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Task 38
Solar Air-Conditioning and Refrigeration

"Life Cycle Assessment of Solar Cooling Systems"

A technical report of subtask D

Subtask Activity D3

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1. Introduction

Renewable energy (RE) systems can certainly allow reducing the use of fossil fuels and the related environmental impacts for building air-conditioning. It is more and more clear that good design of the system and appropriateness of the technology are a key issues on the way to maximise the benefits. Therefore, for systems dealing with solar thermal systems, it has been experienced that wrong choices among RE technologies to meet specific applications could also lead to negative effects in terms of Primary Energy (PE) saving.

This issue is continuously investigated within the Task 38 "Solar air conditioning and refrigeration", promoted by International Energy Agency in the framework of the Solar Heating and Cooling (SHC) Programme. Important results derive by a detailed monitoring activity since many years of operation of a large set of installations. The results of these studies are fundamentals for highlighting performance minimum thresholds of each equipment, rules for design (including the selection of the most appropriate technologies), efficacy of maintenance and operation procedures. A similar consideration can be done for environmental impacts, mainly related to Global Warming Potential (GWP) emissions, dealing with the operation of the systems.

Nevertheless, if we enlarge our point of view from the operation of the systems to its entire life, a new set of information can be available to do a wider energy and environmental balance.

The scientific approach of Life Cycle Assessment (LCA) allows taking into account in all the phases of the systems life resources and energy uses. In this way it is possible to investigate if the use of one technology for a specific application, in a specific climate, is "globally" convenient or not for the environment in the time period of its life.

Unfortunately the application of LCA approach is not an easy task and cannot be considered as a tool available for a designer. The amount of data and information needed to perform materials, energy and resources balances is quite huge. Its gathering is possible through the access of specialised data-bases. Today the main "user" of LCA are scientists and industries.

In scientific literature, there are numerous studies on the LCA of RE systems. Some of them, analyzing the energy and environmental performances of photovoltaic and solar thermal systems, are summarized in the following.

Kannan et al. (2006) performed a LCA of a distributed 2.7 kW_p grid-connected mono-crystalline solar PV system operating in Singapore. The life time of the PV facility is expected to be 25 years. The total energy use in the three life cycle phases of production, use and end-of life, including transportation is 2.94 MJ/kWh_e. The manufacturing of solar PV modules accounted for 81% of the life cycle energy use.

Garcìa-Valverde et al. (2009) carried out a LCA to quantify the energy use and GHG emissions from a 4.2 kW_p stand-alone solar PV system, operating in Murcia (south-east of Spain), with a total nominal area of 35 m^2. The life time of the PV facility is assumed to be 20 years. On the basis of the LCA results, it was found that the facility has about 470 GJ of embodied energy and 13.17 metric tons of embodied CO_2. The biggest energy requirements and emissions are related to the construction phase.

Battisti and Corrado (2005a) used the LCA to assess the energy and environmental impacts of a multi-crystalline silicon PV system located in Rome (Italy), grid-connected and retrofitted on a tilted roof. The chosen FU is 1 kW_p of PV system. Active surface necessary for 1 kW_p is 9.4 m^2. Results showed that the Global Energy Requirement (GER) is 53.2 GJ/kW_p, the GWP is 4730 kg CO_{2eq}/kW_p.

Ardente et al. (2005) applied the LCA to a solar thermal collector (including absorbing collector, water tank and external support) with a total net surface of 2.13 m^2. The average useful life is assumed to be 15 years. The LCA results showed that the GER of the FU is 11.5 GJ and the GWP is 721 kg CO_{2eq}. The energy directly used during the production process and installation is only the 5% of the overall consumption; another 6% is consumed for transports during the various life cycle phases. The remaining percentage is employed for the production of raw materials, used as process inputs. These results show that the direct energy requirement is less important than the indirect one.

Battisti and Corrado (2005b) examined a solar thermal collector with integrated water storage, with a total surface of 1.68 m^2 and an active surface of 1.44 m^2. The GER is 3.1 GJ, the GWP is 219.4 CO_{2eq}. The above impacts are mainly due to the collector production (98%).

Kalogirou (2004, 2009) applied the LCA to two flate-plate collectors. One (1.35 m^2) is integrated in a thermosiphon solar water heating system, constituted by two collectors (2.7 m^2), insulated copper pipes and steel frame. The other (1.9 m^2) is used in a solar water heating system constituted by two collectors (3.8 m^2), insulated copper pipes and steel frame.

The first collector (1.35 m^2) has a GER of 2663 MJ. The embodied energy content for the construction and installation of the complete thermosiphon solar water heating system is 6946 MJ , the emissions of CO_2 are 1.9 tons. The second collector (1.9 m^2) has a GER of

3540 MJ. The GER for the construction and installation of the solar hot water system is 8700 MJ; the CO_2 emissions generated from solar system embodied energy are 1.93 tons.

This report shows how LCA can be applied to SHC System for the assessment of energy and environmental benefits (saved energy and avoided emissions) related to the use of a solar cooling plant, in substitution of a conventional plant.

In particular this subtask activity has been mainly focused on:

- definition of methodological key-issues in the LCA of solar cooling systems and the choice of shared assumptions for the accounting and for the impact assessment;
- analyses of five case studies with different technologies in different climates;
- report of useful data for the main components of a SHC systems which can be useful for further LCA studies

2. Methodology: LCA for innovative heating and cooling systems

2.1. Introduction

The LCA is a useful tool to estimate the effective energy and environmental impacts related to products or services [ISO 14040, 2006]. However, the results of the LCA do not represent „exact“ and „precise“ data, but are affected by a multitude of uncertainty sources.

Although the LCA has been regulated by the international standards of series ISO 14040 [ISO 14040, 2006; ISO 14044, 2006], several approaches and ways to proceed are possible, due to the choices of the analyst.

The reliability of the LCAs strictly depends on complete and sharp data that unfortunately are not always available. ISO 14040 recommends to investigate all those parameters that could heavily influence the final eco-profile. Because of Life Cycle Inventory (LCI) results could be used for comparative purposes, the quality of data is essential to state whether results are valid or not [Huijbregts et al, 1999]. Regarding data quality, LCA studies should include: time-related coverage, geographical coverage, technology coverage, precision, completeness and representativeness of data, consistency and reproducibility of methods used in the LCA, sources of the data and their representativeness, uncertainty of the information.

Despite the quality requirements above mentioned, LCA analysts often employ LCA software in an uncritical way and for this reason the life cycle interpretation represents a step of paramount importance to strength the quality of the LCA study. Several problems and disadvantages could anyway arise with software and databases for life-cycle inventory and impact assessment, as [Kemna et al., 2006]:

- There is a wide discrepancy between emission data for one material or process between the various database sources;
- Documentation regarding the origin of emission data and their validity is often not clear from the tool alone and would requires extensive additional research to explain the differences;
- Public availability of data is limited;
- Prices and training efforts constitute a significant investment, especially for Small and Medium Eneterprises.

In addition to previously listed parameters, other sources of uncertainty are [Bjorklund, 2002]:

– Data inaccuracy (due to errors and imperfection in the measurements);

– Data gaps or not representative data;

– Structure of the model (as simplified model to represent the functional relationships);

– Different choices and assumptions;

– System boundaries definition;

– Characterisation factors and weights (as those used in the calculation of potential environmental impacts);

– Mistakes (unavoidable in every step of LCA).

Furthermore, the eco-profile of the selected FU is strictly related to the service life („Period of time after installation during which all essential properties of an item meet or exceed the required performance“ [ISO 15686, 2000]) and durability („Capability of an item to perform its required function over a period of time“ [ISO 15686, 2000]) concepts.

The following paragraphs define a framework for the collection, processing and reporting of environmental data concerning the investigated case studies plants. Such approach tries to grant the transparency and uniformity of the LCAs and to allow the reproducibility and comparability of results.

2.2. A Methodology framework for LCA

2.2.1. Goal and scope definition

The goal and scope of an LCA shall be clearly defined and shall be consistent with the intended application.

Due to the iterative nature of LCA, the scope may have to be refined during the study.

In defining the goal of an LCA, the following items shall be unambiguously stated:

- the intended application;
- the reasons for carrying out the study:
- the intended audience, i.e. to whom the results of the study are intended to be communicated:
- whether the results are intended to be used in comparative assertions intended to be disclosed to the public.

LCA is more and more used to classified comparative systems or products. To do these analyses, topics have to be clarified to get a transparent report and to be able to reproduce the study.

The following topics have been discussed:

- Choice of the Functional Unit (FU);
- System boundaries;
- Reference data;
- Cut-off rules and allocation rules;
- Environmental impacts indexes;
- Data quality and enclosed metadata;
- Data reporting framework.

2.2.2. Functional Unit

The first step into performing a LCA is the definition of the FU, defined as the “*the quantified performance of a product system for use as a reference unit*” [ISO 14040, 2006]. The FU is important as basis for the data collection and for the comparability of different studies referred to the same product category. The FU specifies the function of the product system being studied and its efficiency. It also provides a reference to which the flows (inputs and outputs) are related and consequently the potential impacts on the environment, human beings, and resources.

However, the choice of FU is not always immediate and unique. Several different options could be handled, driving to very different results [Ardente et al., 2003]. For the evaluation of performance of products and services, the Standard ISO 14031 suggests the use of relative or global Operational Performance Indexes (OPI) compatibly and congruently with the aims of the study [ISO14031, 1999].

The indicators should represent environmental performance as accurately as possible, providing a balanced illustration of environmental aspects and impacts [ISO 14031, 1999]. In addition to absolute values of environmental impacts, measurement units may also address the environmental impact per unit of product or service, per turnover, gross sales or gross value added (‚eco-efficiency' indicators).

Concerning the heating and cooling plants and components, the FU can refer to the entire device or to specific values.

In the first case it is possible to have an overall and complete view of the environmental impacts related to the plant, but it is difficult to compare plants of the same typology but with very different sizes.

Referring the impacts to specific values (as for example to the nominal power, the surface or the energy output) it is possible to compare the performances of different replaceable products or technologies. On the other side, specific values can be related to particular local parameters or use condition, giving therefore misleading information. For example, the output of a solar system is an extremely variable data, depending on the solar energy input and the mutable weather conditions. The FU of a collector referred to the system's output can therefore cause confusion, because the same collector would have a different eco-profile depending on the site where it is installed.

In any case, the European recommendations for the use of indicators in the Environmental Management Systems (EMS) suggest that, for avoiding confusion, indicators should always be accompanied by the absolute values [EC, 2003]. Advantages and drawbacks of different alternatives have been synthesized in Table 1.

We assumed that the main requirements in the selection of the FU are: transparency of the choice and conformity to the goals and scopes. In order to provide to the readers a more complete vision of the results, in the present study the eco-profiles of plants and components will be referred, when possible, to different alternatives:

1) absolute values related to the entire plants;
2) specific values per unit of system technical parameters (power or surface);
3) specific values per unit of energy output.

The report of different FUs is, anyway, dependent on the availability of input data and technical specifications.

Table 1: Choice of the FU

FU Alternatives	*Absolute values*	*Relative/specific Values*	
		Per unit of technical parameter	per unit of energy output
Advantages	It provides an unique and unambiguous view of the global performances of the studied system.	It provides an easy basis for the comparison of various and very different case-study systems	It takes care about the systems efficiency. Results can be easily compared
Drawbacks	Difficulties to compare the performances of plants with different sizes or power, or to compare different technologies	It does not take care about efficiency of the plant or the technology	The eco-profile is depending on site-specific parameters (weather conditions, sun radiation) or managerial and technical choices (setting parameters, working time, useful life, etc)

2.2.3. System Boundaries

The system boundaries determine the unit of processes to be included in the study and what type of life-cycle component, process or phase could be omitted. The choice of system boundaries shall be consistent with the goals of the study. Any decision to omit life cycle stages, processes, inputs or outputs shall be clearly stated, and the reasons and implications for their omission shall be explained [ISO 14044, 2006].

A correct and transparent setting of the system boundaries allows:

- To optimize the necessary time and resources for the analysis, focusing the attention on the elements that are responsible of the highest environmental impacts;
- To compare different LCA study based on the same initial assumptions;
- To reduce the number of LCA data and facilitating the calculations without compromising the reliability, completeness and representativeness of results.

As a general principle, all processes “from cradle to grave” shall be included in the study [IEC, 2008]. For products, where their further use is not known a “from cradle to gate” approach is usually sufficient. For “end-products” a “cradle to grave”-approach is usually relevant.

The following specifications of different boundary settings are relevant [IEC, 2008]:

- Boundary in time shall define/describe the time period which the LCA data are valid for.
- Boundary towards nature shall define the flow of material and energy resources from nature into the system and emissions from the system to air and water as well as waste out of the system.
- Boundary towards geography shall define/describe the geographical coverage of the LCA data including possibilities to handle different regional aspects in the supply chain, if found necessary.
- Boundaries in the life cycle shall define/describe what to be included with regards to e.g. extraction and production of raw materials, refining of raw materials, manufacturing of components and main parts, assembly of products, use of products, and end-of-life processes.
- Boundaries towards other technical systems shall define/describe the flow of materials and components from the product system under study and the outflow of materials to other systems.

In the present study the system boundaries include, where possible:

- Production phase: including extraction of resources, production and transport of raw materials and semi-manufactured goods, production of system components, assembly of the products and production waste management. Impacts due to capital equipments an human labor can be omitted;
- Use phase: including transport of products to final consumers, installation, utilizations of the energy sources and spare parts during the useful life-time and emissions to water, air and soils. Due to the large incidence of use phase in the global life-cycle, the use conditions and assumptions should be described in detail. Environmental impacts from maintenance and production of spare parts with a life cycle more than three years need not to be included;
- End life: including disassembly and dismantling of the plant/component, transport of exhausted materials, recycling processes, waste management and final disposal.

Deviations from any general rule described above for system boundary settings shall be mentioned and justified.

2.2.4. Reference data

Environmental indirect impacts of productive systems are often significant or dominant, and they strongly depend on utilized input data concerning raw materials and energy sources. For these reason it is necessary that the LCA study would be referred to common environmental databases, in order to grant the comparability of the results.

When possible, authors have to refer to the Ecoinvent database [Ecoinvent, 2007], assumed as reference LCA database. Different utilized database, missing data or other employed references have to be cited in the LCA results data-sheet.

2.2.5. Cut-off rules

The ISO standards establish that it is possible to neglect a component only after demonstrating that its incidence on a specific impact is lower than a fixed threshold. The carrying out of LCA studies can therefore become a really difficult task, because the great complexity of products and product systems, characterized often by very small components hard to be explored (for example, electronic parts present in the majority of plants and equipments). But in a so deep analysis, the analyst could have to face the problem of unavailability of data. This assumption cannot be done with an “a priory” approach, but only after a demonstration of its low incidence. On the other side, a detailed and time-consuming investigation of secondary components could distract the analyst to priority elements.

The best way to proceed is therefore to refer to the scientific literature, standardized rules or to “rules of thumbs” (such intending not standardized rules that anyway are generally accepted and shared). It is important to describe the rules for omitting inventory data considered as not relevant.

The ISO 14044 classify the cut-off criteria used in LCA practice to decide which inputs are to be included in the assessment, considering mass, energy and environmental significance. Making the initial identification of inputs based on mass contribution alone may result in important inputs being omitted from the study. Accordingly, energy and environmental significance should also be used as cut-off criteria in this process.

a) Mass: an appropriate decision, when using mass as a criterion, would require the inclusion in the study of all inputs that cumulatively contribute more than a defined percentage to the mass input of the product system being modeled.

b) Energy: similarly, an appropriate decision, when using energy as a criterion, would require the inclusion in the study of those inputs that cumulatively contribute more than a defined percentage of the product system‘s energy inputs.

c) Environmental significance: decisions on cut-off criteria should be made to include inputs that

contribute more than an additional defined amount of the estimated quantity of individual data of the product system that are specially selected because of environmental relevance.

Anyway there are different points of view concerning the percentage of exclusion. For example the IISI (International Iron and Steel Industry) based its report on a cut-off rule of 99.9% (excluding from the calculation only the 0.1% of input materials) [IISI, 2002]. Different rules are instead applied into different environmental product certification schemes: for example, the Environmental Product Declaration (EPD) scheme generally assume a 1% cut-off rule [IEC, 2008], while the French environmental label for the building products assumes a percentage of 5% [AFNOR, 2001].

Sensitivity analysis could represents a efficacious way to check cut-off rules in order to assess how the un-investigated input or output could affect the final results.

2.2.6. Allocation rules

Generally productive systems are characterised by two or more outputs, jointly produced. Consequently, complex systems must be broken down into a set of separate easier sub-systems, trying to analyze them separately. The problem is to find a suitable quantity to act as a partitioning parameter so that the inputs and the outputs from the overall system can be allocated to a single product system. This is known as *allocation procedure*, employed also to ascribe pollutants to processes that cause them.

When allocation have to be applied, the ISO 14044 suggest to follow a stepwise procedure:

a) Step 1: Wherever possible, allocation should be avoided by

1) dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes, or

2) expanding the product system to include the additional functions related to the co-products.

b) Step 2: Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them; i.e. they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.

c) Step 3: Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products.

One parameter commonly used to carry out the allocation procedure is mass. For example, a system requires a total mass (M) and a total energy (E) and produces many products of mass (m_i) and waste of mass (W). Using the mass as partitioning parameter (p_i), it will be:

$$(p_i)=(m_i)/(\sum m_i)$$

and so the partition of energy and mass will be:

$$E_i= E^*(p_i)$$

$$Wi= W^*(p_i)$$

It is possible to use different parameters for allocation, proceeding in a similar way as done for the mass partitioning, for example:

- Physical quantities: volume, quantity of material,
- Energy quantities: net-calorific value, gross-calorific value, enthalpy,
- Economic quantities: market price, price at the production plant.

It is also possible to allocate the energy consumption of sub-products directly to one or several target products. All the other co-products and materials are therefore valued as free of energy consumption or impacts. This assumption comes when the incidence and the role of co-products are assumed as not significant and negligible.

2.2.7. Environmental impacts indexes

In order to uniform the results of the LCA studies, it has been chosen to refer to two of the main environmental indexes enclosed in the EPD scheme [MSR, 2000]. The reported environmental impacts include:

- The **Global Energy Requirement** (**GER**) represents the entire demand, valued as PE, which arises in connection with every life-cycle step of an economic good (product or service). The index is expressed in terms of GJ of PE;
- The **Global Warming Potential** (**GWP**) is a measure of the relative, globally averaged warming effect arising from the emissions of particular greenhouse-gas. The GWP represents the “time integrated commitment to climate forcing from the instantaneous release of 1 kg of a trace gas expressed relative to that from 1 kg of carbon dioxide”. The characterisation factors are expressed as kg of “CO_2 equivalent” and are referred to a period of 100 year;

Environmental characterisation factors can be referred to the EPD guidelines [MSR, 2000; IEC, 2008].

Furthermore, the introduction of RE plants or innovative components could cause additional environmental impacts in the production and installation phases, that are however balanced by the saving of energy and emissions during the use phase. For this reasons, a further set of indexes has been suggested for innovative components, including:

- The **Energy Payback Time** (**E_{PT}**): It is defined as the time during which the system must work to harvest as much energy (considered as renewable and non renewable PE) as it required for its production and disposal. The harvest energy is considered as net of the energy expenditure for the system use.

  The E_{PT} can be likewise defined as the use time necessary for a plant to save as much energy (valued as primary) as that consumed during all the life-cycle phases of system itself: **E_{PT}**

$$E_{PT} = \frac{GER_{innovative} - GER_{reference}}{E_{year}}$$

  where:

  - $GER_{Innovative}$ = PE consumed during LCA phases of innovative system except for the use phase [MJ];
  - $GER_{reference}$ = PE consumed during LCA phases of reference system except for the use phase[MJ];
  - E_{year}= Net Yearly PE saving due to the use of the innovative system [MJ per year].

  The Yearly PE saved can be calculated referring to estimated or measured data concerning the use phase of a replaceable conventional plant, assumed as reference system.

- The **Emission Payback Time** (**EM_{PT}**): It is defined as the time during which the cumulative avoided emissions due to the application of the innovative plant are equal to those released during all the life-cycle of the plant itself. It is possible to calculate the EM_{PT} relatively to the pollutant “i” as:

$$EM_{PT-i} = \frac{EM_{innovative,i} - EM_{reference,i}}{EM_{S-i}}$$

where:

  - $EM_{innovative,i}$ = Global emissions of generic pollutant “i” related to each life-cycle phase of the innovative system except for the use phase [kg_i];
  - $EM_{reference,i}$ = Global emissions of generic pollutant “i” related to each life-cycle phase of the reference system except for the use phase [kg_i];

- EM_{S-i} = Net Yearly emission saving of generic pollutant “i” due the use of the innovative system [kg_i /year].

EM_{S-i} represents the emissions that would be released if no innovative component should have been added. The EM_{S-i} depends on the typology and efficiency of the conventional replaceable plant, assumed as reference system. The EM_{S-i} can be estimated on the basis of the yearly saved energy (E_{year}) previously described and on the basis of the emission factors of traditional plants (data can be referred to previously cited international LCA databases). Although the EM_{PT} can be calculated for all the main air pollutants, in the present study it has been restricted only to the greenhouse gases emissions;

- The **Energy Return Ratio** (**E_{RR}**): it represents how many times the energy saving overcomes the global energy consumption due to the innovative plant.

$$E_{RR} = \frac{E_{Overall}}{GER_{innovative}}$$

where:

- $E_{Overall}$ = GER saving during the overall life-time of studied plant or component [MJ].

This index is particularly significant because it encloses both the GER and the global energy saving during the overall useful life, and it provides a global view of the energy benefits related to the use of such technology.

2.2.8. Data quality and enclosed metadata

In the case of LCA a number of basic difficulties can be distinguished, which render data quality analysis more complicated than in the case of most other decision support systems [CML, 152].

Even the ISO standards mentioned the need to evaluate the data quality although they do not prescribe detailed procedures. Data quality indicators to be covered in the studies are [ISO 14040, 2007; ISO 14048, 2006]:

- time-related coverage: age of data and the minimum length of time over which data should be collected;
- geographical coverage: geographical area from which data for unit processes should be collected to satisfy the goal of the study;
- technology coverage: specific technology or technology mix;
- precision: measure of variability of data values for each data category expressed as e.g. variance.
- completeness: percentage of locations reporting primary data from the potential number in existence for each data category in a unit process.
- representativeness: qualitative assessment of degree to which the data set reflects the true population of interest (time, geography and technology coverage).
- consistency: qualitative assessment of how uniformly the study methodology is applied to the various components of the analysis.
- reproducibility: qualitative assessment of the extent to which information about the methodology and data values allow an independent practitioner to reproduce the results.
- sources of the data;
- uncertainty of the information (e.g. data, models and assumptions).

Several methodologies and approaches have been suggested for the management of data quality in LCA [Heijungs, 1996; Kennedy et al. 1997; Meier, 1997; Weidema, 1996; Wrisberg, 1997]. These are often complicated and time-consuming, requiring a detailed knowledge of systems.

For these reason it has been decided to include in the data reporting sheet a set of additional data (metadata) concerning the study, the considered technical system, the data sources, the main assumptions and rules.

It is also suggest a self –data quality" statement, where the analyst could consider the limits of the study, the strong and weak points, and general completeness, representativeness and reproducibility of the results.

Finally, authors should insert a text sheet where to insert further information concerning the investigated system and its peculiarities. In particular, useful information could regard the incidence of each life cycle step.

2.2.9. Data reporting framework

A data reporting framework for the presentation of data has been prepared and attached in Annex I. The report sheets aims to lead the authors into compile and report the most significant information concerning their study, and to present the LCA results in a standardized format. The sheets have been inspired to the EPD scheme, introducing new descriptive elements that reflex the previous discussed key-issues.

In the case-study report, authors should compile a brief description of their studied system, and to compile the sheets as following:

1. Product: Insert the name of the investigated product or technology;
2. Authors and reference: Insert the name of authors and the study reference;
3. Description of the product: insert a description of the main product components and functionalities, belonging technologies, and main system characteristics, in order to clarify and improve the comprehension of the next LCA steps;
4. Product characteristics: Insert some specific technical characteristics (as nominal power, useful surface, plant output). These data are useful for the calculation of the specific FUs eco-profiles. A detailed description of the working phase and efficiency should be included, in order to better evaluate the environmental impacts during the system utilization.
5. Metadata: as previously explained, metadata are the additional information that improve the understanding, the transparency and the quality of LCA studies. Furthermore metadata improve the comparability of different studies, giving information about methodological and empirical choices. Information to be included in the report are:
    a. *Age of the study*: including the year of the study and;
    b. *Technological representativeness of input data*: it concerns the representativeness of input LCA data employed during the inventory phase and the main assumptions on data availability;
    c. *System boundaries*: with a description of LCA phase that have been included/excluded from the analysis and the description of possible deviations from the general assumptions previously described in paragraph 2.1.2;
    d. *Useful life-time*: assessed or measured data of the plant‘s working time;

e. *Cut-off rules*: description of rules for the exclusions of components in the study, and description of the possible deviations from the general assumptions previously described in paragraph 2.1.3;

f. *Allocation rules*: description of the allocation processes, and description of the possible deviations from the general assumptions previously described in paragraph 2.1.4;

g. *Further details*: additional information that could improve the completeness of the results;

h. *Quality data assessment*: introducing a qualitative description of the consistency of the main employed data, their consistency and representativeness, the age of input data and their suitability for the study purposes;

6. Life Cycle inventory: including a description of the main system‘s raw materials, air and water emissions, and produced wastes;
7. Product eco-profile: a synthesis of the main environmental global indexes, as previously described in paragraph 2.1.6;
8. Primary energy saving: concerning the RE systems and the innovative components, it is possible to calculate the possible benefits and drawbacks related to the use of such technologies and additional elements. The calculation of energy and emission saving, as described into paragraph 2.1.9, requires a detailed definition and description of a reference system which compare the case-study to;
9. Payback indexes: they involve information about system impacts and benefits, trying to make a global life cycle balance and to give to regards a synthetic information about life-cycle performances of the plants.

ANNEX I : Data Report format

Data Report format

1. **Product**
2. **Authors and reference**
3. **Description of the product**

4. **Product characteristics**

Nominal power/surface/other:
Measured/estimated yearly energy production and/or consumption:
Information about the use phase:
Information about the end-of-life phase:

5. **Metadata**

Age of the study:
System boundaries (production phase, use phase, end-of-life phase):
Useful life-time:
Cut-off rules:
Allocation rules:
Further details:
Data Quality Assessment:

6. **Life Cycle Inventory**

<table>
<tr><td rowspan="3">Main employed materials and components:</td><td>Main Air Emissions:</td></tr>
<tr><td>Main Water Emissions:</td></tr>
<tr><td>Main Wastes:</td></tr>
</table>

7. Product Eco-profile:

Global Impact Indexes	Total	Per Unit of Power	Per Unit of Output
Global Energy Requirement (GER)	[GJ]	[GJ/kW]	[GJ/kWh]
Global Warming Potential (GWP)	[kg CO_{2eq}]	[kg CO_{2eq}/kW]	[kg CO_{2eq}/kWh]

8. Primary energy saving and avoided emissions:

Main assumptions and description of the conventional reference system		
Primary Energy Saving (E_{year})		[kWh/year]
Global emissions avoided (Em_{S-i})		[ton CO_{2eq}]

9. Payback indexes

Energy Payback time (E_{PT})		[year]
Emission Payback time (EM_{PT})		[year]
Energy Return Ratio (E_R)		

3. LCA Case Studies

3.1 Solar Cooling systems with Ad, Ab, VC chillers

3.1.1 Definition of case studies

Four different cases have been investigated in order to assess the performances of two different technologies of thermally driven chillers (Absorption - Ab and Adsorption - Ad) in two applications represented by a building loads in two localities: Palermo (South Italy) and Zurich (Switzerland).

All the systems use two pipes fan coils for cooling and heating distribution.

In addition we have decided also to include two possible alternatives in the configurations according to the modality of back-up of the solar cooling systems in summer operation The first case includes an auxiliary conventional chiller supporting the ad/absorption chiller, and it is defined as ―cold back-up". In the second configuration an auxiliary gas boiler, supports the solar system and the ad/absorption chiller heat input; it is defined as ―hot-back-up".

The four basic systems (to be analysed in two locations) resulted to be:

- SHC with Absorption machine (12 kW) and 35 m^2 evacuated tubes with hot-back-up in summer operation
- SHC with Absorption machine (12 kW) and 35 m^2 evacuated tubes with cold-back-up in summer operation
- SHC with Adsorption machine (8 kW) and 25 m^2 flat plate collectors with hot-back-up in summer operation
- SHC with Adsorption machine (8 kW) and 25 m^2 flat plate collectors with cold-back-up in summer operation

In this way the number of investigated combinations systems/load was 8.

More details about the plants will be provided in the next chapters.

The performances of these 4 systems has been compared to a reference heating and cooling defined by: Conventional system with a vapour compression (VC) chiller and a gas boiler.

The first step of the analysis was to calculate, by means of TRNSYS simulations, the energy performances of the selected SHC plants with different technologies and sizes (adsorption machine of 8 kW – absorption machine of 12 kW), for two localities (Palermo and Zurich) with different climatic conditions. Simulations were carried out with meteorological data from the database METEONORM with following peak conditions.

Table 2: **Meteo conditions for the two selected climates**

	Zurich	Palermo
summer	T_{max} = 30.9 °C, x_{max} = 13.5 g/kg	T_{max} = 35.8 °C, x_{max} = 24.3 g/kg
winter	T_{min} = -11.5 °C x_{min} = 1.2 g/kg	T_{min} = 5.2 °C x_{min} = 4.6 g/kg

For this reason four different buildings have been defined in order to have a cooling peak load of 8 kW and of 12 kW in both climatic conditions and the hourly H/C load profile for the typical year.

The buildings have been simulated with type 56b –Multizone Building" (TRNSYS version 16.1).

The following general conditions have been assumed for the simulation:

- Set point temperature for cooling: 26°C
- Set point temperature set point for heating: 20°C
- Relative humidity of set point: 50%
- Infiltration of external air: 0.6/h during the day, 0.1/h during the night

Table 3: Design data for load calculation

Zürich		building		**Palermo**		building
$U_{wall,roof}$	0.2	W/m²K		$U_{wall,roof}$	0.48	W/m²K
U_{window}	1.1	W/m²K		U_{window}	1.8	W/m²K
G_{solar} =	0.6			G_{solar} =	0.7	
shading factor:	10	% winter	40 % summer	shading factor:	60	%
		Internal load : 6 W/m²				
start cooling:		end heating		start cooling:		end heating
15-May		14-May		15-May		30-March
end cooling:		start heating		end cooling:		start heating
14-Sept		15-Sept		30-Sept		1-Dec

All buildings have two floors, similar geometric features and the same relation wall/window on every side.

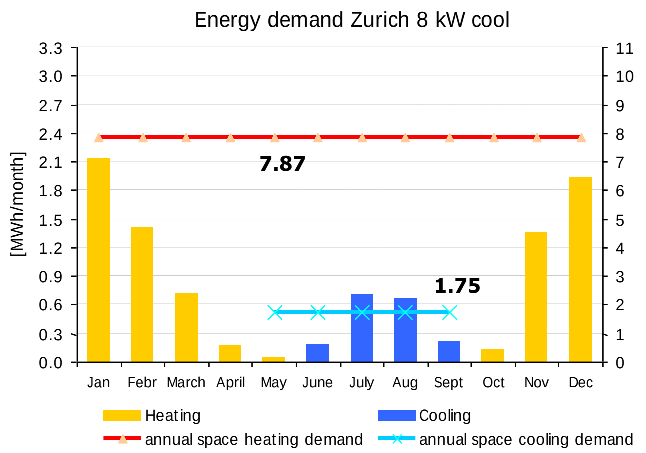
At these conditions, the simulated load profiles came out as showed in Table4.

