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Life Cycle Assessment of Underground Thermal Energy Storage Systems

Aquifer Thermal Energy Storage versus Borehole Thermal Energy Storage

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LIFE CYCLE ASSESSMENT OF UNDERGROUND THERMAL ENERGY STORAGE SYSTEMS:

AQUIFER THERMAL ENERGY STORAGE

versus

BOREHOLE THERMAL ENERGY STORAGE

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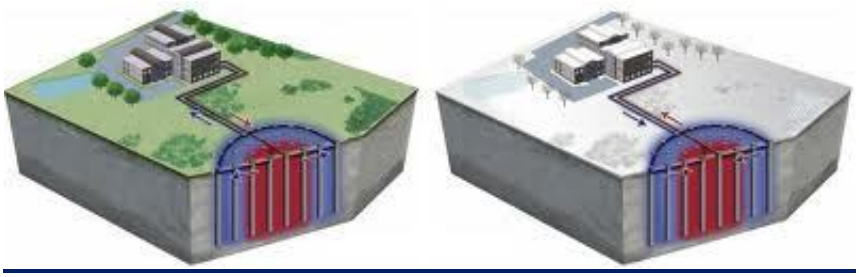

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1. ***Introduction***

We need energy. Even though technological progress provides more energy efficient solutions, at the same time life style change makes energy demanding technologies available for a larger number of users. This trend is causing a consumption of conventional fossil fuels reserves (McKay, 2008). If it is still unknown how really close global peak oil and gas is, everyone agrees with the urge to find alternative energy sources (IEA, OPEC, OECD and World Bank, 2011). Moreover a further large increase of greenhouse gases and other pollutants deriving from conventional energy use is no longer considered acceptable in sustainable scenarios like those enforced in many local and international policies (see, e.g., the European "20-20-20" targets). For this reason we need other solutions to produce energy. Renewable energy sources are the most known and popular alternative but - at the current state of the art - they are not sufficient to supply the global energy demand (MacKay, 2008; Murphy, 2011). The efficiency of the current energy production systems must be improved. This can be achieved through the development of new technologies but also, in an easier and more immediate way, using existing technologies in a clever way, by coupling them in co-generation (or tri-generation) systems or using energy storage systems. As stated in the International Energy Agency [IEA] Annex 20 of the Energy Conservation through Energy Storage [ECES] strategic plan 2011-2015, thermal as well as electrical energy storage technologies can overcome the temporal mismatch between energy supply and demand. Furthermore they prevent energy dispersal and enable its use at other places. This leads to an increase of the total efficiency, as even waste heat can be used. Moreover, physics teaches us that energy is never really produced but only transformed from one form to another (potential, chemical, mechanical, electrical, thermal). This concept is known as the principle of energy conservation and is expressed in the first law of thermodynamics. However during these transformations energy can degrade from a "high quality" to a "low quality" form that is less likely transformed into useful work. Energy quality can also be expressed in terms of exergy and the spontaneous evolution of an isolated system toward a higher entropy state is described in the 2nd law of thermodynamics. Energy storage can be seen as an attempt to conserve as much exergy as possible and is therefore not less important than energy "production" from renewable sources like solar, wind or water energy. At the same time, the use of renewables will additionally strengthen the necessity of energy storage, as suggested in the IEA strategic plan 2011-2015: "*The power sector will be subject to basic changes in future. The percentage of renewable energies is expected to increase. […] This means challenges and also new functions for the grids. The amount of fluctuating energy leads to a requirement of more flexibility and storage capacity. In addition, the demand itself may vary extremely.*" Within the building sector, energy storage bridges the gap between energy efficient measures on the one hand and increasing use of renewables on the other.

As previously mentioned energy storage will also play an important role for the necessary CO2-reduction in future. The IEA strategic plan 2011-2015 reports the figures elaborated during the Energy Technology Perspective (ETP) edition of 2008, where a CO_2 reduction scenario of 50% by 2050 is considered. It states that -in order to reach this goal- the predicted contribution of measures to increase the energy efficiency in the end use sector should be 36%, while the percentage increasing in the use of renewable energy should be 21%.

To sum up, "*energy storage technologies are necessary to increase the efficiency of energy systems in future*" (IEA strategic plan 2011-2015).

1.1 . Underground Thermal Energy Storage (UTES)

In Europe about 40% of the energy is consumed for the heating and cooling of buildings.The European Directive on Energy Performance of Buildings states that high efficiency energy systems such as heat pumps should be considered for new buildings (EC, 2010). Thermal Energy Storage (TES) includes indeed a group of technologies that is mainly applied to increase energy efficiency in the building sector and is often coupled to heat pumps. TES is used to buffer the difference between energy supply and energy demand providing both short-term and long-term applications. The temporal scale can vary from daily to seasonal storage. It is considered an important energy conservation technology and, recently, increasing attention has been paid to its utilization. Both heat, cold or combined heat and cold can be stored (Paksoy, 2007). TES should also be combined with passive measures to reduce the heating and cooling demand and with district heating and cooling systems.

Thermal Energy Storage techniques and examples are copious. Therefore different terminologies are used to define them. The IEA ECES Annex 20 report provides the following classification for cooling thermal energy storage technologies:

- Long term:
  - Underground Thermal Energy Storage (UTES)
- Short term:
  - Phase Change Materials (PCM) in building envelope or in HVAC
  - Ice Storage
  - Chilled Water Storage

Underground Thermal Energy Storage takes advantage of the thermal capacity and large storage volume offered by the underground coupled with the reduced transport velocities of its fluids. UTES technologies are of great interest for several reasons. First of all thermal energy derived from any natural or artificial source can be stored into soils, aquifers or rocks for seasonal or diurnal applications. Moreover, even if UTES systems are already a well established solution in Northern Europe, with The Netherlands being the leading country followed by Germany and Sweden and in North America, (especially Canada, see Lee, 2010), their number is expected to further increase significantly. For example in The Netherlands, under the proposed policy changes, the Underground Energy Taskforce expects that a growth rate of approximately 30% per year can be achieved for UTES deployment and it estimates that, without policy changes, the autonomous growth rate will be approximately 12% per year (Bonte et al., 2011). At the same time UTES is spreading also in other countries: for instance a pilot project has been running for several years in the Stockton College lab (New Jersey, USA) and some implementation can be found also in warmer countries as Turkey and Italy.

Furthermore - compared to the other TES technologies - UTES has a greater potential impact on the environment and on public opinion as their installation is often more invasive and at present irreversible and it demands higher investments as well. For this reason policies and decision making procedures should pay more attention to UTES possible risks. On the contrary, the risks of UTES to groundwater quality are insufficiently known, and policies to address this uncertainty are still lacking (Bonte et al., 2011).

It must also be noted that the underground in general is raising increasing attention for sustainability issues as it may contribute to reduce the emissions of CO_2 by means of

underground storage of CO_2 or use of geothermal energy instead of fossil fuels. At the same time the subsurface is increasingly looked at as a solution to avoid or overcome spatial bottlenecks above ground and underground construction is in full development especially in the modern growing cities. Compared to the long-time exploited surface, the regulations are still insufficient or being defined.

According to the IEA, UTES technologies are the following at present:

- Aquifer Thermal Energy Storage (ATES)
- Borehole Thermal Energy Storage (BTES)
- Thermal Energy Storage in Building Foundation Piles
- Cavity Thermal Energy Storage (CTES)
    - Caverns
    - Pits

ATES and BTES are the two most promising storage options (Paksoy, 2007) as well as the most widespread ones in the countries using underground thermal energy storage. TES applied to the building foundation piles is a relatively new technique applied mainly in Japan. CTES are less common because a suitable cavern or pit is necessary. This paper will therefore concentrate on ATES and BTES systems.

a) Aquifer Thermal Energy Storage (ATES)

As suggested by the name, ATES systems provide cooling or heating using groundwater as the medium of thermal storage and transfer between the external surface and an aquifer. Groundwater has a constant temperature normally related to the mean annual temperature of the site. During winter natural or artificial cold is stored while previously stored heat is pumped out. During summer the stored cold is pumped back and the waste heat from the cooling process or from the external temperature is stored. A heat exchanger transfers the heat or cold from the groundwater loop to the user. The aquifer is connected by conventional water wells. ATES can be used only for cooling purposes or only for heating purposes but in many cases they combine heating and cooling, often using a heat pump for an extended heat or cold production. The system design may vary from one to several wells, from a single storage aquifer to a recirculation system or a couple of aquifers divided by a confining layer. The most common system is a single storage aquifer with two wells used separately for heating and cooling. This type of design is called cyclic regime, as pumping up or injecting in one well is alternated during the hot and cold season. The other possibility with a two (or more) wells installation is the continuous regime where pumping occurs only in one side of the aquifer and injecting in the other. These two options are shown in *Figure 1.*

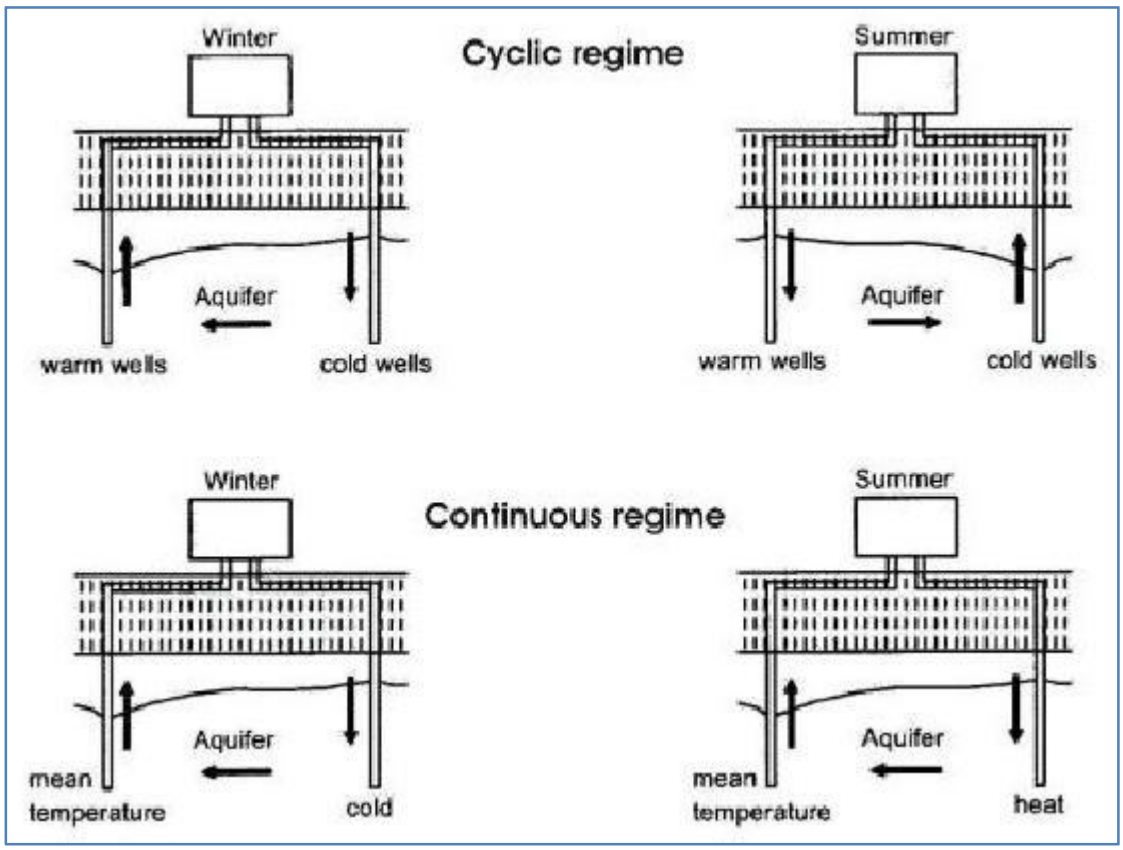


Figure 1. Two basic ATES designs (from Nielsen, 2003).

With a cyclic regime, cold and heat can be stored below or above the natural ground temperature even if in some countries – e.g. in The Netherlands – some restrictions to the temperature interval are enforced by law to avoid potential impacts on the groundwater quality as well as the occurrence of clogging (these issues will be discussed in detail in chapter 4.1). On the other hand the continuous regime can only be used where the load temperatures are close to the natural ground temperatures. The storage part can therefore be considered an enhanced recovery of natural ground temperatures. Some advantages and disadvantages derive from the different characteristics of the two designs. As previously mentioned, cyclic flow allows to store higher or lower temperatures but it will create cold and heat areas around each well or group of wells with a higher impact probability. In addition the well design is more complicated and each well must be equipped with pumps able to both produce and inject ground water. Continuous flow is simpler with regard to system design and well control, and only one well or group of wells need to be equipped with pumps. The disadvantage is the limited temperature range (Nielsen, 2003). ATES can virtually be installed whenever a suitable aquifer is present and where they do not interfere with other functions (notably drinking water wells). *Figure 2* shows a map of European aquifers elaborated by UNESCO in 2004.

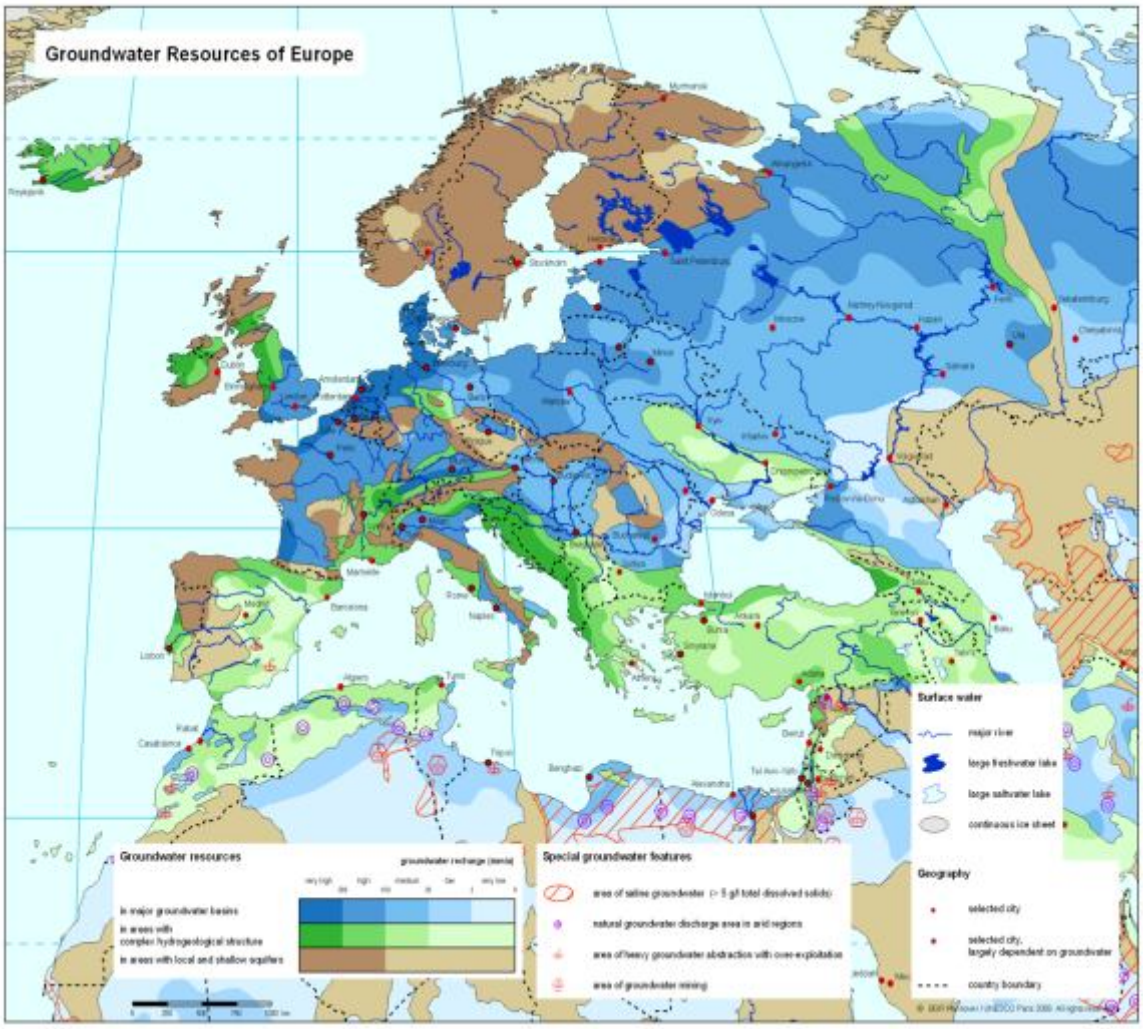
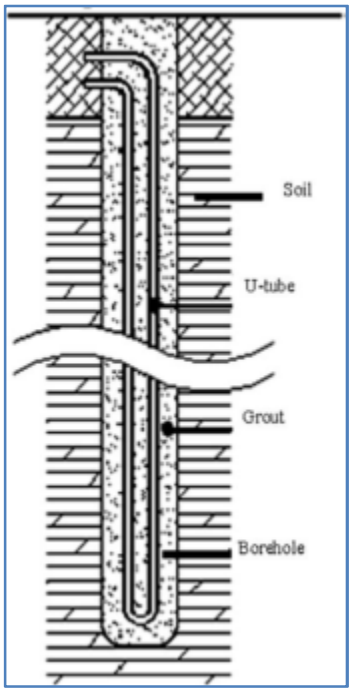


Figure 2. Map of aquifers in EU (from UNESCO, 2004).

b) Borehole Thermal Energy Storage (BTES)



BTES systems are also called closed systems because thermal energy is transferred to the underground by means of conductive flow from a number of closely spaced boreholes. The boreholes must be equipped with borehole heat exchangers (BHEs). The most common BHE is a single U-tube made of plastic pipes (*Figure3*). However, sometimes more effective BHE systems are used, e.g. a double U-tube. Heat or cold is delivered or extracted from the underground by a fluid circulating inside the U-tubes in a closed loop, avoiding direct contact with the underground. The fluid has often an antifreeze to allow the system to work below the freezing point if it is required. As for ATES, heat pumps can be combined with BHEs and the systems are then called Ground Source Heat Pumps (GSHPs) (IEA ECES Report Annex 20, 2011). Among the various GSHPs, the vertical Ground Coupled Heat Pump (GCHP) system has attracted the greatest interest in research field and practical applications as well as it requires less land area and has a wide range of applicability (Yang et al., 2010).

Figure 3. Schematic view of a BTES single U-pipe (from Yang et al., 2010).

For all the above mentioned reasons it is important to further investigate the sustainability of TES. One possible approach in that direction is Life Cycle Assessment (LCA).

1.2. Life Cycle Assessment (LCA)

"*Life Cycle Assessment is a standard analytical tool which, in its complete version, addresses the environmental aspects and potential environmental impacts (i.e. use of resources and environmental consequences of releases related to the functional unit of a product system) throughout a product`s life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal*" (ISO 14040, 2006).

The life cycle assessment goal is then to consider all the stages of a product or a service life, from the production to the dismissal (or recycling or reuse) as well as all the direct and indirect impacts on the environment, human health or other services. It is thereby essential that the boundaries of the analysed product or system are clearly defined. The most important LCA practical applications are the analysis of the contribution of the life stages to the overall environmental load and the comparison between products. Under this perspective LCA can be seen as an instrument to prioritize improvements of a product or a process and to support decision making over different alternatives or uses of an environmental resource, providing scientific and as far as possible quantitative answers to these issues. It is not a coincidence that in recent years life cycle thinking has become a key focus in environmental policy making.

Until today LCA has been mainly performed on products of the industrial and building sector while there are less examples of its application in the field of geo-engineering. Nevertheless LCA is also a useful instrument to determine the sustainability of underground energy storage systems like ATES and BTES and the number of LCA studiesto support environmental management is constantly increasing (EC JRC, 2013; EEA, 1997)

1.3. Aim of the study

Even though UTES are relatively environmental friendly solutions they are not completely free of impacts on the underground. They can have hydro(geo)logical, geochemical, thermal or microbiological impacts. These possible impacts are obviously strongly interrelated. Additionally, UTES require drilling operations and materials use during their installation as well as energy for water pumping and for running a heat pump during the operational phase. As noted in many related researches, the risks of UTES to groundwater quality are insufficiently known, and policies to address this uncertainty are still lacking. This brings up some important UTES related issues:

- When the geological and system requirement conditions allow the installation of both technologies which one is more sustainable?
- In The Netherlands a permission request for ATES is enforced by law while BTES can be installed without regulation as they are closed systems and they do not use groundwater directly: should BTES be regulated as well?
- As previously stated UTES have environmental and energy saving advantages but every kind of underground exploitation prevents other alternative uses. Are UTES the best available technique of exploiting the underground or are there more sustainable options?

These questions are of course too wide to be answered within a single study and the response may vary depending on the location considered but a better knowledge of UTES systems can surely represent a step forward towards the clarification of these issues. In order to improve the understanding and knowledge of UTES techniques, this study aims to perform a Life Cycle Analysis (LCA) on ATES and BTES. The reasons behind are:

- LCA can be a useful instrument to determine the sustainability of underground energy storage systems like ATES and BTES;
- It is a contribution to the increasing number of LCAs applied to environmental services stemming from the subsurface;
- LCA of TES is recommended also by the IEA (ECES strategic plan 2011-2015).

Last but not least, a literature survey as well as detailed descriptions of the ATES and BTES considered are both necessary to define the systems boundaries in order to perform the LCA and complementary to fulfil the uncovered aspects of this approach.

2. Method description

This study consists of two main steps: a literature review to define the state of the art of ATES and BTES technologies and the knowledge of the related issues and a life cycle assessment in order to analyse and quantify the different impacts of the two UTES systems and compare them. The LCA is performed - using the software SimaPro7 - over two average systems with the same heat capacity so that a comparison is possible. The technical data to describe these two systems are withdrawn from the literature and obtained as personal information from private companies.

Before starting with the actual life cycle analysis it is important to describe the conceptual framework of this complex holistic approach and define some parameters that are going to influence the final results.

2.1. LCA framework

According to the ISO standard 14044 the LCA consists of four phases, shown in *Figure 4*.

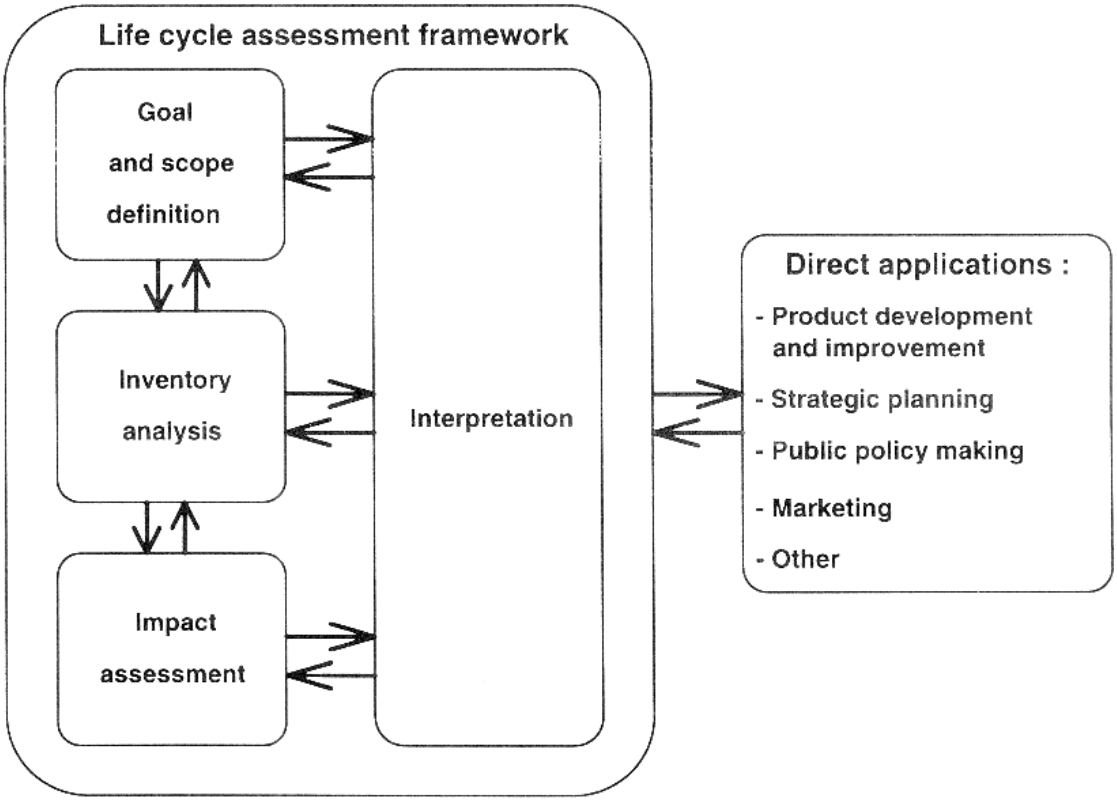


Figure 4. LCA phases (from ISO, International Organization for Standardisation, 2006).

a) Goal and Scope of the study

In this phase the reasons for performing the LCA are defined and the product or service considered is precisely described. This will influence some further aspects, like the database and the impact assessment method choice as well as the interpretation of the results. For example, ISO 14042 suggests that weighting should be avoided in case of a public comparison between two products. If two or more services are to be compared, it is essential

to choose and define a suitable functional unit. It is not always an easy task to define the boundaries of a system and the aspects that reflect its main function but it is of fundamental importance, especially when comparing two different products.

b) Life Cycle Inventory (LCI)

The Life Cycle Inventory phase is basically a data collection phase that includes background and foreground data. Foreground data are the data of the system itself and therefore need to be precise while background data will not drastically influence the result and can be rougher. Data are collected through questionnaires and databases. Databases include also capital goods (trucks, injection moulding machines, infrastructures, etc.) and are very useful to provide background data or emissions associated to background data. A wide (and constantly increasing) number of databases exist and many are included in SimaPro as libraries. For example Ecoinvent (Swiss centre of life cycle inventory) contains more than 4000 processes, is very well documented and includes capital goods and uncertainty data; ELCD, released by EC-JCR (European Commission-Joint Research Centre), is produced by voluntary inputs from the industry sector and contains data on materials, energy carriers, transport and waste management and the US LCI, released by NREL (National Renewable Energy Laboratory), contains a great number of processes like Ecoinvent and has a high transparency.

LCI is certainly a fundamental step of LCA that will affect its overall results but, on the other hand, it represents simply a list of input from and output to nature. From this (often long and technical) list it is difficult to draw any conclusion or evaluation. This leads to the application of the Impact Assessment phase of LCA.

c) Life Cycle Impact Assessment (LCIA)

The ISO 14040 standard defines a LCA as "*a compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system through its life cycle*". From this definition it is clear that impact assessment is an integral part of LCA.

LCIA is defined as the phase in LCA aimed at understanding and evaluating the magnitude and the significance of the potential environmental impacts of a product system (PRè Consultants, 2010). Different steps are involved in the evaluation of the potential impacts: in order to obtain the final output of the assessment - the endpoint that is presented to the final user – one are several midpoints are chosen between the LCI results and the endpoint. Different impact methods use different midpoints and endpoints. The most common endpoints are Impact categories. A single impact category is characterized by a certain number of impact indicators that represent the midpoints of our assessment. In general, indicators close to the inventory results have lower uncertainty because only a small part of the environmental mechanism needs to be modelled but they are more difficult to interpret while indicators close to the endpoint have higher uncertainty but can be easily understood by, for example, decision makers. Endpoints can also be issues of environmental concern, like human health, extinction of species, availability of resources for future generations etc. that can help in the selection of impact categories as long as the environmental model that links the impact category to the endpoint is clearly described.

