School of Production Engineering and Management
Technical University of Crete
Chania, Greece

Stochastic Life Cycle Assessment and Cost analysis in Renewable Energy Systems

Thesis presented to the School of Production Engineering and Management, Technical University of Crete

In partial fulfillment of the requirements for the Degree Master of Science in Applied Mathematics in Engineering Sciences

Submitted by: Maria Milousi

Supervisor: Assistant Professor Tryfonas Daras

Members of the Committee: Constantin Zopounidis, Professor
Michalis Doumpos, Professor

September 2018

Dedicated to my father

Acknowledgements

I would like to take this opportunity to thank the people who have contributed by helping me to this essay.

First of all I would like to express my sincere gratitude to my supervisor Assistant Professor Tryfonas Daras for his help and professional support through the process of this master thesis. My acknowledgments go also to the members of the Committee, Professors Constantin Zopounidis and Michalis Doumpos, for their constant support.

Special thanks go to Associate Professor Minos Petrakis for the inspiring and encouraging conversations during my MSc studies. I would also like to thank George Nikoloudakis who shared his precious time helping me the last two years.

Finally, I must express my very profound gratitude to my mother for providing me with unfailing and continuous encouragement. Heartfelt thanks go to my family who has supported me all the way, both by keeping me harmonious and by helping put my pieces together. This accomplishment would not have been possible without them.

Thank you!

Table of contents

List of Figures

List of Tables

Acknowledgements

This paper is the result of a master thesis within the study program 'Applied Mathematics in Engineering Sciences'. The study was conducted at the School of Production Engineering & Management in the Technical University of Crete.

I would like to take this opportunity to thank the people who have contributed to this study. First of all I would like to thank my supervisor Assist. Prof. Tryfonas Daras for his help and professional support through the process of this master thesis. A special thanks goes to Assist. Prof. Minos Petrakis for the inspiration and the encouraging conversations. Subsequently I would like to express my sincere thanks to George Nikoloudakis who shared his precious time helping me throughout the period of my study.

Finally, I must express my very profound gratitude to my mother for providing me with unfailing and continuous encouragement and to my family who have supported me all the way, both by keeping me harmonious and helping me putting pieces together. This accomplishment would not have been possible without them. Thank you.

Abstract

"Stochastic Life Cycle Assessment and Cost analysis in Renewable Energy Systems"

Life Cycle Assessment (LCA) is a systematic, analytical process for assessing the environmental implications of systems or products, from raw material extraction (or "cradle") through manufacture, use, and end of life (the "grave"). Though it is clear that LCA results are subject to many sources of uncertainty, it is also important to know to what extent the outcome of such an analysis is affected by various types of uncertainty (such as parameter, scenario and model uncertainty) and may occur in the goal and scope definition, the inventory analysis and the impact assessment of an LCA. Proper evaluation of the inherent uncertainties provides useful information for the reliability of LCA-based decisions and a necessary guide for future minimization of inaccuracies. The selection of a proper technique is largely based on the type and extent of details required by the specific case-study (i.e. sensitivity analysis, Monte Carlo simulation, Markov chain, Multiple linear regression, Fuzzy set theory and fuzzy logic, etc.).

There have been several attempts to spot and highlight various statistical-stochastic uncertainties in LCA, as they are increasingly affecting the relevant methodologies, databases and software. The thesis contains a detailed LCA and techno-economic study of selected Renewable Energy Systems: geothermal power plants, photovoltaics (thin-film and crystalline) and solar thermal collectors (flat plate and vacuum tube). The advanced software SimaPro accompanied with the updated Ecoinvent database have been used for the implementation of the LCA case studies, while all technical and economic calculations have been performed through RETSCreen.

Περίληψη

"Στοχαστική Ανάλυση Κύκλου Ζωής και Κόστους σε Συστήματα Ανανεώσιμων Πηγών Ενέργειας"

Η Ανάλυση Κύκλου Ζωής (ΑΚΖ) είναι μια συστηματική, αναλυτική διαδικασία για την εκτίμηση των περιβαλλοντικών επιπτώσεων συστημάτων ή προϊόντων, από την εξόρυξη πρώτων υλών μέσω της κατασκευής, της χρήσης και της λήξης της ζωής. Αν και είναι σαφές ότι τα αποτελέσματα της ΑΚΖ υπόκεινται σε πολλές πηγές αβεβαιότητας, είναι επίσης σημαντικό να γνωρίζουμε σε ποιο βαθμό το αποτέλεσμα μιας τέτοιας ανάλυσης επηρεάζεται από διάφορους τύπους αβεβαιότητας (όπως αβεβαιότητα παραμέτρων, σεναρίων και μοντέλων) και μπορεί να συμβεί στον ορισμό του στόχου και του πεδίου εφαρμογής, στην ανάλυση απογραφής και στην εκτίμηση των επιπτώσεων μιας ΑΚΖ. Η σωστή αξιολόγηση των εγγενών αβεβαιοτήτων παρέχει χρήσιμες πληροφορίες για την αξιοπιστία των αποφάσεων που βασίζονται στην ΑΚΖ και έναν απαραίτητο οδηγό για μελλοντική ελαχιστοποίηση των ανακριβειών. Η επιλογή μιας κατάλληλης τεχνικής βασίζεται σε μεγάλο βαθμό στον τύπο και την έκταση των λεπτομερειών που απαιτούνται από τη συγκεκριμένη μελέτη περίπτωσης (δηλαδή ανάλυση ευαισθησίας, προσομοίωση Monte Carlo, αλυσίδα Markov, πολλαπλή γραμμική παλινδρόμηση, θεωρία ασαφών συνόλων και ασαφούς λογικής κ.λπ.).

Έχουν γίνει αρκετές προσπάθειες να εντοπιστούν και να επισημανθούν διάφορες στατιστικές-στοχαστικές αβεβαιότητες στην ΑΚΖ, καθώς επηρεάζουν όλο και περισσότερο τις σχετικές μεθοδολογίες, βάσεις δεδομένων και λογισμικά. Η μεταπτυχιακή διατριβή περιέχει αναλυτική ΑΚΖ και τεχνικοοικονομική μελέτη επιλεγμένων συστημάτων Ανανεώσιμων Πηγών Ενέργειας: γεωθερμικών σταθμών ηλεκτροπαραγωγής, φωτοβολταϊκά (λεπτών υμενίων και κρυσταλλικά) και θερμικών ηλιακών συλλεκτών (επίπεδου και σωλήνων κενού). Το προηγμένο λογισμικό SimaPro με την ενημερωμένη βάση δεδομένων Ecoinvent χρησιμοποιήθηκαν για την υλοποίηση των μελετών ΑΚΖ, ενώ οι τεχνικοί και οικονομικοί υπολογισμοί πραγματοποιήθηκαν μέσω του RETSCreen.

Chapter 1

Introduction to the methodological approach of the study

*In this Chapter the methodological approach followed throughout the thesis is described in detail. The same evaluation process has been applied to each of the studied renewable energy systems. It comprises two distinct elements: **i.** the environmental part (Life Cycle Assessment and the associated Uncertainty Analysis), and **ii.** the economic part (Life Cycle costing assessment). Each part of the methodology has been implemented through a dedicated software (i.e. SimaPro and RETScreen Expert respectively) which is also presented in detail.*

1.1 Introduction

Between 1973 and 2015, world electricity generation increased from 6131 to 24255 TWh, i.e. 3.95 times. Today, 81.4% of the world primary energy supply originates from fossil fuels (i.e., coal, natural gas and oil), with electricity generation being responsible for more than 40% of global CO_2 emissions. Emissions of greenhouse gases (GHG), such as CO_2 and CH_4, from energy generation have been addressed in numerous studies, which often play a key role in developing GHG mitigation strategies for the energy sector [1], [2].

Newly installed renewable power capacity set new records in 2016, with 161 gigawatts (GW) added, increasing the global total by almost 9% relative to 2015. Solar PV was the star performer in 2016, accounting for around 47% of the total additions, followed by wind power at 34% and hydropower at 15.5%. For the fifth consecutive year, investment in new renewable power capacity (including all hydropower) was roughly double the investment in fossil fuel generating capacity, reaching USD 249.8 billion. The world now adds more renewable power capacity annually than it adds in net new capacity from all fossil fuels combined.

Cost for electricity from solar PV and wind is rapidly falling. Record-breaking tenders for solar PV occurred in Argentina, Chile, India, Jordan, Saudi Arabia and the United Arab Emirates, with bids in some markets below USD 0.03 per kilowatt-hour (kWh). Parallel developments in the wind power sector saw record low bids in several countries, including Chile, India, Mexico and Morocco. Record lows in offshore wind power tenders in Denmark and the Netherlands brought Europe’s industry closer to its goal to produce offshore wind power more cheaply than coal by 2025 [2]–[4].

2016 was the third year in a row where global energy related CO_2 emissions from fossil fuels and industry remained stable despite a 3% growth in the global economy and an increased demand for energy. This can be attributed primarily to the decline in coal consumption, but also to the growth in renewable energy capacity and to improvements in energy efficiency. The decoupling of economic growth and CO_2 emissions is an important first step towards achieving the steep decline in emissions necessary for holding global temperature rise well below 2 degrees Celsius (°C) [5], [6].

The myth that fossil and nuclear power are needed to provide “baseload” electricity supply when the sun isn't shining or the wind isn't blowing has been shown to be false. In 2016, Denmark and Germany successfully managed peaks of 140% and 86.3%, respectively, of electricity generation from renewable sources, and in several countries (e.g. Portugal, Ireland and Cyprus), achieving annual shares of 20-30% electricity from variable renewables without additional storage is becoming feasible. The key lesson for integrating large shares of variable renewable generation is to ensure maximum flexibility in the power system [3], [7].

There has been an upsurge in cities, states, countries and major corporations committing to 100% renewable energy targets because it makes economic and business sense, quite apart from climate, environment and public health benefits. In 2016, 34 additional businesses joined RE100, a global initiative of businesses committed to sourcing their operations with 100% renewable electricity. Throughout 2016, the number of cities across the globe committed to transitioning to 100% renewable energy – in total energy use or in the electricity sector – continued to grow, and some cities and communities already have succeeded in this goal (for example, in more than 100 communities in Japan). Under the Covenant of Mayors for Climate & Energy, more than 7,200 communities with a combined population of 225 million people are committed to reducing emissions 40% by 2030, by increasing energy efficiency and renewable energy deployment. And it is not only corporations and sub-national actors that are looking to go 100% renewable. At the climate conference in Marrakesh, Morocco in November 2016, the leaders of 48 developing nations committed to work towards achieving 100% renewable energy supply in their respective nations [7]–[9].

Life Cycle Assessment (LCA), carbon footprinting and other GHG accounting approaches are commonly used for decision support. In LCA, potential environmental impacts associated with the life cycle of a product and/or service are assessed based on a Life Cycle Inventory (LCI), which includes relevant input/output data and emissions compiled for the system associated with the product/service in question. The comprehensive scope of LCA is useful in avoiding problem shifting from one life cycle phase to another, from one region to another, or from one environmental problem to another [10]. Although a carbon footprint may have more appeal than LCA due to the simplicity of the approach [11], carbon footprints involve only a single indicator and thus this may result in oversimplification. By optimizing the system performance based only on GHG emissions, new environmental burdens may be introduced from other environmental emissions (e.g., NO_x and SO_2). A holistic or system-level perspective is therefore essential in the assessment, and the range of emission types included in a study may critically affect the outcome.

Overall emissions can be categorized into direct emissions (e.g., from the stack of a power plant) and indirect emissions (e.g., related either to upstream provision of fuel, resources, goods, etc. or to downstream management of residues and utilization of by-products). Accounting only for direct emissions from electricity generation and failing to include indirect emissions may result in inaccurate conclusions and lead to decisions that do not provide the intended environmental benefits. Indirect GHG emissions from fossil fuels may represent up to 25% of the overall emissions related to electricity generation; this value is even higher for renewable technologies [12].

Over the past three decades, LCA guidelines (e.g., ISO 14040 [13] and the ILCD handbook [14]) have been developed in an attempt to ensure coherence and comparability among LCA studies. However, these guidelines allow individual researchers to subjectively interpret fundamental methodological aspects (e.g. choice of system boundaries, allocation procedures, and which emissions to include in the assessment). Therefore, a simple statement of compliance accompanying these guidelines is not sufficient to ensure that the results are accurate and robust. Consequently, both LCI data and LCA results can be misused, whether incidentally or intentionally, when the scope of the original LCA study and the requirements of a user do not coincide. To prevent misuse and unjustified decisions, it is thus important that: **i.** methodological choices are described transparently and the scope of the LCA study is narrowly defined and that **ii.** coherent, appropriate choices are made regarding the system boundaries and LCI datasets to reduce the gap between the modeled system and reality. Various approaches exist today among LCA practitioners, but the importance of methodological choices, emission types and contributions from individual life cycle phases has not been critically evaluated in the context of electricity generation. A systematic overview of the consequences of methodological choices and technology performance is needed to provide a transparent and balanced foundation for future LCA modeling of electricity technologies.

LCA is the methodology to be used when comparing the environmental performance (strengths and weaknesses) of different energy technologies, among them renewable systems. The idea behind a life cycle perspective in the context of power generation is that the environmental impacts of electricity are not only due to the power production process itself, but also originate from the production chains of installed components, materials used, energy carriers, and necessary services. Through an LCA analysis, a product is investigated throughout the entire life cycle ("cradle-to-grave"). The main scope of the thesis is to present a holistic evaluation of the energy and environmental profile of three renewable energy technologies: geothermal power plants, photovoltaics and solar thermal collectors. The former technology has been chosen as a major representative of large scale electricity production plants, while photovoltaics can be employed from small scale applications to large power plants. The latter (i.e. solar thermal systems) are mainly focused to residential applications but can play an important role in energy saving schemes as they practically deal with domestic hot water production and can cover significant thermal needs. Various technical variations will be presented for each of the three studied renewable technologies. For the evaluation of each of the renewable energy systems studied in the thesis, the methodological order followed comprises two steps: **i.** LCA and uncertainty analysis (SimaPro) and **ii.** techno-economic assessment (RETScreen). The results of the combined evaluation provide insight on choosing the most appropriate technologies from multiple perspectives including financial and environmental.

This Chapter describes the various methodological aspects of LCA and provides technical details on the two employed software. Chapter 2, contains the detailed description of the technical specifications of the studied renewable systems (i.e. geothermal power plants, photovoltaics and solar thermal collectors). In Chapter 3 the results of the LCA study and the techno-economic assessment of the systems is presented, while Chapter 4 contains the discussion and the concluding remarks.

1.2 Methodological aspects of LCA

The study of environmental impacts of consumer products has a history that dates back to the 1960s and 1970s, when it was recognized that for many products a large share of the environmental impacts is not in the use of the product but in its production, transportation, or disposal. Life Cycle Assessment (LCA) is an established way of measuring total environmental effects of products and services. LCA is a tool for quantifying the environmental performance of products taking into account the complete life cycle, starting from the production and acquisition of raw materials to the final disposal of the products, including material recycling if needed [10], [15]. The most important applications for an LCA [16], are:

– Identification of improvement opportunities through identifying environmental hot spots in the life cycle of a product.
– Analysis of the contribution of the life cycle stages to the overall environmental load, usually with the objective of prioritizing
– Improvements on products or processes.
– Comparison between products for internal or external communication, and as a basis for environmental product declarations.
– The basis for standardized metrics and the identification of Key Performance Indicators used in companies for life cycle management and decision support.

In recent years, life cycle thinking has taken a more prominent role in environmental policy making. Renowned institutions such as the World Resource Institute (WRI), have adopted life cycle thinking and an increasing number of different stakeholders are feeling the pressure to reduce the environmental impact associated with global consumption. As a result, we are witnessing a shift from government-led initiatives towards more private-led initiatives such as the Sustainability Consortium and Product Category Rules (PCR's) developed by trade and governmental organizations. In parallel to these activities the European Commission is working on a standard for environmental footprinting with the ILCD handbook.

LCA provides the quantitative and scientific basis for all these activities. In many cases, LCA feeds the internal and external discussions and communication. Being active in LCA means being able to communicate the environmental impacts of products and business processes.

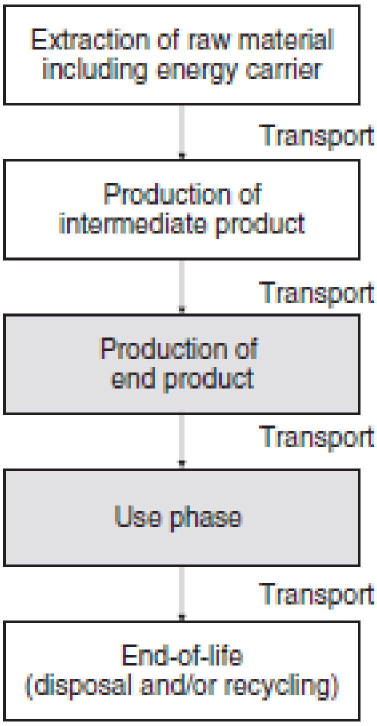


Figure 1: Simplified life cycle route of a product [17].

The first studies, which are now recognized as (partial) LCAs, were already carried out in the 1960s, but it was only in 1990 that SETAC initiated the standardization process that led to the ISO 14040-44 series

[13], [18]. In the introductory part of international standard ISO 14040 serving as a framework, LCA is defined as follows: "*LCA studies the environmental aspects and potential impacts throughout a product's life (i.e. cradle-to-grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences*". This definition limits LCA to the analysis and interpretation of environmental impacts, restricting the method only to the quantification of the ecological aspect of sustainability. The main idea of a Cradle-to-Grave analysis is illustrated in a simplified manner in Figure 1, and it is based on a simplified system study consisting of an extensive linearization of the life cycle of a product.

During the first decade of the 21st century, LCA became part of policy documents and legislation. In 2002, a stronger involvement of multi-sectorial and transversal agents and stakeholders, the United Nations Environment Programme (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC) launched the Life Cycle Initiative, an International Life Cycle Partnership which fosters LC approaches worldwide, aiming to put life cycle thinking into practice and improving the supporting tools through better data and indicators [19]. In 2006, part of the ISO 14040 series of standards was compiled in the form of the new ISO 14040 and ISO 14044 for the application of LCA to products and services [13], [18]. The European Platform on Life Cycle Assessment was established [20], as the EU's knowledge base that responds to business and policy needs for social and environmental assessments through LCA. Later on, the Joint Research Centre released the ILCD Handbook [14]. After 2010, new standards such as ISO 14067 [21] were released to provide guidance for the quantification and reporting of a Product Carbon Footprint (PCF). In 2014, the organizational LCA (OLCA) was internationally standardized with the release of the ISO 14072 [22] while, one year later, the Life Cycle Initiative promoted a guideline for public use (Guidance on organizational LCA), in 2015 [23]. In parallel, the management system ISO 14001 integrated life cycle perspective without requiring a detailed life cycle assessment [24].

The current regulatory framework for LCA is defined by ISO 14040 [13] and ISO 14044 [18]. ISO 14040 considers the principles and framework for an LCA, while ISO 14044 specifies the requirements and guidelines for carrying out an LCA study. The ISO standards are defined in a rather vague language, which makes it difficult to assess whether an LCA has been made according to the standard. Unlike the 14000 standard, it is not possible to get an official accreditation stating that an LCA, LCA methodology, or LCA software has been made according to the ISO standard. Therefore, no software developer can claim that LCAs made with a certain software tool automatically conform to the ISO standards. For example, ISO 14044 does not allow weighting across impact categories for public comparisons between products. However, weighting is explicitly allowed for other applications, and thus SimaPro does support weighting. This means that it is on the user responsibility to use weighting in a proper way. A similar example can be made for issues such as allocation rules, system boundaries etc.

The most important consequence of aiming to adhere to an ISO standard is the need for careful documentation of the goal and scope and interpretation issues. LCA practitioners can perform their LCA in a number of different ways, as long as they carefully document their actions. A second consequence of adhering to the standards is that they might need to include a peer review by independent experts. It is completely up to the LCA practitioners to conform to these standards or to (deliberately) deviate. In case of deviation, it is clear they cannot claim that the LCA has been made according to the international standards, and it will be more difficult to convince others of the reliability of the results.

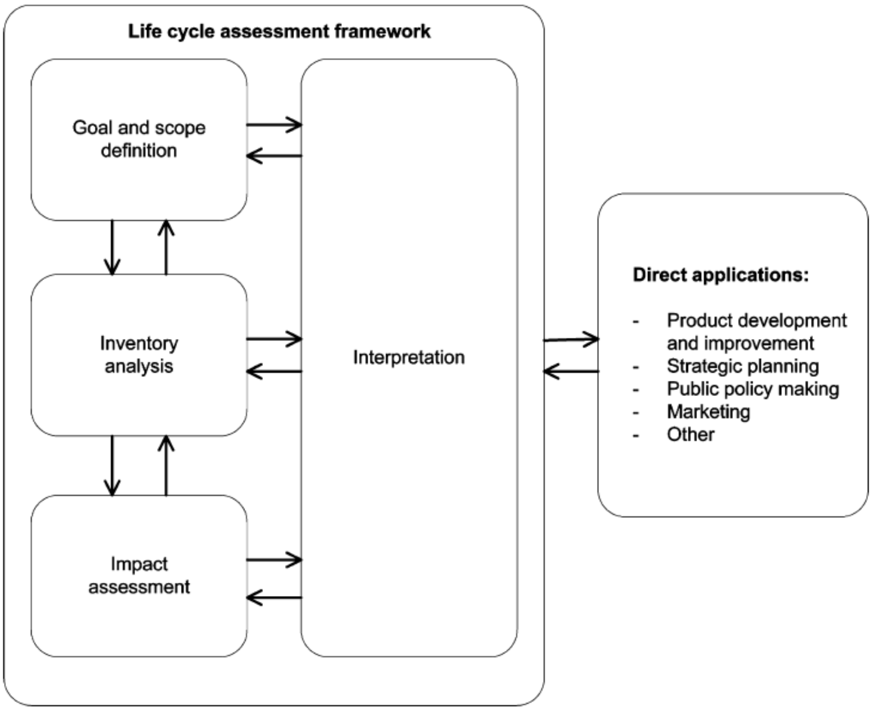


Figure 2: Typical methodological stages of a Life Cycle Assessment [13].

An LCA study is generally carried out by iterating four distinct phases (see Figure 2):

Step 1. Goal and scope definition. During the first step the goal and scope of the study are defined as well as the selection of the functional unit (FU) and the system's boundaries. The meaningful selection and definition of system boundaries and system's analysis are important tasks within every LCA. The functional unit relates to the product function rather than a particular physical quantity and is typically time-bound.

Step 2. Inventory analysis (LCI). In the second step, a life cycle inventory analysis, of relevant energy and material inputs and environmental releases, is made up identifying and quantifying inputs and outputs at every stage of the life cycle. In addition the characteristics of data collection and calculation procedures are defined.

Step 3. Impact assessment (LCIA). This is the phase of LCA, with particular respect to sustainability assessment. During the impact assessment step, the elaboration of which has deliberately been left open by ISO guidelines, the potential environmental impacts associated with identified inputs and releases are categorized in different midpoint and endpoint impact categories (see Figure 3).

LCIA translates emissions and resource extractions into a limited number of environmental impact scores by means of so-called characterization factors. There are two mainstream ways to derive these factors, i.e. at midpoint level and at endpoint level. Midpoint indicators focus on single environmental problems, for example climate change or acidification. Endpoint indicators show the environmental impact on three higher aggregation levels, being the 1) effect on human health, 2) biodiversity and 3) resource scarcity [25].

Step 4. Interpretation of results. In the last step, the results of the inventory analysis and the impact assessment should be interpreted and combined, to help decision makers make a more informative and sound decision. Furthermore, a sensitivity analysis is performed to validate the consistency of the results.

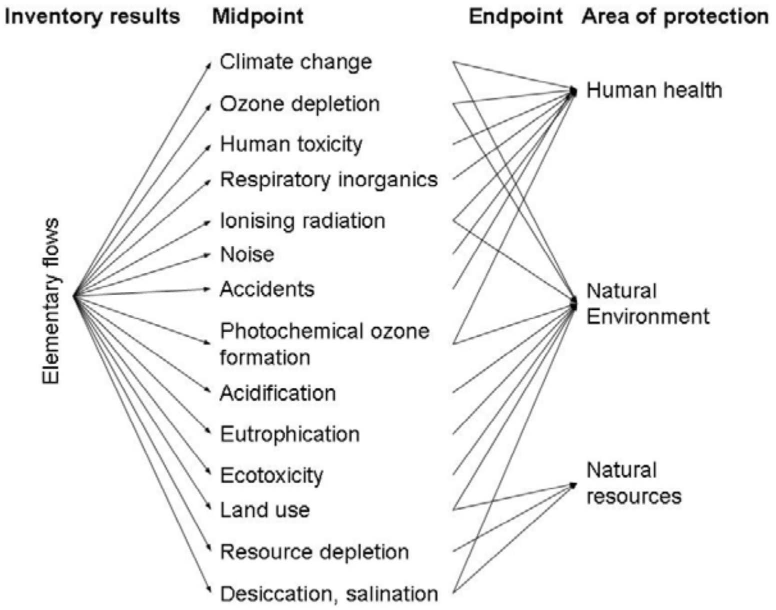


Figure 3: Midpoint and endpoint impact categories characterization [16].

There is a number of impact assessment methods, which are used to calculate environmental impacts. In Table 1 the most representative LCIA methods are depicted.

Table 1: Availability of impact categories per method. ✓ represents that the impact category is contained in the corresponding method and – that it is not.

METHODS	Acidification	Climate change	Resource depletion	Ecotoxicity	Energy Use	Eutrophication	Human toxicity	Ionising Radiation	Land use	Odour	Ozone layer depletion	Particulate matter/ Respiratory inorganics	Photochemical oxidation
CML (baseline)	✓	✓	✓	✓	-	✓	✓	-	-	-	✓	-	✓
CML (non baseline)	✓	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	-	✓
Cumulative Energy Demand	-	-	-	-	✓	-	-	-	-	-	-	-	-
eco-indicator 99 (E)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	-
eco-indicator 99 (H)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	-
eco-indicator 99 (I)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	-
Eco-Scarcity 2006	-	-	✓	-	-	-	-	-	-	-	-	-	-
ILCD 2011, endpoint	✓	✓	-	-	-	✓	✓	✓	✓	-	✓	✓	✓
ILCD 2011, midpoint	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Endpoint (E)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Endpoint (H)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Endpoint (I)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Midpoint (E)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Midpoint (H)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Midpoint (I)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
TRACI 2.1	✓	✓	✓	✓	-	✓	✓	-	-	-	✓	✓	✓
USEtox	-	-	-	✓	-	-	✓	-	-	-	-	-	-

ReCiPe 2016 is the successor of the Eco-indicator and CML-IA. The purpose at the beginning of its development was to integrate the "problem oriented approach" of CML-IA and the "damage oriented approach" of Eco-indicator. The "problem oriented approach" defines the impact categories at a midpoint level. The uncertainty of the results at this point is relatively low. The drawback of this solution is that it leads to many different impact categories which makes the drawing of conclusions with the obtained results complex. On the other hand, the damage oriented approach of Eco-indicator results in only three impact categories, which makes the interpretation of the results easier. However, the uncertainty in the results is higher. ReCiPe implements both strategies and has both midpoint (problem oriented) and endpoint (damage oriented) impact categories [16].

Midpoint level indicators are direct measurements of the impacts arising from the considered phenomena. A total of 18 physical quantities were computed from the LCI results, providing a quantitative description of the single drivers of the environmental impact associated with the study. These include soil acidification (measured in kg SO_2eq), the emission of GHGs (measured in kg CO_2eq), ozone depletion (measured in kg CFC11 eq) and so forth. The default hierarchist version of ReCiPe 2016 (Midpoint) has been used in this study. Figure 4 provides an overview of the structure of ReCiPe 2016 [26].

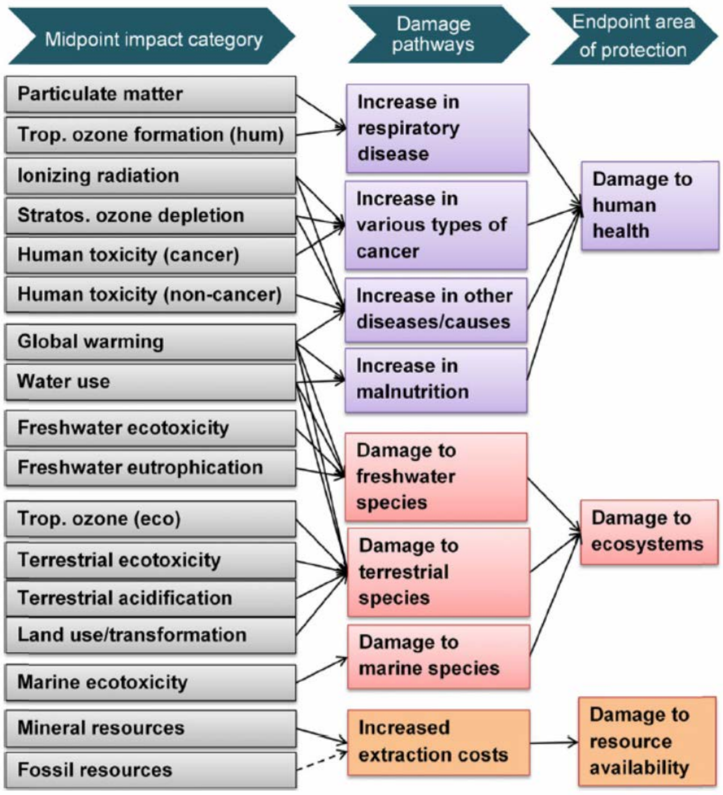


Figure 4: Overview of the impact categories that are covered in the ReCiPe 2016 method and their relation to the areas of protection. The dotted line means there is no constant mid-to-endpoint factor for fossil resources.

1.2.1 Goal and Scope Definition

An LCA models a product, service, or system life cycle. What is important to realize is that a model is a simplification of a complex reality and as with all simplifications this means that the reality will be distorted in some way. The challenge for an LCA practitioner is to develop the model in such a way that the simplifications and distortions do not influence the results too much.

The best way to deal with this problem is to carefully define the goal and scope of the LCA study. In the goal and scope the most important (often subjective) choices are described such as:

- The reason for executing the LCA (the questions which needs to be answered).
- A precise definition of the product, its life cycle and the function it fulfills.
- A definition of the functional unit (especially when products are to be compared).
- A description of the system boundaries and the way co-production will be dealt with.

- Data and data quality requirements, assumptions and limitations.
- The requirements regarding the LCIA procedure, and the subsequent interpretation to be used.
- The intended audiences and the way the results will be communicated.
- If applicable, the way a peer review will be made.
- The type and format of the report required for the study.

The goal and scope definition helps the user to ensure that they have performed the LCA consistently. The goal and scope is not set in stone and can be adjusted if, during the next steps of the LCA, the initial choices reveal themselves not to be optimal or practical. Any adjustments to the goal and scope should be described.

Defining the goal

In the ISO standards there are some specific requirements for the goal definition. The application and intended audiences shall be described unambiguously. This is important since a study that aims to provide data that will be used internally can be structured differently compared to a study that aims to make comparisons between two products public. For example, in the latter case ISO states that weighting may not be used in impact assessment and that a peer review process is necessary. It is therefore important to communicate with stakeholders during the execution of the study. The reasons for carrying out the study should be clearly described. Is the commissioner or practitioner trying to prove something or is the commissioner intending to provide information only, etc. Some LCA studies serve more than one purpose. The results may be used both internally and externally. In such a case the implications of the dual purpose should be clearly described. For example, it could be that different impact assessment methods are used for the internal or external versions of the study.

Defining the Scope

The scope of the study describes the most important methodological choices, assumptions, and limitations as described in the sections below. An LCA is an iterative process, thus the term 'initial' is added to most of the sections below. This means that one may start with a set of choices and requirements that may be adapted later when more information becomes available.

Functional unit and reference flow

A particularly important issue in product comparisons is the functional unit or comparison basis. In many cases, one cannot simply compare product A and B, as they may have different performance characteristics. For example, a milk carton can be used only once, while a returnable milk bottle can be used ten or more times. If the purpose of the LCA is to compare milk packaging systems, one cannot compare one milk carton with one bottle. A much better approach is to compare two ways of packaging and delivering 1000 liters of milk. In that case one would compare 1000 milk cartons with about 100 bottles and 900 washings (assuming 9 return trips for each bottle). Defining a functional unit can be quite difficult since it is not always obvious what function a product fulfills. For example, what is the exact function of an ice cream, a car-sharing system, or a holiday?

Initial system boundaries

Product systems tend to be interrelated in a complex way. For example, trucks are used in an LCA on milk cartons. Trucks are also products with a life cycle. To produce a truck steel is needed; to produce steel, coal is needed; to produce coal, trucks are needed; etc. It becomes apparent that not all inputs and outputs in a product system can be traced and boundaries around the system needs to be defined. By excluding certain parts, which means leaving them outside the system boundaries, the results may be affected.

It is helpful to draw a diagram of the system and to identify the boundaries in this diagram. Important considerations in this area are:

- Will the production and disposal of capital goods be included? For example, the production and disposal of trucks, injection molding machines, etc. As with an energy analysis one can distinguish three orders:
  1. First order: only the production of materials and transport are included (this is rarely used in LCA).
  2. Second order: All processes during the life cycle are included but the capital goods are left out.
  3. Third order: All processes including capital goods are included. Usually the capital goods are only modeled in a first order mode. So, only the production of the materials needed to produce the capital goods are included.
- What is the boundary with nature? For example, in an LCA on paper, it is important to decide if the growing of a tree is also included. If it is, one can include the CO_2 uptake and the land use effect. In agricultural systems it is important to decide if agricultural areas are seen as a part of nature or as a production system (technosphere). If this is seen as nature, all pesticides that are applied are to be seen as an emission. If agricultural areas are seen as an economic system, one can exclude the pesticides that remain in the area, and only include the pesticides that leach out, evaporate, or are accidentally sprayed outside the field.

1.2.2 Inventory analysis

The most demanding task in performing an LCA is data collection. Although a lot of secondary data is available in SimaPro, the user will usually find that at least a few processes or materials are not available. Depending on the available time and budget, there are a number of strategies to collect missing data. It is useful to distinguish between two types of data:

1. Foreground data, which refer to specific data that someone needs to acquire for modeling the system. Typically, it is data that describes a particular product system or a specialized production system.
2. Background data, which are data for the production of generic materials, energy, transport and waste management. This data can be found in SimaPro databases and from literature.

The distinction between these data types is not sharp and depends on the subject of the LCA. If an LCA on dishwashers is the case, the truck that is used to deliver the dishwasher will be probably considered as background data. The truck is probably not specifically made for transporting dishwashers, and there is no need to collect other data than the transport distance and the load efficiency. The inputs and outputs of the truck's life cycle can be delivered from the SimaPro databases.

However, if an LCA of trucks is performed a standard truck cannot be used, and the inputs and outputs that are specific to the trucks will have to be collected as foreground data.

1.2.3 Impact Assessment

Most LCA experts do not develop impact assessment methodologies. They prefer to select one that has already been published. As with the inventory stage, also in impact assessment, the Goal and Scope definition remains the most important source of guidance for the selection of the method and the impact categories. The most important choice an LCA practitioner will have to make is the desired level of integration of the results. This usually depends on how the audience is addressed and the ability of the audience to understand detailed results. Figure 5 presents a schematic overview of some of the possibilities.

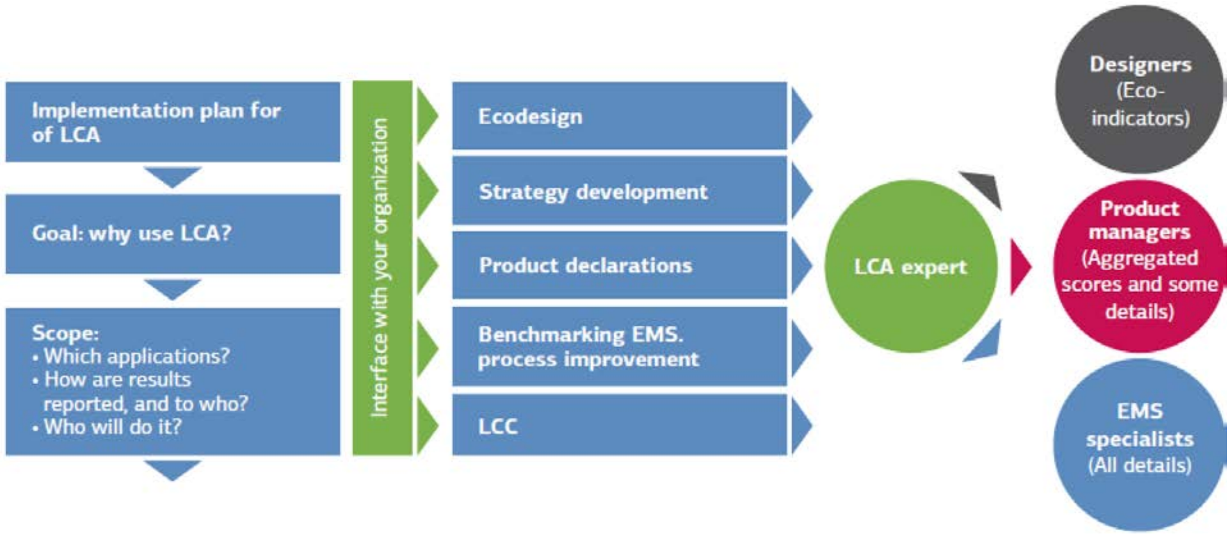


Figure 5: The choice of the impact assessment method depends largely on the audience addressed.

1.2.4 Interpretation

The last of the four steps in LCA is interpretation. The ISO 14044 standard describes a number of checks to test whether conclusions are adequately supported by the data and by the procedures used.

1.3 Variation in LCA methods

An LCA study is typically used to quantify major potential environmental impacts related to the product or service in question. LCAs are often applied as decision support tools for selection between different alternatives providing the same product or service. An LCA is quantified by the concept of a "functional unit" that defines the product or service. The functional unit thereby ensures comparability among the alternative scenarios.

An environmental LCA (eLCA) is the conventional type of LCA that assesses environmental impacts such as material, energy and waste flows of a product from cradle to grave. ELCA differs from assessment tools that focus on one environmental aspect such as "Carbon Footprint" because its comprehensive environmental scope covers greenhouse gases, water emissions, ecosystem quality, natural resources and human health [11].