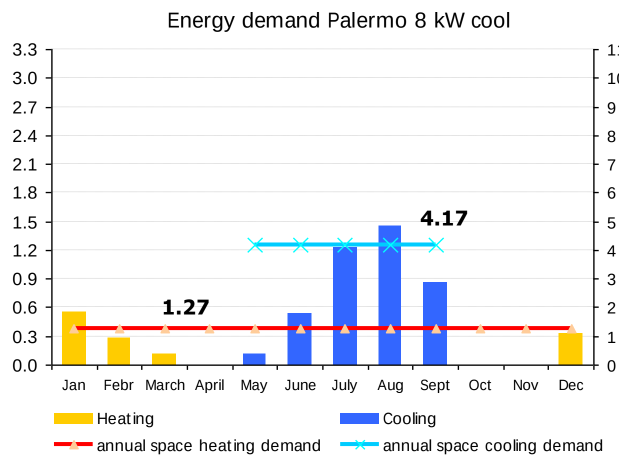
For every building, monthly load profiles have been created by simulation (Table5).

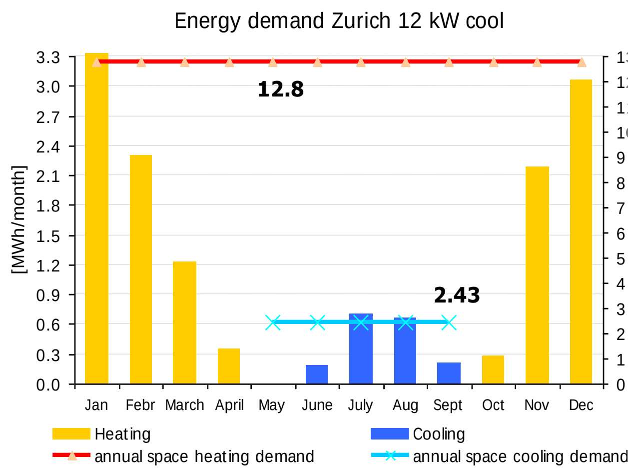
Table 4: Peak loads and seasonal energy demands

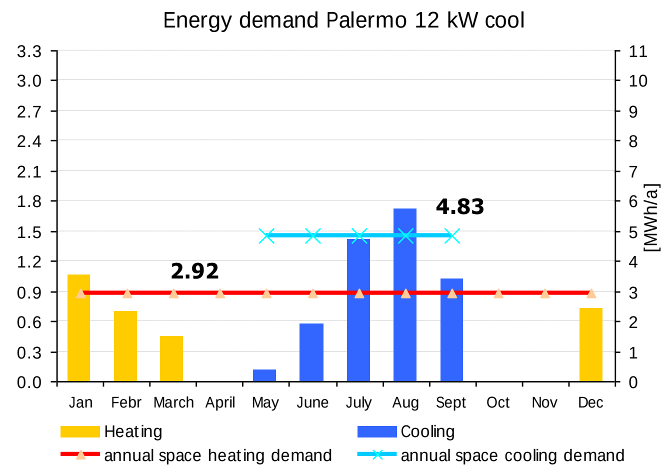
	inertia	P_{cool} peak:	P_{heat} peak:	cooling demand	heating demand
ZÜRICH	**174735**	**12.19**	**23.51**	**2434**	**12794**
12 kW cool	kJ/K	kW	kW	kWh/year	kWh/year
1120 m^3		38.1	73.5	7.6	40.0
S/V: 0.47		W/m^2	W/m^2	kWh/m^2 year	kWh/m^2 year
ZÜRICH	**113033**	**7.38**	**15.06**	**1752**	**7868**
8 kW cool	kJ/K	kW	kW	kWh/year	kWh/year
624 m^3		38.4	78.5	9.1	41.0
S/V: 0.57		W/m^2	W/m^2	kWh/m^2 year	kWh/m^2 year
PALERMO	**94732**	**12.58**	**12.31**	**4834**	**2924**
12 kW	kJ/K	kW	kW	kWh/year	kWh/year
588 m^3		74.9	73.3	28.8	17.4
S/V: 0.6		W/m^2	W/m^2	kWh/m^2 year	kWh/m^2 year
PALERMO	**70800**	**7.38**	**8.31**	**4166**	**1274**
8 kW cool	kJ/K	kW	kW	kWh/year	kWh/year
351 m^3		68.3	76.9	38.6	11.8
S/V: 0.71		W/m^2	W/m^2	kWh/m^2 year	kWh/m^2 year

Table 5: Monthly heating/cooling demands









3.1.2 Air to water vapor compression chiller and gas boiler: general description of the plant

The conventional system consists mainly of two subsystems, namely:

- 10 kW water VC chiller (cooling unit)
- 20 kW gas boiler (heating system)

A schematic diagram of this system is shown in Figure 1.

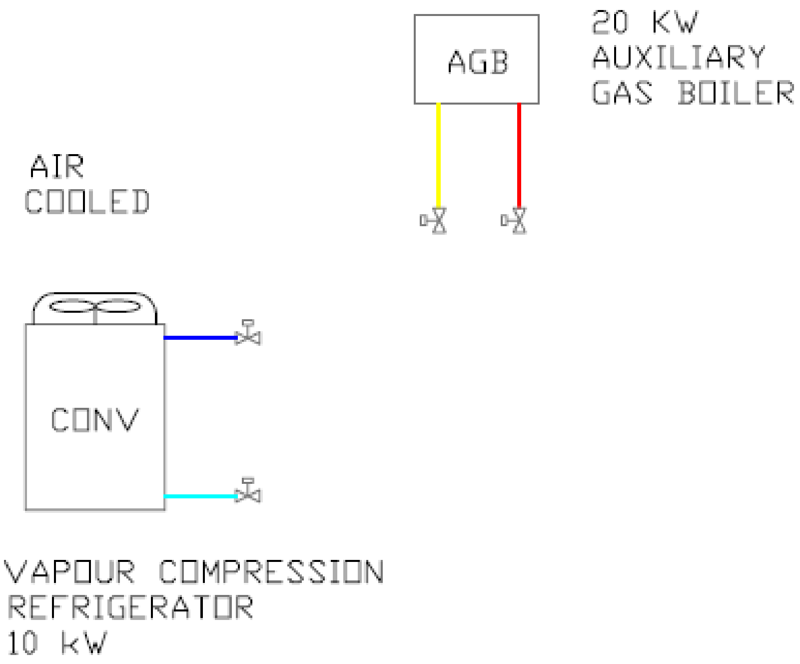


Figure 1: Schematic representation of the conventional system

In this system, the cooling effect is produced by a 10 kW water vapour compression chiller with a COP of 2.5 during the cold season. During winter, the gas boiler is employed to provide the required heating to the building.

The energy and environmental impacts related to the use phase of the conventional plant are summarized in Table 6.

Table 6: Environmental impacts related to the use phase of the conventional plant

Absorption in Palermo
Non-Renewable Energy (NRE): 800.1 GJ-eq; GER: 845.5 GJ-eq; GWP: $50.3*10^3$ kg CO_{2eq}.
Absorption in Zurich
NRE: 1906.1 GJ-eq; GER: 1954.3 GJ-eq; GWP: $101.6*10^3$ kg CO_{2eq}.
Adsorption in Palermo
NRE: 472.3 GJ-eq; GER: 499.8 GJ-eq; GWP: $29.7*10^3$ kg CO_{2eq}.
Adsorption in Zurich
NRE: 1205.8 GJ-eq; GER: 1237.2 GJ-eq; GWP: $64.1*10^3$ kg CO_{2eq}.

3.1.3 Simulation of configurations with hot and cold back up

To simulate the Solar Cooling configurations, the specific TRNSYS-types have been kindly provided by external authors:

- Type 290 - Sortech ACS08-2010 for the Adsorption Machine (Author: Bjòrn Nienborg, Fraunhofer ISE)
- Type 209 - PINK Version 2.0 for the Absorption Machine (Author: Jochen Döll, Fraunhofer ISE)

Types used for solar collectors are:

- Type 1c with datasheet of flat plate collector –Azur 8" Agena Énergies, Switzerland
- Type 71 with datasheet of evacuated tube collectors SLU-1500/16 Tsinghua, China

In the next figure (Figure 2), the TRNSYS scheme of the project with absorption machine and hot back up is shown:

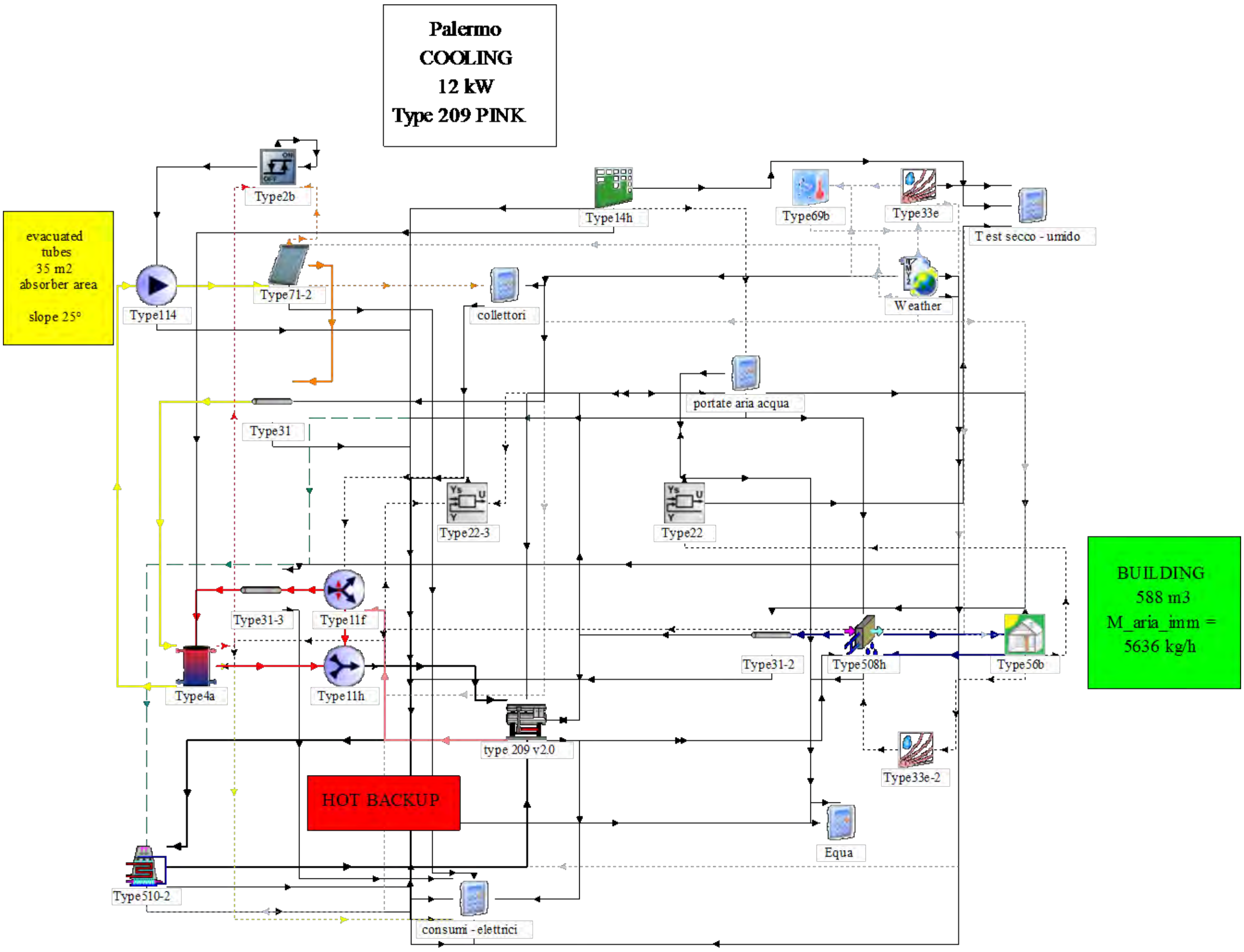


Figure 2: TRNSYS project for simulation of the absorption chiller plant with auxiliary boiler

Some additional conditions in the control of the system operation has been implemented in order to improve the stability of the simulation (meeting of temperature limits which are inputs for the ad-/absorption machines).

The main parameter which controls the function of the plant is the indoor temperature in the building. Depending on this value (T_setpoint = 26°C), the air flow rate in a cooling terminal (fan-coil) is variable between 10% and 100% of the nominal air flow rate. Between the hot storage and the absorption machine, a flow-mixer maintains the inlet temperature to the generator below a maximum value. The minimum temperature in the hot storage, before the auxiliary gas boiler switches on, is set to 75°C for the absorption machine and to 70°C for the adsorption machine.

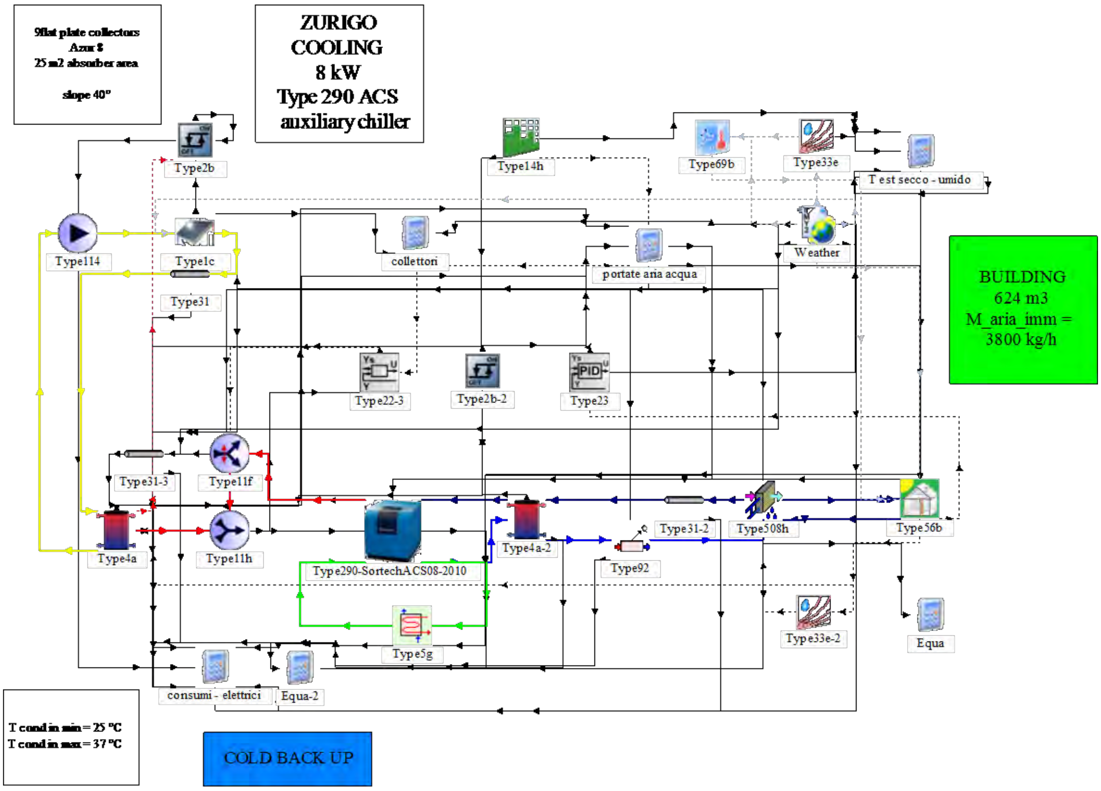


Figure 3: TRNSYS project for simulation of the adsorption chiller plant with cold back up

Figure 3 represents part of TRNSYS project used for the simulation of the adsorption configuration with cold back up. A fictive cold storage had to be inserted, in order to assure a constant cooling load for the type of the Sortech machine, what otherwise created simulation errors. The auxiliary chiller is connected in parallel, and switches on with a maximum outlet temperature from the cold storage.

Heating operation has been simulated in own projects, with only solar collectors, hot storage, auxiliary gas boiler and fan coils.

3.1.4 Simulation results

For calculation of PE consumption, following conversion have been used:

Table 7: Conversion factor for electricity and gas

	SWITZERLAND	ITALY
Electricity conversion factor	0.339	0.334
Gas conversion factor	0.802	0.802

In the next tables, simulation results are shown:

Table 8: Simulation results for adsorption chiller 8 kW at Zurich and at Palermo

Adsorption system SORTECH

Zürich — 8 kW

COP chiller as conventional simulated

		Convent. system	Adsorption system: with hot back up	Adsorption system: with auxiliary chiller
COOLING				
Cooling energy produced by conv/ads.chiller	kWh	1742	1731	1278
Cooling energy produced by back-up chiller				390
Total Cooling energy delivered to the building	kWh	1673	1792	1740
Electricity consumed by chiller/chiller+solar pump	kWh	685	201	404
Auxiliary energy consumed (gas)	kWh	0	670	0
Solar fraction			**82%**	**100%**
COP el		2.44	8.92	4.31
COP therm			0.53	0.52
PE_{spec}	kWh/kWh	1.02	0.65	0.58
PRIMARY ENERGY SAVING			**36%**	**43%**
HEATING				
Total heating energy produced	kWh	8470	11758	11758
Total heating energy delivered to the building	kWh	8416	8583	8583
Electricity consumed by solar pump	kWh	0	77	77
Auxiliary energy consumed (gas)	kWh	9411	7328	7328
Solar fraction			**23%**	**23%**
PE_{spec}	kWh/kWh	1.12	0.88	0.88
PRIMARY ENERGY SAVING			**22%**	**22%**

Palermo — 8 kW

		Convent.system	Adsorption system: with hot back up	Adsorption system: with auxiliary chiller
COOLING				
Cooling energy produced by conv/abs.chiller	kWh	3255	3268	2902
Cooling energy produced by back-up chiller				460
Cooling energy delivered to the building	kWh	3163	3193	3328
Electricity consumed by chiller/chiller+solar pump	kWh	1213	494	606
Auxiliary energy consumed (gas)	kWh	0	585	0
Solar fraction			**92%**	**100%**
COP el		2.6	6.5	5.5
COP therm			0.49	0.51
PE_{spec}	kWh/kWh	1.07	0.61	0.51
PRIMARY ENERGY SAVING			**42%**	**53%**
HEATING				
Total heating energy produced	kWh	1393	3413	3413
Total heating energy delivered to the building	kWh	1373	1372	1372
Electricity consumed by solar pump	kWh	0	54	54
Auxiliary energy consumed (gas)	kWh	1548	346	346
Solar fraction			**75%**	**75%**
PE_{spec}	kWh/kWh	1.13	0.35	0.35
PRIMARY ENERGY SAVING			**69%**	**69%**

The first configuration with adsorption cooling machine 8 kW and auxiliary heater as hot back up in Zurich reaches PE savings of only 36%, nevertheless electrical COP is extremely high (above 8). On the other hand, the cooling energy demand is the lowest of all considered case studies, causing poor exploitation of the machine. Using an auxiliary chiller as back-up, PE-savings rise up to 43%.

It must be always considered that results of energy production and consumption are not-linear, due to restrictions in the simulation of control strategies with rapid changes (for instance electricity consumption for the external heat-exchanger).

In heating operation, PE-savings in Zurich are very low (23%), such as Solar Fraction is in the same range.

For the Palermo climate, the configuration with hot back-up reaches 43% PE-savings, and 53% with cold back-up.

This shows that the choice of hot back-up is not convenient in case of very low thermal COP (around 0.5 for the considered adsorption machine).

Solar Heating is, as foreseen, convenient at Palermo (Solar Fraction 75%), whereas at Zurich a solar plant which is designed to feed a small adsorption machine, due to a higher heating demand and lower solar radiation, provides only 23% of energy.

Table 9: Simulation results for absorption chiller 12 kW at Zurich and at Palermo

Absorption system PINK

Zürich 12 kW

COP chiller as conventional simulated

		Convent. system	Absorption system	
COOLING			**with hot back up**	**with auxiliary chiller**
Cooling energy produced by conv/abs.chiller	kWh	2438	2301	2199
Cooling energy produced by back-up chiller				182
Total Cooling energy delivered to the building	kWh	2410	2325	2369
Electricity consumed by chiller/chiller+solar pump	kWh	1046	655	693
Auxiliary energy consumed (gas)	kWh	0	177	0
Solar fraction			**94%**	**100%**
COP el		2.30	3.55	3.42
COP therm			0.71	0.7
PE $_{spec}$	kWh/kWh	1.09	0.78	0.73
PRIMARY ENERGY SAVING			**28%**	**33%**
HEATING				
Total heating energy produced	kWh	13456	17619	17619
Total heating energy delivered to the building	kWh	13380	13080	13080
Electricity consumed by solar pump	kWh	0	81	81
Auxiliary energy consumed (gas)	kWh	14951	10165	10165
Solar fraction			**30%**	**30%**
PE $_{spec}$	kWh/kWh	1.12	0.79	0.79
PRIMARY ENERGY SAVING			**29%**	**29%**

Palermo 12 kW

		Convent. system	Absorption system	
COOLING			**with hot back up**	**with auxiliary chiller**
Cooling energy produced by conv/abs.chiller	kWh	4875	4659	4083
Cooling energy produced by back-up chiller				403
Cooling energy delivered to the building	kWh	4899	4696	4521
Electricity consumed by chiller/chiller+solar pump	kWh	1995	937	1065
Auxiliary energy consumed (gas)	kWh	0	246	0
Solar fraction			**96%**	**100%**
COP el		2.5	5.0	4.2
COP therm			0.69	0.68
PE $_{spec}$	kWh/kWh	1.13	0.61	0.65
PRIMARY ENERGY SAVING			**46%**	**42%**
HEATING				
Total heating energy produced	kWh	2478	6381	6381
Total heating energy delivered to the building	kWh	2455	2966	2966
Electricity consumed by solar pump	kWh	0	52	52
Auxiliary energy consumed (gas)	kWh	2754	414	414
Solar fraction			**87%**	**87%**
PE $_{spec}$	kWh/kWh	1.12	0.18	0.18
PRIMARY ENERGY SAVING			**84%**	**84%**

Results reveal that the absorption chiller 12 kW at Zurich is less efficient than the first configuration (Adsorption), with PE-savings of only 28% respectively 33% (hot/cold back-up). This can be explained again from low cooling energy demand in the building and higher temperature differences in the plant.

On the other hand, the larger solar collector area and use of evacuated tubes lead up to higher Solar Fraction (30%) in heating operation.

A different scenario come out for the absorption plant 12 kW at Palermo; here the configuration with auxiliary heater is more convenient than the one with cold back-up. In this case the climatic conditions favor high solar heat contribution correlated with high cooling demand. Due to good exploitation of the absorption machine, also electrical COP is relatively high (5.0)

In heating period, likewise high PE-savings are obtained (84%).

3.1.5 Study field: FU, system boundaries, data quality, cut-off rules, assumptions

The analysis has been carried out using the LCA software SimaPro and Ecobat, the environmental database Ecoinvent and the EPD 2007 and Cumulative Energy Demand as impact assessment methods.

The main choices and assumptions of the LCA study are the following:

- FUs:
  - a solar cooling plant with absorption or adsorption chiller;
  - 1 kW of power of the main component of the plant: the absorption chiller;
  - 1 kWh of energy produced by plant.
- System boundaries: production of the main plant components, use of the plant and end-of-life of the main plant components.
- In the study have not been taken into account the energetic and environmental impacts related to:
  - Transport of the plant components from the production site to the utilization site;
  - Transport of the plant components at the end-of-life from the utilization site to the disposal site;
  - The maintenance phase.
- The eco-profiles of evacuated solar thermal collectors, gas boiler, heat storage, vapor compression chiller, pumps and piping, have been referred to Ecoinvent database: the eco-profiles of the absorption chiller and the cooling tower have been assessed starting from data collected in field.
- The useful life of each plant component is 25 years.
- The energetic and environmental impacts related to the electricity use are referred to the Italian and Swiss energy mix.
- Because of data regarding 20 kW gas boiler have not been available, they have been estimated starting from the eco-profile of a 10 kW gas boiler and the masses of the two gas boilers, using a conversion factor of 0.267.
- Because of data about conventional vapor chiller have not been available, the eco-profile of the chiller was estimated starting from the eco-profile of an heat-pump and using a conversion factor of 1.53. The eco-profile of the heat-pump has been referred to Ecoinvent database.

- Data regarding the eco-profile of the pumps (with different power) have been estimated starting from the eco-profile of a 40W pump.
- Detailed metadata related to each plant component are described in Annex 2.

3.1.6 Absorption chiller

In the following, the LCA of a solar cooling plant is performed according to the LCA standards of the ISO 14040 series [ISO 14040, 2006; ISO 14044, 2006]. The plant works with two different configurations: hot backup and cold backup and it is installed in two different locations: Palermo and Zurich.

3.1.6.1 General description of the plants (with cold and hot backup)

The solar absorption chiller plant, with hot backup configuration, consists mainly of five subsystems, namely:

- 12 kW ammonia/water adsorption machine from Solarnext/Pink;
- evacuated solar thermal collector field of 35 m^2, (azimuth: south; slope: 40° at Zurich, 25° at Palermo);
- 2000 l hot water insulated storage tank;
- 35 kW wet cooling tower;
- 20 kW heating system (gas boiler).

A schematic diagram of this system is shown in Figure 4

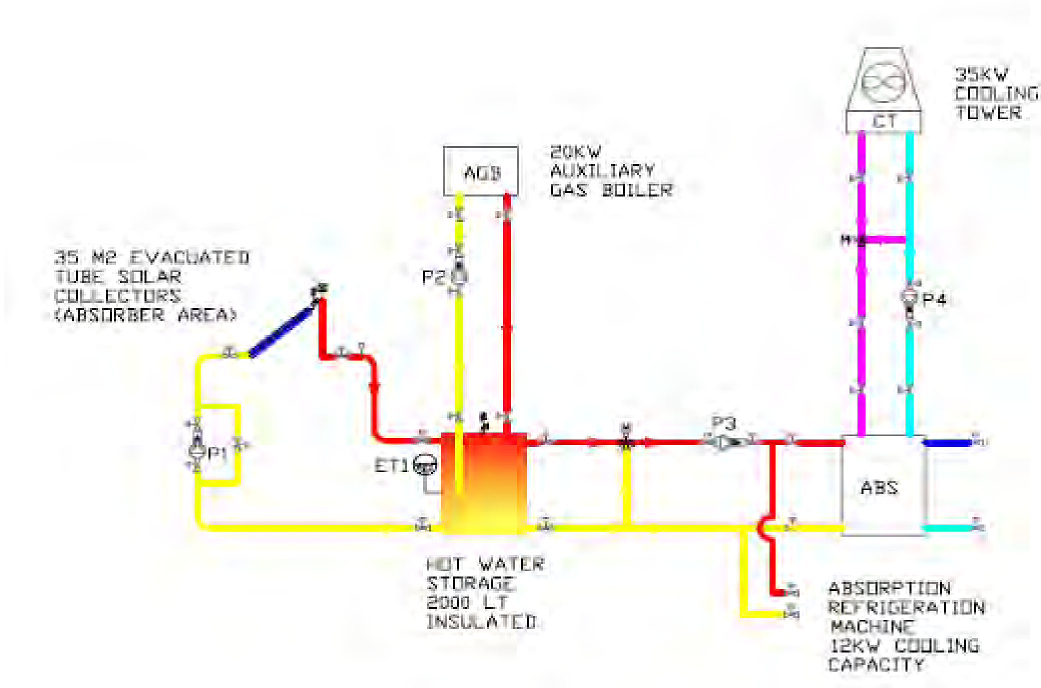


Figure 4: Schematic representation of the absorption chiller plant (hot backup configuration)

The solar absorption chiller plant, with cold backup configuration, consists of the same subsystem as above, with the cold back system which is a 10kW vapor compression chiller.

A schematic diagram of this system is shown in Figure 5.

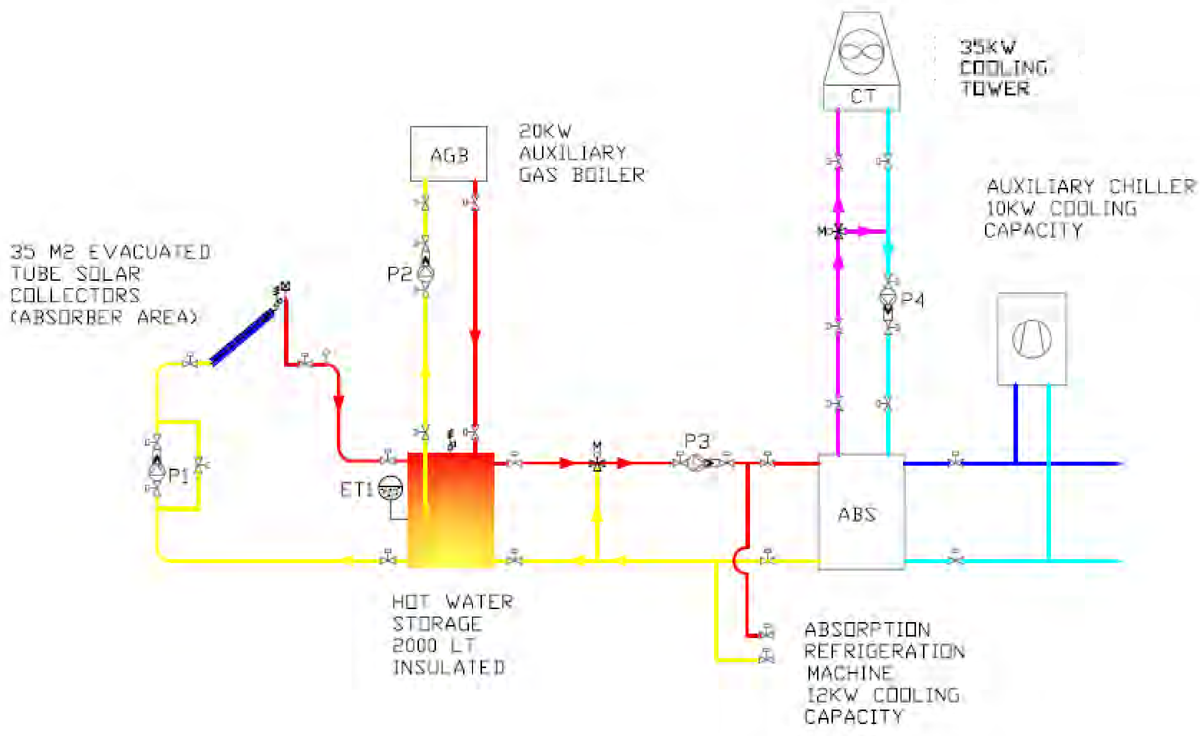


Figure 5: Schematic representation of the absorption chiller plant (cold backup configuration)

3.1.6.2 Eco-profile of the absorption chiller

The investigated product is the SolarNext/Pink chilli®PSC12 Absorption chiller. The absorption chiller, filled with ammonia/water solution, generates cold through a closed, continuous cycle.

The absorption chiller consists of four main components: the generator (also named boiler or expeller), the condenser, the evaporator and the absorber. Inside the generator (Figure 6), hot water is supplied to the chiller through a heat exchanger. A part of the ammonia is being expelled from the ammonia / water solution and condensed again inside the condenser. The ammonia condensate is fed to the evaporator where it is evaporated. During this process, heat energy is discharged from the cooling cycle which cools it down. Inside the absorber, the ammonia is absorbed from the low concentrated refrigerant ammonia/water solution and the cycle starts over again.