SimaPro features different impact assessment methods: each method contains a different combination of impact categories and indicators that in certain cases can be aggregated into a single score. The preference for one method should be established based on the scope of

the research (significant impact categories) and on the desired level of aggregation (single scores or detailed scores) which -in turn- depends on the final audience of the LCA results.

The basic structure of impact assessment methods in SimaPro is:

1. Classification
2. Characterization
3. Damage assessment (optional)
4. Normalization
5. Weighting

Classification

As previously mentioned, the results obtained from a LCI are a list of substances emitted to the environment that contribute to one or more impact categories. The classification step involves a simple allocation into categories of the impacts caused by the inventory substances. A single substance can contribute to more than one impact category.

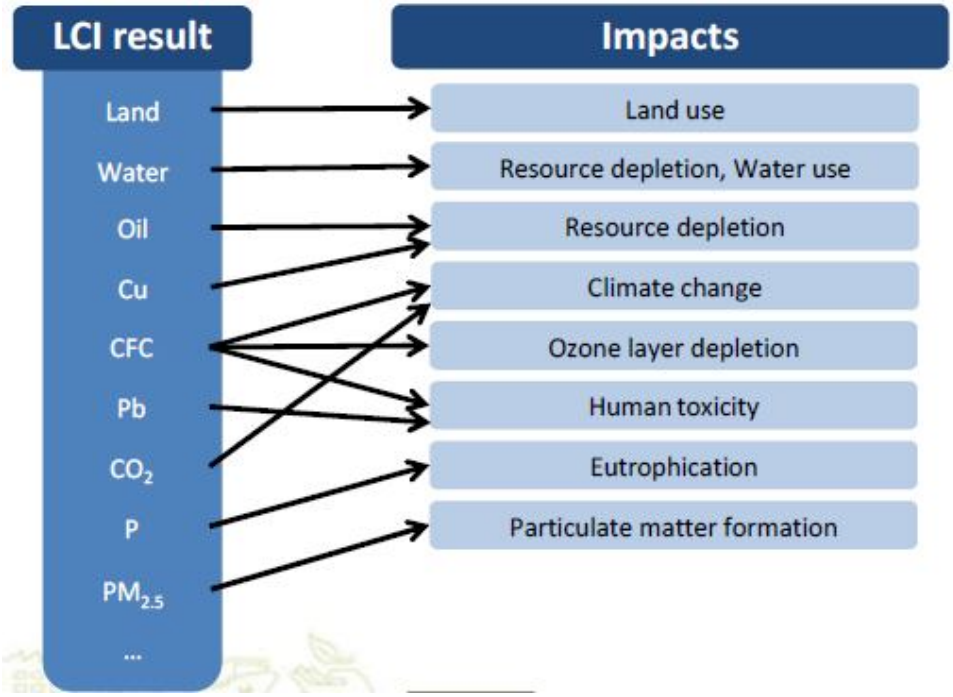


Figure 5. Example of classification into impact categories (from PRè Consultants).

Characterization

The quantities of the LCI substances are multiplied by a characterization factor that expresses the relative contribution of a particular substance to the considered impact category. For example, according to the Global Warming Potential Factors reported by the Intergovernmental Panel on Climate Change (IPCC) 1 Kg of methane is equivalent to 25 kg of CO_2 (IPCC, 2007) as CH_4 is considered 25 times stronger than CO_2 as a greenhouse gas. Therefore, the characterization factors used for carbon dioxide and methane in the impact category Climate Change are 1 and 25 respectively. This means the release of 1 kg methane causes the same amount of climate change as 25 kg CO_2. The total results of a specific impact category are called Impact category indicators.

Damage assessment

In the damage assessment step, Impact category indicators are combined into a Damage category (e.g. Human Health or Ecosystem Quality). Impact Category Indicators with a common unit can be added. For example, in the Eco-indicator 99 method, all impact categories that refer to Human Health are expressed in DALY (disability adjusted life years). In this method it is allowed to add DALYs caused by carcinogenic substances to DALYs caused by climate change. Damage assessment is a relatively new step in impact assessment. It has been added to make use of the so called 'endpoint methods', such as the Eco-indicator 99 and the EPS2000.

Normalization

Many methods allow the impact category indicator results to be compared with a reference value. The results are normalized, therefore divided by the reference value. A commonly used reference is the average yearly environmental load in a country or continent, divided by the number of inhabitants. However, also other references can be chosen. Once normalized the impact category indicators can be compared directly as they all have the same unit. Normalization can be applied on both characterization and damage assessment results.

Weighting

The Impact (or Damage) category indicator results can be multiplied by weighting factors and eventually summed up to create a total or single score. Weighting is possible only with some impact assessment methods and it can be applied with or without normalization. Weighting factors assignment is obviously a subjective step. The main weighting options are:

- *Distance to target*

The ratio of the current environmental load to the reduction target is used as a weighting factor. Both scientific and political targets can be used.

- *Monetisation*

The willingness to pay in order to avoid damage is used.

- *Panel weighting*

Opinions of selected groups of people are collected through surveys.

It is important to note that in ISO 14042 classification and characterisation are described as obligatory elements of an impact assessment while normalisation and weighting are defined as optional elements.

d) Interpretation

This phase should include uncertainty and sensitivity analysis as well as a process contribution investigation, as underlined also in the ISO standard 14044.

2.2. *Impact Assessment Methods*

The impact assessment methods list is quiet long as various universities, research institutes, private companies and institutions have developed their own methods. The main method chosen to establish UTES impacts and compare ATES and BTES is Eco-Indicator 99. It is one of the most common methods, which makes confrontations with other studies possible, it presents both Impact and Damage categories and the methodology used is very transparent. Other methods are used in this study to verify if the results are consistent with the Eco-Indicator ones or if the method choice can influence the final outcome: EPD

(Environmental Product Declaration) is more recent (2008) and is commonly used in many EU countries while IMPACT 2002+ is a combination of four different methods(Impact 2002, Eco-Indicator 99, CML and IPCC). Last but not least, the single issue methods Cumulative Energy Consumption and Cumulative Exergy Consumption are used to calculate the energy and exergy output respectively. Eco-Indicator is described in details in the following chapter while for the other method descriptions see the impact methods manual in Annex A.

- **Eco-Indicator 99**

The Eco-Indicator 99 (E-I 99) method uses the damage-oriented approach and displays -as a default- three main damage categories: **Human Health**, **Ecosystem Quality** and **Resources**. Even if it is a Damage assessment method it also uses midpoint indicators that contribute to the creation of its three damage categories. The midpoints considered are called Impact categories. In the following paragraph, E-I 99 Impact categories are listed and the main substances responsible of the relative impacts are described, as reported by ECN, the Dutch Energy Resource Centre, with some additional information taken from the 4th IPCC report, as far as the Climate Change category is concerned.

Impact categories

Carcinogenic substances
A prolonged exposure to many chemicals might provoke cancer in humans or animals. Some commonly known carcinogens include asbestos, radon, arsenic, benzene etc.

Respiratory inorganics
Exposure to high levels of gases like nitrogen oxides (NO_X) or sulphur dioxide (SO_2) can damage the respiratory airways. As nitrogen oxides form during fuel combustion at high temperatures, the primary sources for the NO_X are motor vehicle and industrial technologies that burn fuel. When NO_X and volatile organic compounds react at high heat or sunlight, ground-level ozone is formed. The ground-level ozone can cause serious health effects, such as lung damages. In addition, nitrogen oxides react with different compounds and liquid droplets in the air to form particulates that can penetrate deeply into the lungs and cause severe respiratory diseases. Sulphur dioxide is formed when fuel containing sulphur, such as coal and oil, is burned, and when gasoline is extracted from oil. Similar to NO_X, SO_2 contributes to respiratory illness and to formation of atmospheric particles.

Respiratory organics
Some toxic organic materials can cause damage to the respiratory airways as well. These chemicals - like Polyaromatic Hydrocarbons, Polychlorinated Biphenyls, Dioxins and Furans - are usually produced during incomplete combustion of fuels.

Climate change
The main greenhouse gases are water vapour, carbon dioxide (CO_2), and methane (CH_4). According to the Intergovernmental Panel on Climate Change (IPCC, 2007), CO_2 – because of its increased concentrations in the atmosphere since pre industrial times - is responsible of the major contribution to increases in radiative forcing (resulting in higher temperatures). Radiative forcing is a concept used in climate science that can be related through a linear relationship to the global mean equilibrium temperature change at the Earth surface. It is

defined as: "*the change in net [..] irradiance (solar plus longwave, in W/m^2) at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium but with surface and tropospheric temperatures and state held fixed at the unperturbed values*" (Ramaswamy et al., 2001 and IPCC, 2007). The global increase in CO_2 concentration is mainly due to anthropogenic activity such as combustion of fossil fuels and deforestation. Methane is another important greenhouse gas with a Global Warming Potential (GWP) 25 times higher than CO_2 (using the 100 years GWP factors reported by the IPCC) but less abundant in the atmosphere. The major sources of the CH_4 emission derived from human activities are energy production, landfills, waste treatment, animal farming and biomass burning. Although water vapour is the most common and an extremely potent greenhouse gas, it is not possible to directly influence atmospheric water vapour concentration, as its concentration in the atmosphere mainly depends on air temperature.

Radiation

Frequent exposures to nuclear radiation can cause cancer and other severe health effects. The major source of radiation is power production by nuclear and coal-fired power plants. Radioactive materials, such as uranium-235 or plutonium-239, are used to generate electricity by nuclear power plants. The spent fuel is highly radioactive and temporally stored while methods for final disposal are still discussed. However, measured radiation exposure is higher around coal-fired power plants than nuclear plants (Scientific American, 2007). The main radioactive materials released to the environment by coal-fired power plants are uranium and thorium, as part of coal combustion.

Ozone layer

Ozone forms a layer in the stratosphere that reduces the amount of UV radiation reaching the surface. Human exposure to UV increases the risk of skin cancer, cataracts, and suppression of the immune system. When ozone reacts with natural and human produced chemicals – such as chlorinated and brominated hydrocarbons–chemical reactions occur and the ozone molecule is destroyed.

Ecotoxicity

A big variety of chemicals (like PCBs, dioxins, pesticides, heavy metals, VOCs etc.)emitted to water, air and soil affect the environment and the organisms living in it. Moreover biomagnification effects might occur and enhance this phenomenon.

Acidification/Eutrophication

SO_2 and NOx both react with water vapour in the atmosphere to form Sulfuric acid (H_2SO_4) and Nitric acid (HNO_3). This results in acid rain. Many marine species dies if the water becomes too acidic. Plants will be damaged and eventually die when the acid seeps into the leaves disrupting the process of photosynthesis. Acid rain also damages buildings and marble statues. Eutrophication is a response of the ecosystem to the human activities that artificially enrich water bodies with nitrogen and phosphorus. Eutrophication can lead to changes in animal and plant population and degradation of water. Since it is not possible to determine whether the damage is caused by changes in the nutrient level or by acidity, these two impact categories are combined.

Land use

Every human activity leads to a modification of the natural ecosystem. This modification includes land degradation, reduction of local biodiversity, suppression of the natural resources, etc. In addition, it may raise demographical, economical and political problems. The Eco-indicator 99 method used in these calculations considers the following land use aspects: occupation of forests, construction sites, industrial areas, mineral extraction sites and traffic areas.

Minerals depletion

Mineral extraction has an environmental impact due to energy use , production of waste and greenhouse gas emissions. At the same time it causes the depletion of finite resources.

Depletion of fossil fuels

Fossil fuels are currently a primary source of energy. Coal is mainly used to produce electricity, oil as a transportation fuel and natural gas for heating. In addition, oil is used to manufacture products such as plastics, asphalts, medications, paints, etc. The world's total amount of fossil resources is limited.

Damage categories

Each damage category consists of a number of impact categories combined together and all measured in the same unit. This structure facilitates interpretation of the results, allowing analysis of the data separately for each damage category without applying any subjective weighting.

Human Health

The Human Health damage category takes into account respiratory and carcinogenic effects, ozone layer depletion, greenhouse gas and ionizing radiation. Damage to human health is expressed in DALY (Disability Adjusted Life Years). DALY is the number of disability years caused by exposure to toxic material multiplied by a "disability factor", a number between 0 and 1 that describes severity of the damage (0 for being perfectly healthy and 1 for being fatal). This index is also used by the World Health Organization.

Ecosystem Quality

Damages of ecosystem quality include ecotoxicity, acidification, eutrophication and land use. The common unit of the Ecosystem Quality category is PDF×m2×year.PDF (Potentially Disappeared Fraction) is the probability for the plants species to disappear from a certain area as a result of acidification, eutrophication and land use and it is combined with PAF (Potentially Affected Fraction) that is the percentage of the species that are exposed to the toxic emission.

Resources

The Eco-indicator 99 methodology analyses only non-renewable resources such as minerals and fossil fuels. The unit of the Resources damage category is MJ "surplus energy"/ kg that indicates the expected increase of extraction energy per kg of extracted material in relation to the decrease of its concentration in the Earth`s crust.

The Damage categories and the relative Impact categories are outlined in *Figure 6.*

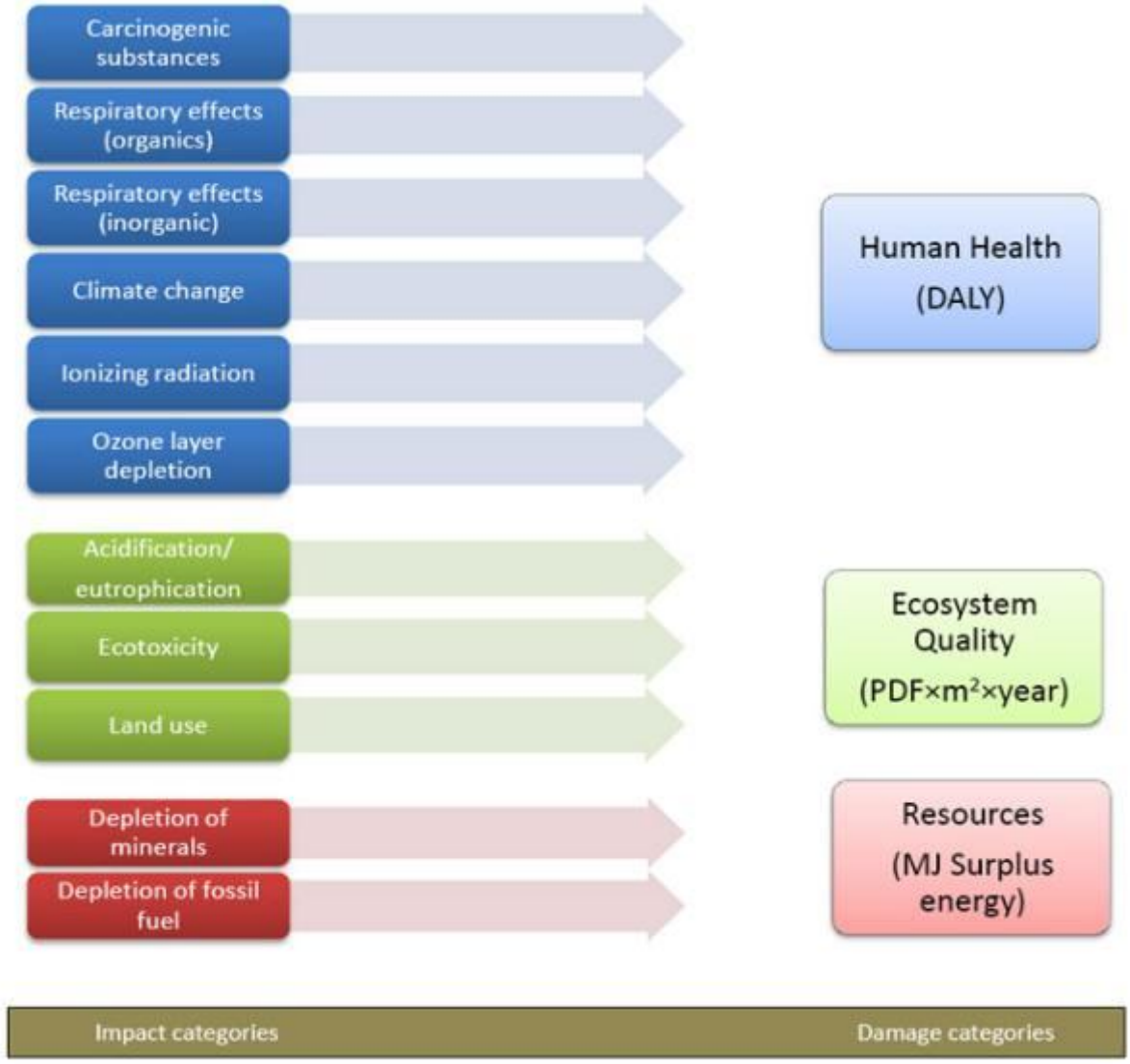


Figure 6. Eco-Indicator 99 Impact and Damage categories (from ECN, Energy Resource Centre, The Netherlands).

In order to link the inventory data to the Impact and Damage categories, a series of models that allow to define the kind of damage caused by the emission of a substance or by the exploitation of a resource and to determine its magnitude has been developed.

The following steps are applied to the *Human Health* category:

- *"Fate analysis"*: This step describes variation in the concentration of the emitted substance in the environmental compartment considered.
- *"Exposure analysis".* The above mentioned concentration is now linked to a specific dose to which the population or an individual is exposed.
- *"Effects analysis".* The dose is linked to the actual effects on human health (e.g. the number and type of tumours or the respiratory effects).

- *"Damage analysis"*. The health effects are associated to the number of years of life lost and the number of years lived disabled. These are combined as Disability Adjusted Life Years (DALYs).

For the *Ecosystem Quality* Damage category the following steps are applied:

- *"Fate analysis".* Emissions in the ecosystem are linked to the actual concentrations in the different environmental compartments.
- *"Effect analysis."* The concentrations levels are linked to the levels of toxicity and acidity or to the nutrients increase.
- *"Damage analysis".* Those effects are connected with the potential disappearance of plants.

Note that this obviously does not include the Impact category Land use that is based on empirical data.

The steps involved in the *Resources* category definition are only two:

- *"Resource analysis"* that links the extraction of a resource to its concentration reduction.
- *"Damage analysis"* that links the decrease in the resource availability with the increase of the energy needed for its future extraction.

Eco-indicator 99 comes in three versions, built on three out of the five archetypes proposed by the so called "Cultural Theory", a widely used support in policy making. The Cultural Theory aims to describe the different categories of individuals in the modern society as well as their vision and reactions over potential risks.

Cultural Theory

The model of the Cultural Theory used was proposed by Thompson et al. (1990) and combines anthropological and ecological insights. The three archetypes of the Cultural Theory considered (and therefore the three perspectives used in Eco-indicator 99) are the following:

1. *Egalitarian perspective*
2. *Hierarchist perspective*
3. *Individualist perspective*

Egalitarian perspective

In the Egalitarian perspective the chosen time perspective is extremely long-term, Substances are included if there is just an indication regarding their effect. In the Egalitarian perspective, damages cannot be avoided and may lead to catastrophic events. In the case of fossil fuels the assumption is made that fossil fuels cannot be substituted. Oil, coal and gas are to be replaced by a future mix of brown coal and shale.

Hierarchist perspective

In the Hierarchist perspective the chosen time perspective is long-term and substances are included if there is consensus regarding their effect. Damages are assumed to be avoidable by good management. In the case of fossil fuels the assumption is made that fossil fuels cannot easily be substituted. Oil and gas are to be replaced by shale, while coal is replaced by brown coal.

Individualist perspective

In the Individualist perspective the chosen time perspective is short-term (100 years or less). Substances are included if there is complete proof regarding their effect. Damages are assumed to be recoverable by technological and economic development. In the case of fossil fuels the assumption is made that fossil fuels cannot really be depleted.

Table 1 summarizes the main characteristics of the individualist, Hierarchist and Egalitarian perspectives.

Table 1. Cultural Theory archetypes. The time perspective years are approximate.

	Time perspective	Manageability	Required level of evidence
Individualist (I)	**Short time (20y → 100y)**	**Technology can avoid many problems**	**Only proven effects**
Hierarchist (H)	**Balance between short and long term**	**Proper policy can avoid many problems**	**Inclusion based on consensus**
Egalitarian (E)	**Very long time (> 500y → ∞)**	**Problems can lead to catastrophe**	**All possible effects**

Consequently, the three correspondent Eco-Indicator versions differ in terms of type and magnitude of included effects and in terms of weighting set. Nevertheless, also an average weighting set can be chosen. The Hierarchist perspective can be considered half way between the Individualist and the Egalitarian one and for this reason its use, with an average weighting set, is recommended in SimaPro.

3. Results

3.1. Literature review

The following paragraphs resulted from a literature review aimed to list all the possible ATES and BTES impacts on the underground. It must be stressed out that it is not sure whether the considered impacts will actually occur and - in case of impacts related to the formation of a thermal gradient around the wells or pipes - they would be moderated as the temperature difference between the stored heat and the underground accounts only for a few degrees Celsius.

3.1.1. ATES

Possible impacts

Even though ATES are relatively environmental friendly solutions, they are not completely free of impacts on the underground. The most common impacts can be classified in four categories even if it should be noticed that these categories are strongly interrelated.

- *Hydro(geo)logical impacts*

ATES systems have no net extraction because the same amount of groundwater is injected back into the aquifer. Nevertheless the pumping and injection can result in perturbations in the groundwater flow that can occur up to a distance of several kilometres (Ferguson, 2006). This can affect the size and geometry of other groundwater wells capture zones. As a result the presence of ATES wells can alter the groundwater aquifer quality, depending on factors such as land use or aquifer heterogeneity and reactivity as well as the interaction between surface and groundwater. For example a normally gaining stream can turn into a losing stream and vice versa depending on ATES operation. The affected wells might easily be drinking wells, increasing the possible impacts magnitude. Another possible damage can occur when a borehole is drilled into more than one aquifer (confined aquifers): cross-aquifer contamination can then be caused by poorly designed or poorly constructed systems. That is the case of a borehole screened in several aquifers and of boreholes that lack adequate clay or grout plugs to prevent leakage, respectively.

- *Geochemical impacts*

Groundwater contains a certain amount of dissolved inorganic chemicals with different concentrations depending on the nature of the reservoir and on the interaction with the reservoir materials. This could result in chemical precipitation that could clog and/or corrode ATES systems. Indeed after a literature revision of existing ATES projects and experiments, Bonte et al. (2011) stated that it is known that problems due to precipitation of iron and/or carbonates occur frequently. In general these processes are initiated by changes of pH and redox potential of water. This can happen in case of CO_2 stripping, mixing of a reduced and an oxidized type of water or reduced water getting in contact with oxygen. For these reasons the wells should be designed to be airtight and constantly under pressure and excessively large drawdowns in the well should be limited to avoid CO_2 stripping and O_2 penetration. Scaling and corrosion are not directly an environmental problem but - as noted by Willemsen (1990) - precipitation of carbonates is a common problem encountered in many cases where hard water is heated. Problems can be prevented by an adequate water treatment but when water treatment is used the effects of the resulting change in composition on the water quality should be taken into account. Moreover any efficiency reduction or secondary

intervention to solve this problem should be taken into account in the overall sustainability balance. Bonte et al. (2011) noted that most of the published research that focuses on changes in mineral solubility, reaction kinetics and organic matter oxidation suggests that these processes will play a significant role at temperature above 30 ºC. On the other hand Prommer and Stuyfzand (2005) suggest that redox reactions are more sensitive to temperature changes, as observed in a deep well injection experiment in which oxic water was injected in an anoxic aquifer and the temperature increase from 5 to 15 ºC strongly accelerated pyrite oxidation.

Last but not least, an ATES system extracting and injecting water from an aquifer affects the groundwater stratification and therefore the natural buffering effect of the aquifer. Firstly, this can affect the quality of the groundwater, in particular of the deeper nitrate-free layers. Secondly, mixing groundwater might also cause mobilization of contaminants in urban areas that would be otherwise relatively confined under natural conditions, even if this aspect is still unclear and needs further investigation (Bonte et al., 2011). Thirdly, when ATES systems mix groundwaters with too large of a salinity contrast, this can result in the net loss of fresh groundwater (Hartog et al. 2013). The latter issues are of particular importance for aquifers used for drinking water protection.

- *Thermal impacts*

In 2007 IF Technology published the results of an inventory of 67 ATES systems in the Dutch territory and they found out that almost none of the investigated systems had a thermal balance "*meaning that cold or heat is discharged into the aquifer and long-term cooling or warming of groundwater is occurring*."This can obviously reduce the efficiency of the system and – as noted by Ferguson (2009) - also negatively affect downstream users of groundwater and aqueous ecosystems. However IF Technology also reported that the more years a project was running, the more favorable was the cumulative thermal balance, with the exception of the projects with a five years survey. The explanation for this phenomenon must still be investigated. The results are summarized in *Table 2*, that reports the number of projects with a thermal balance < 10%.

Table 2. Thermal balance of 67 ATES projects over different operating years. From IF Technology, 2007.

projecten met	aantal projecten	aantal projecten met onbalans <10%	% van aantal projecten met onbalans <10%
1 meetjaar	14	1	7%
2 meetjaren	15	2	13%
3 meetjaren	11	3	27%
4 meetjaren	7	2	29%
5 meetjaren	6	1	17%
> 5 meetjaren	14	7	50%
totaal	**67**	**16**	**24%**

Moreover, even if it is almost impossible to reach a thermal balance within a single building, it could be achieved using the system for heating or cooling more than one building with different requirements (for example cooling two buildings and heating only one if the predicted imbalance is an excess of cold storage). Another solution could be to recharge the system with the necessary temperature, using solar concentrators or discharge water from industries or surface waters and outside air. At the same time it is almost impossible to

forecast the exact weather conditions and therefore the peak loads of an area and the real system`s efficiency is often far from the predicted one (usually it requires the pumping of a larger water capacity). If the system operates with a thermal imbalance over a too long period of time, it might reach a steady state and change the ground temperature conditions. Zeng at al. (2002) suggested that it might take 10 years or longer to cause a permanent change of the underground temperature. As the solubility of the minerals depends upon temperature, thermal changes will cause shifts in chemical equilibrium, resulting in a possible dissolution or precipitation of elements (Dufour, 1990). This will happen not only in presence of a thermal imbalance but normally during heat storage around the warm well.

- *Microbiological impacts*

ATES induces water movements and, especially temperature changes in sandy aquifers that may affect the indigenous microflora. It is true that typically ATES water is anaerobic and little literature exists on the presence of indigenous microorganisms in deep anoxic waters. However, anaerobic microrganisms such as *Clostridia, Bacillus* and *Legionella* are ubiquitous in the environment, including in soils and might be present in the aquifer. Other microorganisms that can be found in anaerobic groundwater may include *Mycobacteria, Aeromonas* and amoeba (Schijven et al., 2011). In general, the microbiological equilibrium conditions can be disturbed by a sudden change of temperature, by periodic temperature fluctuations, by the change of groundwater composition or by the increased groundwater flow. This may result in bacterial growth or in bacterial mediated iron precipitation and metal corrosion by sulphate reducing bacteria (Dufour, 1990). Moreover, during the installation, maintenance or repair activities, non indigenous microorganisms can be introduced in the aquifer. On the other hand, nutrients mobilization and groundwater mixing caused by pumping as well as increased temperature may accelerate biodegradation (Langwaldt and Puhakka, 2000). Nutrients could also be introduced in the aquifer during the drilling using biodegradable drilling fluids.

Usually there are no sources of contamination for enteric pathogens in ATES, especially when they use groundwater from a deep or confined aquifer. This is because the part of ATES near the surface and aboveground is a closed system. Nevertheless some ATES could be situated directly under huge sources of enteric pathogens, as it is the case of, for example, animal farms. If faecal pathogens were present in the system they would be inactivated by high temperatures but their life span would be enhanced by cold temperatures. To date, there is little knowledge about the actual consequences of ATES on the groundwater microbiological communities but it is certain that the microbiological communities' function of nutrient removal is very important to prevent the growth of pathogens in drinking water.