Current ISO standards provide guidelines for carrying out an LCA study, but allow freedom for interpretation of key methodological issues [11]. The data acquisition approach itself might significantly affect the results, despite the fact that data should be collected from published sources and should be appropriate to the relevant technologies and processes and that the data selection criteria should be clearly stated [18]. Data collection is often simplified by applying cut-off criteria to exclude less relevant processes from the system. This simplification leads, however, to an overall underestimation of the impact [27].

The most established methods in LCAs are process LCA and IO-LCA (input-output LCA). The process LCA is a traditional way of analyzing product life cycle emissions. The principle of the process LCA is to calculate GHGs of each process of the product life cycle individually, in order to form a chain of the processes that covers the whole life cycle. Each process analysis is conducted using process-specific primary (i.e., material and energy flows in the manufacturing process) and secondary data (i.e., amount of GHG emissions per manufacturing process), which lead into very accurate results of the modeling. However, there is nearly an indefinite amount of single processes in a product life cycle, and including all of them in the modeling is practically impossible. This problematic characteristic of process LCA modeling is known as a truncation problem. A process LCA practitioner has to define a border that separates the processes included in the modeling from those that are left out of it. Thus, it is probable that significant processes are also left out of the modeling along with the insignificant ones. Process LCAs are also very laborious and require a large amount of data since secondary data has to be acquired separately for each process [12], [28].

Another widely used LCA method, IO-LCA, converts monetary costs into environmental effects, often according to national input-output matrices. There are a few different IO-LCA models for different economies, but also more and more prevalent are the so-called multi-region IO models. The truncation problem is not an issue in IO-LCAs since every sector of a national economy is included in a model and the number of included sectorial transactions is indefinite. Additionally, data requirements are significantly different between IO-LCAs and process LCAs. IO-LCAs require monetary transaction data, whereas process LCAs requires detailed data on the material and energy flows of all processes in a production process chain. All required secondary data in the IO-LCAs lie within the IO-LCA matrices, while process LCAs require case-specific secondary data [12], [28].

IO-LCA suffers from the aggregation problem, since even in the most disaggregated models several industries as well as all the products of a specific industry are aggregated into each IO sector. The industry sectors in IO-LCAs thus represent the averages of several sectors of an economy, making the method not applicable in modeling specific products or comparing similar products within one industry. Additionally, IO-LCA models in general appear as a “black box” to the LCA practitioner. Thus, examining characteristics of a specific process within an IO-LCA model is usually impossible. Partly related to the same issue, two other well recognized problems of IO-LCAs are homogeneity and proportionality assumptions. Of these, the homogeneity assumption means that sector outputs are assumed to be proportional to price, regardless of the variation of products inside a sector. The proportionality assumption means that the inputs to a sector are assumed to be linearly proportional to its output. A hybrid LCA method combines the process LCA and IO-LCA into a single model. The method combines the advantages of the two traditional LCAs and avoids known problems. Using hybrid LCA avoids the truncation problem of the process LCA and relieves the issue of the aggregation problem inherent in IO-LCA modeling. One of the most popular applications of hybrid LCA is tiered hybrid LCA, which consists of process LCA for the emissions of production processes, whereas the indirect emissions are modeled with IO-LCA. As a result, the model is accurate since process data is used for the most important processes (avoiding the aggregation problem) and IO-LCA covers the supply chains (avoiding the truncation problem) [12], [28].

1.4 Life Cycle Costing

Life Cycle Costing (LCC) is a valuable financial approach for evaluating and comparing different designs in terms of initial cost increases against operational cost benefits with a long-term perspective. The key incentive for applying a LCC analysis is to increase the possibility of cost reductions for the operational phase, even if an additional increase in the initial investment is necessary. By applying a LCC perspective in the early design phase, decision makers are able to obtain a deeper understanding of costs during the life cycle for different design strategies. Buildings for example are a long-term investment associated with environmental impacts over a long duration. Fundamental environmental responsibility aims for a long-term view and with that an understanding that initial design decisions have a significant impact over a building's life span.

LCC is defined as "*a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors, both in terms of initial costs and future operational costs*" [29]. It is important to notice that traditional LCC is purely economical and does not take into account environmental aspects. Earlier development has focused on developing LCC methodology for the construction industry and placing LCC in an environmental context [28].

Essential decisions and activities to undertake an LCC analysis are:

1. Defining alternative strategies to be evaluated: specifying their functional and technical requirements.
2. Identifying relevant economic criteria: discount rate, analysis period, escalation rates, component replacement frequency and maintenance frequency.
3. Obtaining and grouping of significant costs: in what phases different costs occur and what cost category.
4. Performing a risk assessment: a systematic sensitivity approach to reduce the overall uncertainty.

Typical LCC assessments compare durable products with a purchase price that only makes up a small part of the life cycle cost. Other costs over the lifetime of the product are discounted to current values [30], [31]. Although discounting is a generally accepted practice, the applied discount rate is often controversial. In business circles high discount rates are applied such that current financial flows have a higher weight, but from a societal or environmental point of view, low discount rates are preferred to avoid the fact that current activities impose large costs on future generations [32]–[34].

In order to deal with financial, environmental and social concerns, four LCC types have been introduced: financial LCC (fLCC), Environmental LCC (eLCC), full environmental LCC (feLCC) and societal LCC (sLCC) [35] which can be used either in combination or mostly as stand-alone methodologies. Conventional LCC assessments that only focus on private investments from one actor are categorized as fLCC [36] and usually consider the economic lifetime matters [37], [38]. On the other hand, an eLCC builds upon data of fLCC and extends it to life cycle costs borne by other actors considering the full life cycle of a product [39]. The focus remains, however, on real cash flows that are internalized or expected to be internalized. There is no conversion from environmental emissions to monetary measures. In contrast with fLCC, eLCC uses a steady state cost model in which all variables are kept constant over time and moreover, discounting is not applied [17], [37] The feLCC is not a commonly accepted sustainability assessment tool, which extends eLCC with monetized, non-internalized environmental costs that can be identified by an environmental assessment method such as eLCA. In sLCC, all costs borne by anyone in society, today or in the future, associated with the life cycle of a product, are taken into account translated into monetized measures [33], [40].

When combining the LCA tools with an eLCC, we should take into account that the used metric is different, as an LCC expresses all units in monetary terms whereas an LCA denominates flows by physical quantities. Additionally, in LCA, all environmental impacts of upstream processes have to be gathered to calculate the total environmental impacts of a particular product, while in LCC assessments the price of a given process input can serve as a measure for the aggregated upstream costs, so detailed costs of upstream activities need not to be known [37].

The LCC methodology can (and must) be criticized. A LCC analysis is based on the estimation and valuation of uncertain future events and outcomes. Hence, subjective factors are involved in the process and will affect the results]. Even though LCC is not recognized as theoretically accurate, the LCC methodology presents many benefits. For example, the analysis provides an indication of what strategic options and aspects to seriously consider, the results of the LCC analysis are presented with a common unit (currency), an LCC analysis processes and simplifies a huge amount of information and provides a valuable life cycle perspective to the different alternative options. From a user and consumer perspective, it is valuable to link environmental issues with financial outcomes in a strategic decision making context. However, it is important to note that the LCC methodology is developed only for financial analysis, whilst LCA assessment focuses on the environmental impact.

1.5 Uncertainty in LCA

As outlined by ISO 14040 series standards, any life cycle assessment requires a number of phases beginning with goal and scope definition, inventory analysis, impact assessment, and interpretation. Each of these phases, along with their associated databases and models, has significant associated uncertainties. A general motivation for quantifying uncertainties is to increase the transparency of LCA data and results. Uncertainty is undeniably present in many aspects of analysis, and treating it explicitly will aid in several ways. A variety of specific uncertainty sources are listed below.

Database uncertainty. When defined as the error introduced on the outcome due to variability on measurements, lack of data, and deficient model assumptions, uncertainty has been a subject of intensive study in LCA during recent years [41], being an essential tool to improve LCA reliability and usefulness for practitioners [42], [43]. Normally, input output uncertainty data cannot be derived from available information, as there is commonly one source of information which gives average values without any data about uncertainty [44].

Model uncertainty. The models relating design decisions to impacts may have uncertainties that could affect the quality of the assessment outputs. Simplified models may not capture exact cause-and-effect mechanisms, or data regression may have the wrong functional form. There may be unknown interactions among model parameters. This category can also more generally include lack of knowledge about the functioning of the system being studied. The combined use of Economic Input/Output Life Cycle Assessment (EIO-LCA) techniques with process-based LCA has been proposed to mitigate this uncertainty [45]. However, such approaches do not address aleatory uncertainty associated with stochastic variables such as discount (interest) rates for future economic, social, or environmental costs or impacts.

Statistical/measurement error. Estimating distributions of properties from a limited set of sample data creates statistical variability. The sample data may also have measurement errors, or the standards used to collect and quantify the data may not be known.

Uncertainty analysis focuses in the extent of uncertainties produced in model outputs due to the existed uncertainties in input values. One of the several methods that propagate uncertainties is Monte Carlo simulation. This method makes use of an algorithm capable of producing a series of random numbers, within the uncertainty value of every input and output taken into account in the scenarios created, for which it assumes a lognormal distribution, with a confidence interval of 95%. The ecoinvent LCA database includes quantitative uncertainty values for parameters in many of its processes.

In this study, a Monte Carlo analysis was selected as the statistical method and was performed using SimaPro 8.5 software (5000 runs) for each scenario and impact category.

1.6 Software and databases: SimaPro and ecoinvent

In order to evaluate the environmental and economic performance of systems specific and dedicated software and datasets have been used. Thus, the environmental impacts have been assessed and quantified through an LCA study implemented via SimaPro 8.5 [46] (incorporating the EcoInvent 3.4 database), while the evaluation of the economic and energy impacts associated with the systems has been realized through RETScreen Expert [47]. In the following paragraphs the detailed characteristics of both software are presented.

SimaPro is the leading LCA software package, with a 25-year reputation in industry and academia in more than 80 countries. It is an accurate and science-based tool that provides the highest level of transparency of all LCA packages currently available. SimaPro allows the control of entire supply networks and provides total insight into databases and unit processes, giving the user full ownership of their choices and assumptions. It is essential for high quality research and it is also necessary for educating LCA practitioners who understand the conceptual basis of what they are doing, and don't just push the buttons they were taught to push. SimaPro allows the effective application of LCA expertise, empower solid decision-making, change products' life cycles for the better, and improve company's positive impact. SimaPro has been designed to be a source of science-based information, providing full transparency and avoiding black-box processes.

SimaPro is a professional tool to collect, analyse and monitor the sustainability performance data of products and services. The software can be used for a variety of applications, such as sustainability reporting, carbon and water footprinting, product design, generating environmental product declarations and determining key performance indicators. With SimaPro, the user can: **i.** easily model and analyse complex life cycles in a systematic and transparent way, **ii.** measure the environmental impact of the products and services across all life cycle stages, **iii.** identify the hotspots in every link of the supply chain, from extraction of raw materials to manufacturing, distribution, use, and disposal.

The Swiss Centre for Life Cycle Inventories (the ecoinvent Centre) has the mission to promote the use and good practice of life cycle inventory analysis through supplying life cycle inventory (LCI) data to support assessment of the environmental and socio-economic impact of decisions. The strategic objective is to provide the most relevant, reliable, transparent and accessible LCI data for users worldwide.

The ecoinvent database comprises LCI data covering all economic activities. Each activity dataset describes an activity at a unit process level. The complete list of all names of datasets, elementary exchanges, and of all regional codes is available at www.ecoinvent.org. Consistent and coherent LCI datasets for different human activities make it easier to perform LCA studies, and increase the credibility and acceptance of the LCA results. The assured quality of the life cycle data and the user-friendly access to the database are prerequisites to establish LCA as a reliable tool for environmental assessment that will support an integrated product policy. Data quality is maintained by a rigorous validation and review system.

The ecoinvent LCI datasets are intended as background data for LCA studies where problem- and case-specific foreground data are supplied by the LCA practitioner. The LCI and life cycle impact assessment (LCIA) results of ecoinvent datasets, may be used for comparative assessments with the aim to identify environmentally preferable goods or services, but should not be used without considering the relevance and completeness of the data for the specific assessment. The ecoinvent datasets may also be useful as background datasets for studies in material flow accounting and general equilibrium modelling. The ecoinvent Centre is interested in a dialogue with such user groups, to improve the usability of the datasets in such contexts outside the narrower LCA field.

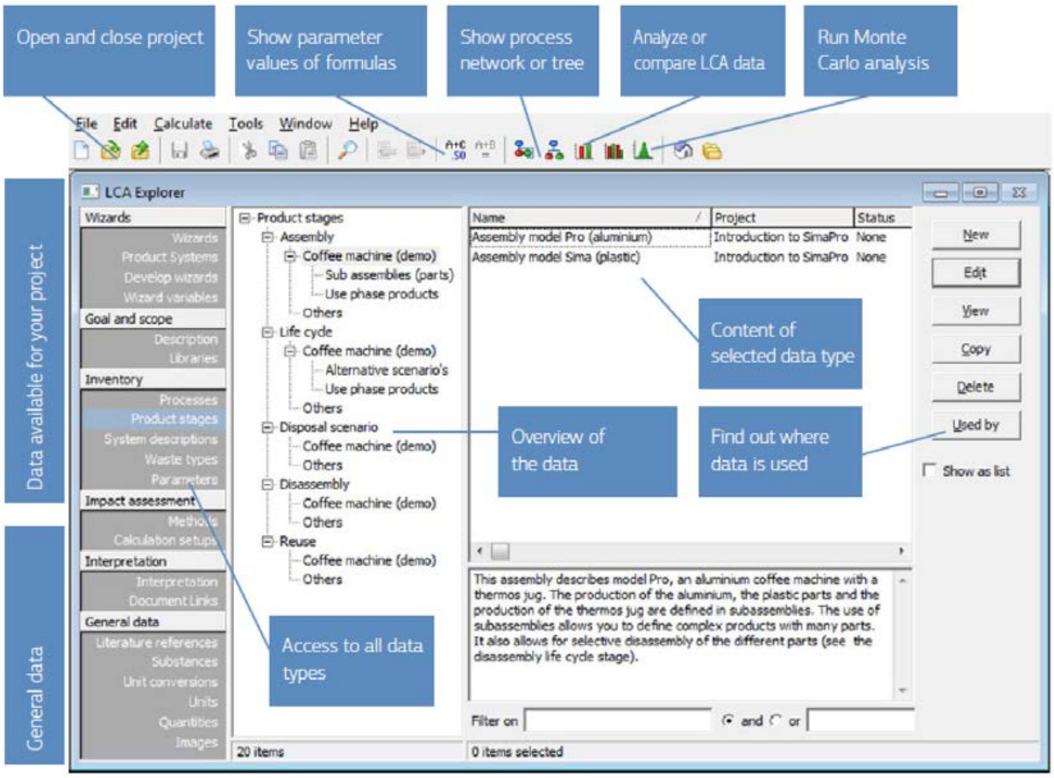


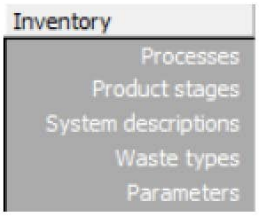
Figure 6: Overview of the LCA Explorer on the left-hand side of the screen.

1.6.1 SimaPro

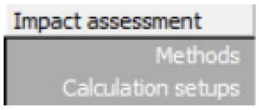
One of the most helpful elements in SimaPro is the LCA Explorer (see Figure 6**Error! Reference source not found.**). It is structured as a checklist for the realization LCA process, as data are entered or edited in the order defined in this list. However, LCA is an iterative process, which means the user needs to step back and re-evaluate the earlier actions a few times. Initial calculations on a model filled with rough data can show which parts of the life cycle or which processes seem to be the most relevant, and thus need further attention. After a few hours of editing the database, the user can check if all results are reasonable and justifiable. If not, some mistakes may have been made or the data supplied may contain errors. This means that the user has to go through the Goal and scope, Inventory, and Impact assessment steps in an iterative way many times.

Describe Goal and Scope. Under description, a number of text fields will be found. These provide the structure for describing the goal and scope. Libraries are used in SimaPro as resources where standard data and standard impact assessment methodologies are stored. The user can select which libraries are considered to be in line with the requirements of the study.

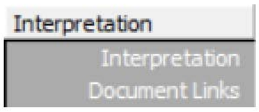
Inventory. This section provides access to processes and product stages; the two main data types in SimaPro. System descriptions are used as additional documentation in some processes. Waste types are labels used by SimaPro when handling materials in waste scenarios.



Impact assessment. In the calculation setup section one can define which life cycles, processes and assemblies need to be repeatedly analyzed and compared. The benefit of using a calculation setup is that all life cycles or assemblies always appear in the same order, with the same colors and the same scale.

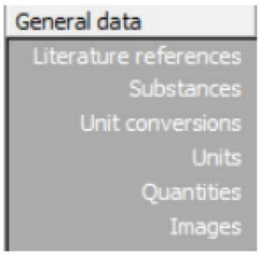


Interpretation. As the end of the project approaches, it will be time to draw the conclusions and make a number of checks. The text fields under interpretation act as a guide that help check which issues need to be addressed.



General data. The other data types like scripts and general data are not frequently edited during the LCA study, but contain useful supporting tables, like:

- Literature references that can link in the process records.
- Substance names: SimaPro holds one central table in which all substance names are stored.
- Unit conversions as they are used in wizards.
- Units and Quantities; these are used in other parts of SimaPro.



1.7 Software and databases: RETSCreen Expert

The RETScreen Clean Energy Management Software (usually shortened to RETScreen) is a software package developed by the Government of Canada [47]. RETScreen Expert is the current version and allows for the comprehensive identification, assessment and optimization of the technical and financial viability of potential renewable energy, cogeneration and energy efficiency projects; as well as the measurement and verification of the actual performance of facilities and the identification of energy savings/production opportunities.

"Viewer mode" in RETScreen Expert is free and permits access to all of the functionality of the software. Unlike past versions of RETScreen, however, a new "Professional mode" (which allows users to save, print, etc.) is now available on an annual subscription basis.

RETScreen empowers professionals and decision-makers to rapidly identify, assess and optimize the technical and financial viability of potential clean energy projects. This decision intelligence software platform also allows managers to easily measure and verify the actual performance of their facilities and helps find additional energy savings/production opportunities.

RETScreen offers a five step standard analysis, including energy analysis, cost analysis, emission analysis, financial analysis, and sensitivity/risk analysis. The technologies included in RETScreen's project models are all-inclusive, and include both traditional and non-traditional sources of clean energy as well as conventional energy sources and technologies. A sampling of these project models include: energy efficiency (from large industrial facilities to individual houses), heating and cooling (e.g., biomass, heat pumps, and solar air/water heating), power (including renewables like solar, wind, wave, hydro, geothermal, etc. but also conventional sources such as gas/steam turbines and reciprocating engines), and combined heat and power (or cogeneration). Fully integrated into these analytical tools are benchmark, product, project, hydrology and climate databases (the latter with 6,700 ground-station locations plus NASA satellite data covering the entire surface of the planet), as well as links to worldwide energy resource maps. And, to help the user to rapidly commence the analysis, RETScreen has built in an extensive database of generic clean energy project templates.

RETScreen Expert (see Figure 7) comprises several sub-elements and entails analysis capabilities covering an entire project life cycle:

Benchmark Analysis allows the user to establish reference climate conditions at a facility site for any location on earth and compare the energy performance of various types of reference (benchmark) facilities with the estimated (modeled) or measured (actual) annual energy consumption of a facility. Energy benchmarking allows designers, facility operators, managers and senior decision-makers to quickly gauge a facility's energy performance, i.e., expected energy consumption or production versus reference facilities, as well as scope for improvements.

Feasibility Analysis permits decision-makers to conduct a five step standard analysis, including energy analysis, cost analysis, emission analysis, financial analysis, and sensitivity/risk analysis. Fully integrated into this five-step analysis are benchmark, product, project, hydrology and climate databases, as well as links to worldwide energy resource maps. Also built in is an extensive database of generic clean energy project templates as well as specific case studies.

Performance Analysis allows a user to monitor, analyze, and report key energy performance data to facility operators, managers and senior decision-makers, including a facility's actual energy performance versus predicted performance. The Performance Analysis module integrates near real-time satellite-derived weather data from NASA for the entire surface of the planet and is connected to the Green Button Standard.

Portfolio Analysis allows a user to manage energy across a large number of facilities, spanning multiple energy efficiency measures in a single residential property to a portfolio comprising thousands of buildings, factories and power plants in multiple locations. Within the software, a user can create a new portfolio or open an existing file. The "My portfolio" database file is made up of individual facilities analyzed with RETScreen. Additional facilities can easily be added to the portfolio database. Sub-portfolios can be created to allow for comparison across different facility types and geographic regions, and a mapping tool helps the user visualize assets across the globe.

With a populated database, the user can enable a portfolio-wide analysis dashboard. The dashboard can be configured to include the results of benchmark, feasibility and performance analysis for each individual facility in the portfolio. The dashboard allows the user to consolidate results to readily track energy consumption and/or production, as well as costs and greenhouse gas emissions, all of which can be sorted by facility type, fuel type, country, etc. These results can then be used to report key metrics to various stakeholders.

Figure 7: RETScreen Expert initial page.

Virtual Energy Analyzer rapidly determines the energy production and savings potential for any location in the world employing a five-star benchmark ranking system and without requiring a site visit. The user can start a new project using the Virtual energy analyzer by clicking on the map icon on the Open tab on the File worksheet or in the ribbon of the Location worksheet. By selecting the facility information and location, the software can rapidly determine the energy production and savings potential for any location in the world employing a five-star benchmark ranking system, and without requiring an actual site visit. The Virtual Energy Analyzer's comprehensive database of Facility Archetypes allows a user to quickly and inexpensively start a pre-feasibility study or energy audit for a facility. Archetypes are available for a full complement of facility types, including power generation, industrial, commercial/institutional, residential and agricultural, while individual measures can also be selected.

Chapter 2

Description of the studied Renewable Energy Systems

*In this Chapter the three studied renewable energy technologies (**i.** geothermal plants, **ii.** photovoltaics and **iii.** solar thermal collectors) are presented in detail and their technical characteristics and specifications are discussed.*

2.1 Introduction

Renewable energy sources are considered to be those that are primary, clean, low risk, and inexhaustible. Renewable energy sources include biomass, hydropower, (shallow and deep) geothermal, solar, wind and marine energies [4], [7]. Sustainable development requires methods and tools to measure and compare the environmental impacts of human activities for various products. In order to understand where net savings in GHG emissions can be accomplished and the magnitude of the relevant opportunities, renewable energy systems should be analyzed and compared with the energy systems they would replace. The LCA methodology has been widely used to study the environmental burdens of energy produced from various renewable and non-renewable sources [48], [49]. Depending on the scope of the LCA study, life stages of energy production systems may include all or part of: **i.** fuel production (i.e., to also account for the non-consumable portion of the produced fuel) and transportation to the plant, **ii.** facility construction, **iii.** facility operation and maintenance, and **iv.** dismantling.

In this chapter we present the technical details for the three studied renewable energy systems: **i.** geothermal power plants, **ii.** photovoltaics and **iii.** solar thermal collectors.

2.2 Geothermal technologies

One of the biggest limitations of renewable technologies, especially wind power and solar devices, is the intermittent nature of the resources they use. This leads to variable power output, a relatively low capacity factor, and a higher economic life cycle cost per kWh [50]. In this context, the exploitation of geothermal resources is advantageous [3]. Geothermal technologies are characterized by their reliability, high capacity factor (frequently over 90% [51]), and constant base-load power [52], thus overcoming the key restriction of intermittent renewable technologies. These factors make conventional geothermal technology one of the cheapest means of producing electricity, with a price of 0.04-0.07$kWh^{-1} [3], [7]. Geothermal installed capacity is currently ~10.7GWe worldwide with 29% located in the United States, 18% in the Philippines, 11% in Indonesia, 9% in Mexico, and 8% in Italy [53]. To date, few LCAs have been performed for geothermal power plants and publications on this topic are quite recent [54]. Overall, the results presented in these studies are consistent. Mean emissions of GHGs from geothermal installations are commonly estimated in the range of 40-60gCO_2-eq kWh_e^{-1} with minimum values around 11.0gCO_2-eq kWh_e^{-1} [55] and maximum estimates around 78.0gCO_2-eq kWh_e^{-1} [56]. These values are of the same order of magnitude as the majority of other renewable technologies reviewed in this paper. The main sources of GHG emissions from geothermal installations are from the diesel used to drive the electric generating set (~33% of life cycle GHG emissions) [51], [56]. Other important sources of life cycle GHG emissions include the embedded GHGs in the pig iron used in the construction of the plant (~10% of life cycle GHG emissions), and a range of lesser sources including the light fuel oil in the industrial furnace, sinter iron at plant, lignite burned in power plant, and natural gas in industrial furnace [56].

Applications of geothermal technologies can be summarized in the following categories: Combination of Geothermy and Biomass; District and Domestic heating; Electricity generation; Environmental studies on pre-existing power plants; Greenhouse heating; Improvement of existing technologies of geothermal systems. Some categories have been studied more than others, electricity generation for example. Most of the power generation technologies currently available in the geothermal industry have been designed for exploiting the conventional convective geothermal systems. The selection process of the most suitable geothermal power generation technology essentially depends on the properties of the geothermal resource (fluid and reservoir) that require to be exploited (i.e., geological, chemical, physical and thermodynamic properties) [57].

Geothermal resources suitable for power generation can be categorized in three major groups:

1. Vapor dominated systems with temperatures >240°C
2. Liquid (or hot water) dominated systems with temperatures up to 350°C
3. Petro-thermal or solidified hot dry rock resources with temperatures up to 650°C.

Groups (1) and (2) are related to the convective hydrothermal systems which are commercially exploited in the world, whereas group (3) is referred to the exploitation project of the hot dry rock (HDR) or enhanced geothermal systems (EGS) [57].

The energy conversion technology used for exploiting the geothermal systems depends on the reservoir properties (e.g., geological, geophysical, geochemical, physicochemical, thermodynamic, among others). Three types of mature technologies have been commercially and successfully used for the exploitation of geothermal resources: dry steam, flash (single, double and triple) and binary cycle power plants. A brief overview of these technologies is given as follows [57].

Dry steam. There are privileged places, such as The Geysers in California and Larderello in Italy, where the earth’s gradient temperature leads to reservoirs with high temperature (>240°C). The vapor extracted from these reservoirs is transported to a steam turbine that converts thermal energy into mechanical energy, which is then sent to a generator from where electricity is produced and distributed into the grid (see Figure 8A). This conversion technology is known as dry steam, and due to its plant set up it is the cheapest geothermal generation process.

Single and multi-stage (double and triple) flash steam. If the geothermal fluid in the reservoir is a liquid-vapor mixture, then a separation process commonly known as flash is used for the power generation.

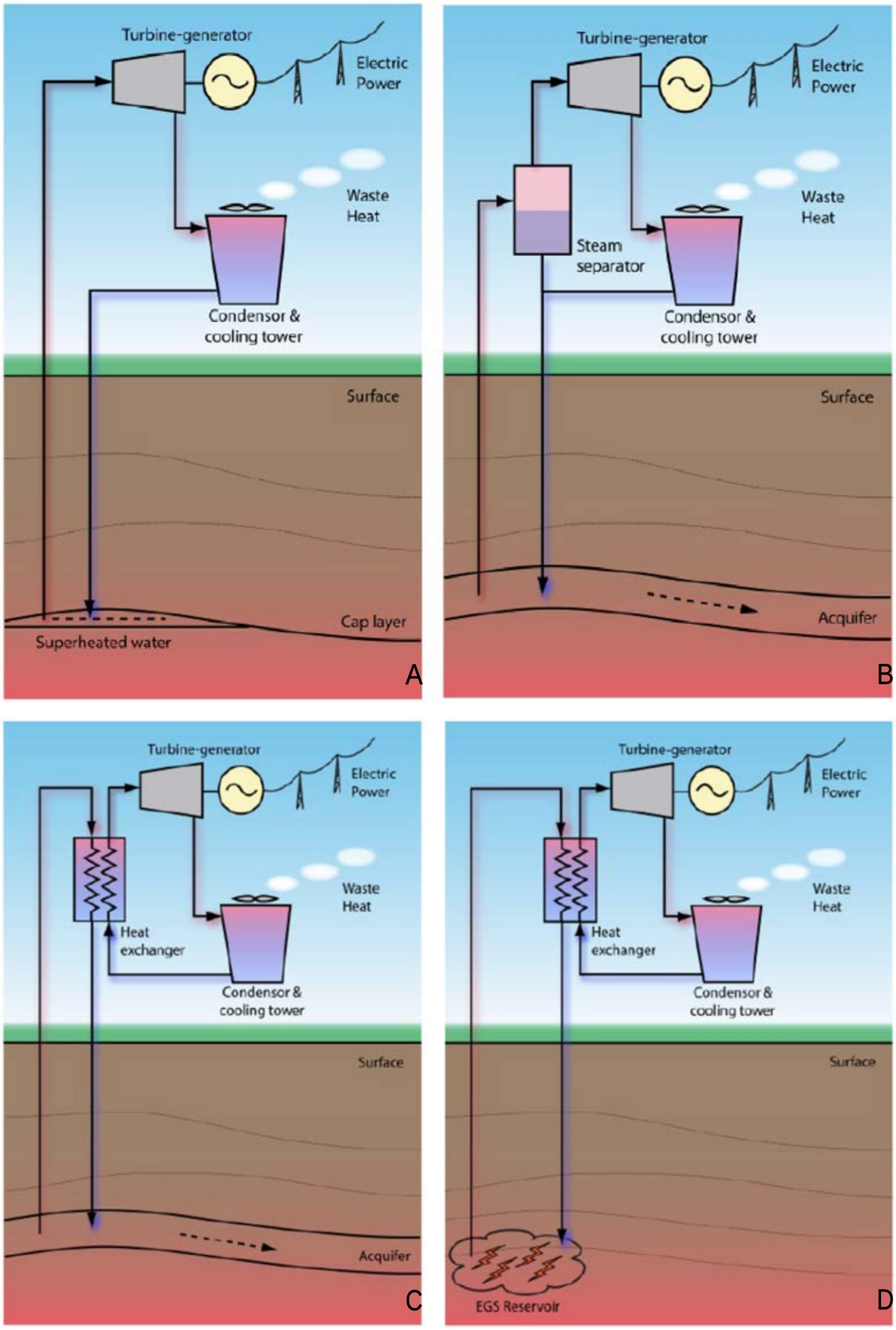


Figure 8: Simplified schematic diagrams of the typical geothermal power generation technologies. A: Dry steam, B: Flash steam C: Binary cycle D: EGS hydrothermal plants [58].

Based on the thermodynamic mixture's characteristics, the separation process can include one, two or three stages, namely single-, double-, and triple-flash systems, respectively. When the mixture temperature is over 210°C, a single-flash set up is generally used (see dotted lines in Figure 8B). In this case, the geothermal fluid is extracted from the production well and sent to a cyclonic separator where the liquid and vapor phases of the mixture are efficiently separated due to a difference in densities. The primary vapor passes from the separator to an expansion steam turbine and finally to a generator to complete the process. The remaining liquid phase mixture (also known as brine) obtained from the separator is sent to a reinjection well, which in turns receives cooling water from a condensation process that is designed to treat steam coming from the expansion turbine.

Binary cycle. In liquid-dominated reservoirs with temperatures lower than 200°C, a binary cycle system is used for power generation, which represents 12% of the worldwide installed capacity. In this system, the geofluid cannot be used directly as in other power generation technologies previously described. This is due to the low temperature of the geofluid, which leads to a poor vapor production. However, the thermal energy available can be used to vaporize a working fluid (which has a lower boiling point, e.g., n-isobutane, n-isopentane and pentane), and produce electricity. The heat transfer process occurs in a heat exchanger from where an organic vapor is produced and sent to a turbo generation system for producing electricity (see Figure 8C). Remaining steam coming from the turbine is sent to a condenser whose brine is conducted to the heat exchanger, thus closing the thermodynamic cycle.

Engineered or enhanced geothermal systems (EGS). The power generation process theoretically proposed for the exploitation of Enhanced Geothermal Systems (EGS) is generally the same as the one described for binary cycle plants. These systems are aimed to exploit widely available deep underground reservoirs (namely hot dry rock, hot wet rock and hot fractured rock resources), where insufficient water exists and/or the rock-formation permeability is low.

In order to exploit such geothermal systems, an enhanced process in the rock permeability is required either by opening preexisting fractures in the rock or by forming new ones to create an artificial reservoir. The thermal energy is generally exploited by injecting water, or another appropriate fluid into the hot fractured rock (or artificial reservoir) to stimulate an intense heat exchange, and to extract most of the energy available in the rock. Sometimes, there is circulation of the fluid already present in the rock formation, which acts as a geothermal fluid loop. The hot fluid is extracted from production wells and pumped to a power plant installed on the surface to generate electricity. In spite of the potential use of the EGS, the implementation of these systems in the commercial market is not widespread. This is explained because the learning curve of this technology is at an early stage. Nowadays, there are technological advances with the installation of some pilot projects in Australia, U.S., Italy, France, Germany, Switzerland, Japan, and El Salvador, which have demonstrated the feasibility of exploiting these systems at depths between 3 km and 10 km [57].

Classical EGS systems seek to extract heat from low-permeability rocks where there is relatively little water in place by constructing a heat exchanger between two or more boreholes in the rock mass. Such systems were referred to as Hot Dry Rock (HDR) systems. More recently, classical HDR systems have become known as Petrothermal systems, to emphasize the distinction from hydrothermal (conventional geothermal) systems where there is a significant quantity of hot water in-place. Petrothermal systems are also known as EGS systems. However, there is no consensus as to whether "EGS" denotes Enhanced or Engineered Geothermal Systems. A sensible distinction between the two is to identify Engineered Geothermal Systems as Petrothermal systems, to emphasize the fact that they involve the engineering of the heat exchanger. Enhanced Geothermal Systems are more logically identified with poorly-performing conventional geothermal systems whose productivity has been enhanced by applying reservoir stimulation technology.

2.3 Photovoltaics

Electricity produced from photovoltaics (PV) is now one of the most promising renewable energy sources [4], [7], [59]. The primary energy source (i.e. solar radiation) is practically infinite on the scale of human needs (providing a few thousand kWh $m^{-2}y^{-1}$, depending on location). Solar PV technology enables direct conversion of sunlight into direct-current (DC) electricity through semi-conductor devices called solar cells, which are interconnected and hermetically sealed to constitute a PV module (which is typically up to 50-200W depending on the selected technology). The PV modules are integrated with other components (such as inverters, storage batteries, electrical components, and mounting systems) to constitute complete solar PV systems and power plants that are highly reliable and modular in nature.

PV power generation employs solar panels to produce power on both a standalone basis using batteries or on a grid-connected basis using an inverter and electrical utility lines. Currently commercially available PV modules are considered as not highly efficient (~16% efficiencies) and maybe expensive for large scale deployment [60]. However, their prices per installed MW has fallen by about 60% since 2008. Mostly thanks to governmental subsidies, PV is gaining ground in most countries with a global installed capacity of 303GW in 2016 compared to 6GW back in 2006 [3], [9]. Most of this growth has come from grid connected systems, though the off-grid market has also continued to expand [61]. The high cost of PV cells and associated Balance of System (BoS) are the main barriers to uptake [60], [61]. Consequently, there is an intense R&D effort in many countries for the development of new technological solutions to the challenge of producing commercial PV with increased efficiencies.

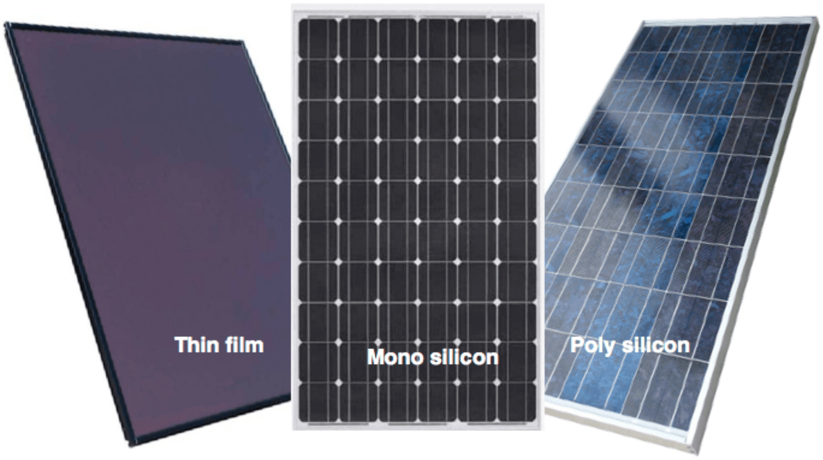


Figure 9: Photovoltaic technologies [62].

There are two main classes of PV technology (see Figure 9), based on the semiconductor materials employed for the cells: **i.** crystalline technologies, e.g. single-crystalline silicon (sc-Si) or multi-crystalline silicon (mc-Si), and **ii.** thin-films, e.g. amorphous silicon (a-Si), Cadmium Telluride (CdTe), Copper-Indium-diSelenide (CIS), Copper-Indium-Gallium-diSelenide (CIGS). In the literature there exists a number of life cycle analyses carried out for solar PV systems [63], primarily for sc-Si and a-Si cells. For sc-Si systems, estimates of GHG emissions (gCO_2-eq kWh_e^{-1}) range from 9.4 to 300 (mean 91.1) [55], [60], [64]–[66]. For a-Si systems, estimates of GHG emissions (gCO_2-eq kWh_e^{-1}) range from 15.6 to 50.0 (mean 30.5) [55], [60], [65].

The output of photovoltaic modules is a product of the area, the efficiency, and the insolation of specific systems and locations. The sunlight received by the array is affected by a combination of tilt, tracking and shading. The seasonality and climate strongly affects the output of PV arrays. Monthly energy production varies substantially from winter months to summer months. Typically, highest yields usually occur in spring and summer and lowest yields occur in winter months. The performance of PV modules depends on the temperature and the solar irradiance, but the exact dependence varies between different types of PV modules.

