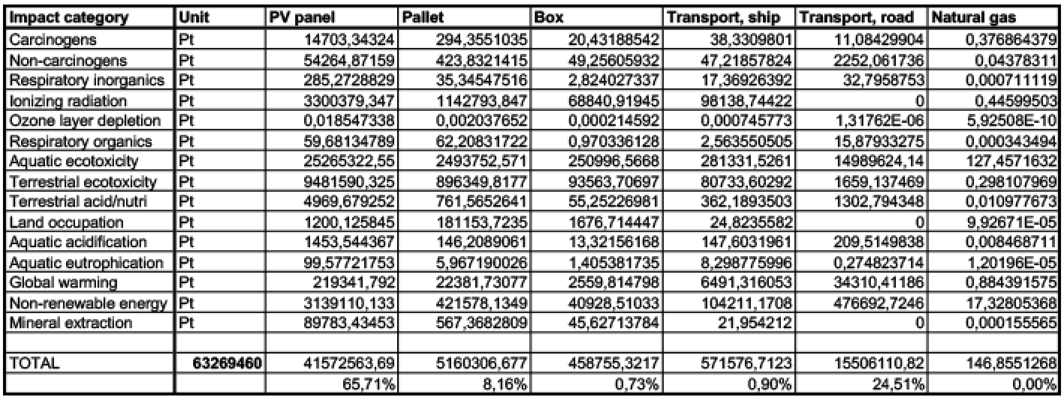
Impact category	Unit	PV panel	Pallet	Box	Transport, ship	Transport, road	Natural gas
Carcinogens	Pt	35,23674252	0,715326408	0,071227692	0,06010262	0,086684678	3,34035E-06
Resp. organics	Pt	0,017540581	0,015273038	0,000251944	0,000631043	0,003862687	9,04535E-08
Resp. inorganics	Pt	26,42111376	3,026845478	0,242415492	1,508684309	2,821864216	5,69364E-05
Climate change	Pt	5,268803043	0,54981307	0,063369534	0,157420162	0,838580358	2,24707E-05
Radiation	Pt	0,075431479	0,026133698	0,001573371	0,002239877	0	1,06407E-08
Ozone layer	Pt	0,002153328	0,000236445	2,39758E-05	8,86163E-05	1,40823E-07	7,20628E-11
Ecotoxicity	Pt	8,104984325	0,175767483	0,017220977	0,051197282	0,004734591	1,31068E-07
Acidification / Eutr	Pt	0,905132337	0,138623209	0,010083027	0,065910529	0,237065319	1,9976E-06
Land use	Pt	0,418843139	34,95601015	0,328056761	0,013674453	0	4,79846E-08
Minerals	Pt	18,37900275	0,117774209	0,010906421	0,004961201	0	5,67015E-08
Fossil fuels	Pt	38,53098348	3,787109565	0,424929499	1,525790234	8,328024665	0,000291686
TOTAL	**193,751596**	133,3607308	43,50891275	1,170058694	3,390700326	12,32081666	0,000376768
		68,83%	22,46%	0,60%	1,75%	6,36%	0,00%

Table D.6: Detail of the IMPACT results.



Impact category	Unit	Jinko Solar	GP Tech	LG Chem	Steel Foundation
Carcinogens	Pt	15067,92237	1118,028323	2115,204393	5672,264644
Non-carcinogens	Pt	57037,28389	4312,596152	5451,984041	4311,644402
Respiratory inorganics	Pt	373,6082357	50,28856116	85,25375551	104,3244721
Ionizing radiation	Pt	4610153,304	1123750,135	1486715,065	1320018,93
Ozone layer depletion	Pt	0,021546673	0,003410158	0,004256949	0,003230777
Respiratory organics	Pt	141,303228	28,93939295	31,10790301	24,12816551
Aquatic ecotoxicity	Pt	43281154,81	11471195,15	16698592,98	8299159,692
Terrestrial ecotoxicity	Pt	10553896,89	3259454,065	4925858,231	3564382,713
Terrestrial acid/nutri	Pt	7451,491462	707,5452608	1310,72096	1106,794205
Land occupation	Pt	184055,3875	424,9347642	489,7162277	493,6498253
Aquatic acidification	Pt	1970,201483	261,342141	495,9070367	297,7252757
Aquatic eutrophication	Pt	115,523401	77,10714305	139,6833971	19,5014187
Global warming	Pt	285085,9499	37165,86594	48164,0962	72731,91665
Non-renewable energy	Pt	4182538,002	663440,0857	865550,1436	1142838,107
Mineral extraction	Pt	90418,38432	6645,482435	7972,114554	38337,22049
TOTAL	**118330562**	63269460,08	16568631,57	24042972,21	14449498,61
		53,47%	14,00%	20,32%	12,21%

Table D.7 Detail of the IMPACT results. Contribution of the PV panel.