The possible ATES impacts are summarized in *Table 3*. The probability associated to each impact was established by Bonte et al. (2011) based on a review of existing projects in The Netherlands. It is important to note that the probability of occurrence is not directly a measure of the risk because it accounts for neither the kind of consequences nor the order of magnitude of the effect. Risk can indeed be defined as the probability of occurrence of an hazard multiplied by the vulnerability of the target. At the same time some considerations on the data provided by Bonte are necessary: the probability of poorly sealed boreholes, might be moderate rather than high, as the companies involved in ATES installation are usually

more competent and reliable than the ones involved in BTES installation, also due to the fact that a licence is necessary for the installation of the open systems. Moreover the microbiological population shift depends on temperature and species. The systems considered store a maximum heating temperature < 30 ºC (as enforced by the Dutch law). Last but not least, the probability assessment is only qualitative and not quantitative and lacks of a scientific description of the method used to calculate the above mentioned probabilities.

Table 3. ATES possible impacts. *The probability - established by Bonte et al. (2011) based on a review of existing projects in the Netherlands- is a qualitative description of the possibility of occurrence that does not represent a measure of the risk associated to ATES.*

ATES impacts	Probability	Effects
Hydrological		
Influence in other wells capture zones	Extremely high	Increased vulnerability
Water level and fluxes modifications	Extremely high	Desiccation, water logging, subsidence and other ground settlements
Poorly sealed boreholes	High/Moderate	Cross-aquifer flow and contamination
Chemical		
Ca and Fe carbonates precipitation	Low (variable)	Scaling and clogging
Iron hydroxide formation	Moderate	Corrosion
Mixing processes	Extremely high	Salinity, change in water quality
Reactivation of groundwater pollution plumes	Moderate	Inorganic and organic micro pollutants
Thermal		
Change in water temperature	Extremely high	Reduced system efficiency, reactions kinetics, ecosystem(?)
Microbiological		
Microbiological population shift	High/Moderate (unsure)	Unknown
Increased biodegradation rate	Moderate	Nutrients and micro pollutants removal
Introduction or mobilization of pathogens	Low	Drinking water contamination

Technical issues

Apart from the possible environmental impacts, ATES (and BTES) may present various technical issues that can notably reduce the efficiency of the system.

First of all, a suitable aquifer is necessary. Aquifers that can be utilized for ATES are limited to deposits of sands and gravels and highly fractured rock, preferably within about 150 m to surface. Some important parameters are high porosity, medium to high hydraulic conductivity around the boreholes, but a minimum of ground water flow through the reservoir. Ground water chemistry (e.g. limited mineral content) represents another important parameter in order to prevent scale formation and furring (Nielsen, 2003). These conditions make ATES less universally applicable than BTES, which can be applied in almost all geological formations. Because of the required characteristics, suitable aquifers may overlap with drinking water aquifers leading to greater concern for the possible impacts and to licensing restrictions.

As stated under the chemical impacts list, a commonly encountered problem is well clogging. Two main types of clogging are observed in the field: clogging at the borehole wall (mechanical clogging) and clogging of the well screen (chemical clogging). Clogging at the borehole is mainly caused by accumulation of particles that are mobilized and transported towards the well due to the flow velocity increased by the pumping. These particles reduce the permeability of the aquifer near the well bore wall and therefore decrease the pumping efficiency. Moreover, as the water level inside the well will lower, air will replace it and this will cause oxidation of the metal parts, creating large iron particles (de Zwart, 2007). Chemical well clogging is due to precipitation and scaling (especially in hot water storage).

While deep geothermal plants recover a much higher temperature that is used to generate electricity, in the case of UTES water at much lower temperatures is stored and recovered, hence the heat is used directly instead of being transformed in other forms of energy. This implies that a short distance is necessary between the wells and the buildings or facilities that will benefit from UTES use as long-distance heat transport is expensive. This is usually not a big issue because UTES uses underground space but it can represent a problem in densely populated cities where the underground is already exploited, in the vicinity of a drinking aquifer (i.e. inside the protection zone) or in other spots where the underground is not suitable for an ATES installation (e.g. hard rock formations).

A good design should avoid interference between the two wells, especially when the hydraulic conductivity is higher than desired for the ATES system. The effective storage capacity will be drastically reduced if mixing occurs therefore a proper system design is of great importance.

Another main issue is that the actual usage regime is unknown during the design. This causes great uncertainties in predicting the effect of ATES systems caused by temperature changes and by groundwater withdrawal and decreases the system`s efficiency. In fact IF Technology`s investigation on 67 Dutch projects showed that the actual use parameters never fully correspond to the predicted ones. The actual temperature difference resulted to be almost half than predicted both for cold and heat storage. Moreover, seasonal temperature variations affect the heat demand, therefore influencing the amount of water withdrawn and reinjected.

3.1.2. BTES

Possible impacts

Many of the potential ATES impacts can occur also with BTES installation. The differences between the two systems are listed below.

- *Hydrological impacts*

Poorly sealed boreholes can cause cross-aquifer contamination: this problem can occur more frequently with BTES compared to ATES because in some countries, like The Netherlands, a licence is not necessary to build BTES and by consequence there are no controls or enforcements on the drilling procedures and design. On the other hand, as BTES is designed as closed system, the water level and capture zones of the groundwater aquifer should not be affected.

- *Chemical impacts*

For the above mentioned reason mixing processes that can affect the water quality are not occurring during BTES. An additional problem could be the leakage of antifreeze fluids or additives from the wells. BTES systems use cooling fluids that, in the case of a poorly installed, damaged, or aged system, can leak into the aquifer. The coolant is often a mixture of an antifreeze agent such as glycol, a biocide, and a corrosion inhibitor (Klotzbücher et al., 2007). Although both aerobic and anaerobic biodegradation has been observed in soils for frequently used antifreeze agents such as ethylene glycol, propylene glycol, the addition of corrosion inhibitors or biocides in BTES systems can inhibit biodegradation (Klotzbücher et al. 2007). Given the growing number of BTES systems in the Netherlands alone and the lack of regulations to enforce the quality of drilling work, the risk of groundwater system contamination is likely to increase.

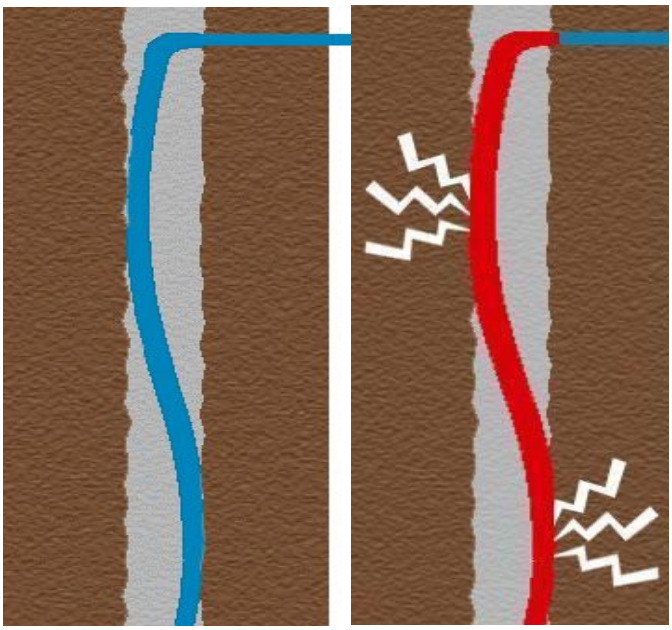


Figure 7. Example of BTES wrong installation (from Rehau Ltd.). *Point loads occur as the pipe presses against the borehole wall during installation and then thermally expands during operation. This can damage the pipe and in some cases, cause rupture and antifreeze leakage.*

Table 4. BTES possible impacts. *The probability - established by Bonte et al. (2011) based on a review of existing projects in the Netherlands- is a qualitative description of the possibility of occurrence that does not represent a measure of the risk associated to ATES*

Possible BTES impacts	Probability	Effects
Hydrological		
Poorly sealed boreholes	High	Cross-aquifer flow and contamination
Chemical		
Anti-freeze fluids or additives leakage	Moderate	
Thermal		
Change in water temperature	Extremely high	Reduced system efficiency, reactions kinetics, ecosystem(?)
Microbiological		
Microbiological population shift	High	Unknown
Increased biodegradation rate	Moderate	Nutrients and micro pollutants removal
Introduction or mobilization of pathogens	Low	Drinking water contamination

Technical issues

In order to install BTES the presence of an aquifer is not necessary. In case of BTES installed in the presence of a groundwater aquifer instead of rock or other geological layers, low conductivity parameters are necessary to avoid heat or cold dispersion. As for ATES a short distance from the buildings is required.
BTES configurations may include one, tens, or even hundreds of boreholes, each containing one or double U-tubes. The large number of boreholes and pipes at depth up to several hundred meters is usually not removed after usage but filled with clay or other impermeable materials to avoid leakage.

3.1.3. Heat pumps

Both ATES and BTES systems can be coupled with heat pumps when the energy stored is not sufficient to provide enough heating or cooling (because of legal boundaries that limit the maximum storage temperature as in the Netherlands or because of peak demand).
A basic heat pump consists of four components:

- Evaporator
- Compressor
- Condenser
- Expansion valve

It also requires a refrigerant running into a closed circuit connecting the four components and the compressor requires an external source of energy. Basically the refrigerant absorbs energy from a low temperature source (the warm water extracted from UTES in our case) and evaporates in the evaporator and then its pressure is increased in the compressor. Finally the refrigerant releases its energy in the condenser (through a heat exchanger) before passing through the expansion valve. A heat pump can also be used in the other thermal direction to provide cooling (that is the air conditioner principle).

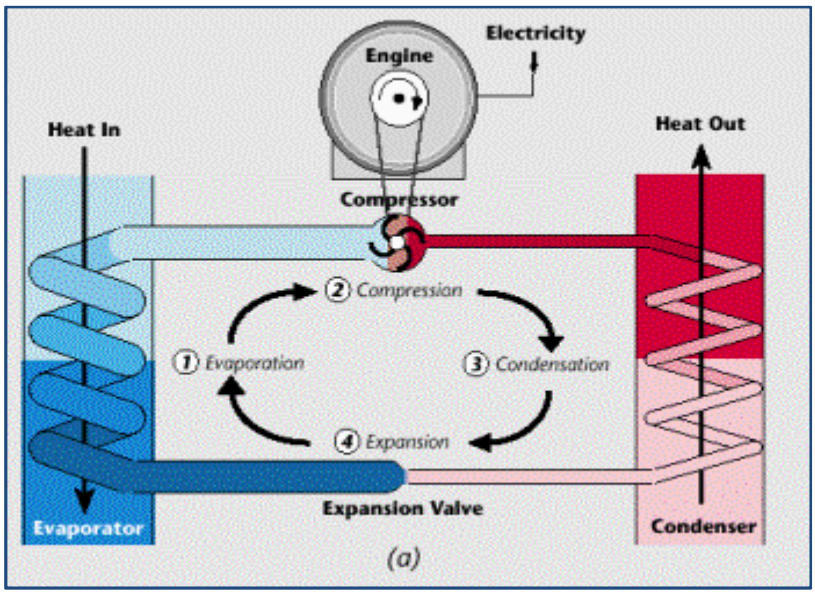


Figure 8. Basic heat pump structure. (www.heatlight.co.za).

As noted by Zeng et al., (2003) GSHP (Ground Source Heat Pumps) have a higher efficiency than Air-source heat pumps because the ground provides a warmer heat source during winter and a colder one during summer. Water-air heat pumps usually have a coefficient of performance of 4:1.

3.2. Systems boundaries and technical data

The main goal of thisstudy, beside the literature review, is toperform a LCA of ATES and BTES. Beforeanalyzing the LCA resultsit is important todescribe the systems considered in order todefinetheirboundaries.

- Capacity: 250kW. The capacity is chosen in order to allow a comparison between open and closed systems. Therefore 250kW is an average power that represents a small ATES or a large BTES, nevertheless maintaining realistic conditions. Deltares (2010) reported that the average power requirement to heat a home is 6kW. Therefore the systems considered could serve around 40 houses or 2 buildings of approximately 1500 m^2 each. These data are obviously indicative and will vary depending on the climate, insulation and weather conditions.
- Systems function: heating.

- Functional unit: 25 years. The systems operate 2000hours/year at full capacity. Even if the life span might last longer with perfect maintenance, this seems a reasonable period considering that UTES technologies are often connected to the buildings heating systems and that other alternatives might replace them in the future. Nevertheless high density polyethylene loop fields used in BTES are estimated to last approximately 50 years by the producing companies. Moreover the projected service life of geothermal heat pump systems (GHPs) is longer than that of conventional heating and cooling equipment because GHPs don't experience the same extremes of environmental operating conditions as conventional systems (Cross et al., 2011).
- Ground composition: sand and clay.
- Water table depth: ~2 m below the surface.
- Climate and underground temperature: average Dutch conditions. While the climate and weather conditions can be quiet different, the underground temperature in the first 200 m is around 12 ºC and presents little variations.
- Transport distance to and from the drilling site: 50km.
- Destiny of the drilling muds: in open landscapes the drilling muds are usually spread on the surface in the proximity of the drilling site. Nevertheless UTES systems can be installed also in urban zones or where the surface is already committed to other uses. Therefore in the life cycle model drilling muds and waste are allocated 50% to landfarming and 50% to a residual material landfill.
- End of life: the sealing of the pipes or wells with bentonite is considered while the landfill of plastic pipes is used as a proxy for underground deposit as this kind of impact is still not included in the LCIA methods.
- Annual regeneration of the ATES wells:~100kWh pumping * 25 years = 2500kWh. Pumping water up and down is the most common practice to regenerate a clogged well. Chemical treatment is rare, because it is undesired and often requires special permission from the competent bodies. Preventive maintenance is done every year by simply extracting water from each well and discharging the water into the sewerage or surface water.
- The drilling rig and digging machine assemblies are not included in the life cycle because they are re-used in a great number of other drilling operations. Therefore the allocation is very low and the consequent impacts are negligible. Nevertheless their weight is taken into account in the transportation calculation.
- Other relevant technical data are summarized in *Table 5* for the ATES system and *Table 6* for the BTES system.

Table 5. Technical data for a 250 kW ATES system in The Netherlands [personal information from TerraTechbv].

	ATES				
Drilling	**Depth**	**Number of boreholes**	**Boreholes Diameter**	**Additives**	**Fuel/Electricity**
	80m	2	500 mm	Water 600m3	500 ltrs (diesel)
Pipes installation	**Material**	**Dimensions**	**Backfill**		**Fuel/ Electricity**
	PVC	250x230,8mm (40m)	Gravel	Well filters	500 kWh (cleaning and testing of the wells)
		200x184,6mm (130m)	Bentonite	Clay confining layers	
			Sand	Other layers	
Use phase	**Pump capacity**	**Heat pump**	**Time**	**Δ T**	**Energy consumption (pump)**
	30m3/h	49 kW	2000h/year	7K	4kW

Table 6. Technical data for a 250 kW BTES system in The Netherlands [personal information from TerraTechbv].

	BTES				
Drilling	**Depth**	**Number of boreholes**	**Boreholes Diameter**	**Additives**	**Fuel/Electricity**
	100m	75	150 mm	Water 20.000m3	3500 ltrs (diesel)
Pipes installation	**Material**	**Dimensions**	**Backfill**		**Antifreeze**
	PE	32x26mm	Bentonite	Clay confining layers	Ethylene glycol
			Sand	Other layers	
Use phase	**Pump capacity**	**Heat pump**	**Time**	**Δ T**	**Energy consumption (pump)**
	60m3/h	63kW	2000h/year	3,5K	10kW

3.3. LCA results and discussion

3.3.1. Eco- Indicator 99: ATES

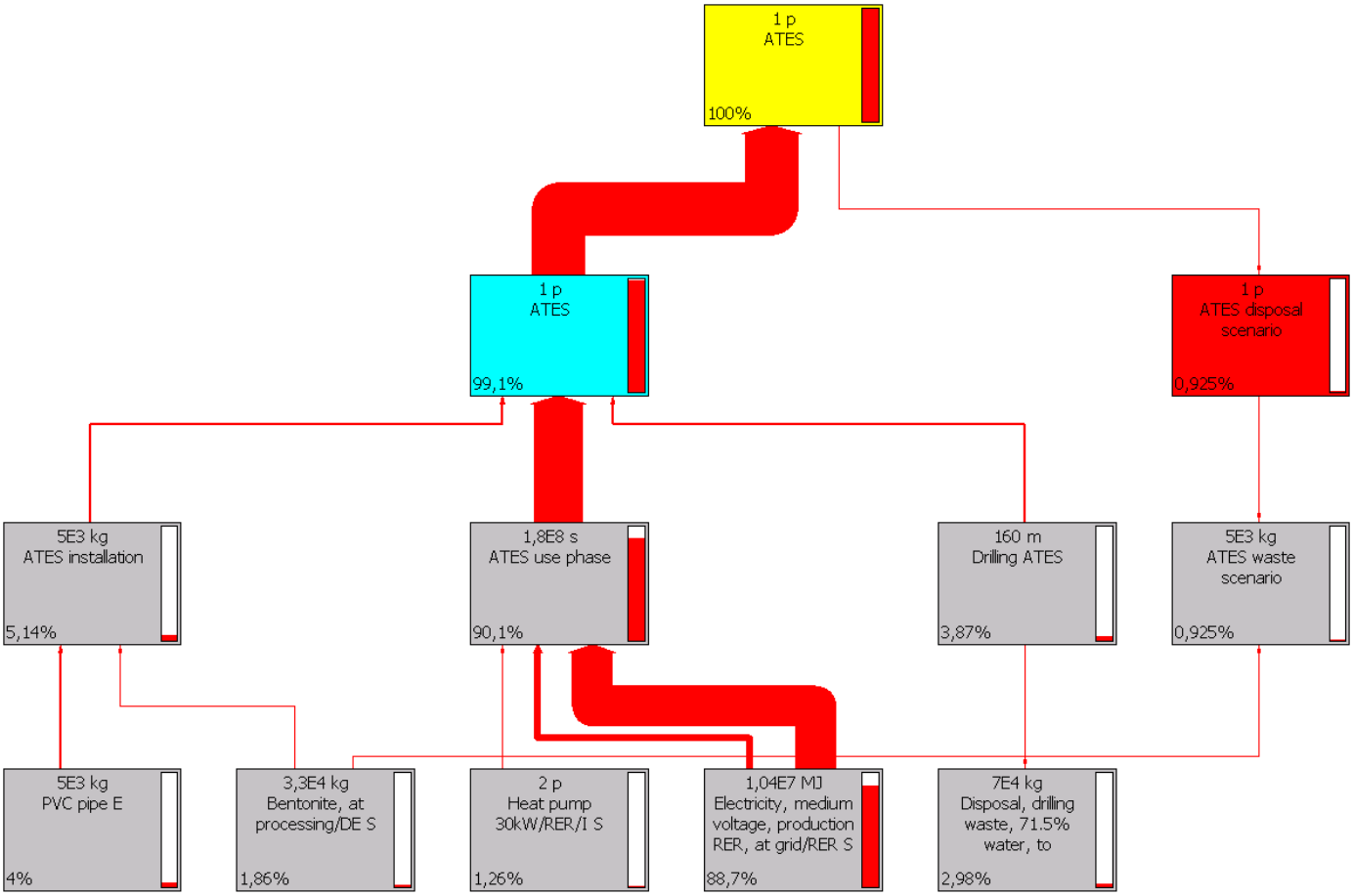


Figure 9. Life Cycle Tree of ATES. Eco-Indicator 99 (EI 99) Hierarchist perspective/ Average weighting (H/A). Cut off: 1%.

Figure 9 shows the main processes involved in the life cycle of a two wells ATES system with a capacity of 250 kW in The Netherlands. The width of the red arrows is proportional to the magnitude of the impacts of the material or process considered on the overall life cycle, calculated according to Eco-Indicator 99 impact method.

The normalized Impact categories indicators for ATES are shown in *Figure 10*. The normalization factor used is the environmental load of an average EU citizen per year. To compare the different impact categories it is not necessary to change this default factor but it is useful to remind that the functional unit chosen is 25 years so each result should be divided by 25 in order to obtain a fair comparison of the ATES impacts with the impacts caused by an average EU citizen.

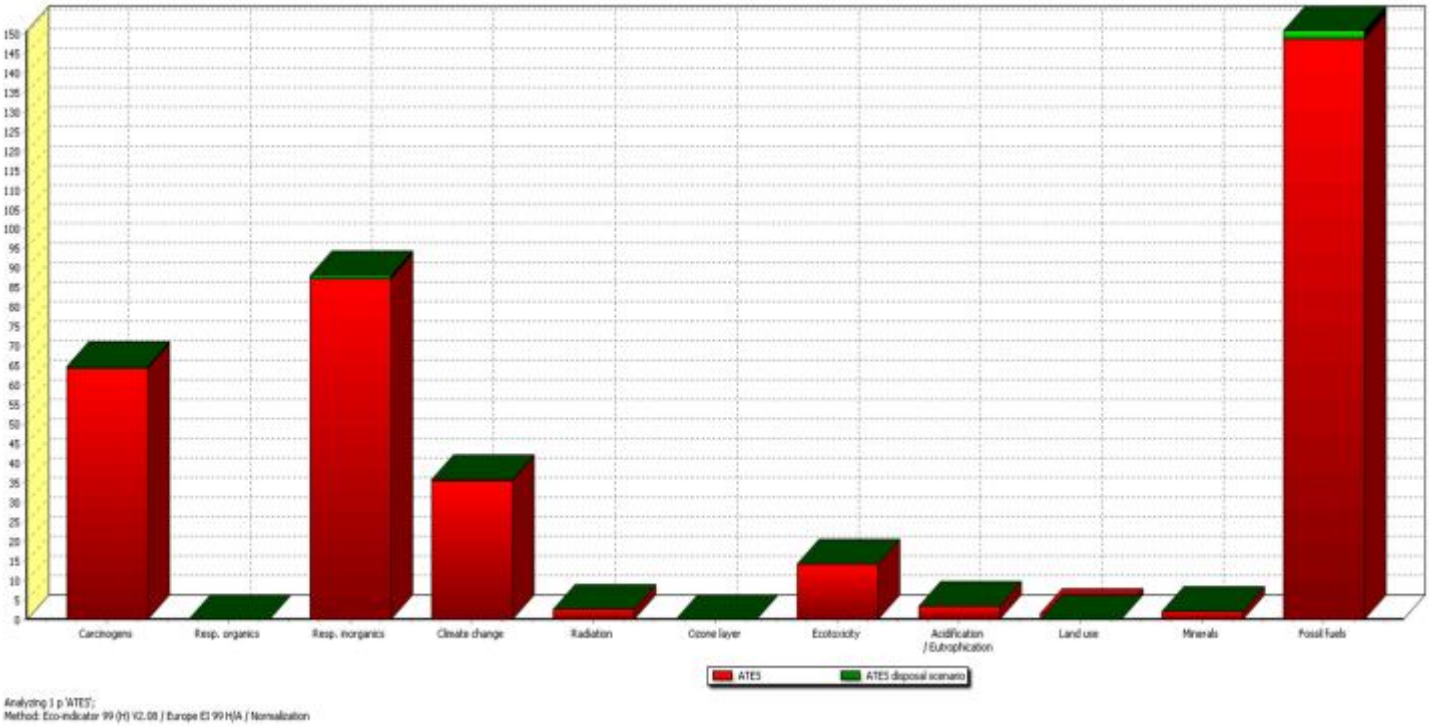


Figure 10. ATES. EI 99 H/A. Normalization. Impact categories.

As far as the Damage categories are concerned, the Ecosystem Quality category scores much lower compared to Human Health and Resources (*Figure 11*). The weighting procedure changes the proportions among the categories (*Figure 12*): in particular the Human Health category gains importance while the Resources one becomes less significant even if the Ecosystem Quality scores remain very low compared to the other two categories. This is probably due to the fact that EI 99 (as well as all the other impact methods available nowadays)does not take into account the possible hydrogeological, geochemical, microbiological and thermal impacts deriving directly from the production and reinjection of groundwater. At the same time, the Land use Impact category considers only the land occupation and transformation above the subsurface and not in the underground. The absence of these factors can be seen in *Table 7* that show the weighted contribution of the single processes of ATES life cycle to the Ecosystem Quality Damage category.