For this research thesis four PV technologies will be evaluated: **i.** single crystalline silicon (sc-Si), **ii.** multi-crystalline silicon (mc-Si), **iii.** Copper-Indium-diSelenide (CIS), and **iv.** amorphous silicon (a-Si). Detailed technical information on PV module efficiencies is provided in Table 2.

Table 2: Technical characteristics of employed PV cell technologies.

	Photovoltaic technology	Technical characteristics
Crystalline technologies	Single crystalline silicon cells (sc-Si)	The active material is made from a single crystal without grain boundaries. The sc-Si cells have the highest efficiencies (for commercial cells: 13-18%).
	Multi-crystalline silicon cells (mc-Si)	The cell material consists of different crystals. The cells have a lower efficiency, but it is cheaper in production. Commercial mc-Si cells have efficiencies in the range of 11-16%.
Thin-Film Technologies	Copper-Indium-diSelenide (CIS)	CIS modules are constructed by depositing extremely thin layers of photovoltaic materials on a low cost layer (such as glass, stainless steel or plastic). Material costs are lower because less semi-conductor material is required; secondly, labor costs are reduced because the thin films are produced as large, complete modules and not as individual cells that have to be mounted in frames and wired together. The efficiency is about 8-11%.
	Amorphous cells (a-Si)	A new developed thin-film technology is hydrogenated amorphous silicon. The efficiency of amorphous cells is about 6-9% and decreases during the first hundred operation hours.

Solar cell technologies make up the large part of a PV power plant. These cells are characterized from conversion efficiency factors, capacity factors and geographic location factors. These factors are critical in determining the energy performance and financial viability of solar PV projects. High capital investment costs, or total system costs represent the most important barrier to PV deployment. Total system costs are composed of the sum of module costs plus the expenses for the BoS including mounting structures, inverters, cabling and power management devices. While the costs of different technology module types vary on a per watt basis, these differences are less significant at the system level, which also takes into account the efficiency and land-use needs of the technology. The panels, cells and inverters are all lower in capital cost compared to multi crystalline PV parts and accessories. The BoS costs and operating and maintenance (O&M) costs for thin film is higher than crystalline. The thin-film panels are cheaper than crystalline at initial capital cost; however, more PV modules are needed and materials to produce the same amount of electricity. The number of key components for the mounting structure, including the labor costs and transport costs, increase because more materials are required for thin-film installations. These additional costs in the BoS components and O&M expenditures counterbalance the cheaper costs of the thin film modules.

Thin-film technologies are less expensive overall in the production stages versus crystalline silicon because the materials and processes to manufacture the wafer-based silicon are far more expensive than producing thin-film based technologies. The main advantages of thin films are not their conversion efficiency but their capital cost and their relatively low consumption of raw materials, high automation and production efficiency. Thin films are also easier from integration on residential and commercial infrastructure. The current drawbacks are the lower conversion efficiencies require more modules which require more roof top space which is limited on residential and commercial properties [3], [4], [7], [8], [59].

2.4 Solar thermal systems

Solar thermal electricity generation technologies can be categorized into parabolic trough, central receiver, paraboloidal dish, solar chimney and solar pond. In the parabolic trough solar electricity generation system, the solar receiver consists of a large array of parabolic trough reflectors that reflect the sunlight to a black absorber tube. This tube is cooled by a heat-transferring fluid which, when hot, is pumped to a heat exchanger for power generation through a Rankine cycle. In the central receiver solar electricity generation systems two-axis tracked field of mirrors (heliostats) reflect the beam of radiation to a centrally placed receiver mounted on top of a tower [67]. In the paraboloidal dish solar electricity generation system, a paraboloidal dish reflector is used as the solar collector. The heat to electricity conversion is achieved using a stirling engine. A solar pond is usually a large reservoir of water with a black bottom absorbing the solar diffuse and beam radiation and transforming it to heat in the form of hot water [68], [69]. There have been a limited number of life cycle analyses looking specifically at solar thermal technologies. Emissions of GHGs (gCO_2-eq kWh_e^{-1}) have been estimated for central receiver systems as between 36.2 and 43 (mean 39.6), while emissions from parabolic trough technologies have been estimated as being 196 g CO_2-eq kWh_e^{-1} [70]–[72].

Low temperature solar thermal technologies, especially those that do not generate electricity, rely on the scientific principles behind the greenhouse effect to generate heat. Electromagnetic radiation from the sun, including visible and infrared wavelengths, penetrates into the collector that is absorbed by the surfaces inside the collector. Once the radiation is absorbed by the surfaces within the collector, the temperature rises. This increase in temperature can be used to heat water. Thus, another area of interest, the hot water and house heating appeared in the mid 1930s, but gained interest in the last half of the 40s. Until then millions of houses were heated by coal burn boilers. The idea was to heat water and fed it to the radiator system that was already installed.

The manufacture of Domestic Solar Water Heaters (DSWH) began in the early 60s. The industry of SWH expanded very quickly in many countries of the world. Two main components of DSWH are solar collectors and storage tanks. A solar collector is a device that collects and/or concentrates solar radiation from the sun. These devices are primarily used for active solar heating and allow for the heating of water for personal use. These collectors are generally mounted on the roof and must be very sturdy as they are exposed to a variety of different weather conditions. There are many different types of configurations and collectors. The most commonly used type of collector are the flat plate and the evacuated tubes systems. These collectors consist of airtight boxes with a glass, or other transparent material cover and in many cases are of the thermosyphonic type and typically consist of two flat plate solar collectors having an absorber area between 3 and 4 m^2, a storage tank with capacity between 150 and 180 l and a cold water storage tank, all installed on a suitable frame. An auxiliary electric immersion heater and/or a heat exchanger, for central heating assisted hot water production, are used in winter during periods of low solar insolation. Another important type of DSWH is the force circulation type. In this system only the solar panels are visible on the roof, the hot water storage tank is located indoors in a plantroom and the system is completed with piping, pump and a differential thermostat. Obviously, this latter type is more appealing mainly due to architectural and aesthetic reasons, but also more expensive especially for small-size installations. DSWH is an effective method of utilizing available energy sources to perform useful work. The energy from the sun can provide hot water for many domestic and industrial applications, displacing the need to burn fossil fuels.

Figure 10: Typical flat plate solar collector [73].

Flat plate solar collectors (see Figure 10), are the most common type of DSWH which have been in use since the 1950s. The main components of a flat plate panel are a dark colored flat plate absorber with an insulated cover, a heat transferring liquid containing antifreeze to transfer heat from the absorber to the water tank, and an insulated backing. The flat plate feature of the solar panel increases the surface area for heat absorption. The heat transfer liquid is circulated through copper or silicon tubes contained within the flat surface plate. Some panels are manufactured with a flooded absorber that involves having two sheets of metal and allowing the liquid to flow between them. Using a flooded absorber increases surface area and gives a marginal boost in efficiency. The absorber plates themselves are usually made from copper or aluminium and are painted with a selective heat coating which is much better at absorbing and retaining heat than ordinary paints. In an area with an average level of impinging solar radiation of 200 W/m^2 (i.e. London) the amount of thermal energy generated by a flat plate solar collector of around 8m^2 is enough to completely cover the hot water needs for one 4-member family house.

Polymer flat plate collectors are an alternative to metal plate collectors. Metal plates are more prone to freezing whereas the polymer plates themselves are freeze tolerant so can dispense with antifreeze and simply use water as a heat transferring liquid. Any antifreeze that is added to the heat transfer liquid will reduce its heat carrying capacity at a marginal rate. A benefit of polymer plates is that they can be plumbed straight into an existing water tank removing the need for a heat exchanger which increases efficiency. Some polymer panels are painted with matte black paint rather than a selective heat coating. This is done to prevent overheating although high temperature silicone is now normally used to prevent overheating. This design of solar panel is, overall, slightly less compact and less efficient when compared with an evacuated tube system, however this is reflected in a cheaper price. Such solar collectors can work well in all climates and can have a life expectancy of over 25 years.

Figure 11: Typical vacuum tubes solar collector [73].

Vacuum tube (or evacuated) solar collectors (see Figure 11), are another popular type of domestic solar thermal systems in operation. An evacuated solar system is the most efficient and a common means of solar thermal energy generation with a rate of efficiency of 70%. As an example, if the collector generates 3000 kWh of energy in a year then 2100 kWh would be utilized in the system for heating water. The rate of efficiency is achieved because of the way the evacuated tube systems are constructed (i.e. use of vacuum tube for minimization of heat losses), meaning they have excellent insulation and are virtually unaffected by variations in ambient air temperature.

The collector itself is made up of rows of insulated glass evacuated tubes that contain copper pipes at their core. Water is heated in the collector and is then sent through the pipes to the water tank. This type of collector is the most efficient, but also the most expensive. There are two main types of tubes that are used inside the collector which are glass-glass and glass-metal. The glass-glass version uses two layers of glass fused together at both ends. The double glass tubes have a very reliable vacuum but reduce the amount of light that reaches the absorber inside. The double glass system may also experience more absorber corrosion due to moisture or condensation forming in the non-evacuated area of the tube. The second kind of tube is a glass-metal combination. The glass-metal combination allows more light to reach the absorber and reduces the chances of moisture corroding the absorber. The cylindrical shape of evacuated tubes means that they are able to collect sunlight throughout the day and at all times in the year. Evacuated tube collectors are also easier to install as they are light, compact and can be carried onto the roof individually. What's more, the tubes can be replaced individually if one becomes faulty, avoiding the need to replace the whole collector. The system is an efficient and durable system with the vacuum inside the collector tubes having been proven to last for over twenty years. The reflective coating on the inside of the tube will also not degrade unless the vacuum is lost.

Figure 12: Roof mounted solar collectors. Left: vacuum tubes and Right: flat plate.

In chapter 3 of the thesis the results of the environmental and economic evaluation for roof mounted flat plate and vacuum tubes solar collectors (see Figure 12) will be presented.

Chapter 3

Detailed results for the studied Renewable Energy Systems

The detailed results of the environmental and economic analysis for each of the three studied renewable energy technologies are presented in this Chapter. For each renewable system the LCA results are given first and the economic analysis results follow. The Chapter ends with discussion and concluding remarks.

3.1 Geothermal systems

3.1.1 LCA analysis of geothermal systems

In the context of LCA in geothermal power generation, construction, operation and end-of-life of a geothermal power plant with its different subsystems (as depicted in Figure 8) need to be included. On the one hand, geothermal power plants do not consume any fuel and show no direct emissions during the operation period. But, on the other hand, the construction of geothermal power plants requires large amounts of energy and material. Hence, the question is if such plants are also environmentally promising from a cradle-to-grave point of view. By using the LCA methodology, a comprehensive set of potential environmental impacts derived from the whole life cycle of geothermal power plants can be analyzed. The range of environmental burdens includes emissions to air, soil and water, land use, and consumption of energy and non-energy resources.

The conducted LCA refers to the construction of the geothermal power plant at the surface, resulting in a coupled underground and surface system. It collects all parts necessary to build a geothermal power plant: deep well drilling, stimulation, and surface power generation installations. It further includes the implementation of a downhole pump connected with the power generator. Two systems (5.5MW_{el} and 2.9MW_{el} respectively) are studied and include all components of a deep geothermal power plant.

Goal and scope of the LCA in geothermal power plants is the quantification of environmental burdens during the complete life cycle of deep geothermal systems per unit of electricity (and heat) generated under various conditions. Among all types of geothermal systems, the focus is on both deep hydrothermal and petrothermal (EGS) geothermal energy systems, primarily for electricity production. Figure 13 shows the system boundaries of the system under research. The system can also be imagined as divided into the surface system with the power generating unit and the subsurface system with the wells, the stimulation process, and the downhole pump.

The functional unit of the LCA carried out is the production of 1 kWh net electricity with a deep geothermal power plant (petrothermal or hydrothermal), with parameters adapted to EU specific conditions.

The inventory analysis accounts for all energy and material inputs, land transformation and occupation, emissions of substances to air, water and soil as well as extraction of energy and non-energy resources in the processes of the foreground system. Background data are taken from the worldwide leading LCI database ecoinvent 3.4; the complete set of life-cycle-inventory (LCI) data is compiled according to the data format and quality guidelines of ecoinvent.

In order to validate the environmental impacts a Cradle-to-Grave LCA has been implemented for each of the studied geothermal power plants. For this purpose, SimaPro 8.5 with ecoinvent version 3.4 have been employed, while ReCiPe 2016 Midpoint Hierarchist (H) has been chosen as the LCIA method as it provides the most extensive set of midpoint impact categories. The hierarchist perspective was chosen as it is the most balanced model based on common policy principles over a common time frame, compared to the individualistic and egalitarian perspectives which consider a short and a long time frame respectively [74].

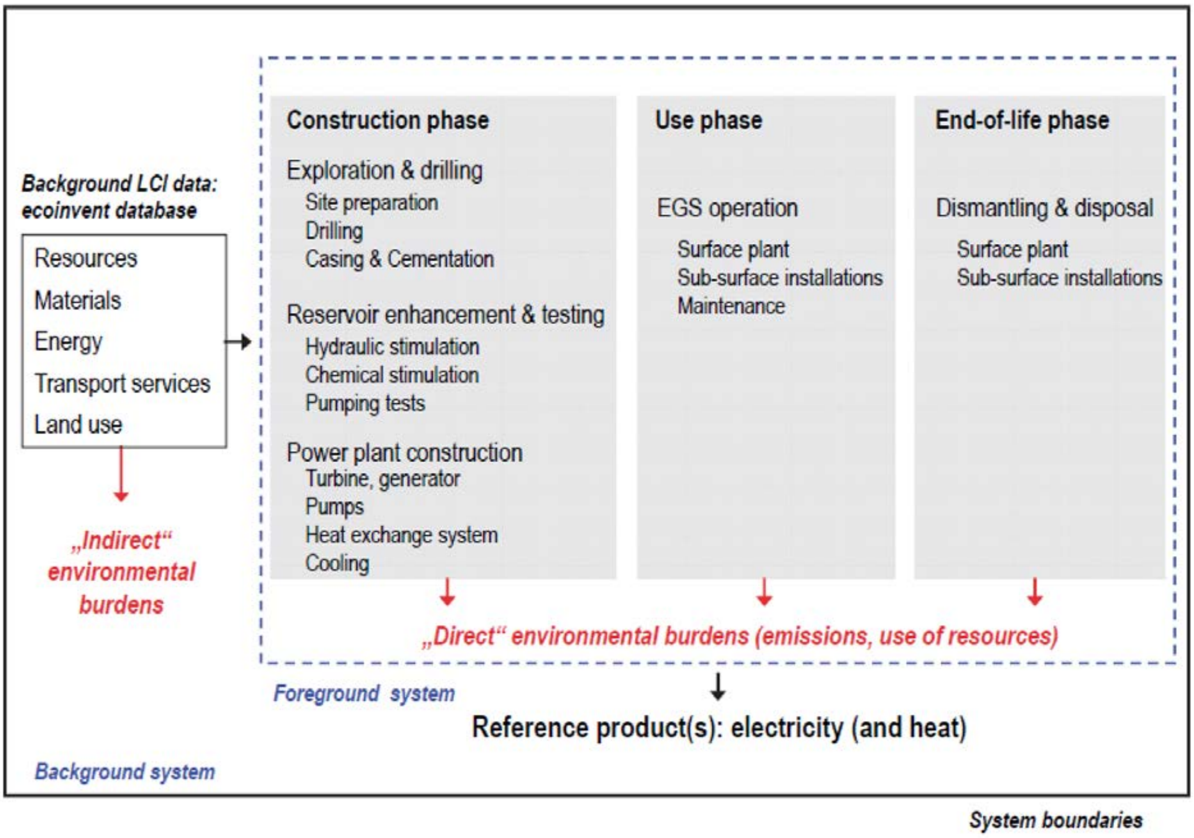


Figure 13: System boundaries for the LCA of deep geothermal power generation [58].

Enhanced Geothermal systems (EGS), also known as Hot-Dry-Rock (HDR) systems, enable the exploration of the Earth's interior heat outside known geothermal provinces. EGS are exploited with artificial stimulation of tight rock formations by hydraulic fracturing in order to create an underground heat exchanger. Fluid is circulated in a closed circle during operation, whereby reservoir pressures and fluid throughputs are managed by balanced production and injection rates in multiple well array.

The two HDR systems modelled vary in capacity of the geothermal source: medium and low (5.5 and 2.9 MW_{el} respectively).Both systems are binary cycle geothermal power plants and consist of deep boreholes (three and six respectively) with depths between 5000m and 6000m. One of the boreholes is used as the injection well for the cold fluid leaving the generation unit, the other two as production wells, which provide the hot fluid, heated up within the hot rock formation. One test drilling of 2000m depth for exploration (rock, temperature gradient, aquifers, etc.) is conducted. Then, the injection and the production wells are drilled. The injection well is used for the stimulation of the rock (fracturing): A mixture of water and sand is pressed down with high pressure in order to enlarge the present fractures in the rock and to make it more permeable. During the operation of the power plant, water will pass through this permeable (hot) rock, be heated and pumped through the production well to the Organic Rankine Cycle (ORC) unit. A temperature gradient of 35-40°C per kilometer depth can be assumed. Binary cycle ORC units with capacity of 5.5 and 2.9 MW_{el} respectively are used for electricity generation for each of the studied geothermal power plants. Further key components are the underground chromium steel pipes between the injection wells and the generation unit and for water supply. A lifetime of 30 and 20 years respectively is assumed for the two power plants. Most of the dismantling activities have not been included. In addition motor vehicles for internal transport and minor maintenance items were not considered. The chromium steel pipes usually remain in the ground after use, while no outputs to the environment (leaching) were taken into account. Table 3 presents the key physical parameters for the studied systems.

Table 3: Key physical parameters of the studied geothermal power plants.

Parameter	Medium capacity	Low capacity
Net plant power [MW_{el}]	5.5	2.9
Well depth [km]	5	5
Number of wells	6 (2 well triplets)	3 (1 well triplet)
Surface plant life time [years]	30	20
Well (reservoir) life time [years]	20	20
Reservoir temperature [°C]	190	165
Electrical efficiency [%]	14	13
Net thermal efficiency [%]	9	14
Annual net energy generation [GWh yr^{-1}]	46	24
Annual net energy generation per installed capacity [GWh MW^{-1} yr^{-1}]	8.36	8.27
Total energy produced per installed capacity [GWh MW^{-1}]	250.8	165.4
Total energy produced [GWh]	7524	3308
Plant cost [€/kW_{el} installed]	4900	

Simapro has two ways of finding the contribution from a process: **i**. the graphical representation of a process tree or network, and **ii**. the contribution analysis section of the results screen. All subsystems shown in the trees are included in the system parameters. The effect of using cut-off criteria can help to analyze more or less processes in the obtained network in SimaPro. In many LCAs, process trees become extremely large, as LCAs with over 2000 processes are quite common. These process trees contain items that have a negligible contribution. This can be illustrated by setting the cut-off threshold for displaying processes in the process tree at a certain percentage of the environmental load (for a single score or an impact category). Two cut-off thresholds (i.e. 10% and 1%) have been demonstrated for all systems throughout this study. Figures 14-17 below demonstrate the LCA networks for the two studied geothermal plants. According to the network trees the thick red line, also known as the elementary flow, indicates the environmental bottleneck or burden in each process.

Both studied geothermal power plants comprise three main constituent components-modules: **i.** the heat and power generating unit, **ii.** the stimulation of the deep geothermal well and **iii.** the drilling of the deep geothermal well. For the medium capacity geothermal power plant, 96.8% of all total inflows and outflows are due to the drilling of the two triplet deep well sets. The stimulation of these wells (requiring water and energy), the generation unit and other inputs play a very minor role, only 2.2% of the energy and materials inflow. The main environmental impacts originate from the drilling phase of the deep well sets of the plant. There are also impacts associated with the electricity production, transportation and system disposal which are taken into consideration. Similar values stand for the case of the low capacity geothermal power plant: 96.9% of the impacts come from the drilling phase of one triplet deep well set, 1.3% for the building machine processing, and 1.6% for the heat and power co-generation unit in the organic Rankine cycle. As the networks clearly show, the drilling stage contributes the most important part of the environmental impacts in the life cycle of the studied geothermal power plants. The elementary flows indicate that most inflows of materials and energy for both medium and low capacity plants occur during the drilling phase; subsequently large emissions and impacts to the environment and human health follow with this stage of the geothermal power plant lifecycle. Based on this, we can conclude that the drilling phase causes the major part of environmental impacts in all impact categories with the steel and cement use for the casing and the electricity use for the drilling rig being dominant contributors. In contrast, the stimulation phase only contributes very little to the total environmental impacts, even when assuming a very high energy and water use in this context.

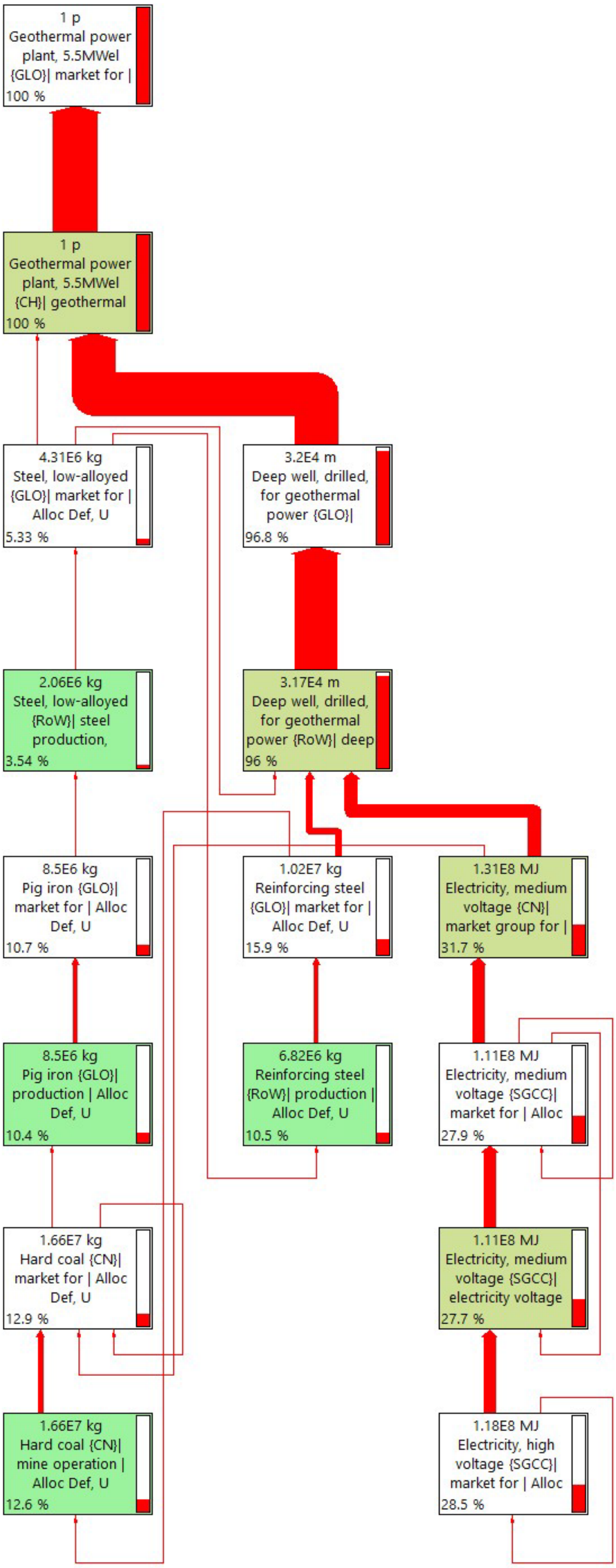


Figure 14: Process network for medium capacity geothermal power plant. Cut-off threshold: 10%, total nodes: 10930.

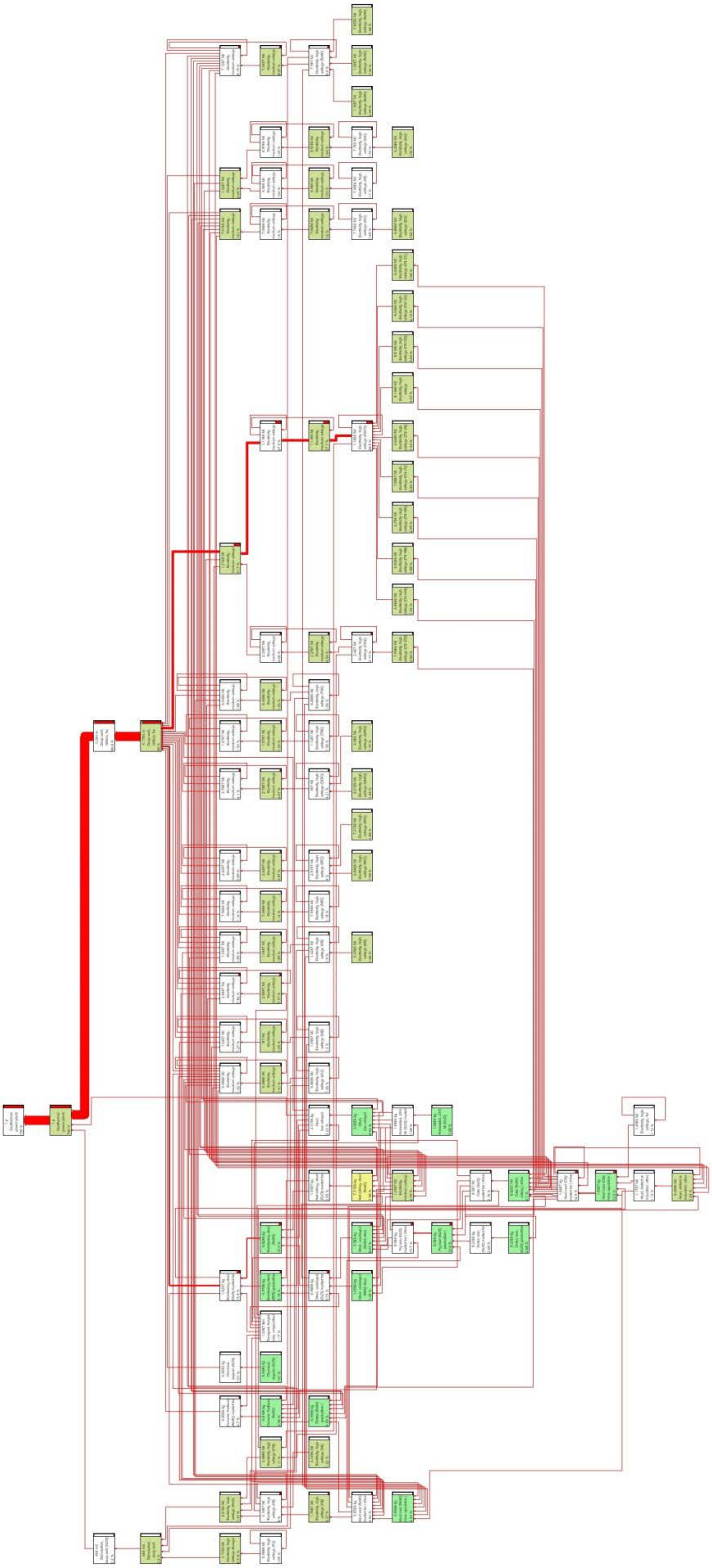


Figure 15: Process network for medium capacity geothermal power plant. Cut-off threshold: 1%, total nodes: 10930.

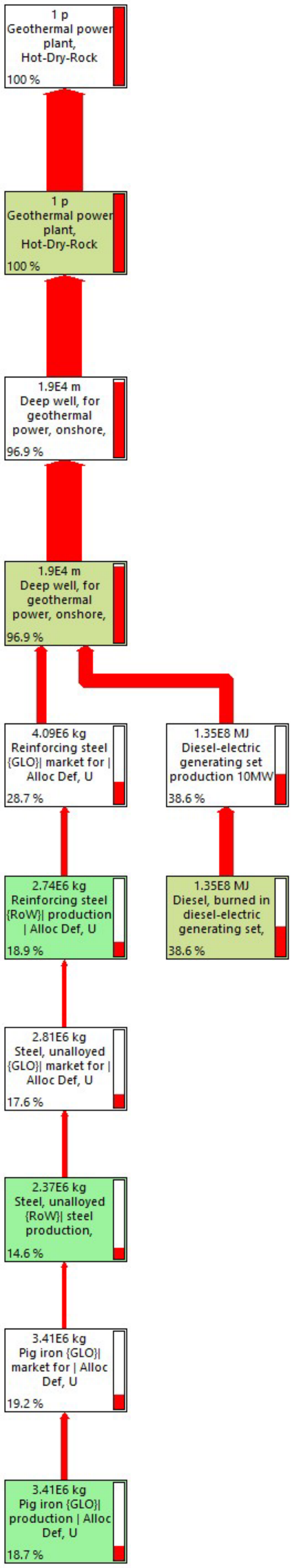


Figure 16: Process network for low capacity geothermal power plant. Cut-off threshold: 10%, total nodes: 10938.

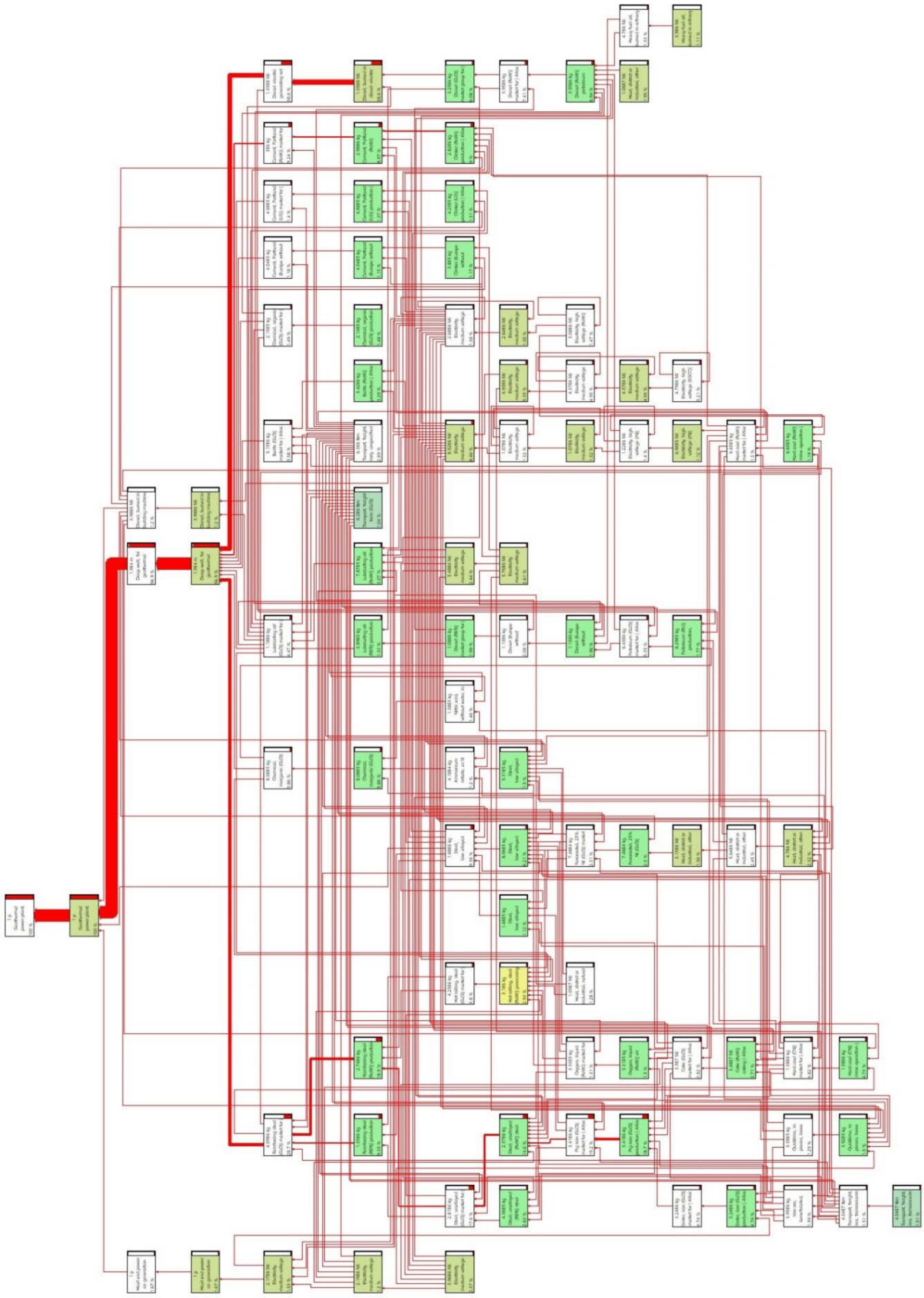


Figure 17: Process network for low capacity geothermal power plant. Cut-off threshold: 1%, total nodes: 10938.

The environmental impacts of geothermal plants have been calculated by means of a Cradle-to-Gate LCA. Only normal operation has been covered, i.e. accident cases have not been considered. Groundwater pollution due to faulty drilling operations as well as induced seismicity due to stimulation or fluid reinjection are therefore not represented in the results. Further, issues with great uncertainties due to lack of experience have not been incorporated. Examples of such factors include the number of unsuccessful wells, methane leakage during drilling and deposits in the pipes from the geo-fluid. In Table 4 and Figure 18 the aggregated LCA inventory results for the studied geothermal systems are depicted. These are "harmonized" data representing the LCA results (for each impact category) per total electricity exported to grid (in kWh) per installed capacity (in MW_e) for each geothermal system, thus providing a holistic evaluation indicator (i.e. environmental burden per total energy produced).

Table 4: Aggregated LCA inventory results for the studied geothermal power plants.

Impact category	Unit (per MW_e installed)	Medium capacity geothermal power plant	Low capacity geothermal power plant
Global warming	kg CO2 eq/kWh	1.818E-02	2.206E-02
Stratospheric ozone depletion	kg CFC11 eq/kWh	5.846E-09	2.505E-08
Ionizing radiation	kBq Co-60 eq/kWh	2.166E-03	6.693E-04
Ozone formation, Human health	kg NOx eq/kWh	3.898E-05	1.731E-04
Fine particulate matter formation	kg PM2.5 eq/kWh	4.294E-05	4.501E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq/kWh	3.963E-05	1.765E-04
Terrestrial acidification	kg SO2 eq/kWh	7.275E-05	1.158E-04
Freshwater eutrophication	kg P eq/kWh	8.837E-06	6.259E-06
Terrestrial ecotoxicity	kg 1,4-DCB eq/kWh	4.044E-05	1.065E-04
Freshwater ecotoxicity	kg 1,4-DCB eq/kWh	4.957E-04	6.922E-04
Marine ecotoxicity	kg 1,4-DBC eq/kWh	6.786E-04	9.611E-04
Human carcinogenic toxicity	kg 1,4-DBC eq/kWh	1.632E-03	2.996E-03
Human non-carcinogenic toxicity	kg 1,4-DBC eq/kWh	4.888E-01	7.807E-01
Land use	m2a crop eq/kWh	3.696E-04	3.563E-04
Mineral resource scarcity	kg Cu eq/kWh	1.371E-04	4.136E-04
Fossil resource scarcity	kg oil eq/kWh	4.042E-03	6.799E-03
Water consumption	m3/kWh	1.538E-04	2.597E-04

The midpoint indicators in LCA correspond to different impact categories, in which emissions, materials use, water-land use, with the same "damage mechanism" are aggregated. Equivalence factors (relative to one substance in each category) are used for aggregated quantification. For example, all greenhouse gas emissions from the total life cycle are compiled in the category "Global warming", calculated as CO_2 equivalents, according to their individual global warming potentials, based on CO_2 as the reference substance.

The impact of the production of one kWh electricity with deep geothermal power depends largely on the capacity of the power plant, i.e. how efficiently the wells can be used and how much electricity can be produced over the lifetime of both the power plant and wells. Therefore, the results for the medium and low capacity cases, can be interpreted as representing almost the absolute range of impacts. These cases also show the relative importance of individual elements in the life cycle of the geothermal electricity production.

Figure 18 presents the relative contributions to the impact categories (based on the ReCiPe 2016 midpoint evaluation) for the studied geothermal power plants. The cumulative CO_2-eq emissions per kWh for each MW_{el} installed over the whole life cycle of the power plants vary between approximately 1.8×10^{-2} and 2.2×10^{-2} kg CO_2 eq/kWh·MW_{el} and the plant with the lowest capacity shows the highest impacts. This is due to the lower output of electricity over its whole life, while impacts from the dominating drilling phase are not lower for this plant. In addition, it should be considered that for both plants and due to technological implications (i.e. scaling, localized geothermal field degradation, etc), the drilling of an additional well (triplet) per reservoir might be necessary during the plant's lifetime.

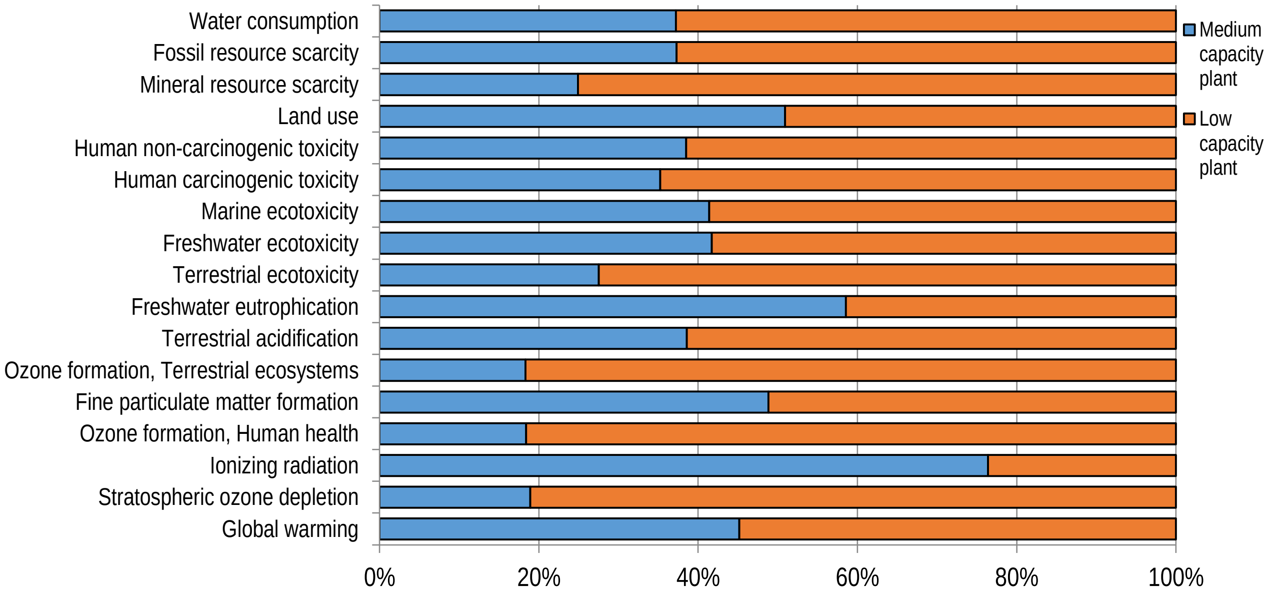


Figure 18: LCA results for the studied geothermal power plants: relative contributions to the impact categories.