As the water chilling process produces waste heat (which is the case for compression cooling for example), a cooling tower is required. Compared with water/lithium bromide absorbers, ammonia absorbers differ for the pressure levels (ammonia is driven with high pressure and water with a vacuum) and for the different evaporator temperatures.

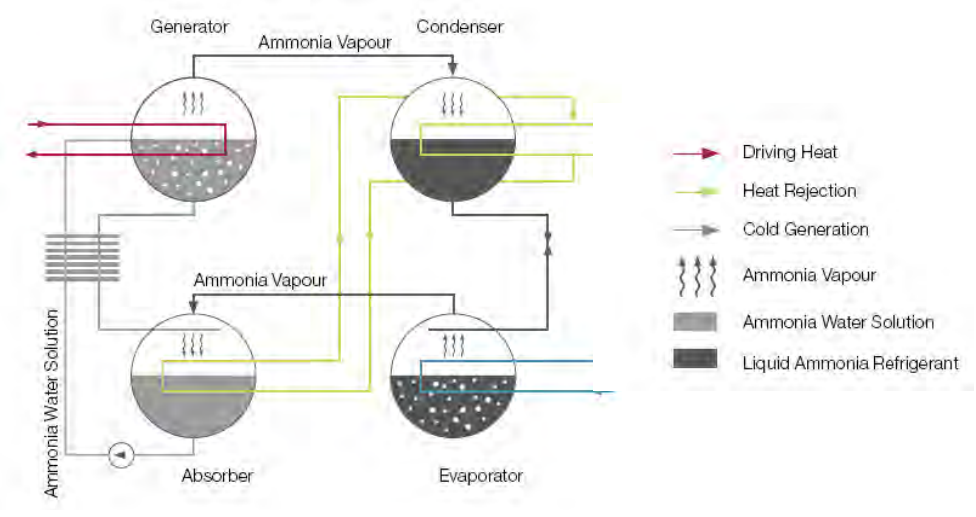


Figure 6: Ammonia cycle into Absorption Chiller [Solarnext, 2009]

Figure 7 depicts the structure of the chiller and shows a detail of system components. Detail of utilized masses has been analyzed in Table 10.

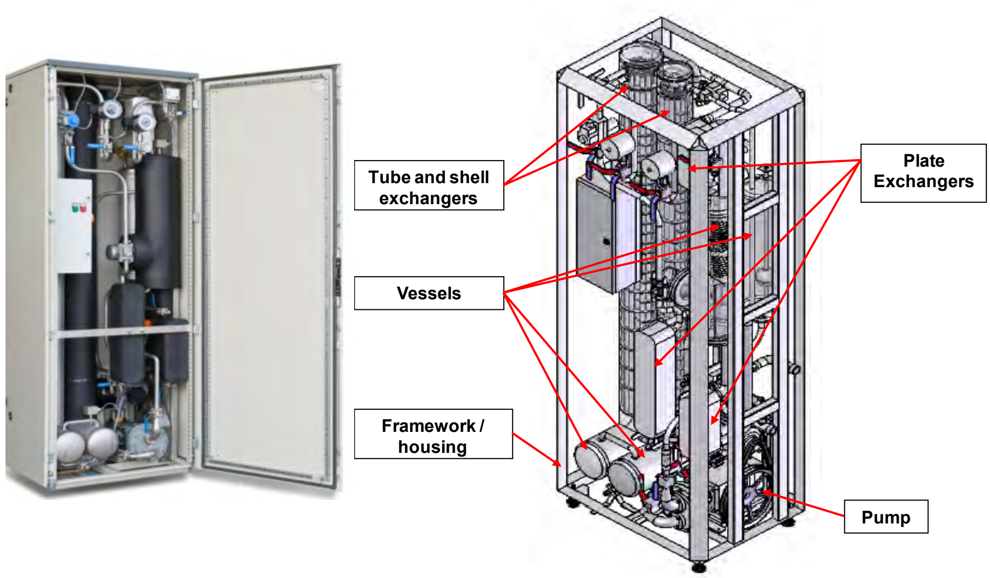


Figure 7: **The studied SolarNext/Pink Absorption Chiller**

Carrying out the LCA of the investigated chiller, the following main assumptions have been considered:

- The FU is the ―production of one complete Absorption Chiller - SolarNext/Pink chilli®PSC12”;
- The LCA follows a ―cradle to grave” approach;
- A cut off rule of 5% has been adopted. Electronic components (electric cables, sensors, manometers and motor parts), that represent the 4.1% of the overall system mass, have been neglected;
- System boundaries includes: production and delivery of raw materials, production process in the factory and disposal of production wastes at the end-of-life;
- Eco-profiles of raw materials are referred to Ecoinvent database [Frischknecht et al., 2007].
- The absorption chiller is produced in the plant of the ―Pink” company, sited in Austria. Impacts related to the use of electricity refer to the Austrian energy mix. Eco-profiles of raw materials refers to average European data;
- Concerning the assessment of the specific consumption of electricity and production of wastes per FU, allocation has been undergone with a mass criterion. In particular, the yearly consumption of electricity (50,000 kWh/year), the heat consumption (155,000 kWh/year from biomass district heating) and the disposed wastes (metal scraps 10,000 kg/year) have been allocated considering that the produced absorption chiller represent about 4% of the yearly company‘s production;

- Concerning the insulation, Armaflex® is employed. It is a closed cell, CFC free elastomeric rubber material made in tube and sheets form for insulating piping, ducts and vessels. Missing data about such insulation, eco-profile of common rubber have been considered.

The supplying of raw metal materials comes mainly from North Italy, France and North Europe (Table 10). Few components are locally purchased. Almost all the transportations occur by road, except a short shipping from Sweden to Denmark. Total transportations amount to *266 tkm* by large capacity trucks and *2 tkm* by ship.

The production of the chiller consists mainly in the cutting, TIG welding (Tungsten Inert Gas welding with argon gas)[1] and assembling of semi-manufactured components. Altogether, about 10 hours of TIG are carried out in the production of one boiler. A detail of the production process flow is shown in Figure 8.

Data previously described have been implemented to describe the eco-profile of the FU. Results are shown in Table 11, Figure 9 and Figure 10.

Table 10: Detail of system components

System Component	Material	Mass [kg]	Supplying from:
Housing	Carbon Steel	136	France
Tube&shell HEX	Stainless steel	110	North Italy
Vessels	Stainless steel	25	North Italy
Working solution	Ammonia (60%) & water (40%)	25	Austria
Plate-HEX	Stainless steel	21	Sweden
Piping	Stainless steel	20	North Italy
Pumping system	Carbon Steel	15	Italy
	Stainless steel	5	
	Aluminium	10	
	Copper	5	
	others	6	
Electric, Sensors, Manometers	Electronics (various)	10	Austria
Insulation	Armaflex ®	4	Germany
Valves	Cast iron	2	Denmark
	Total	**394**	

[1] Compared to other welding technologies, TIG is characterized by lower impacts because it avoids to use consumables electrodes. Anyway, few data have been found into references concerning TIG emissions. Some data have been derived by a private company report and it consider specific emissions of: PM_{10} 8.16 g/hr and Mn 0.9 g/hr. Argon consumption amounts to 5.5 l/min [Krűgher, 1994].

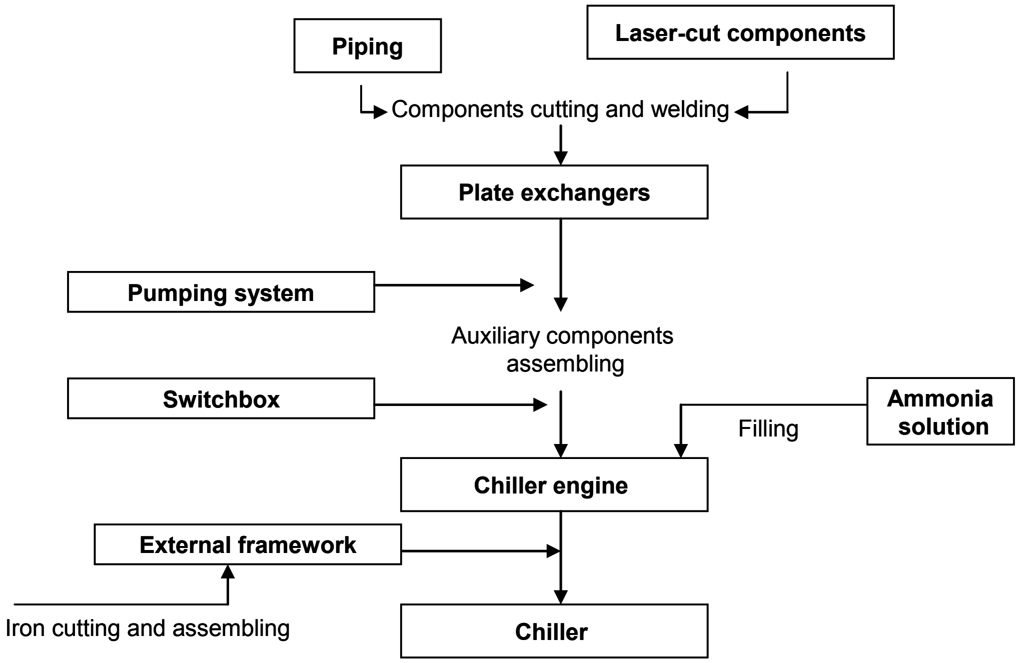


Figure 8: **Production diagram flow**

Table 11: Energetic and environmental impacts of the absorption chiller

	NRE (MJ-eq)	GER (MJ-eq)	GWP (kg CO_{2eq})
Production of chiller components	24941	23482	1399
Production process	1284	3827	68.9
Transports	700	748	44.8
End-of-life	3.0	3.2	12.6
Total	26928	28060	1525

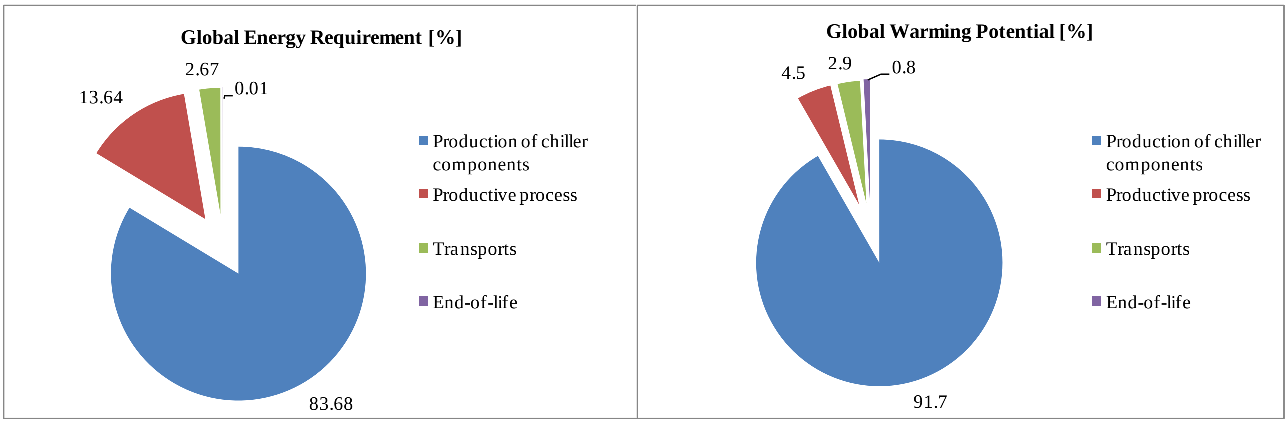


Figure 9: Percentage contribution of different phases of the chiller life-cycle to GER and GWP

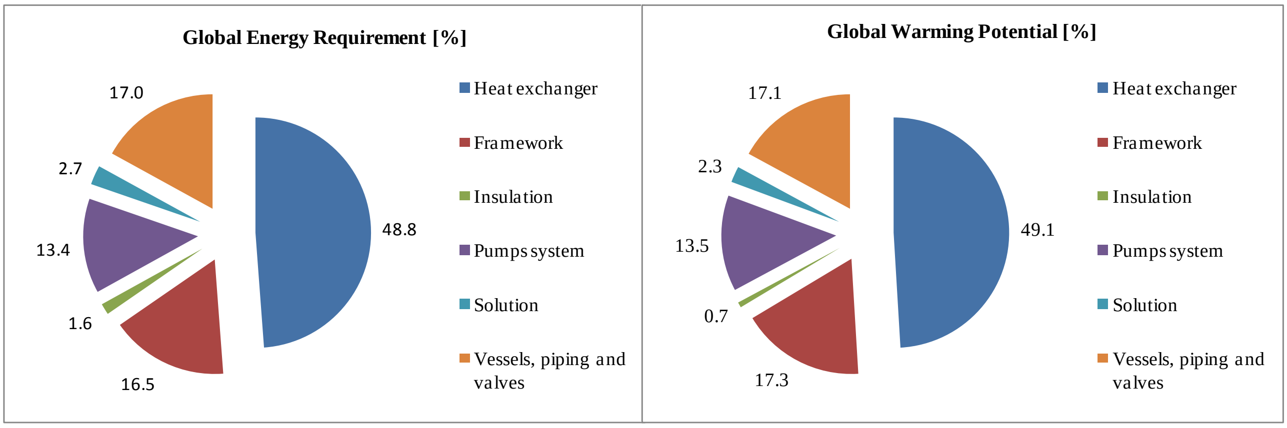


Figure 10: Percentage contribution of different chiller components to GER and GWP

It is possible to observe that:

- GER amounts to 28 GJ and GWP amounts to 1526 kg$CO_{2eq.}$;

- the life cycle of the FU causes the production of about 33.4 kg of non hazardous wastes, whose 92 % consists of metal scraps produced during the production process;

- - the production process of chiller components has, in the entire life cycle, a large incidence on the GER (84%) and GWP (92%);

- in the production phase of the chiller components, the main contributions to GER and GWP are due to the heat exchanger (respectively 48.8% for GER and 49.1% for GWP). The framework, pipes and valves and pumps system contribute, each one, from 13% to 17% of the total impacts.

3.1.6.3 Eco-profile of the plants

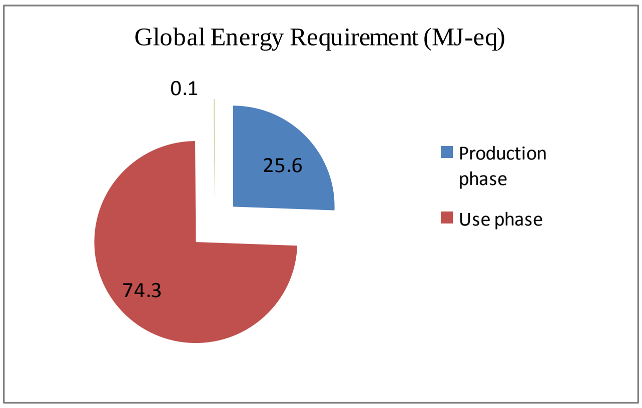
Hot backup configuration

The energetic and environmental impacts of the solar cooling plant (F.U. 1 solar cooling plant) are showed in Table 12.

Table 12: Energetic and environmental impacts of the solar cooling plant (hot backup configuration)

	Components	NRE (MJ-eq)	GER (MJ-eq)	GWP (kg CO_{2eq})
Production of plant components	Absorption chiller	23457	28058	1757
	Solar collectors	54987	59415	3437
	Heat storage	13622	15209	852
	Cooling Tower/Heat Rejection	2902	2972	154
	Gas boiler	1726	1853	103
	Glycol (only for plant in Zurich)	2039	2100	103
	Piping+insulation	7961	8399	510
	Pumps	1017	1095	66
Use phase Palermo	Cooling	258719	279604	16766
	Heating	59109	60425	3556
Use phase Zurich	Cooling	166883	193422	3431
	Heating	1154443	1161699	66939
End-of-life	Absorption chiller	3	3	13
	Solar collectors	398	419	315
	Heat storage	21	21	13
	Cooling Tower/Heat Rejection	0	0	0
	Gas boiler	16	17	5
	Glycol (only for plant in Zurich)	459	461	39
	Piping+insulation	12	13	92
	Pumps	3	3	1
Total Palermo		423954	457506	27637
Total Zurich		1429949	1475160	77828

In Figure 11 and Figure 12 the contribution (%) to energy consumption and to GWP related to each life cycle phase of the plant are showed, respectively for Palermo and Zurich. In Figure 13 and Figure 14 the contribution (%) to energy consumption and to GWP related to the production of the main plant components are showed, respectively for Palermo and Zurich.



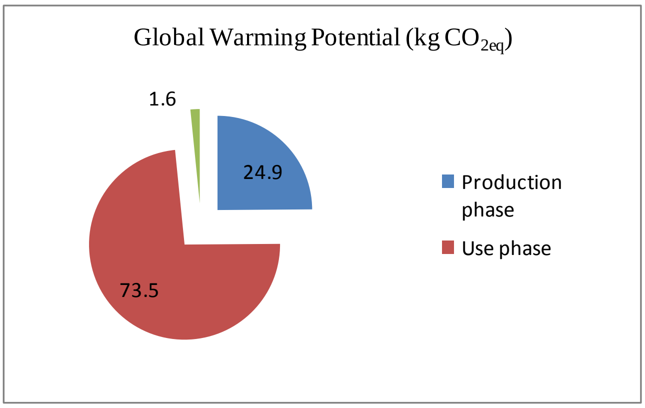
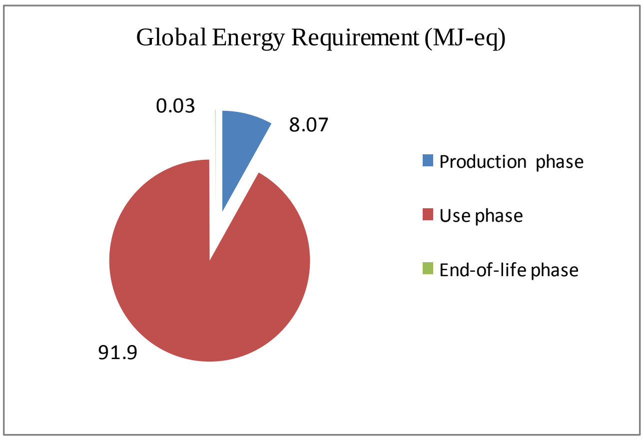


Figure 11: Percentage contribution of different phases of the plant life-cycle to GER and GWP for Palermo



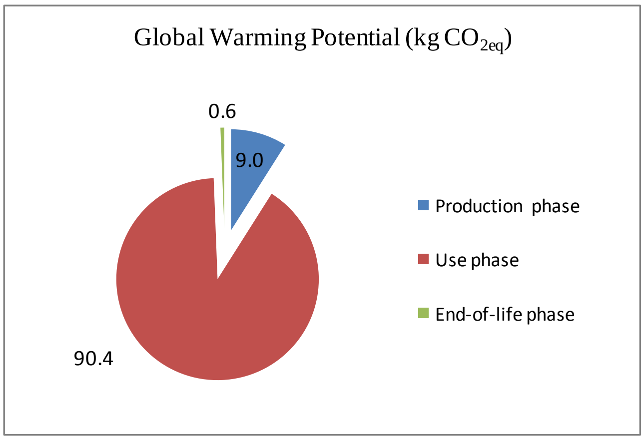
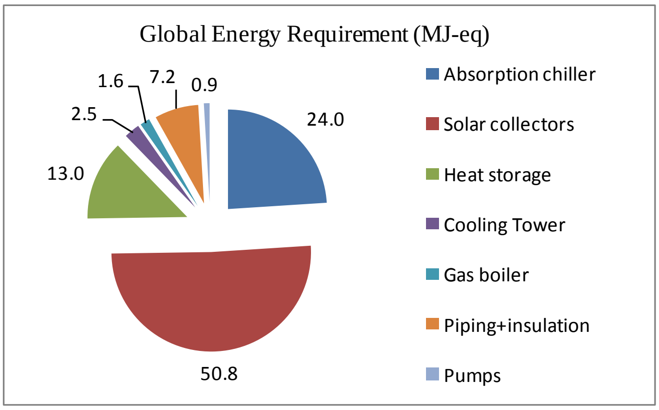


Figure 12: Percentage contribution of different phases of the plant life-cycle to GER and GWP for Zurich



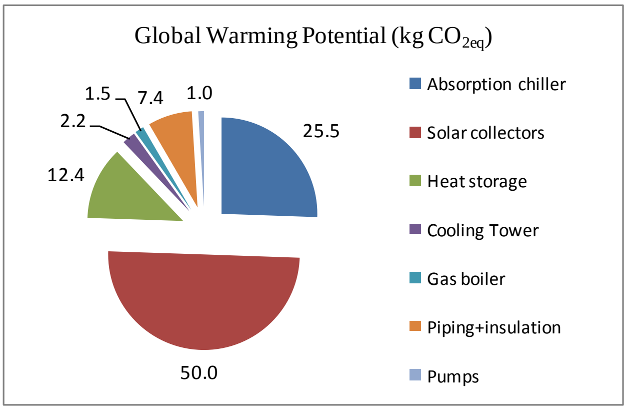


Figure 13: Production phase. Percentage contribution of different plant components to GER and GWP for Palermo

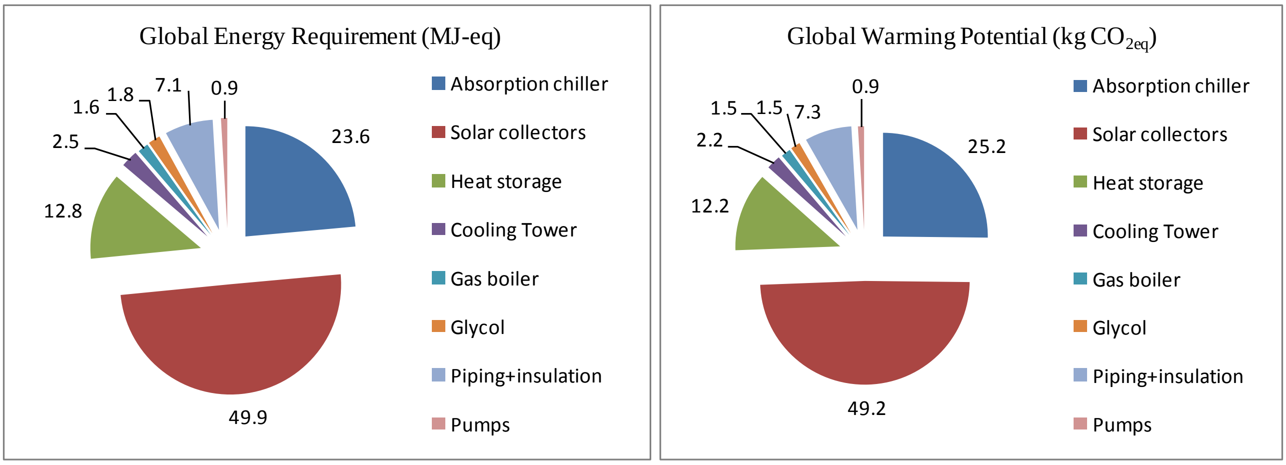


Figure 14: Production phase. Percentage contribution of different plant components to GER and GWP for Zurich

In Table 13 and Table 14 the energetic and environmental impacts related to different F.U.s are showed, respectively for Palermo and Zurich. To calculate the impacts related to the F.U. “1 kWh of produced energy”, are used the following values of produced energy in 25 years: for Palermo 191,550 kWh, for Zurich 385,125 kWh.

Table 13: Energetic and environmental impacts of the solar cooling plant (hot backup configuration) for Palermo: comparison among different F.U.

		NRE (MJ-eq)	GER (MJ-eq)	GWP (kg CO_{2eq})
F.U. 1 solar cooling plant	Production	105673	117000	6878
	Use phase	317828	340029	20322
	End-of-life phase	453	477	438
F.U. 1 kW of chiller power	Production	8806	9750	573
	Use phase	26486	28336	1693
	End-of-life phase	38	40	36
F.U. 1 kWh of produced energy	Production	0.55	0.61	0.04
	Use phase	1.66	1.78	0.11
	End-of-life phase	0.002	0.002	0.002

Table 14: Energetic and environmental impacts of the solar cooling plant (hot backup configuration) for Zurich: comparison among different F.U.

		NRE (MJ-eq)	GER (MJ-eq)	GWP (kg CO_{2eq})
F.U. 1 solar cooling plant	Production	107712	119101	6981
	Use phase	1321326	1355121	70370
	End-of-life phase	912	938	477
F.U. 1 kW of power	Production	8976	9925	582
	Use phase	110110	112927	5864
	End-of-life phase	76	78	40
F.U. 1 kWh of produced energy	Production	0.28	0.31	0.02
	Use phase	3.43	3.52	0.18
	End-of-life phase	0.002	0.002	0.001

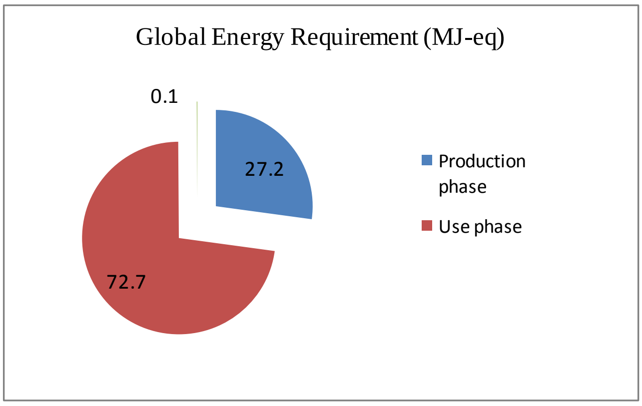
Cold backup configuration

The energetic and environmental impacts of the *solar cooling* plant (F.U.: 1 *solar cooling plant*) are showed in Table 15.

Table 15: Energetic and environmental impacts of the solar cooling plant (cold backup configuration)

	Components	NRE (MJ-eq)	GER (MJ-eq)	GWP (kg CO_{2eq})
Production of plant components	Absorption chiller	23457	28058	1757
	Solar collectors	54987	59415	3437
	Heat storage	13622	15209	852
	Cooling Tower/Heat Rejection	2902	2972	154
	Gas boiler	1726	1853	103
	Glycol (only for plant in Zurich)	2039	2100	103
	Piping+insulation	7961	8399	510
	Pumps	1017	1095	66
	Conventional chiller	11847	12504	2394
Use phase Palermo	Cooling	262807	286435	17223
	Heating	59109	60425	3556
Use phase Zurich	Cooling	155632	183637	2403
	Heating	1154443	1161699	66939
End-of-life	Absorption chiller	3	3	13
	Solar collectors	398	419	315
	Heat storage	21	21	13
	Cooling Tower/Heat Rejection	0	0	0
	Gas boiler	16	17	5
	Glycol (only for plant in Zurich)	459	461	39
	Piping+insulation	12	13	92
	Pumps	3	3	1
	Conventional chiller	12	12	39
Total Palermo		439901	476854	30527
Total Zurich		1430557	1477891	79232

In Figure 15 and Figure 16 the contribution (%) to energy consumption and to GWP related to each life cycle phase of the plant, respectively for Palermo and Zurich, are showed. In Figure 17 and Figure 18 the contribution (%) to energy consumption and to GWP related to the production of the main plant components, respectively for Palermo and Zurich, are showed.



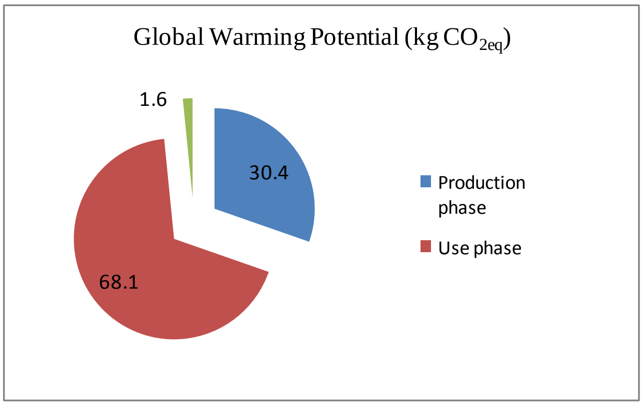
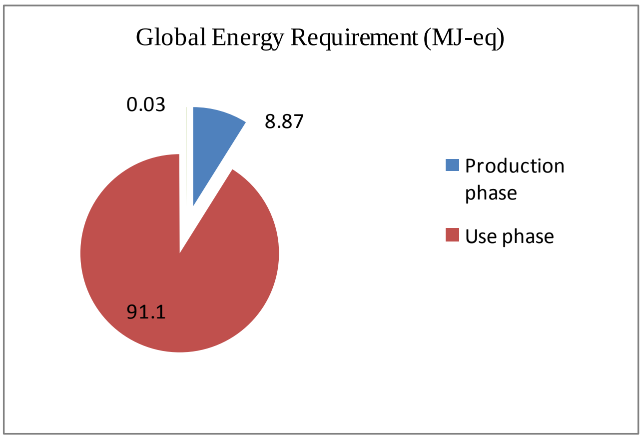


Figure 15: Percentage contribution of different phases of the plant life-cycle to GER and GWP for Palermo



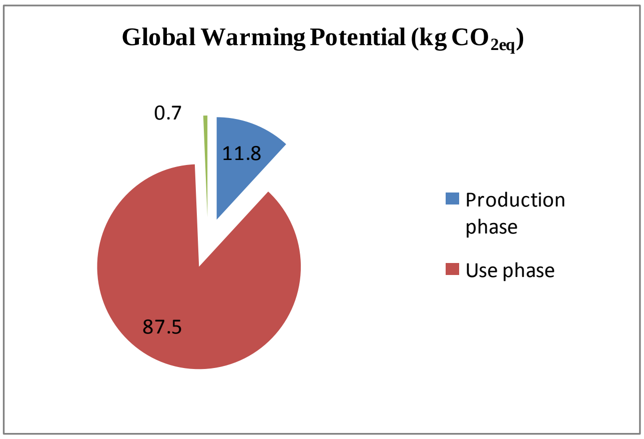
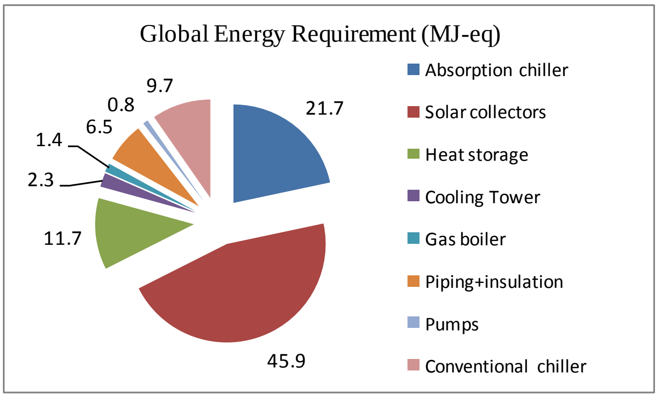


Figure 16: Percentage contribution of different phases of the plant life-cycle to GER and GWP for Zurich



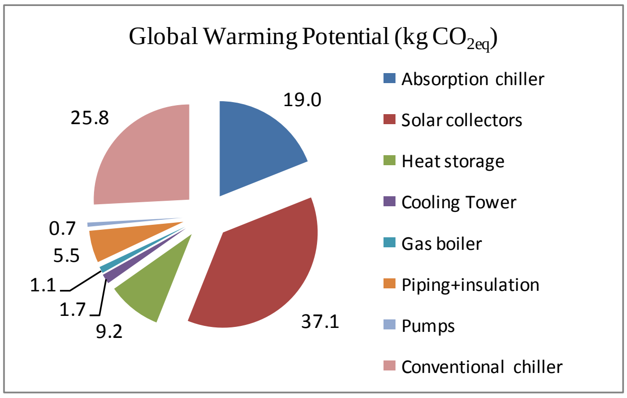


Figure 17: Production phase. Percentage contribution of different plant components to GER and GWP for Palermo

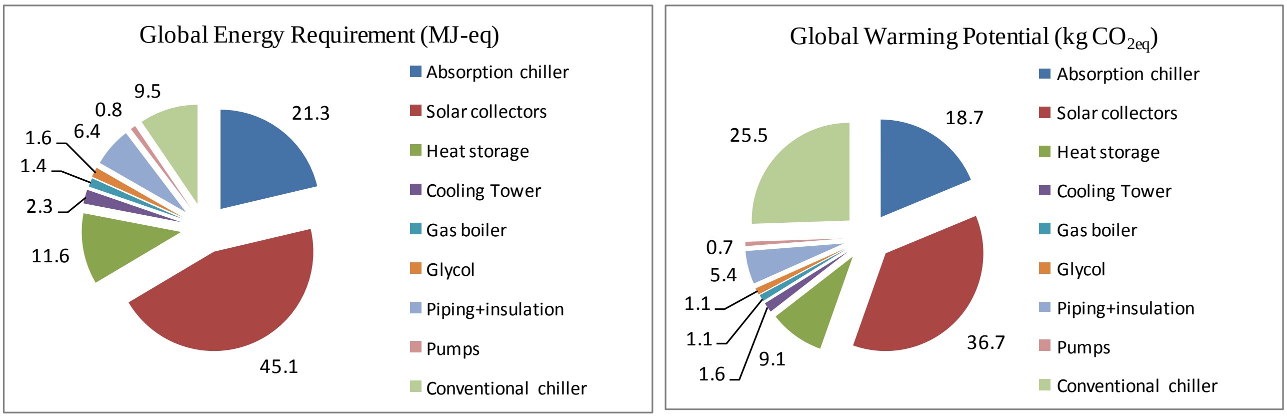


Figure 18: Production phase. Percentage contribution of different plant components to GER and GWP for Zurich

In Table 16, Table 17 and Figure 19 the energetic and environmental impacts related to different FUs are showed, respectively for Palermo and Zurich. To calculate the impacts related to the FU “1 kWh of produced energy”, are used the following values of produced energy in 25 years: for Palermo 187175 kWh, for Zurich 386225 kWh.