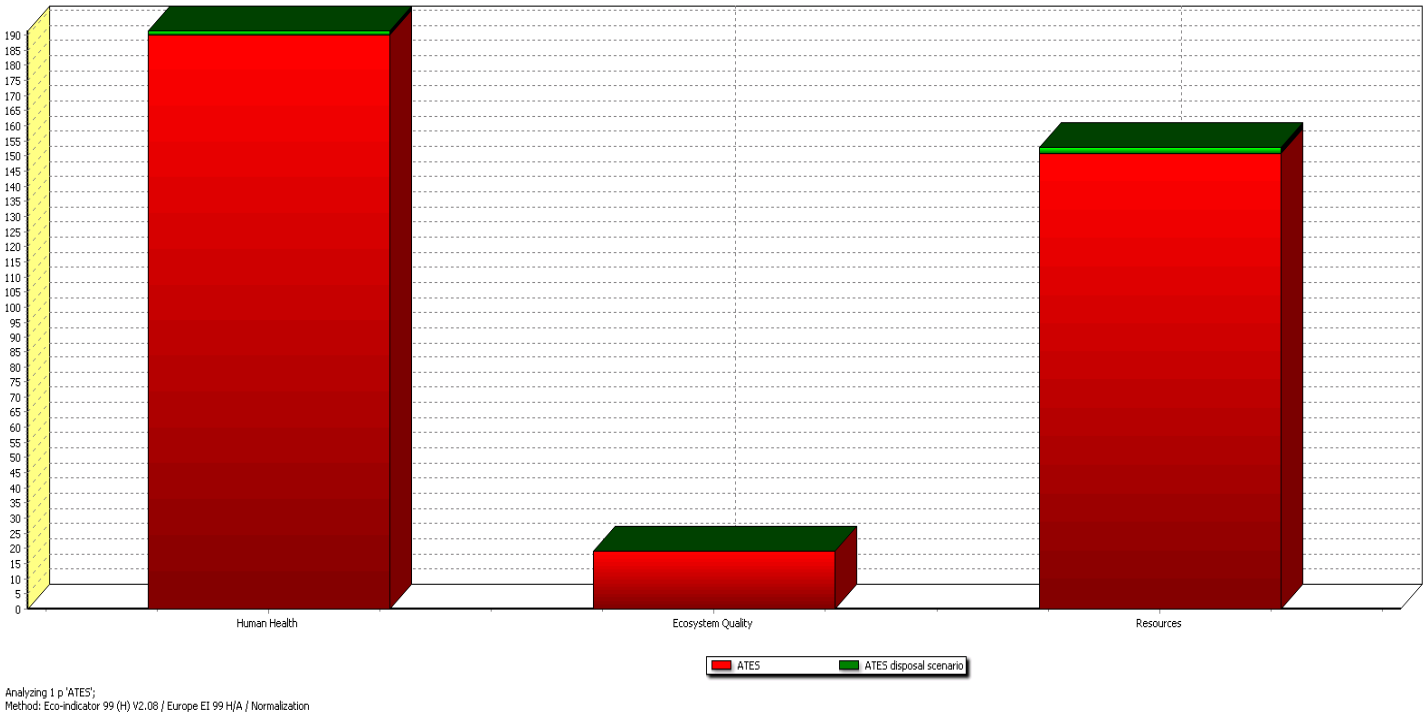


Figure 11. ***ATES. EI 99 H/A. Normalization. Damage categories.***

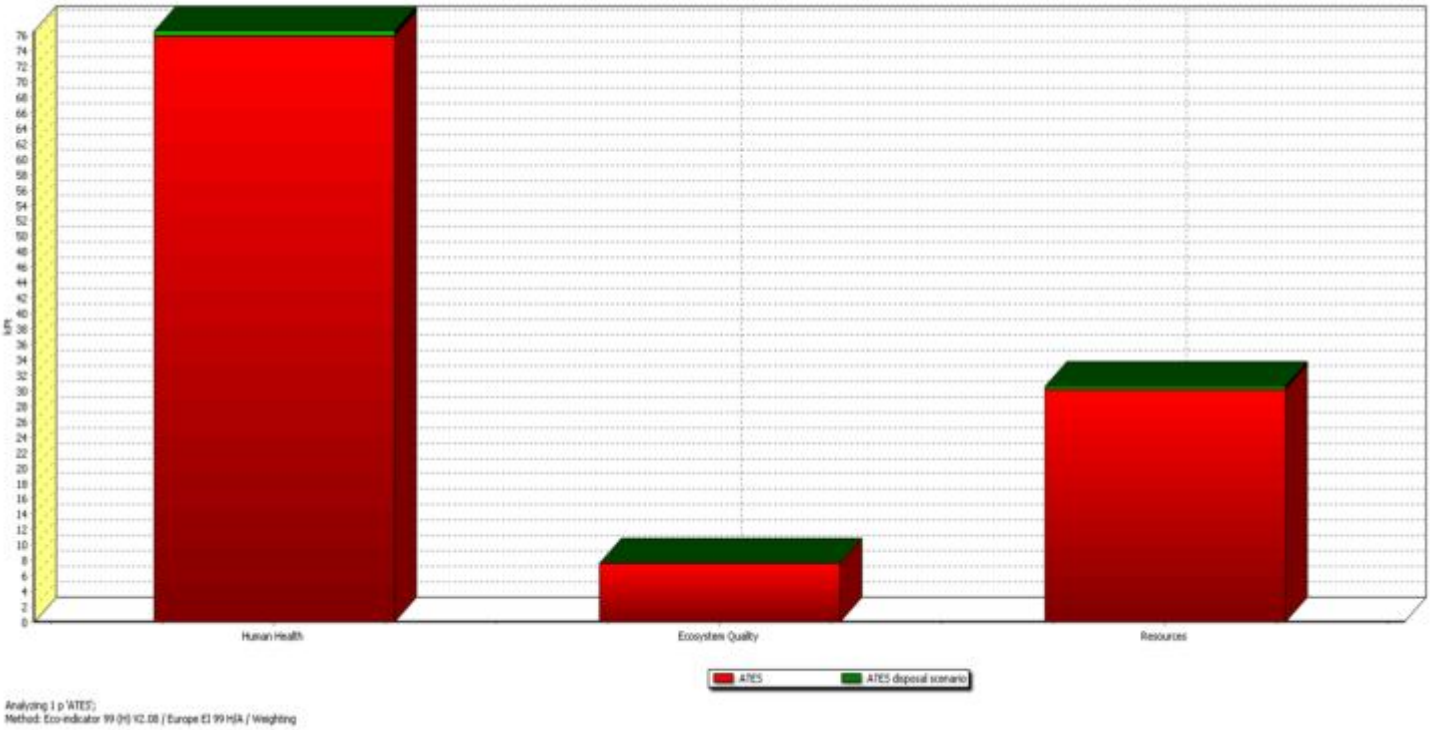


Figure 12. ATES. EI 99 H/A. Weighting. Damage Categories.

Table 7. ATES. EI 99 H/A. Weighting. Ecosystem Quality process contribution. Weighting. Cut off: 1%.

Process	Contribution %
Electricity	55.20
Disposal drilling waste to landfarming (50% allocation)	42.30
Heat pump production	1.18
Remaining processes	1.27

It is interesting to investigate the process contribution to the Human Health and Resources categories as well. The results are shown in *Table 8* and in ***Errore. L'origine riferimento non è stata trovata.*** respectively. Finally, in *Figure 14,* the results are displayed as a single score that sums up all the damage categories

Table 8. ATES. EI 99 H/A. Weighting. Process contribution. Damage category: Human Health. Cut off:1%.

Process	Contribution %
Electricity	90.60
PVC pipes production	4.65
Heat pump production	1.52
Bentonite	1.51
Disposal drilling waste to landfill	1.15
Remaining processes	0.54

The electricity production process contributes to more than 90% of the damages caused to Human Health. The electricity production process chosen is a European countries mix. As revealed in *Figure 13* ,in 2009, 51.3 % of the total gross European electricity production was generated from fossil fuelsof which more than 25% from coal and lignite (EUROSTAT, 2010).

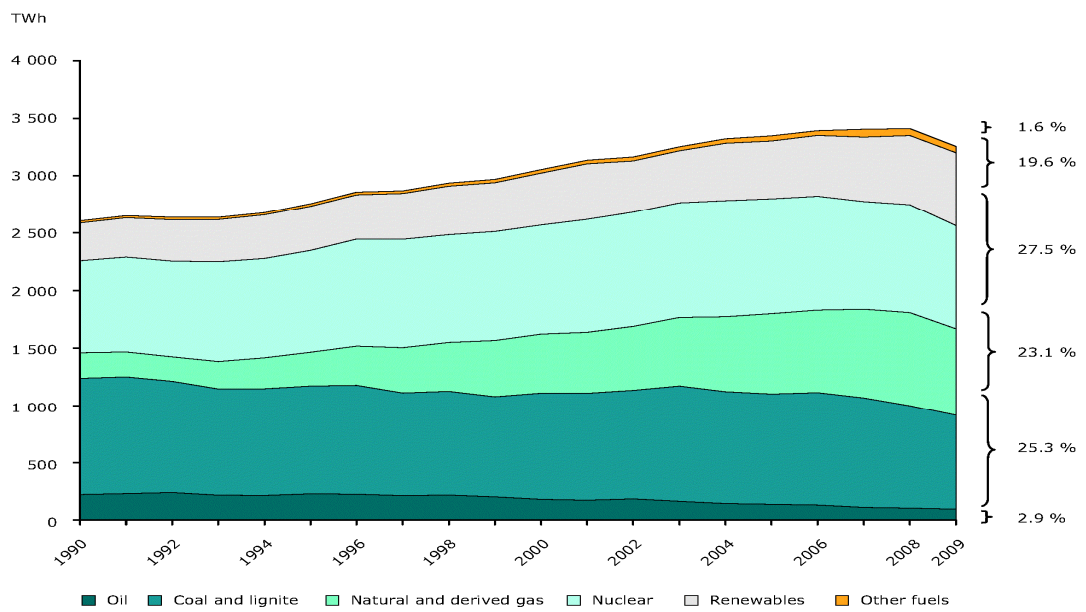


Figure 13. Electricity production by fuel in EU (from Eurostat 2010).

Electricity production can have negative impacts on the environment and human health. The fuel mix used for electricity production provides a broad indication of whether these effects are likely to diminish or will be enhanced. The type and the extent of pressures on the environment and human health stemming from electricity production depend upon the type and the amount of fuels used for electricity generation as well as the use of abatement technologies. Electricity production from fossil fuels can provide a proxy indicator of resource depletion, CO_2 and other greenhouse gas emissions and air pollution levels (e.g. SO_2 and NO_x; European Environmental Agency, 2012). ***Errore. L'origine riferimento non è stata trovata.*** shows the contribution of the single substances to the Human Health damage category: the listed substances can indeed be emitted during the burning of fossil fuels, especially coal and oil. The only exception is the tetrachlorodibenzodioxin that is emitted during the production of the PVC pipes (Thornton, 2002).

Table 9. ATES. Process contribution. Damage category: Resources. Weighting. Cut off:1%.

Process	Contribution %
Electricity	92.30
PVC pipes production	3.30
Bentonite	3.06
Remaining processes	1.35

Table 10. ATES. Damage category Human Health. Contribution by substance. Weighting. Cut off: 1%.

Substance	Contribution %
Arsenic, ion	24.34
Carbon dioxide, fossil	17.43
Particulates <25 um	15.65
Sulfur dioxide	14.75
Nitrogen oxides	13.23
Cadmium, ion	4.36
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	3.97
Particulates >2.5 um and < 10um	2.08
Remaining substances	4.17

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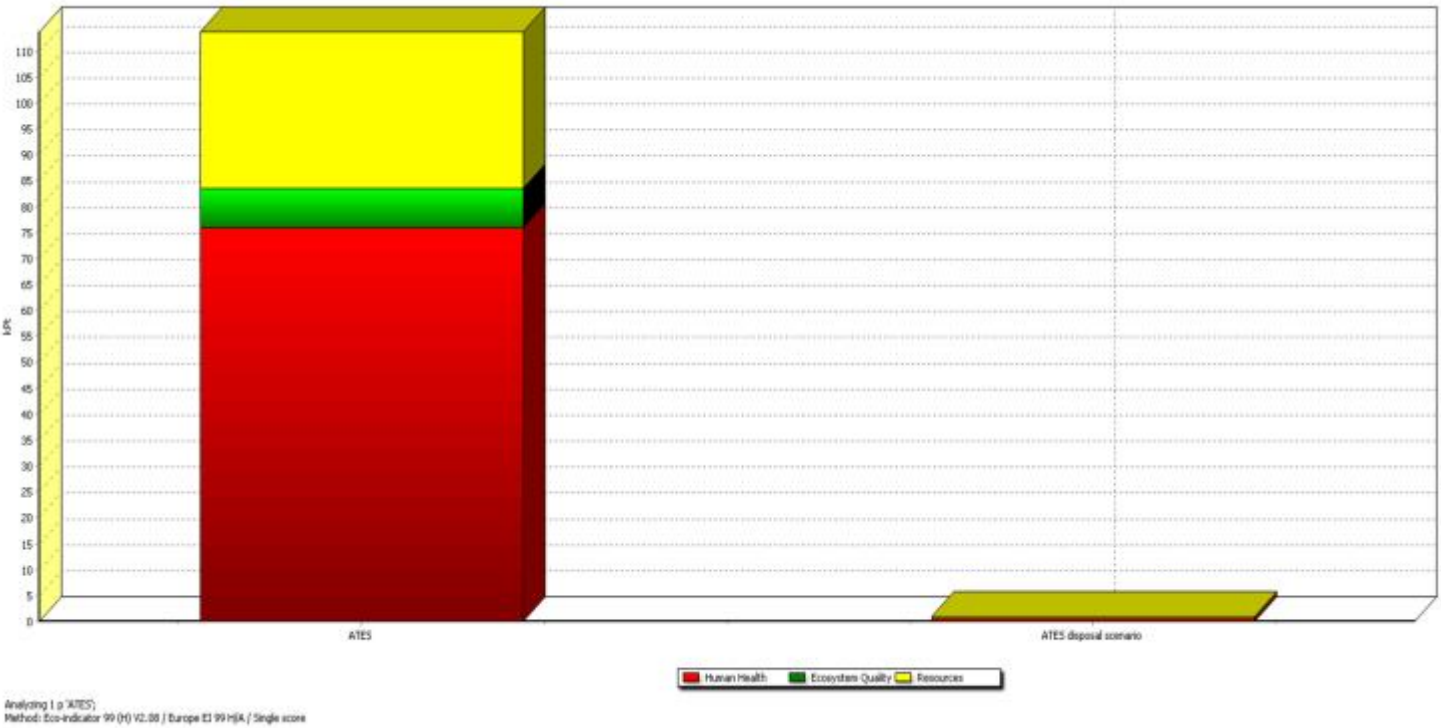

Figure 14. ATES. EI 99 H/A. Single score. Damage categories.

As far as the disposal scenario is concerned, it is important to note that the impacts of the remaining plastic wells and pipes in the underground at present are still impossible to model within SimaPro. Therefore a proxy has been used, namely the landfill disposal. Sealing of the pipes in the underground with bentonite is considered. The modelled disposal scenario accounts only for less than 1% of the total impact results (*Figure 14*). In that case, the use of a proxy does not seem to be of major relevance due to the little percentage of its impact compared to the overall life cycle.

Last but not least, *Table* shows the LCA processes contribution to the total potential impacts caused by ATES. As predictable form the previous results, the operational phase of ATES that requires electricity use (with a functional unit of 25 years) is responsible of most of the impacts calculated with Eco-indicator 99.

Table 11. ATES. Process contribution. Single score. Cut off: 1%.

Process	Contribution %
Electricity	88.70
PVC pipes production	4.00
Disposal drilling waste to landfarming (50% allocation)	2.98
Bentonite	1.86
Heat pump production	1.26
Remaining processes	1.20

3.3.1. Eco-Indicator 99: BTES

The results produced for the ATES LCA have also been produced for an average BTES system with the same capacity as the ATES considered and the same underground and climate conditions. These results will be discussed here.

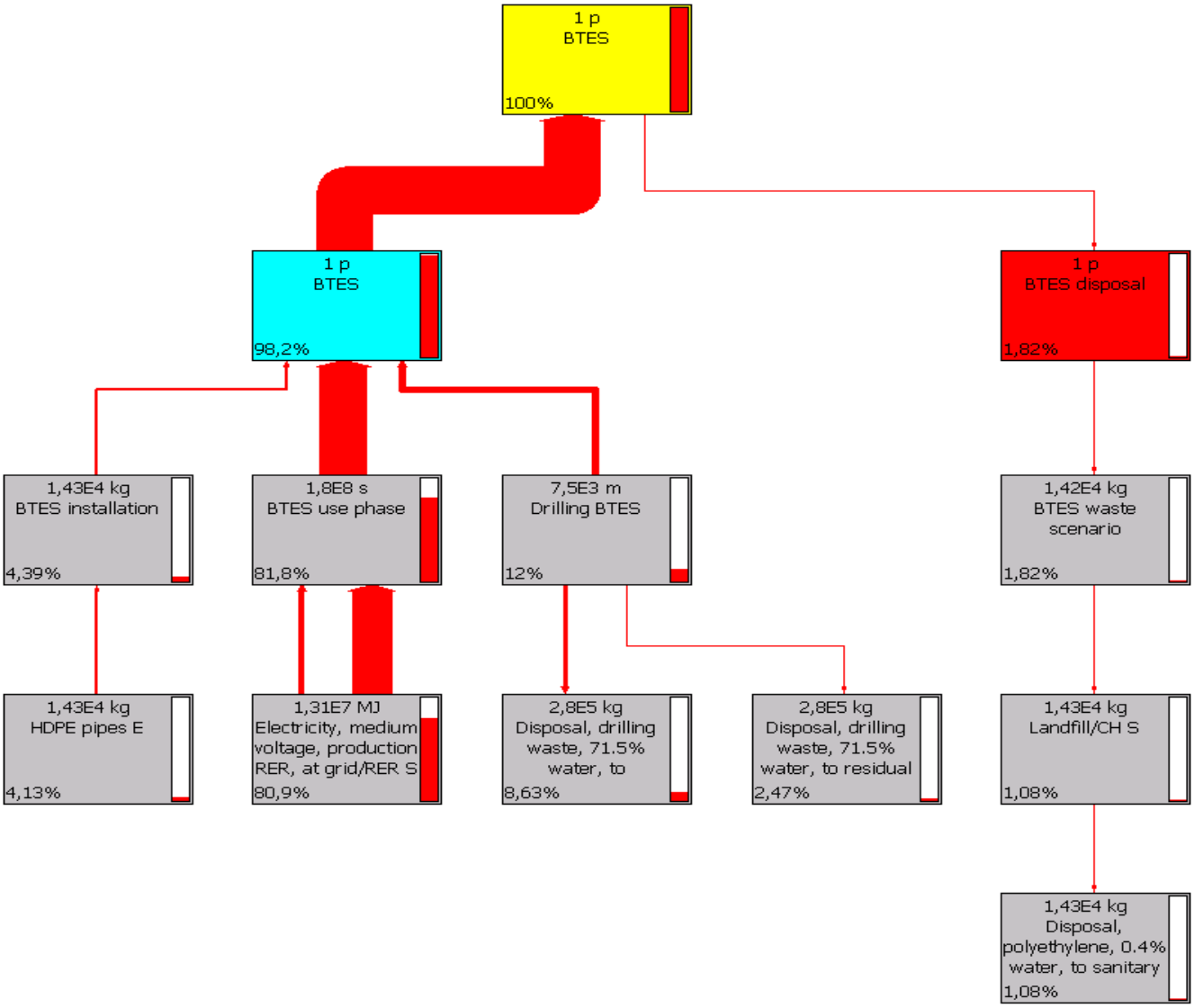

Figure 15. Life cycle tree of BTES. EI 99 H/A. Cut off 1%.

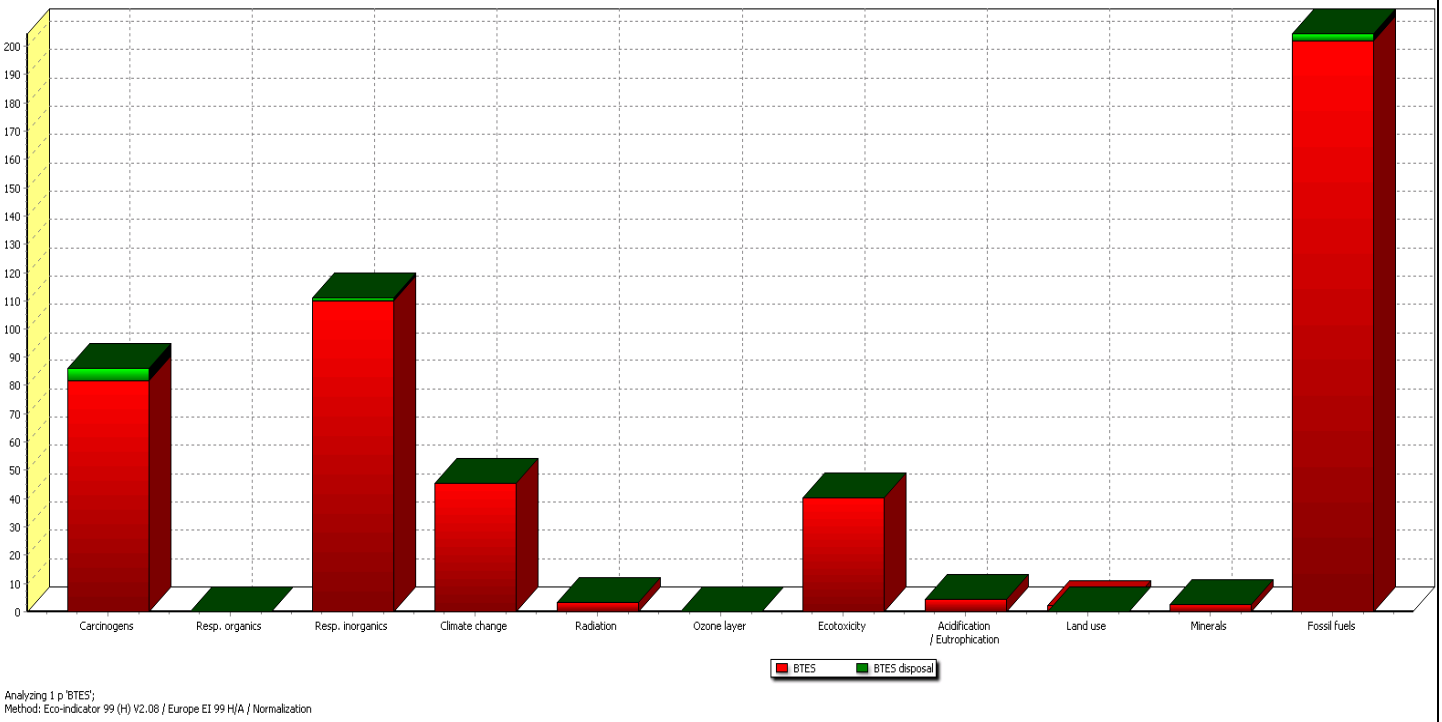

Figure 16. BTES. EI 99 H/A. Normalization. Impact categories.

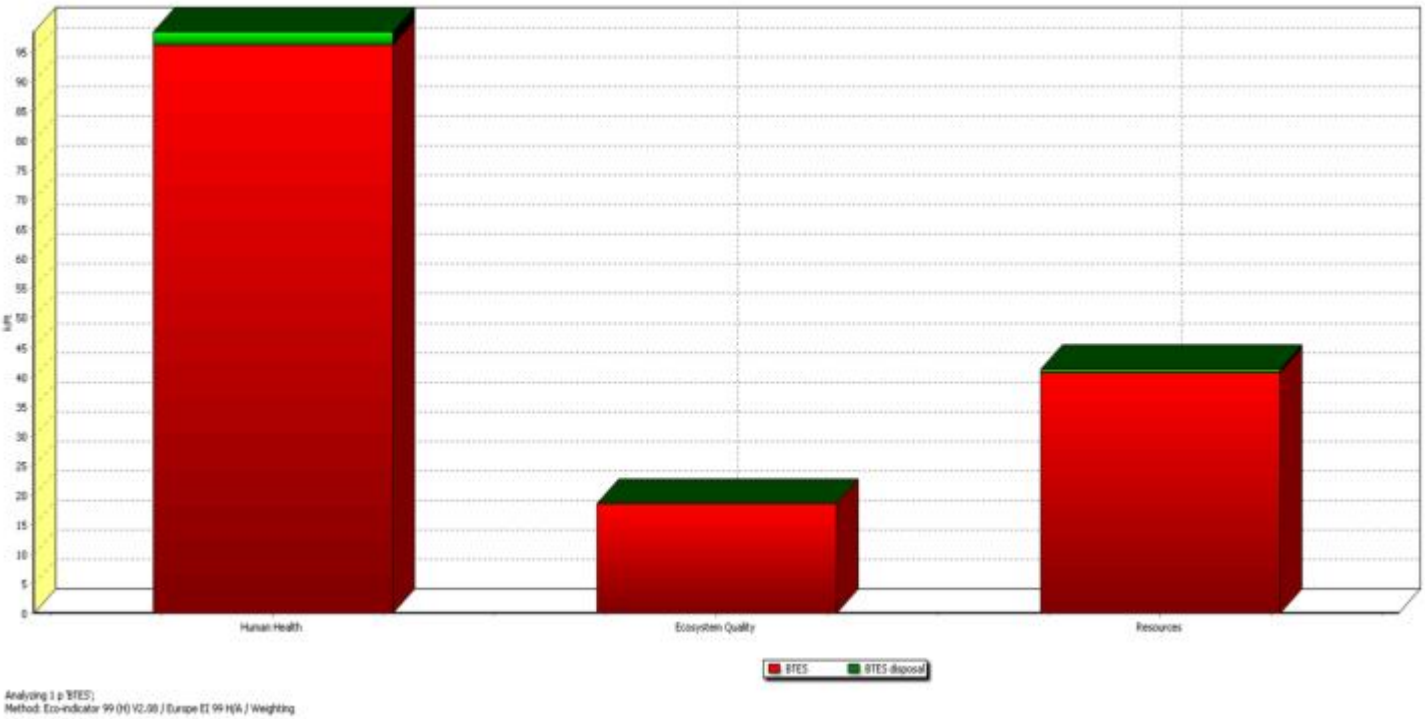

Figure 17.*BTES. EI 99 H/A. Weighting. Damage categories.*

The Ecosystem Quality category scores lower than Human Health and Resources also in this case. The same consideration relative to the open system are valid for the closed system as well: the low Ecosystem Quality score is probably due to the fact that the impact method does not take into account either the possible hydrogeological, geochemical, microbiological and thermal impacts or the underground occupation.

Table 12. BTES. EI 99 H/A. Weighting. Process contribution. Damage category: Ecosystem Quality. Cut off: 1%.

Process	Contribution %
Disposal drilling waste to landfarming (50% allocation)	69.50
Electricity	28.50
Remaining processes	1.93

In this case the main process responsible for the Ecosystem Quality damage is the drilling waste disposal to landfarming. The reason is that - in order to install a closed system - the number of boreholes required is much higher compared to the open one. It is important to note that, as the destiny of the drilling waste is uncertain and it changes depending on the drilling location and on the drilling company involved, an allocation has been used as a proxy. In particular 50% of the drilling waste was destined to landfarming and the other 50% to landfill. It is interesting to note that the landfarming process impacts have a score almost 3.5 times higher than the landfill ones in the overall life cycle. This might depend on the lower control possible over this bioremediation technique versus a landfill as well as on the longer time required by landfarming.

Figure 18 and *Table* show the single score results and the process contribution to the complete life cycle, respectively. Some similarities with ATES results are noticeable in this case as well: the end of life impacts contribute to a very low extent to the life cycle impacts and, even if the drilling disposal process causes more damage due to a greater quantity of drilling waste, the main process contribution to the overall BTES life cycle is caused by the electricity consumption during the operational phase. A landfill proxy is used also for the BTES end-of-life scenario and the same considerations made previously for ATES are valid for BTES.

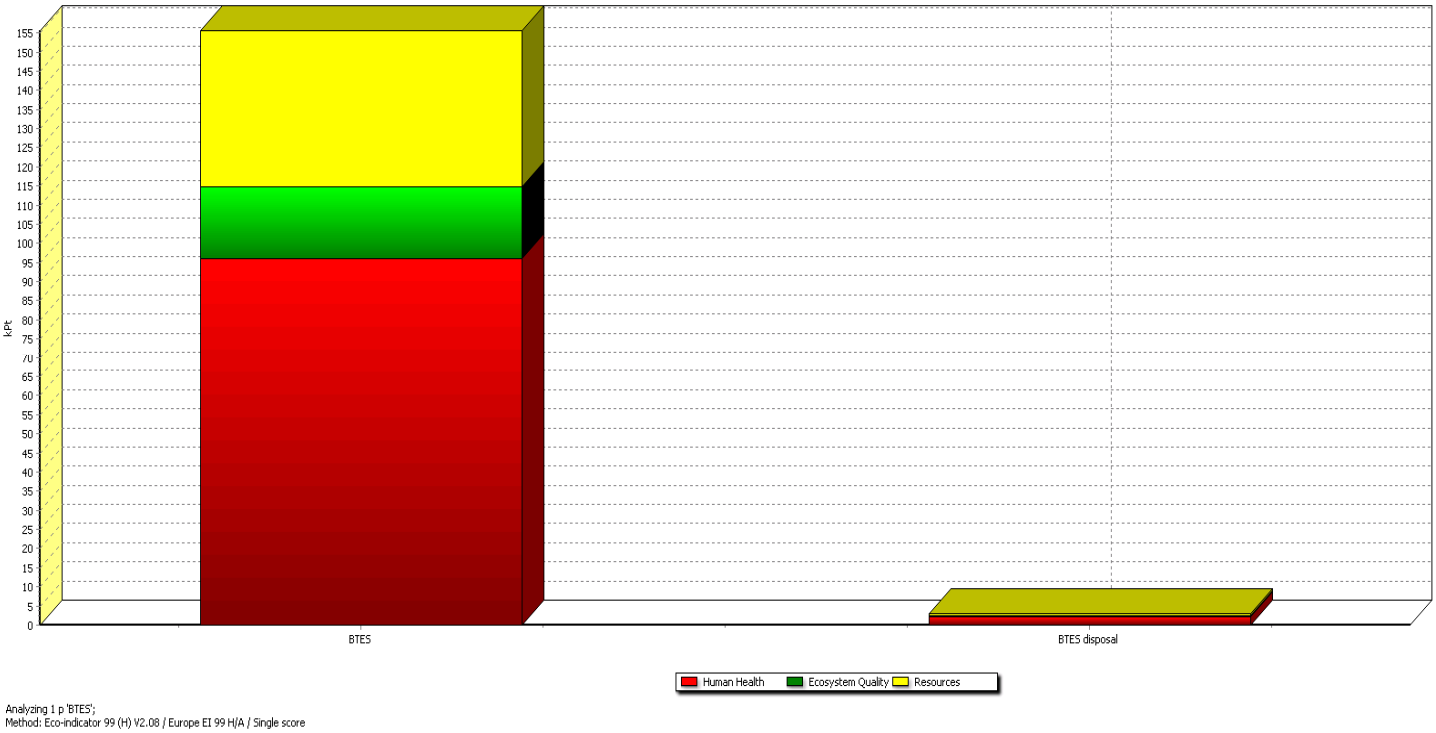

Figure 18.BTES. EI 99 H/A. Single score. Damage categories.