For all cases the results denote that drilling phase clearly dominates the climate change impacts. The stimulation with water and energy, the generation unit and other inputs play a very minor role. Within the generation unit the construction of the building and the related steel use are dominant, whereas the choice of the working fluid plays only a marginal role. Energy consumption and the use of steel for the casing dominate the impact of drilling wells – even with electricity as the energy source. Data on drilling fluids are still somewhat uncertain. They may have a higher or lower influence. The choice of the working fluid does not influence the results in a significant manner.

For the purposes of this study, a Monte Carlo analysis of the LCA results has been implemented through a comparison between the two studied geothermal power plants (**A**: medium capacity plant and **B**: low capacity plant) which was repeated for 5000 iterations (requiring about 40 min of CPU time). During the Monte Carlo analysis a stochastic variation of various parameters in the initial inventory database for each of the two plants (A and B) is performed, altering the LCA results and thus affecting the A-B outcome. A random variable is selected for each value within the uncertainty range which is specified and the impact assessment results are recalculated. The same process is repeated by taking different samples within the uncertainty range, and all results are stored. After repeating the procedure for a set number of times (e.g. 5000), 5000 different results are obtained thus forming the uncertainty distribution.

In Figure 19 the results of the uncertainty analysis are depicted in a bar chart form, showing the percentage of times when plant A has a greater impact than plant B (A-B≥0, in orange) and vice versa (A-B<0, in blue). In general, we can assume that if the outcome of 90 to 95% of the Monte Carlo runs are favorable for a product (e.g. A-B>0 ⇨ A>B and vice versa), the difference is significant and thus the conclusion may be considered solid.

It is clear that for the studied geothermal plants, case A has increased impacts compared to case B in all midpoint categories, thus proving its deteriorated environmental performance. Water consumption is the only category that plant B appears to have similar impacts as plant A (i.e. for the 45.7% of the completed 5000 iterations).

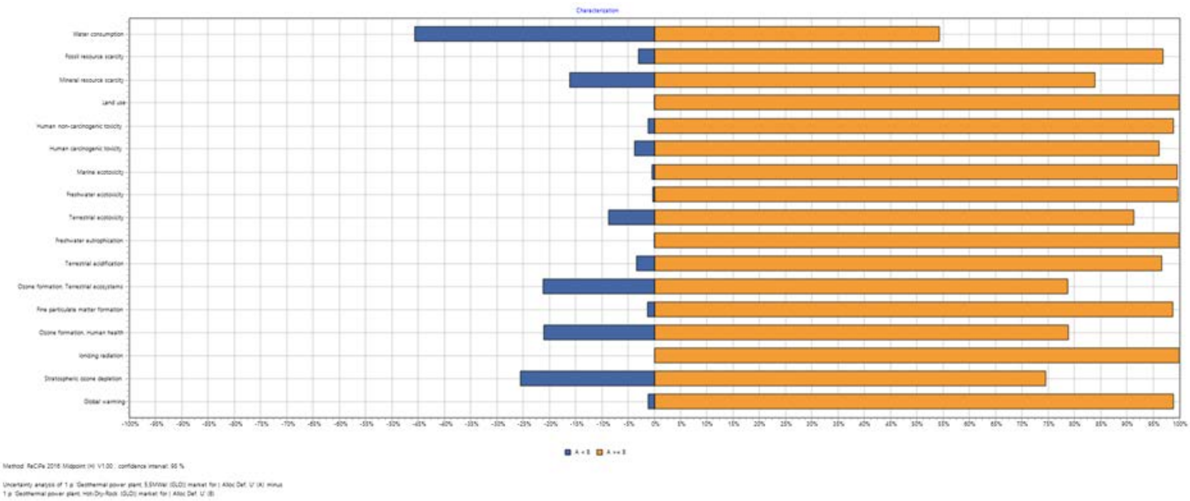


Figure 19: Monte-Carlo simulation results of LCIA uncertainties between studied geothermal power plants: medium capacity (A) and low capacity (B).

It is very important to stress the fact that the results depicted in both Figures 19 and 20 refer to the comparison of the raw LCA data and not the harmonized results as mentioned in Table 4 and Figure 18 (i.e. LCA results for each impact category per total electricity exported to grid and per installed capacity for each geothermal system). Thus these data do not include the provision for energy production from the plants for 30 or 20 years (depending on the medium or low capacity system respectively), and in this way the results ameliorate the behavior of the low capacity geothermal power plant.

In addition, Figure 20 presents a histogram of the Gaussian curve of results' distribution, which shows the probability in which plant A has a greater Global warming impact than plant B. The vertical axis displays the probability that a certain value is reached. This is a normal distribution and it is evident from the graph that in 98.8% of the 5000 studied cases A≥B, thus strengthening the results presented in Figure 19. Four lines are shown. The middle ones represent the mean and median value. The two other lines represent the 95% confidence interval. We use it to know the uncertainty of the difference between two products. If the difference is entirely positive or negative, it is clear there is a significant difference between A and B (thus strengthening the results of Figure 19).

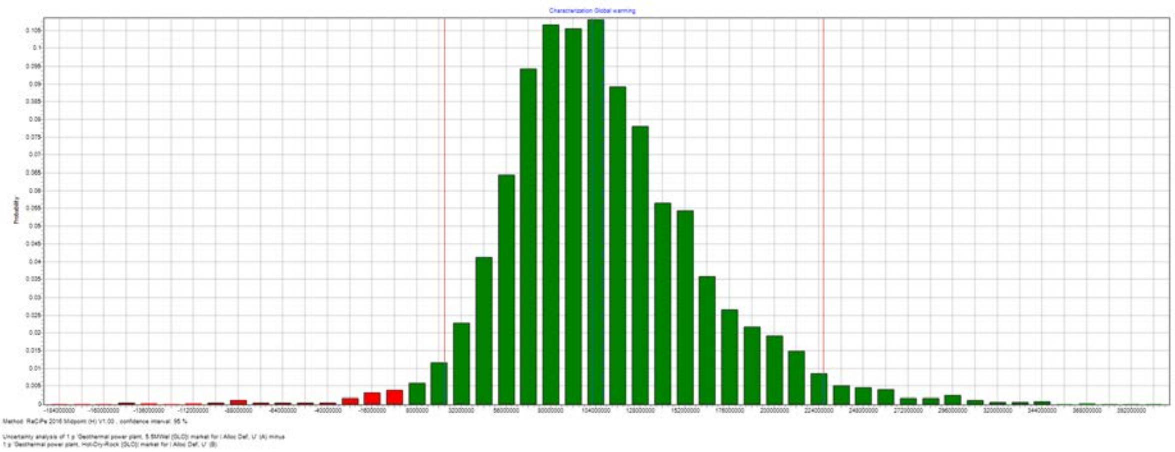


Figure 20: Monte Carlo analysis distribution of medium capacity (A) minus low capacity (B) geothermal power plant.

3.1.2 Energy and economic assessment of geothermal systems

The economic and energy assessment of the geothermal plants has been carried out using RETScreen. The site location for the installation of the systems was chosen to be the Acrotiri area in Chania, assuming the existence of the necessary geothermal potential as defined by the technical specifications for each plant (see Table 3). After selecting the location area the complete RETScreen analysis for each one of the studied geothermal plants has been conducted. This analysis comprised four discrete steps: **i.** selection of the technology (i.e. low and medium capacity plants) and specification of the technical parameters (see Figures 21 and 24), **ii.** energy analysis (see results in Table 3) **iii.** emissions analysis (see Figures 22 and 25), **iv.** financial analysis (see Figures 23 and 26). The exact technical characteristics of the studied geothermal plants have been incorporated thus allowing the precise quantification of the annual electricity production.

For all financial calculations the electricity price has been set to 0.15€/kWh (feed-in-tariff) and we have considered that the installation was funded by own means (no bank loan). The electricity produced allows for the mitigation of 32.3 and 17.3 ktons of CO_2-eq annually for the medium and the low capacity plant respectively. Both plants require a significant initial investment for their installation (14.4 and 27 million € for the low and medium plant respectively) but provide very fast payback time (i.e. 4.4 years) and have similar IRR values (i.e. ~25). The reason for this optimum performance lies in the fact that the capacity factor of both plants is 93% (or in other words their down-time is 7%), which is a realistic value for this kind of technology and geothermal fields. The economic viability of both systems is practically guaranteed, thus denoting the need of further investigation for proper locations for installation of such systems. A major difference of the studied plants is their anticipated lifetime (20 and 30 years) and this affects the overall environmental performance, as the medium capacity geothermal power plant will produce renewable electricity for 10 more years compared to the low capacity plant, while their environmental footprint per installed MW is practically very similar.

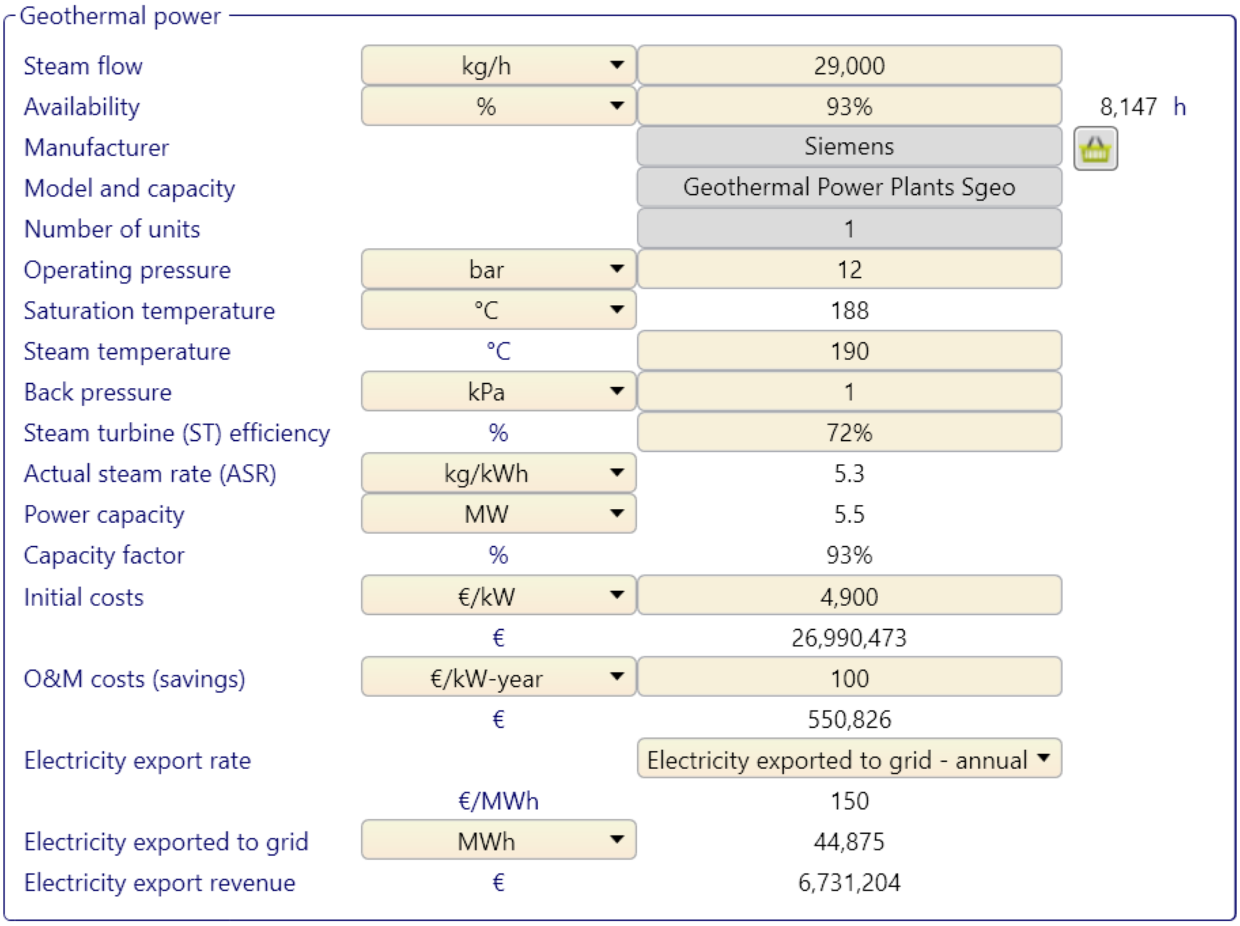


Figure 21: Technical specifications of the studied medium capacity geothermal power plant.

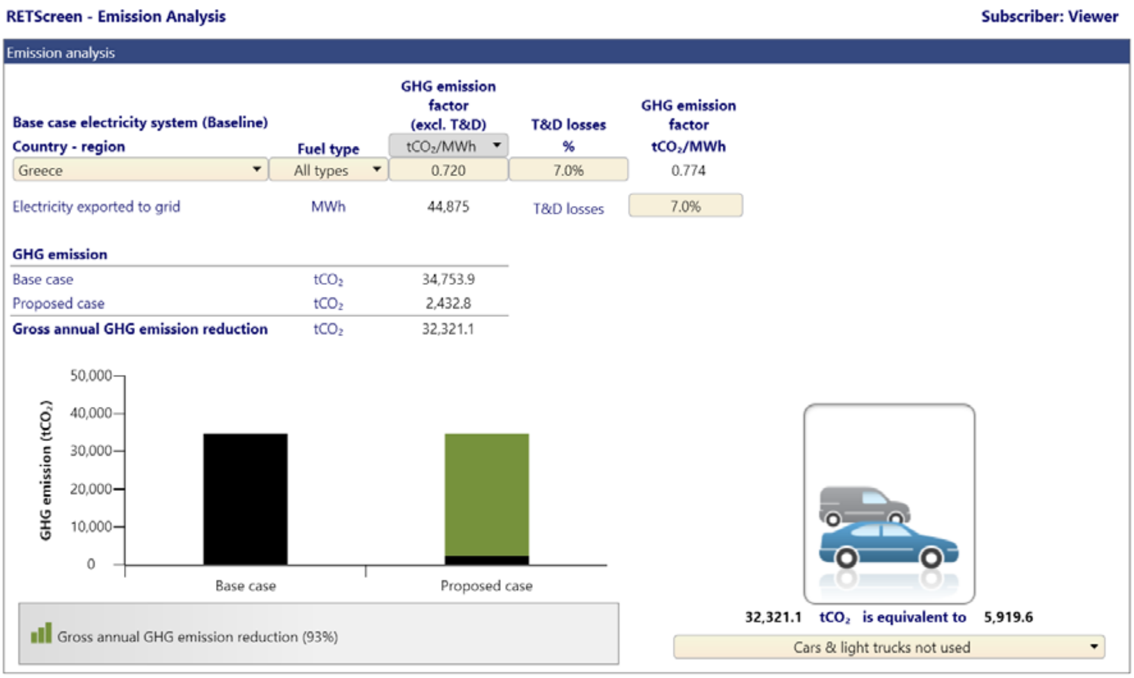


Figure 22: Air emissions analysis results of the studied medium capacity geothermal power plant.

Figure 23: Financial analysis results of the studied medium capacity geothermal power plant.

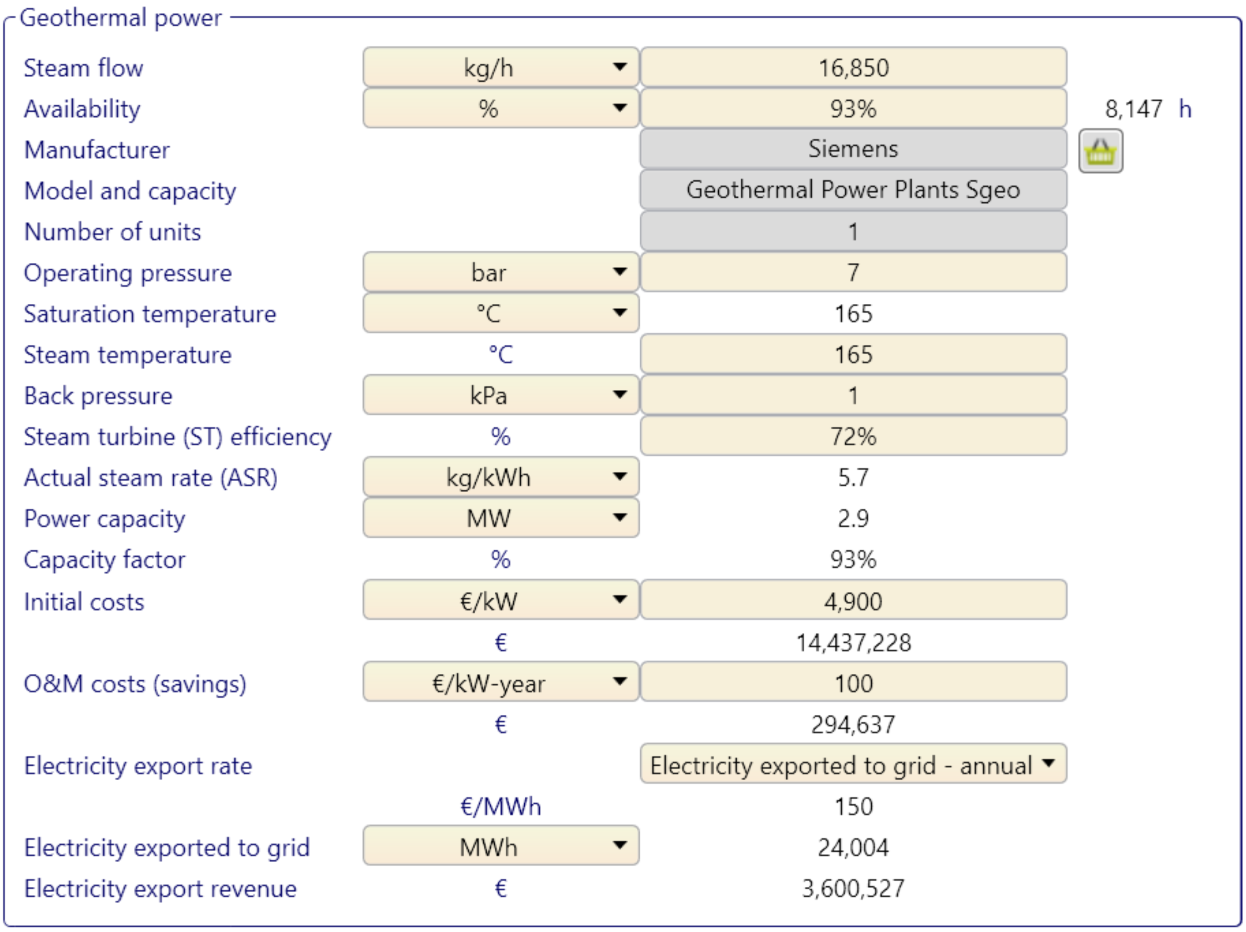


Figure 24: Technical specifications of the studied low capacity geothermal power plant.

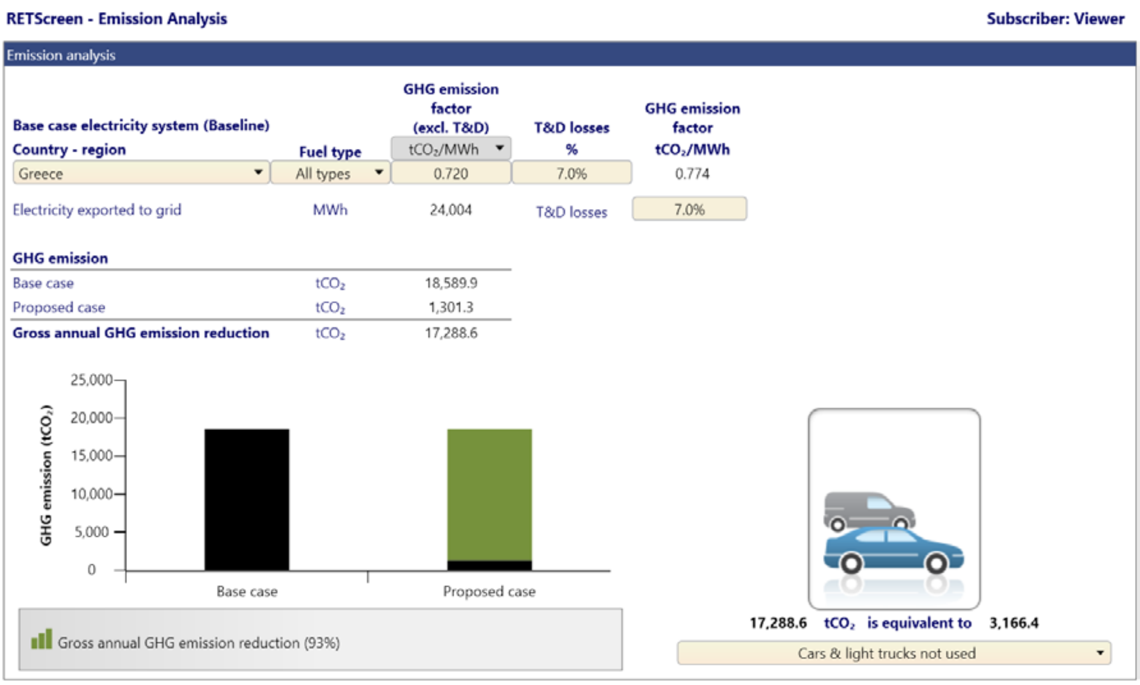


Figure 25: Air emissions analysis results of the studied low capacity geothermal power plant.

RETScreen - Financial Analysis | **Subscriber: Viewer**

Financial parameters

General		
Inflation rate	%	2%
Discount rate	%	9%
Project life	yr	20
Finance		
Incentives and grants	€	
Debt ratio	%	0%
Income tax analysis		☐

Annual revenue

Electricity export revenue		
Electricity exported to grid	MWh	24,004
Electricity export rate	€/kWh	0.15
Electricity export revenue	€	3,600,527
Electricity export escalation rate	%	2%
GHG reduction revenue		
Gross GHG reduction	tCO_2/yr	17,289
Gross GHG reduction - 20 yrs	tCO_2	345,772
GHG reduction revenue	€	0
Other revenue (cost)		☐
Clean Energy (CE) production revenue		☐

Costs | Savings | Revenue

Initial costs			
Initial cost	100%	€	14,437,228
Total initial costs	**100%**	**€**	**14,437,228**
Annual costs and debt payments			
O&M costs (savings)		€	294,637
Total annual costs		**€**	**294,637**
Annual savings and revenue			
Electricity export revenue		€	3,600,527
Total annual savings and revenue		**€**	**3,600,527**

Financial viability

Pre-tax IRR - equity	%	25%
Pre-tax IRR - assets	%	25%
Simple payback	yr	4.4
Equity payback	yr	4.1
Net Present Value (NPV)	€	20,962,157
Annual life cycle savings	€/yr	2,296,330
Benefit-Cost (B-C) ratio		2.5
Debt service coverage		No debt
GHG reduction cost	€/tCO_2	-133
Energy production cost	€/kWh	0.08

Yearly cash flows

Year #	Pre-tax €	Cumulative €
0	-14,437,228	-14,437,228
1	3,372,007	-11,065,221
2	3,439,447	-7,625,773
3	3,508,236	-4,117,537
4	3,578,401	-539,136
5	3,649,969	3,110,833
6	3,722,968	6,833,802
7	3,797,428	10,631,230
8	3,873,376	14,504,606
9	3,950,844	18,455,450
10	4,029,861	22,485,311
11	4,110,458	26,595,769
12	4,192,667	30,788,436
13	4,276,521	35,064,957
14	4,362,051	39,427,007
15	4,449,292	43,876,299
16	4,538,278	48,414,577
17	4,629,043	53,043,621
18	4,721,624	57,765,245
19	4,816,057	62,581,302
20	4,912,378	67,493,679

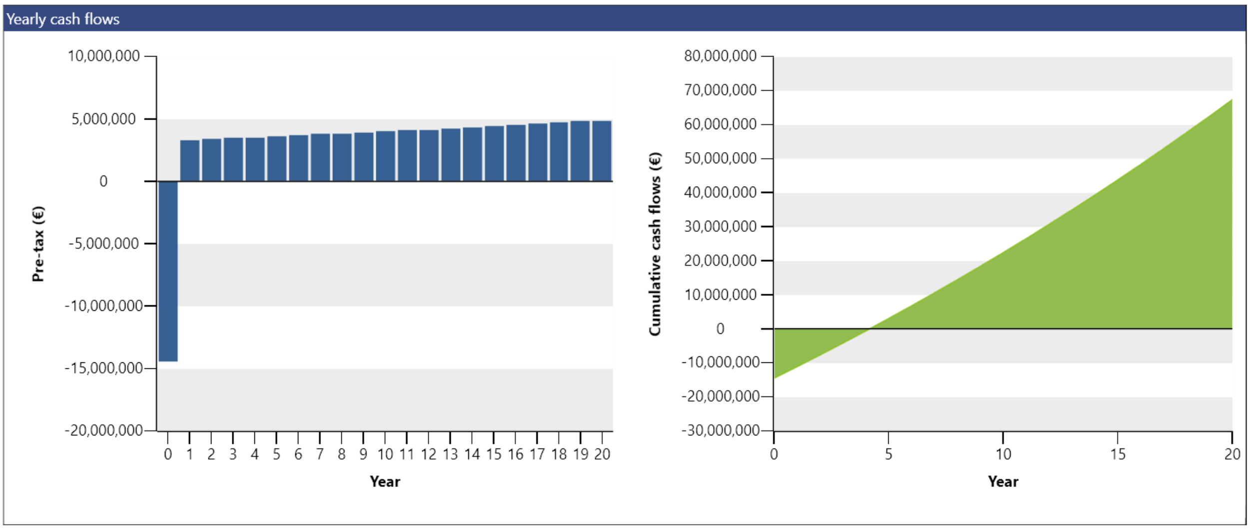


Figure 26: Financial analysis results of the studied low capacity geothermal power plant.

3.2 Photovoltaics

3.2.1 LCA analysis of PV systems

The LCA results have been used for the evaluation of the environmental impacts of various types of PV technologies. Four different PV systems using crystalline and thin-film technologies (as described in Table 2 at paragraph 2.3) were evaluated in this thesis, all having the same nominal capacity of 3kW. In this section the detailed results from the LCA of the studied PV systems are presented in order to determine which technologies are more hazardous to human health and ecosystem quality in a comparative assessment, distinguish which lifecycle stage of the PV energy production represents the majority of these impacts and finally evaluate their overall energy performance.

The LCA of a PV system starts with the extraction of raw materials (cradle) and follows along the product to the end of its life and the disposal (grave) of the PV components. The first stage of the process entails the mining of raw materials, for example quartz sand for silicon based PVs, followed by further processing and purification stages, to achieve the required high purities, which typically entails a large amount of energy consumption and related emissions. Other raw materials included are those for BoS components, for example silica for glass, copper ore for cables, and iron and zinc ores for mounting structures. At the end of their lifetime, PV systems are decommissioned and the valuable parts and materials are disposed. Although PV power systems do not require finite energy sources (fossil, nuclear) during their operation, a considerable amount of energy and emissions are released for their production. The environmental issues associated with this energy use for PV manufacturing will also affect the environmental profile of PV power systems. The environmental themes that are strongly related to the PV energy system are: exhaustion of finite resources, human health implications and climate change [75]–[77].

Goal and Scope. The goal of this LCA study is to evaluate over the lifecycle the impacts of the electricity produced by four different grid-tied 3kWp PV installations. The LCIA method used for the characterization of PV technologies is ReCiPe Midpoint, aiming to highlight the global warming potential and GHG emissions, fossil fuels and climate change impacts related to each technology. The results are ranked from worst to best environmental performance and will be used to validate the environmental impacts of each PV system. The objective of conducting the LCA study is to make a comparative environmental analysis of different PV systems with a focus on comparing crystalline with thin film technologies.

The system boundaries account for all the impacts from cradle to grave related to production, transportation and system disposal of PV systems. The main parts of the studied systems are: i. the PV-panels, ii. the inverter, iii. the electric installation, iv. the roof mounting structure. The process data for a 3kWp PV installation includes quartz reduction, silicon purification, wafer, panel and laminate production, manufacturing of inverter, mounting, cabling, infrastructure, assuming 30 years' operational lifetime. The following items were studied for each production stage as far as data were available:

- energy consumption,
- air and waterborne process-specific pollutants at all production stages (materials, chemicals, etc.),
- transport of materials, energy carriers, semi-finished products and the complete power plant,
- waste treatment processes for production wastes,
- dismantling of all components,

– infrastructure for all production facilities with its land use.

The PV systems have the same nominal installed capacity (i.e. 3kWp) and differ according to the cell type (single- and multi-crystalline silicon, thin film cells with amorphous silicon, and CIS). All systems are assumed to be installed on existing buildings (slanted roof installation).

Life Cycle Inventory analysis involves creating an inventory of flows from and to nature for a product system. Eco-invent v3.4 database has been employed for the inventories of PV systems, which can be assumed to be representative for typical PV installations. The eco-invent database provides detailed and transparent background data for a range of materials and services used in the production chain of photovoltaics. The delivery of the different PV parts to the final construction place is assumed with 100 km by a delivery van. This includes the transport of the construction workers. It is assumed that 20% of the panels are produced overseas and thus must be imported to Europe by ship. The lifetime of the inverter is assumed to be 15 years.

In Figures 27-34 the process networks for the studied PV systems are depicted for cut-off thresholds 1% and 10% respectively. The thick red line in the network trees is known as the elementary flow and indicates the environmental bottleneck or burden in each process. For the CIS system, 64.2% of all total inflows and outflows are due to the production of the photovoltaic panel. The installation phase and the inverter require 23.3% and 9.5% respectively of the energy and materials inflow. The main environmental impacts include the panel and cell production, inverter and installation/construction phases. There are also impacts associated with the electricity, transportation and system disposal, which are taken into consideration. Similar values stand for the case of a-Si panel: 56.9% for the production phase, 32.5% and 8% for the installation phase and the inverter respectively. For the sc-Si and mc-Si panels, 77.6% and 72.5% respectively of all total inflows and outflows are due to the production of the photovoltaic panel, installation is 13.1% and 16.5% respectively, while inverter accounts for 7% and 8.3% respectively.

As the networks clearly show, the production stage contributes the most important part of the environmental impacts in the life cycle of all studied PV technologies. The elementary flows indicate that most inflows of materials and energy for both thin-film and crystalline technologies occur during the cell and panel production phase; subsequently large emissions and impacts to the environment and human health follow this stage of the PV systems' lifecycle. Based on the above, we can conclude that the cell and panel production phase are the most important inputs to the development of a 3kWp PV system, followed by the inverter and construction of the mounting systems.

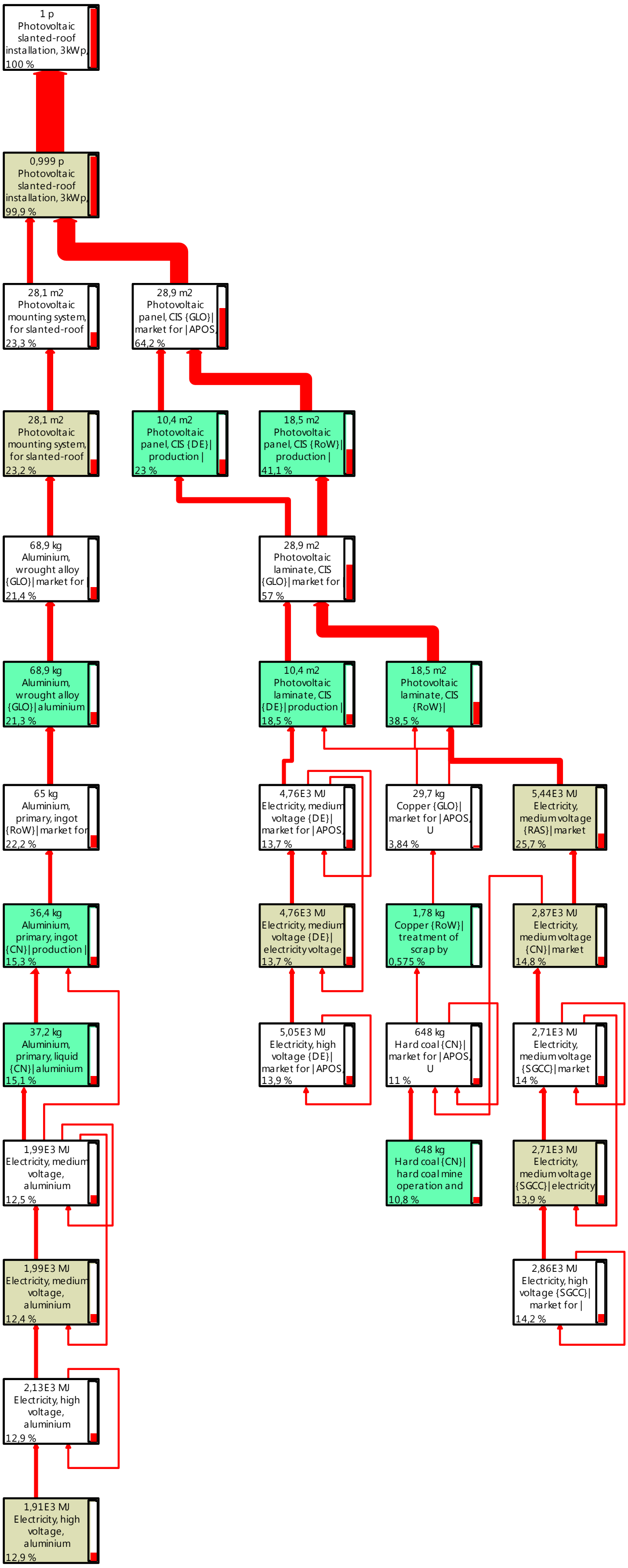


Figure 27: Process network for CIS PV system. Cut-off threshold: 10%, total nodes: 11607.

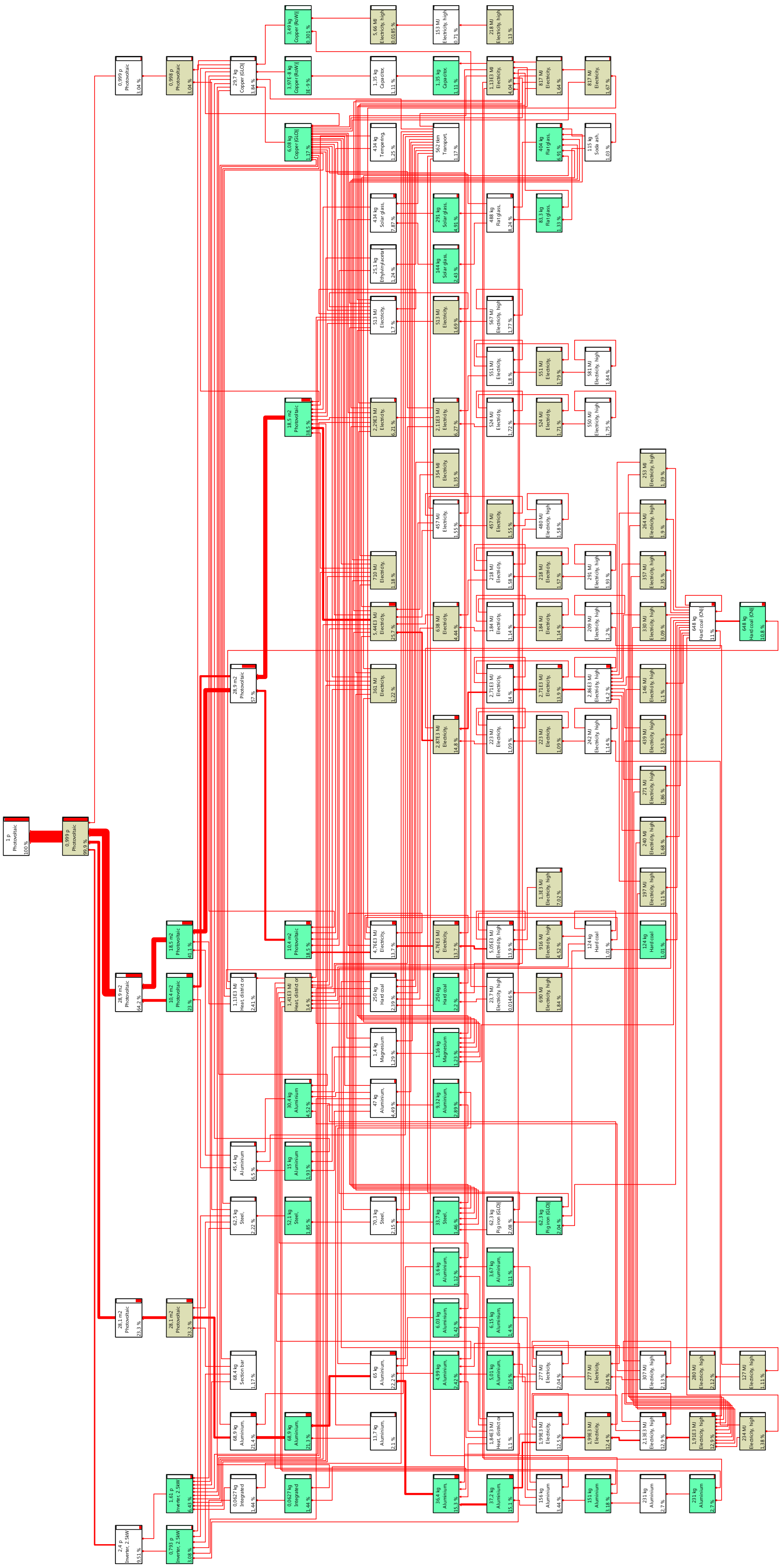


Figure 28: Process network for CIS PV system. Cut-off threshold: 1%, total nodes: 11607.