Table 16: Energetic and environmental impacts of the solar cooling plant (cold backup configuration) for Palermo: comparison among different FU.

		NRE (MJ-eq)	GER (MJ-eq)	GWP (kg CO_{2eq})
F.U. 1 *solar cooling plant*	Production	117520	129505	9271
	Use phase	321917	346860	20779
	End-of-life	464	489	477
F.U. 1 kW of power	Production	9793	10792	773
	Use phase	26826	28905	1732
	End-of-life	39	41	40
F.U. 1 kWh of produced energy	Production	0.63	0.69	0.05
	Use phase	1.72	1.85	0.11
	End-of-life	0.002	0.003	0.003

Table 17: Energetic and environmental impacts of the solar cooling plant (cold backup configuration) for Zurich: comparison among different FU.

		NRE (MJ-eq)	GER (MJ-eq)	GWP (kg CO_{2eq})
FU 1 *solar cooling plant*	Production	119559	131605	9374
	Use phase	1310075	1345336	69341
	End-of-life	923	950	516
FU 1 kW of power	Production	9963	10967	781
	Use phase	109173	112111	5778
	End-of-life	77	79	43
FU 1 kWh of produced energy	Production	0.31	0.34	0.02
	Use phase	3.39	3.48	0.18
	End-of-life	0.002	0.002	0.001

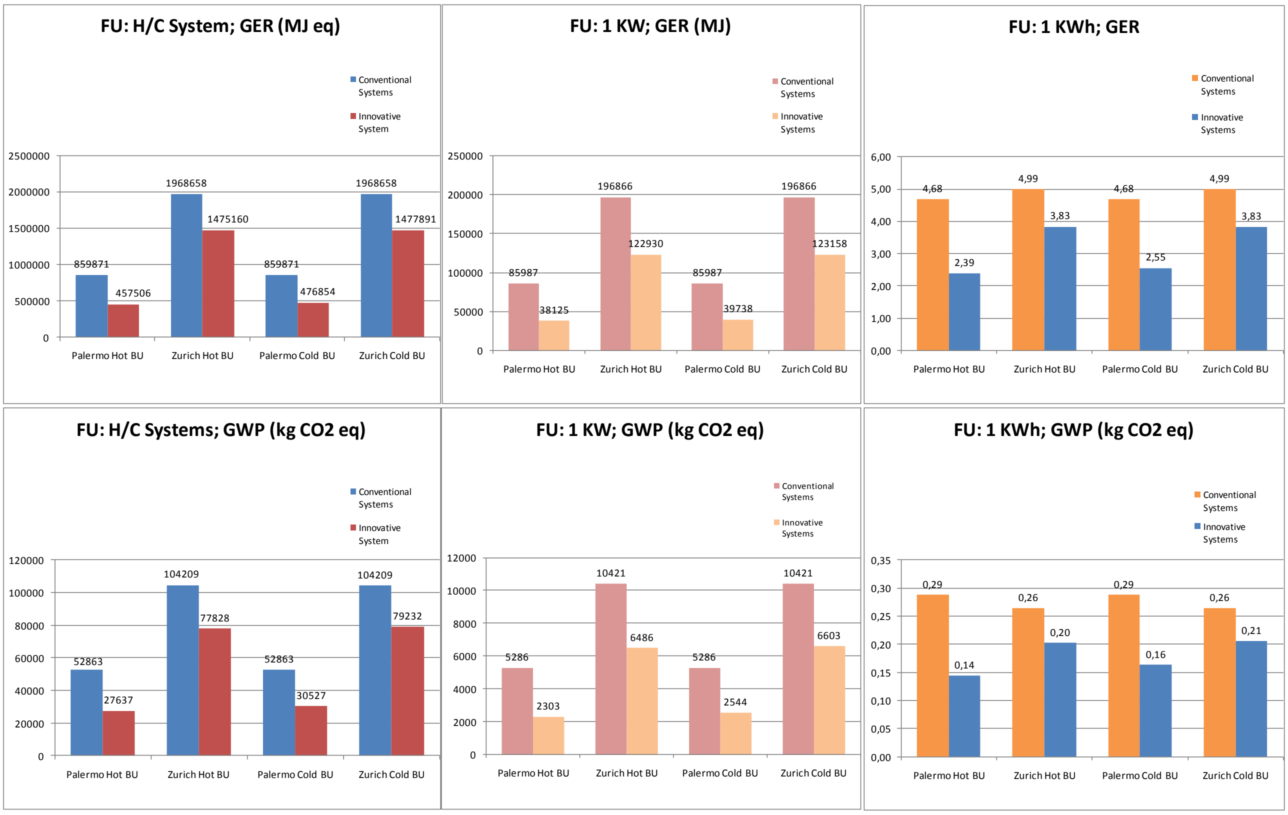


Figure 19: GER and GWP Absorption Solar Cooling systems with hot and cold back-up for different FUs and in comparison with conventional heating and cooling plants

3.1.6.4 Discussion of the results for systems with absorption chiller

Regarding hot and cold backup configurations for Palermo, GER varies from 457.5 GJ to 476.8 GJ, with an increase of about 4.2%, due to an additional use of electricity in the last configuration. GWP varies from 27637 kg CO_{2eq} to 30527 kg CO_{2eq}, with an increase of about 10.5%, due to the higher electricity consumption in the cold backup configuration compared to hot backup configuration and to the use of a conventional chiller in the last configuration.

Dealing with the results for Zurich, it can be observed that GER varies from 1475.1 GJ (hot backup configuration) to 1477.9 GJ (cold backup configuration), with an increase of about 0.18%; GWP varies from 77828 kg CO_{2eq} (hot backup configuration) to 79232 kg CO_{2eq} (cold backup configuration) with an increase of about 1.8%. These increases are due to the use of a conventional chiller in the last configuration.

Analyzing the percentage contribution of different phase of the plant life-cycle for hot and cold backup configurations, it can be noted that the main contribution to GER and GWP is due to the use phase. In detail, in the hot backup configuration the contribution of this phase to GER varies from 74.3% (for Palermo) to 91.9% (for Zurich) and the contribution to GWP varies from 73.5% (for Palermo) to 90.4% (for Zurich). In the cold backup configuration, for

Palermo the contributions of use phase to GER and GWP are, respectively, 72.7% and 68.1%; for Zurich are, respectively, 91.1% and 87.5%.

In the hot backup configuration, the production phase contributes to GER of about 25.6% for Palermo and of about 8.1% for Zurich; the contribution to GWP is of about 25% for Palermo and 9% for Zurich.

In the cold backup configuration, the incidence of the production phase to GER varies from 27.2% for Palermo to 8.9% for Zurich; the incidence to GWP varies from 30.4% for Palermo to 11.8% for Zurich.

A negligible contribution to GER and GWP is related to the end-of-life phase for both configuration and cities.

In the production phase, the main contributions to GER and GWP are due to the production of solar collectors (45–50% for GER and 37–50% for GWP) and absorption chiller (21–24% for GER and 19–25% for GWP).

On the basis of the results of LCA of the systems also the payback indexes (E_{PT}, EM_{PT} and E_{RR}) have been calculated.

The following table shows the figures of the three indexes for the systems using an Absorption machine.

Table 18: Payback indexes for the case studies

	E-$_{PT}$ year	**EM-$_{PT}$** year	**E_{RR}**
Palermo Hot BU	5,10	3,98	4,30
Palermo Cold BU	5,80	6,02	3,84
Zurich Hot BU	4,41	3,93	4,99
Zurich Cold BU	4,85	5,58	4,59

The indexes have been calculated taking into account the GER of the innovative system <u>related to the construction and end of life</u>.

If on the other hand we decide to include the use-phase energy consumption in the GER values all the indexes will assume negative values due to the high difference among the energy consumption of conventional systems and the innovative one.

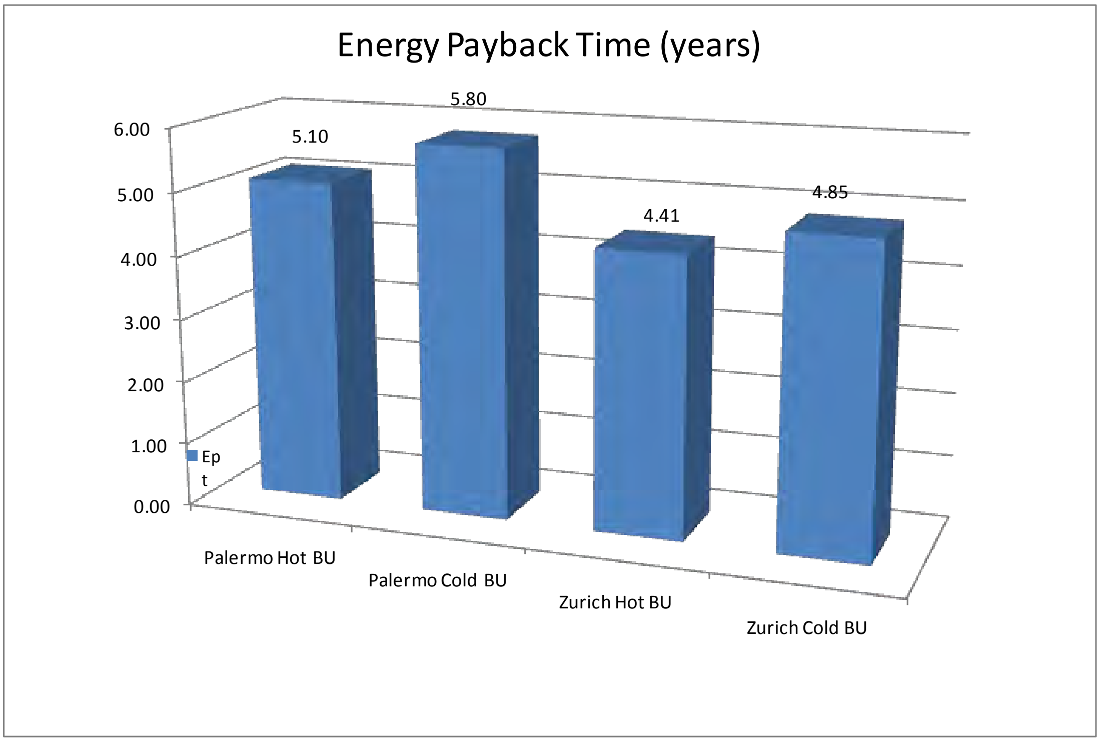


Figure 20:E_{PT} for Absorption Solar Cooling systems with hot and cold back-up

The E_{PT} (Figure 20) is for the case studies Zurich lower than in Palermo. The main reason is the highest use of the system all year round due to the very low heating energy demand in winter in Palermo.

Best results are achieved in general with the configuration with hot back up. This is due to the fact that the systems with cold back up have an additional component (vapour compression chiller) with respect to the ones with hot back-up.

In order to appreciate the influence of some performance parameters of the systems a sensitivity analysis has been developed.

The parameters which have been varied from the design conditions are:

- equivalent hours of cooling operation (defined as the ratio between the cooling energy delivered and the nominal cooling power)
- equivalent hours of heating operation (defined as the ratio between the heating energy delivered and the nominal heating power)
- annual consumption of electricity for cooling (with the same amount of cooling energy delivered)
- annual consumption of gas for heating (with the same amount of heating energy delivered).

The results are shown in the following graphs. X-values represent the ratio between the value of the parameter and its design value.

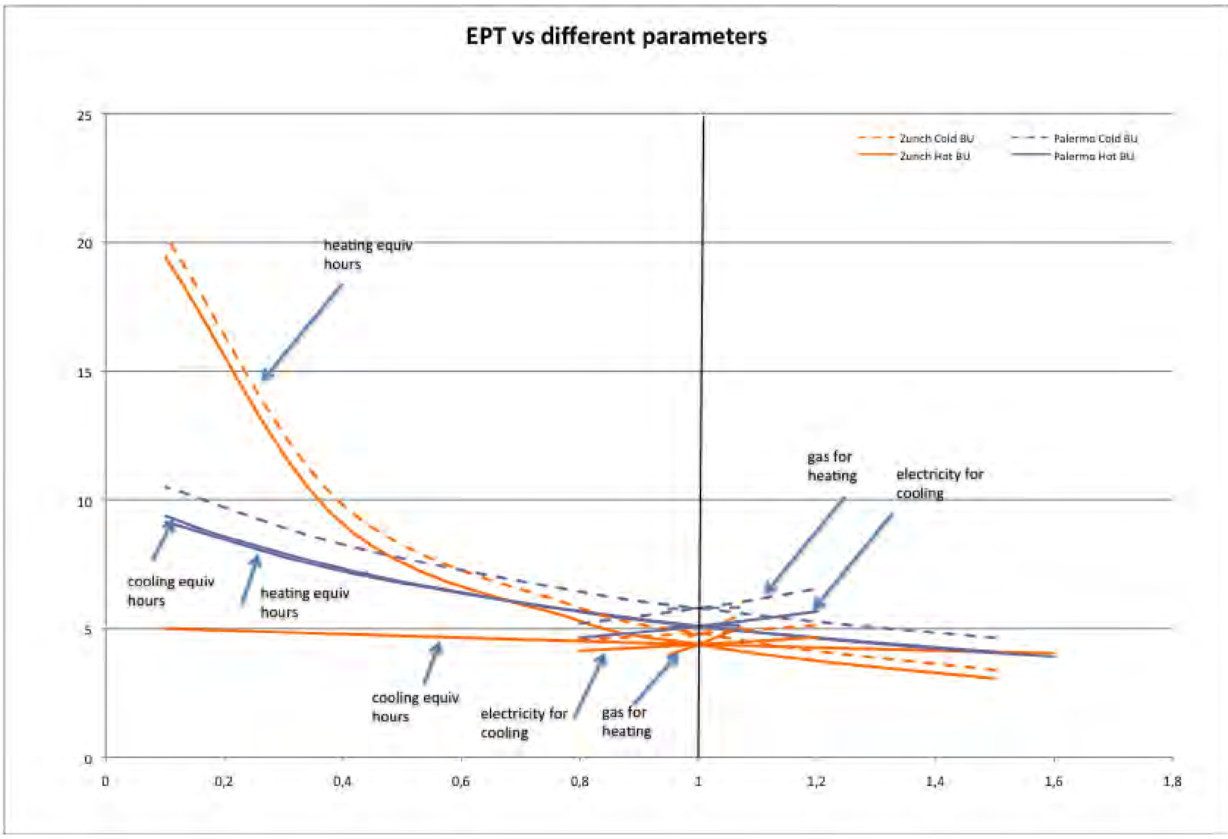


Figure 21: **Relationship between E_{PT} and several parameters for Absorption Solar Cooling systems with hot and cold back-up**

This graph allows to compare the influence of the four parameters in the different case studies.

It can be noted that the strongest slopes are the ones related to the gas consumption and heating equivalent hours in Zurich installations. A reduction of heating equivalent hours for heating in Zurich for the system with Hot Back Up higher than 30% can lead to E_{PT} higher than in Palermo. For systems with Cold Back Up this reduction must be higher than 40%. This can be observed in the following graph.

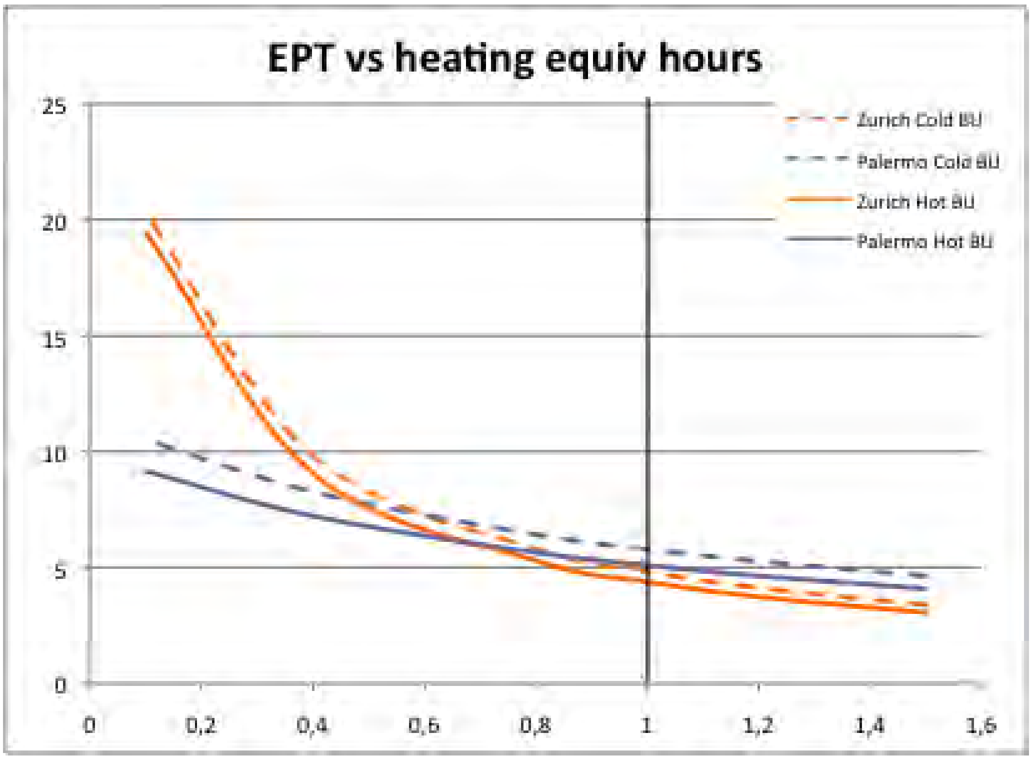


Figure 22: **Relationship between E_{PT} and the number of equivalent hour of heating operation for Absorption Solar Cooling systems with hot and cold back-up**

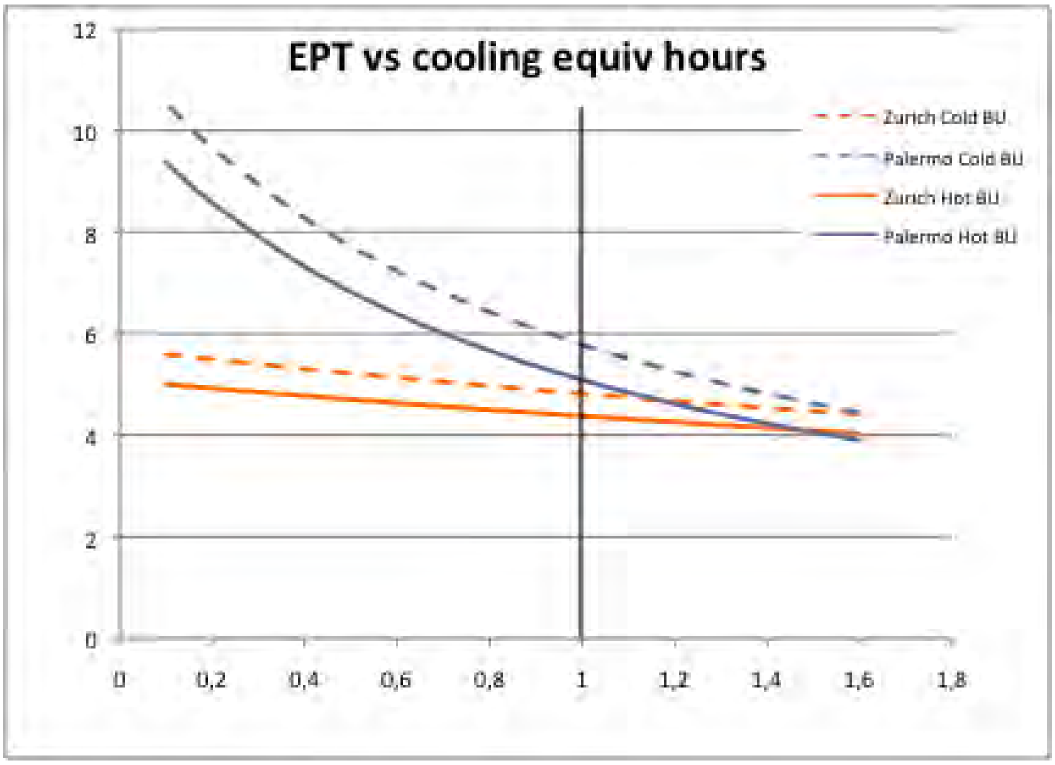


Figure 23: Relationship between E_{PT} and the number of equivalent hour of cooling operation for Absorption Solar Cooling systems with hot and cold back-up

A relevant influence is given by changes in cooling equivalent hours in Palermo.

The E_{PT} is quite sensitive to this parameter, especially in Palermo. Also electricity for cooling changes causes variations of the E_{PT} of a certain relevance Good sizing and application with operation schedules as long as possible must be considered in order to maximise the Energy and environmental performance.

The E_{PT} is strongly sensitive heating equivalent hours, especially in Zurich, where the highest heating loads are fulfilled by the plant. Good sizing and application with operation schedules as long as possible in winter time must be considered in order to maximise the Energy and environmental performance.

Small reduction of operational schedules can cause very huge weakening of performance figures.

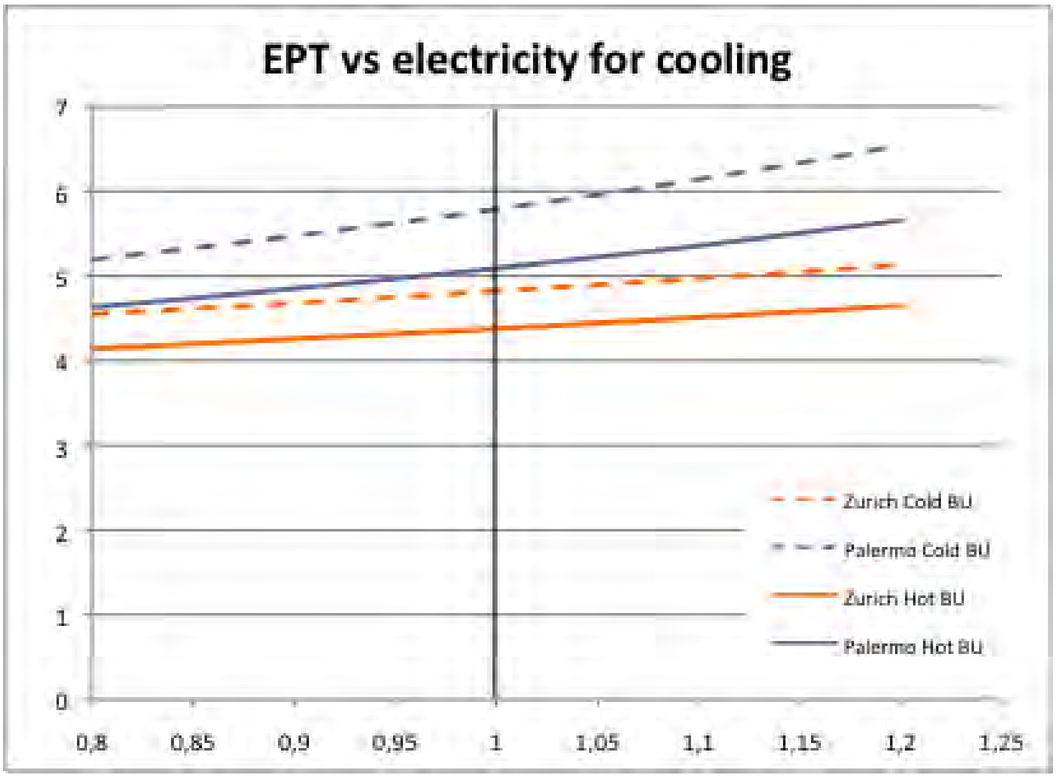


Figure 24: Relationship between E_{PT} and electricity consumption for cooling operation for Absorption Solar Cooling system with hot and cold back-up

This parameter depends on the electricity consumption of auxiliary equipment (with the same amount of cooling energy delivered). Very small increase in electricity consumption can cause relevant changes in E_{PT}.

The results are very similar if we observe the influence of the electricity consumption during the whole year.

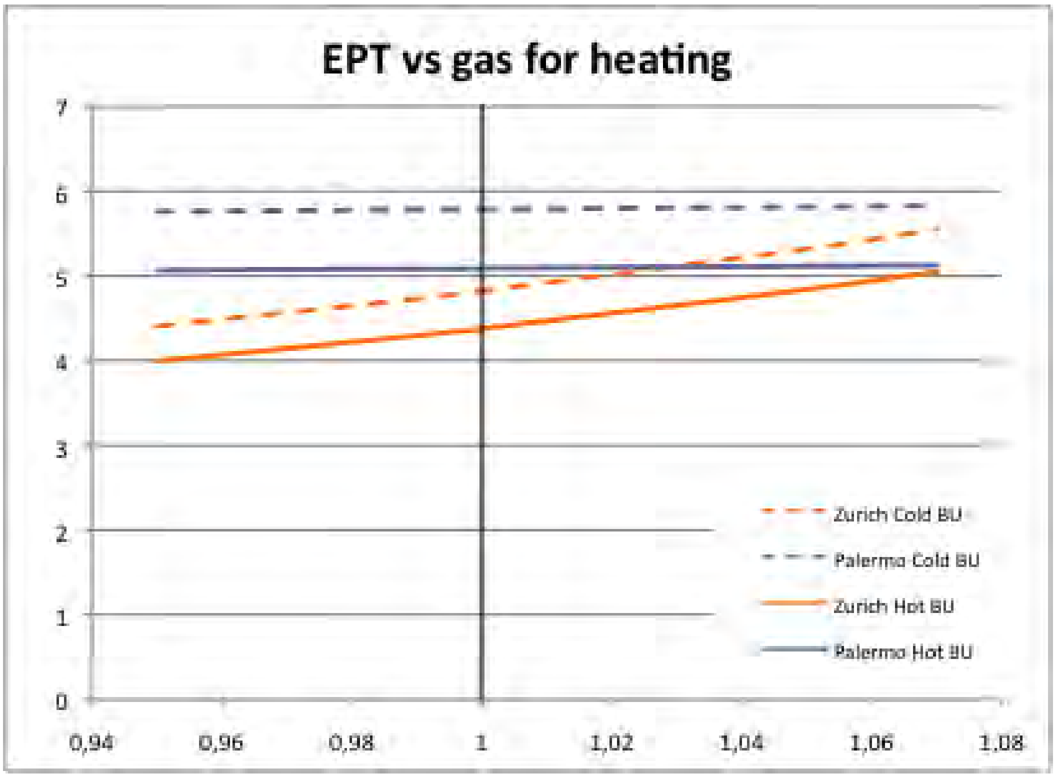


Figure 25: Relationship between E_{PT} and gas consumption for Absorption Solar Cooling systems with hot and cold back-up

Also in this case the highest influence of this parameter is observed for the installation in Zurich where the higher heating load is fulfilled. I must be noted that variation of about 10% of this parameter can change the payback time of about one year.

The influence of gas consumption for heating in Palermo is almost null in this range. Very interesting results have been obtained also for the Emissions Payback Time and E_{RR}.

In both installations, Palermo and Zurich the time to recover the emission related to the installation and disposal of the plant are less than six years.

E_{RR} gives how many times the energy saving achieved overcomes the global energy consumption of the plant life cycle. In all the cases the results are satisfactory while the systems give back from four to five time the energy expenditure for their construction and disposal.