Table 13. BTES. EI 99 H/A. Process contribution. Single score. Cut off: 1%.

Process	Contribution %
Electricity	80.90
Disposal drilling waste to landfarming (50% allocation)	8.60
Polyethylene pipes production	4.10
Disposal drilling waste to landfill (50% allocation)	2.47
Disposal polyethylene to landfill (proxy)	1.08
Remaining processes	2.82

From these results it is easy to conclude that the main impacts - assessed with the Eco-Indicator 99 method - of the considered open and closed thermal energy storage systems are caused by the electricity production partially deriving from fossil fuels fired power plants. It is intuitive that, if it was possible to use entirely renewable energy for the pumping process, like solar or wind energy, the impact results would certainly be less important. This aspect will be further investigated during the sensitivity analysis.

3.3.3. Eco-Indicator 99: ATES and BTES comparison

One of the aims of this study is to compare ATES and BTES systems. The most straightforward way to achieve this goal is to look at the LCA single scores results that show the overall performance of the two systems.

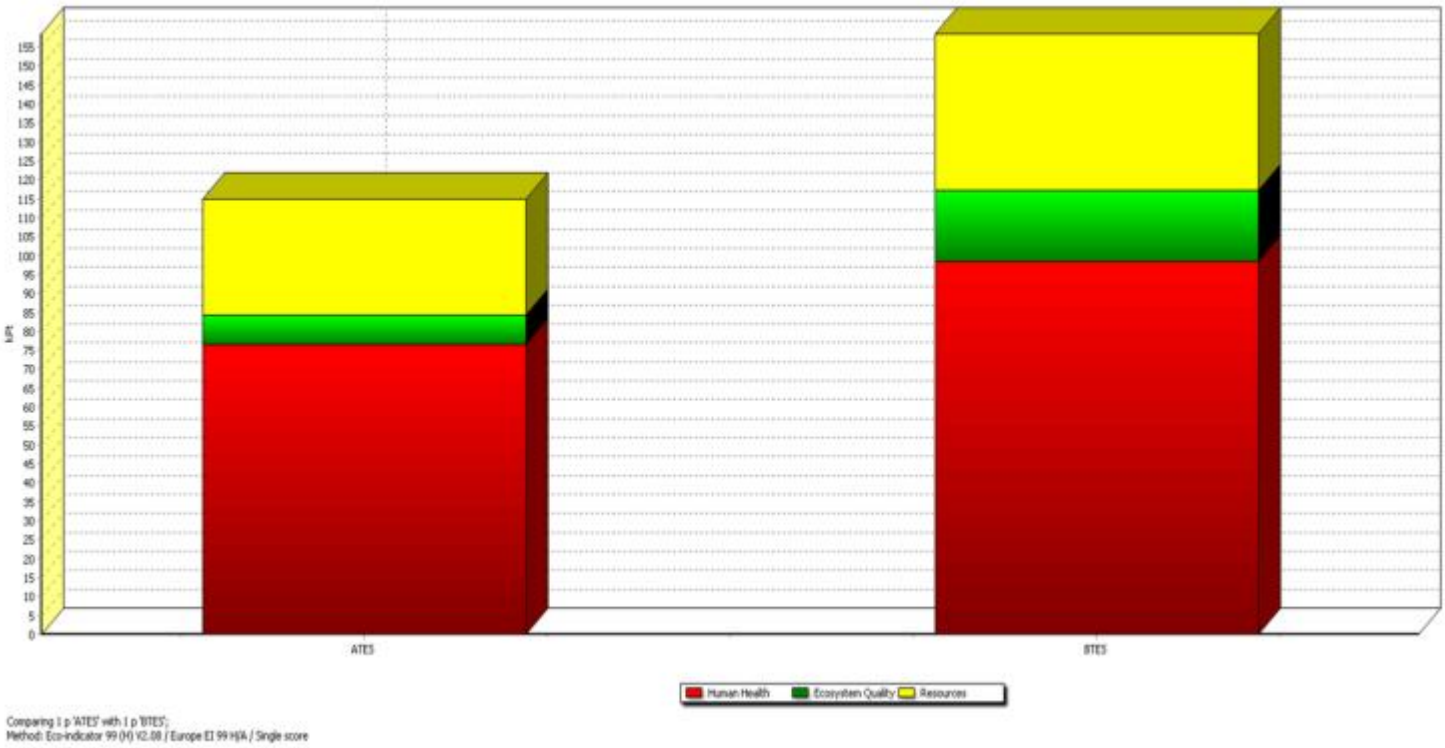

Figure 19. ATES and BTES comparison. EI 99 H/A. Single score.

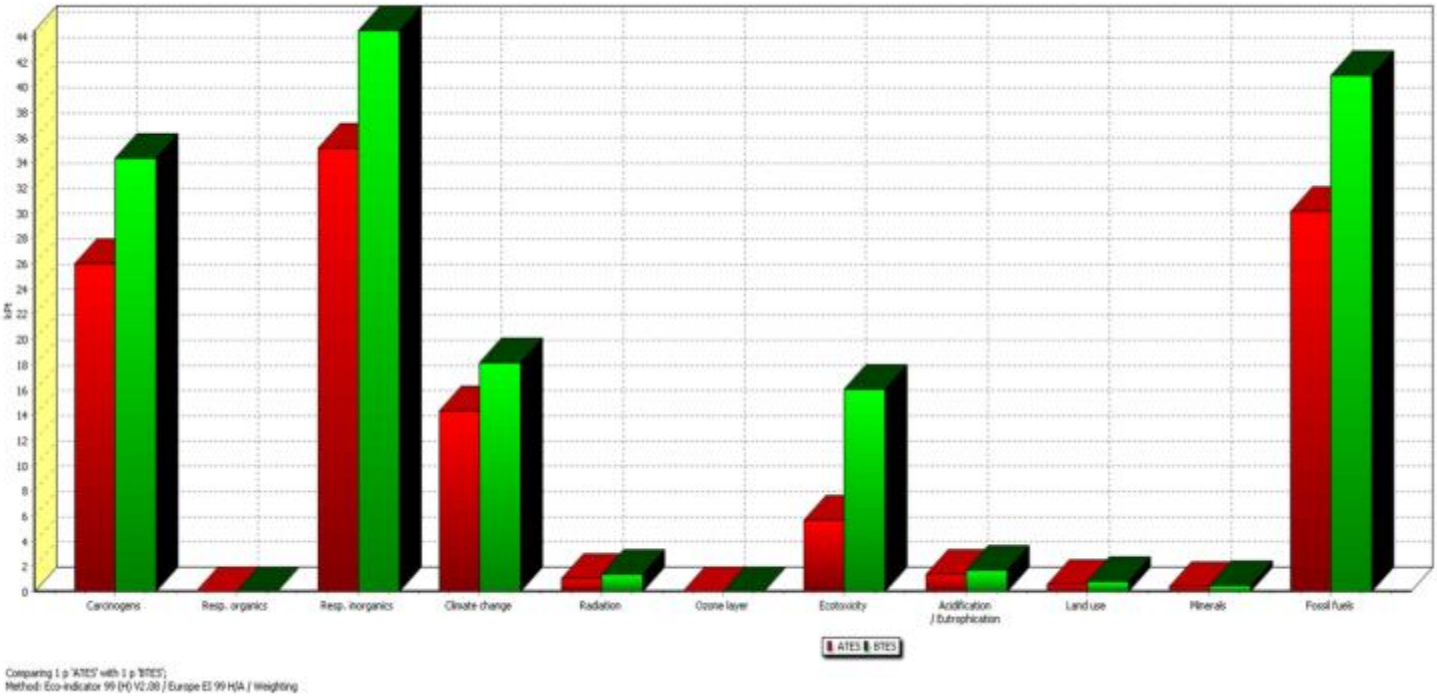

Figure 20. ATES and BTES comparison. EI 99 H/A. Weighting. Impact categories.

From *Figure 19* it is easy to see that ATES performs better than BTES, as a lower score means lower impacts. Each Damage category is associated to fewer points for ATES compared to BTES as well. It is interesting to check also the single Impact categories scores (*Figure 20*). Once again, every single Impact category scores lower for ATES compared to BTES.

The reason for the better performance of ATES is that - for both systems - the main impacts are caused by the electricity consumption that is higher for BTES (the water is recovered at a lower temperature than it is stored, therefore more cubic metres are to be pumped and/or the heat pump use is more frequent). Moreover, because of the greater quantity of materials produced and required by the closed systems, also the drilling waste impacts and the plastic tubes production are more significant.

3.3.4. Eco-Indicator 99: UTES versus natural gas traditional heating system

It is interesting to investigate the impacts of UTES compared to a traditional heating system like a boiler burning natural gas. The system is chosen directly from the Eco-Invent library of SimaPro and the heat provided is of course equal to the heat recoverable with the ATES and BTES considered over the functional unit of 25 years: 4.5 x 10^7 MJ. The chosen traditional heating system`s name in the library is "natural gas, burned in boiler modulating >100kW" and the included processes are fuel input from high pressure (RER) network, infrastructure (boiler), emissions, and electricity needed for operation. The module uses the average net efficiency for the type of boiler (estimated from literature). The geographical cover is

extrapolated from Switzerland to Europe (RER) and the technology is as of the new models on market.

Figure 21 compares the Impact categories of the three heating systems. The relevant categories are Carcinogens, Respiratory inorganics, Climate change, Ecotoxicity and Fossil fuels. Both UTES systems score worse in three of these categories, namely Carcinogens, Respiratory inorganics and Ecotoxicity. The higher carcinogenic and respiratory inorganics impacts of the UTES technologies derive essentially from the mixed electricity production necessary to obtain the pumping energy while the ecotoxicity is mainly due to the drilling waste disposal first and then to the electricity production as well. The Climate change and Fossil fuels categories have obviously higher impacts for the natural gas heating system due to the direct burning of this fossil fuel leading to CO_2 and CH_4 emissions.

Tables 14 to 18 show the different substances contribution to the above mentioned Impact categories in the three heating systems.

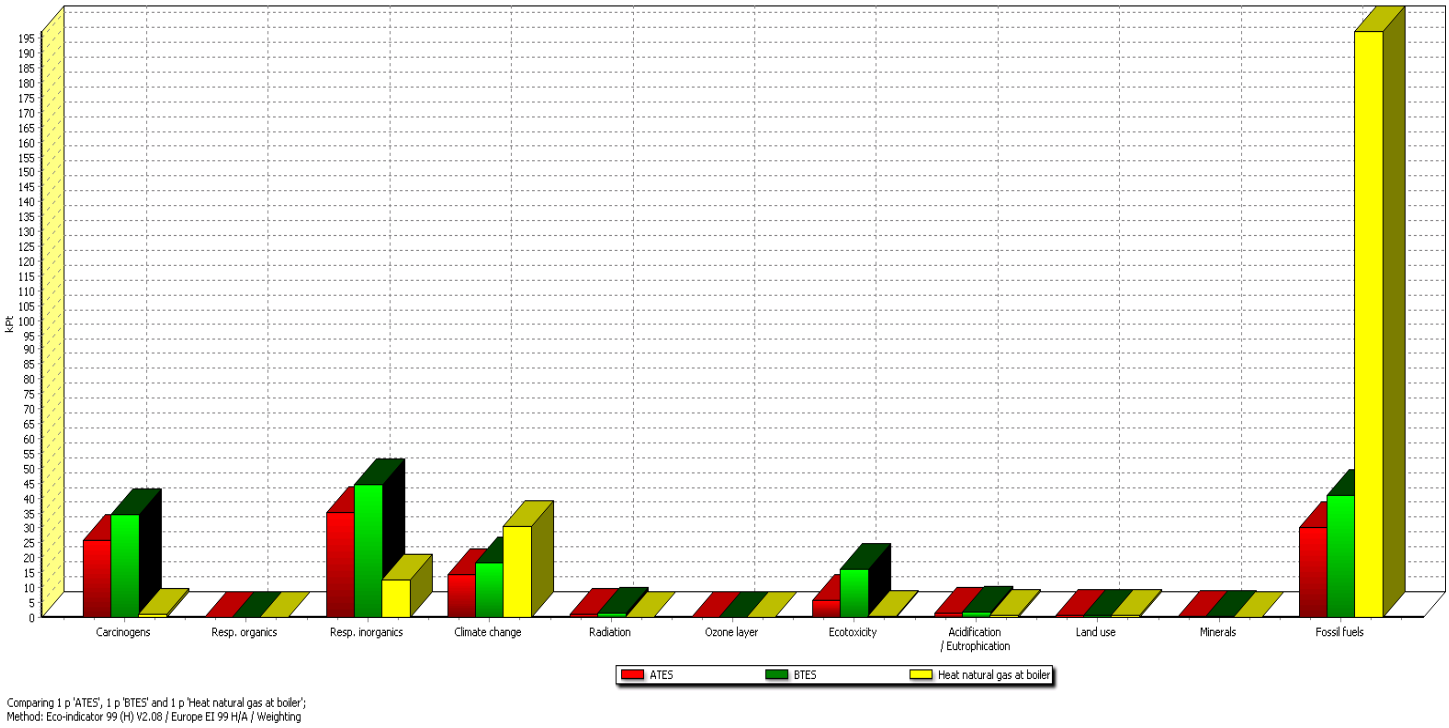

Figure 21. ATES, BTES and Natural Gas Boiler comparison. EI 99 H/A. Weighting. Impact categories.

Carcinogens:

Table 14. ATES, BTES and Natural Gas Boiler comparison. EI 99 H/A. Substance contribution to the Carcinogens Impact category. Cut off: 1%.

Substance	Contribution % (ATES)	Substance	Contribution % (BTES)	Substance	Contribution % (boiler)
Arsenic ion	71.7	**Arsenic ion**	75	**Arsenic ion**	75.3
Cadmium ion	12.9	**Cadmium ion**	16.4	**Cadmium ion**	21.1
Dioxin, 2,3,7,8 tetrachloro dibenzo-p-	11.7	**Dioxin, 2,3,7,8 tetrachloro dibenzo-p**	3.8	**Particulates <2.5um**	1.78

The arsenic ion and the cadmium ion derive from the electricity production process (they are a waste of fossil fuels power plants, especially coal). The tetrachlorodibenzodioxin derives mainly from the production of the PVC and HDPE pipes production.

Respiratory inorganics:

Table 15. ATES, BTES and Natural Gas Boiler comparison. EI 99 H/A. Substance contribution to the Respiratory inorganics Impact category. Cut off: 1%.

Substance	Contribution % (ATES)	Substance	Contribution % (BTES)	Substance	Contribution % (boiler)
Particulates < 2.5um	33.6	**Particulates < 25um**	33.6	**SO_2**	60.9
SO_2	32.1	**SO_2**	32	**NOx**	23.6
NOx	28.8	**NOx**	29.1	**Particulates < 25 um**	11.6
Particulates >2.5 um < 10 um	4.55	**Particulates >2.5 um < 10 um**	4.49	**Particulates >2.5 um < 10 um**	3.86

Climate change:

Table 16. ATES, BTES and Natural Gas Boiler comparison. EI 99 H/A. Substance contribution to the Climate change Impact category. Cut off: 1%.

Substance	Contribution % (ATES)	Substance	Contribution % (BTES)	Substance	Contribution % (boiler)
CO_2	93.2	**CO_2**	92.6	**CO_2**	94.6
CH_4	3.67	**CH_4**	3.67	**CH_4**	4.98
N_2O	1.03	**N_2O**	1.03	-	-

All the substances in *Table 15* and *16* derive from the burning of fossil fuels, so the main process that contributes to the respiratory inorganics and climate change impacts of UTES is again electricity production necessary for the operational phase of the system.

Ecotoxicity:

Table 17. ATES, BTES and Natural Gas Boiler comparison. EI 99 H/A. Substance contribution to the Ecotoxicity Impact category. Cut off: 1%.

Substance	Contribution % (ATES)	Substance	Contribution % (BTES)	Substance	Contribution % (boiler)
Zinc	43.8	**Zinc**	56.84	**Nickel**	29.52
Chromium	28.3	**Chromium**	27.8	**Zinc**	28.76
Nickel	24.43	**Nickel**	10.82	**Chromium**	24.92
Copper	3.23	**Copper**	1.49	**Copper**	8.63
Lead	1.62	**-**	-	**Lead**	5.07

Ecotoxicity is mainly due to metals leakage and emission into soil, water and air during the disposal of the drilling waste to landfarming (56% for ATES and 80%for BTES) and to a minor extent during the production of electricity from power plants (40% for ATES and 18% for BTES).The ecotoxicity of natural gas heating system is much smallerand is due to the emission of lower quantities of metal ions during gas combustion and steel pipes production.

Fossil fuels:

Table 18. ATES, BTES and Natural Gas Boiler comparison. EI 99 H/A. Substance contribution to the Fossil fuels Impact category. Cut off: 1%.

Substance	Contribution % (ATES)	Substance	Contribution % (BTES)	Substance	Contribution % (boiler)
Natural gas	71.4	**Natural gas**	69.1	Natural gas	99.4
Crude oil	23.68	**Crude oil**	26.56	-	-
Hard coal	4.75	**Hard coal**	4.41	-	-

Natural gas, oil and coal consumption is due to the electricity and pipe production for UTES while natural gas is obviously consumed through direct combustion in the traditional heating system.

As far as the Damage categories are concerned, as a consequence of the Impact categories scores, the natural gas boiler turns out to cause lower damages to human health and ecosystem quality but definitely higher resources depletion (*Figure 22*).

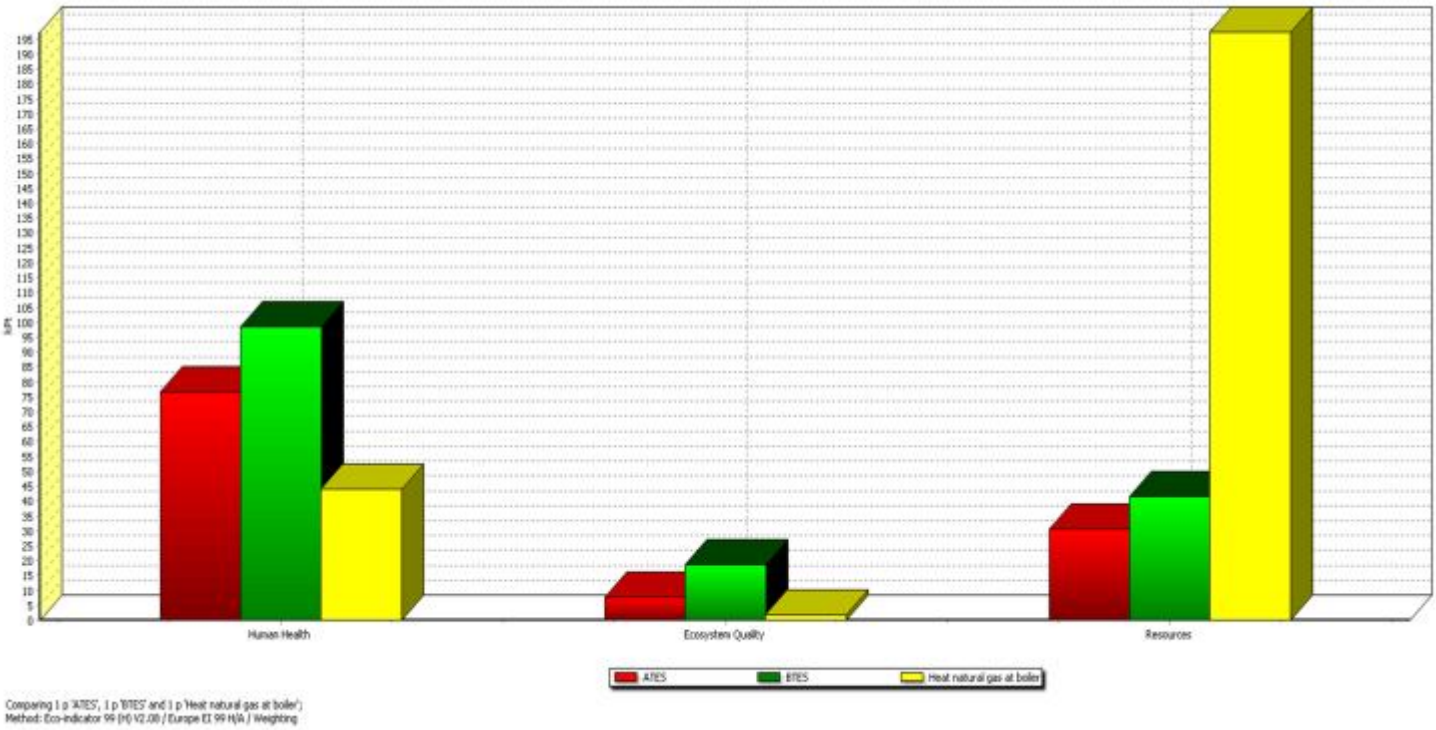

Figure 22. ATES, BTES and Natural Gas Boiler comparison. EI 99 H/A. Weighting. Damage categories.

Finally, as shown in *Figure 23,* the single score results suggest that the overall damages caused by the use of the traditional heating system are higher than those caused by the use of both ATES or BTES. The difference is a factor of 2 for the ATES and 1.5 for the BTES.

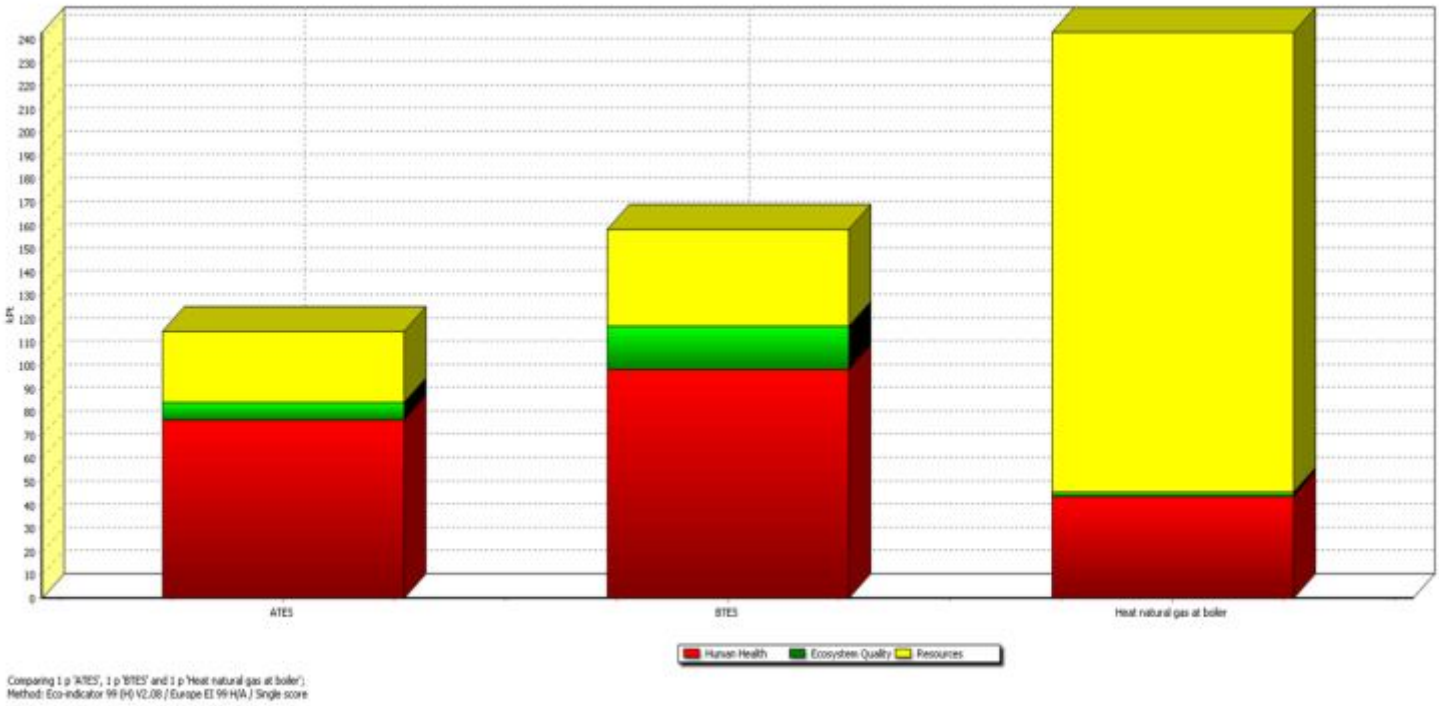

Figure 23. ATES, BTES and Natural Gas Boiler comparison. EI 99 H/A. Single score.

3.3.5. Cumulative Energy Demand (CEnD)

This method aims to investigate the energy use throughout the life cycle of a good or a service. This includes the direct uses as well as the indirect or grey consumption of energy due to the use of, e.g., construction materials or raw materials. CEnD values can be used to compare the results of a detailed LCA study with others where only primary energy demand is reported. Indeed many papers report only the primary energy savings without considering the energy demand of the entire life cycle of the good or service. For example, the primary energy demand of the ATES and BTES systems considered would be equal to the electricity requirements for the pumping plus the heat pump functioning during the operational phase, so 53 KW and 73 KW respectively (*Table 5*and*Table 6*). This would result in a primary energy saving of~3.5 x 10^7 MJ for ATES and ~3 x 10^7 MJ for BTES, representing 77% and 70% of primary energy savings respectively, a figure comparable to the ones reported in other papers and documents relative to UTES energy savings (Desmedt and Hoes, 2005;Stockton college, 2013).

The life cycle energy demand calculated with the CEnD method is3.28 x 10^7MJ for ATES and 4.22 x 10^7MJ for BTES (*Table 19*). These figures (especially the CEnD of BTES) are actually slightly lower than the total thermal energy recovered (4.5 x 10^7 MJ). This result could suggest that UTES are not particularly energetically advantageous or might even be disadvantageous in case of low efficiency of the system due, for example, to a poor system design. On the contrary, the energetic efficiency of the systems should be evaluated relatively to the alternative possible options to retrieve the same amount of heat. Indeed, when compared with the traditional natural gas heating system, UTES cumulative energy demand is consistently lower, especially ATES one (*Figure 24*). Moreover, sometimes more energy of one form is spent to retrieve a smaller amount of another form of energy that is required in a particular location at a particular moment in time. This might depend on the energy cost as well as on its availability.

When using the CEnD method it is fundamental to point out that different concepts for determining the primary energy requirement exist. For CEnD calculations one may chose the lower or the upper heating value of primary energy carriers where the latter includes the evaporation energy of the water present in the fuel. Furthermore one may distinguish between energy requirements of renewable and non-renewable resources. Finally, different ways to handle nuclear and hydro electricity exist. Unfortunately, so far there is no standardized way for this type of assessment method. Due to the existence of diverging concepts and the unclear basis for the characterization of the different primary energy carriers, the CEnD indicator implemented in SimaPro is split up into eight categories (*Table*) and no aggregated value is presented.

Table 19. Impact assessment method cumulative energy demand (CEnD) implemented in Ecoinvent (database used in SimaPro).