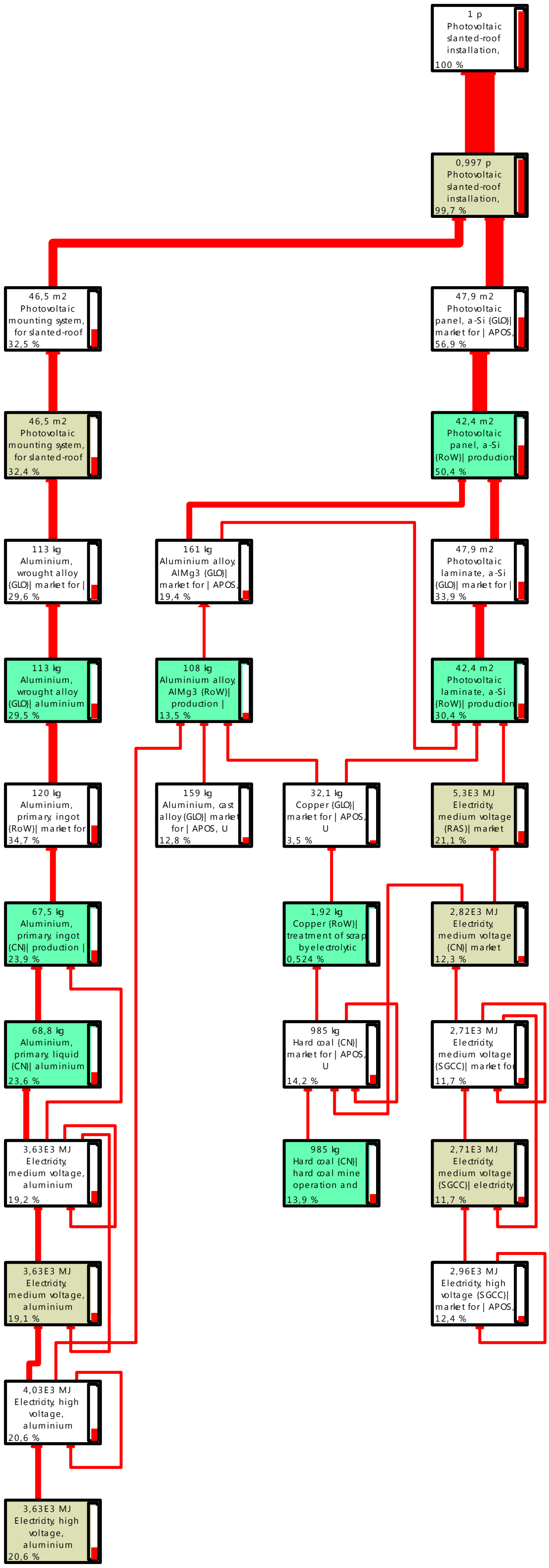


Figure 29: Process network for a-Si PV system. Cut-off threshold: 10%, total nodes: 11607.

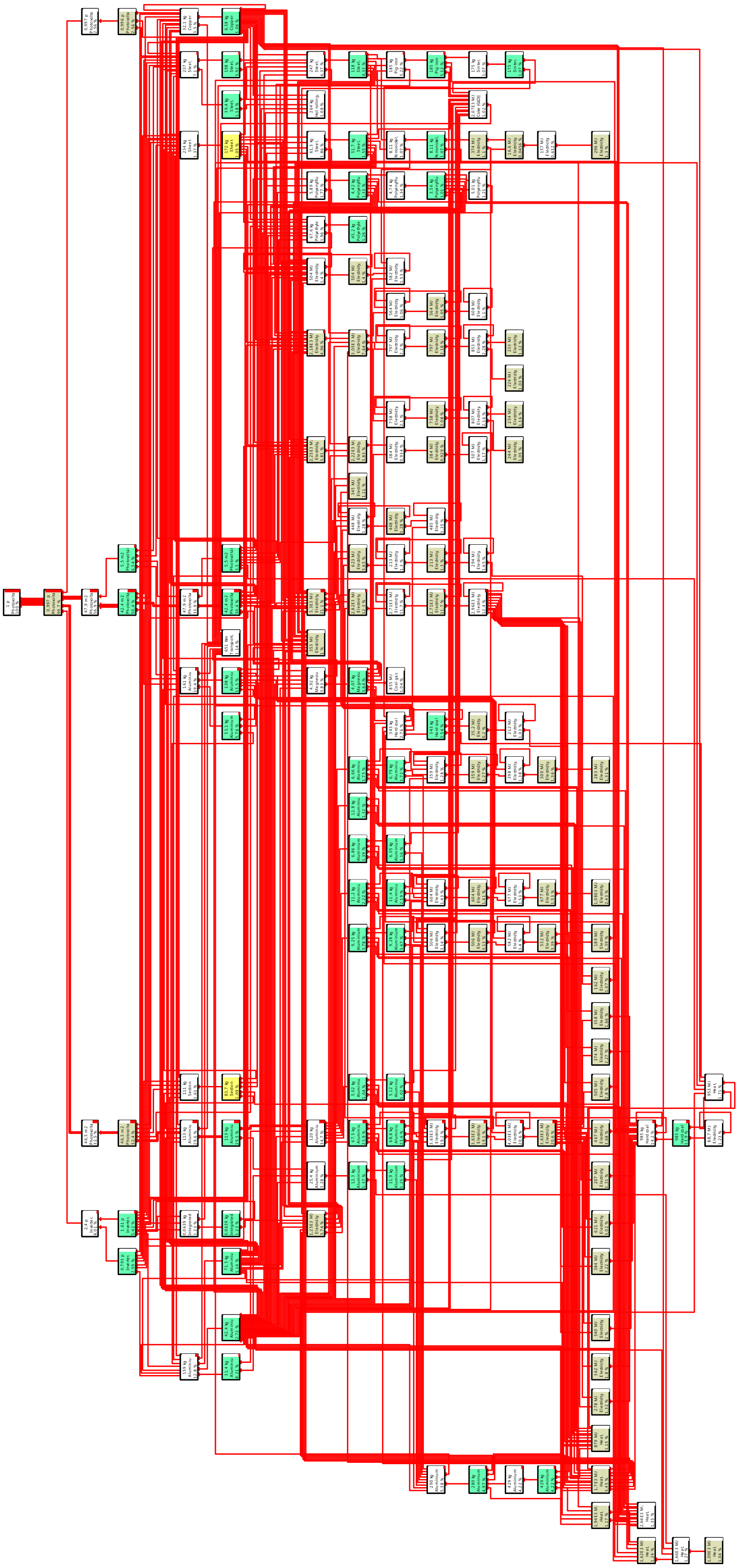


Figure 30: Process network for a-Si PV system. Cut-off threshold: 1%, total nodes: 11607.

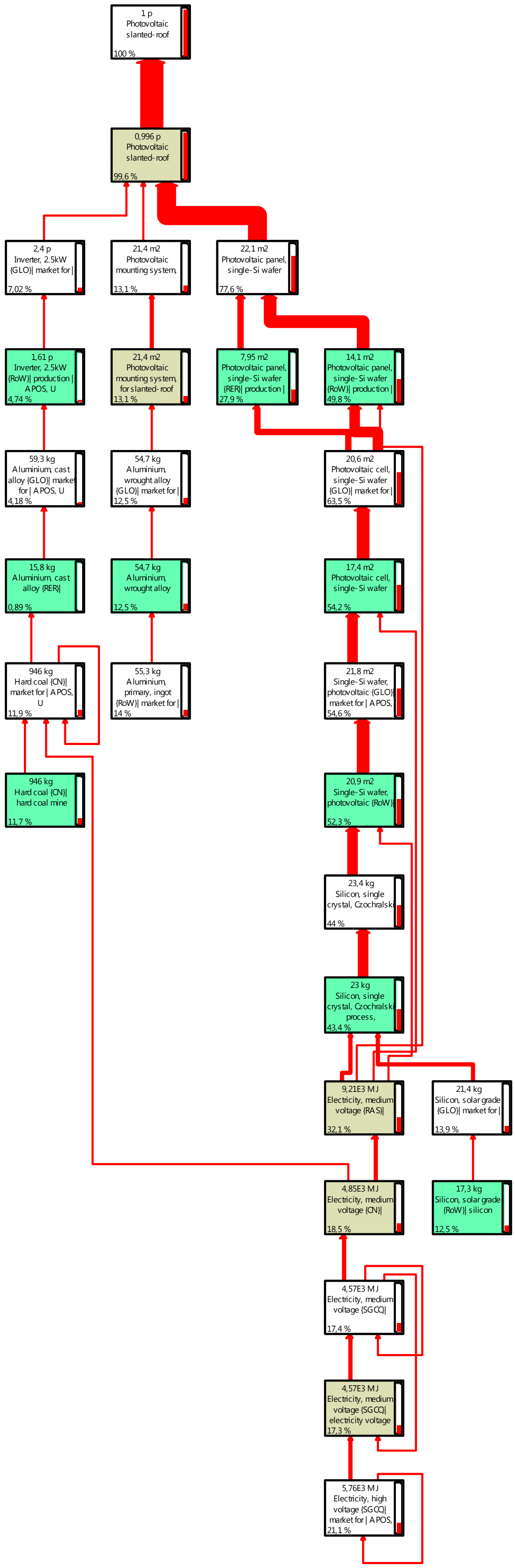


Figure 31: Process network for sc-Si PV system. Cut-off threshold: 10%, total nodes: 11607.

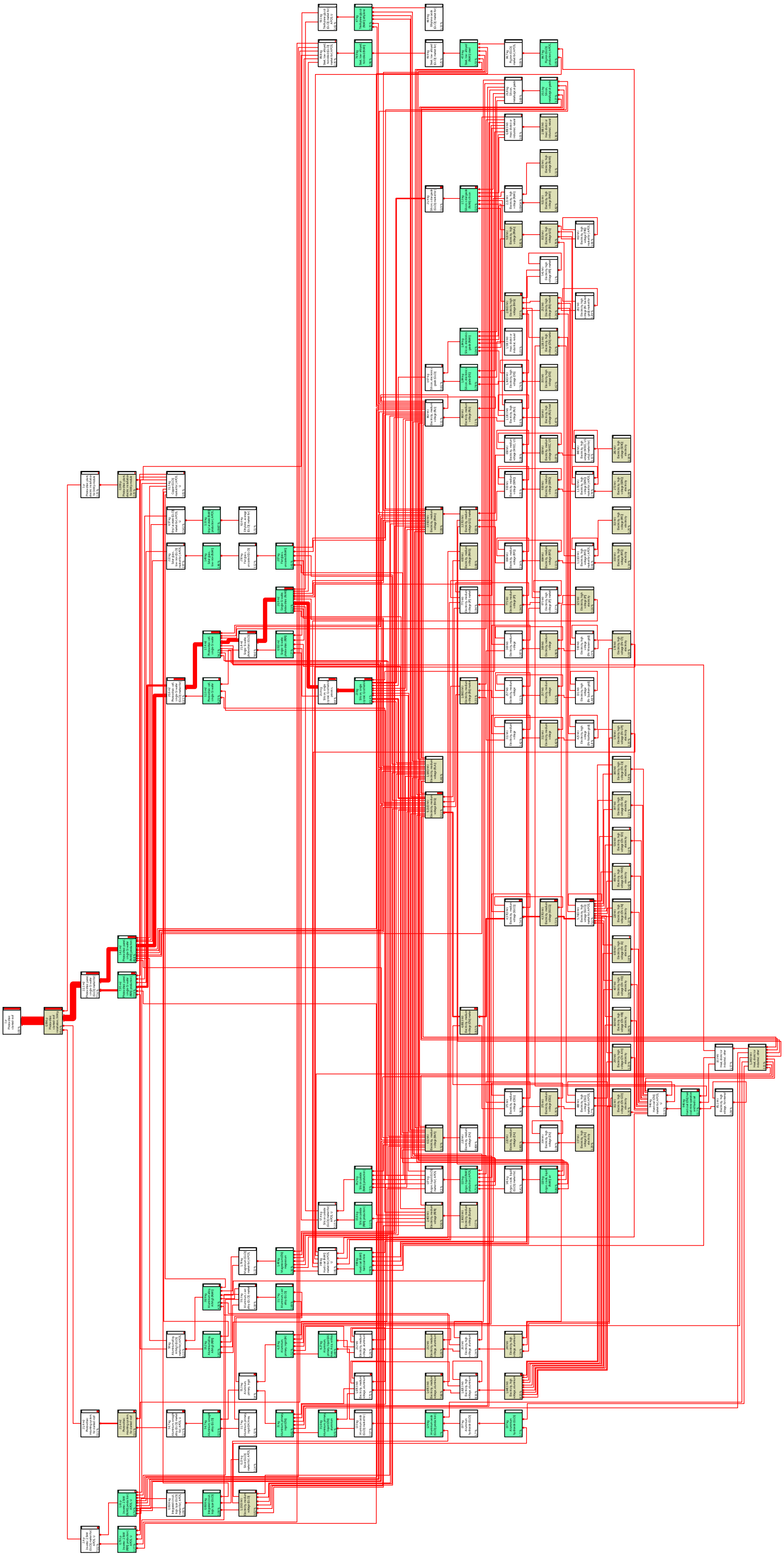


Figure 32: Process network for the sc-Si PV system. Cut-off threshold: 1%, total nodes: 11607.

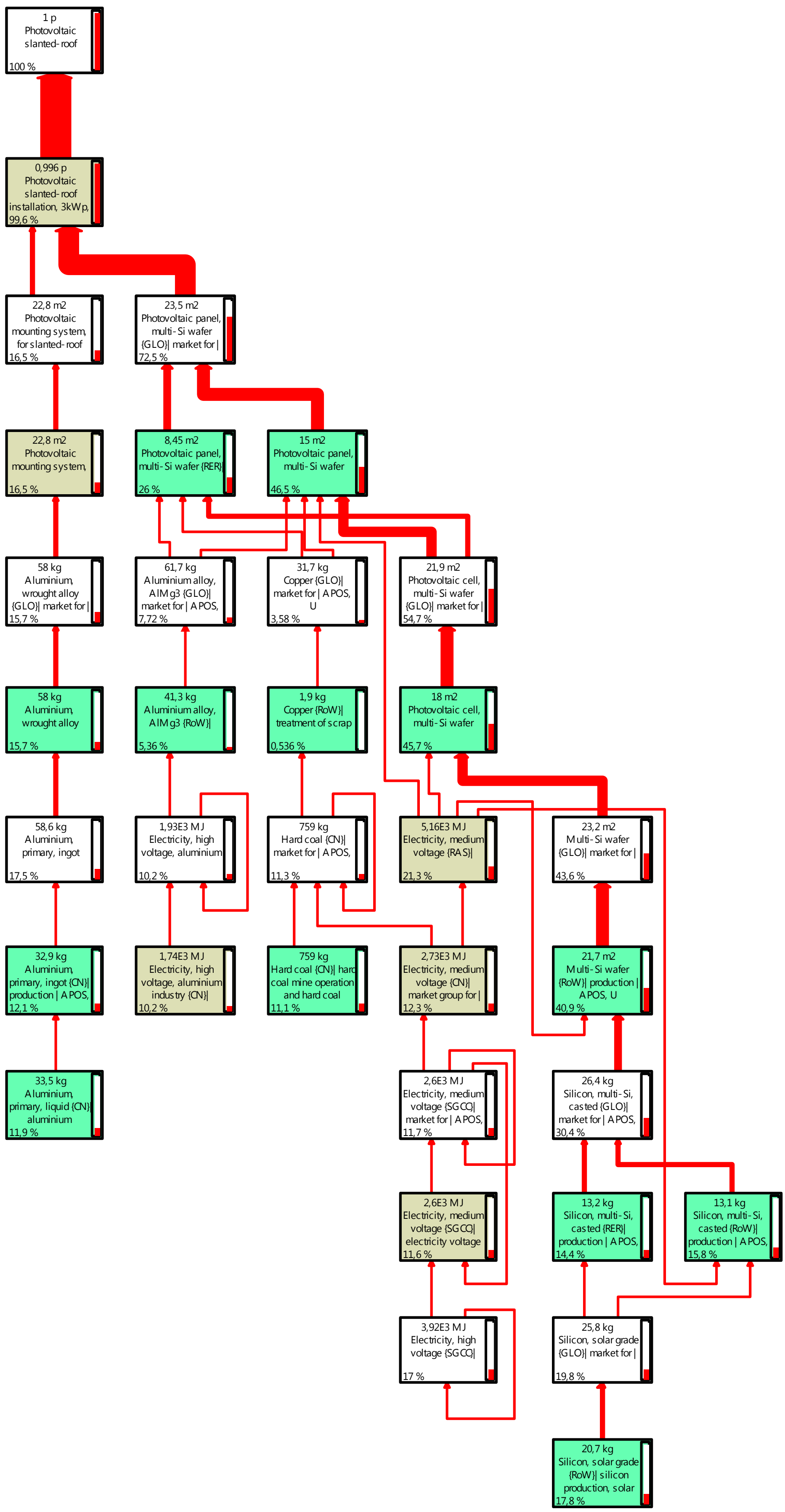


Figure 33: Process network for the mc-Si PV system. Cut-off threshold: 10%, total nodes: 11607.

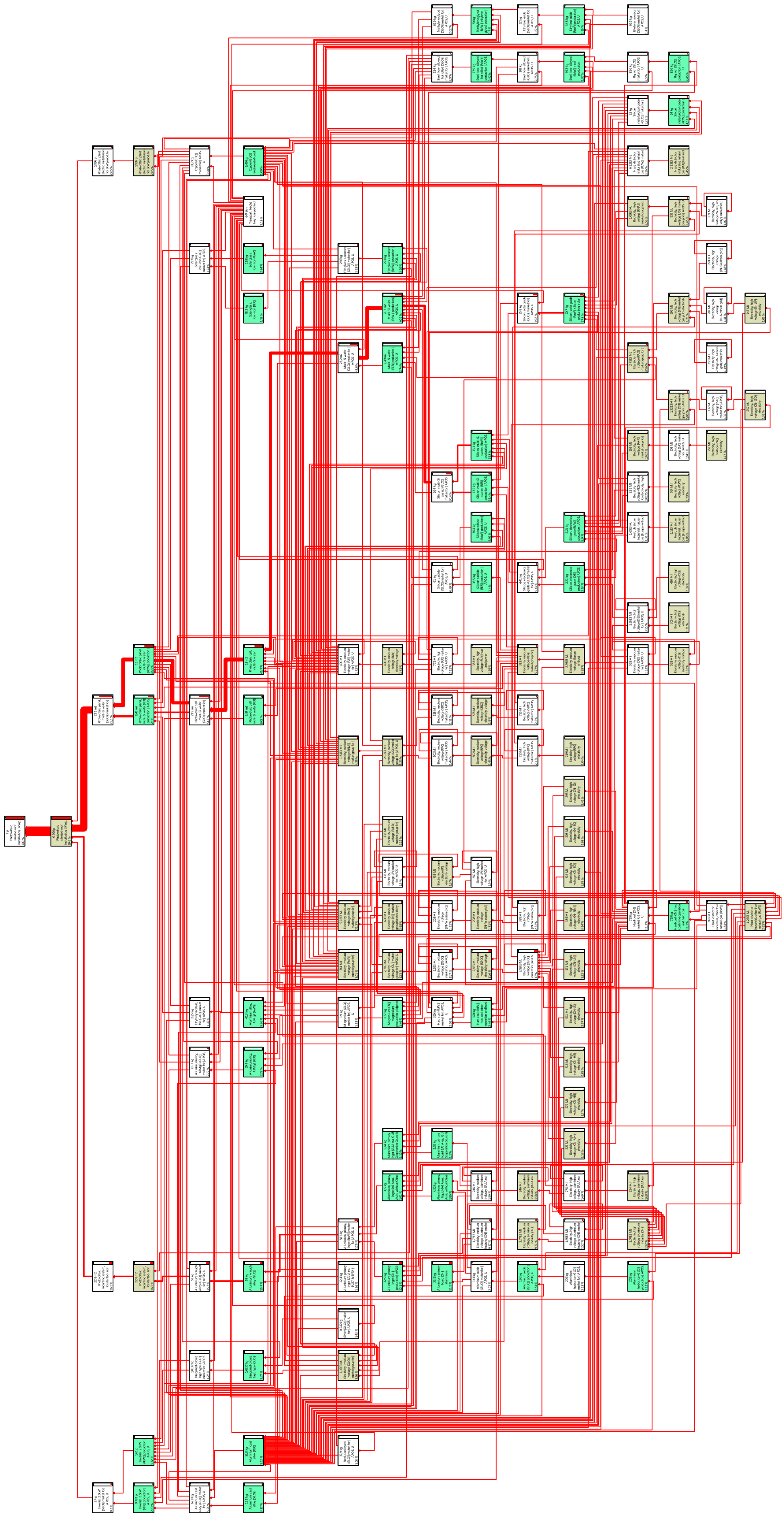


Figure 34: Process network for mc-Si PV system. Cut-off threshold: 1%, total nodes: 11607.

The environmental impacts of PV systems have been calculated by means of a Cradle-to-Grave LCA. Typical operation of PV systems has been taken under consideration. In Table 5 and Figure 35 the aggregated LCA inventory results for the studied PV systems are presented. These are harmonized data representing the LCA results (for each impact category) per total electricity exported to grid (in kWh) by each 3kWp PV system, thus providing a holistic evaluation indicator (i.e. environmental burden per total energy produced).

Table 5: Aggregated LCA inventory results for the studied PV systems.

Impact category	Unit	a-Si	CIS	mc-Si	sc-Si
Global warming	kg CO2 eq/kWh	4.35E-02	3.95E-02	4.43E-02	5.24E-02
Stratospheric ozone depletion	kg CFC11 eq/kWh	1.70E-08	1.75E-08	2.06E-08	2.45E-08
Ionizing radiation	kBq Co-60 eq/kWh	3.95E-03	3.96E-03	4.08E-03	4.45E-03
Ozone formation, Human health	kg NOx eq/kWh	9.83E-05	9.09E-05	1.05E-04	1.20E-04
Fine particulate matter formation	kg PM2.5 eq/kWh	1.09E-04	9.39E-05	1.04E-04	1.23E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq/kWh	1.01E-04	9.26E-05	1.10E-04	1.25E-04
Terrestrial acidification	kg SO2 eq/kWh	2.25E-04	2.07E-04	2.21E-04	2.47E-04
Freshwater eutrophication	kg P eq/kWh	3.55E-05	4.62E-05	3.78E-05	4.07E-05
Terrestrial ecotoxicity	kg 1,4-DCB eq/kWh	4.69E-01	4.62E-01	1.17E+00	1.13E+00
Freshwater ecotoxicity	kg 1,4-DCB eq/kWh	1.11E-02	1.30E-02	1.16E-02	1.17E-02
Marine ecotoxicity	kg 1,4-DBC eq/kWh	1.43E-02	1.69E-02	1.53E-02	1.54E-02
Human carcinogenic toxicity	kg 1,4-DBC eq/kWh	6.50E-03	4.19E-03	4.17E-03	4.33E-03
Human non-carcinogenic toxicity	kg 1,4-DBC eq/kWh	1.46E-01	2.00E-01	1.63E-01	1.64E-01
Land use	m2a crop eq/kWh	1.13E-03	9.60E-04	1.23E-03	1.23E-03
Mineral resource scarcity	kg Cu eq/kWh	6.60E-04	8.21E-04	5.54E-04	5.42E-04
Fossil resource scarcity	kg oil eq/kWh	1.04E-02	9.40E-03	1.08E-02	1.27E-02
Water consumption	m3/kWh	4.51E-04	3.22E-04	1.35E-03	1.17E-03

The midpoint indicators in LCA correspond to different impact categories (as depicted in the first column of Table 5), in which all emissions, material use, water or land use with the same "damage mechanism" are aggregated. Equivalence factors (relative to one substance in each category) are used for aggregated quantification. For example, all greenhouse gas emissions from the total life cycle are compiled in the category "Global warming", calculated as CO_2 equivalents (CO_2-eq) according to their individual global warming potentials based on CO_2 as the reference substance.

In Figure 35 the relative contributions to the impact categories (based on the ReCiPe 2016 midpoint evaluation) for the studied PV systems are shown. The cumulative CO_2-eq emissions per kWh over the whole life cycle of the PV systems vary between approximately 3.9×10^{-2} and 5.2×10^{-2} kg CO_2 eq/kWh.

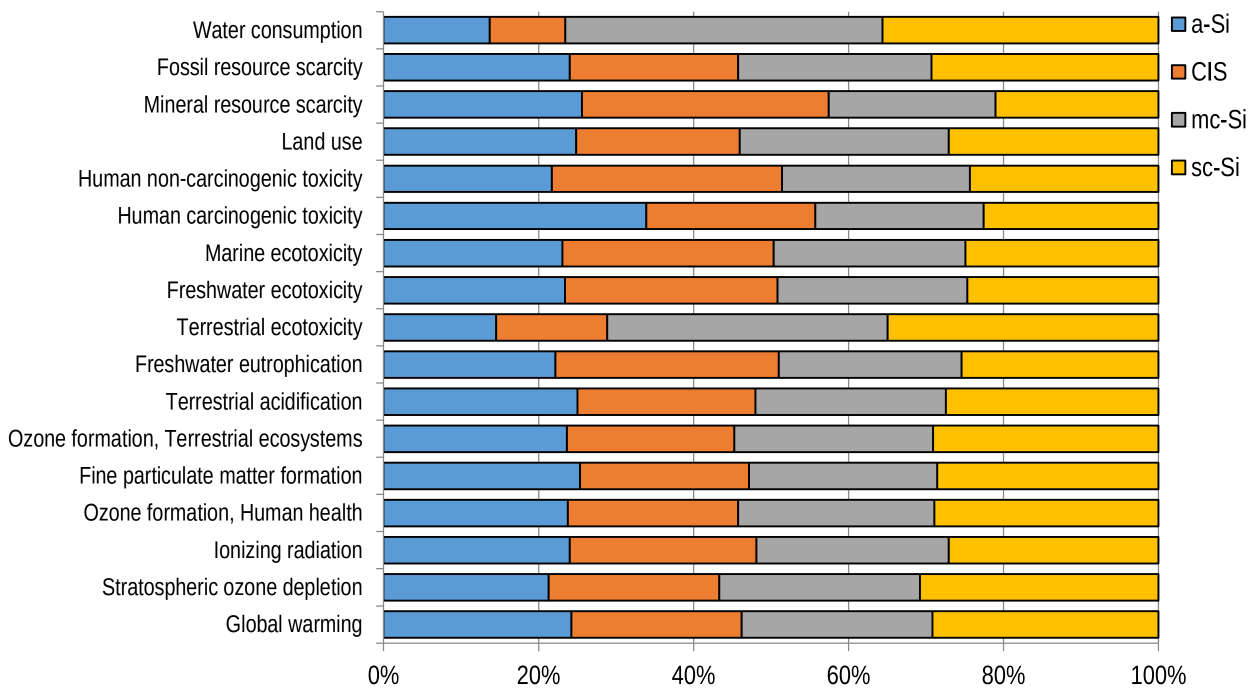


Figure 35: LCA results for the studied PV systems: relative contributions to the impact categories.

During the lifecycle of a PV system, initially, the extraction of resources leads to emissions that affect human health, including carcinogens and respiratory inorganics, while at a second level the use of fossil fuel during the production and manufacturing processes releases large amounts of greenhouse gases in the atmosphere causing climate change. Processes occurring during the panel production phase can significantly affect air quality as hazardous substances are emitted into the atmosphere and biosphere.

According to this analysis, the most severe burdens seem to be gathered to the following categories: global warming, fossil fuels resource scarcity, carcinogens, ecotoxicity and land use. The crystalline technologies (mc-Si and sc-Si) have increased values in almost all impact categories. Thin-film CIS, exhibits the lower impacts in most categories and seems to be an optimum selection from an environmental perspective compared to its other counterparts. Results indicate that there are impacts in all indicators, especially those affecting human health from the substances released into the air and water. The manufacturing of a-Si PV cells and panels requires silicon and the energy intensive "Siemens process" [78]. On the other hand, thin film PV systems have lower efficiencies and thus a 3kWp installation will require larger number of cells-panels and more materials for the mounting systems. According to this analysis, thin-film technologies require less materials' inflows for their construction and installation phases compared to crystalline systems and this coincides with reduced airborne pollutants – emissions and energy (also connected with transportation, distribution and mounting of the systems).

For the purposes of this study, two Monte Carlo analyses of the LCA results (repeated for 5000 iterations) have been implemented for a comparison between the PV systems in each studied technology (i.e. crystalline and thin film). The first analysis was conducted between A: a-Si and B: CIS PV systems, and the results in a bar chart form are depicted in Figure 36, showing the percentage of times when system A has a greater impact than system B (A-B≥0, in orange) and vice versa (A-B<0, in blue). This is a balanced graph and in general we can conclude that A has increased impacts compared to B in most of the studied midpoint categories. This is quite evident for the Human carcinogenic toxicity category, in which A has distinctively increased impacts compared to B for the 96.6% of the completed iterations. Respectively, Human non-carcinogenic toxicity and Freshwater eutrophication are the two cases that B appears to be worse than A, for almost 80% of the completed iterations.

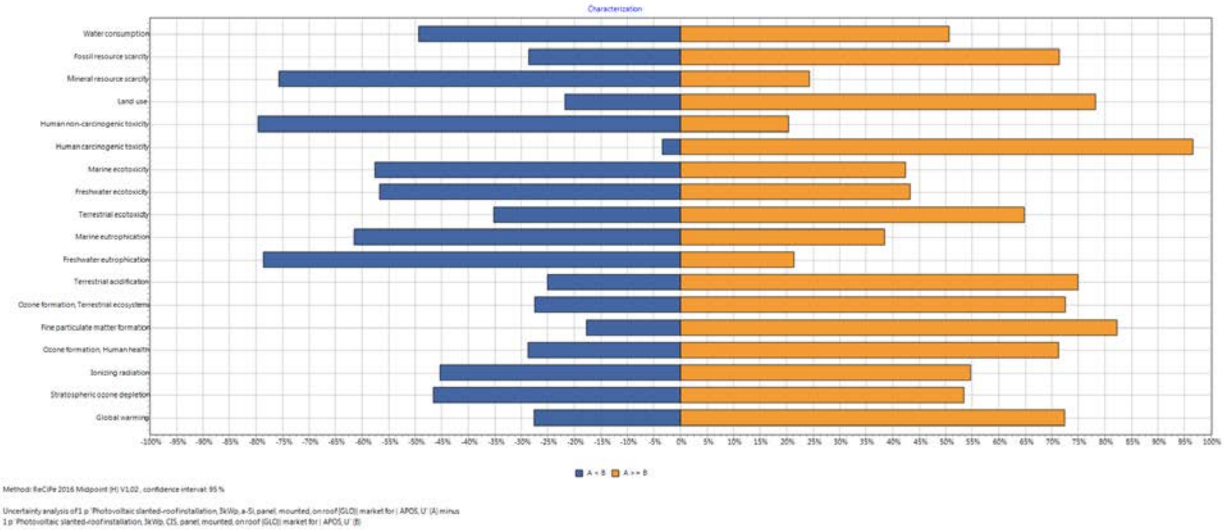


Figure 36: Monte-Carlo simulation results of LCIA uncertainties between a-Si (A) and CIS (B) PV systems.

The abovementioned results are also validated from Figure 37 which presents a histogram of the Gaussian curve of results' distribution, which shows the probability in which system A has a greater Global warming impact than system B. The vertical axis displays the probability that a certain value is reached. This is a normal distribution and it is evident from the graph that in 72.4% of the 5000 studied cases A≥B, thus strengthening the results presented in Figure 36.

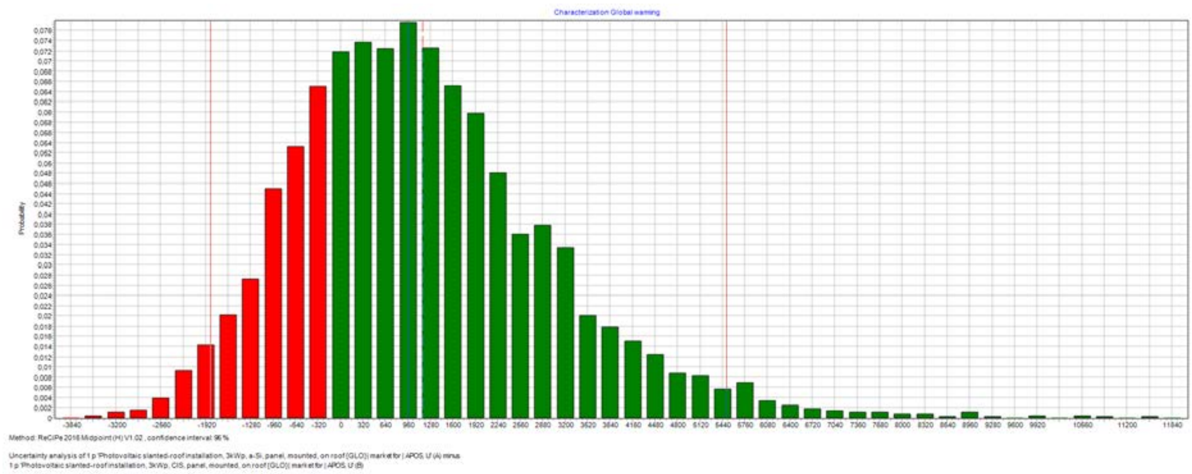


Figure 37: Monte Carlo analysis distribution of a-Si (A) minus CIS (B) PV systems.

The second Monte Carlo analysis was conducted between A: mc-Si and B: sc-Si PV systems. Figure 38 presents the results in a bar chart form, showing the percentage of times when system A has a greater impact than system B (A-B≥0, in orange) and vice versa (A-B<0, in blue). In this case it is evident that case A has lower impacts compared to B in most of the studied midpoint categories. The only impact categories that a balanced result is observed is the Land use, Water consumption, Mineral resource scarcity, Marine ecotoxicity and Freshwater ecotoxicity.

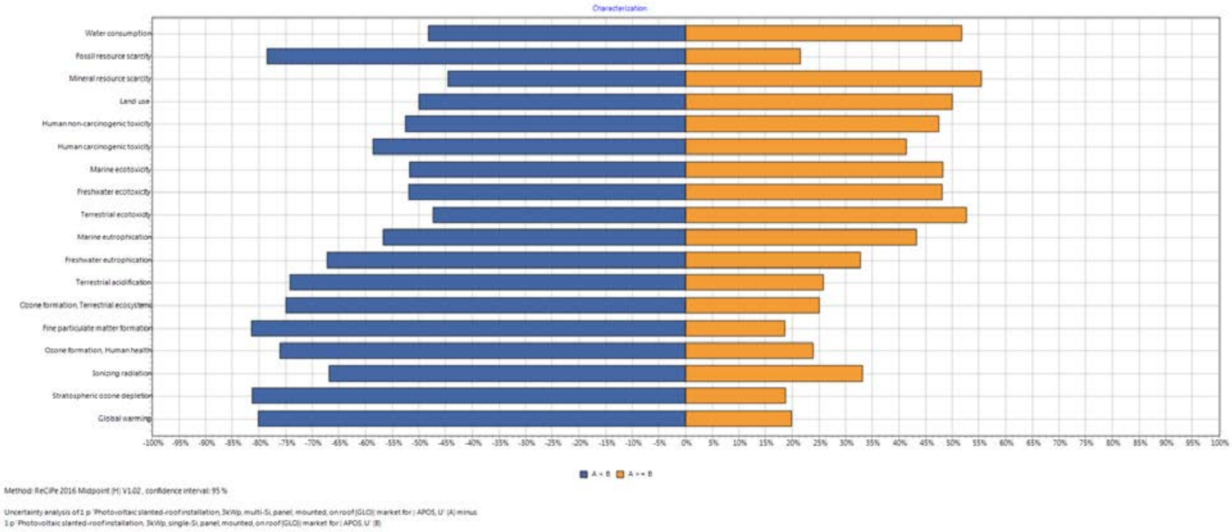


Figure 38: Monte-Carlo simulation results of LCIA uncertainties between mc-Si (A) and sc-Si (B) PV systems.

Figure 39 validates the abovementioned results for the Global warming impact category. This is a normal distribution and it is evident from the graph that in 80.0% of the 5000 studied cases A<B.

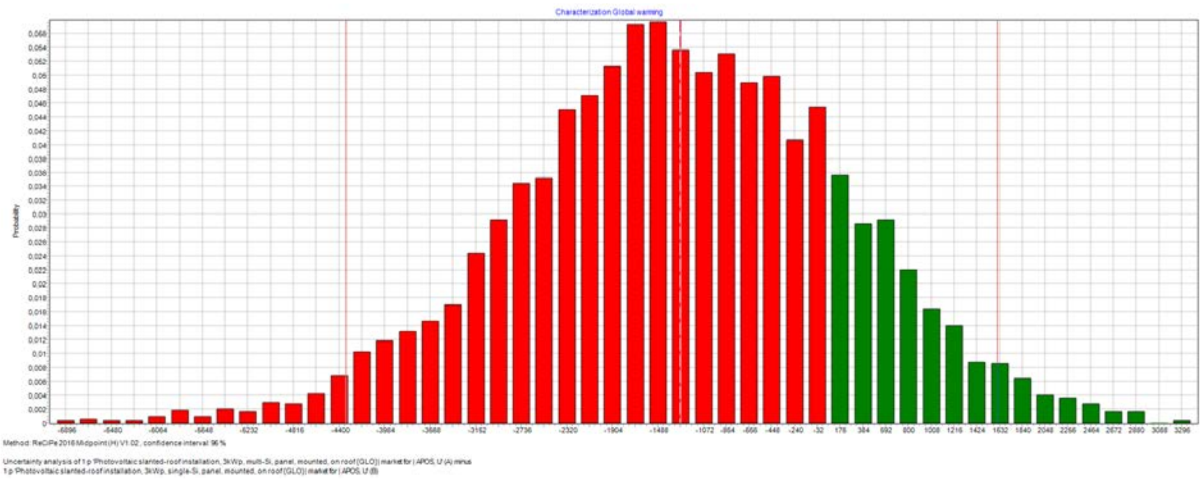


Figure 39: Monte Carlo analysis distribution of mc-Si (A) minus sc-Si (B) PV systems.