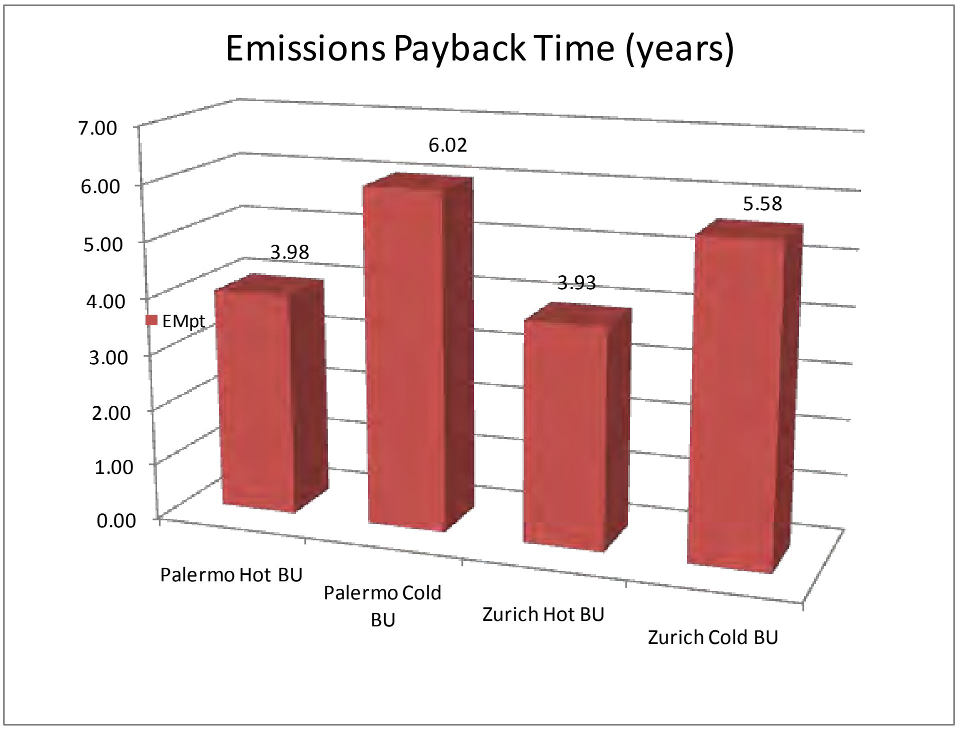


Figure 26: Emissions Payback Time for Absorption Solar Cooling systems with hot and cold back-up

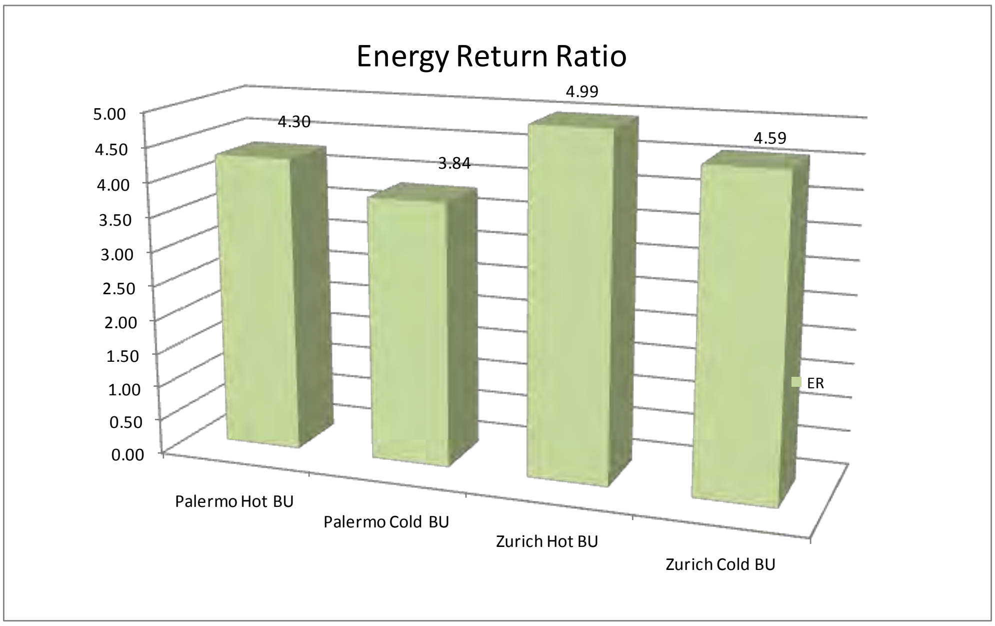


Figure 27: E_{RR} for Absorption Solar Cooling systems with hot and cold back-up

3.1.7 Adsorption chiller

3.1.7.1 General description of the plants (with cold and hot backup)

The solar adsorption chiller plant consists mainly of six subsystems, namely:

- 8 kW compact silica gel/water adsorption machine from SorTech AG (ACS 08)
- flat plate collector field of 25 m^2 or evacuate tubes
- 1300 l hot water insulated storage tank
- 24 kW air cooled heat exchanger (dry cooler)
- 20 kW heating system (gas boiler and for hot back-up configuration)
- 20 kW compressor chiller (for cold back-up configuration only)

A schematic diagram of this system is shown in . Figure 28.

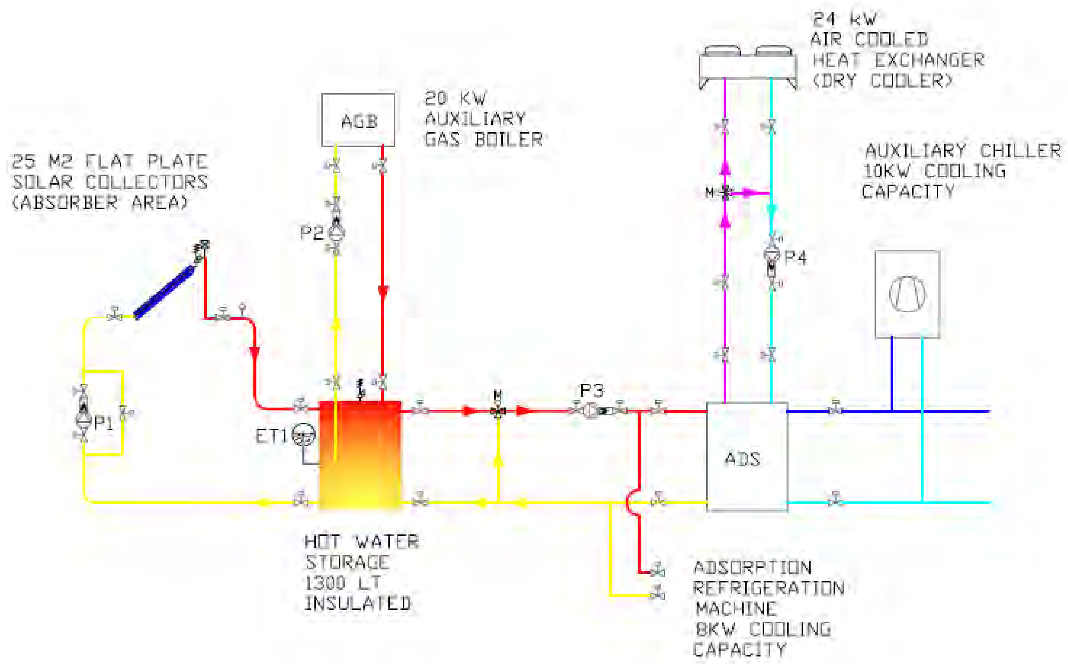


Figure 28: Schematic representation of the adsorption chiller plant

In this system, the adsorption machine is driven by the hot water in the tank that is heated by the solar collectors. Heat coming from the cooling circuit of the adsorption machine is rejected by means of an air cooled heat exchanger, also known as dry cooler.

In case of insufficient solar energy, two solutions of backup system are used : (1) a gas boiler used to heat the storage tank or (2) a chiller water unit for cooling .

3.1.7.2 Eco-profile of the adsorption chiller

The investigated product is the Sortech ACS 08 adsorption chiller (Figure 29). The adsorption chiller, filled with silica gel/water pair, generates cold through a closed and continuous cycle.

Figure 29: Adsorption chillers SorTech ACS 08 [Sortech, 2009]

The chillers use silica gel as sorption material and the internal structure follows a four compartments principle: evaporator, condenser and two compartments, interchanging periodically between adsorber and desorber function. The empty weight of the ACS 08 is 265 kg.

The four process chambers are connected to each other by internal, automatically-functioning steam valves. These valves influence the directional flow of the evaporated coolant into adsorber chambers or the condenser, depending on the phase of the process. In operating phase 1, hot water passes through adsorber 1. The coolant, which has accumulated on the inner surface of the silica gel, is expelled, thus causing it to condense on the cooled condenser. The condensation heat emitted is removed through the re-cooling circuit. The condenser has a constantly low temperature and pressure level and, therefore, acts as a temperature sink. Simultaneously, adsorber 2 adsorbs (i.e. water vapor from the evaporator is bound in the silica gel). During the conversion of the state of aggregation from a liquid to a gas, energy is extracted from the coolant (enthalpy of evaporation). This lower temperature level is led away through the evaporator as the cooling circuit. During adsorption of the water vapor in the silica gel, adsorption heat is released. This heat is removed through the re-cooling circuit of the ACS. This process is concluded once the average target temperature is reached.

All hydraulic components, necessary for the internal switchings, are installed inside of the chiller; this allows an easy connection of the chiller to the external three hydraulic circuits (high temperature source HT, heat rejection circuit MT and chilled water circuit LT). The basic hydraulic structure of the chillers is presented in Figure 30. [Rupp et al., 2009] and [Sortech 2009].

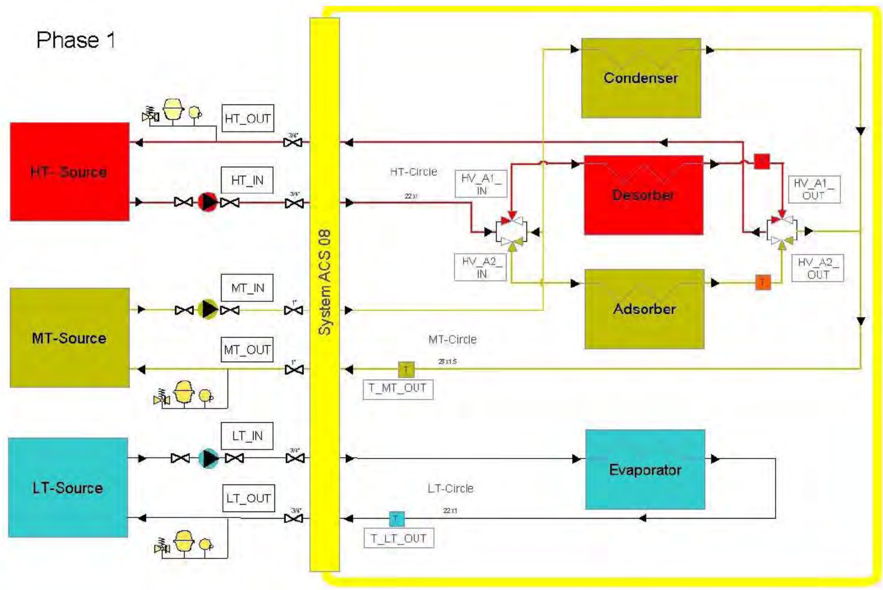


Figure 30: Main internal hydraulic components of the SorTech chiller and external connections. The figure presents the operation phase, of which the upper of the two sorption compartments is currently being desorbed by applying hot water and the lower sorption compartment is working as adsorber, thus taking up the vaporized refrigerant. The refrigerant circle, either fluid or vaporized, is not included into the figure. [Rupp, 2009]

The LCIA of the adsorption chiller has been done, thanks to the information given by Sortech. The following assumptions have been taken, regarding the calculation of one adsorption chiller ACS08:

- All materials have been taken in account excluded some vacuum components representing less than 1% of the mass.
- The energy use for the fabrication of the chiller has not been taken in account.
- The transport of the materials to the plant is not taken in account, because we do not have those information.

At the end, the impacts related to the chiller include the materials use for the fabrication and their end-of-life. The Table 19 gives the total impacts for the three indicators for the Sortech chiller. Those impacts are not detailed by materials, as the company want to keep this information rather confidential. Therefore, hereafter it will consider as a **black box**.

Table 19: Environmental impacts of one Sortech adsorption chiller (265kg empty)

	NRE (MJ-eq)	GER (MJ-eq)	GWP (kg CO_2-eq)
Production of chiller components	22‘202	24‘187	1‘380
End-of-life	12	12	21
Total	22‘214	24‘199	1‘401

The contribution of the production is close to 100% for the NRE and GER and close to 98.5% for the GWP. The impacts of the elimination phase are very low, as most of the components use in the chiller can be recycled. The small impacts are related to some plastics and electric components that cannot be recycled.

The impacts of the energy phase for the production and the transport phase would not give much more on the total impacts on the whole installation.

3.1.7.3 Eco-profile of the plants

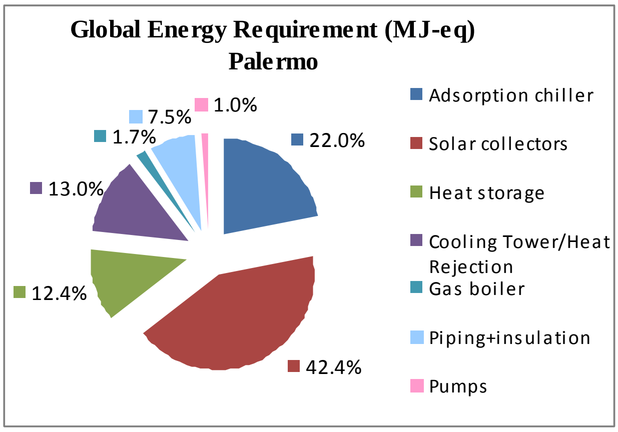
<u>Configuration A) Hot backup</u>

The environmental impacts of the adsorption solar chiller (F.U. 1 solar chiller) are showed in Table 20. The glycol use in the plant for the Zurich location is needed in winter. No glycol is used at Palermo location. The results are presented for three different phases: production phase of the plant components, use phase and end-of-life phase of the components.

In Figure 31:Production phase: Percentage contribution of different plant components to GER and GWP for Palermo and Figure 32: Production phase: Percentage contribution of different plant components to GER and GWP for Zurich the contributions (expressed in %) of the global PE consumption and of the GWP related to the production of the main plant components are showed, respectively for Palermo and Zurich. For both climates, the solar collectors are the most impacting followed by the production of the adsorption chiller. Gas boiler as Piping+insulation and glycol are negligible but not insignificant (1.0% and more). The difference between both climates is the glycol containing in the Zurich system.

Table 20: Environmental impacts of the solar cooling plant (hot backup configuration)

	Components	NRE (MJ-eq)	GER (MJ-eq)	GWP (kg CO_2-eq)
Production of plant components	Adsorption chiller	22'202	24'187	1'380
	Solar collectors (25 m2)	40'723	46'604	2'385
	Heat storage 1300l	12'124	13'690	735
	Cooling Tower/Heat Rejection	12'680	14'348	770
	Gas boiler 20kW	1'726	1'853	103
	Glycol (only for plant in Zurich)	1'576	1'636	64
	Piping+insulation	7'821	8'256	412
	Pumps	1'017	1'095	66
Use phase Palermo	Cooling demand	187'295	198'483	11'825
	Heating demand	52'002	53'335	3'142
Use phase Zurich	Cooling demand	120'033	128'418	5'090
	Heating demand	836'423	842'404	48'321
End-of-life	Adsorption chiller	12	12	21
	Solar collectors (flat plate)	200	215	247
	Heat storage 1300l	18	19	11
	Cooling Tower/Heat Rejection	9	9	105
	Gas boiler 20kW	16	17	5
	Glycol (only for plant in Zurich)	459	461	39
	Piping+insulation	12	13	92
	Pumps	3	3	1
Total Palermo		337'860	362'140	21'299
Total Zurich		1'057'054	1'083'240	59'846



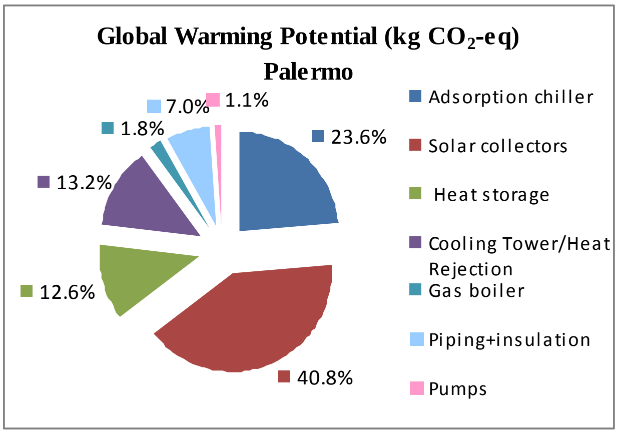


Figure 31:Production phase: Percentage contribution of different plant components to GER and GWP for Palermo

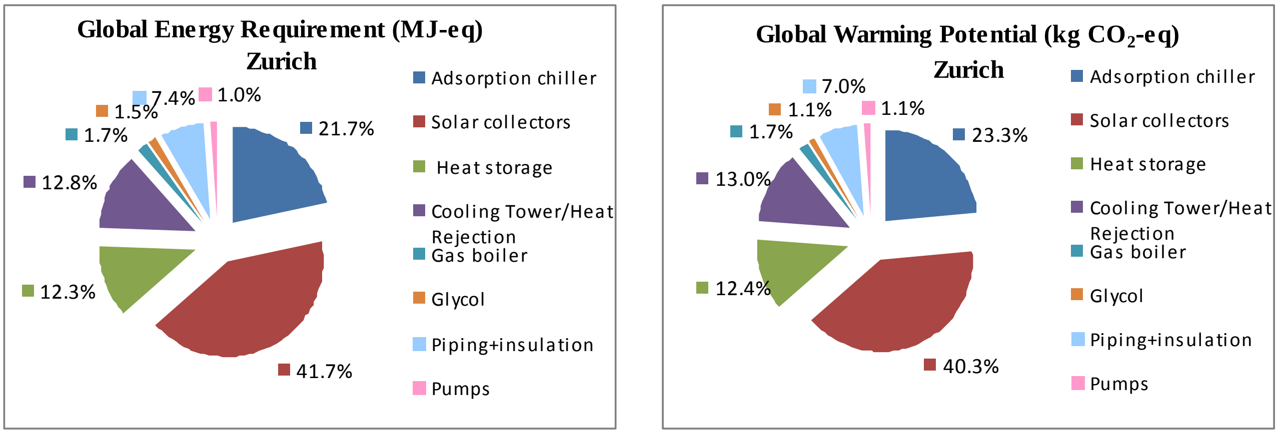


Figure 32: Production phase: Percentage contribution of different plant components to GER and GWP for Zurich

The Figure 33: Relative contribution of the three different phases for the whole life-cycle to GER and GWP for Palermo and Figure 34: Relative contribution of the three different phases for the whole life-cycle to GER and GWP for Zurich show the contributions (expressed in %) of the global PE consumption and of the GWP related to each life cycle phase of the plant, respectively for Palermo and Zurich. The most impacting phase is the use phase in both climates. The production phase represents more impacts in Palermo then in Zurich, due to the great demand in heating for winter. The end-of-life is negligible, even with the glycol part in Zurich.

In Table 21 and Table 22 the environmental impacts related to different F.U.s are showed, respectively for Palermo and Zurich. To calculate the impacts related to the F.U. “1 KW of the adsorption chiller power”, an 8kW power is used and to the. F.U. “1 kWh of produced energy”, the following values of produced energy in 25 years are used: for Palermo 114‘125 kWh, for Zurich 259‘375 kWh.

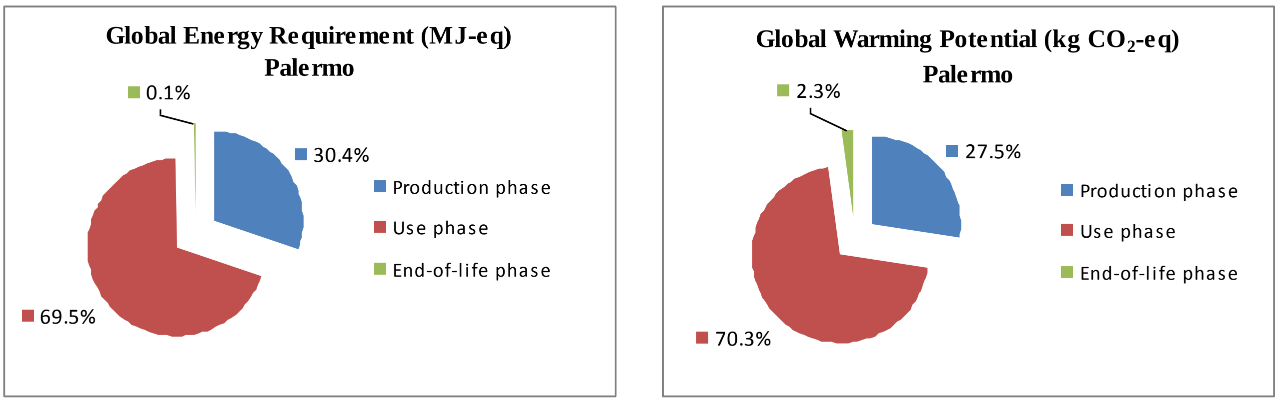


Figure 33: Relative contribution of the three different phases for the whole life-cycle to GER and GWP for Palermo

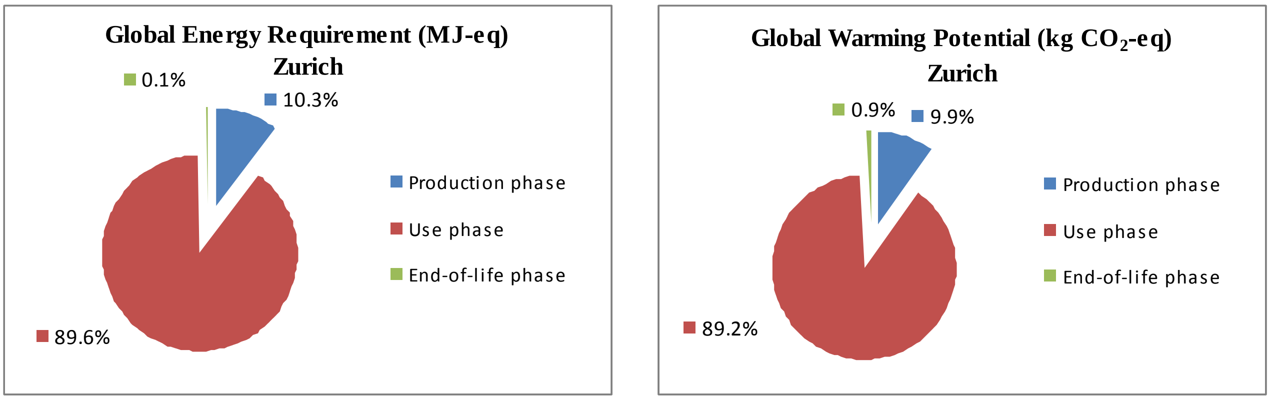


Figure 34: Relative contribution of the three different phases for the whole life-cycle to GER and GWP for Zurich

Table 21: Environmental impacts of the solar cooling plant (hot backup configuration) for Palermo: comparison among different F.U

		NRE (MJ-eq)	GER (MJ-eq)	GWP (kg CO_2-eq)
FU 1 solar cooling plant	Production	98‘293	110‘033	5‘850
	Use phase	239‘297	251‘819	14‘967
	End-of-life phase	270	288	482
FU 1 kW of chiller power	Production	12‘287	13‘754	731
	Use phase	29‘912	31‘477	1‘871
	End-of-life phase	34	36	60
FU 1 kWh of produced energy	Production	0.861	0.964	0.051
	Use phase	2.097	2.207	0.131
	End-of-life phase	0.002	0.003	0.004

Table 22: Environmental impacts of the solar cooling plant (hot backup configuration) for Zurich: comparison among different F.U.

		NRE (MJ-eq)	GER (MJ-eq)	GWP (kg CO_2-eq)
FU 1 solar cooling plant	Production	99‘869	111‘669	5‘914
	Use phase	956‘456	970‘822	53‘411
	End-of-life phase	729	749	521
FU 1 kW of power	Production	12‘484	13‘959	739
	Use phase	119‘557	121‘353	6‘676
	End-of-life phase	91	94	65
FU 1 kWh of produced energy	Production	0.385	0.431	0.023
	Use phase	3.688	3.743	0.206
	End-of-life phase	0.003	0.003	0.002

<u>Configuration B) Cold backup</u>

The environmental impacts of the adsorption solar chiller (FU 1 solar chiller) are showed in Table 23. The glycol use in the plant for the Zurich location is needed in winter. No glycol is used at Palermo location. The results are presented for three different phases: production phase of the plant components, use phase and end-of-life phase of the components. The conventional chiller is adding for the cooling backup.

The Figure 35: Production phase: Percentage contribution of different plant components to GER and GWP for Palermo and 36 show the contributions (expressed in %) of the global PE consumption and of the GWP related to the production of the main plant components, respectively for Palermo and Zurich, are showed. The adding of the conventional chiller is not negligible. It represents more than 10% of the GER impacts and around 29% of the GWP. For this last indicator, it represents as much impacts as the solar collectors see before as the higher impacts in both indicators. The rest of the components have the same proportion of impact as for the hot backup.

Table 23: Environmental impacts of the solar cooling plant (cold backup configuration)

	Components	NRE (MJ-eq)	GER (MJ-eq)	GWP (kg CO_2-eq)
Production of plant components	Adsorption chiller	22‘202	24‘187	1‘380
	Solar collectors 25m2	40‘723	46‘604	2‘385
	Heat storage 1300l	12‘124	13‘690	735
	Cooling Tower/Heat Rejection	12‘680	14‘348	770
	Gas boiler	1‘726	1‘853	103
	Glycol (only for plant in Zurich)	1‘576	1‘636	64
	Piping+insulation	7‘821	8‘256	412
	Pumps	1‘017	1‘095	66
	Conventional chiller	11‘847	12‘504	2‘394
Use phase Palermo	Cooling demand	149‘541	162‘985	9‘800
	Heating demand	52‘002	53‘335	3‘142
Use phase Zurich	Cooling demand	90‘729	107‘055	1‘401
	Heating demande	836‘423	842‘404	48‘321
End-of-life	Adsorption chiller	12	12	21
	Solar collectors (25m2)	200	215	247
	Heat storage 1300l	18	19	11
	Cooling Tower/Heat Rejection	9	9	105
	Gas boiler	16	17	5
	Glycol (only for plant in Zurich)	459	461	39
	Piping+insulation	12	13	92
	Pumps	3	3	1
	Conventional chiller	12	12	39
Total Palermo		311‘965	339‘158	21‘708
Total Zurich		1‘039‘608	1'074‘394	58‘590

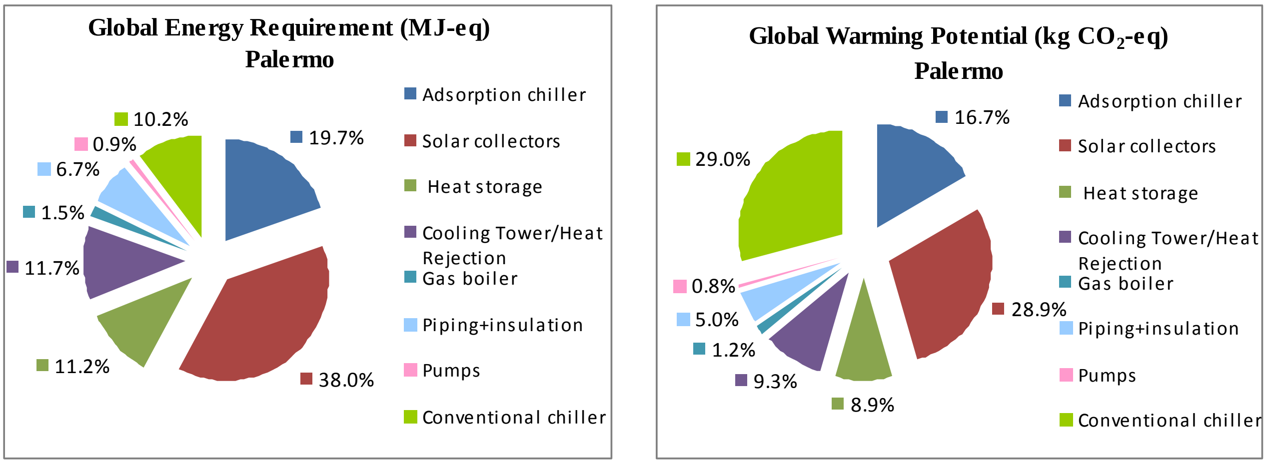


Figure 35: Production phase: Percentage contribution of different plant components to GER and GWP for Palermo

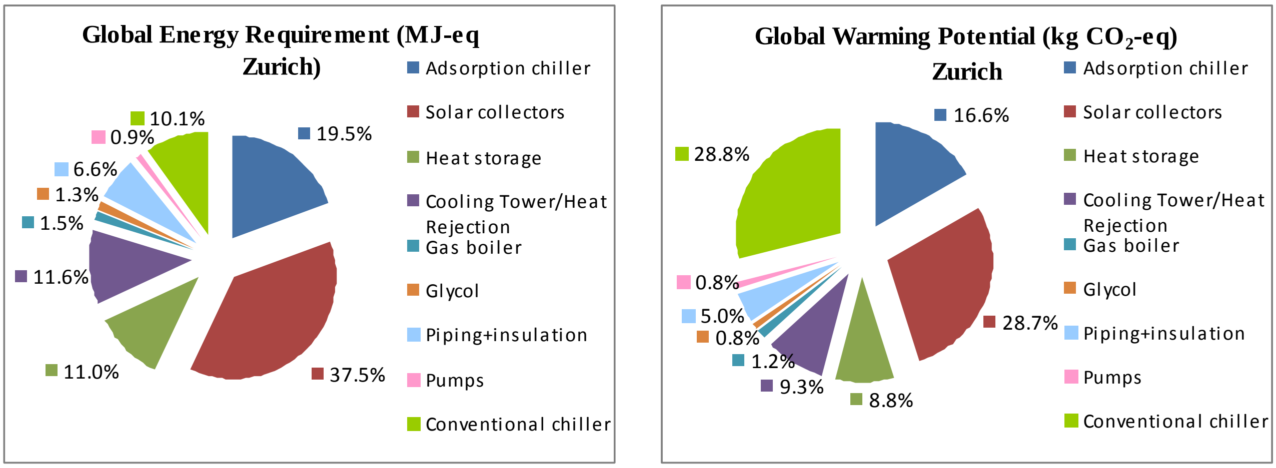


Figure 36: Production phase: Percentage contribution of different plant components to GER and GWP for Zurich

In Figure 37 and Figure 38 the contributions (expressed in %) of the global PE consumption and of the GWP related to each life cycle phase of the plant, respectively for Palermo and Zurich, are showed. There is no really change with the hot backup analyses (see Figure 33: Relative contribution of the three different phases for the whole life-cycle to GER and GWP for Palermo and Figure 34: Relative contribution of the three different phases for the whole life-cycle to GER and GWP for Zurich).

In Table 24 and Table 25Table 25 represent the environmental impacts related to the different F.U., respectively for Palermo and Zurich. To calculate the impacts related to the FU “1 KW of the adsorption chiller power”, an 8kW power is used and to the. F.U. “1 kWh of produced energy”, the following values of produced energy in 25 years are used: for Palermo 117‘500 kWh, for Zurich 258‘075 kWh.

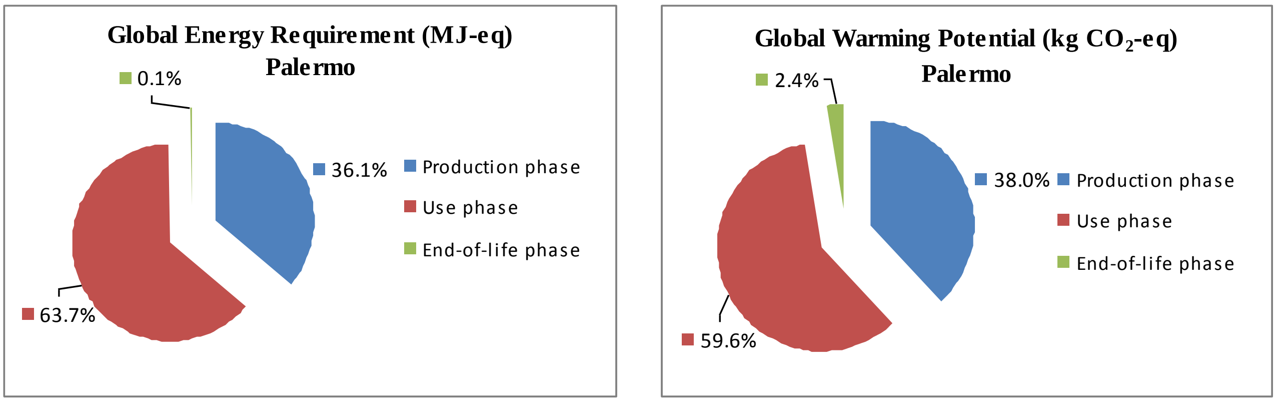


Figure 37: Percentage contribution of the three different phases for the whole life-cycle to GER and GWP for Palermo

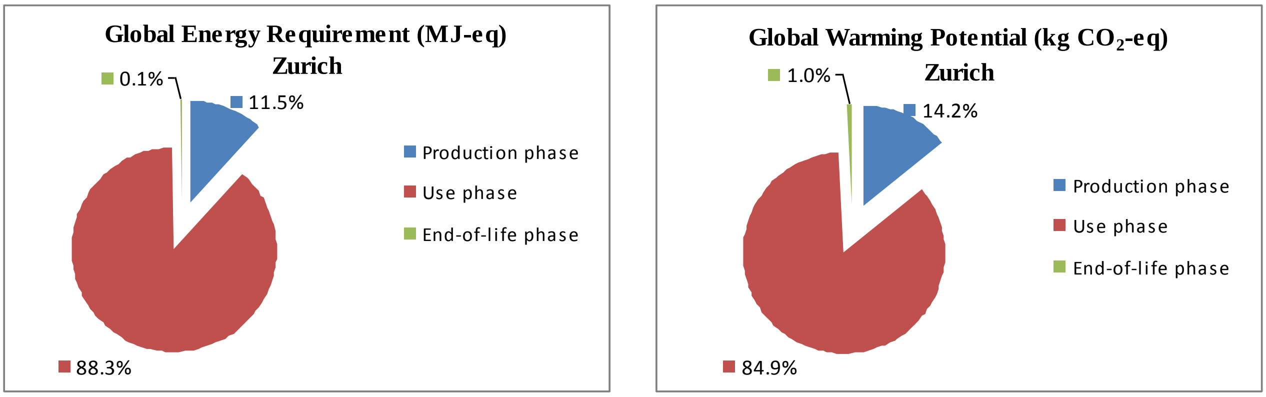


Figure 38: Percentage contribution of the three different phases for the whole life-cycle to GER and GWP for Zurich

Table 24: Environmental impacts of the solar cooling plant (cold backup configuration) for Palermo: comparison among different F.U.