Category	Subcategory	includes
Non-renewable resources	fossil	hard coal, lignite, crude oil, natural gas, coal mining off-gas, peat
	nuclear	uranium
	primary forest	wood and biomass from primary forests
Renewable resources	biomass	wood, food products, biomass from agriculture, e.g. straw
	wind	wind energy
	solar	solar energy (used for heat & electricity),
	geothermal	geothermal energy (shallow: 100-300m)
	water	run-of-river hydro power, reservoir hydro power

Common to all categories is the assumption that all energy carriers have an intrinsic value. This intrinsic value is determined by the amount of energy withdrawn from nature. *Table* shows the impact factors (MJ-eq / unit) of the different energy resources as well as their subcategory in the CEnD method as implemented in the database Ecoinvent (used in SimaPro).

Table 20. Impact factors for the cumulative energy demand implemented in ecoinvent data v2.0. From Ecoinvent Centre, 2007.

Name	Category	SubCategory	Unit	cumulative energy demand fossil	cumulative energy demand nuclear	cumulative energy demand primary forest	cumulative energy demand biomass	cumulative energy demand wind	cumulative energy demand solar	cumulative energy demand geothermal	cumulative energy demand water
SubCategory											
Name				non-renewable energy resources, fossil	non-renewable energy resources, nuclear	non-renewable energy resources, primary forest	renewable energy resources, biomass	renewable energy resources, kinetic (in wind), converted	renewable energy resources, solar, converted	renewable energy resources, geothermal, converted	renewable energy resources, potential (in barrage water), converted
Location				GLO	GLO	GLO	GLO	GLO	GLO	GLO	GLO
Unit				MJ-Eq	MJ-Eq	MJ-Eq	MJ-Eq	MJ-Eq	MJ-Eq	MJ-Eq	MJ-Eq
Coal, brown, in ground	resource	in ground	kg	9.90							
Coal, hard, unspecified, in ground	resource	in ground	kg	19.10							
Energy, gross calorific value, in biomass	resource	biotic	MJ				1.00				
Gas, mine, off-gas, process, coal mining	resource	in ground	Nm3	39.80							
Gas, natural, in ground	resource	in ground	Nm3	38.29							
Uranium, in ground	resource	in ground	kg		560'000						
Oil, crude, in ground	resource	in ground	kg	45.80							
Peat, in ground	resource	biotic	kg	9.90							
Energy, geothermal, converted	resource	in ground	MJ							1.00	
Energy, kinetic (in wind), converted	resource	in air	MJ					1.00			
Energy, potential (in hydropower reservoir), converted	resource	in water	MJ								1.00
Energy, solar, converted	resource	in air	MJ						1.00		
Energy, gross calorific value, in biomass, primary forest	resource	biotic	MJ			1.00					

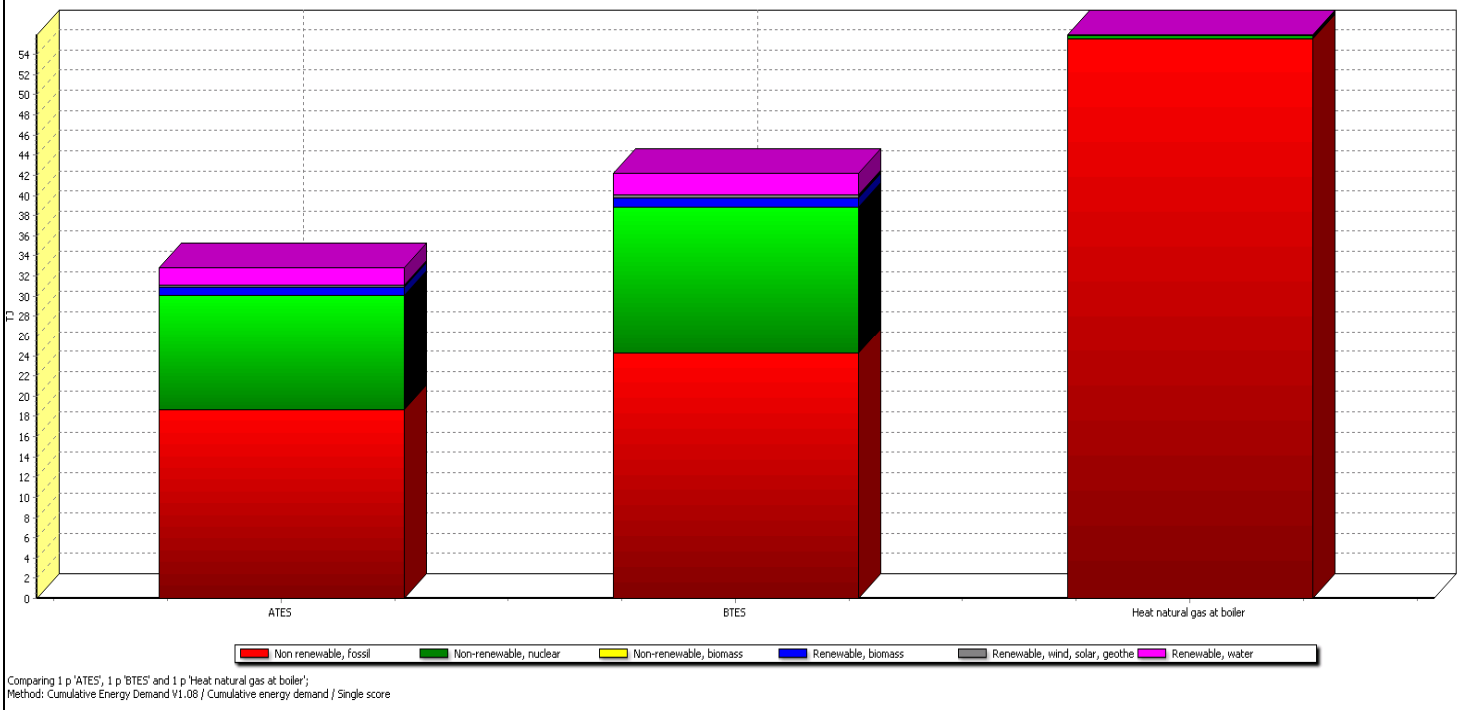

Figure 24. ATES, BTES, Natural gas comparison. CEnD. Single Score.

As calculated, the main process contribution to the total energy consumption for ATES and BTES is the electricity use (*Table 21* and *Table 22*). In the case of BTES also the polyethylene pipes production affects the final result in the amount of about 3%.

The main source of energy for all three solutions is fossil fuels but this obviously accounts for almost 100% of the energy demand for the traditional heating systems while only for about 55% for the UTES systems (**Errore. L'origine riferimento non è stata trovata.**). The latter can also use renewable energy sources. This aspect is not taken into account in the CEnD method, where each Impact category is given the weighting factor 1.

Cumulative energy analysis can indeed be a good screening or complementary investigation of life cycle thinking. But it does not replace the use of comprehensive impact assessment methods such as Eco-indicator 99.

Table 9. ATES. CEnD. Process contribution to single score. Cut off: 0.5%.

Process	Unit	ATES	%
Total of all processes	MJ	1.15E7	100
Remaining processes	MJ	5.57E4	0.49
Electricity, medium voltage, production RER, at grid/RER S	MJ	1.13E7	99
Bentonite, at processing/DE S	MJ	5.90E4	0.51

Table 10. BTES. CEnD. Process contribution to single score. Cut off: 0.5%.

Process	Unit	BTES	%
Total of all processes	MJ	4.22E7	100
Remaining processes	MJ	2.40E5	0.57
Electricity, medium voltage, production RER, at grid/RER S	MJ	4.01E7	95.1
HDPE pipes E	MJ	1.22E6	2.89
Water, deionised, at plant/CH S	MJ	3.81E5	0.90
Bentonite, at processing/DE S	MJ	2,25E5	0.53

3.3.6. Cumulative Exergy Demand (CExD)

In addition to CEnD, CExD can be considered. The CExD method results differ significantly from the Cumulative Energy Demand ones: indeed- as stated in the first law of thermodynamics - energy can be transformed but is always conserved while exergy - according to the second law of thermodynamics-is consumed in all real world processes and entropy is produced. As previously stated, exergy takes into account the quality of energy and its ability to produce work. Exergy is stored in resources in the form of chemical, thermal, kinetic, potential, nuclear and radiative energy. CExD accounts for the exergy captured in non-energetically used materials and is specified in MJ equivalents to highlight that it is an impact assessment indicator and not an inventory elementary flow. For some energy-intensive processes, for example transport processes, the result of CExD is very similar to CEnD. In these cases, CExD does not provide additional information and it may be sufficient to apply the (less comprehensive) CEnD. However, for other products this is not the case, as some of the additionally considered resources, such as water and minerals, may be relevant from a resource quality perspective.

CExD is calculated using *Equation 1*:

$$CExD = \sum m_i * Ex_{(ch),i} + \sum n_j * r_{ex-e(k,p,n,r,t),i} \quad (Eq.\ 1)$$

CExD= cumulative exergy demand per unit of product or process (MJ-eq)

m_i = mass of material resource i (kg)

$Ex_{(ch),i}$= exergy per kg of substance i (MJ-eq/kg)

n_j= amount of energy from energy carrier j (MJ)

$r_{ex-e(k,p,n,r,t),i}$= exergy to energy ratio of energy carrier *j* (MJeq/MJ)

ch= chemical

k = kinetic

p = potential

n = nuclear

r = radiative

t = thermal exergy

The methodology to calculate the exergy of energetic and non-energetic raw materials and the exergy values for elements and industrially used resources are taken from Szargut et al.,(1988; 2005).

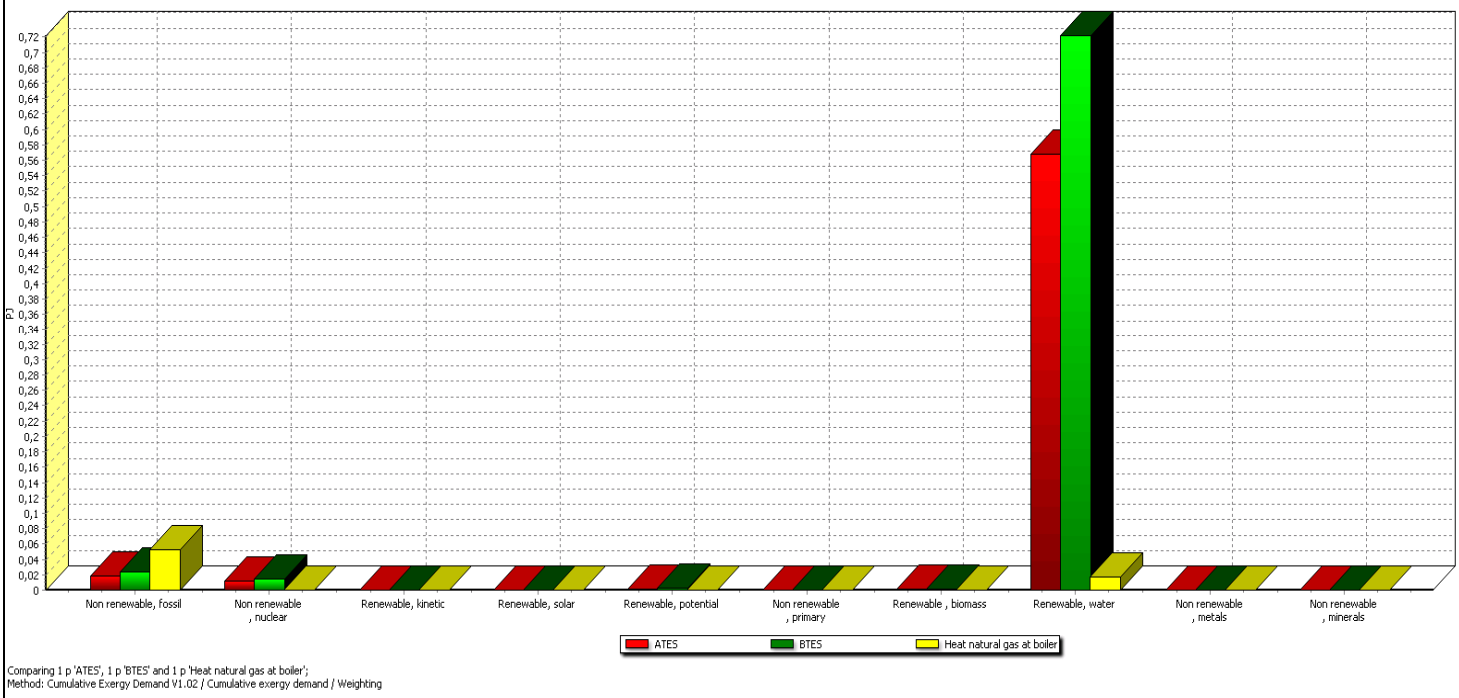

Figure 25. ATES, BTES, Natural gas comparison. CExD. Weighting (PJ).

Using this method, the exergy demand of ATES and BTES turns out to be more than one order of magnitude higher than the energy demand. For the natural gas heating system the increase is smaller: the exergy demand is twice as big as the energy demand (please refer to *Table 23* for the specific amounts). The calculated exergy demand of UTES is consistently higher than the exergy demand of the natural gas system (*Figure 26*) but this is due to the assumed use of water to generate electricity (*Table 23*).

When analysing the results of CExD many considerations are needed. First of all, while exergy demand is considered as a valuable indicator for the destruction of energy quality, there are still limitations to the comprehensive quantification of the quality of a resource. For instance, aspects like societal demand or technical availability and scarcity are not considered. For example one litre of potable water might be a more valuable resource in arid regions as compared to one kg of platinum in an ore and low exergy but scarce resources might be of higher concern compared to high exergy but abundant resources. For that reason CExD should be integrated with other models that include further resource depletion indicators that aim at assessing resource scarcity (even if information on global resource scarcity of specific resources is difficult to obtain and more assumptions are needed).Moreover, the exergy in renewable energy sources is an input from outside the Earth system (provided by solar irradiation) and thus of completely different quality as compared to exergy extracted from the ground, i.e. within the earth system. While solar radiation allows for an increase in exergy on Earth, the latter leads to a decrease in exergy.

The indicator CumulativeExergy Demand accounts for the exergy of resources that are removed from nature and thus are not accessible anymore for future exploitation (Ecoinvent Centre, 2007) but at the same time it does not consider the nature of the renewable energy sources that can take advantage of the external source of exergy represented by the sun and by consequence turn back to be accessible.

The advantages of this method are that CExD covers more resources than the other methods, because exergy values can easily be calculated for all resources with known composition. Therefore and in contrast to the other methods, no resources had to be neglected in the assessment. The main source of uncertainty is the (sometimes unknown) composition of mineral resources, such as rocks and ores.

Whether or not to aggregate the exergy of all resource types into a single score is subject of debate. In SimaPro several categories are defined to support the differences among the various types of resources. First, exergy in energy carriers is destroyed while exergy in material is, in many cases, only removed from nature and it might be recovered at the end of the product life-cycle with appropriate waste treatment technologies and management. Furthermore, as previously stated there is a difference between the exergy associated to renewable and non renewable energy sources and – even within the renewable sources- the consumption of solar energy is differently accounted for in technical systems like solar panels, hydroelectric power plants, wind power plants and biomass.

Finally, water use is considered and is, in some cases, relevant. This is considered to be an advantage of the CExD concept, as the consumption and scarcity of water is a major concern in some countries and particularly in arid regions, which is so far not reflected by the conventional methods (Ecoinvent centre, 2007). However, in this study, water used in hydroelectrical plants is particularly relevant and deeply affects the final CExD of UTES to the extent of 94%. As noted by the Ecoinvent centre (2007), in the future there may be other methods that will assess water use more appropriately, e.g. taking into consideration clean water availability. As previously stated, the renewable nature of the hydroelectrical power versus the fossil fuels depletion is not taken into account.

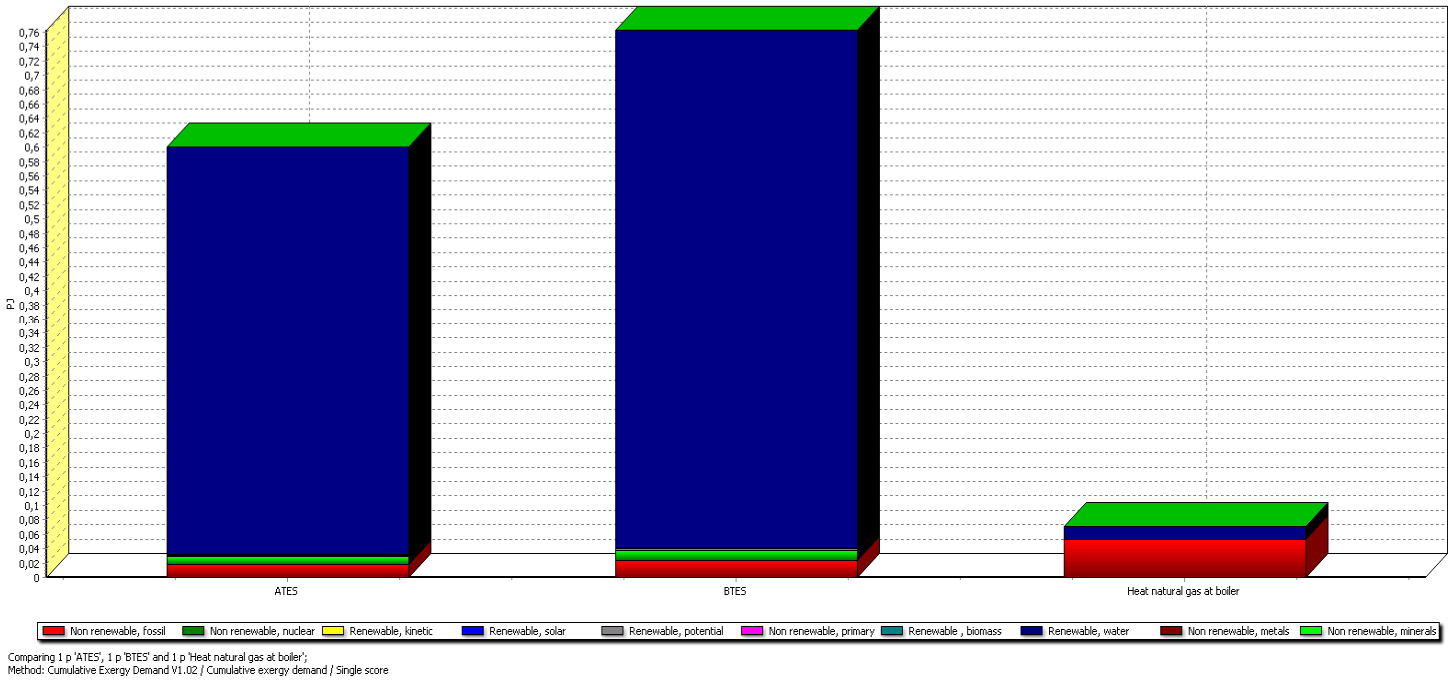

Figure 26. ATES, BTES, Natural gas comparison. CExD. Single score.

Table 11. CExD. Substance contribution ATES, BTES and natural gas to single score. Cut off: 1%.

Substance	Unit	ATES ▼	BTES	Heat natural gas at boiler
Total	MJ	6.00E8	7.63E8	7.02E7
Remaining substances	MJ	1.76E7	2.34E7	1.34E6
Water, turbine use	MJ	5.65E8	7.17E8	1.74E7
Uranium	MJ	1.15E7	1.45E7	-
Coal, hard	MJ	6.46E6	8.13E6	-
Gas, natural	MJ	-	-	5.15E7

4. Uncertainty and Sensitivity Analysis

Life Cycle Assessment is a holistic approach that allows a complete vision and evaluation of the issues and impacts related to the studied systems. At the same time, for the above mentioned reason, it can be complex and associated to a relatively high degree of uncertainty. For a correct interpretation of the results it is important to consider and analyse these uncertainties at the maximum extent possible with the available knowledge. In certain cases some processes are not included in the databases and proxies are used instead. Moreover, some foreground data might not be available and must therefore be estimated, omitted if they are neglectable for the final results or replaced with the best available information.

In LCA it is common to find two types of uncertainties:

- Uncertainties deriving from the correctness of the model such as the choice of system boundaries (inclusion of a certain effect even if there is still no clear scientific proof of its existence, lifespan choice, allocation, etc.), the impact method selection and similar. Moreover, the uncertainty linked to the impact method model must be further developed. This aspect can be investigated through a sensitivity analysis.

- Data uncertainties. This type of uncertainty arises during the inventory phase and is easier to handle because it can be expressed in terms of range or standard deviation.

The method used to calculate uncertainty in SimaPro is Monte Carlo analysis. A probability distribution is chosen among normal, lognormal, triangular or uniform and random sampling is repeated to obtain a distribution result.

When two products or services are compared it is important to consider the uncertainties in order to be able to establish whether one product actually performs better than the other. These results can indeed be considered reliable if they are coherent (meaning that one system scores higher than the other in at least 90% of the trials).Coupled sampling techniques are used in SimaPro so that - if a certain process exists in both assemblies - the same variation for this process is used in a single Monte Carlo sample for both the products. This is important in the specific case of ATES and BTES as the life cycle of the two systems consists of very similar processes.

The Monte Carlo analysis is performed with a fixed number of runs of 1000 and a confidence interval of 95%.

4.1. Uncertainty analysis

Before calculating the uncertainty associated to the comparison of the two UTES systems, it is worthwhile to analyse the uncertainty associated to ATES and BTES systems alone.

4.1.1. ATES uncertainty analysis

The coefficient of variation (CV) of the single score is 21.4%. As far as Impact categories are concerned, Radiation and Carcinogens are associated to a high uncertainty with a CV of 119% and 76.8%, respectively, while the other categories have a lower uncertainty, ranging from a CV of 43.6% for Land use to a CV of 13.8% for Fossil fuels (*Figure 27*). As far as the Damage categories are concerned, the Ecosystem quality one is the one that shows less uncertainty related to the data input (*Figure 28*).

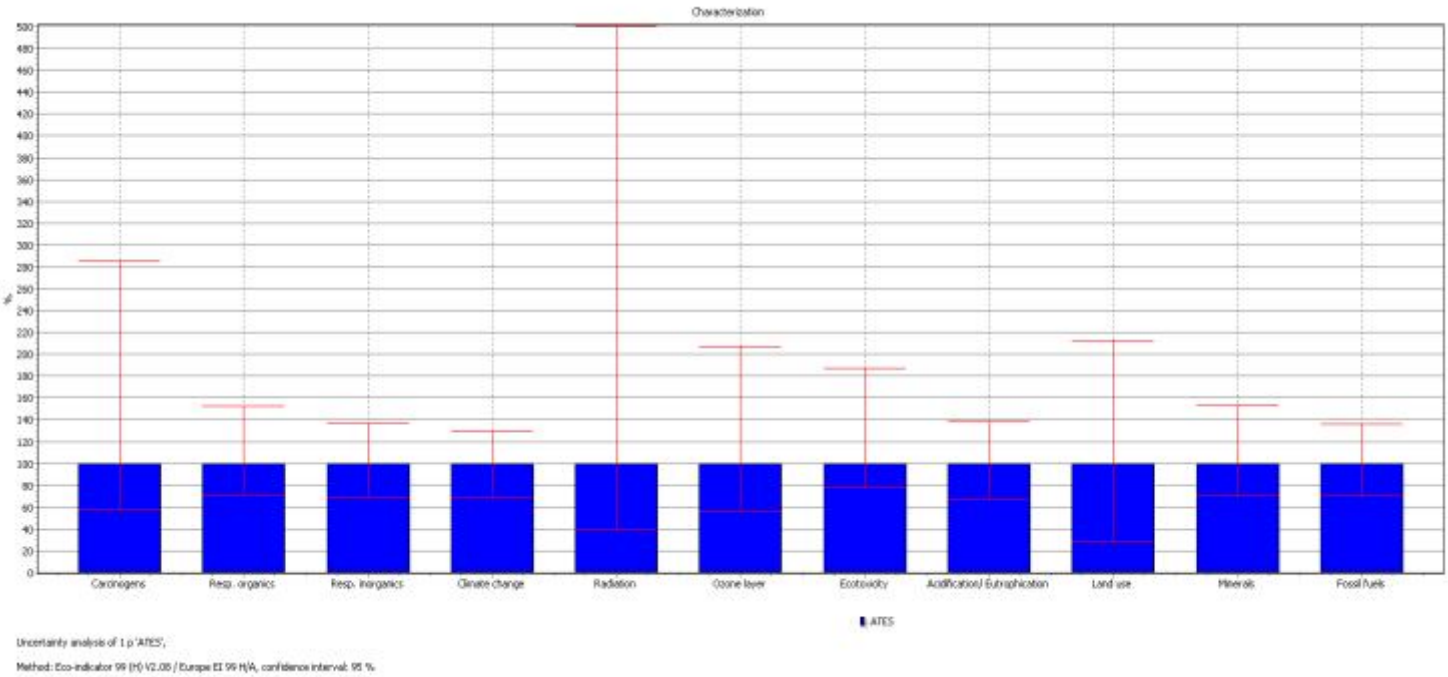

Figure 27. ATES. Uncertainty analysis (Monte Carlo). E-I 99. Impact categories. Characterization.

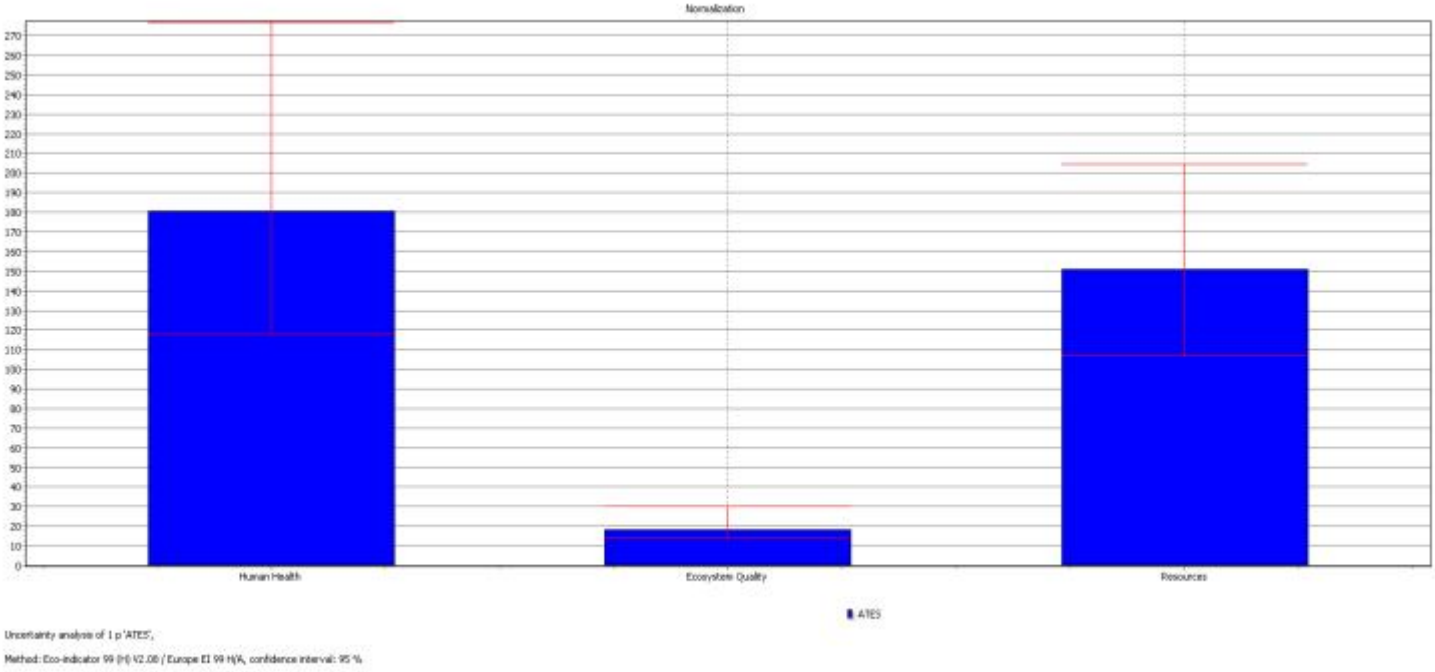

Figure 28. Uncertainty analysis (Monte Carlo). ATES. E-I 99. Damage categories. Normalization.