It is very important to stress the fact that the results depicted in Figures 36 – 39 refer to the comparison of the raw LCA data and not the harmonized results as mentioned in Table 5 and Figure 35 (i.e. LCA results for each impact category per total electricity exported to grid for each PV system). Thus these data do not include the provision for varying energy production for each of the studied systems.

Various additional technical components, the so-called Balance of System (BoS) elements, can also play an increasingly important role for the comparison of different types of PV technologies with different efficiencies and thus different sizes of mounting systems for the same electric output. These BoS elements can have a significant share of 30% to 50%. On the one hand, this is due to the improvements, which could be observed for the production chain until the output of the final photovoltaic cell. On the other hand, now a more detailed investigation of these additional elements is available, which for example also includes electronic components of the inverter. The low efficiency systems need larger amounts of mounting structure and cabling which partly outweighs the better performance per kWp of module alone [79]. Overall in the entire life cycle of both types of PV technologies, it was observed that the magnitude of environmental impacts of crystalline was greater than that of thin film.

3.2.2 Energy and economic assessment of PV systems

The first step in a pre-feasibility study of a solar (i.e. PV) project is to define the solar energy potential of the region in which the PV systems will be installed. This serves as a planning tool to quantify the anticipated electricity production and plant costs.

	Unit	Climate data location	Facility location	Source
Latitude		35.5	35.5	
Longitude		24.2	24.1	
Climate zone		3A - Warm - Humid		Ground+NASA
Elevation	m	146	0	Ground – Ground
Heating design temperature	°C	5.8		Ground
Cooling design temperature	°C	33.1		Ground
Earth temperature amplitude	°C	9.3		NASA

Month	Air temperature	Relative humidity	Precipitation	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days 18 °C	Cooling degree-days 10 °C
	°C	%	mm	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
January	11.0	77.3%	78.15	2.31	101.2	3.2	15.1	217	31
February	10.8	76.4%	62.94	3.20	101.1	3.3	14.9	202	22
March	12.6	74.4%	55.84	4.57	101.0	3.6	15.9	167	81
April	15.7	70.5%	29.35	6.30	100.8	3.7	17.9	69	171
May	20.1	64.4%	19.84	7.45	100.8	3.3	21.2	0	313
June	24.6	57.2%	7.48	8.45	100.7	3.2	24.7	0	438
July	26.6	57.9%	2.64	8.41	100.5	2.9	26.8	0	515
August	26.1	59.8%	2.15	7.58	100.5	3.0	27.3	0	499
September	23.3	65.9%	18.01	6.14	100.8	2.9	25.8	0	399
October	19.9	71.8%	45.27	4.28	101.1	2.8	22.8	0	307
November	15.6	75.8%	88.59	2.65	101.1	2.8	19.3	72	168
December	12.1	78.7%	102.22	2.05	101.2	3.2	16.4	183	65
Annual	**18.2**	**69.1%**	**512.48**	**5.29**	**100.9**	**3.2**	**20.7**	**910**	**3,009**
Source	Ground	Ground	NASA	NASA	NASA	Ground	NASA	Ground	Ground
Measured at					m	10	0		

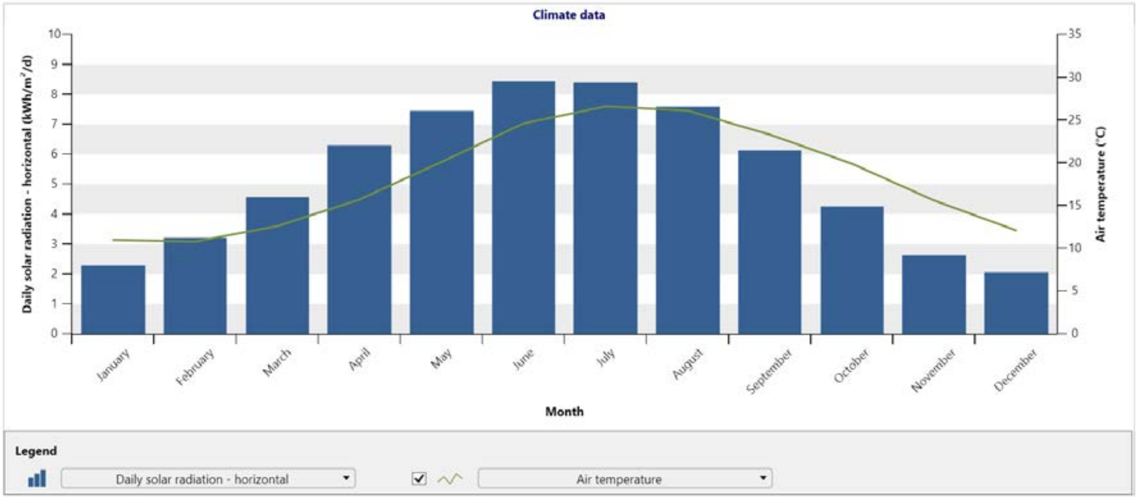


Figure 40: Average climate conditions for the PV systems' installation area (data extracted from RETScreen).

The evaluation of these PV technology costs, require in-depth analysis of site-specific solar energy potential, costs of solar technologies, customer types, meter types, utility types, physiographic conditions, local, regional and national laws and regulations, feed-in-tariffs and financial mechanisms, etc. The techno-economic analysis carried out in this part of the thesis quantifies the energy output and the economic income associated with each of the studied 3kWp PV power plants for installation in Crete, Greece. The economic and energy assessment of the PV systems has been carried out using the RETScreen software. The completed study involves quantifiable results for energy – economic impacts and savings for the chosen PV system. The site location for the installation of the PV systems was chosen to be the Acrotiri area in Chania, while all meteorological data (annual time series of average climate conditions as presented in Figure 40) have been extracted from RETScreen referring to a weather station of Souda Bay, Chania.

The results of the RETScreen economic analysis provide a reliable and comprehensive evaluation of the anticipated energy production, emissions reduction, investment cost, financial viability and risks associated with the specific project. The most suitable or appropriate technological means will be identified and the methodology for procurement, installation, operation, and end use of the PV systems will also be indicated. The accuracy of RETScreen is considered to be more than sufficient for preliminary feasibility studies and a small reduction in accuracy due to the use of monthly rather than hourly solar radiation data, is more than compensated for due to the ease-of-use of the software.

After selecting the location area the complete RETScreen analysis for each one of the studied PV systems has been conducted. This analysis comprised four discrete steps: **i.** selection of the technology (i.e. sc-Si, mc-Si, CIS, a-Si) and specification of the technical parameters (see Figures 42, 44, 46, 48), **ii.** energy analysis (see results in Table 6), **iii.** emissions analysis (see Figure 41 for the sc-Si system), **iv.** financial analysis (see Figures 43, 45, 47, 49).

Table 6: Results of the techno-economic assessment for the studied PV systems.

	PV technology	Cell efficiency [%]	Frame area [m²]	Capacity per unit [W]	Total area [m²]	Cost [€/kW]	Capacity factor [%]	Total electricity exported to grid [MWh]	Annual revenue [€/yr]	IRR [%]	Payback time [years]
Crystalline	sc-Si	17	1.18	200	17.7	1600	20.6	162.6	813	17.8	6.4
	mc-Si	12.3	1.02	125	24.5	1500	20.6	162.6	813	18.9	6
Thin-film	CIS	10.6	0.94	100	28.2	1600	20.2	159.3	797	17.4	6.5
	a-Si	6.1	0.82	50	49.2	1500	21.8	171.6	858	20.0	5.6

For all financial calculations the electricity price has been set to 0.15€/kWh and we have considered that the installation was funded by own means (no bank loan). In Table 6 the main results of the RETScreen analysis for all studied PV systems have been gathered. The cell efficiencies of the PV systems vary (from 6.1% to 17%) but this parameter does not play an important role as the nominal capacity of all systems is set to 3 kW. On the other hand the larger the efficiency of the panel the less the area needed for the installation (from 17.7m^2 to 49.2m^2). The economic viability of all systems is obvious, as the simple payback period is 5.6 - 6.5 years and IRR values vary from 17.4 to 20.0. The a-Si system seems to have higher annual energy yield. This is practically due to the ability of these systems to produce more electricity under haze or cloudy conditions and thus their capacity factor is increased (21.8%) compared to their counterparts. The electricity produced allows for the mitigation of ~4 tons of CO_2-eq annually for all PV systems.

According to the comparison the different PV technologies, the anticipated energy production, emissions reduction, investment cost, financial viability and risks associated with the four technologies are approximately the same. All technologies portray relatively equal cost benefit ratios and financial parameters. This is mainly due to the fact that our selection of comparing 3kWp systems harmonizes the influence of all technical advantages amongst technologies. On the other hand, the sc-Si system is the most efficient per cell thus needing less area per installation compared to the other cases.

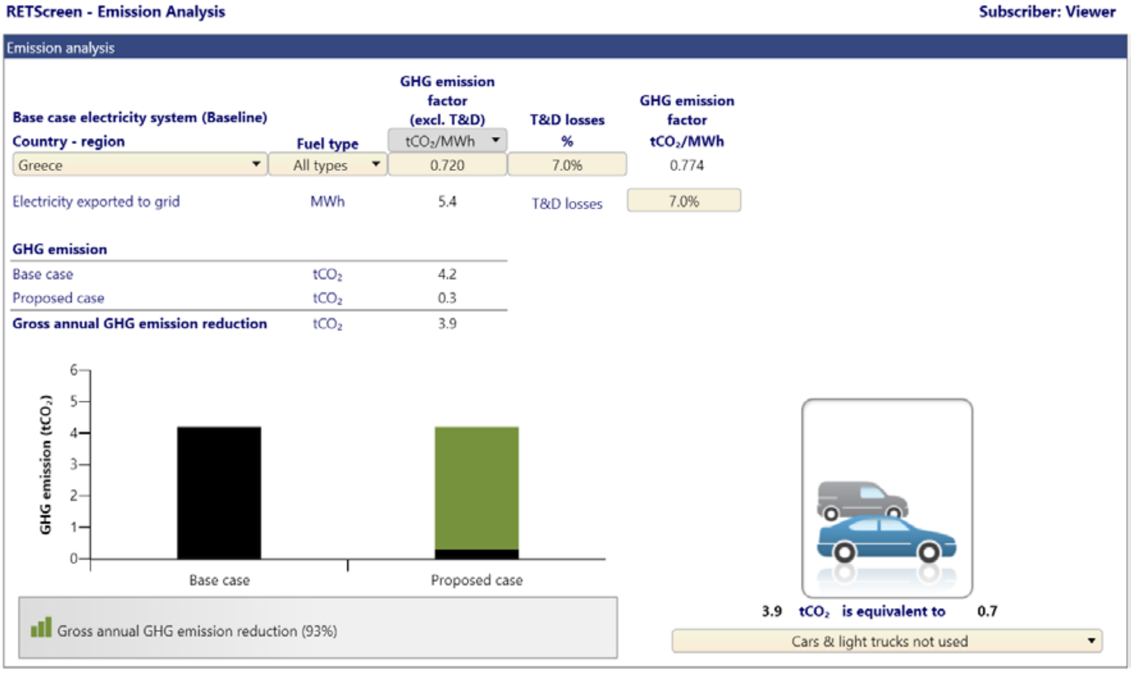


Figure 41: Air emissions analysis results of the studied sc-Si PV system.

Photovoltaic - Level 2

Resource assessment

Solar tracking mode		Fixed
Slope	°	30
Azimuth	°	0

Show data

Month	Daily solar radiation - horizontal kWh/m²/d	Daily solar radiation - tilted kWh/m²/d	Electricity export rate €/kWh	Electricity exported to grid MWh
January	2.31	3.30	0.15	0.282
February	3.20	4.14	0.15	0.318
March	4.57	5.29	0.15	0.442
April	6.30	6.55	0.15	0.519
May	7.45	7.05	0.15	0.565
June	8.45	7.63	0.15	0.577
July	8.41	7.74	0.15	0.598
August	7.58	7.61	0.15	0.588
September	6.14	6.96	0.15	0.529
October	4.28	5.52	0.15	0.445
November	2.65	3.74	0.15	0.302
December	2.05	3.01	0.15	0.257
Annual	**5.29**	**5.72**	**0.15**	**5.421**

Annual solar radiation - horizontal	MWh/m²	1.93
Annual solar radiation - tilted	MWh/m²	2.09

Photovoltaic

Type		mono-Si
Power capacity	kW	3
Manufacturer		Sanyo
Model		mono-Si - HIP-200BA3
Number of units		15
Efficiency	%	17%
Nominal operating cell temperature	°C	45
Temperature coefficient	% / °C	0.4%
Solar collector area	m²	17.6
Miscellaneous losses	%	4%

Inverter

Efficiency	%	97%
Capacity	kW	3
Miscellaneous losses	%	0%

Summary

Capacity factor	%	20.6%
Initial costs	€/kW	1,600
	€	4,800
O&M costs (savings)	€/kW-year	20
	€	60
Electricity export rate		Electricity exported to grid - annual
	€/kWh	0.15
Electricity exported to grid	MWh	5.4
Electricity export revenue	€	813

Figure 42: Technical specifications of the studied sc-Si PV system.

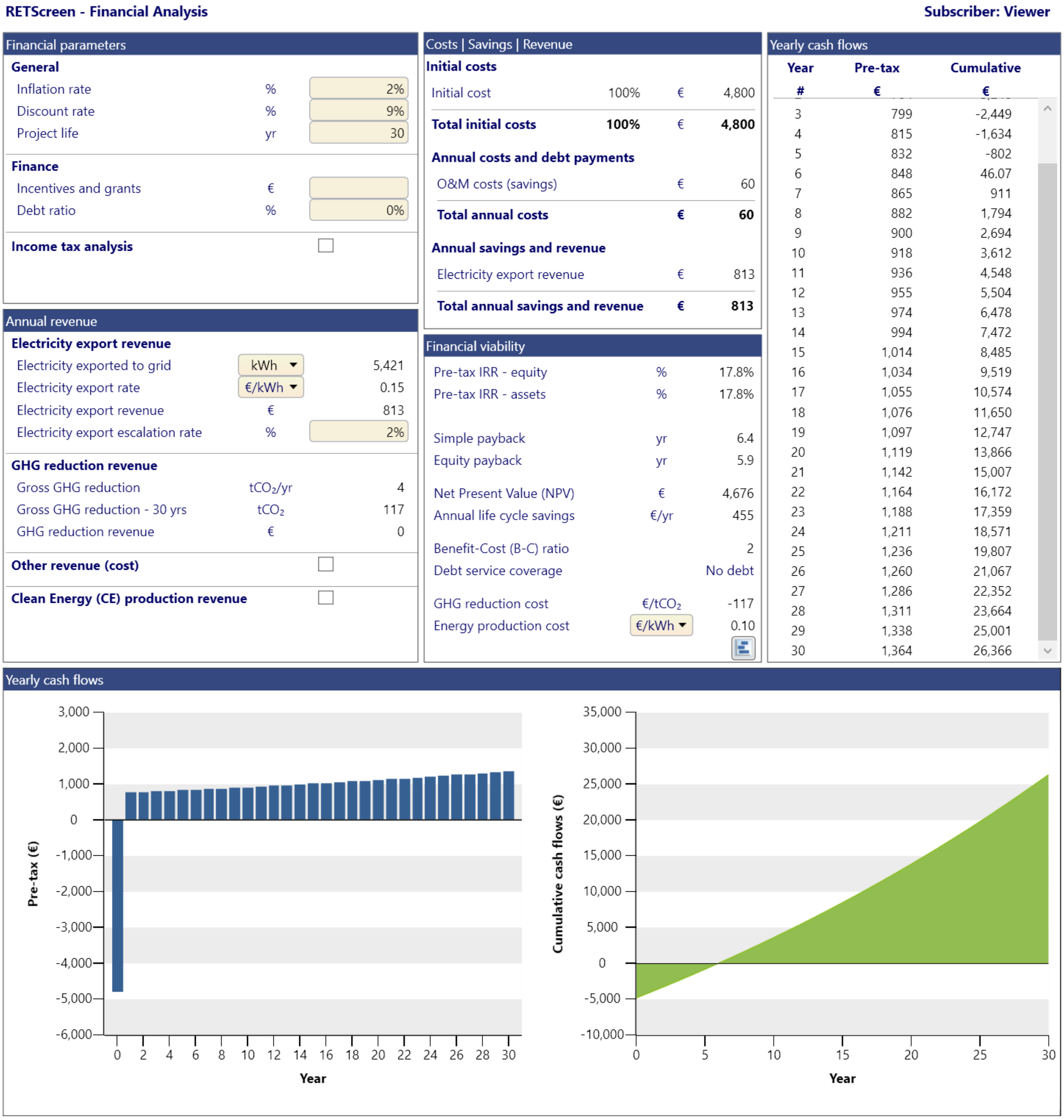


Figure 43: Financial analysis results of the studied sc-Si PV system.

Photovoltaic - Level 2

Resource assessment

Solar tracking mode		Fixed
Slope	°	30
Azimuth	°	0

Show data

Month	Daily solar radiation - horizontal kWh/m²/d	Daily solar radiation - tilted kWh/m²/d	Electricity export rate €/kWh	Electricity exported to grid MWh
January	2.31	3.30	0.15	0.282
February	3.20	4.14	0.15	0.318
March	4.57	5.29	0.15	0.442
April	6.30	6.55	0.15	0.519
May	7.45	7.05	0.15	0.565
June	8.45	7.63	0.15	0.577
July	8.41	7.74	0.15	0.598
August	7.58	7.61	0.15	0.588
September	6.14	6.96	0.15	0.529
October	4.28	5.52	0.15	0.445
November	2.65	3.74	0.15	0.302
December	2.05	3.01	0.15	0.257
Annual	**5.29**	**5.72**	**0.15**	**5.421**

Annual solar radiation - horizontal	MWh/m²	1.93
Annual solar radiation - tilted	MWh/m²	2.09

Photovoltaic

Type		poly-Si
Power capacity	kW	3
Manufacturer		BP Solar
Model		poly-Si - BP 3125
Number of units		24
Efficiency	%	12.3%
Nominal operating cell temperature	°C	45
Temperature coefficient	% / °C	0.4%
Solar collector area	m²	24.4
Miscellaneous losses	%	4%

Inverter

Efficiency	%	97%
Capacity	kW	3
Miscellaneous losses	%	0%

Summary

Capacity factor	%	20.6%
Initial costs	€/kW	1,500
	€	4,500
O&M costs (savings)	€/kW-year	20
	€	60
Electricity export rate		Electricity exported to grid - annual
	€/kWh	0.15
Electricity exported to grid	MWh	5.4
Electricity export revenue	€	813

Figure 44: Technical specifications of the studied mc-Si PV system.

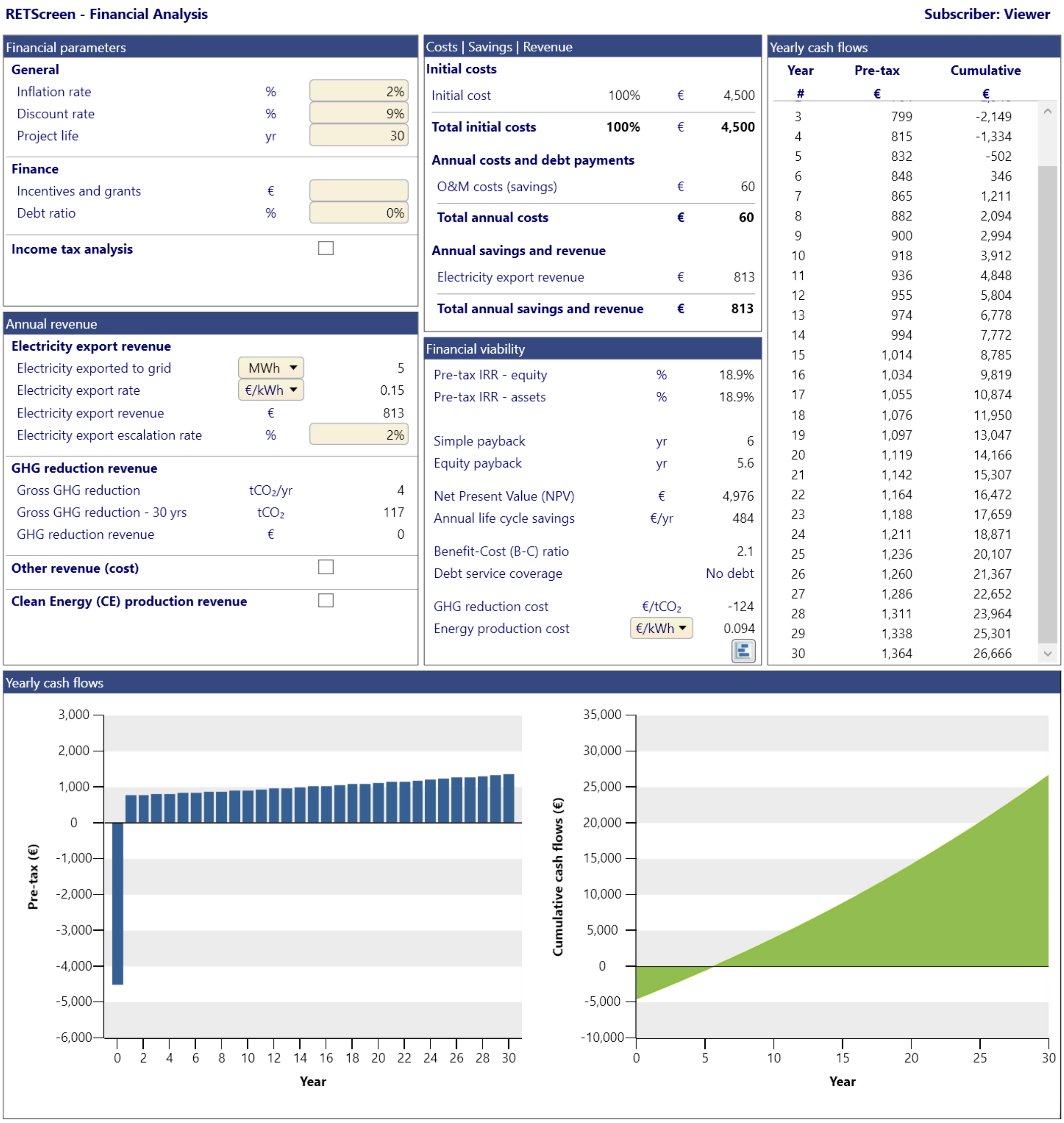


Figure 45: Financial analysis results of the studied mc-Si PV system.

Photovoltaic - Level 2

Resource assessment

Solar tracking mode		Fixed
Slope	°	30
Azimuth	°	0

Show data

Month	Daily solar radiation - horizontal kWh/m²/d	Daily solar radiation - tilted kWh/m²/d	Electricity export rate €/kWh	Electricity exported to grid MWh
January	2.31	3.30	0.15	0.280
February	3.20	4.14	0.15	0.314
March	4.57	5.29	0.15	0.436
April	6.30	6.55	0.15	0.509
May	7.45	7.05	0.15	0.552
June	8.45	7.63	0.15	0.561
July	8.41	7.74	0.15	0.581
August	7.58	7.61	0.15	0.571
September	6.14	6.96	0.15	0.515
October	4.28	5.52	0.15	0.436
November	2.65	3.74	0.15	0.299
December	2.05	3.01	0.15	0.255
Annual	**5.29**	**5.72**	**0.15**	**5.310**

Annual solar radiation - horizontal	MWh/m²	1.93
Annual solar radiation - tilted	MWh/m²	2.09

Photovoltaic

Type		CIS
Power capacity	kW	3
Manufacturer		Q-Cells
Model		CIS - Q.Smart UF L 100W
Number of units		30
Efficiency	%	10.64%
Nominal operating cell temperature	°C	47
Temperature coefficient	% / °C	0.46%
Solar collector area	m²	28.2
Miscellaneous losses	%	4%

Inverter

Efficiency	%	97%
Capacity	kW	3
Miscellaneous losses	%	0%

Summary

Capacity factor	%	20.2%
Initial costs	€/kW	1,600
	€	4,800
O&M costs (savings)	€/kW-year	20
	€	60
Electricity export rate		Electricity exported to grid - annual
	€/kWh	0.15
Electricity exported to grid	MWh	5.3
Electricity export revenue	€	797

Figure 46: Technical specifications of the studied CIS PV system.

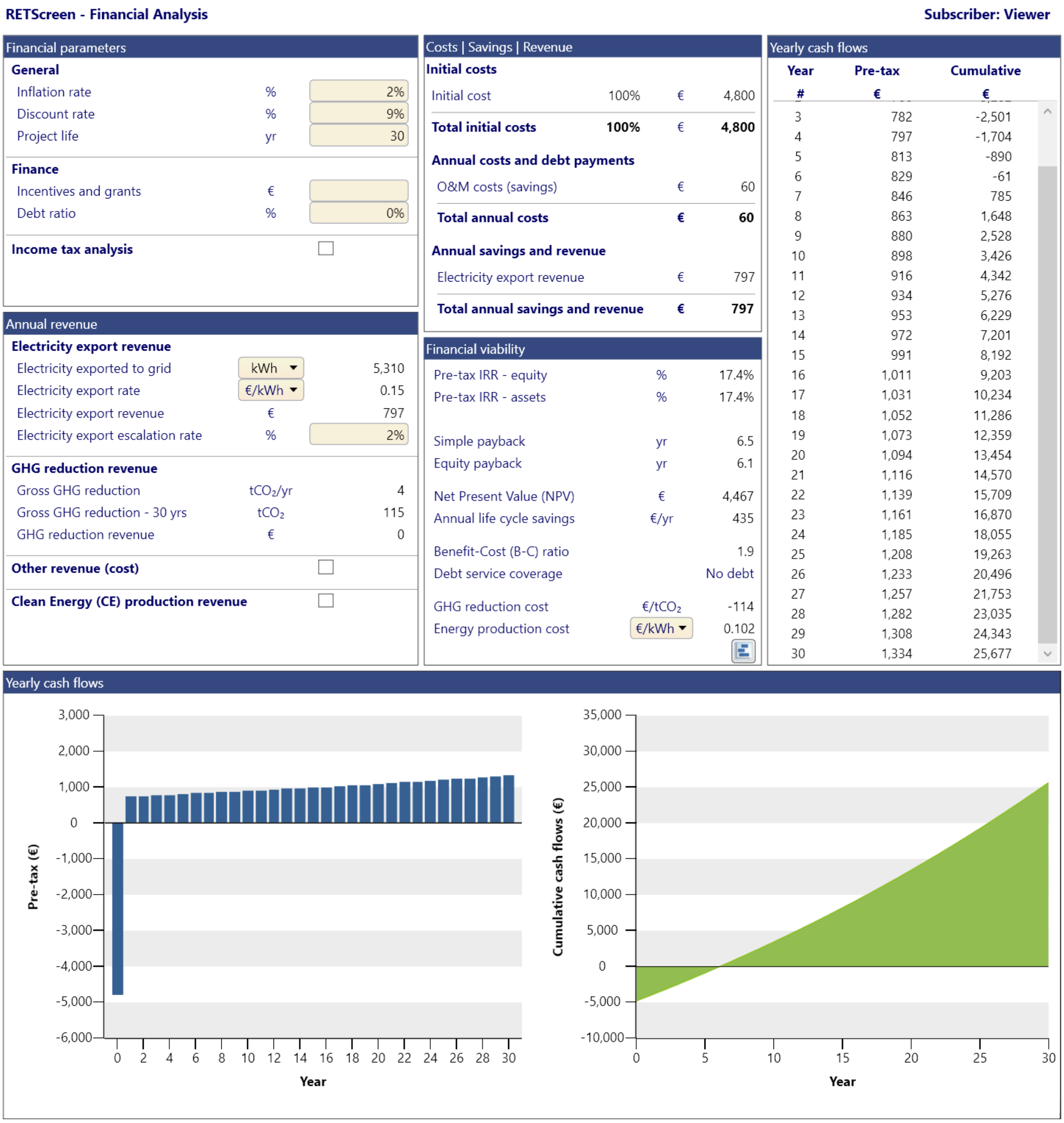
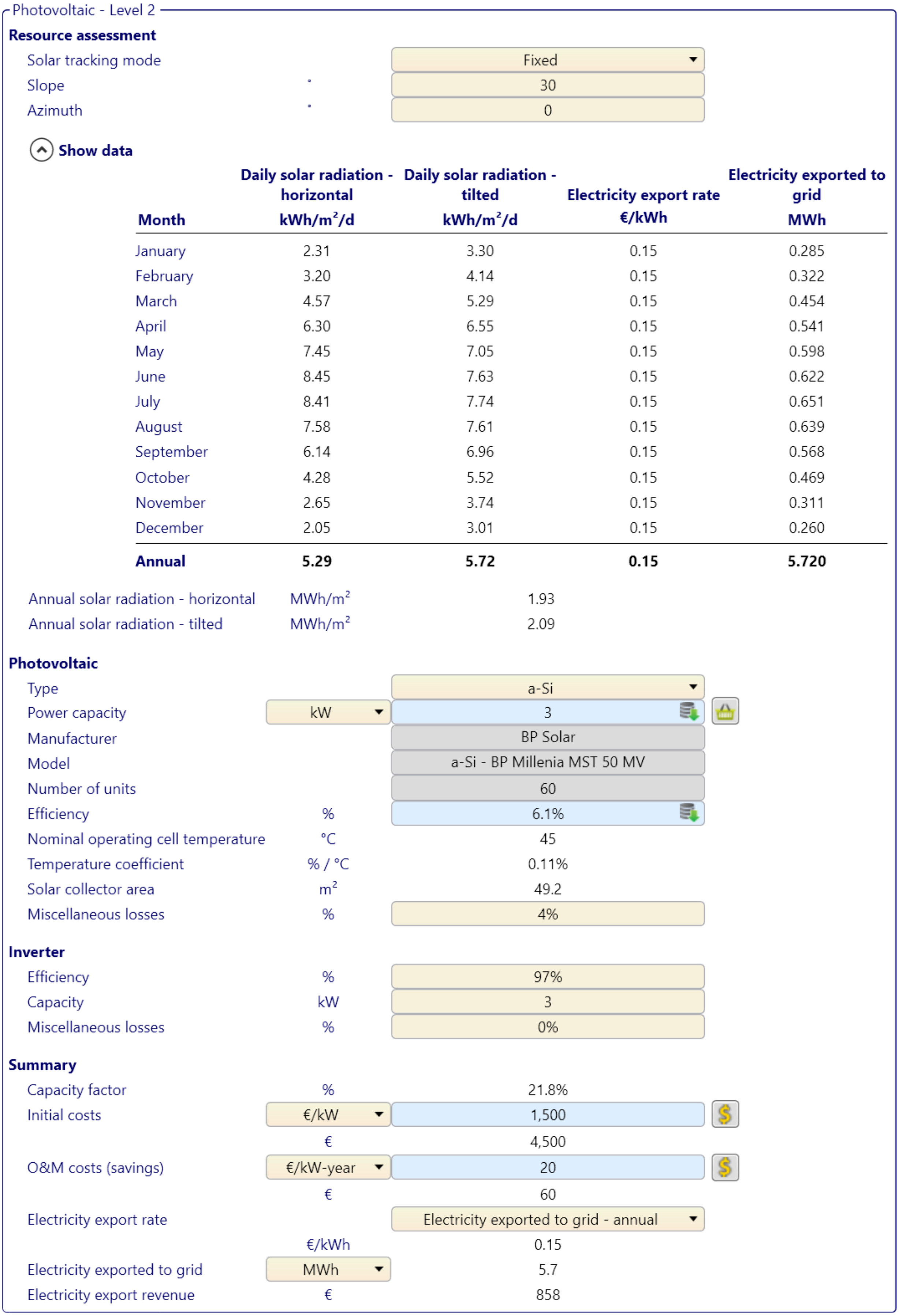


Figure 47: Financial analysis results of the studied CIS PV system.



Photovoltaic - Level 2

Resource assessment

Solar tracking mode		Fixed
Slope	°	30
Azimuth	°	0

Show data

Month	Daily solar radiation - horizontal kWh/m²/d	Daily solar radiation - tilted kWh/m²/d	Electricity export rate €/kWh	Electricity exported to grid MWh
January	2.31	3.30	0.15	0.285
February	3.20	4.14	0.15	0.322
March	4.57	5.29	0.15	0.454
April	6.30	6.55	0.15	0.541
May	7.45	7.05	0.15	0.598
June	8.45	7.63	0.15	0.622
July	8.41	7.74	0.15	0.651
August	7.58	7.61	0.15	0.639
September	6.14	6.96	0.15	0.568
October	4.28	5.52	0.15	0.469
November	2.65	3.74	0.15	0.311
December	2.05	3.01	0.15	0.260
Annual	**5.29**	**5.72**	**0.15**	**5.720**

Annual solar radiation - horizontal	MWh/m²	1.93
Annual solar radiation - tilted	MWh/m²	2.09

Photovoltaic

Type		a-Si
Power capacity	kW	3
Manufacturer		BP Solar
Model		a-Si - BP Millenia MST 50 MV
Number of units		60
Efficiency	%	6.1%
Nominal operating cell temperature	°C	45
Temperature coefficient	% / °C	0.11%
Solar collector area	m²	49.2
Miscellaneous losses	%	4%

Inverter

Efficiency	%	97%
Capacity	kW	3
Miscellaneous losses	%	0%

Summary

Capacity factor	%	21.8%
Initial costs	€/kW	1,500
	€	4,500
O&M costs (savings)	€/kW-year	20
	€	60
Electricity export rate		Electricity exported to grid - annual
	€/kWh	0.15
Electricity exported to grid	MWh	5.7
Electricity export revenue	€	858

Figure 48: Technical specifications of the studied a-si PV system.

RETScreen - Financial Analysis — **Subscriber: Viewer**

Financial parameters

General		
Inflation rate	%	2%
Discount rate	%	9%
Project life	yr	30
Finance		
Incentives and grants	€	
Debt ratio	%	0%
Income tax analysis		☐

Annual revenue

Electricity export revenue		
Electricity exported to grid	kWh	5,720
Electricity export rate	€/kWh	0.15
Electricity export revenue	€	858
Electricity export escalation rate	%	2%
GHG reduction revenue		
Gross GHG reduction	tCO_2/yr	4
Gross GHG reduction - 30 yrs	tCO_2	124
GHG reduction revenue	€	0
Other revenue (cost)		☐
Clean Energy (CE) production revenue		☐

Costs | Savings | Revenue

Initial costs			
Initial cost	100%	€	4,500
Total initial costs	**100%**	**€**	**4,500**
Annual costs and debt payments			
O&M costs (savings)		€	60
Total annual costs		**€**	**60**
Annual savings and revenue			
Electricity export revenue		€	858
Total annual savings and revenue		**€**	**858**

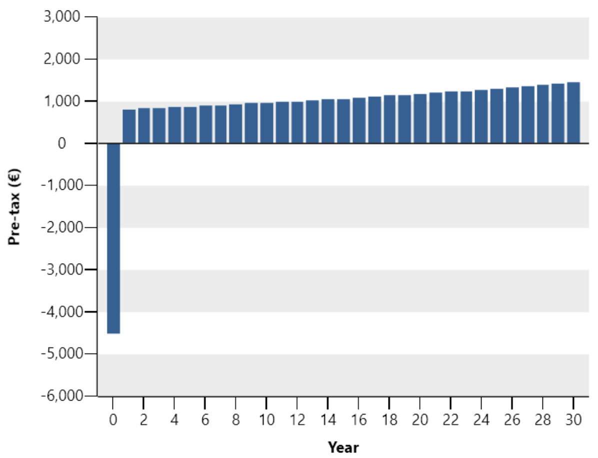
Financial viability

Pre-tax IRR - equity	%	20%
Pre-tax IRR - assets	%	20%
Simple payback	yr	5.6
Equity payback	yr	5.3
Net Present Value (NPV)	€	5,540
Annual life cycle savings	€/yr	539
Benefit-Cost (B-C) ratio		2.2
Debt service coverage		No debt
GHG reduction cost	$€/tCO_2$	-131
Energy production cost	€/kWh	0.089

Yearly cash flows

Year #	Pre-tax €	Cumulative €
3	847	-2,009
4	864	-1,145
5	881	-264
6	899	634
7	917	1,551
8	935	2,486
9	954	3,439
10	973	4,412
11	992	5,404
12	1,012	6,416
13	1,032	7,448
14	1,053	8,501
15	1,074	9,575
16	1,095	10,670
17	1,117	11,788
18	1,140	12,927
19	1,162	14,090
20	1,186	15,275
21	1,209	16,485
22	1,234	17,718
23	1,258	18,977
24	1,283	20,260
25	1,309	21,569
26	1,335	22,904
27	1,362	24,266
28	1,389	25,656
29	1,417	27,073
30	1,445	28,518

Yearly cash flows



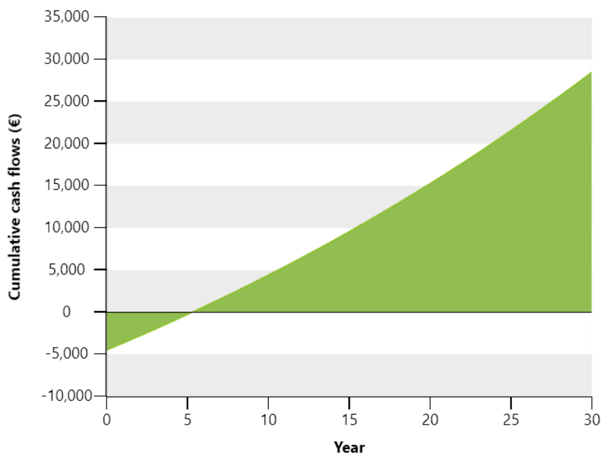


Figure 49: Financial analysis results of the studied a-Si PV system.

3.3 Solar thermal systems

3.3.1 LCA analysis of solar thermal systems

In this section the detailed results from the LCA of the two studied types of solar collectors will be presented. The two studied systems are: **i.** Flat plate collector with copper absorber and **ii.** Vacuum (or evacuated) tube collector. In order to validate the environmental impacts a Cradle-to-Grave LCA has been implemented for each of the two studied systems.

Goal and Scope. The goal of this LCA study is to evaluate over the lifecycle, the impacts of the thermal energy converted to hot water needs and consequently to the equivalent avoided electricity, for the two types of solar collectors for use in a typical single house family. For this purpose, SimaPro 8.5 has been employed, while ReCiPe 2016 Midpoint Hierarchist (H) has been chosen as the LCIA method as it provides the most extensive set of midpoint impact categories, aiming to highlight the global warming potential and GHG emissions, fossil fuels and climate change impacts related to each technology. The results are ranked from worst to best environmental performance. These results will be used to distinguish the impacts of each solar system and can be used during the combined environmental and technical assessment of installing such solar energy harvesting technologies.