Impact category	Unit	PV panel	Pallet	Box	Transport, ship	Transport, road	Natural gas
Carcinogens	Pt	14703,34324	294,3551035	20,43188542	38,3309801	11,08429904	0,376864379
Non-carcinogens	Pt	54264,87159	423,8321415	49,25605932	47,21857824	2252,061736	0,04378311
Respiratory inorganics	Pt	285,2728829	35,34547516	2,824027337	17,36926392	32,7958753	0,000711119
Ionizing radiation	Pt	3300379,347	1142793,847	68840,91945	98138,74422	0	0,44599503
Ozone layer depletion	Pt	0,018547338	0,002037652	0,000214592	0,000745773	1,31762E-06	5,92508E-10
Respiratory organics	Pt	59,68134789	62,20831722	0,970336128	2,563550505	15,87933275	0,000343494
Aquatic ecotoxicity	Pt	25265322,55	2493752,571	250996,5668	281331,5261	14989624,14	127,4571632
Terrestrial ecotoxicity	Pt	9481590,325	896349,8177	93563,70697	80733,60292	1659,137469	0,298107969
Terrestrial acid/nutri	Pt	4969,679252	761,5652641	55,25226981	362,1893503	1302,794348	0,010977673
Land occupation	Pt	1200,125845	181153,7235	1676,714447	24,8235582	0	9,92671E-05
Aquatic acidification	Pt	1453,544367	146,2089061	13,32156168	147,6031961	209,5149838	0,008468711
Aquatic eutrophication	Pt	99,57721753	5,967190026	1,405381735	8,298775996	0,274823714	1,20196E-05
Global warming	Pt	219341,792	22381,73077	2559,814798	6491,316053	34310,41186	0,884391575
Non-renewable energy	Pt	3139110,133	421578,1349	40928,51033	104211,1708	476692,7246	17,32805368
Mineral extraction	Pt	89783,43453	567,3682809	45,62713784	21,954212	0	0,000155565
TOTAL	**63269460**	41572563,69	5160306,677	458755,3217	571576,7123	15506110,82	146,8551268
		65,71%	8,16%	0,73%	0,90%	24,51%	0,00%

Table D. 5: IMPACT tree diagram, exclusion value: 5%.

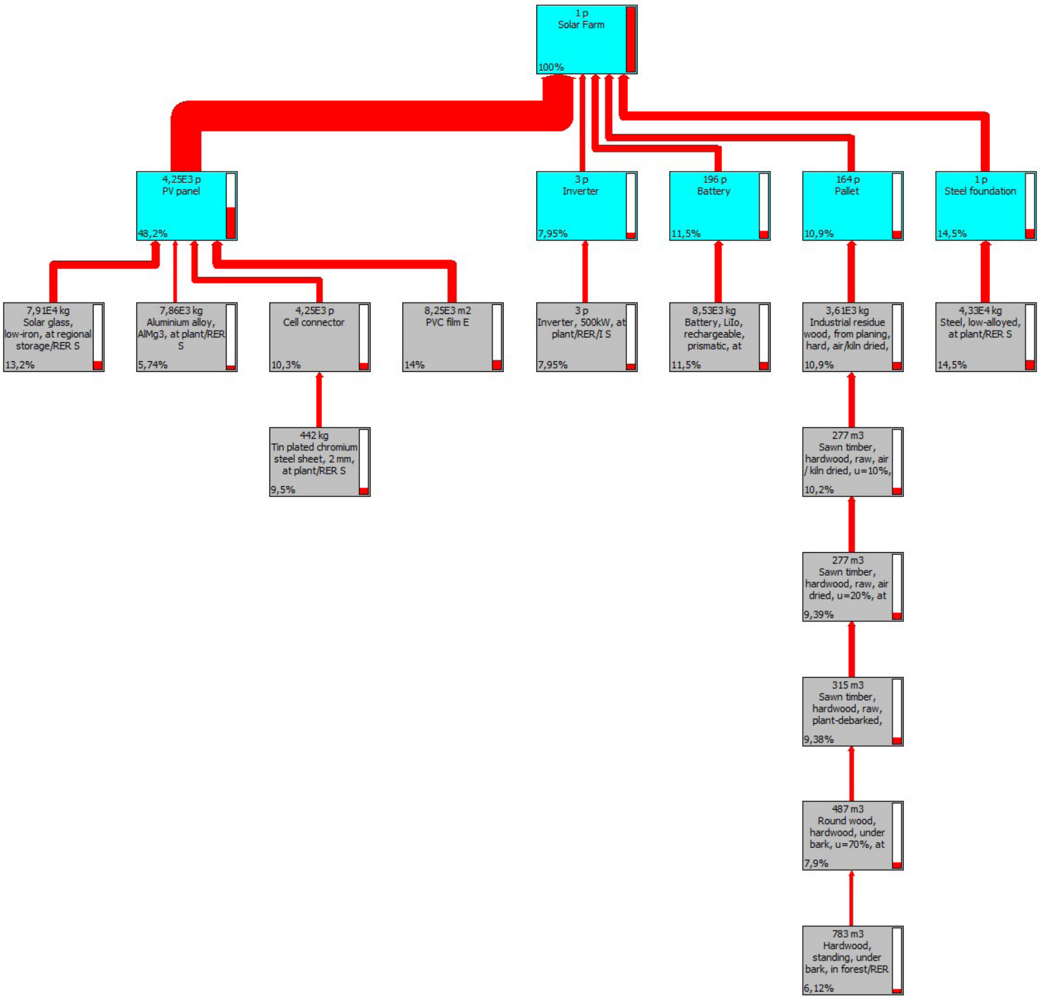
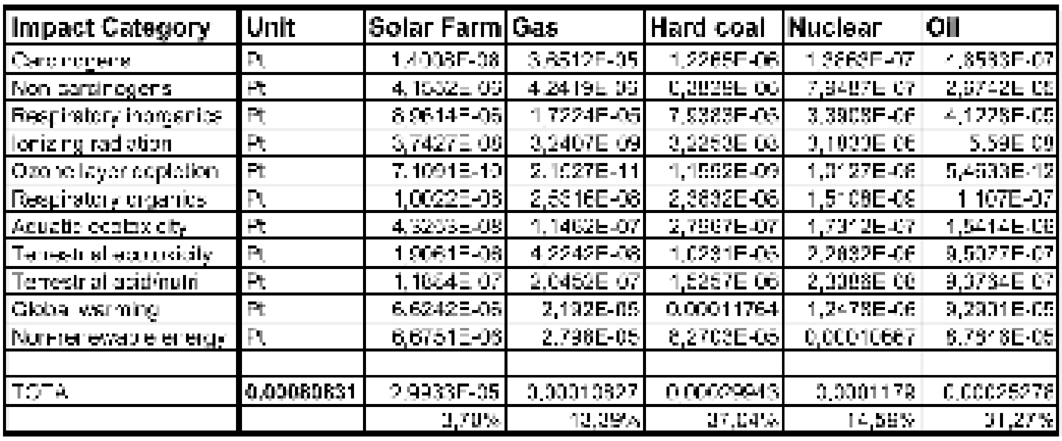