4.1.2. BTES uncertainty analysis

The CV of the single score is 25%. As far as Impact categories are concerned, Radiation and Carcinogens are associated to a high uncertainty with a CV of 108% and 99.6% respectively while the other categories have a lower uncertainty, ranging from a CV of 30,9% of Land use to a CV of 13.7% of Fossil fuels (*Figure 29*). Therefore, the uncertainties associated to ATES and BTES inventory data are very similar, as of the processes involved in their life cycle.

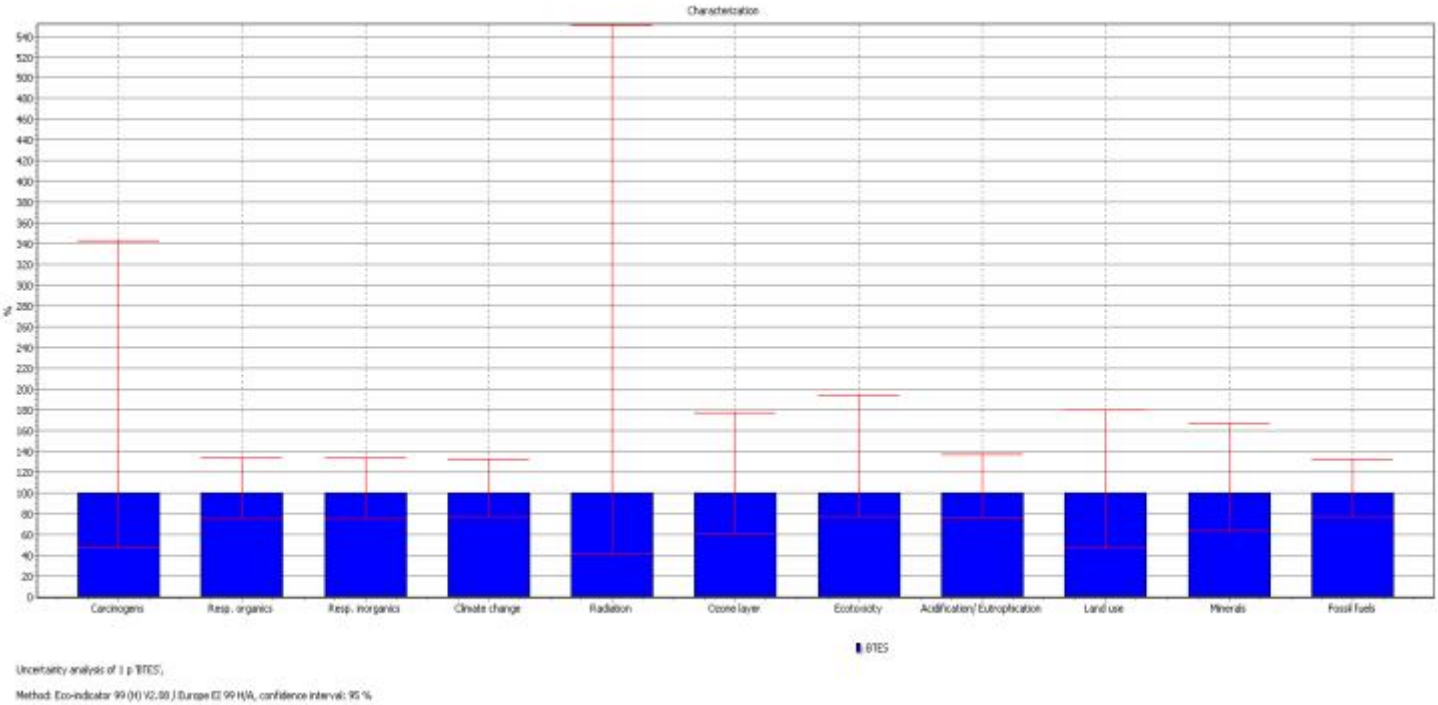

Figure 29. BTES. Uncertainty analysis (Monte Carlo). E-I 99. Impact categories. Characterization.

4.1.3. UTES comparison: uncertainty analysis

Another important investigation is the uncertainty associated to the results of the compared LCA of the open and closed systems. The results of the uncertainty analysis applied to the comparison of ATES and BTES are shown in *Figure 30*that displays the characterized Impact categories scores and in *Figure 32* that displays the weighted Damage categories scores. For each Monte Carlo run, the scores associated to the traditional heating system`s Impact (or Damage) categories are subtracted from the scores associated to the open system`s Impact (or Damage) categories and the results of this operations are plotted as coloured bars where the red bar means that ATES scores < natural gas heating system scores and the green bar means the opposite. The length of the bars is proportional to the percentage of Monte Carlo runs that give the result associated to their colour. The Eco-Indicator 99 characterization results of ATES are lower than the ones of BTES in 100% of the cases for almost all the Impact categories. The only exception is the land use category where ATES presents higher results than BTES in less than 5% of the random trials, as shown in *Figure 31*. In this particular case, this result is expected as the LCIA output showed that ATES performs better than BTES for all the Impact categories and the processes involved in the life cycle of the two systems are very similar, so they vary together.

From these results it is possible to confirm that –even taking the uncertainties into account- within the considered UTES systems analysed with Eco-Indicator 99, ATES performs better than BTES in all the Impact categories, therefore in all the Damage categories and in the overall.

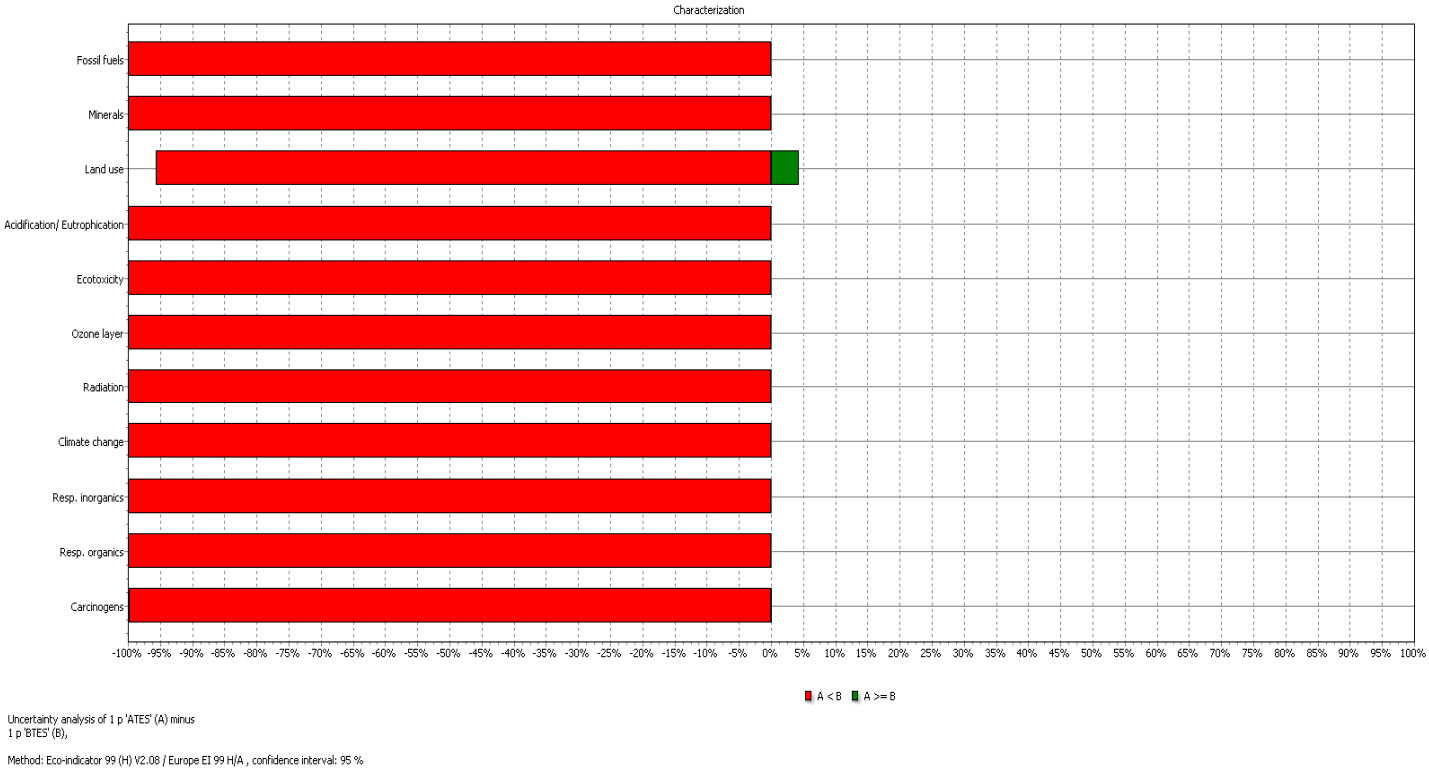

Figure 30. ATES and BTES comparison. Uncertainty analysis (Monte Carlo). E-I 99 H/A. Impact categories.

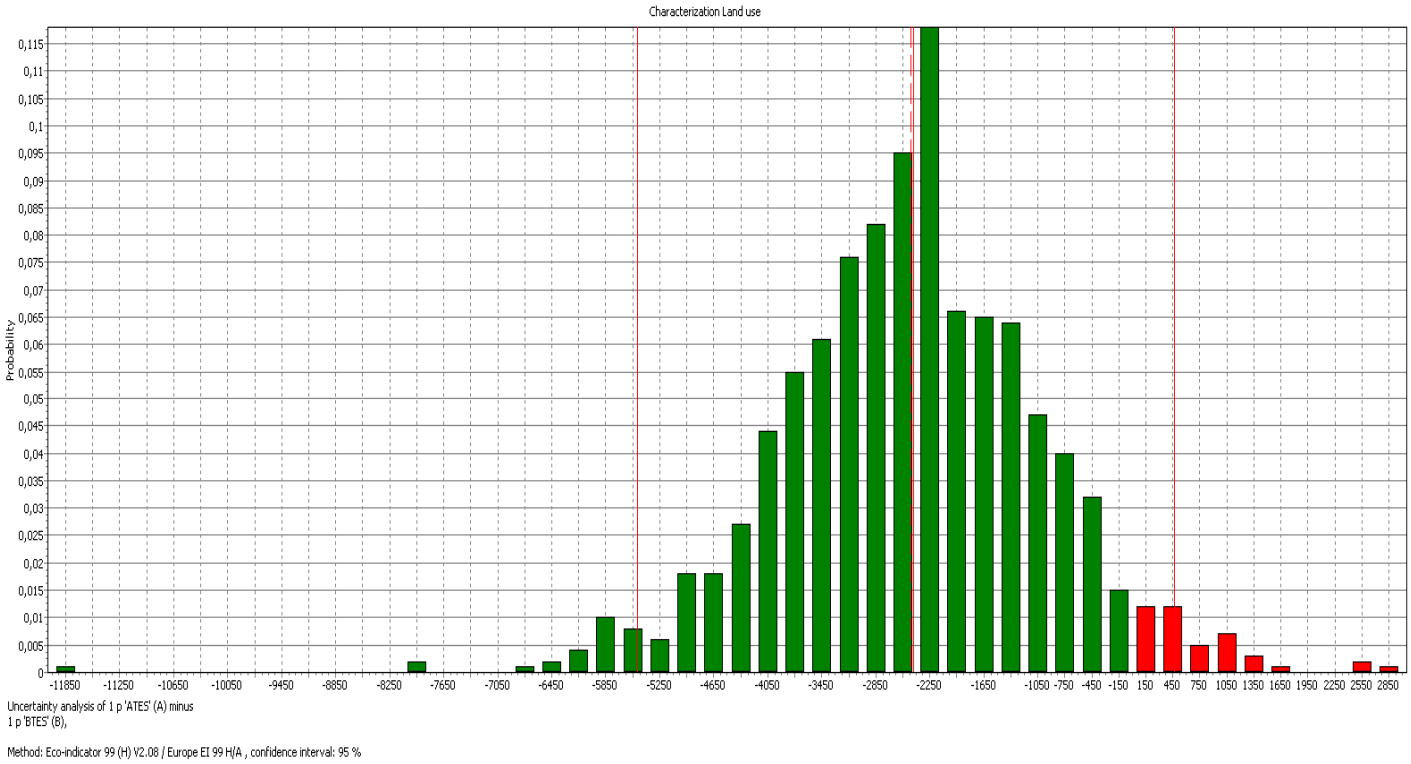

Figure 31. ATES and BTES comparison. Uncertainty analysis (Monte Carlo). E-I 99 H/A. Land use category.

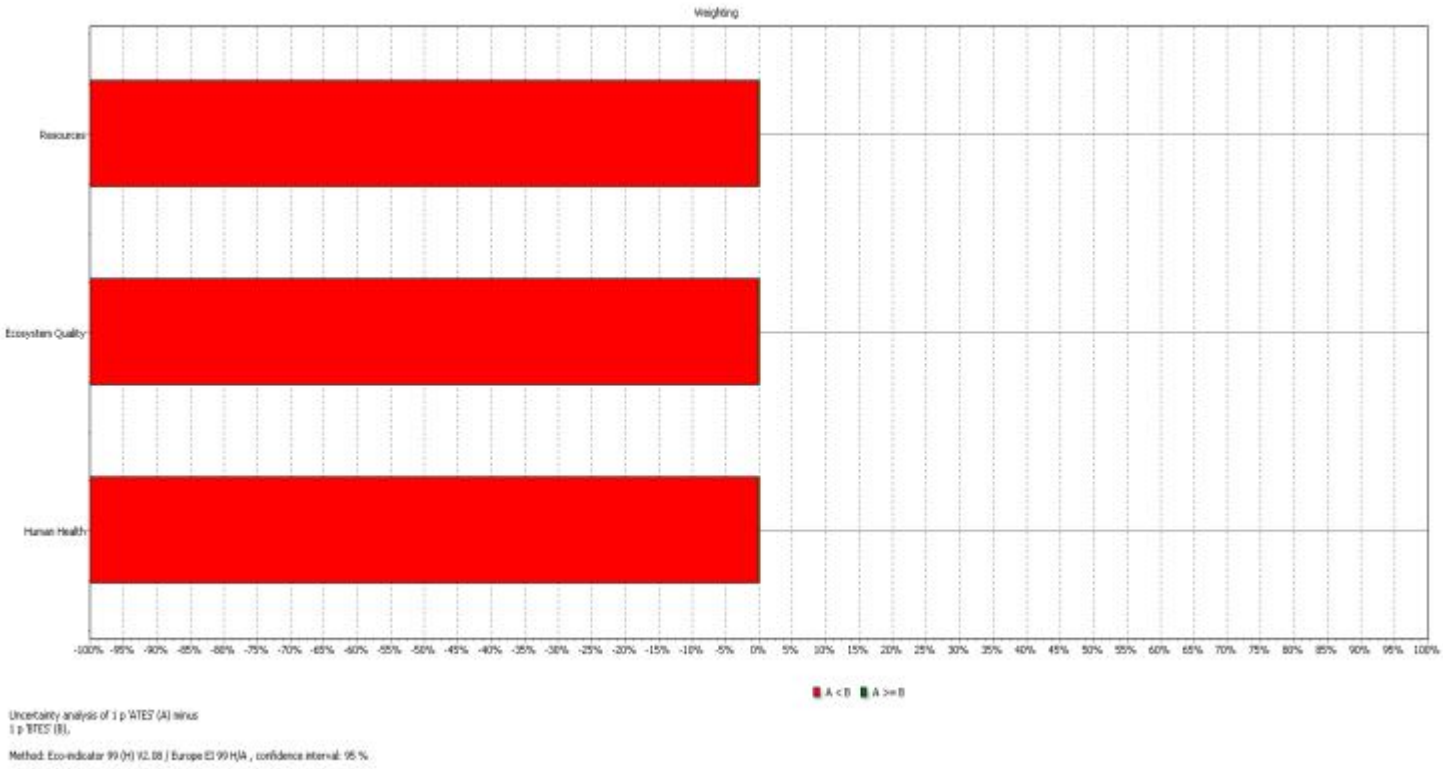

Figure 32. ATES and BTES comparison. Uncertainty analysis (Monte Carlo). E-I 99 H/A. Damage categories.

4.1.4. ATES and natural gas heating system comparison

The uncertainty associated to the Impact categories of ATES compared to a traditional heating system with natural gas is shown in *Figure 33* and *Table 24.*.

The Radiation, Minerals, Ecotoxicity, Carcinogens, Respiratory Inorganics, Acidification/Eutrophication categories score higher for ATES in more than 90% of the Monte Carlo runs while the opposite result applies to the Respiratory Organics, Fossil Fuels and Climate Change categories. For the Ozone layer and especially the Land Use ones the uncertainties do not allow to establish whether one system has less impacts than the other. Nevertheless, when the Impact categories are grouped together into Damage categories, the traditional system appears to represent a stronger threat to Human Health and Ecosystem Quality in almost 100% of the cases while the opposite statement is valid for the Resources category (*Figure 34*). When referring to the single score results, according to E-I 99, ATES is a better solution over heating with natural gas with a confidence of almost 100% (*Figure 35*).

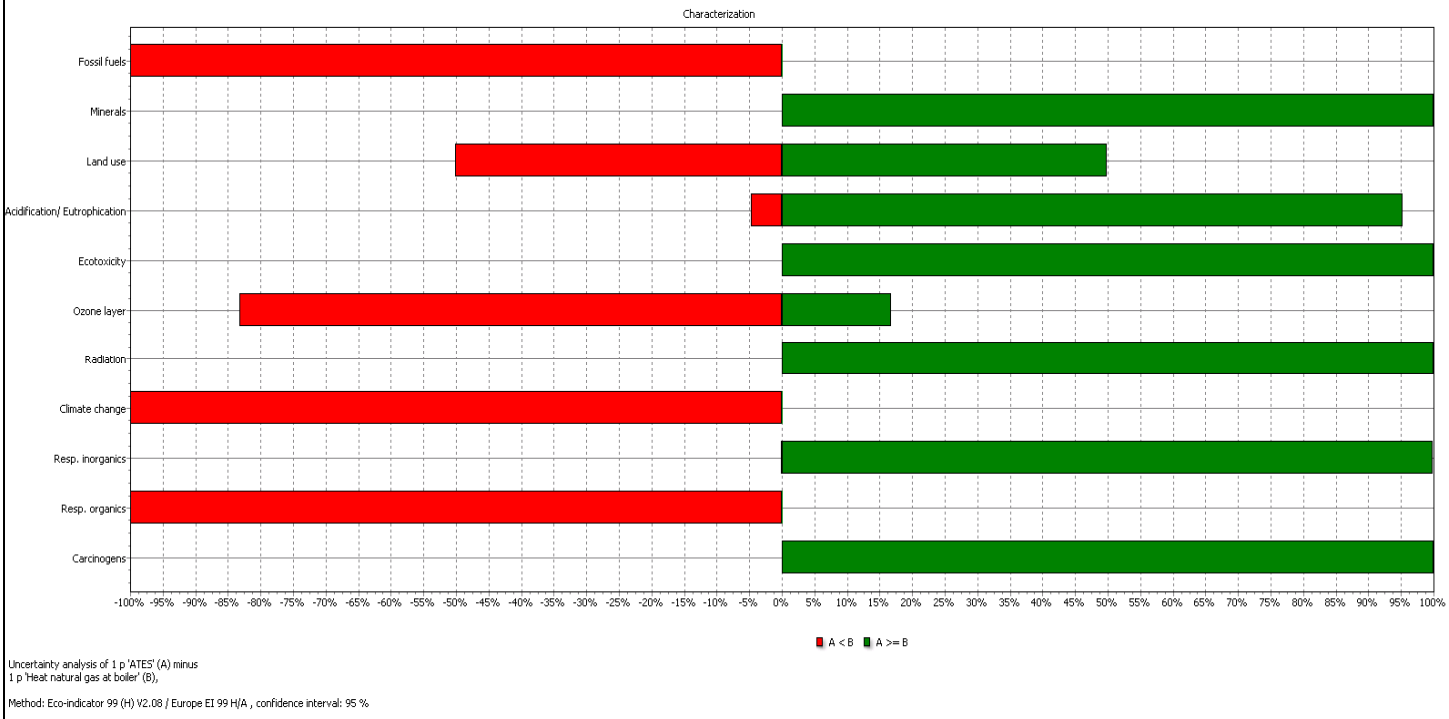

Figure 33. ATES and natural gas comparison. Uncertainty analysis (Monte Carlo). E-I 99 H/A. Impact categories.

Table 12. ATES and natural gas comparison. Uncertainty analysis (Monte Carlo). E-I 99 H/A. Impact categories. Statistical indicators.

Impact category	*A >= B*	*Mean*	*Median*	*SD*	*CV*
Radiation	100%	0.0229	0.0161	0.0211	92,30%
Minerals	100%	1.17E4	1.11E4	4.12E3	35,20%
Ecotoxicity	100%	7.73E5	7.21E5	1.98E5	25,70%
Carcinogens	100%	0.519	0.415	0.329	63,30%
Resp. inorganics	99.80%	0.499	0.501	0.132	26,40%
Acidification/ Eutrophication	95.20%	7.53E3	7.84E3	4.34E3	57,70%
Land use	49.90%	-562	-22.3	6.99E3	-1,24E+01
Ozone layer	16.80%	-0.00015	-0.000132	0.000172	-115%
Resp. organics	0%	-0.00091	-0.000831	0.000404	-44,,0%
Fossil fuels	0%	-6.26E6	-6.09E6	1.80E6	-28,80%
Climate change	0%	-0.351	-0.35	0.068	-19,40%
Confidence interval:	95				

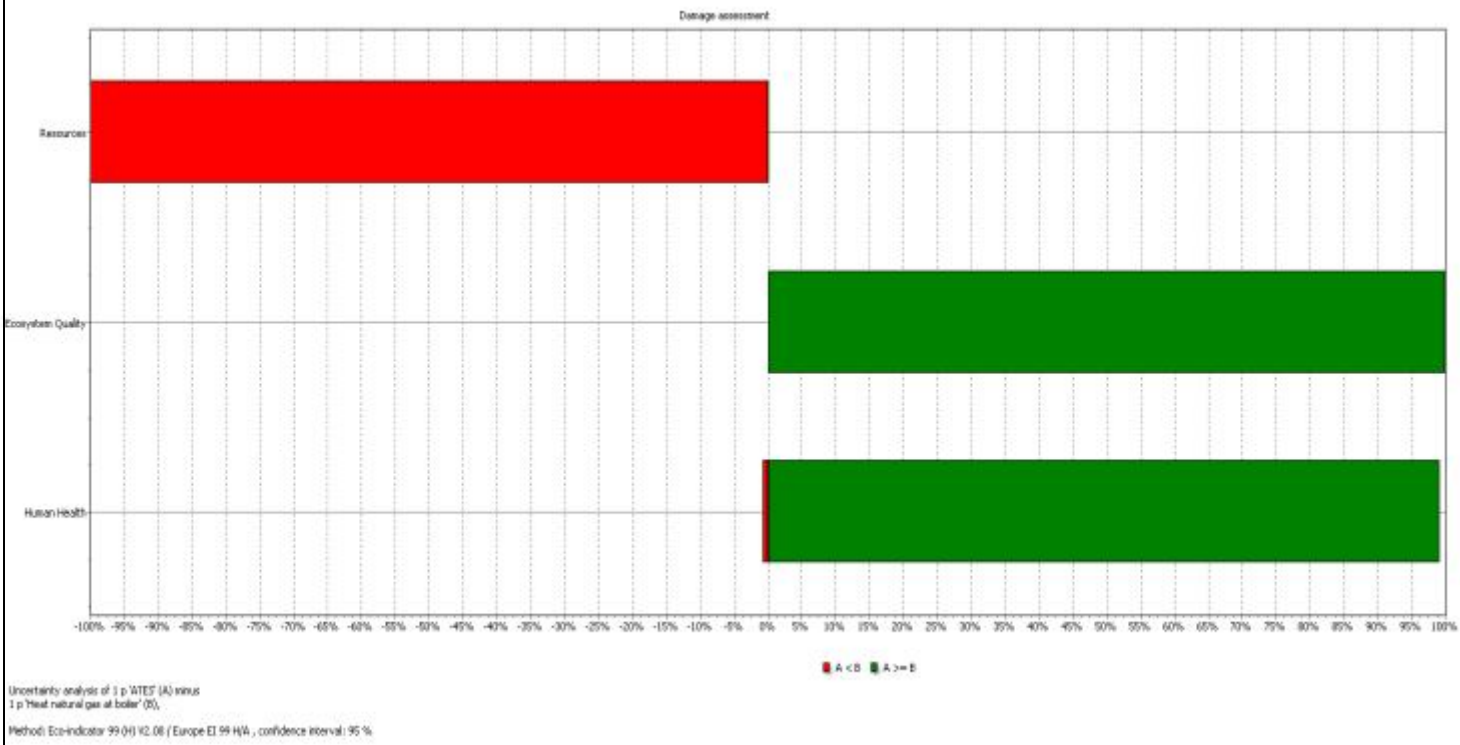

Figure 34. ATES and natural gas comparison. Uncertainty analysis (Monte Carlo). E-I 99 H/A. Damage categories.

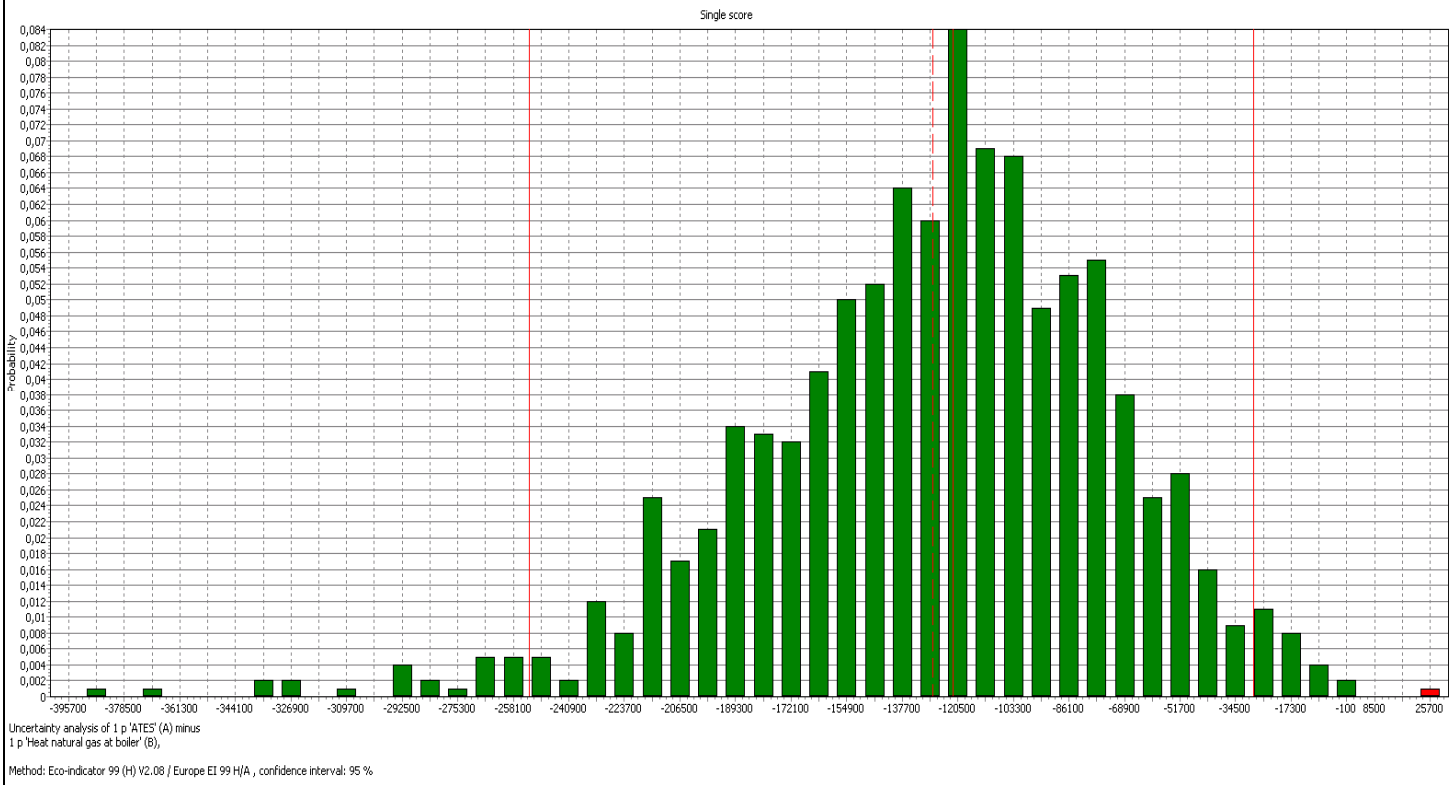

Figure 35. ATES and natural gas comparison. Uncertainty analysis (Monte Carlo). E-I 99 H/A. Single score.