		NRE (MJ-eq)	GER (MJ-eq)	GWP (kg CO_2-eq)
F.U. 1 *solar cooling plant*	Production	11‘0140	122‘537	8‘243
	Use phase	20‘1543	216‘320	12‘942
	End-of-life	282	300	522
F.U. 1 kW of power	Production	13‘768	15‘317	1‘030
	Use phase	25‘193	27‘040	1‘618
	End-of-life	35	38	65
F.U. 1 kWh of produced energy	Production	0.937	1.043	0.070
	Use phase	1.715	1.841	0.110
	End-of-life	0.002	0.003	0.004

Table 25: Environmental impacts of the solar cooling plant (cold backup configuration) for Zurich: comparison among different F.U.

		NRE (MJ-eq)	GER (MJ-eq)	GWP (kg CO_2-eq)
F.U. 1 *solar cooling plant*	Production	111‘716	124‘173	8‘307
	Use phase	927‘152	949‘459	49‘721
	End-of-life	741	761	561
F.U. 1 kW of	Production	13‘965	15‘522	1‘038

power	Use phase	115‘894	118‘682	6‘215
	End-of-life	93	95	70
F.U. 1 kWh of produced energy	Production	0.433	0.481	0.032
	Use phase	3.593	3.679	0.193
	End-of-life	0.003	0.003	0.002

3.1.7.4 Comparison with the conventional system

The comparisons of the innovative system (hot or cold back-up) with the conventional system (vapor compressor chiller + gas boiler) for the three different FU are showed from the Figure 39 to Figure 41 for GER and GWP. This comparison takes into account, the impacts of materials and energy required for heating and cooling over the whole life span.

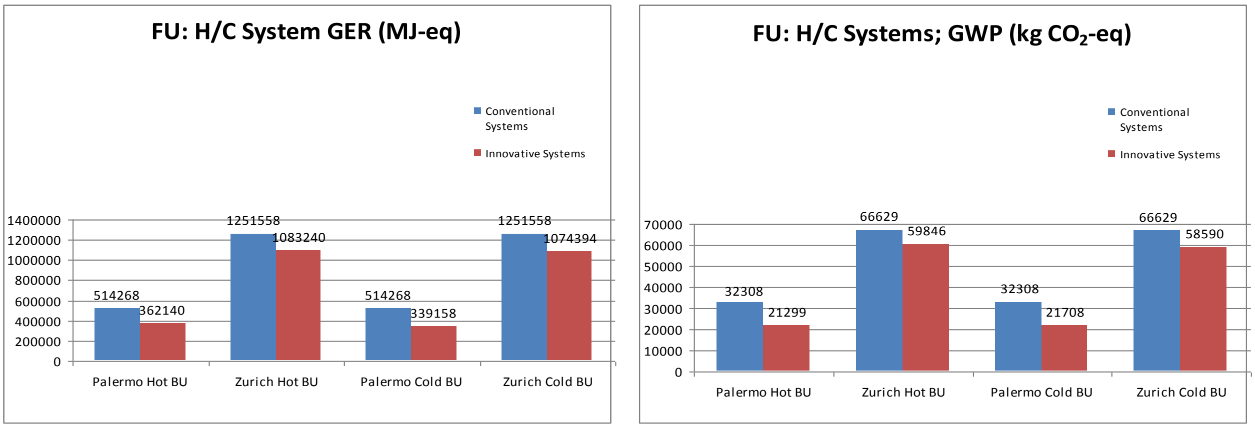


Figure 39: Comparison for the whole system during 25 years of energy use in both climates and both back-up for GER and GWP

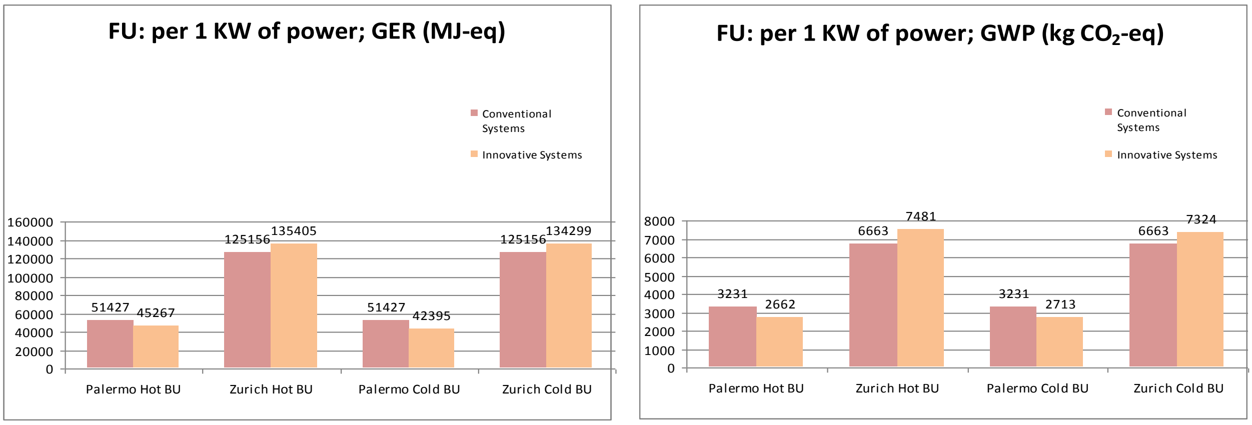
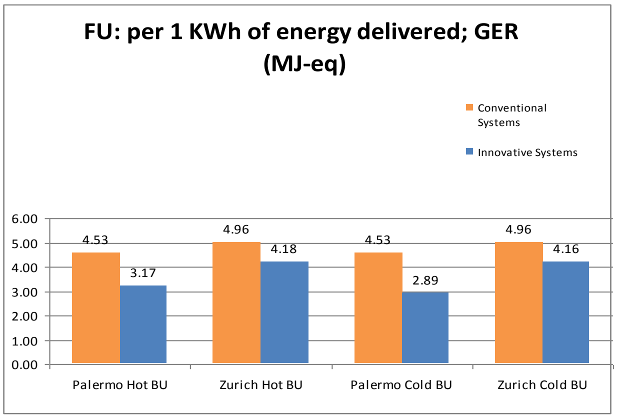


Figure 40: Comparison per 1kW of cooling power during 25 years of energy use in both climates and both back-up for GER and GWP



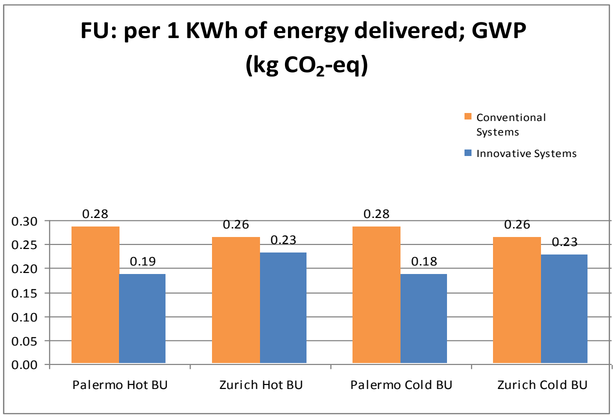


Figure 41: Comparison per 1kWh of energy produced during 25 years of energy use in both climates and both back-up for GER and GWP

Taking in account the whole system during the 25 years of use or per kWh of energy produced (Figure 39 and Figure 41), the innovative system is better than the conventional system. On the contrary, the impacts are lower for the conventional system when expressed by kW power of the chiller (Figure 40). As we know that the conventional system has a power of 10kW instead of the innovative system which has an 8kW power.

3.1.7.5 Discussion of the results

In Palermo, the GER varies from 362 GJ (hot back-up) to 339 GJ (cold back-up) with a decrease of 6.4%. This is due to lower energy consumption for the cold back-up with a COP chiller of 2.5. Indeed, the 585 kWh gas needed in hot back-up with 494 kWh of electricity for the auxiliary are higher than the 606 kWh electricity for the cold back-up. This implies a decrease of the use part (cooling and heating demand) of 14.1%, but the adding of the conventional chiller for cold back-up leads to an increase of 3.7% extra on the total impacts of the cold back-up system.

For the GWP indicator, the impacts goes from 21‘299 kg CO_2-eq (hot back-up) tot 21‘708 kg CO_2-eq (cold back-up), with a decrease is 1.9%. That takes into account a decrease of 13.5% due to the use phase and an extra amount of 11.0% for the conventional chiller materials impact.

For the Zurich climate, The GER decrease by 0.8% (hot back-up: 1‘083 GJ to cold back-up: 1‘074 GJ) for the same reasons than in Palermo. The use phase decrease by 2.2% and the conventional chiller impacts correspond of 1.2% of the whole system impacts with cold back-up. For the GWP the difference is higher with a decrease of 2.1% (hot back-up: 59‘846 kg CO_2-eq to cold back-up: 58‘590 kg CO_2-eq) on the total amount due to the energy decrease of 6.9% and an increase impacts of 4.1% due to materials of the conventional chiller.

These results show that the materials impacts of the compressor chiller are not negligible as for the absorption system (Figure 35: Production phase: Percentage contribution of different plant components to GER and GWP for Palermo and Figure 36: Production phase: Percentage contribution of different plant components to GER and GWP for Zurich). Due to the high heating demand in Zurich, those impacts become lower than for Palermo, where they represents 11.0% for the GWP.

For all system and all the indicators, the life-cycle phase with the most contribution is the utilisation, related to the energy consumption. Respectively for cold and hot back-up, in Zurich it represents 88.3% up to 89.6% of the GER and from 84.9% to 89.2% for GWP. These proportion decreases in Palermo from 63.7% to 69.5% of the GER and from 59.6% to 70.2% for the GWP. End-of-life does not have an influence on the total impacts.

One of the most useful indicators is the ratio between the total impact and the total energy delivered (cold and hot) as show in the 2 diagrams in Figure 41. All the innovative systems are better than the conventional one. In Palermo for the GER, the reduction is 30.7% for heating and 36.2% for cooling, and for the GWP the reduction is 32.1% for heating and 35.7% for cooling. This is due to the reduction of energy consumption in the adsorption chiller, due to the solar collectors which provides energy for the cooling demand. The heating demand is so small that it becomes insignificant. In Zurich, the reduction is less important. For the GER, we have 15.7% (hot back-up) and 16.1% (cold back-up) as for the GWP we have 11.5% for hot and cold. This difference is caused by the lower need in cooling and the higher heating demand in winter, even with solar collectors , which can give only a part of the heating.

The production of the components phase should not be neglected as seen previously. Specially for climates with a high solar fraction such as in Palermo. So we must not only work on a lower energy requirement, but also on the choice of materials use for the systems production. In the other hand the energy saving by using solar collectors are much higher than the energy need to produce them. So more we use energy saving systems by adding more material (Solar thermal collectors or photovoltaic, etc.), more we will arrived by a reversed contribution of the phases (the contribution of materials will be higher than the use phase). The reflection on the materials used must be taken into account.

Outside the framework of the IEA Task 38, an additional study was done with adsorption machine in comparison with other combined heating-coolong systems for the Zürich and the Barcelona climates. From the point of view of environmental impact, this study gives same conclusion than the current one between adsorption machine and conventional chiller. In fact, in both types of climate, the innovative system has lower impacts than the gas boiler with conventional chiller.

Like the previous chapter about absorption chiller, some payback indexes (E_{PT}, EM_{PT} and E_{RR}) have been calculated. Table 26: Payback indexes for the case studies shows the figures of the three indexes for systems using the adsorption machine.

Table 26: Payback indexes for the case studies

	E_{PT} year	EM_{PT} year	E_{RR}
Palermo Hot BU	9.31	6.03	2.25
Palermo Cold BU	9.25	8.92	2.31
Zurich Hot BU	8.87	8.60	2.37
Zurich Cold BU	9.30	10.63	2.30

The indexes have been calculated taking into account the cumulative energy demand of the innovative system including from the construction to the end of life of the systems.

The E_{PT} (Figure 42:) is defined as the use time during which the system must work to produce as much Energy as it requires for its production and disposal.

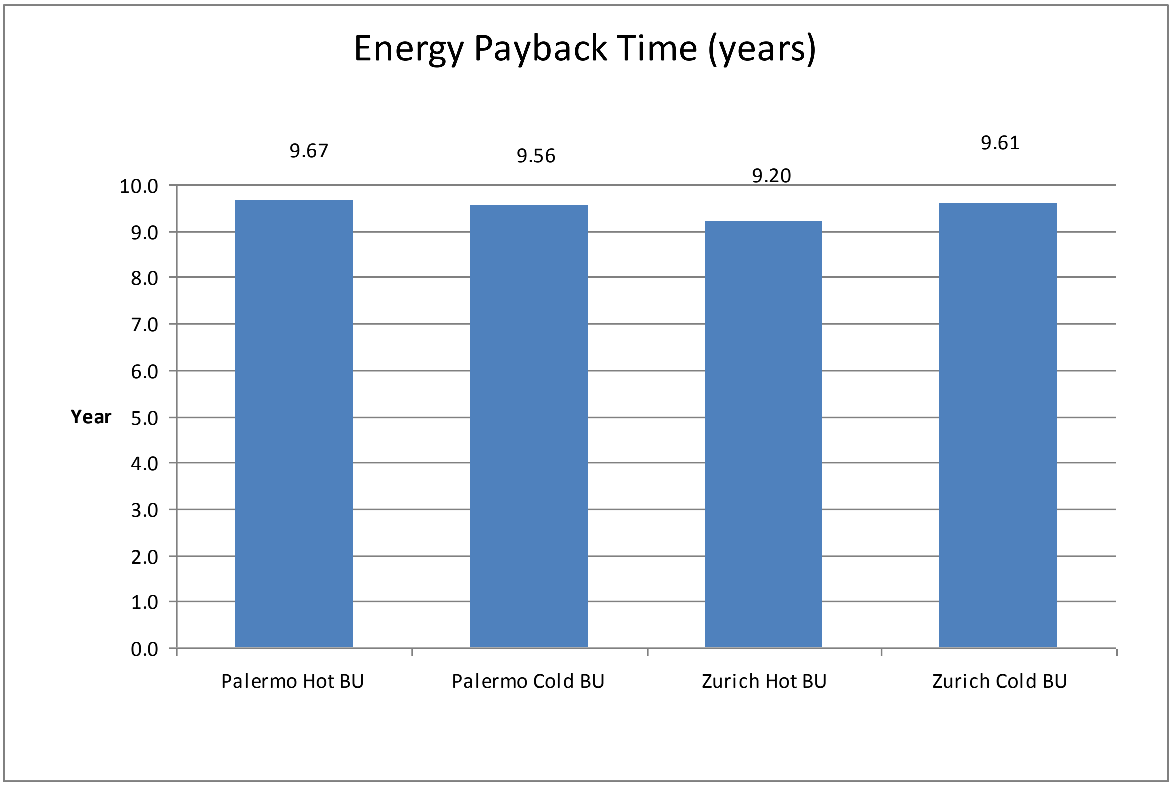


Figure 42: E_{PT} for Adsorption Solar Cooling systems with hot and cold back-up

Zurich figures are slightly lower than for Palermo (less than 5%).

- EM_{PT} and E_{RR} are two other indicators than can be used to compare the different systems.

A) EM_{PT} indicator shows how many year we need to compensate the GHG emission due to the use of the innovative system during the life span of the plant.

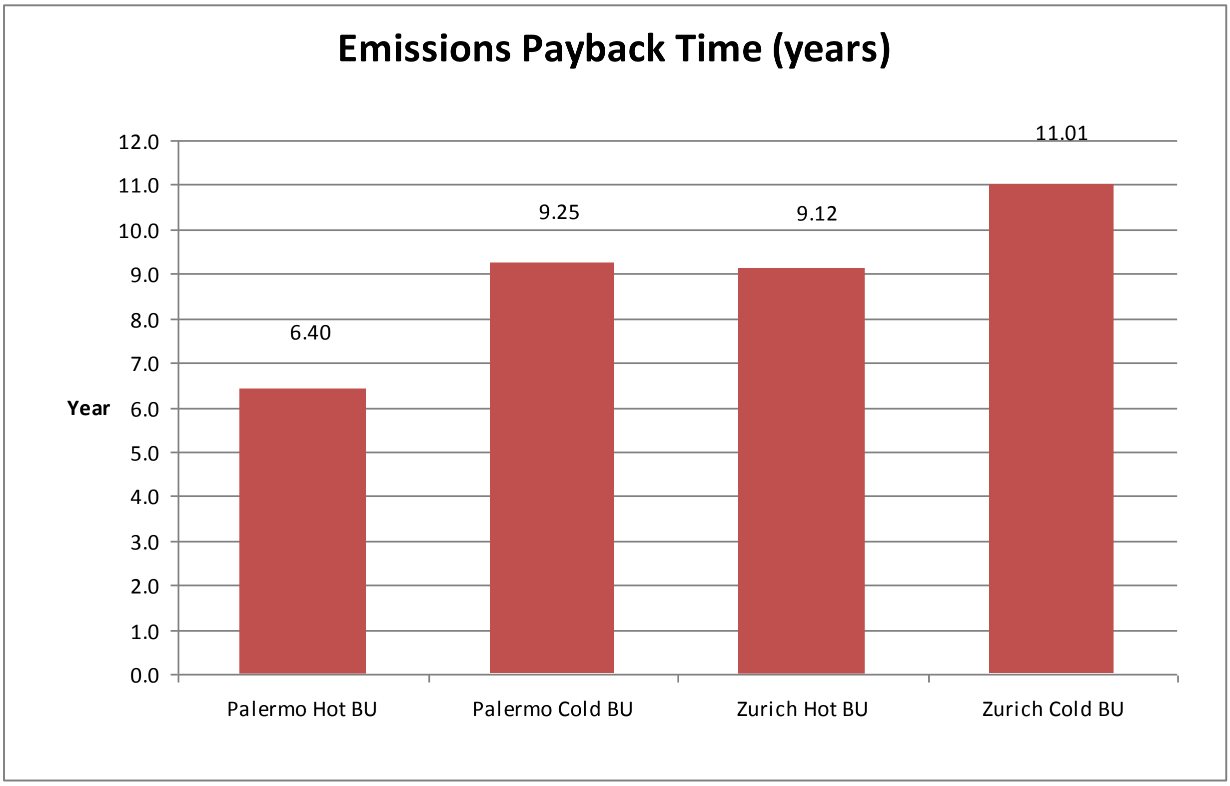


Figure 43: Emissions Payback Time for Adsorption Solar Cooling systems with hot and cold back-up

Differences between hot and cold back-up are mainly due to the impact of the material of the additional back-up chiller, which is higher than in the hot back-up system.

B) E_{RR} indicates how many times the energy savings on the lifetime of the installation is relative to the energy needed to manufacture the innovative system.

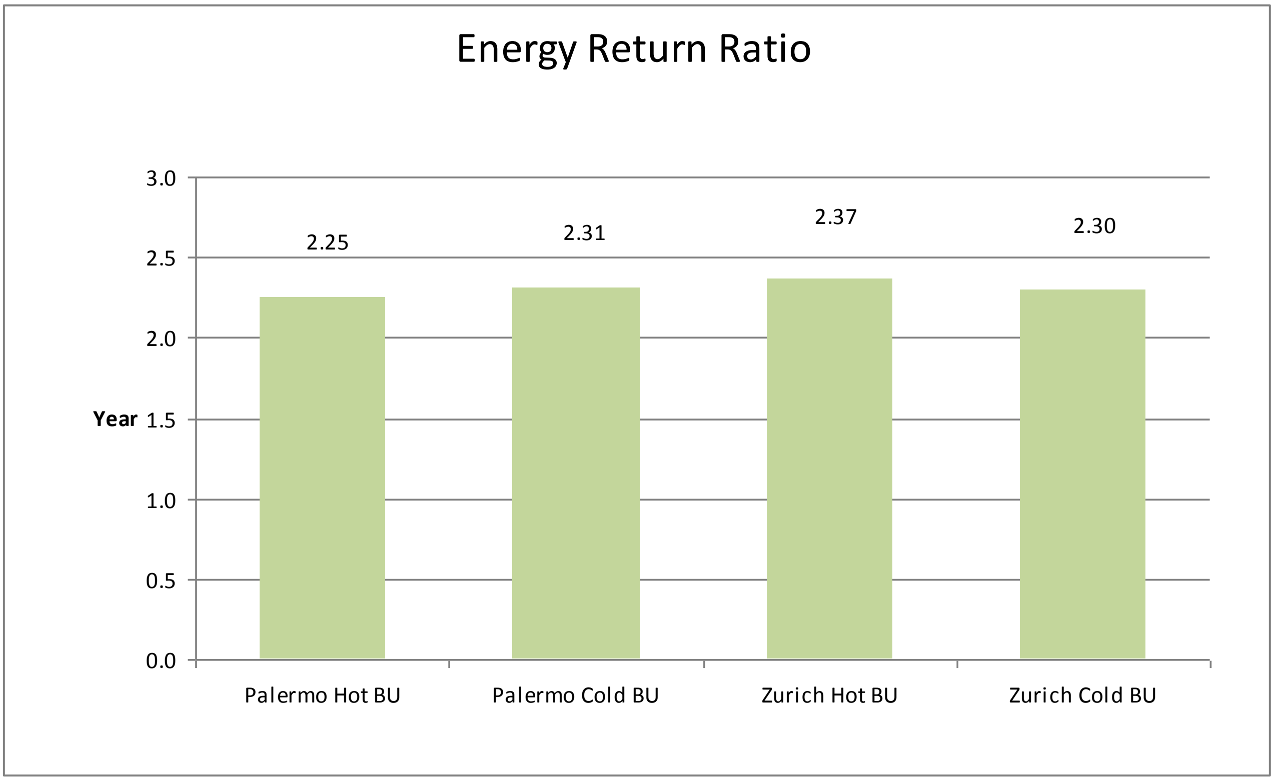


Figure 44: **E_{RR} for Adsorption Solar Cooling systems with hot and cold back-up**

In all the cases the results are satisfactory while the systems give back from more than 2 times the energy expenditure for their construction and disposal useful for the difference between innovative and conventional system. As for the E_{PT}, differences are not relevant between all systems, less than 5%.

3.2 Solar DEC vs Conventional AHU: results from the operation phase of a plant in Palermo, Italy (DREAM)

The solar assisted DEC systems can be included in the product category of the ―Energy Using Products” [Directive 2005/32/EC]. In this context, the operating phase cover a key-role and it has to be investigated more in detail. The case study plant of the DREAM is already operative and the collected data can be used to extrapolate general considerations about the life-cycle impact about the system‘s operation.

Table 27: **Monitored and estimated consumptions**

	Solar DEC - DREAM		Conventional System	
	Electricity [kWh]	LPG [kWh]	Electricity [kWh]	LPG [kWh]
Jan	530	213	519	816
Feb	479	574	466	1217
Mar				
Apr				
May				
Jun	(*)		1559	623
Jul	2207		2987	1328
Aug	2099		2641	1021
Sep	1411		1559	623
Oct				
Nov				
Dec	554	515	536	1268
Total	8691	1302	10267	6897

* Missing data

As first step, the analysis of the DREAM focuses on the assessment of impacts and benefits related to the operating phase. Table 27 shows a comparison among the consumptions of the experimental solar DEC and of a replaceable conventional system that operates under the same operating conditions. Consumptions include the global electricity utilized by all the system components (mainly chiller, pumps and fans), and the Liquid Petroleum Gas[2] (LPG) consumed by the auxiliary heating system.

Monitored data refer to the testing period (May 2008 – March 2009). Data about June 2008 are missing due to system start up problems.

[2] At the time of the compilation of table 1LPG was used to fire the gas boiler. After, it was substitutes with natural gas.

These data have been implemented into SimaPro software for the calculation of synthetic environmental indexes. The analysis aims at assessing the energy and environmental benefits related to the use of the experimental plants. Obtained results are however strictly depending on the input eco-profiles of energy sources for the life-cycle inventory.

A preliminary discussion about key-issues of such life-cycle analysis has been following synthesized:

- *Energy mix*: electricity is the largest energy input of the studied system. It is also responsible of large environmental impacts strictly depending on the ―energy mix", meaning the set of different processes and plants utilized for the electricity production. The choice of a reliable electricity mix weights significantly on the final results and net benefits, and it has to be carefully checked. In the studied context, the Italian national energy mix is based mainly on thermoelectric generation systems (oil and gas fired plants) and imports from other countries. The Sicilian regional mix, instead, is based by thermoelectric plants with a significant presence of hydroelectric plants and wind farms. It could be possible even to refer to an average international ―energy mix" that refers to an average European production. Data about the Italian and the average European[3] ―electricity mix" are included into Ecoinvent database, while the eco-profile of the regional mix is missing. It has been therefore calculated starting from data about the regional electricity production[4] and the specific eco-profiles per generating plant (included in the Ecoinvent database).

- *LPG (Liquefied Petroleum Gas):* it is utilized to fire a conventional gas boiler employed as auxiliary system during the winter-time. The considered conventional system utilizes also LPG in the summer for the post-heating in the air treatment unit. The Ecoinvent database does not include the eco-profile of the LPG boiler.

Therefore, it has been carried out a reference analysis about the available data. The acquired eco-profiles are:

- o LPG fired in industrial equipments, concerning average USA technology in the late 1990's [Franklin, 1998];
- o Derived data from the combustion of hydrocarbons (considering LPG as a mix of 60% propane and 40% butane). Impacts related to the hydrocarbon use and production refer to ―The Boustead Model", for the Italian context in the 2000's.

3 Average production of electricity in the UCTE (Union for the Co-ordination of Transmission of Electricity), concerning 24 European countries and 36 national operators for the electricity production.

4 From the Sicilian Regional Energy Plan (data from 2005), it resulted that in Sicily the electricity production is so subdivided: fossil fuels fired thermoelectric 83.1 %; hydropower 11.9 %; other renewable 5%.

- *Useful life*: the life length is another basic parameter that influences the LCA results. Generally eco-profiles of products are improved extending the useful lifetime; but for Energy Using Products, a loss in the energy efficiency could compromise the related benefits. At this stage it is difficult to state the lifetime of the experimental system, being the operating time too small and being the plant constituted by several different components with different useful life. From a survey about the characteristics of system‘s components, it is expected an average life of 20 years, but this value could have a ±20% variation.

Following these considerations, it has been decided to proceed to a scenario analysis in order to define a “base-case” scenario to which compare different alternatives concerning the above key issues. This <u>Scenario 0</u> supposes:

- To assess impacts due to electricity considering the national energy mix;
- To assess impacts due to LPG consumption considering the derived gas mix;
- To consider 20 years useful time;
- To use monitored data without modifies over the time due to the efficiency. In order to allow the extrapolation of the results in a life-cycle perspective, <u>monthly consumptions of June have been assumed equal to September</u>. This assessment is realistic, being the average weather conditions of the two months similar.

Successively, Scenario 0 has been compare with the following alternative scenarios:

- <u>Scenario 1</u>: impacts related to electricity are assessed considering different energy mix (national and regional);
- <u>Scenario 2</u>: Impacts related to LPG combustions are related to a different available eco-profile;
- <u>Scenario 3</u>: Due to efficiency losses, energy consumptions of DEC are supposed to grow constantly, arriving to a +20% increase of consumption at the last operating year;
- <u>Scenario 4</u>: based on the above hypothesis of Scenario 3, lifetime is furthermore considered to vary from 16 to 24 years. In the longest lifetime scenario, it is expected that during the last 4 operating years, the efficiency will further decrease with a yearly increase of the energy consumptions.
- <u>Scenario 5</u>: Impacts due to some innovative components are included in the calculation of the environmental indexes of the “base- case” (Scenario 0).

Results of scenarios are following described.

3.2.1. Scenario 0: Basic case-study

Eco-profiles of the innovative DEC plant and the conventional system have been calculated. Results are shown in Table 28.

From a first comparison it is possible to observe that the innovative system is characterized by lower impacts concerning all the considered environmental indexes. Therefore, the solar plant allows a sensible reduction of the environmental burdens, with considerable benefits.

Table 28: **Comparison of Eco-profiles – Innovative and conventional systems**

		Conventional	**Innovative**	**Variation**
GWP	[kg $CO_{2\text{-Eq.}}$]	171.139	117.497	-31,3%
Ozone Depletion Potential (ODP)	[kg CFC_{11}]	0,0102	0,0086	-15,4%
Photochemical Ozone Creation Potential (POCP)	[kg C_2H_4]	213	66	-68,7%
Acidification Potential (AP)	[kg SO_2]	931	585	-37,1%
Nutrification Potential (NP)	[kg PO_4]	95	42	-55,4%
GER	[$MJ_{Prim]}$	2.531.876	1.785.334	-29,5%

The seasonal detail outlines that the majority of the impacts are related to the summer working time (Figure 45 and Figure 46). The differences between the two plants are more pronounced during this period, when innovative DEC is characterised by sensible lower consumptions. In fact, the use of desiccant wheel allows to avoid the air post-heating, that is instead included into the conventional reference system. During the wintertime, differences between the two systems are smaller, but innovative DEC is anyway characterised by better environmental performances.