The **system boundaries** account for all the impacts from Cradle-to-Grave related to production, transportation and disposal for both complete solar systems (excluding auxiliary heating), including various technical components, heat exchange fluid, installation of copper pipes, transportation of parts, delivery with a van and montage on the roof. The main parts of the studied systems are: **i.** the solar collectors – absorbers (with aperture area 12.3 m^2 and 10.5 m^2 for the flat plate and the vacuum tube collectors respectively), **ii.** the 200l heat storage tank, **iii.** the roof mounting structure. Both systems are aimed for installation on existing buildings (slanted roof installation) and their operational lifetime has been assumed to be 20 years.

Life Cycle Inventory analysis involves creating an inventory of flows from and to nature for a product system. Eco-invent v3.4 database has been employed for the inventories of solar collectors. The eco-invent database provides detailed and transparent background data for a range of materials and services used in the production chain of solar collectors.

In Figures 51-54 the process networks for the studied solar collectors systems are depicted for cut-off thresholds 1% and 10% respectively. The thick red line in the network trees is known as the elementary flow and indicates the environmental bottleneck or burden in each process. For the flat plate system, 57% and 27.1% of all total inflows and outflows are due to the production of the collector and the tank respectively, while for the vacuum tube system the corresponding values are 45.3% and 34.8%. Thus, as the networks clearly show, the production stage of the collector component contributes the most important part of the environmental impacts in the life cycle for both studied systems.

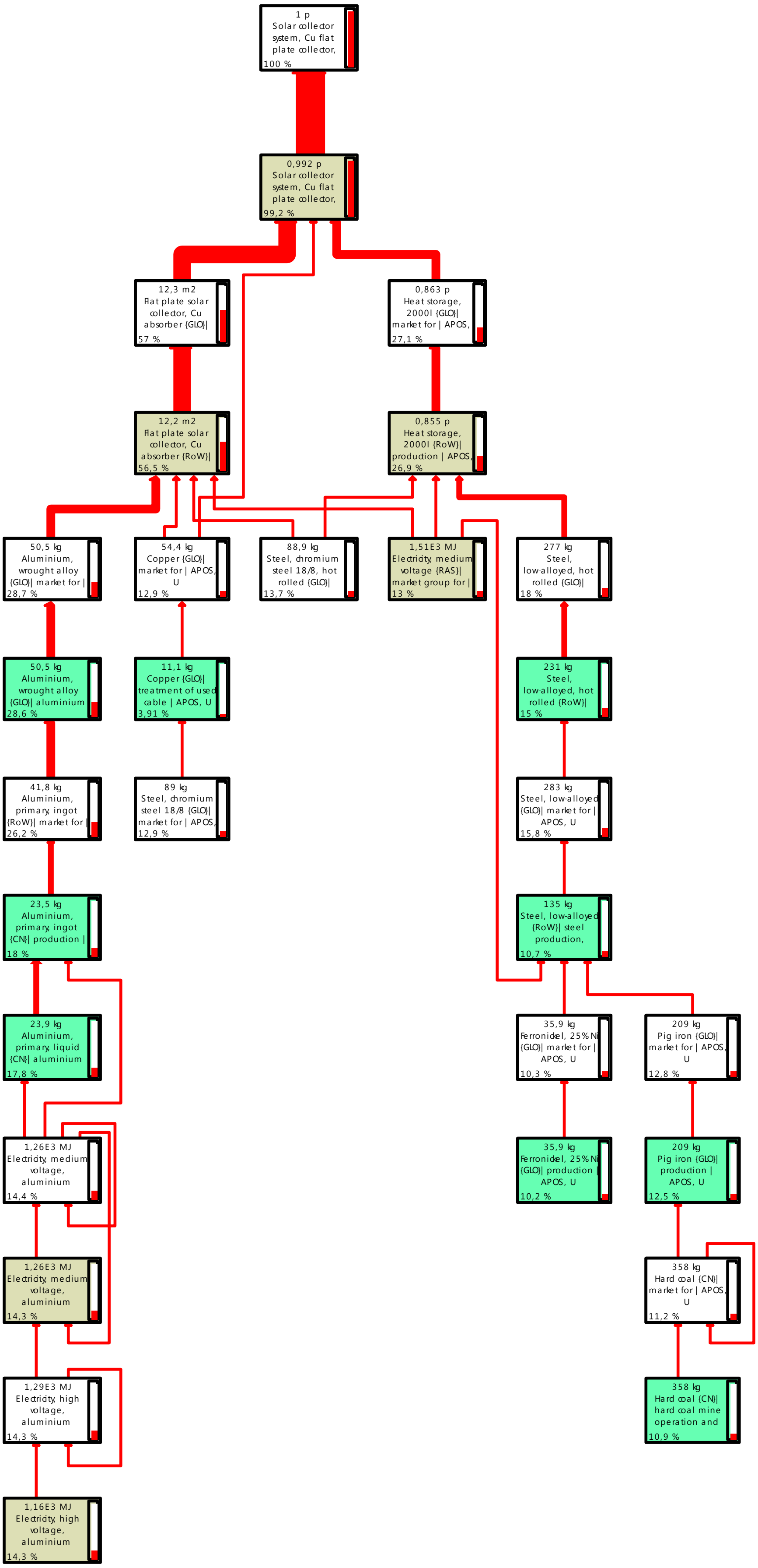


Figure 50: Process network for the flat plate solar collector. Cut-off threshold: 10%, total nodes: 11607.

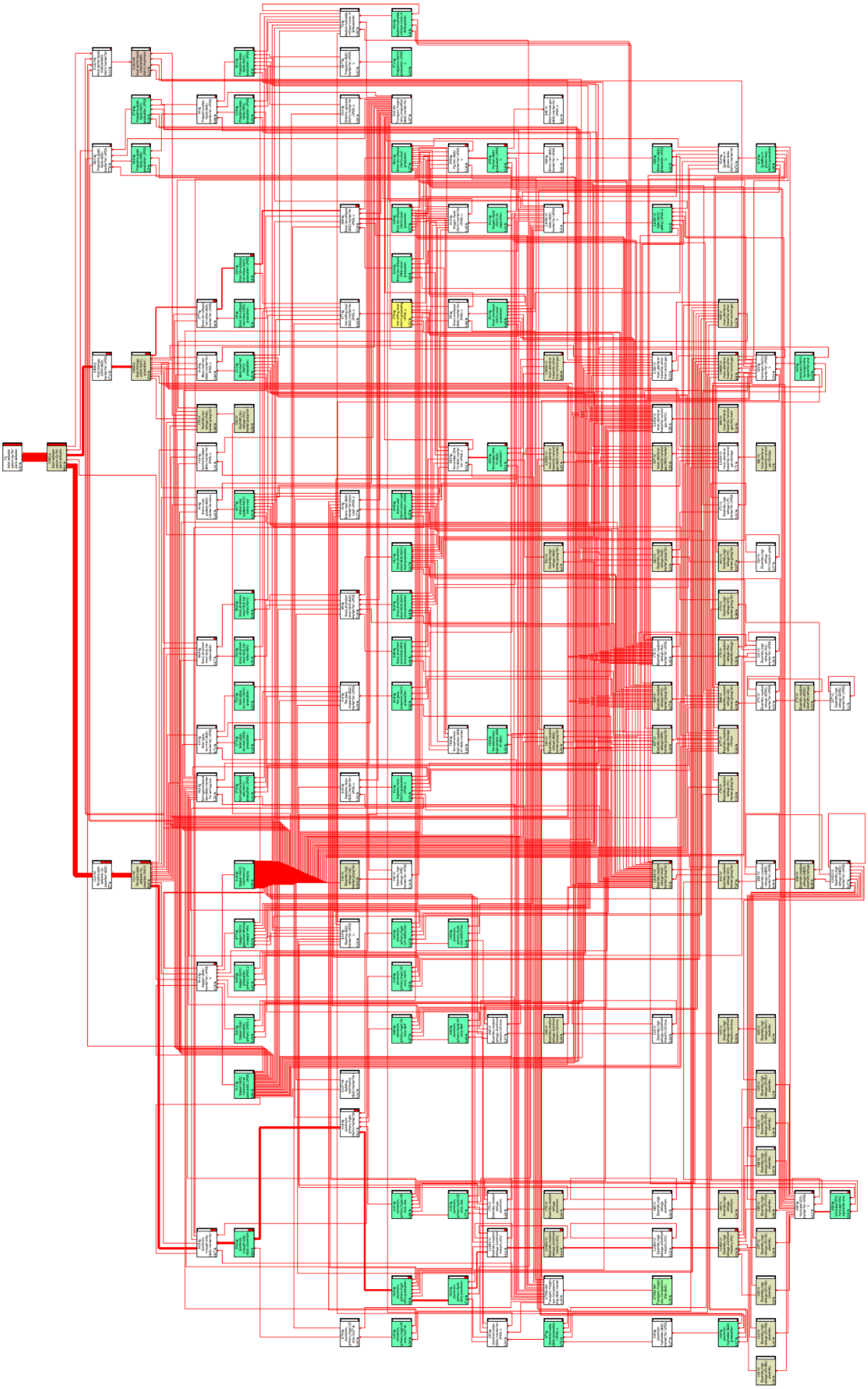


Figure 51: Process network for the flat plate solar collector. Cut-off threshold: 1%, total nodes: 11607.

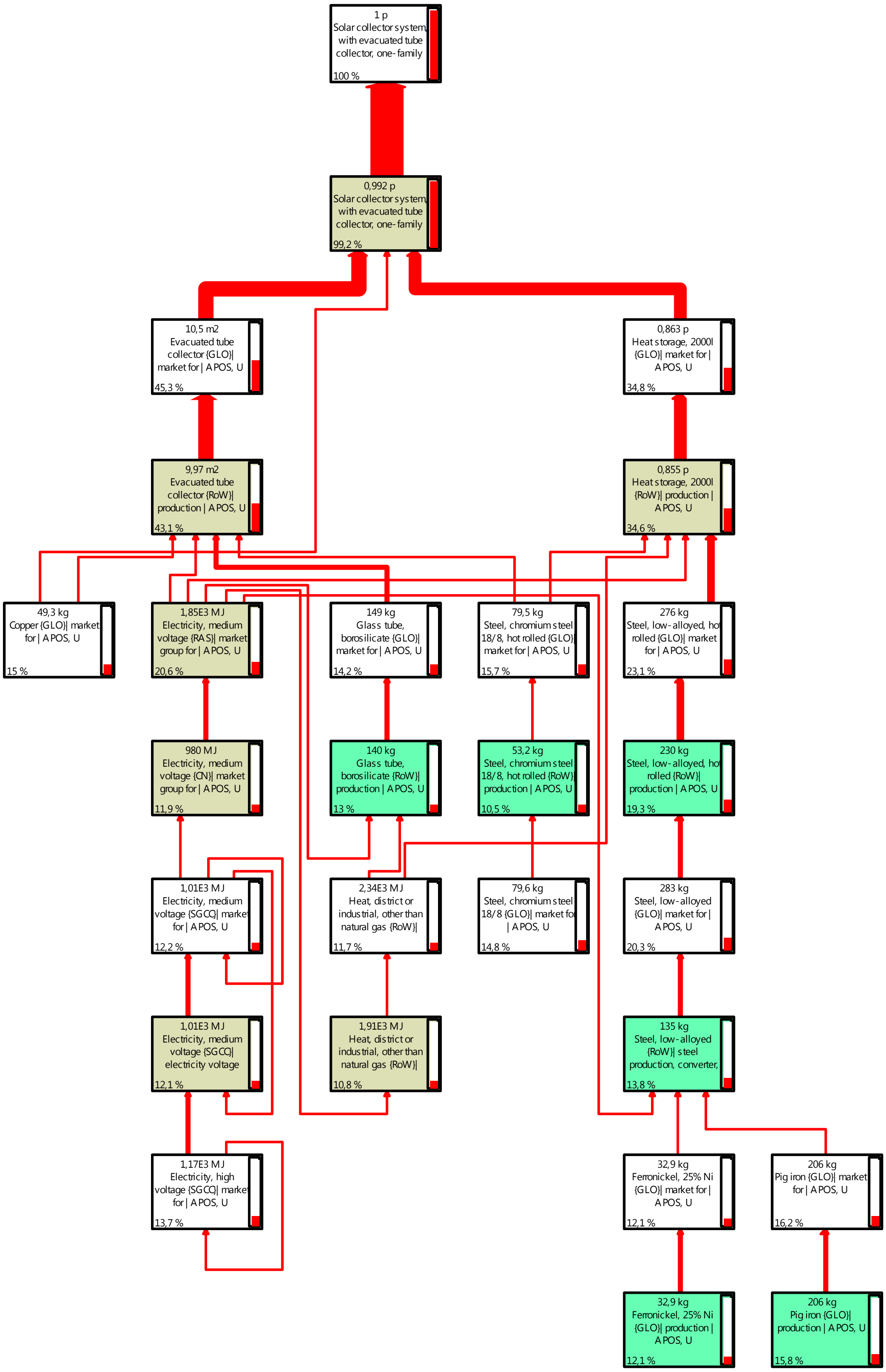


Figure 52: Process network for the vacuum tube solar collector. Cut-off threshold: 10%, total nodes: 11607.

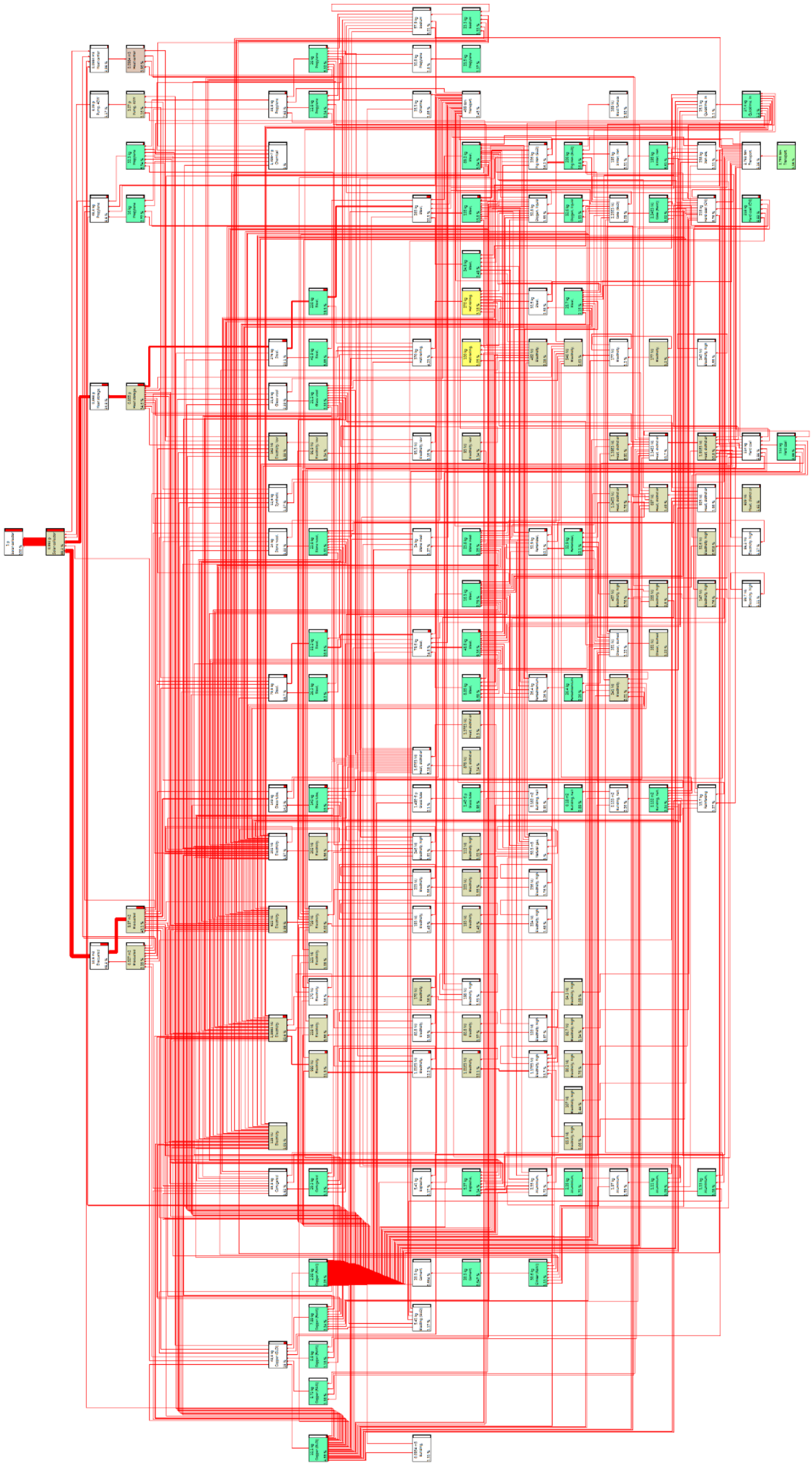


Figure 53: Process network for the vacuum tube solar collector. Cut-off threshold: 1%, total nodes: 11607.

In Table 7 and Figure 54 the aggregated LCA inventory results for the studied solar thermal systems are depicted. These are harmonized data representing the LCA results (for each impact category) per total energy produced per aperture area (in kWh/m^2) by each solar collector, thus providing an holistic evaluation indicator (i.e. environmental burden per total energy produced). It is important to stress the fact that the electricity mentioned above in kWh corresponds to the necessary energy for heating water, which is substituted by the operation of the solar collectors which convert solar radiation to heat transferred to stored hot water in their tank. As depicted in Table 7 the cumulative CO_2-eq emissions over the whole life cycle of the solar systems are quite close, varying between 2.22×10^{-2} and 2.38×10^{-2} kg CO_2 eq/kWh·m^2, and the lowest value corresponds to the vacuum tube collector.

Table 7: Aggregated LCA inventory results for the studied solar thermal systems.

Impact category	Unit (per m^2)	Flat plate collector	Vacuum tube collector
Global warming	kg CO2 eq/kWh	2.38E-02	2.22E-02
Stratospheric ozone depletion	kg CFC11 eq/kWh	1.29E-08	1.36E-08
Ionizing radiation	kBq Co-60 eq/kWh	1.61E-03	1.88E-03
Ozone formation, Human health	kg NOx eq/kWh	6.50E-05	6.89E-05
Fine particulate matter formation	kg PM2.5 eq/kWh	8.78E-05	8.61E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq/kWh	6.66E-05	7.07E-05
Terrestrial acidification	kg SO2 eq/kWh	2.07E-04	2.01E-04
Freshwater eutrophication	kg P eq/kWh	3.89E-05	4.16E-05
Terrestrial ecotoxicity	kg 1,4-DCB eq/kWh	8.55E-01	9.31E-01
Freshwater ecotoxicity	kg 1,4-DCB eq/kWh	6.42E-03	6.94E-03
Marine ecotoxicity	kg 1,4-DBC eq/kWh	9.27E-03	1.00E-02
Human carcinogenic toxicity	kg 1,4-DBC eq/kWh	6.56E-03	6.53E-03
Human non-carcinogenic toxicity	kg 1,4-DBC eq/kWh	2.24E-01	2.44E-01
Land use	m2a crop eq/kWh	1.25E-03	1.52E-03
Mineral resource scarcity	kg Cu eq/kWh	1.02E-03	1.03E-03
Fossil resource scarcity	kg oil eq/kWh	5.45E-03	5.38E-03
Water consumption	m3/kWh	2.39E-04	2.33E-04

In Figure 54 the relative contributions to the impact categories (based on the ReCiPe 2016 midpoint evaluation) for the solar systems are depicted. The results are mixed with the two systems exhibiting similar environmental impacts in most categories, but the vacuum tube collector has highest values in most cases.

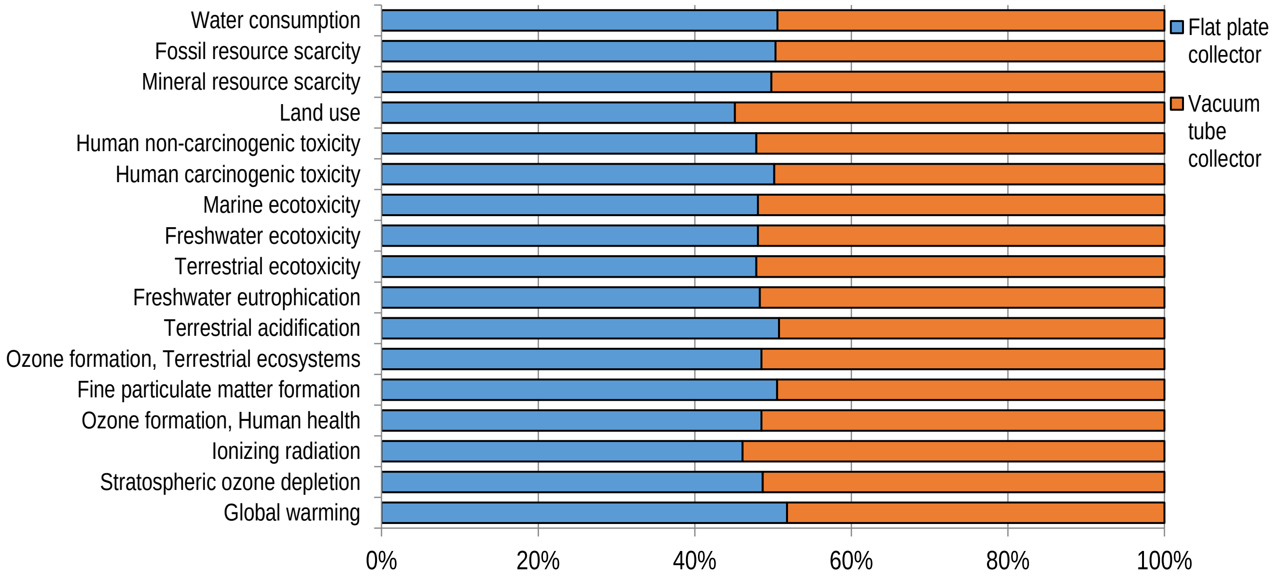


Figure 54: LCA results for the studied solar thermal systems: relative contributions to the impact categories.

For the purposes of this study, a Monte Carlo analysis of the LCA results has been implemented through a comparison between the two studied solar collectors (A: flat plate and B: vacuum tube collector) which was repeated for 5000 iterations. In Figure 55 the results of the uncertainty analysis are depicted in a bar chart form, showing the percentage of times when collector A has a greater impact than collector B (A-B≥0, in orange) and vice versa (A-B<0, in blue). It is clear that for the studied solar collectors, A has increased impacts compared to B in most of the studied midpoint categories. Land use is the only case that B appears to be worse than A, for the 53.4% of the completed iterations. It is important to keep in mind that these outcomes refer to the direct LCA results, which are non-harmonized (i.e. they do not take into account the environmental impacts per energy production and per aperture area for each system).

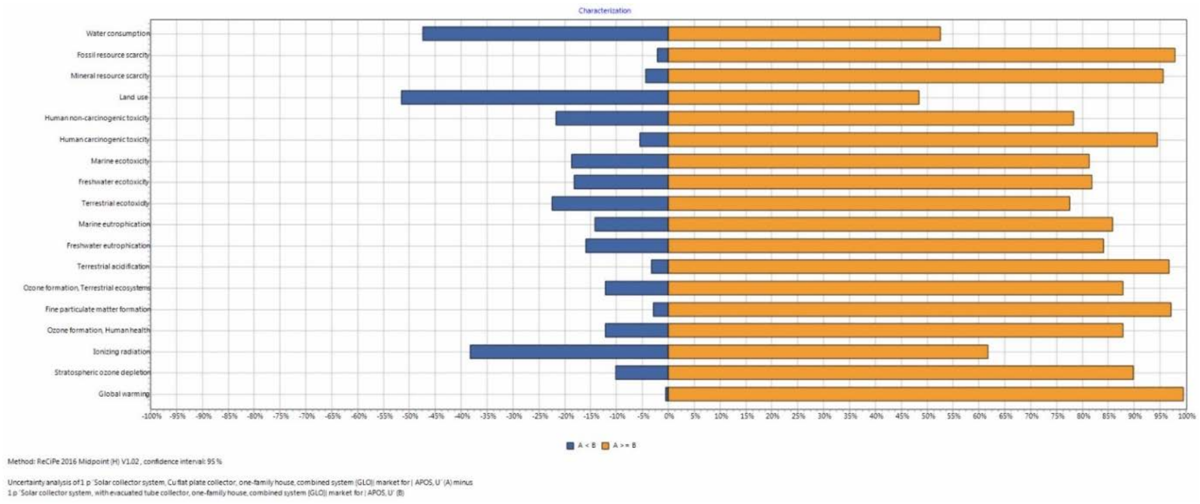


Figure 55: Monte-Carlo simulation results of LCIA uncertainties between flat plate (A) and vacuum tube (B) collectors.

The abovementioned results for the Global warming impact category are also depicted in Figure 56 which presents a histogram of the Gaussian curve of results' distribution, presenting the probability of collector A having greater Global warming impact than collector B. This is a normal distribution and it is evident from the graph that in 99.5% of the 5000 studied cases A≥B.

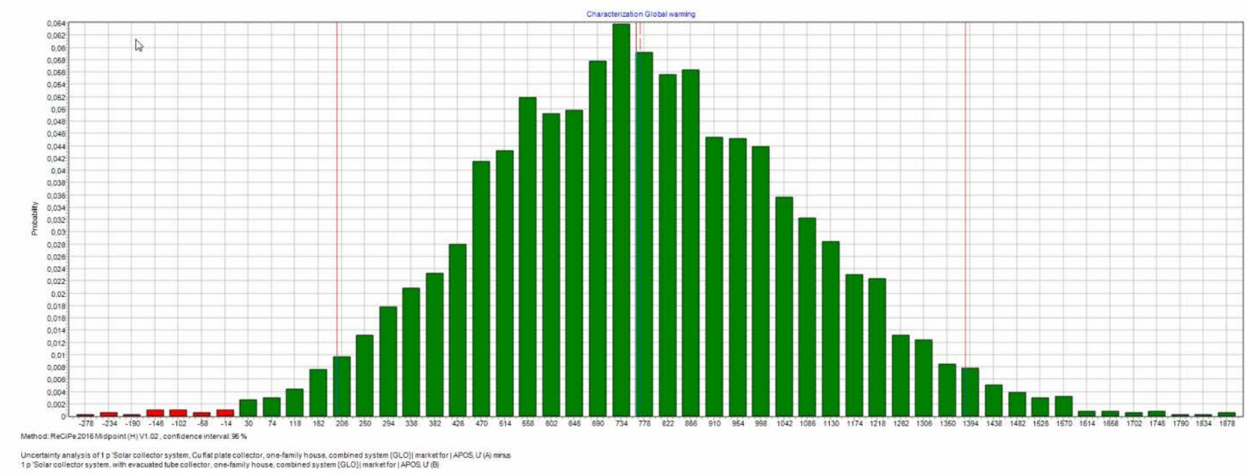


Figure 56: Monte Carlo analysis distribution of flat plate (A) minus vacuum tube (B) collector.

3.3.2 Energy and economic assessment of solar thermal systems

The comparative techno-economic assessment of the installation of the two solar thermal collectors has been carried out through RETScreen. The installation location site was chosen to be the Acrotiri area in Chania, while all meteorological data (annual time series of average climate conditions as presented in Figure 40) have been extracted from RETScreen referring to a weather station of Souda Bay, Chania. After selecting the location area, the complete RETScreen analysis for each solar collector has been conducted. This analysis comprised the following discrete steps: **i.** determination of the annual hot water needs for the studied single family house (see Figure 57), **ii.** selection of the auxiliary hot water heating system (see Figure 58), **iii.** selection of the solar collector technology (i.e. flat plate and vacuum tube) and specification of the technical parameters (see Figure 59, Figure 62), **iv.** energy analysis (see aggregated results in Table 8), **v.** financial analysis (see Figure 61, Figure 64).

For all financial calculations the electricity price has been set to 0.15€/kWh and we have considered that the installation was funded by own means (no bank loan). The hot water needs for a typical family house with 4 occupants (taking as granted 100% occupancy rate and 24 operating hours per day) have been estimated to 2817kWh per year. A typical auxiliary hot water heating system burning oil has been considered for backup. In Table 8 the main results of the RETScreen analysis for the studied solar thermal collectors have been gathered. Both selected systems belong to the CALPAK company (see Figures 10 and 11) and they can be considered as top-class products, while the purchase cost of the vacuum tube collector is significantly higher, i.e. 1300€ vs 900€.

The thermal losses coefficient, F_rUL, is increased for the flat plate collector compared to the vacuum tube system, i.e. 4.6 *vs* 1.7 $(W/m^2)/°C$ respectively. This is due to the completely different thermal losses suppression design followed in each system, which practically makes vacuum tube collector unaffected by variations in ambient temperature. In addition, the solar fraction value (practically denoting the percentage of hot water needs covered by the system annually) for the vacuum tube system is higher that the flat plate collector (i.e. 62.7% vs 55.3% respectively). On the other hand, it is evident that overall this parameter does not play an important role in the energy outcome of the systems, as finally the flat plate collector provides slightly more energy per aperture area throughout the year. This is mainly due to two reasons: **i.** the weather conditions in Crete (high intensity solar radiation for extended time periods and with increased ambient temperatures throughout the year) are favorable for solar systems and thus the advantageous thermal insulation and the ability to reach high temperatures of the vacuum system is not necessary, **ii.** the pump in the vacuum system requires more electricity due to increased friction in the collector (more complex circulation system).

Table 8: Results of the techno-economic assessment for the studied solar thermal collectors.

Solar collector type	Aperture area [m^2]	F_rUL [(W/m^2)/°C]	Cost [€]	Total energy saved [kWh]	Total energy saved per aperture area [kWh/m^2]	Solar fraction [%]	Annual savings [€/yr]	IRR [%]	Payback time [years]
Flat plate	2.32	4.6	900	27260	11750	55.3	352	41.8	2.6
Vacuum tube	2.61	1.7	1300	29980	11487	62.7	341	28.5	3.8

The comparison of the annual energy-fuel consumption and the economic savings between the base case (auxiliary hot water heating system) and the solar collectors are also depicted in Figures 60 and 63 for both the studied systems. Annual savings of 352€ (flat plate system) and 341€ (vacuum tube system) are anticipated, and their economic viability is obvious. The simple payback period is 2.6 and 3.8 years and IRR values 41.8 and 28.5 for the the flat plate and the vacuum tube system respectively. The above mentioned results prove that the selection of a flat plate system is rather mandatory for typical installations in Crete while vacuum tube systems could be selected for demanding applications.

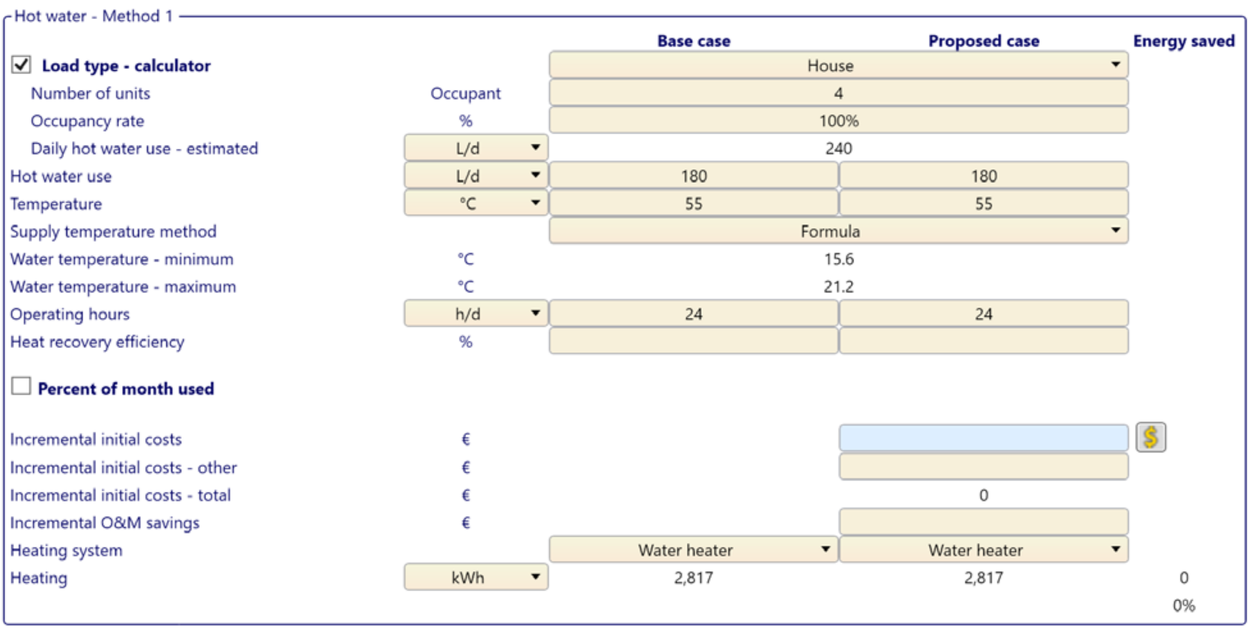
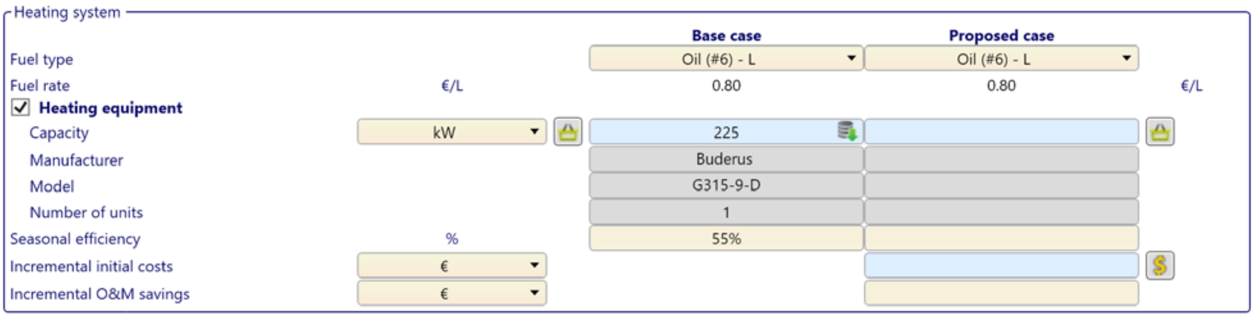


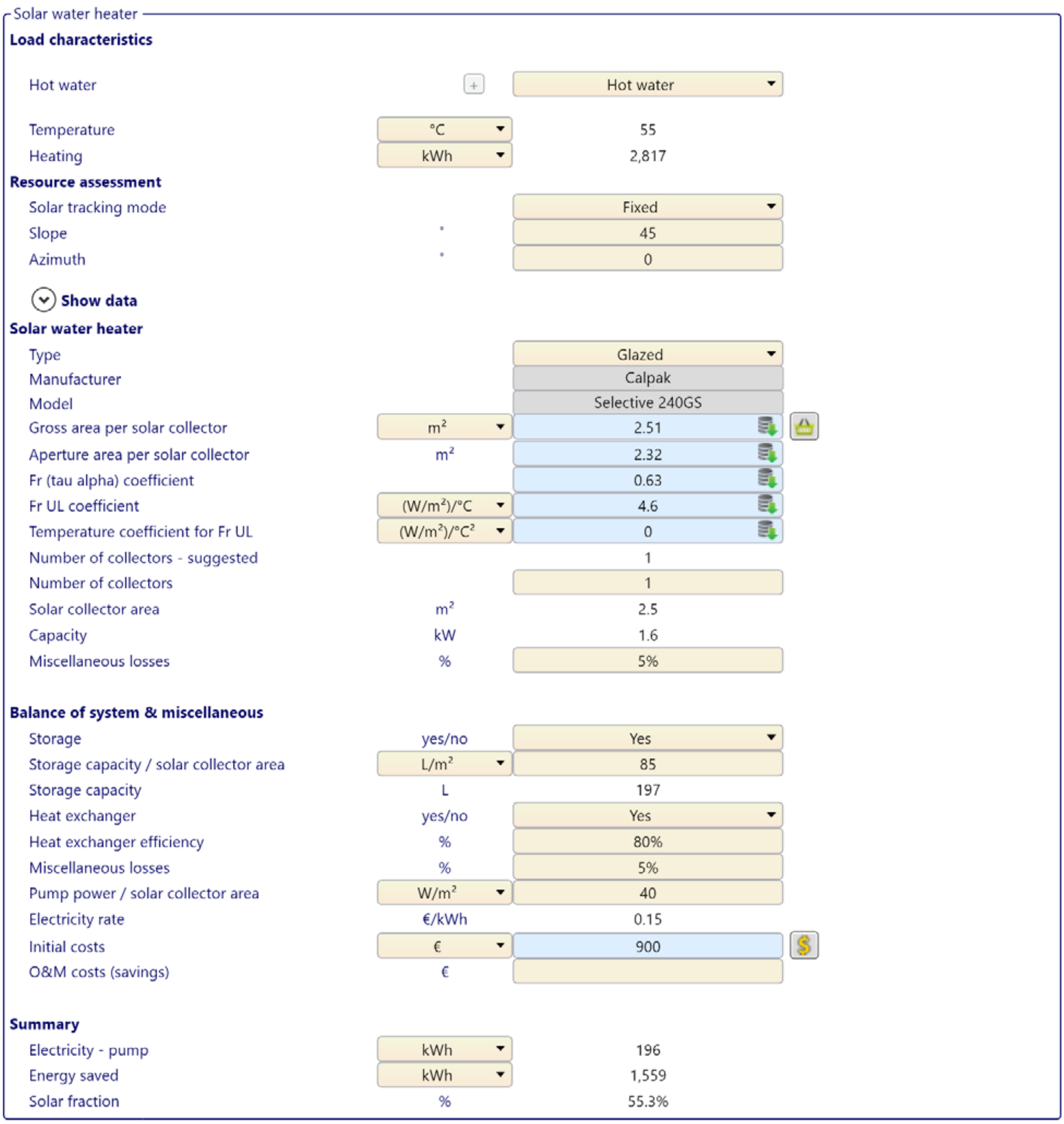
Figure 57: Annual hot water needs for the studied house.