Table D.8: EPD of the PV panel in detail.

Impact category	Global warming (GWP100)	Ozone layer depletion	Photochemical oxidation	Acidification	Eutrophication	Non renewable, fossil
Unit	**kg CO2 eq**	**kg CFC-11 eq**	**kg C2H4 eq**	**kg SO2 eq**	**kg PO4 eq**	**MJ eq**
Tempered glass	20,29440379	2,25536E-06	0,013456725	0,166709233	0,024098449	264,8370391
Network cable	0,51417058	6,19826E-08	0,000679523	0,005818908	0,005590184	8,737086304
Aluminium alloy	10,67417485	5,27562E-07	0,004079299	0,028940718	0,014388426	107,1174277
String connector	0,613948616	8,21636E-08	0,001337429	0,011857482	0,017414606	9,239535989
Photovoltaic cell	2,917256528	1,85281E-06	0,006127574	0,008314119	0,006021676	50,21176561
Junction Box	0,355204604	2,67E-08	0,000329286	0,002760498	0,002310381	5,488486504
Cell connector	8,53377866	6,90621E-07	0,006974146	0,050986567	0,033456233	129,12931
PVC film	6,092270415	0	0,002840432	0,024249415	0,002295282	132,1174696
Silicon, solar grade	1,344530931	3,07382E-07	0,000698828	0,00259015	0,000748699	21,68019002
Total	51,33973897	5,80455E-06	0,036523242	0,302227091	0,106323936	728,5583108

Table D.9: Detail of the results of the comparison between the Solar Farm and other sources of energy.



Impact Category	Unit	Solar Farm	Gas	Hard coal	Nuclear	Oil
Carcinogens	Pt	1,4008E-08	3,6512E-05	1,2265E-06	1,3663E-07	1,8593E-07
Non carcinogens	Pt	4,1532E-05	4,2419E-05	6,2029E-06	7,3487E-07	2,8742E-05
Respiratory inorganics	Pt	8,9614E-06	1,7724E-05	7,5383E-06	3,3908E-06	4,1278E-05
Ionizing radiation	Pt	3,7427E-09	3,2407E-09	3,2253E-08	3,1023E-06	5,59E-09
Ozone layer depletion	Pt	7,1091E-10	2,1527E-11	1,1552E-09	1,3127E-08	5,4533E-12
Respiratory organics	Pt	1,0022E-08	2,5316E-08	2,3832E-08	1,5108E-08	1,107E-07
Aquatic ecotoxicity	Pt	4,3203E-08	1,1462E-07	2,7967E-07	1,7312E-07	1,5414E-08
Terrestrial ecotoxicity	Pt	1,9061E-08	4,2242E-08	1,0231E-06	2,2032E-06	9,5077E-07
Terrestrial acid/nutri	Pt	1,1064E-07	2,0452E-07	1,5257E-06	2,3308E-08	9,3734E-07
Global warming	Pt	6,6242E-05	2,192E-05	0,00011764	1,2478E-06	9,2331E-05
Non-renewable energy	Pt	6,6751E-06	2,798E-05	8,2703E-05	0,00010667	6,7918E-05
TOTAL	0,00080831	2,9933E-05	0,00010827	0,00029943	0,0001178	0,00025278
		3,70%	12,29%	37,04%	14,58%	31,27%

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