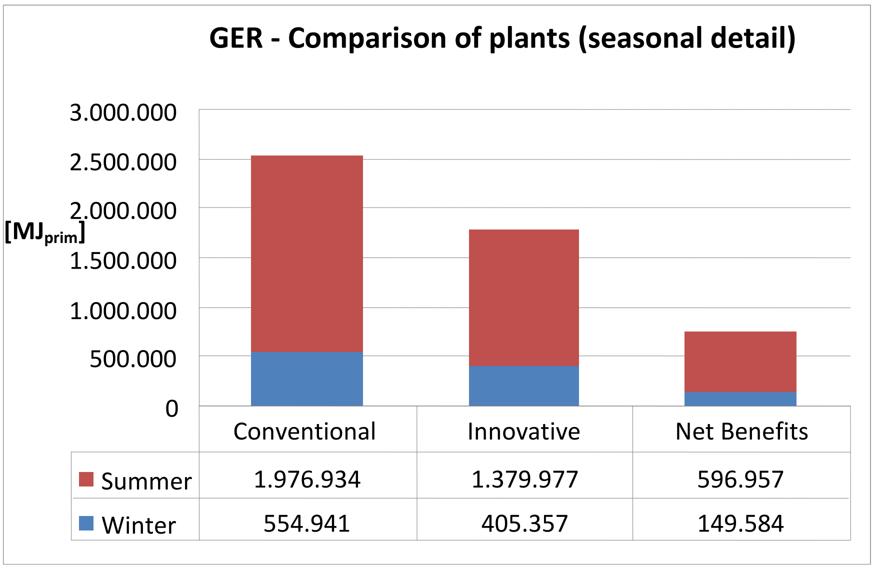


Figure 45: Comparison of seasonal impacts of the considered systems (GER)

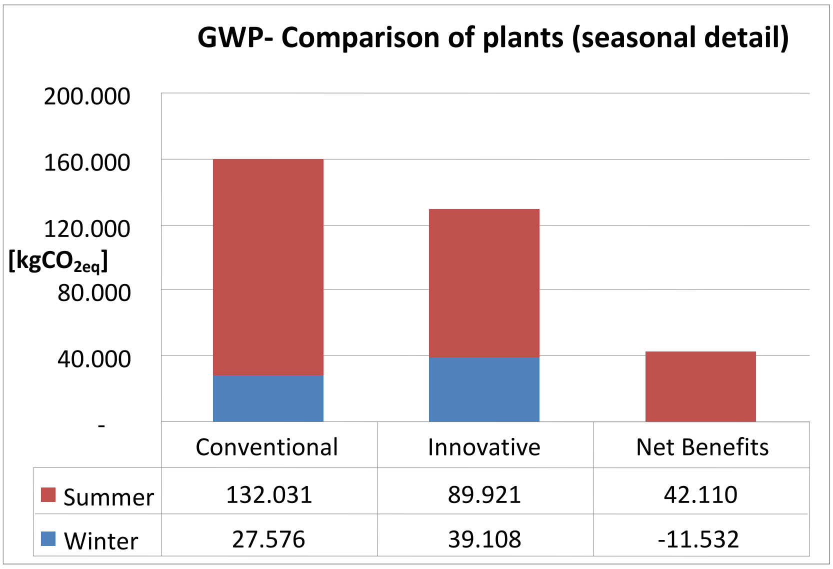


Figure 46: **Comparison of seasonal impacts of the considered systems (GWP)**

A further detail concerned the subdivision about the used energy sources (Figure 47 and Figure 48). It is possible to observe that the majority of the impacts are related to the use of electricity, due to the large consumptions and the eco-profile of the electricity production in the Italian context. The incidence of LPG is marginal, especially in the innovative system.

The environmental impacts have been therefore detailed about each system‘s components, in order to identify the most impacting elements. Consumptions of DEC have been subdivided into the following components:

- Auxiliary system: it encloses electrical consumption for pumps and actuators;

- AHU - Air Handling Unit: it encloses electrical consumption for fans, humidifiers, electrical engines of rotors;
- Radiant ceiling: it encloses electrical consumption for pumps and actuators;
- Chiller;
- Gas boiler, fired by LPG.

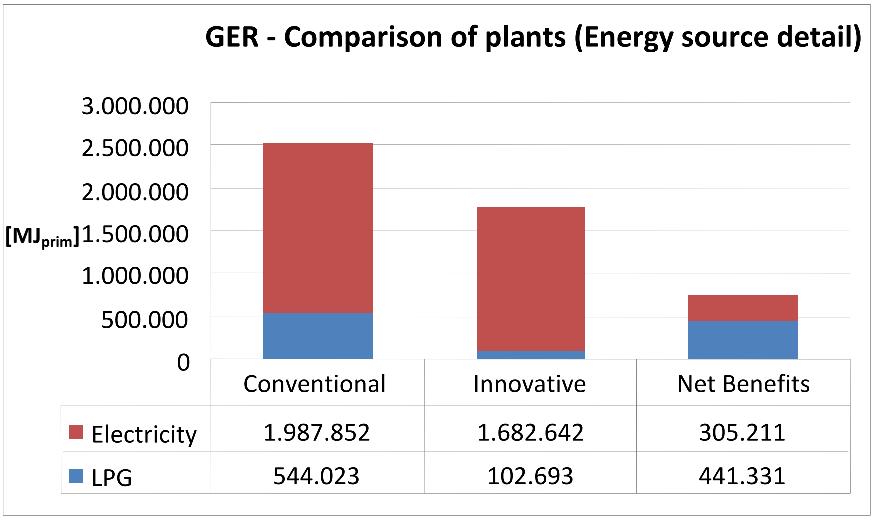


Figure 47: **Comparison of impacts due to energy sources use (GER)**

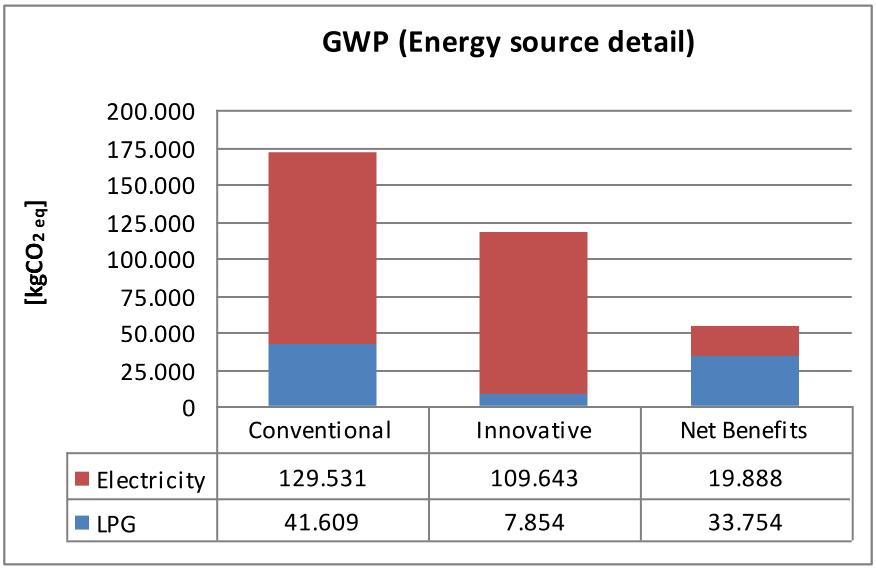


Figure 48: **Comparison of GWP impacts due to energy sources use**

The analysis (Figure 49 and Figure 50) shows that, concerning for example the GER and the GPW indexes, the chiller and AHU are the most impacting components, and together they are responsible of about 80% of the overall greenhouse gas emissions and PE consumption. Similar results have been observed for the other impact categories.

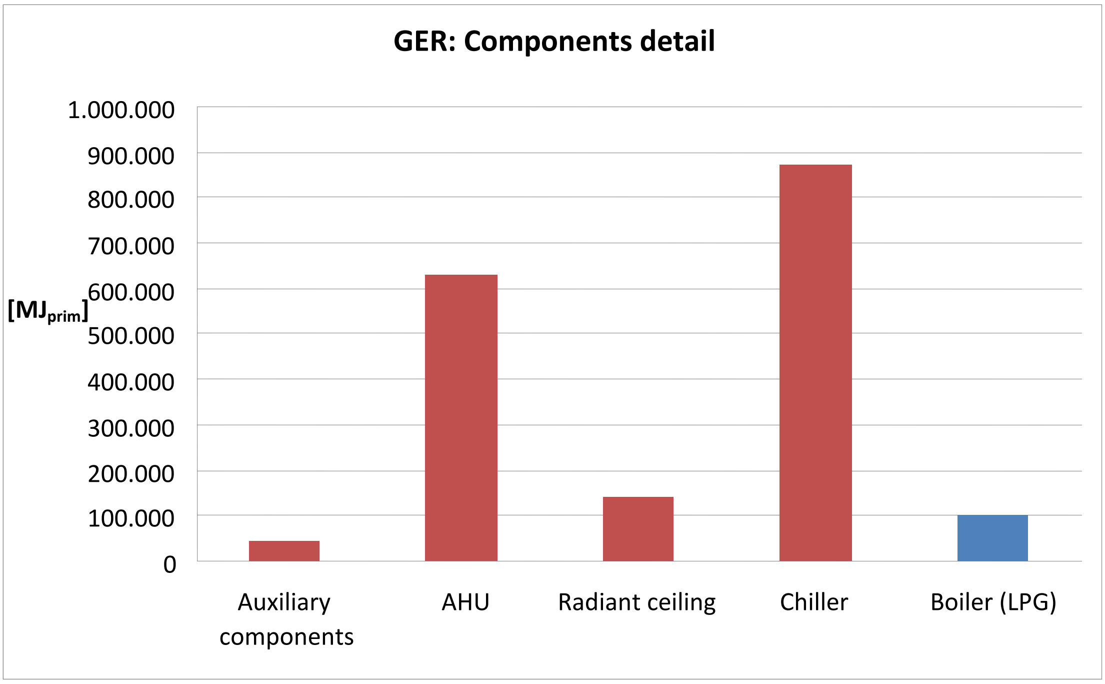


Figure 49: **Comparison of impacts related to system components (GER)**

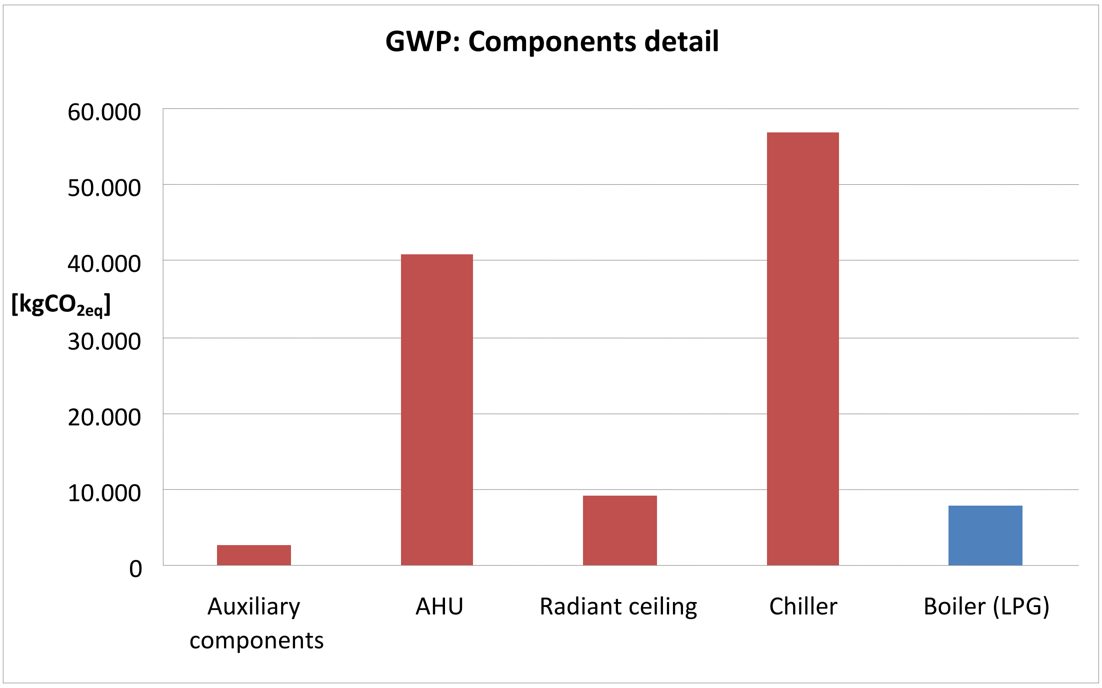


Figure 50: **Comparison of impacts related to system components (GWP)**

3.2.2 Scenario 1: Electricity mix.

The previous analysis confirmed the key role of the electricity consumption in the DEC system eco-profile. A more detailed analysis about impacts related to electricity is therefore necessary. Eco-profile of different electricity production mix have been implemented, as described in paragraph 3.2. The new results about of the eco-profiles of the innovative system are shown in Table 29.

Table 29: Changes of the eco-profile of the innovative systems due to different electricity mix

		National En. Mix	Regional En. Mix		International En. Mix	
		(Scenario 0)	Values	Variation respect to Scenario 0	Values	Variation respect to Scenario 0
GWP	[kg $CO_{2\text{-}Eq.}$]	117.497	112.523	-4,2%	111.493	-5,1%
Ozone Depletion Potential (ODP)	[kg CFC_{11}]	0,009	0,011	33,7%	0,004	-48,6%
Photochemical Ozone Creation Potential (POCP)	[kg C_2H_4]	66	57	-13,9%	56	-15,0%
Acidification Potential (AP)	[kg SO_2]	585	181	-69,1%	530	-9,4%
Nutrification Potential (NP)	[kg PO_4]	42	28	-34,7%	35	-16,8%
GER	[MJ_{Prim}]	1.785.334	1.907.952	6,9%	2.121.334	18,8%

The estimated variations are often significant or very significant. The smallest differences are related to the GWP and the GER indexes. It has been identified that the GWP varies from $111 \cdot 10^3$ kg $CO_{2\text{-}Eq.}$ to $117 \cdot 10^3$ kg $CO_{2\text{-}Eq}$, while the GER (Figure 51) varies from 1.78 10^6 MJ_{Prim} to 2.1 10^6 MJ_{Prim}.

Very significant changes are instead related to the AP and the ODP indexes. This last can be related to the very small values previously detected. Therefore, even small changes into the calculated values can cause large variations. The ODP values are, however always almost negligible.

The adoption of regional or international energy mixes causes contrasting effects, increasing the values of GER, but decreasing the other impacts indicators.

The current scenario confirms the large variability due to electricity data. Anyway, national energy mix still represents the most reliable input data, being the international average electricity mix small fitting with the current case study, and being the eco-profile of the regional electricity mix an assessment extrapolated from reference data.

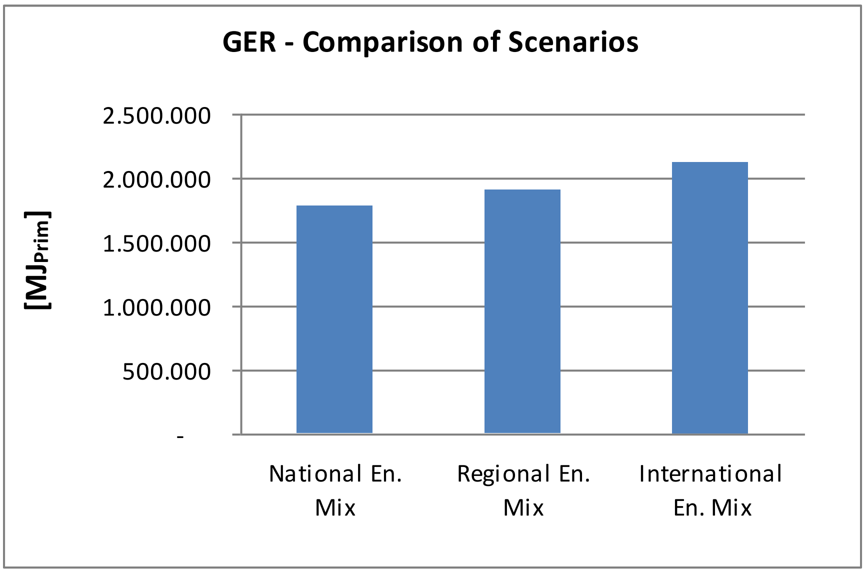


Figure 51: **Comparison of GER values due to different electricity eco-profiles**

3.2.3 Scenario 2: LPG eco-profiles

A further analysis about impacts related to LPG combustion has been carried out. Impacts estimated due to the assessed LPG eco-profile have been compared to the impacts assessed by Franklin Ltd for an average plant in the USA. Scenario results are shown in Table 30 and Figure 52.

Results showed that the incidence of LPG eco-profile changes is minor into GER and GWP indexes, especially concerning the innovative plant. Larger variations are instead detected into AP, POPC and NP indexes.

Table 30: Incidence of LPG eco-profile into the global systems impacts

		Conventional		Innovative	
		Scenario 0	LPG ecoprofile from Franklin	Scenario 0	LPG ecoprofile from Franklin
GWP	[kg $CO_{2\text{-Eq.}}$]	171.139	163.755	117.497	116.103
Ozone Depletion Potential (ODP)	[kg CFC_{11}]	0,0102	0,0102	0,0086	0,0086
Photochemical Ozone Creation Potential (POCP)	[kg C_2H_4]	213	74	66	40
Acidification Potential (AP)	[kg SO_2]	931	694	585	541
Nutrification Potential (NP)	[kg PO_4]	95	45	42	33
GER	[MJ_{Prim}]	2.531.876	2.491.928	1.785.334	1.777.794

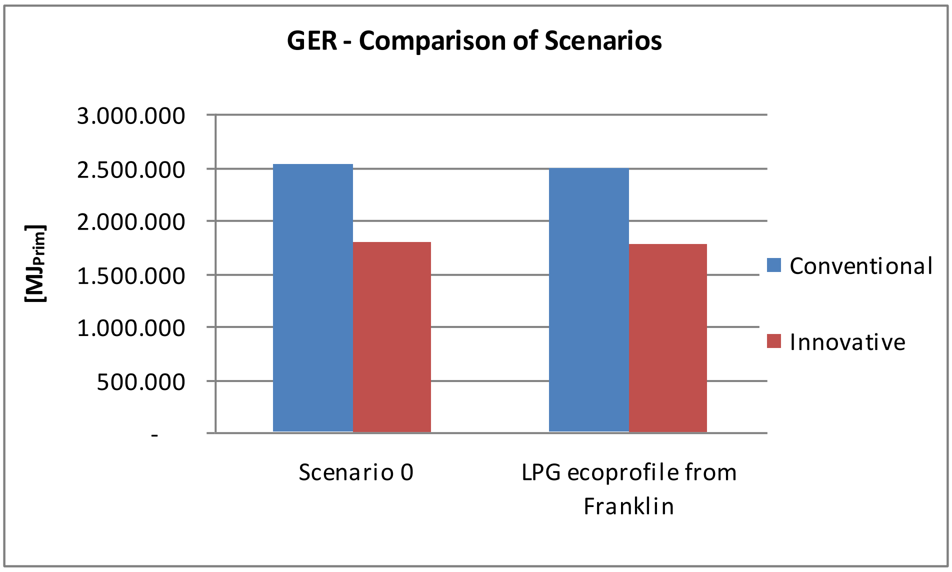


Figure 52: Changes of GER due to different LPG eco-profiles

3.2.4 Scenario 3: Efficiency

Variations of the energy consumptions, mainly of electricity, would significantly influence the final eco-profile of the studied plant. On the other side, the short monitoring period makes difficult to extrapolate results for the entire life-cycle. In particular, the system could suffer a loss of efficiency during the operating time due to several causes (inadequate maintenance, dirty on the system components, wear and deterioration of parts). Deterioration can influence especially the performance of outdoor components of the plant (as solar collectors), exposed to variable weather conditions.

The eco-profile of the innovative system has been therefore calculated supposing a constant yearly loss of efficiency of 1%. The new estimated yearly consumptions are shown in Table 31.

Changes into the eco-profile of the innovative system compared to the initial base-case scenario are shown in

Table 32. It is possible to observe that, following the new assumptions, the global impacts have a general increment of about 10%. Values of GER compared to conventional plant and the related net benefits are shown in Figure 53. In particular, it is interesting to note that, even under the assumption of significant energy losses, the environmental benefits of DEC are still outstanding.

These results, of course, strictly depend on the initial assumptions and the survey data. More precise and reliable results could be obtained only after a longer monitoring over the years.

Table 31: **Yearly consumption over the years of the innovative DEC plant**

year	Electricity [kWh]	LPG [kWh]	year	Electricity [kWh]	LPG [kWh]
1	8.777	1.315	11	9.646	1.445
2	8.864	1.328	12	9.733	1.458
3	8.951	1.341	13	9.820	1.471
4	9.038	1.354	14	9.907	1.484
5	9.125	1.367	15	9.994	1.497
6	9.212	1.380	16	10.081	1.510
7	9.299	1.393	17	10.168	1.523
8	9.386	1.406	18	10.255	1.536
9	9.473	1.419	19	10.342	1.549
10	9.560	1.432	20	10.429	1.562
			Tot.	**192.060**	**28.774**

Table 32: **Eco-profile changes due to assumptions about efficiency loss**

		Scenario 0	Efficiency scenario
GWP	[kg $CO_{2\text{-}Eq.}$]	117.497	129.834
Ozone Depletion Potential (ODP)	[kg CFC_{11}]	0,009	0,009
Photochemical Ozone Creation Potential (POCP)	[kg C_2H_4]	66	73
Acidification Potential (AP)	[kg SO_2]	585	647
Nutrification Potential (NP)	[kg PO_4]	42	47
GER	[MJ_{Prim}]	1.785.334	1.972.793

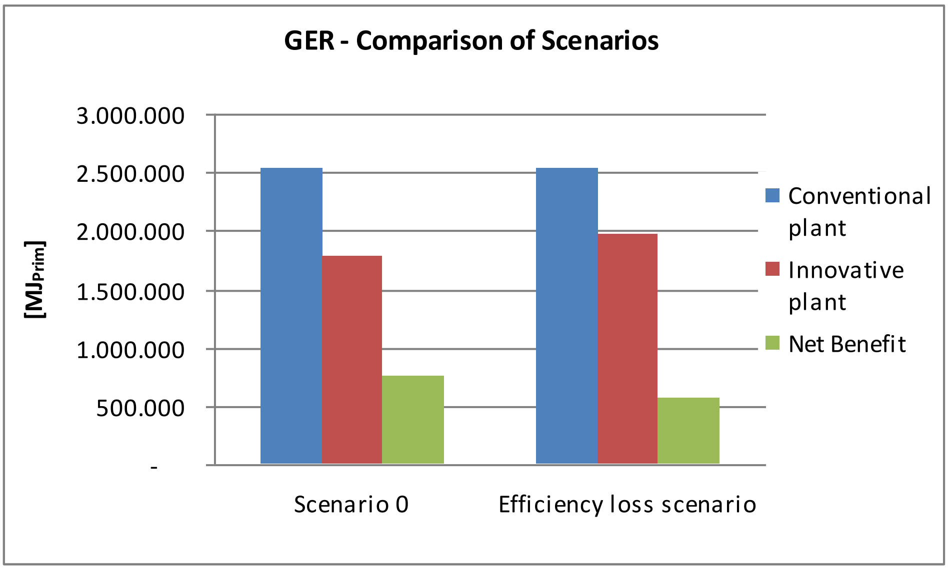


Figure 53: **Comparison of GER index from different scenarios**

3.2.5 Scenario 4: Lifetime

The length of the operating time is another key parameter in the life-cycle balance of the plants. It has been decided to make different hypotheses about the useful life, varying it from 16 to 24 years. This scenario have been coupled with the previous one, supposing a constant +1% yearly increase of the energy consumptions until the 20th year, and, successively, a +2.5% increase in the last 4 years.

The impacts have been still compared to a conventional system supposing its efficiency to be not decreased over the time. This choice is based on the following assumptions:

- The assessment of the consumptions of the conventional system is an ―average" data, based on simulating tools that already take into account the average performances of the plant over the years. The estimation of the life-cycle consumptions of the DEC system is instead based on the monitored data that, currently, refer only to the first operating year;

- Efficiency losses are ascribed only to the innovative system, in order to evaluate its performances even in a -pessimistic" scenario.

The yearly consumptions of the innovative plant are shown in Table 33. Environmental impacts are synthesized in Table 34.

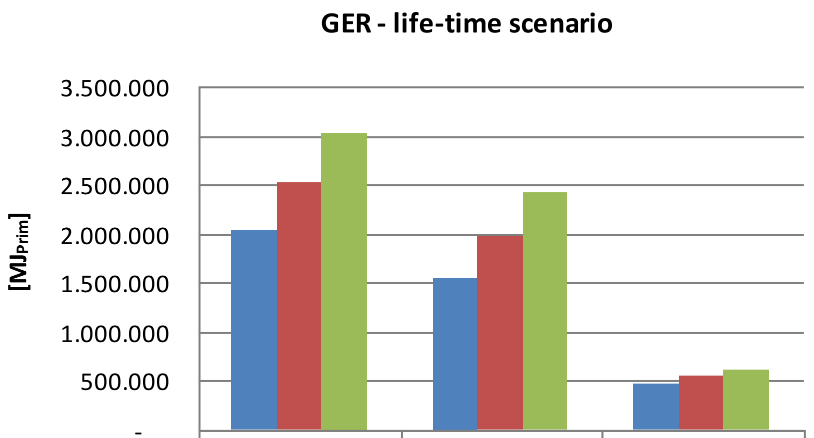
Table 33: **Yearly consumption over the time (scenarios at 16, 20 and 24 years)**

year	Electricity [kWh]	LPG [kWh]	year	Electricity [kWh]	LPG [kWh]	year	Electricity [kWh]	LPG [kWh]
1	8.777	1.315	9	9.473	1.419	17	10.168	1.523
2	8.864	1.328	10	9.560	1.432	18	10.255	1.536
3	8.951	1.341	11	9.646	1.445	19	10.342	1.549
4	9.038	1.354	12	9.733	1.458	20	10.429	1.562
5	9.125	1.367	13	9.820	1.471	21	10.646	1.595
6	9.212	1.380	14	9.907	1.484	22	10.863	1.628
7	9.299	1.393	15	9.994	1.497	23	11.080	1.660
8	9.386	1.406	16	10.081	1.510	24	11.298	1.693
Tot. 16 years	**150.867**	**22.603**	**Tot. 20 years**	**192.060**	**28.774**	**Tot. 24 years**	**235.947**	**35.349**

Table 34: **Eco-profile changes due to lifetime (scenarios at 16, 20 and 24 years)**

	Conventional (16 year)	Conventional (20 year)	Conventional (24 year)	Innovative (16 year)	Innovative (20 year)	Innovative (24 year)
GWP	136.911	171.139	205.367	101.988	129.834	159.502
Ozone Depletion Potential (ODP)	0,008	0,010	0,012	0,007	0,009	0,012
Photochemical Ozone Creation Potential (POCP)	170	213	255	58	73	90
Acidification Potential (AP)	745	931	1.117	508	647	794
Nutrification Potential (NP)	76	95	114	37	47	57
GER	2.025.494	2.531.876	3.038.248	1.549.671	1.972.793	2.423.590

It is possible to observe (Figure 54) that the Net Benefits grow always with the length of the useful life, even under the pessimistic assumption of large efficiency losses during the time. It confirms that the durability of the innovative DEC is a key factor, and that eco-design initiatives should focus on solutions to extent the operating life of such plant.



	Conventional	Innovative	Net Benefits
16 years	2.025.494	1.549.671	475.823
20 years	2.531.876	1.972.793	559.082
24 years	3.038.248	2.423.590	614.658

Figure 54: **Eco-profile changes due to lifetime**

3.2.6: Scenario 5: Additional components

In order to increase the precision and reliability of the results, it has been decided to compute in this stage of the analysis data about innovative elements of the DEC. In particular, the attention has been focused on the solar thermal collectors that represents one of the biggest differences between the considered conventional and innovative systems.

Table 35: **Inclusion of solar collectors into the LCA of the innovative system**

		Innovative system (Scenario 0)	Innovative system (Scenario 5)	Variation
GWP	[kg $CO_{2\text{-Eq.}}$]	117.497	125.113	6,5%
Ozone Depletion Potential (ODP)	[kg CFC_{11}]	0,009	0,009	-
Photochemical Ozone Creation Potential (POCP)	[kg C_2H_4]	66	71	6,4%
Acidification Potential (AP)	[kg SO_2]	585	638	9,0%
Nutrification Potential (NP)	[kg PO_4]	42	50	17,5%
GER	[MJ_{Prim}]	1.785.334	1.906.813	6,8%

The studied DEC involve 22.5 m^2 of collectors surface. Impacts related to their life-cycle have been computed in the previous calculation of ―Scenario 0". The new results are shown in Table 35. The inclusion of solar collector into the LCA of the DEC causes a general growth of the environmental impacts from +6.4% to +9%. A larger incidence is observed only for the NP indicator. Net benefits generally decrease about -15% (Table 36 and Figure 55).

Table 36: Changes in net benefits due to inclusion of solar collectors

		Net Benefits		
		Innovative system (Scenario 0)	**Innovative system (Scenario 5)**	**Variation**
GWP	[kg $CO_{2\text{-}Eq.}$]	53.642	46.026	-14%
Ozone Depletion Potential (ODP)	[kg CFC_{11}]	-	-	-
Photochemical Ozone Creation Potential (POCP)	[kg C_2H_4]	146	142	-3%
Acidification Potential (AP)	[kg SO_2]	346	293	-15%
Nutrification Potential (NP)	[kg PO_4]	52	45	-14%
GER	[MJ_{Prim}]	746.541	625.062	-16%

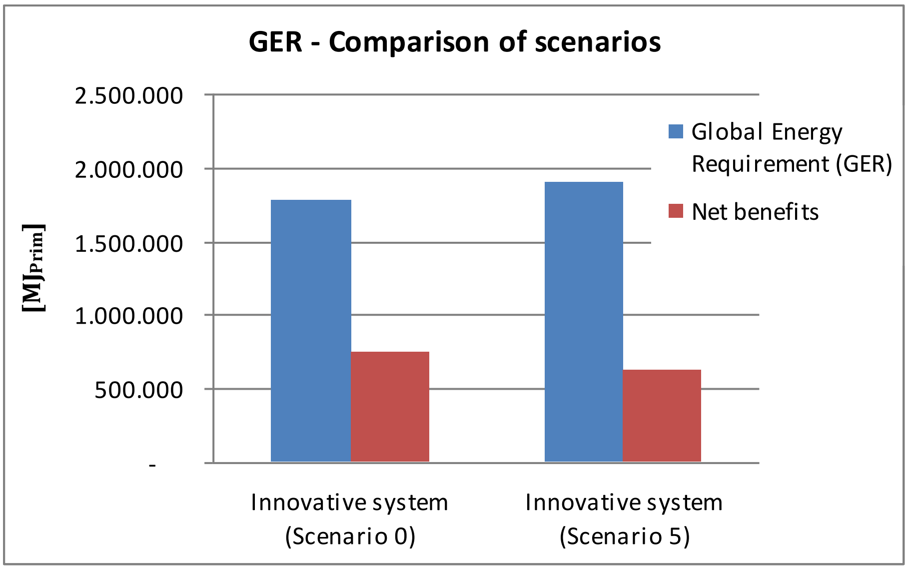


Figure 55: GER - comparison of scenarios

Concerning this scenario, it is also possible to partially assess the payback indexes (Table 37). From the calculation resulted that the impacts due to the life-cycle of collectors are recovered after about 3 years of operating time of the innovative system.

Table 37: **Payback indexes**

	[year]
E_{PT}	3,3
GWP Payback Time	2,8

3.2.7 Net benefits

The Net benefits concerning the previous scenarios have been compared in order to outline the general performances of the DEC system (Table 38). It is possible to observe that values are always positive, confirming the positive judgment on the convenience of DEC system compared to conventional ones.

Smaller variations of benefits have been observed for the GWP and GER indexes. In particular, GER values (Figure 56) varies from 410 GJ_{Prim} to 746 GJ_{Prim}.

Larger variations have been instead observed for other indicators and, in particular, the AP.