Heating system

		Base case	Proposed case	
Fuel type		Oil (#6) - L	Oil (#6) - L	
Fuel rate	€/L	0.80	0.80	€/L
☑ **Heating equipment**				
Capacity	kW	225		
Manufacturer		Buderus		
Model		G315-9-D		
Number of units		1		
Seasonal efficiency	%	55%		
Incremental initial costs	€			
Incremental O&M savings	€			

Figure 58: Technical specifications of the auxiliary hot water heating system.



Solar water heater

Load characteristics		
Hot water		Hot water
Temperature	°C	55
Heating	kWh	2,817
Resource assessment		
Solar tracking mode		Fixed
Slope	°	45
Azimuth	°	0
Show data		
Solar water heater		
Type		Glazed
Manufacturer		Calpak
Model		Selective 240GS
Gross area per solar collector	m²	2.51
Aperture area per solar collector	m²	2.32
Fr (tau alpha) coefficient		0.63
Fr UL coefficient	(W/m²)/°C	4.6
Temperature coefficient for Fr UL	(W/m²)/°C²	0
Number of collectors - suggested		1
Number of collectors		1
Solar collector area	m²	2.5
Capacity	kW	1.6
Miscellaneous losses	%	5%
Balance of system & miscellaneous		
Storage	yes/no	Yes
Storage capacity / solar collector area	L/m²	85
Storage capacity	L	197
Heat exchanger	yes/no	Yes
Heat exchanger efficiency	%	80%
Miscellaneous losses	%	5%
Pump power / solar collector area	W/m²	40
Electricity rate	€/kWh	0.15
Initial costs	€	900
O&M costs (savings)	€	
Summary		
Electricity - pump	kWh	196
Energy saved	kWh	1,559
Solar fraction	%	55.3%

Figure 59: Technical specifications of the studied flat plate solar collector.

Summary - Electricity and fuels

	Fuel type		Base case		Proposed case		Savings	
Fuel type	Fuel rate	Fuel consumption - unit	Fuel consumption	Fuel cost	Fuel consumption	Fuel cost	Fuel saved	Savings
Oil (#6)	€ 0.80	L	477	€ 381	0	€ 0	477	€ 381
Electricity	€ 0.15	kWh	0	€ 0	196	€ 29.34	-196	€ (29.34)
Total				€ 381		€ 29.34		€ 352

Figure 60: Comparison of annual energy-fuel consumption and economic savings between the base case (auxiliary hot water heating system) and the flat plate solar collector.

Financial parameters

General		
Fuel cost escalation rate	%	2%
Inflation rate	%	2%
Discount rate	%	9%
Project life	yr	20
Finance		
Incentives and grants	€	
Debt ratio	%	0%
Income tax analysis		☐

Annual revenue

GHG reduction revenue		
Gross GHG reduction	tCO_2/yr	1
Gross GHG reduction - 20 yrs	tCO_2	26
GHG reduction revenue	€	0
Other revenue (cost)		☐

Costs | Savings | Revenue

Initial costs			
Incremental initial costs	100%	€	900
Total initial costs	**100%**	**€**	**900**
Annual costs and debt payments			
O&M costs (savings)		€	0
Fuel cost - proposed case		€	29
Total annual costs		**€**	**29**
Annual savings and revenue			
Fuel cost - base case		€	381
Total annual savings and revenue		**€**	**381**

Financial viability

Pre-tax IRR - equity	%	41.8%
Pre-tax IRR - assets	%	41.8%
Simple payback	yr	2.6
Equity payback	yr	2.5
Net Present Value (NPV)	€	2,869
Annual life cycle savings	€/yr	314
Benefit-Cost (B-C) ratio		4.2
Debt service coverage		No debt
GHG reduction cost	$€/tCO_2$	-242

Yearly cash flows

Year	Pre-tax	Cumulative
#	€	€
0	-900	-900
1	359	-541
2	366	-175
3	374	199
4	381	580
5	389	968
6	396	1,365
7	404	1,769
8	412	2,181
9	421	2,602
10	429	3,031
11	438	3,469
12	446	3,915
13	455	4,370
14	464	4,835
15	474	5,309
16	483	5,792
17	493	6,285
18	503	6,787
19	513	7,300
20	523	7,823

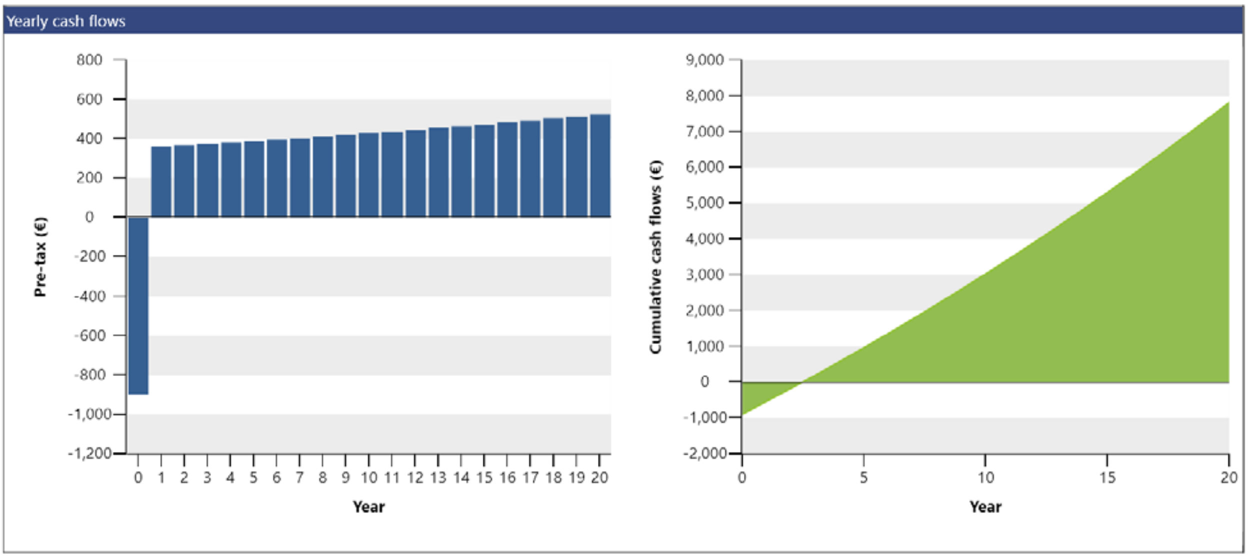


Figure 61: Financial analysis results of the studied flat plate solar collector.

Solar water heater

Load characteristics		
Hot water	+	Hot water
Temperature	°C	55
Heating	kWh	2,817
Resource assessment		
Solar tracking mode		Fixed
Slope	°	45
Azimuth	°	0
Show data		
Solar water heater		
Type		Evacuated
Manufacturer		Calpak
Model		16 VTN
Gross area per solar collector	m²	2.86
Aperture area per solar collector	m²	2.61
Fr (tau alpha) coefficient		0.51
Fr UL coefficient	(W/m²)/°C	1.73
Temperature coefficient for Fr UL	(W/m²)/°C²	0
Number of collectors - suggested		1
Number of collectors		1
Solar collector area	m²	2.9
Capacity	kW	1.8
Miscellaneous losses	%	5%
Balance of system & miscellaneous		
Storage	yes/no	Yes
Storage capacity / solar collector area	L/m²	85
Storage capacity	L	222
Heat exchanger	yes/no	Yes
Heat exchanger efficiency	%	80%
Miscellaneous losses	%	5%
Pump power / solar collector area	W/m²	40
Electricity rate	€/kWh	0.15
Initial costs	€	1,300
O&M costs (savings)	€	
Summary		
Electricity - pump	kWh	269
Energy saved	kWh	1,768
Solar fraction	%	62.7%

Figure 62: Technical specifications of the studied vacuum tube solar collector.

Summary - Electricity and fuels

	Fuel type		Base case		Proposed case		Savings	
Fuel type	Fuel rate	Fuel consumption - unit	Fuel consumption	Fuel cost	Fuel consumption	Fuel cost	Fuel saved	Savings
Oil (#6)	€ 0.80	L	477	€ 381	0	€ 0	477	€ 381
Electricity	€ 0.15	kWh	0	€ 0	269	€ 40.35	-269	€ (40.35)
Total				€ 381		€ 40.35		€ 341

Figure 63: Comparison of annual energy-fuel consumption and economic savings between the base case (auxiliary hot water heating system) and the vacuum tube solar collector.

Financial parameters

General		
Fuel cost escalation rate	%	2%
Inflation rate	%	2%
Discount rate	%	9%
Project life	yr	20
Finance		
Incentives and grants	€	
Debt ratio	%	0%
Income tax analysis		☐

Annual revenue

GHG reduction revenue		
Gross GHG reduction	tCO_2/yr	1
Gross GHG reduction - 20 yrs	tCO_2	25
GHG reduction revenue	€	0
Other revenue (cost)		☐

Costs | Savings | Revenue

Initial costs			
Incremental initial costs	100%	€	1,300
Total initial costs	**100%**	€	**1,300**
Annual costs and debt payments			
O&M costs (savings)		€	0
Fuel cost - proposed case		€	40
Total annual costs		**€**	**40**
Annual savings and revenue			
Fuel cost - base case		€	381
Total annual savings and revenue		**€**	**381**

Financial viability

Pre-tax IRR - equity	%	28.5%
Pre-tax IRR - assets	%	28.5%
Simple payback	yr	3.8
Equity payback	yr	3.6
Net Present Value (NPV)	€	2,351
Annual life cycle savings	€/yr	258
Benefit-Cost (B-C) ratio		2.8
Debt service coverage		No debt
GHG reduction cost	€/tCO_2	-208

Yearly cash flows

Year	Pre-tax	Cumulative
#	€	€
0	-1,300	-1,300
1	348	-952
2	355	-597
3	362	-236
4	369	133
5	376	510
6	384	894
7	392	1,286
8	400	1,685
9	407	2,093
10	416	2,508
11	424	2,932
12	432	3,365
13	441	3,806
14	450	4,255
15	459	4,714
16	468	5,182
17	477	5,660
18	487	6,147
19	497	6,644
20	507	7,150

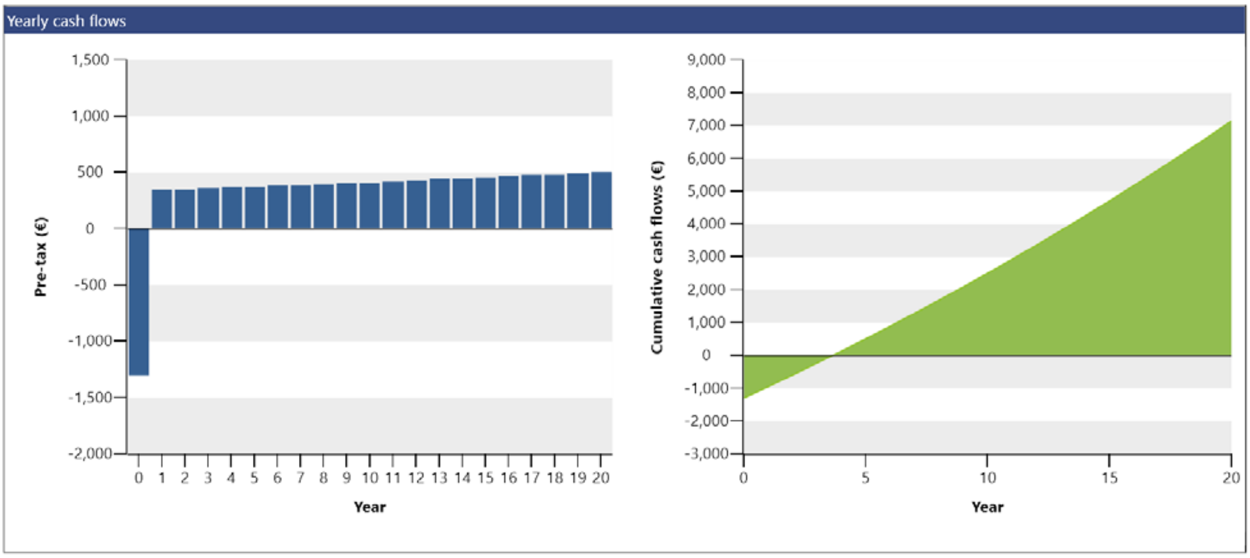


Figure 64: Financial analysis results of the studied vacuum tube solar collector.

Chapter 4

Discussion and conclusions

This Chapter contains the results of the environmental and techno-economic analysis of the studied renewable energy systems alongside with their discussion and concluding remarks.

4.1 General remarks

During the previous chapters of the thesis the energy and environmental profile of the three selected renewable energy technologies (i.e. geothermal power plants, photovoltaics and solar thermal collectors) have been presented. The selection contains two systems for electricity production, i.e. geothermal and photovoltaics, and the former refer to large scale electricity production plants while the latter can start from nominal capacity of some Watts and easily reach the mega-Watts scale. For each studied renewable technology technical variations have been presented. The two studied geothermal plants have been chosen based on the thermal capacity and expected lifetime of the corresponding geothermal field. On the other hand, two representatives of the two main technological families of the photovoltaic industry (i.e. thin film and crystalline silicon) have been selected and are studied in detail. For the solar thermal collectors, the selection of flat plate and vacuum tube systems has been made as they practically represent 100% of this market. The methodological evaluation of each of the studied renewable energy systems, comprised two steps: **i.** the LCA and uncertainty analysis (via SimaPro) and **ii.** techno-economic assessment (via RETScreen).

In the following paragraphs a synopsis of the results for each renewable technology is presented followed by the detailed discussion and conclusions.

4.1.1 Geothermal power plants

The impact of the production of one kWh electricity form deep geothermal reservoirs depends largely on the capacity of the power plant, i.e. how efficiently the wells can be used and how much electricity can be produced over the lifetime of both the power plant and wells. Thus the main idea under the comparison of the proposed geothermal power plants was to validate the environmental and economic feasibility of a medium and a low capacity geothermal reservoir. The environmental impacts of the two geothermal plants (with installed nominal capacities 5.5 and 2.9 MW) have been calculated by means of a Cradle-to-Gate LCA. The analysis for both systems indicated that the main environmental impacts (more than 96% of all total inflows and outflows) originate from the drilling phase of the deep well sets of the plants. There are also impacts associated with the electricity production, transportation and system disposal which are taken into consideration. For all cases the results denote that drilling phase clearly dominates the climate change impacts, while the stimulation with water and energy, the generation unit and other inputs play a very minor role. The cumulative CO_2-eq emissions per kWh for each MW_e installed over the whole life cycle of the power plants vary between approximately 1.8×10^{-2} and 2.2×10^{-2}

kg CO_2 eq/kWh·MW_e and the plant with the lowest capacity shows the highest impacts. This is due to the lower output of electricity over its whole life, while impacts from the dominating drilling phase are not lower for this plant.

The economic and energy assessment of the geothermal plants showed that the electricity produced allows for the mitigation of 32.3 and 17.3 ktons of CO_2-eq annually for the medium and the low capacity plant respectively. The anticipated lifetime is different for the plants (20 and 30 years for the low and medium capacity plants respectively) and this affects the overall environmental performance, as the medium capacity geothermal power plant will provide electricity for 10 additional years. Both plants require a significant initial investment for their installation (14.4 and 27 million € for the low and medium plant respectively), but the economic viability of both systems is practically guaranteed as they have a very fast payback time (i.e. 4.4 years). This is due to the fact that their capacity factor is 93% which is an extremely high value for renewable energy based power plant. It should be noted that the employed feed-in-tariff (i.e 0.15€/kWh) is a real guaranteed value for electricity production from large geothermal plants in Greece (while for photovoltaics the policy of the local energy regulator is quite different and is practically based on net-metering schemes and not guaranteed prices per electricity produced).

4.1.2 Photovoltaics

All studied PV systems were selected to have the same nominal installed capacity of 3kWp, representing a typical choice for residential applications. The production stage contributes the most important part of the environmental impacts in the life cycle of all studied PV technologies (followed by the inverter and construction of the mounting systems), as 60-70% (depending on the system) of inflows of materials and energy for both thin-film and crystalline PV systems occur during the cell and panel production phase.

The crystalline technologies (mc-Si and sc-Si) have increased values in almost all environmental impact categories. Thin-film CIS, exhibits the lower impacts in most categories and seems to be an optimum selection from an environmental perspective compared to its other counterparts. On the other hand, a-Si PV cells require an energy intensive manufacturing process which affects their environmental profile. The cumulative CO_2-eq emissions per kWh over the whole life cycle of the studied PV systems vary between approximately 3.9×10^{-2} and 5.2×10^{-2} kg CO_2 eq/kWh.

The efficiencies vary from 6.1% to 17% with thin-films based PV systems exhibiting the lowest values, but this parameter does not play an important role as the nominal capacity of all systems is identical (i.e. 3kWp). On the other hand, the larger the efficiency of the panel the less the area needed for the installation (from 17.7m^2 to 49.2m^2) and less materials will be required for the mounting systems. The economic viability of all systems is obvious, as the simple payback period is 5.6 - 6.5 years and IRR values vary from 17.4 to 20.0. The a-Si based systems seems to have higher annual energy yield due to their ability to produce more electricity under haze or cloudy conditions and thus their capacity factor is increased (21.8%) compared to their counterparts (values ~20.5). The electricity produced allows for the mitigation of ~4 tons of CO_2-eq annually for all PV systems. In general, the anticipated values for energy production, emissions reduction, investment cost, financial viability and risks associated with the four 3kWp PV technologies are quite similar. For real case installations, parameters like total cost and necessary area for installation might play decisive role for the final selection amongst the proposed technologies.

4.1.3 Solar thermal collectors

The comparison of flat plate and vacuum tube solar thermal collectors aimed at stressing the advantages and disadvantages of both technologies. The production stage of the collector component contributes the most important part of the environmental impacts in the life cycle for both studied systems. Thus, for the flat plate system, 57% and 27.1% of all total inflows and outflows are due to the production of the collector and the tank respectively, while for the vacuum tube system the corresponding values are 45.3% and 34.8%. The two systems exhibited similar environmental impacts in most categories, but the vacuum tube collector has highest values in most cases. The cumulative CO_2-eq emissions over the whole life cycle of the solar systems are quite close, varying between 2.22×10^{-2} and 2.38×10^{-2} kg CO_2 eq/kWh·m^2, and the lowest value corresponds to the vacuum tube collector.

Both collectors can cover more than half of the annual hot water needs (equal to spending 2817kWh in a typical auxiliary hot water heating system) for a family house with 4 occupants, as the solar fraction values are 62.7% and 55.3% for the vacuum tube and the flat plate collector respectively. The vacuum tube collector is practically unaffected by the variations in ambient temperature due to its significantly lower thermal losses coefficient, but this technical advantage is not reflected in its final energy outcome mainly due to the favorable weather conditions (i.e. extended time periods with high intensity solar radiation and increased ambient temperatures) in the selected installation location which make the flat plate collector equally efficient and to the increased electricity consumption of its pump. In addition the purchase cost of the vacuum collector is almost 45% higher, thus stressing the fact that for typical installations in Crete the flat plate system should be the principal option. The economic viability of both systems is proved as the simple payback period is 2.6 and 3.8 years for the flat plate and the vacuum tube system respectively.

4.2 Concluding remarks

As indicated in the previous analysis all the studied renewable energy systems have environmental impacts during their production phase and through their operation they manage to mitigate significant amounts of emitted greenhouse gases due to the avoided use of fossil fuels. Even though a technical comparison of the studied renewable energy systems might not make any sense, in the following we will try through the concept of carbon footprint (thus focusing on global warming impacts) to comment on several comparison points. The comparison that follows does not contain the solar thermal collectors as they practically refer to direct conversion of solar radiation to heat.

Measurement of life-cycle greenhouse gas emissions involves calculating the global-warming potential of electrical energy sources through life-cycle assessment of each energy source. The findings are presented in units of global warming potential per unit of electrical energy generated by that source, i.e. gCO_2 eq / kWh. The goal of such assessments is to cover the full life of the source, from material and fuel mining through construction to operation and waste management [80], [81]. In Table 9 the values of emitted, avoided and the lifetime balance for the greenhouse gases and the total energy produced from the geothermal plants and the photovoltaic systems are presented. All renewable energy systems avoid the emission of significant amounts of GHG through their operation and energy production. It is evident that the magnitude of the total avoided emissions is higher for geothermal power plants compared to photovoltaics and this has to do with the difference in the installed capacity of the two technologies (some MW compared to some kW).

Table 9: Comparative carbon footprint results for the studied renewable energy systems.

	Total emitted GHG [gCO_2 eq]	Total avoided GHG [gCO_2 eq]	Lifetime GHG balance [gCO_2 eq]	Total energy produced [kWh]	Carbon footprint [gCO_2 eq / kWh]	Carbon footprint [gCO_2 eq / kWh] by refs
Medium capacity geothermal plant	2.51E+10	9.70E+11	8.32E+11	1.35E+09	18.6	6-79
Low capacity geothermal plant	1.06E+10	3.46E+11	3.15E+11	4.80E+08	22.1	
a-Si PV	7.47E+06	1.24E+08	1.17E+08	1.72E+05	43.5	26-60
CIS PV	6.29E+06	1.15E+08	1.09E+08	1.59E+05	39.5	
mc-Si PV	7.20E+06	1.17E+08	1.10E+08	1.63E+05	44.3	
sc-Si PV	8.52E+06	1.17E+08	1.08E+08	1.63E+05	52.4	
Wind						9-35
Hydroelectric						1-24
Nuclear						4-110
Natural gas						410-650
Oil						778
Coal						740-1050

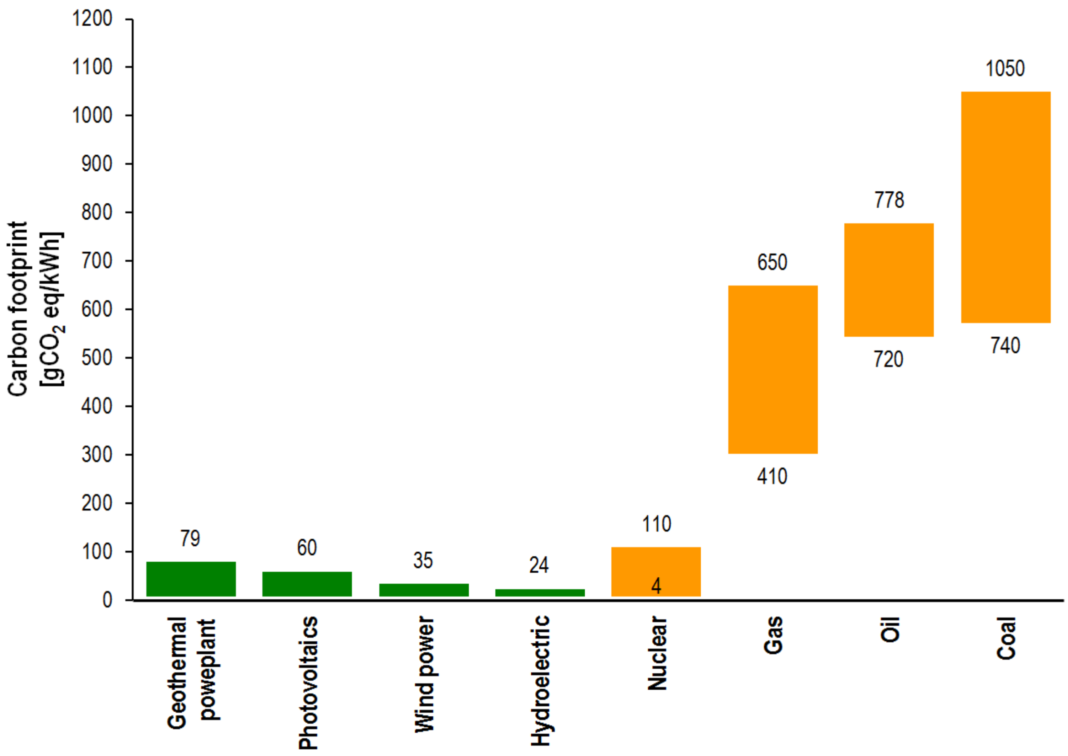


Figure 65: Carbon footprint of electricity producing technologies.

The carbon footprint has been calculated for the studied renewable systems, and in addition, typical values for other energy production technologies (either renewables or fossil-fuel based) are also depicted in Table 9 and Figure 65 [54], [80]–[83]. The carbon footprint for photovoltaics seem to be lower compared to geothermal systems, while both technologies alongside with wind, hydroelectric and nuclear are quire far from fossil fuel based power plants (which exhibit carbon footprint values ranging from 400-1050). This is an expected result as the environmental advantage of renewable over conventional energy sources is unambiguous.

References

[1] R. Turconi, A. Boldrin, and T. Astrup, “Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations,” *Renew. Sustain. Energy Rev.*, vol. 28, pp. 555–565, 2013.

[2] IEA, “Key World Energy Statistics,” 2017.

[3] REN21, “Highlights of the REN21 Renewables 2017,” 2017.

[4] OCDE & IEA, “Market Report Series: Renewables 2017, analysis and forecats to 2022,” 2017.

[5] IEA, “World Energy Outlook 2017,” 2017.

[6] IPCC, “Summary for Policymakers,” 2013.

[7] REN21, “Advancing the Global Renewable Energy Transition: Highlights of the REN21 Renewables 2017 Global Status Report in Perspective,” 2018.

[8] IRENA, “Planning for the Renewable Future,” 2017.

[9] IRENA, “Renewable Energy Prospects for the European Union,” 2018.

[10] G. Finnveden *et al.*, “Recent developments in Life Cycle Assessment,” *J. Environ. Manage.*, vol. 91, no. 1, pp. 1–21, Oct. 2009.

[11] B. P. Weidema, M. Thrane, P. Christensen, J. Schmidt, and S. Løkke, “Carbon Footprint,” *J. Ind. Ecol.*, vol. 12, no. 1, pp. 3–6, Feb. 2008.

[12] D. Weisser, “A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies,” *Energy*, vol. 32, no. 9, pp. 1543–1559, Sep. 2007.

[13] ISO, “EN ISO 14040, Environmental management - Life cycle assessment - Principles and framework,” 2006.

[14] EC-JRC, “International Reference Life Cycle Data System (ILCD), Handbook - general guide for Life Cycle Assessment - detailed guidance Luxembourg, Publications Office of the European Union.” 2010.

[15] J. B. Guinée *et al.*, “Life cycle assessment: Past, present, and future,” *Environ. Sci. Technol.*, vol. 45, no. 1, pp. 90–96, 2011.

[16] PreConsultants, “Introduction to LCA with SimaPro,” 2018.

[17] W. Klöpffer and B. Grahl, *Life cycle assessment (LCA): A guide to best practice*. 2014.

[18] ISO, “EN ISO 14044 Environmental management -Life cycle assessment - Requirements and guidelines,” 2006.

[19] UNEP-SETAC, “Towards a Life Cycle Sustainability Assessment: Making Informed Choices on Products,” Paris, France, 2011.

[20] EC-JRC, “European Commission - Joint Research Centre Life Cycle Thinking and Assessment,” 2017. [Online]. Available: eplca.jrc.ec.europa.eu.

[21] ISO, “ISO 14067, Carbon footprint of products - Requirements and guidelines for quantification and communication,” 2013.

[22] ISO, “ISO 14072, Environmental management - Life cycle assessment - Requirements and guidelines for Organizational Life Cycle Assessment,” 2014.

[23] UNEP, “Guidance on Organizational Life Cycle Assessment.” 2015.

[24] ISO, “ISO 14001, Environmental management systems - Requirements with guidance for use,”

2015.

[25] "ReCiPe 2016," *Dutch National Institute for Public Health and the Environment (RIVM)*, 2018. [Online]. Available: www.rivm.nl/en/Topics/L/Life_Cycle_Assessment_LCA/ReCiPe.

[26] M. A. J. Huijbregts *et al.*, "ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level," *Int. J. Life Cycle Assess.*, vol. 22, no. 2, pp. 138–147, 2017.

[27] C. Hendrickson, A. Horvath, S. Joshi, and L. Lave, "Economic Input–Output Models for Environmental Life-Cycle Assessment," *Environ. Sci. Technol.*, 1998.

[28] M. Ristimäki, A. Säynäjoki, J. Heinonen, and S. Junnila, "Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design," *Energy*, vol. 63, pp. 168–179, 2013.

[29] ISO, "ISO 15686, Standardized Method of Life Cycle Costing for Construction Procurement," 2008.

[30] Y. Asiedu and P. Gu, "Product life cycle cost analysis: State of the art review," *Int. J. Prod. Res.*, 1998.

[31] P. Gluch and H. Baumann, "The life cycle costing (LCC) approach: A conceptual discussion of its usefulness for environmental decision-making," *Build. Environ.*, 2004.

[32] C. Azar and T. Sterner, "Discounting and distributional considerations in the context of globalwarming," *Ecol. Econ.*, 1996.

[33] A. Rabl, "Discounting of long-term costs: What would future generations prefer us to do?," *Ecol. Econ.*, 1996.

[34] M. L. Weitzman, "On the 'environmental' discount rate," *J. Environ. Econ. Manage.*, 1994.

[35] M. Finkbeiner, E. M. Schau, A. Lehmann, and M. Traverso, "Towards life cycle sustainability assessment," *Sustainability*, 2010.

[36] B. Ness, E. Urbel-Piirsalu, S. Anderberg, and L. Olsson, "Categorising tools for sustainability assessment," *Ecological Economics*. 2007.

[37] T. E. Swarr *et al.*, "Environmental life-cycle costing: A code of practice," *International Journal of Life Cycle Assessment*, 2011.

[38] G. A. Norris, "Integrating Economic Analysis into LCA," *Environ. Qual. Manag.*, 2001.

[39] W. Kloepffer, "Life cycle sustainability assessment of products," *Int. J. Life Cycle Assess.*, 2008.

[40] R. Hoogmartens, S. Van Passel, K. Van Acker, and M. Dubois, "Bridging the gap between LCA, LCC and CBA as sustainability assessment tools," *Environmental Impact Assessment Review*. 2014.

[41] C. R. Bojacá and E. Schrevens, "Parameter uncertainty in LCA: Stochastic sampling under correlation," *Int. J. Life Cycle Assess.*, 2010.

[42] M. A. J. Huijbregts, W. Gilijamse, A. M. J. Ragas, and L. Reijnders, "Evaluating uncertainty in environmental life-cycle assessment. A case study comparing two insulation options for a Dutch one-family dwelling," *Environ. Sci. Technol.*, 2003.

[43] B. Weidema and A. S. H. De Beaufort, "Framework for Modelling Data Uncertainty in Life Cycle Inventories," *Int. J. Life Cycle Assess.*, 2001.

[44] B. P. Weidema *et al.*, "Overview and methodology. Data quality guideline for the ecoinvent database version 3," 2013.

[45] E. D. Williams, C. L. Weber, and T. R. Hawkins, “Hybrid framework for managing uncertainty in life cycle inventories,” *J. Ind. Ecol.*, 2009.

[46] “Sima Pro,” 2018. [Online]. Available: simapro.com.

[47] “RETScreen Expert,” 2018. [Online]. Available: www.nrcan.gc.ca/energy/software-tools/7465.

[48] S. Ghafghazi, T. Sowlati, S. Sokhansanj, X. Bi, and S. Melin, “Life cycle assessment of base-load heat sources for district heating system options,” *Int. J. Life Cycle Assess.*, 2011.

[49] N. Y. Amponsah, M. Troldborg, B. Kington, I. Aalders, and R. L. Hough, “Greenhouse gas emissions from renewable energy sources: A review of lifecycle considerations,” *Renew. Sustain. Energy Rev.*, vol. 39, pp. 461–475, 2014.

[50] J. Skea, D. Anderson, T. Green, R. Gross, P. Heptonstall, and M. Leach, “Intermittent renewable generation and the cost of maintaining power system reliability,” *IET Gener. Transm. Distrib.*, 2008.

[51] M. Lacirignola and I. Blanc, “Environmental analysis of practical design options for enhanced geothermal systems (EGS) through life-cycle assessment,” *Renew. Energy*, vol. 50, pp. 901–914, 2013.

[52] F. P. Sioshansi and K. H. Williamson, “Geothermal Power: The Baseload Renewable,” *Gener. Electr. a Carbon-Constrained World*, pp. 303–321, Jan. 2010.

[53] A. Holm, L. Blodgett, D. Jennejohn, and K. Gawell, “Geothermal Energy: International Market Update,” 2010.

[54] W. Moomaw *et al.*, “Renewable Energy and Climate Change,” in *Renewable Energy Sources and Climate Change Mitigation*, O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlomer, and C. von Stechow, Eds. Cambridge: Cambridge University Press, 2011, pp. 161–208.

[55] H. Hondo, “Life cycle GHG emission analysis of power generation systems: Japanese case,” *Energy*, vol. 30, no. 11–12, pp. 2042–2056, Aug. 2005.

[56] S. Frick, M. Kaltschmitt, and G. Schröder, “Life cycle assessment of geothermal binary power plants using enhanced low-temperature reservoirs,” *Energy*, vol. 35, no. 5, pp. 2281–2294, 2010.

[57] C. Tomasini-Montenegro, E. Santoyo-Castelazo, H. Gujba, R. J. Romero, and E. Santoyo, “Life cycle assessment of geothermal power generation technologies: An updated review,” *Appl. Therm. Eng.*, vol. 114, pp. 1119–1136, 2017.

[58] S. Hirschberg, S. Wiemer, and P. Burgherr, *Energy from the Earth. Deep Geothermal as a Resource*. 2015.

[59] IEA, “Key World Energy statistics,” 2017.

[60] M. Ito, K. Kato, K. Komoto, T. Kichimi, and K. Kurokawa, “A comparative study on cost and life-cycle analysis for 100 MW very large-scale PV (VLS-PV) systems in deserts using m-Si, a-Si, CdTe, and CIS modules,” *Prog. Photovoltaics Res. Appl.*, vol. 16, no. 1, pp. 17–30, Jan. 2008.

[61] Varun, R. Prakash, and I. K. Bhat, “Energy, economics and environmental impacts of renewable energy systems,” *Renew. Sustain. Energy Rev.*, vol. 13, no. 9, pp. 2716–2721, Dec. 2009.

[62] “PV technologies.” [Online]. Available: www.cleanenergyreviews.info/blog/pv-panel-technology.

[63] N. Jungbluth and M. Stucki, “Life cycle inventories of photovoltaics,” *ESU-services Ltd.* p. 250, 2012.

[64] R. Kannan, K. C. Leong, R. Osman, H. K. Ho, and C. P. Tso, “Life cycle assessment study of

solar PV systems: An example of a 2.7 kWp distributed solar PV system in Singapore," *Sol. Energy*, vol. 80, no. 5, pp. 555–563, May 2006.

[65] E. A. Alsema, "Energy pay-back time and CO2 emissions of PV systems," *Prog. Photovoltaics Res. Appl.*, vol. 8, no. 1, pp. 17–25, Jan. 2000.

[66] R. PRAKASH and N. K. BANSAL, "Energy Analysis of Solar Photovoltaic Module Production in India," *Energy Sources*, vol. 17, no. 6, pp. 605–613, Nov. 1995.

[67] X. Zhou, F. Wang, and R. M. Ochieng, "A review of solar chimney power technology," *Renew. Sustain. Energy Rev.*, 2010.

[68] A. A. El-Sebaii, M. R. I. Ramadan, S. Aboul-Enein, and A. M. Khallaf, "History of the solar ponds: A review study," *Renew. Sustain. Energy Rev.*, vol. 15, no. 6, pp. 3319–3325, Aug. 2011.

[69] V. Velmurugan and K. Srithar, "Prospects and scopes of solar pond: A detailed review," *Renew. Sustain. Energy Rev.*, vol. 12, no. 8, pp. 2253–2263, Oct. 2008.

[70] M. LENZEN, "GREENHOUSE GAS ANALYSIS OF SOLAR-THERMAL ELECTRICITY GENERATION," *Sol. Energy*, vol. 65, no. 6, pp. 353–368, Apr. 1999.

[71] F. Kreith, P. Norton, and D. Brown, "A comparison of CO2 emissions from fossil and solar power plants in the United States," *Energy*, vol. 15, no. 12, pp. 1181–1198, Dec. 1990.

[72] Y. Lechón, C. de la Rúa, and R. Sáez, "Life Cycle Environmental Impacts of Electricity Production by Solarthermal Power Plants in Spain," *J. Sol. Energy Eng.*, vol. 130, no. 2, p. 021012, May 2008.

[73] "Calpak," *2018*. [Online]. Available: www.calpak.gr.

[74] M. Goedkoop, R. Heijungs, A. De Schryver, J. Struijs, and R. Van Zelm, "ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Characterisation.," 2013.

[75] V. M. Fthenakis, "End-of-life management and recycling of PV modules," *Energy Policy*, 2000.

[76] V. M. Fthenakis and H. C. Kim, "Photovoltaics: Life-cycle analyses," *Sol. Energy*, 2011.

[77] V. Fthenakis, W. Wang, and H. C. Kim, "Life cycle inventory analysis of the production of metals used in photovoltaics," *Renewable and Sustainable Energy Reviews*. 2009.

[78] K. Pauls, K. W. Mitchell, W. Chesarak, and R. R. King, "Silicon Concentrator Solar Cells Using Mass-Produced, Flat-Plate Cell Fabrication Technology," in *Conference Record of the Twenty-Third IEEE Photovoltaic Specialists Conference*, 1993, vol. 2, pp. 824–827.

[79] N. Jungbluth, M. Tuchschmid, and M. de Wild-Scholten, "Life Cycle Assessment of Photovoltaics: Update of ecoinvent data v2. 0," *ESU-services Ltd., 2008*, 2008.

[80] S. Schlömer *et al.*, "ANNEX III: Technology-specific Cost and Performance Parameters. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," 2014.

[81] R. Pichs-Madruga *et al.*, "Special Report on Renewable Energy Sources and Climate Change Mitigation. Summary for Policymakers and Technical Summary. A Report of Working Group III of the Intergovernmental Panel on Climate Change," 2011.

[82] B. K. Sovacool, "Valuing the greenhouse gas emissions from nuclear power: A critical survey," 2008.

[83] J. L. Sullivan, C. E. Clark, J. Han, and M. Wang, "Life-Cycle Analysis Results of Geothermal Systems in Comparison to Other Power Systems," 2010.