Table 38: **Net Benefits - Comparison of scenarios**

Scenarios		**0**	**1.a**	**1.b**	**2**	**3**	**4.a**	**4.b**	**5**
GWP	[kg $CO_{2\text{-}Eq.}$]	53.642	58.617	59.647	47.651	41.305	34.923	45.865	46.026
Ozone Depletion Potential (ODP)	[kg CFC_{11}]	-	-	-	-	-	-	-	-
Photochemical Ozone Creation Potential (POCP)	[kg C_2H_4]	146	155	156	34	139	112	165	142
Acidification Potential (AP)	[kg SO_2]	346	750	401	154	284	237	322	293
Nutrification Potential (NP)	[kg PO_4]	52	67	60	12	48	39	56	45
GER	[MJ_{Prim}]	746.541	623.924	410.541	714.134	559.082	475.823	614.658	625.062

(red) Minimum value

(green) Maximun value

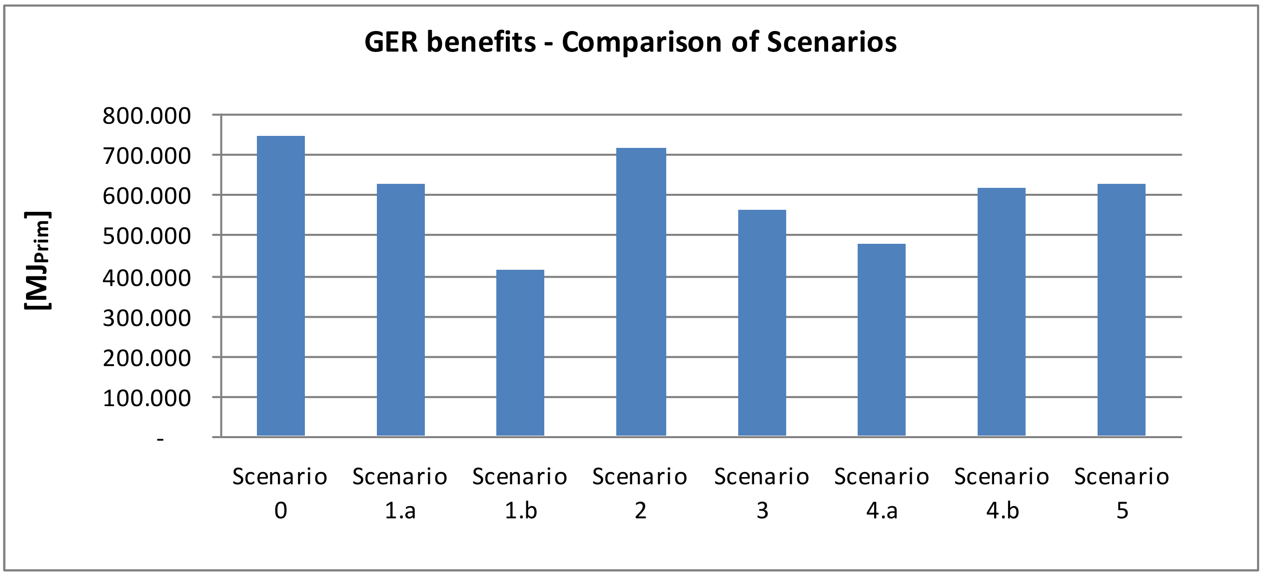


Figure 56: **GER Benefits- Comparison of scenarios**

3.2.8 Conclusions and expected progress

The analysis on the operating phase of the innovative system showed the great energy and environmental convenience of this technology. Impacts due to the DEC plant are about one third lower compared to those related to a conventional system. From the analysis of different alternative scenarios, it resulted that:

- GWP and GER indexes are generally affected by small variations due to hypotheses changes;
- Other indicators (as AP, NP and POPC) have, instead large variations, especially due to changes into electricity or LPG combustion eco-profiles;
- ODP index has generally very low or negligible values;
- The longer is the operating time of the DEC, the larger are the Net benefits, even accounting a continuously efficiency loss, up to a +30% growth of the energy consumptions after 24 years;
- The analysis of innovative components of the plants have not been included into the environmental balances, due to data availability and to the project scopes, aiming at assessing the net benefits of DEC system compared to a conventional ―reference" plant. For this reason, it is important to focus the attention only on the exclusive innovative elements, meaning the element contained in the DEC system and missing in the reference system. A first step on this direction has been made, including in the computation the life-cycle impacts of solar thermal collectors. Their

inclusion causes a reduction of net benefits of about 15%, with a payback time of about 3 years.

4. Conclusions

LCA of solar cooling plants has been performed according to the LCA standards of the ISO 14040 series. The research aimed to evaluate and compare the energy and environmental performances of solar cooling systems with traditional plants.

Four different cases have been investigated in order to assess the performances of two different technologies of thermally driven chillers (Absorption and Adsorption) applied in two localities: Palermo (South Italy) and Zurich (Switzerland).

In addition two possible alternatives in the configurations according to the modality of back-up of the solar cooling systems in summer operation (cold back-up and hot-back-up) have been included.

The performances of these 4 systems has been compared to a conventional system with a vapour compression chiller and a gas boiler.

A detailed LCA study was performed for the absorption (ABS) and adsorption (ADS) chillers, that represent the main components of the two examined plants.

Comparing the eco-profiles of the ABS and the ADS chillers, the highest values of GER and GWP are related to the first one. In detail GER and GWP for ABS chiller are, respectively, 28 GJ and 1524 kg CO_{2eq}; for the second one are, respectively, 24 GJ and 1401 kg $_{CO2eq}$.

The differences are principally due to the system boundaries: for ABS the energy use for the fabrication of the chiller and the transport of the materials to the plant have been included, for the

ADS where not because of lack of information. Also differences could be due to different quantities of raw materials used in the production process.

For both chillers the main impacts on GER and GWP are due to the production phase.

The comparison of the eco-profiles of ABS and ADS plants showed that for both configurations (hot and cold backup) the highest impacts are related to the absorption plant (Figure 54). The differences are mainly observable in the use phase, that is responsible of the main impacts during the life-cycle of both plants.

The impacts caused by the plants installed in Zurich are higher than those in Palermo, mainly due to the higher energy consumption in the first one during the use phase.

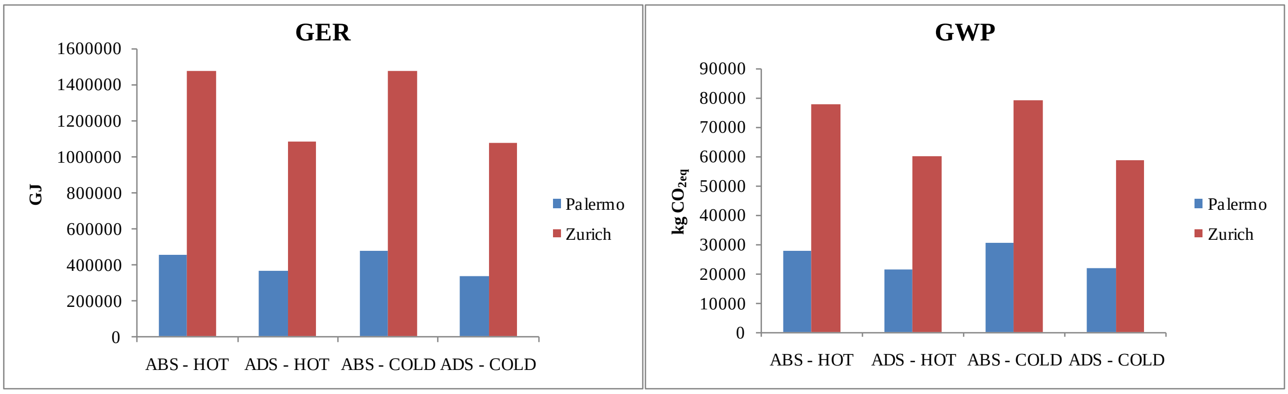


Figure 54: Comparison of GER (MJ) and GWP for ABS and ADS plants

The innovative systems have been compared with the conventional one using three different FUs: a solar cooling plant with absorption or adsorption chiller; 1 kW of power of the chiller; 1 kWh of energy produced by plant.

Analyzing the results it can be observed that the absorption plant has lower impacts than the conventional one for all different FUs. The impacts of the adsorption plant result lower than the conventional one; the only exception is represented by the choice of 1 kW of power of the chiller as FU.

In order to assess the effective energy and environmental advantage related to the use of innovative systems, the E_{PT}, the E_{RR} and the EM_{PT} time have been calculated.

A summary of the results for both plants is shown in Figure 55.

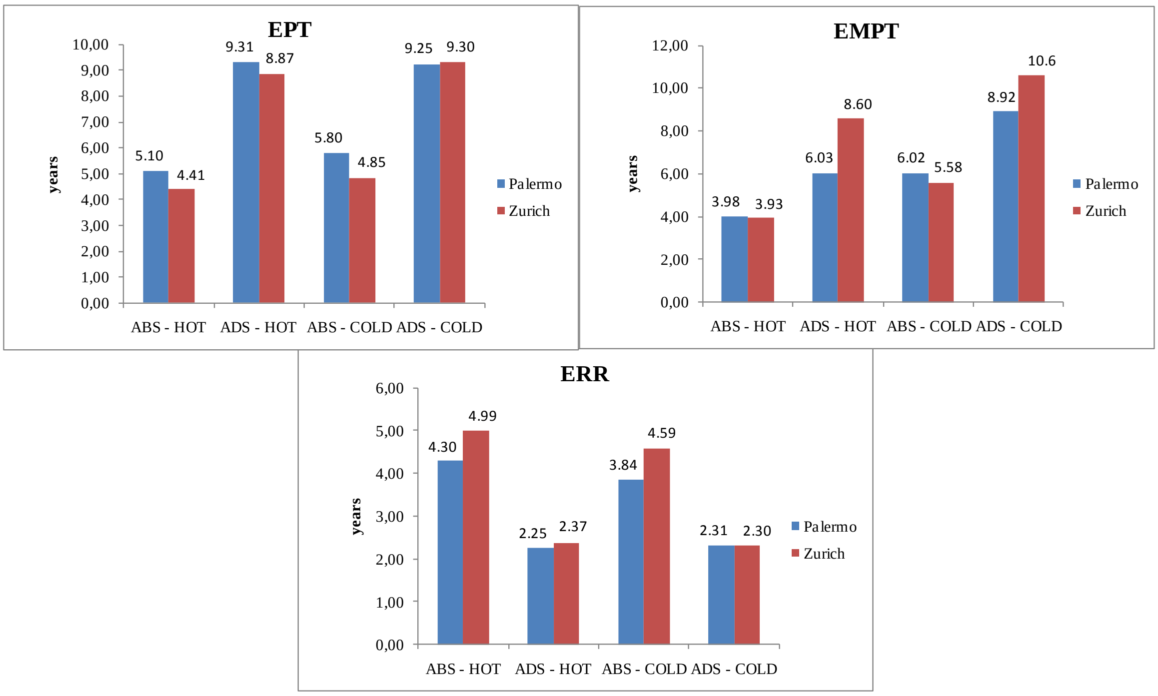


Figure 55: Comparison of E_{PT}, EM_{PT} and E_{RR} for ABS and ADS plants

In general it can be said that results are almost fair. E_{PT} ranges in all cases from 4.5 to 9.5 years. Emission paybacks ranges from 4 to 10.5 years. The systems which requires less years to give back the energy needed for its construction, operation and disposal are the one using ABS chillers.

In general, for the E_{PT}:

- for a given climate and back-up typology: systems with ABS chillers performs better than one with ADS chillers
- for a given system the colder the climate the lower the energy return
- for a given climate and chiller typology: the «hot back-up» is slightly better than the «cold back-up» (with some exception)

and for the emissions:

- for a given climate and back-up typology: systems with ABS chillers performs better than ones with ADS chillers
- for a given system with ABS chiller, the colder the climate the higher the emission payback
- for a given system with ADS chiller, the colder the climate the higher the emission payback
- for a given climate and chiller typology: the «hot back-up» is better than the «cold back-up»

It is worth noting that the results obtained show good performances of almost all the configurations form the environmental point of view. They can be used to show the net environmental benefits related to SHC systems despite the larger amount of energy and emissions related to their construction.

Anyway it must be stressed that although they are referred to the two case studies above described, the study has demonstrated the possibility to apply LCA method to every solar H/C system. New applications can be made for other systems by considering different sizes, climate, loads, energy mix, emissions factors.

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6. Annex 1 . DATA BASE OF LCIs OF EQUIPMENTS FOR SHC PLANTS

6.1 Solar thermal collectors (evacuated)

1. **Product:** Evacuated tube collectors (F.U.: 1 m^2 of evacuated tube collectors)
2. **Authors and reference:** data published by Niels Jungbluth in Ecoinvent ver.2.0
3. **Description of the product:** Evacuated tube collectors for hot water production.
4. **Product characteristics**

Nominal power/surface/other: surface 1 m^2
Measured/estimated yearly energy production and/or consumption:-
Information about the use phase: -
Information about the end-of-life phase: wastes as plastics, packaging, hazardous wastes and others are incinerated. Glass and rock wool wastes are recovered.

5. **Metadata**

Age of the study: Materials data have been investigated for a collector produced in 2002. Data for energy uses during production have been investigated for 2001.
System boundaries (production phase, use phase, end-of-life phase): data are referred to the production of an evacuated tube collector in Northern-Ireland, including materials and energy use of production, and disposal of the product at the end of life.
Useful life-time: 25 years.
Cut-off rules: impacts related to transport of the solar thermal collectors from the productive site to the utilization site and to the use phase are not included.
Allocation rules: -
Further details: -
Data Quality Assessment: input data of materials used to produce the solar thermal collector have been collected using questionnaires. *Energy uses during production investigated in another factory for another type of tube collector.* *Data have been validated.*

6. **Life Cycle Inventory**

Main employed materials and components:	Main Air Emissions:
Electricity (medium voltage): 17 kWh	CO2: 101.3 kg
Natural gas: 16.5 MJ	SO2: 505 g
Water: 53.6 kg	NOx: 329 g
	Particulates: 249 g

	Glass tube: 14.2 kg Chromium steel: 4 kg Packaging: 3.33 kg Sheet rolling, copper: 2.8 kg Copper: 2.8 kg Rock wool: 2.03 kg Synthetic rubber: 667 g Propylene glycol, liquid: 645 g Hydrochloric acid: 113 g Brazing solder, cadmium free: 100 g Silicon: 53.3 g Chemicals organic: 11.3 g Anti-reflex-coating, etching, solar glass: 1 m^2 Selective coating, copper sheet: 1 m^2	CH4: 196 g CO: 182 g NMVOC: 41.7 g CS2: 12.2 g SO42-: 11.6 g HCl: 9.06 g Cr: 3.49 g N_2O: 2.75 g Main Water Emissions: Si: 3.44 kg Cl^-: 2.11 kg Ca^{2+}: 1.47 kg SO_4^{2-}: 724 g Na^+: 612 g COD: 586 g BOD_5: 309 g TOC: 184 g DOC: 178 g Al: 143 g Solid substances: 143.5 g Fe^2+: 88.8 g Mg: 24 g Oils: 21.7 g NO^{3-}: 14 g Main Wastes: Oils: 21.4 g

7. Product Eco-profile

Global Impact Indexes	Total
Global Energy Requirement (GER)	1.71 [GJ]
Global Warming Potential (GWP)	101.2 [kg CO_{2eq}]

6.2 Solar thermal collectors (plate)

1. **Product:** Flat plate collectors (F.U.: 1 m^2 of flat plate collectors)
2. **Authors and reference:** data published by Niels Jungbluth in Ecoinvent ver.2.0
3. **Description of the product:** Flat plate collectors for hot water production.
4. **Product characteristics**

Nominal power/surface/other: surface 1 m^2
Measured/estimated yearly energy production and/or consumption:-
Information about the use phase: -
Information about the end-of-life phase: wastes as plastics and packaging are incinerated. Glass and mineral wool wastes are recovered.

5. **Metadata**

Age of the study: Materials data have been investigated for a collector produced in 2002. Data for energy uses during production have been investigated for 2001.
System boundaries (production phase, use phase, end-of-life phase): data are referred to the production of a flat plate collector in Switzerland, including materials, water and energy use of production, and disposal of the product at the end of life. The flat plate collector has selective black chrome coating on copper made in United States. Main components of the collector are imported from United States. The glass is coated in Denmark.
Useful life-time: 25 years.
Cut-off rules: impacts related to transport of the solar thermal collectors from the productive site to the utilization site and to the use phase are not included.
Allocation rules: -
Further details: -
Data Quality Assessment: input data of materials used to produce the solar thermal collector have been collected using questionnaires. Energy uses during production investigated in another factory. Data have been validated.

6. **Life Cycle Inventory**

Main employed materials and components:	Main Air Emissions:
Electricity (medium voltage): 1.16 kWh	CO_2: 102.8 kg
Water: 10.78 kg	SO_2: 682 g
Chromium steel: 4.14 kg	NO_x: 316 g
Corrugated board: 3.68 kg	Particulates: 327 g
	CH_4: 191.6 g

	Sheet rolling, copper: 2.82 kg Copper: 2.82 kg Rock wool: 2.43 kg Synthetic rubber: 732 g Propylene glycol, liquid: 1.01 kg Solar glass, low-iron: 9.12 kg Aluminium: 3.93 kg Brazing solder, cadmium free: 3.68 g Silicone product: 58.8 g Soft solder: 58.8 g Anti-reflex-coating, etching, solar glass: 1 m^2 Selective coating, copper sheet: 1 m^2	CO: 511 g NMVOC: 46.9 g HCl: 7.26 g Cr: 3.61 g N_2O: 3.05 g Main Water Emissions: Si: 4.02 kg Cl^-: 2.94 kg Ca^{2+}: 1.07 kg SO_4^{2-}: 693 g Na^+: 1.18 kg COD: 846 g BOD_5: 457 g TOC: 264 g DOC: 255 g Al: 232 g Solid substances: 136.2 g Fe^2+: 92.9 g Mg: 24.8 g Oils: 34.4 g NO^{3-}: 15.3 g Main Wastes: Oils: 35.6 g

7. Product Eco-profile

Global Impact Indexes	Total
Global Energy Requirement (GER)	1.87 [GJ]
Global Warming Potential (GWP)	110 [kg CO_{2eq}]

6.3 Cooling tower

1. **Product:** Cooling tower (F.U. 1unit)
2. **Authors and reference:** Sonia Longo, Maurizio Cellura, Marco Beccali
3. **Description of the product:** the cooling tower components are:

- axial fan, made of fibreglass-reinforced polyester. It has a low noise level and it is statically and dynamically balanced;
- PVC/Polypropylene exchangeable packs (fill material), very resistant to all types of acid and oil-polluted water as well as to high temperatures The PVC/Polypropylene droplet separator, specially designed to prevent the water loss due to the action of the fan;
- The water distribution system, made up of one or several polypropylene or galvanized steel pipes, with ABS water spray nozzles and waterways big enough to avoid the obstruction by accumulated sediments;
- Compact casing made of galvanized steel and fibreglass-reinforced polyester, with supports inlaid in the polyester. This material is highly resistant to all aggressive conditions, as well as to extreme temperatures.

4. **Product characteristics**

Nominal power/surface/other: - *Nominal power: 34-48 kW;* - *Weight empty: 53 kg;* - *Weight in service: 144 kg;* - *Motor power: 0.33 kW.*
Measured/estimated yearly energy production and/or consumption:-
Information about the use phase:-
Information about the end-of-life phase: all wastes are recycled.

5. **Metadata**

Age of the study: 2010.
System boundaries (production phase, use phase, end-of-life phase): system boundaries include the life-cycle of materials used to produce the tower and the disposal of the product at the end of life.
Useful life-time: 25 years.
Cut-off rules: impacts related to transport of the tower from the productive site to the utilization site and to the use phase are not included. *Environmental impacts and benefices related to the recycling of wastes at the end-of-life of the tower are not included.*
Allocation rules:-

	Further details:-
	Data Quality Assessment: estimation based to direct measurements.

6. Life Cycle Inventory

Main employed materials and components:	Main Air Emissions:
Galvanized steel: 19.7 kg Fibreglass-reinforced polyester: 19.4 kg PVC: 11.5 kg Polypropylene: 2.4 kg	CO_2: 120.2 kg CO: 593.3 g CH_4: 398.2 g SO_2: 331 g NO_x: 298 g Particulates: 258 g NMVOC: 125 g N_2O: 77 g SO_4^{2-}: 15.6 g Al: 11.8 g HCl: 6.62 g CS_2: 4.56 g
	Main Water Emissions:
	Cl^-: 6.08 kg Na^+: 1.68 kg Si: 1.58 kg COD: 1.08 kg BOD_5: 514 g SO_4^{2-}: 479 g Ca^{2+}: 260 g TOC: 191 g DOC: 186 g Solid substances: 77.4 g Al: 66.5 g Fe^2+: 54.8 g Mg: 25 g Acetic acid: 24.2 g K^+: 21.1 g Oils: 16.4 g PO_4^{3-}: 14.1 g
	Main Wastes:
	-

7. Product Eco-profile

Global Impact Indexes	Total
Global Energy Requirement (GER)	2.97 [GJ]
Global Warming Potential (GWP)	152.4 [kg CO_{2eq}]

6.4 Dry cooling tower (Adsorption)

8. **Product:** dry cooling tower (F.U. 1unit)

9. **Authors and reference:** Lesbat (HEIG-VD, Switzerland)

10. **Description of the product:** The dry cooling tower (recooler) is the heat rejection part of the installation.The major components are steel, aluminum, cooper and plastic as PEHD.

11. **Product characteristics**

Nominal power/surface/other: - *Nominal power: 24 kW;*
Measured/estimated yearly energy production and/or consumption:-
Information about the use phase:-
Information about the end-of-life phase: all metals are recycle and plastics are burned

12. **Metadata**

Age of the study: 2010
System boundaries): production phase; All the components of the chiller are included in the production phase. As we do not have the energy use for fabrication phase, it is not included. No transport to the production site is taken in account as we do not have those information. Use phase; during the use phase, the energy is included in the LCIA of the whole installation. The maintenance is negligible. The transport is not included. End-of-life phase; All components which can be recycled have no impact (ecoinvent® rules) the rest is or for incineration, or for disposal in CH. The recycling has a cut-off approach.
Useful life-time: 25 years.
Cut-off rules: impacts related to transport of the tower from the productive site to the utilization site and to the use phase are not included. *The recycling has a cut-off approach.*
Allocation rules:-
Further details:-
Data Quality Assessment: The amount of material results of the company data.

13. **Life Cycle Inventory**

Main employed materials and components:	Main Air Emissions:
Steel : 86 kg Aluminium : 58 kg Cooper : 35 kg	Heat waste: 15136 MJ CO_2: 967.1 kg SO_2: 17.6 kg CO: 8.8 kg

	Plastic (PEHD) : 35 kg	NO_x: 6.5 kg CH_4: 2.1 kg Particulates: 4.3 kg Water: 1.2 kg Al: 800 g NMVOC: 702 g CS_2: 408 g NH_3: 327 g Cu: 89 g Pb: 80 g Ni: 63 g HF: 42 g
		Main Water Emissions: Heat waste: 803.3 MJ Si: 23.7 kg SO_4^{2-}: 12.1 kg Na^+: 7.1 kg Cl^-: 6.1 kg Ca^{2+}: 4.7 kg COD: 3.7 kg Al: 2.6 kg BOD_5: 1.9 kg TOC: 1.3 kg DOC: 1.3 kg Ti^+: 997 g Fe^2+: 640 g Solid substances: 406 g Solved solids: 344 g Oils: 333 g F^-: 250 g PO_4^{3-}: 14.1 g
		Main Wastes: Heat waste: 22.65 MJ Oils: 345 g

14. Product Eco-profile

Global Impact Indexes	Total

	Global Energy Requirement (GER)	14.345[GJ]	
	Global Warming Potential (GWP)	770 [kg CO_{2eq}]	

6.5 Heat pump brine-water

1. **Product:** Heat pump brine-water (F.U. 1 unit)
2. **Authors and reference:** data published by Thomas Heck in Ecoinvent ver.2.0
3. **Description of the product:** heat pump brine-water 10 kW of output. Refrigerant R134a.
4. **Characteristics of the product**

Nominal power/surface/other: power 10 kW
Measured/estimated yearly energy production and/or consumption:-
Information about the use phase:-
Information about the end-of-life phase: plastic wastes are incinerated. The end-of-life of other wastes is not included.

5. **Metadata**

Age of the study: 2004.
System boundaries (production phase, use phase, end-of-life phase): The module includes the most important materials used for production. It includes also the transport of these materials, energy and water needed for production. It includes emissions of refrigerant (R134a) during production and scrapping. It does not include emissions during operation. It does not include the borehole heat exchanger. A buffer heat storage is not included. Data are referred to the end of life of some parts of the product.
Useful life-time: 25 years.
Cut-off rules: impacts related to transport of the storage from the productive site to the utilization site and to the use phase are not included.
Allocation rules:
Further details:
Data Quality Assessment: input data have been collected using literature and manufacturer information.

6. **Life Cycle Inventory**

Main employed materials and components:	Main Air Emissions:
Electricity, medium voltage: 140 kWh	CO_2: 376.9 kg
Natural gas: 1400 MJ	CO: 2.52 kg
Tube insulation, elastomere: 10 kg	Particulates: 1.35 kg
Refrigerant R134a: 3.09 kg	CH_4: 963.8 g
Copper: 22 kg	NO_x: 1.07 kg
Polyvinylchloride: 1 kg	SO_2: 3.17 kg
	NMVOC: 263 g

	Steel, low-alloyed: 20 kg Reinforcing steel: 75 kg Lubricating oil: 1.7 kg	Al: 188 g NH_3: 78.9 g HCl: 13.9 g Cr: 1,58 g Si: 2.19 g N_2O: 10.6 g
		Main Water Emissions: Si: 5.61 kg Cl^-: 3.93 kg SO_4^{2-}: 2.77 kg COD: 1.01 kg Ca^{2+}: 1.28 kg BOD_5: 479 g TOC: 430 g DOC: 428 g Na^+: 1.51 kg Solid substances: 269 g Fe^2+: 190 g Al: 184 g Mg: 85.9 g PO_4^{3-}: 60.2 g Oils: 75 g K^+: 42.7 g
		Main Wastes: Oils: 74.5

7. Product Eco-profile

Global Impact Indexes	Total
Global Energy Requirement (GER)	8.18 [GJ]
Global Warming Potential (GWP)	1590 [kg CO_{2eq}]

6.6 Heat storage

8. **Product:** Heat storage (F.U. 1 unit)

9. **Authors and reference:** data published by Niels Jungbluth in Ecoinvent ver.2.0

10. **Description of the product:** heat storage with a capacity of 2000 l for use in a solar collector heating system

11. **Characteristics of the product**

Nominal power/surface/other: capacity 2000 l
Measured/estimated yearly energy production and/or consumption:-
Information about the use phase:-
Information about the end-of-life phase: packaging wastes are incinerated. Rock wool wastes are recovered. The end-of-life of other wastes is not included.

12. **Metadata**

Age of the study: 2003.
System boundaries (production phase, use phase, end-of-life phase): data are referred to the production of an heat storage in Switzerland, including materials and energy use of production, and disposal of the product at the end of life.
Useful life-time: 25 years.
Cut-off rules: impacts related to transport of the storage from the productive site to the utilization site and to the use phase are not included.
Allocation rules:
Further details:
Data Quality Assessment: input data of materials used to produce the storage have been collected using questionnaires. *Data have been validated.*

13. **Life Cycle Inventory**

Main employed materials and components:	Main Air Emissions:
Electricity, medium voltage: 45 kWh	CO_2: 796 kg
Electricity, photovoltaic: 45 kWh	CO: 8.11 kg
Natural gas: 198 MJ	Particulates: 3.89 kg
Energy from biomass (wood): 146 MJ	CH_4: 2.14 kg
Rock wool: 25 kg	NO_x: 2.03 kg
Chromium steel: 35 kg	SO_2: 2 kg
Steel: 305 kg	NMVOC: 417 g
Water: 800 kg	Al: 181 g
	NH_3: 140 g
	HCl: 73.8 g

		CS_2: 69 g Cr: 39,6 g Si: 17.8 g N_2O: 16.3 g
		Main Water Emissions: Si: 44.3 kg Cl^-: 5.46 kg SO_4^{2-}: 4.1 kg COD: 2.89 kg Ca^{2+}: 2.78 kg BOD_5: 1.27 kg TOC: 1.1 kg DOC: 1.1 kg Na^+: 1.03 kg Solid substances: 1.2 kg Fe^2+: 794 g Al: 678 g Mg: 240 g PO_4^{3-}: 207 g Oils: 137 g K^+: 118 g
		Main Wastes: Oils: 126

14. Product Eco-profile

Global Impact Indexes	Total
Global Energy Requirement (GER)	15.2 [GJ]
Global Warming Potential (GWP)	780.9 [kg CO_{2eq}]

6.7 Gas boiler

1. **Product:** Gas boiler (F.U. 1 unit)
2. **Authors and reference:** data published by Thomas Heck in Ecoinvent ver.2.0
3. **Description of the product** Gas boiler (10 kW of power)
4. **Characteristics of the product**

Nominal power/surface/other: power 10 kW
Measured/estimated yearly energy production and/or consumption::
Information about the use phase:
Information about the end-of-life phase: wastes as plastics, packaging and hazardous wastes are incinerated. Rock wool wastes are discharged in an inert material landfill. The end-of-life of other wastes is not included.

5. **Metadata**

Age of the study: Materials data have been investigated in 1993. Data for energy use during the production phase have been estimated on the basis of an environmental report for 1998.
System boundaries (production phase, use phase, end-of-life phase): data are referred to the production of a gas boiler in Switzerland and in Germany, including materials and energy use of production, and disposal of the product at the end of life. The transport of these materials and the energy and water needed for production are included.
Useful life-time:25 years
Cut-off rules: impacts related to transport of the gas boiler from the productive site to the utilization site and to the use phase are not included.
Allocation rules:
Further details:
Data Quality Assessment: input data have been extrapolated assuming that the material requirement for a gas boiler is approximately the same as for an oil boiler. Moreover, is has been assumed that these materials are about the same in modern (2000) boilers as well as in average installed boilers.

6. **Life Cycle Inventory**

Main employed materials and components:	Main Air Emissions
Electricity, medium voltage: 81.7 kWh	SO_2: 1.4 kg
Natural gas: 472 MJ	CO_2: 371.5 kg
Light fuel oil: 249 MJ	CO: 3.19 kg
Water: 182 kg	Particulates: 1.53 kg
	CH_4: 0.9 kg

	Alkyd paint, white, 60% in solvent: 1.25 kg Aluminium: 7.5 kg Brass: 0.05 kg Brazing solder, cadmium free: 4 kg Chromium steel: 5 kg Copper: 3.03 kg Polyethylene, HDPE granulate: 0.9 kg Rock wool: 8 kg Corrugated board, mixed fibres: 5 kg Steel, low-alloyed: 115 kg	NO_x: 0.96 kg NMVOC: 201 g Al: 113 g NH_3: 57.9 g HCl: 20.7 g CS_2: 50 g N_2O: 9.36 g Main Water Emissions Si: 12.4 kg Cl^-: 2.92 kg SO_4^{2-}: 2.46 kg COD: 1.15 kg Ca^{2+}: 1.14 kg BOD_5: 598 g TOC: 434 g DOC: 430 g Na^+: 0.79 kg Solid substances: 664 g Fe^2+: 247 g Al: 266 g Mg: 93.4 g PO_4^{3-}: 81.5 g Oils: 93.2 g K^+: 41 g Main Wastes: Oils: 90.9 g

7. Product Eco-profile

Global Impact Indexes	Total	Per unit of power
Global Energy Requirement (GER)	7 [GJ]	0.7 [GJ/kW]
Global Warming Potential (GWP)	392 [kg CO_{2eq}]	39.2 [kg CO_{2eq}/kW]