4.2. Sensitivity analysis

A sensitivity analysis is applied to verify whether and in which amount the variation of input data, system boundaries or methodology affects the final results.

In this study, a sensitivity analysis is applied to the following aspects:

- Impact method → both the other two perspectives of the E-I99 method (Individualist and Egalitarian) and different impact methods (Environmental Product Declaration and Impact 2002+) are used to verify the consistency of the results of E-I99 Hierarchist perspective or the contingent differences.
- Water table → the supposed water table depth is increased from 2 m to 12 m (this will apply only to ATES as BTES does not necessarily require the presence of a water table in order to be installed).
- Electricity use → the electricity chosen for the operational phase will originate from renewable resources instead of a European countries mix (deriving from fossil fuels, renewables and nuclear plants).

The transport distance, usually an important aspect of LCA when analysing commercial products and, therefore, subject to sensitivity analysis is, in this case, negligible as it accounts to less than 1% of the final score for ATES and BTES.

4.2.1. E-I 99: Egalitarian and Individualist perspectives

E-I 99 has been used choosing the Hierarchist version and an average weighting set. It is interesting to investigate the variation on the results using the more “extreme” Egalitarian and Individualist perspectives and weightings.

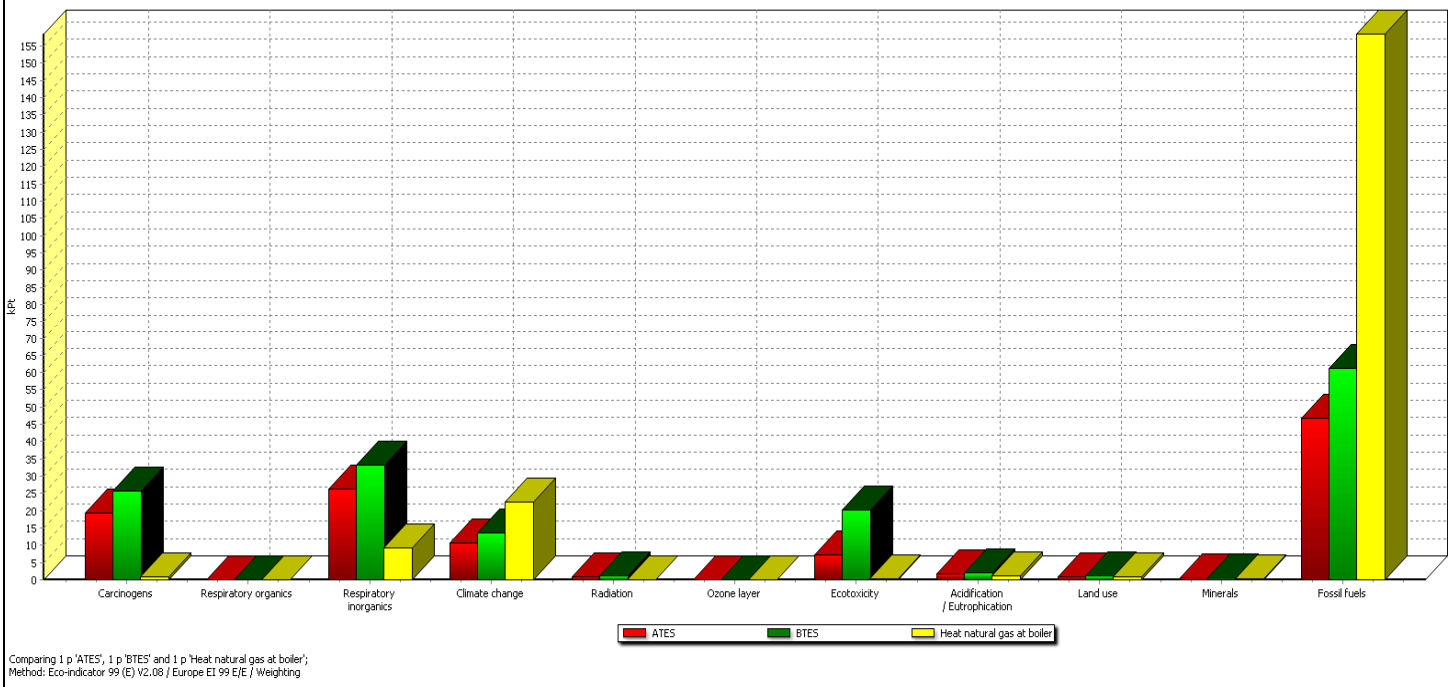

***Figure 36Figure 21. ATES, BTES and Natural Gas Boiler comparison. EI 99 H/A. Weighting. Impact** categories.*

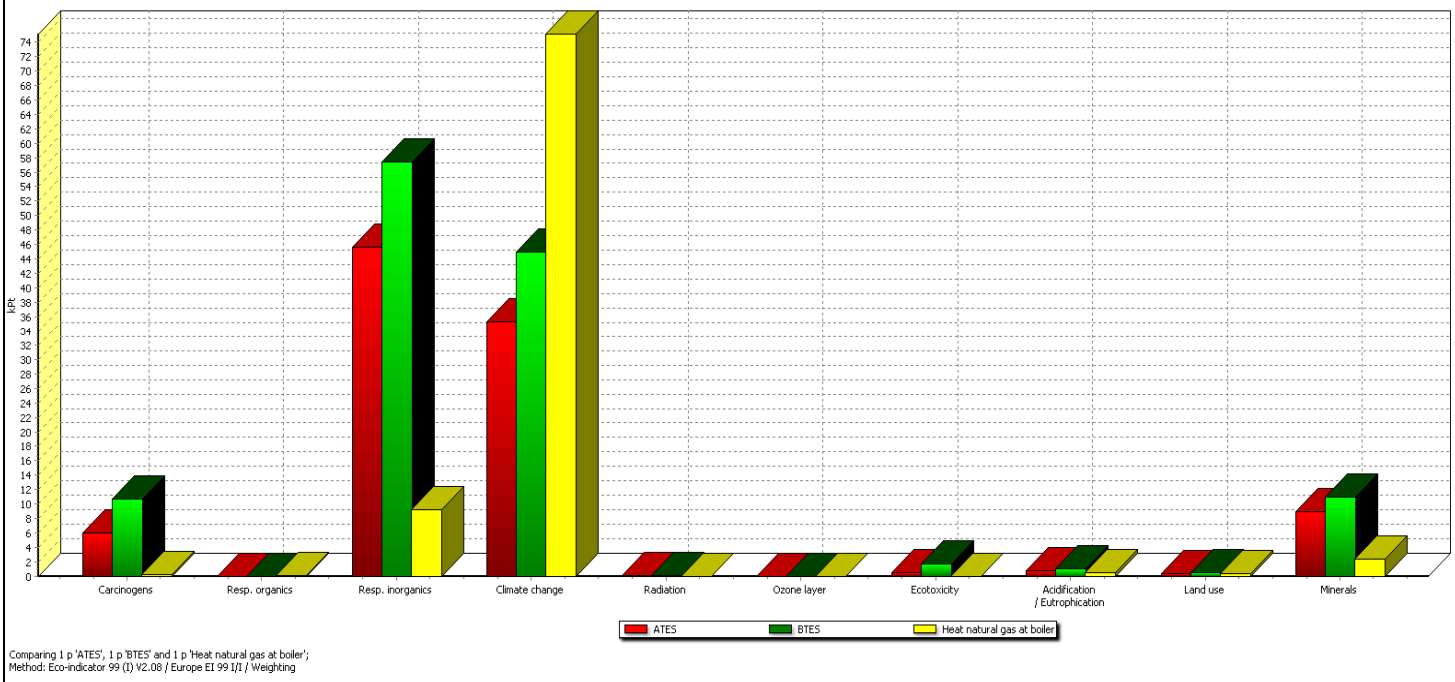

Figure 37. ATES, BTES and Natural Gas Boiler comparison. EI 99 I/I. Weighting. Impact categories.

Figure 36 and *Figure 37* show the Impact categories results of the three considered heating systems using E-I 99 Egalitarian perspective/Egalitarian weighting set (E/E) and Individualist perspective/Individualist weighting set (I/I) respectively. The proportions among the three heating systems` scores are roughly respected within the same impact category but the orders of magnitude change consistently as well as the proportions among the different impact categories. In the individualist perspective fossil fuels are not included and - as the only remaining impact category related to resources depletion is depletion of minerals - this becomes more important.

Figure 38 and *Figure 39* show a comparison among the single and damage categories scores of ATES and BTES, respectively, using different perspectives and weighting sets of E-I 99: the Hierarchist perspective/Hierarchist weighting set (H/H) and the E/E configurations have very similar results for both the damage categories and the single score. I/I is the perspective that dissociates the most from the other ones (stressing the importance of human health and underestimating the other two damage categories) while with the Hierarchist perspective/Average weighting set (H/A) setting the single and ecosystem quality scores are very similar to E/E and H/H. Also, the Human Health and Resources outputs deviate less from E/E and H/H than with the I/I configuration.

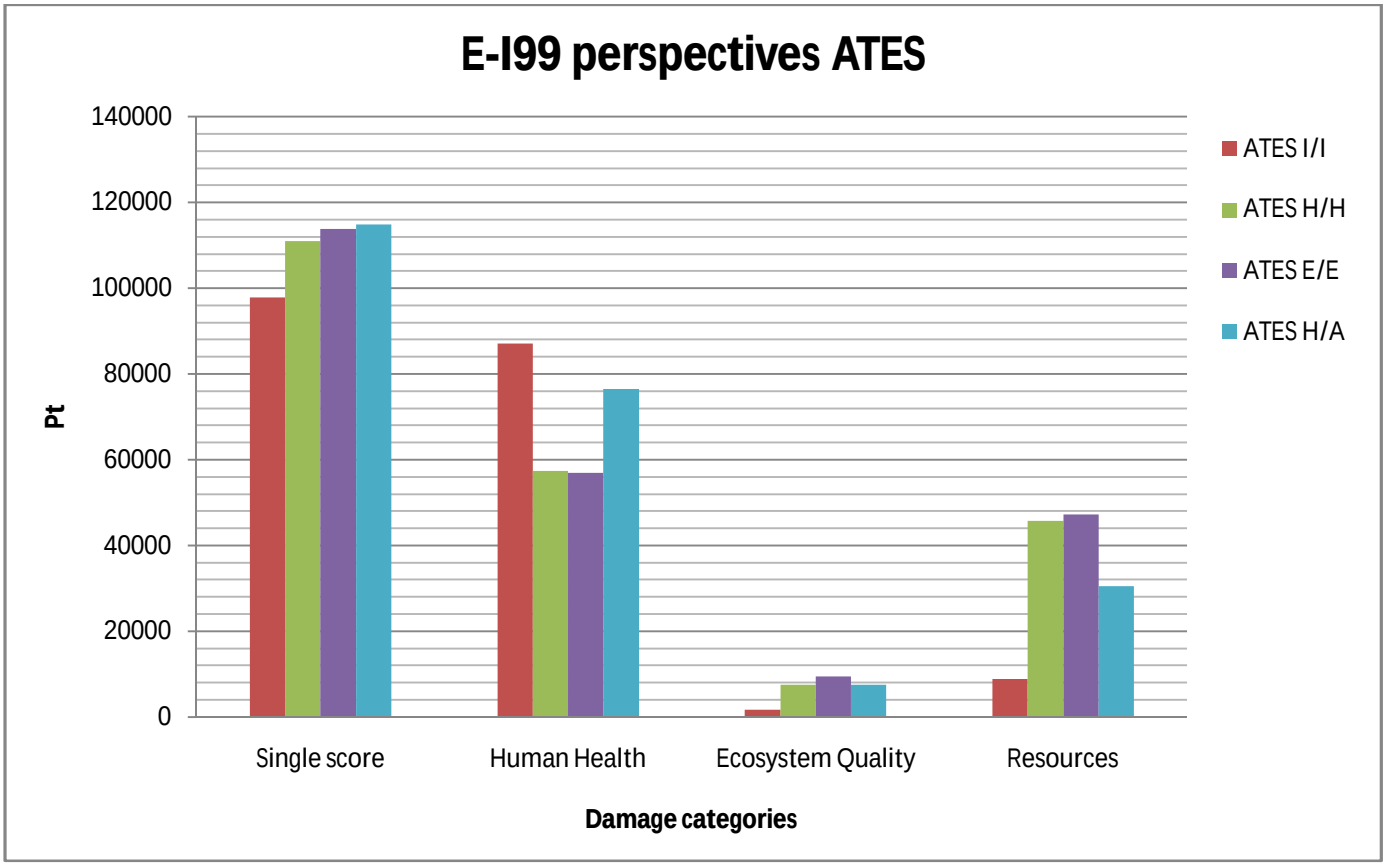

Figure 38. ATES. E-I 99 perspectives comparison. Single score and Damage categories.

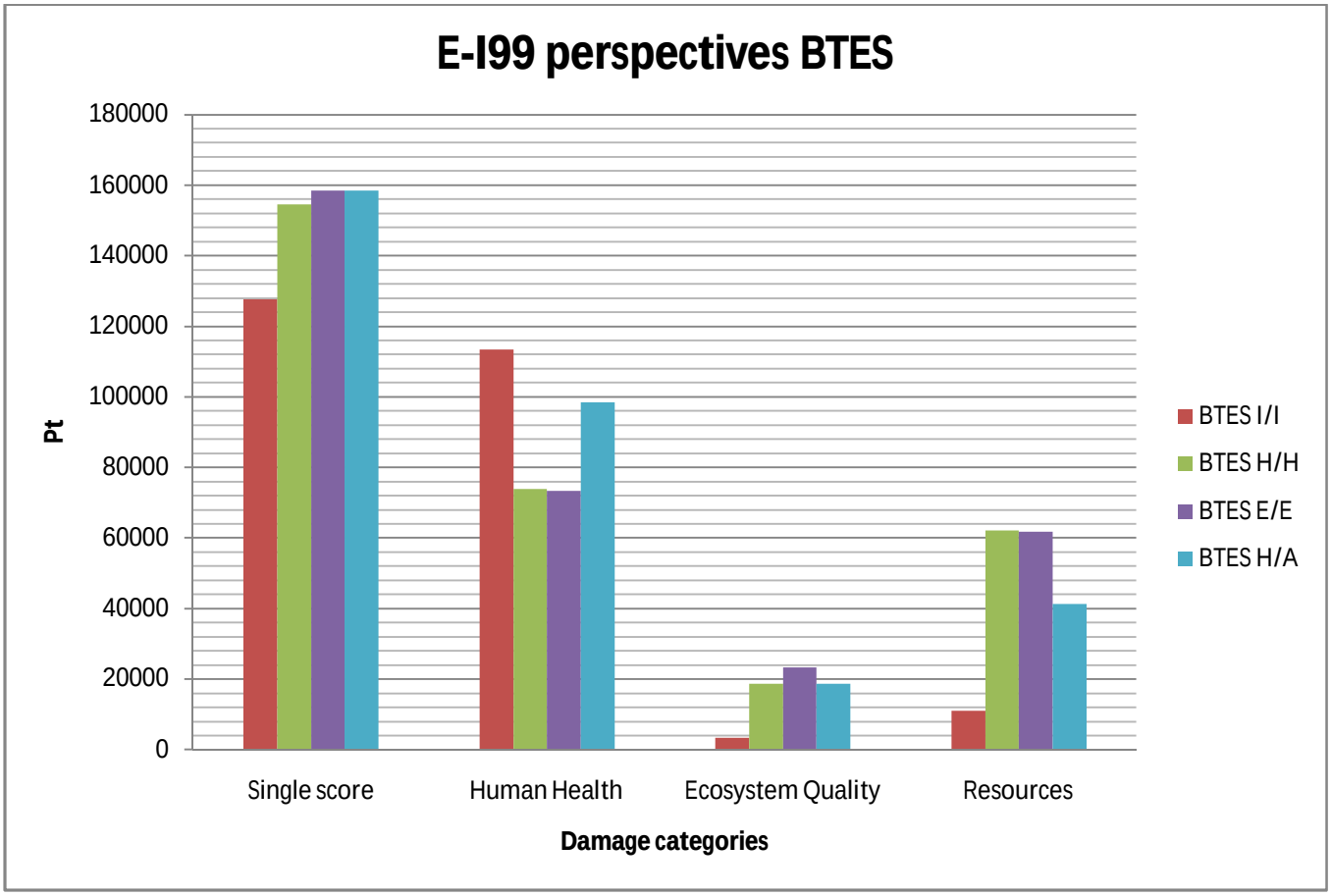

Figure 39. BTES. E-I 99 perspective comparison. Single score and Damage categories.

4.2.2. Impact 2002+

Impact 2002+ is an impact assessment methodology originally developed at the Swiss Federal Institute of Technology. Via 14 midpoint categories and four damage categories, it is a combination of four different methods: Impact 2002, Eco-Indicator 99, CML and IPCC. For this reason Impact 2002+ should be considered rather comprehensive. For more information, please refer to Annex A.

The results of the Impact 2002+ method apparently contradict E-I 99 ones as the traditional heating system performs slightly better than ATES and consistently better than BTES (*Figure 40*). The main category responsible of the greater impact of the UTES systems is the terrestrial ecotoxicity (*Figure 41*) that is linked to the drilling waste disposal (*Table 13*). The life cycle boundaries of the traditional heating system do not include the drilling operations used to extract natural gas and, by consequent, they do not include the impacts of the drilling operations and waste disposal. At the same time those impacts should be allocated based on the m^3 of gas used within the considered functional unit over the total volume of recoverable gas in the reservoir. Last but not least, the drilling waste composition used for UTES is not specific for those systems but is taken from the Ecoinvent library as a background datum. The composition of the drilling waste might therefore overestimate the presence of toxic metals and additives deriving from drilling within a different soil composition (e.g. rocks) and depth.

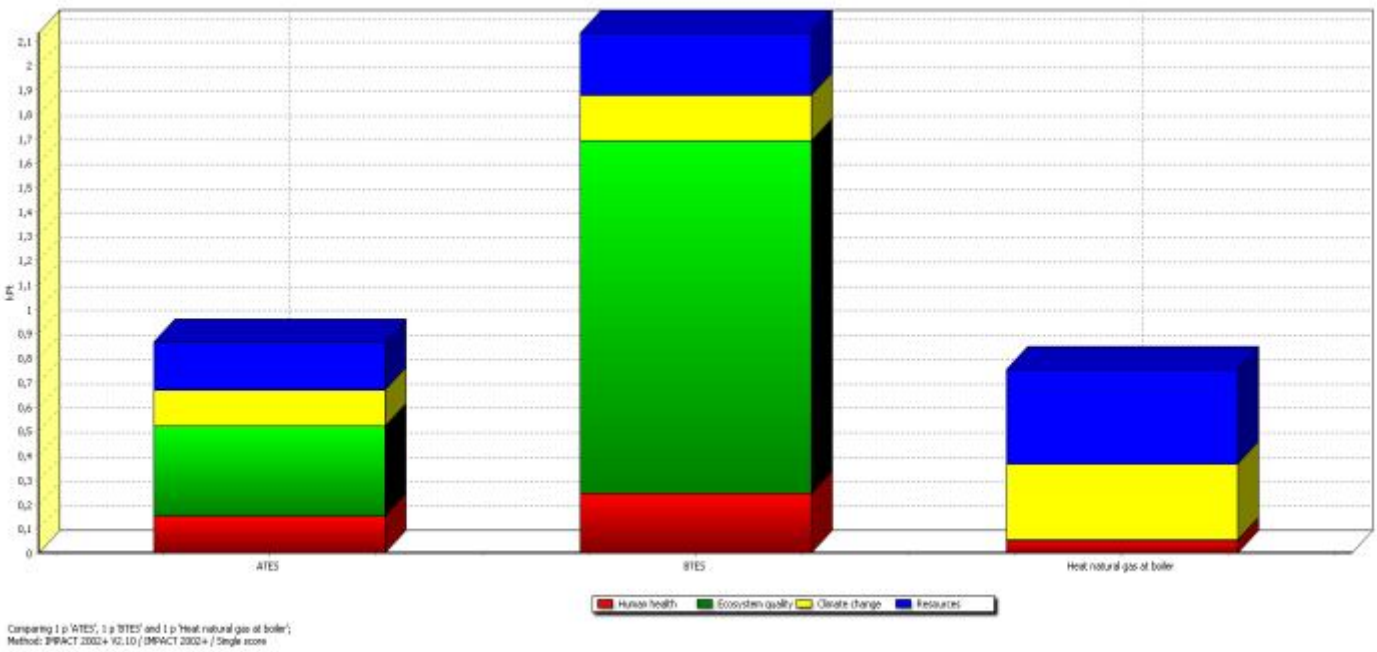

Figure 40. ATES, BTES and Natural Gas Boiler comparison. Impact 2002+. Single score (Damage categories).

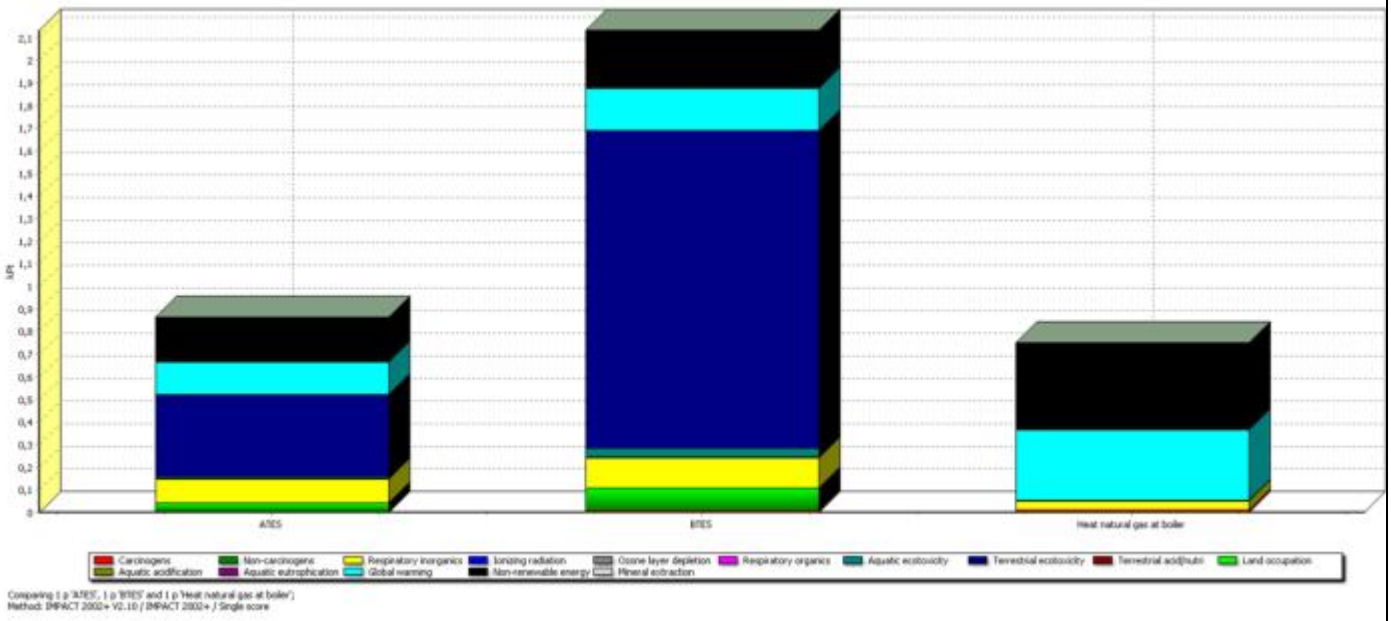

Figure 41. ATES, BTES and Natural Gas Boiler comparison. Impact 2002+. Single score (Impact categories).

Table 13. ATES, BTES and Natural Gas Boiler comparison. Impact 2002+. Substance contribution to the Terrestrial ecotoxicity Impact category.

Substance	Unit	ATES	BTES	Heat natural gas at boiler
Total	%	100	100	100
Remaining substances	%	1,26	0,59	12,31
Aluminium	%	86,09	87,46	71,98
Zinc	%	10,19	10,27	8,93
Chromium	%	1,28	1,29	1,07
Aluminium	%	1,17	0,37	5,70

4.2.3. Environmental Product Declaration (EPD)

This method is usually used for the creation of certified Environmental Product Declarations (EPDs). For more information please refer to Annex A of this report or to the website http://www.environdec.com/.

Normalization and weighting are not part of this method. By consequence a visualization of the results in the form of a single score is not possible as the different impact categories have different units. This method might be considered a midpoint one: the output interpretation is more complicated but the uncertainties deriving from the model implementation are less important compared to an endpoint method like Eco-Indicator 99. The characterisation scores for the EPD Impact categories of ATES, BTES and the traditional heating system are reported in *Table 14*, while *Figure 42*shows a straightforward comparison among the three systems. The traditional heating system scores worst than UTES in terms of global warming, ozone layer depletion, photochemical oxidation and fossil fuels impacts while the opposite happens for the acidification and eutrophication categories. The high acidification and eutrophication scores of ATES and

BTES are mainly due – once again- to the electricity production, in particular to phosphate (eutrophication), sulphur dioxide and nitrogen oxides emissions. The UTES process contribution to the EPD impact categories is shown in *Annex B*. The electricity production is the primary process that affects all the Impact categories with the exception of the Ozone layer depletion one as more kg of CFC equivalents are emitted during the heat pump production process than during the electricity production one. The main results obtained using E-I 99 are consistent with the EPD outputs: electricity production is the process of UTES responsible of the heavier environmental load and ATES performs better than BTES.

Table 14. ATES, BTES and Natural Gas Boiler comparison. Impact 2002+. Characterization scores of Impact categories.

Impact category	Unit	ATES	BTES	Heat natural gas at boiler
Global warming (GWP100)	kg CO_2eq	1497021	1902692	3181958
Ozone layer depletion (ODP)	kg CFC-11 eq	0.21	0.24	0.70
Photochemical oxidation	kg C_2H_4eq	462.81	609.82	973.36
Acidification	kg SO_2eq	5822.88	7347.42	2112.69
Eutrophication	kg PO^{4-}eq	4508.45	6308.16	402.34
Non renewable, fossil	MJ eq	30151338	38863298	55831387

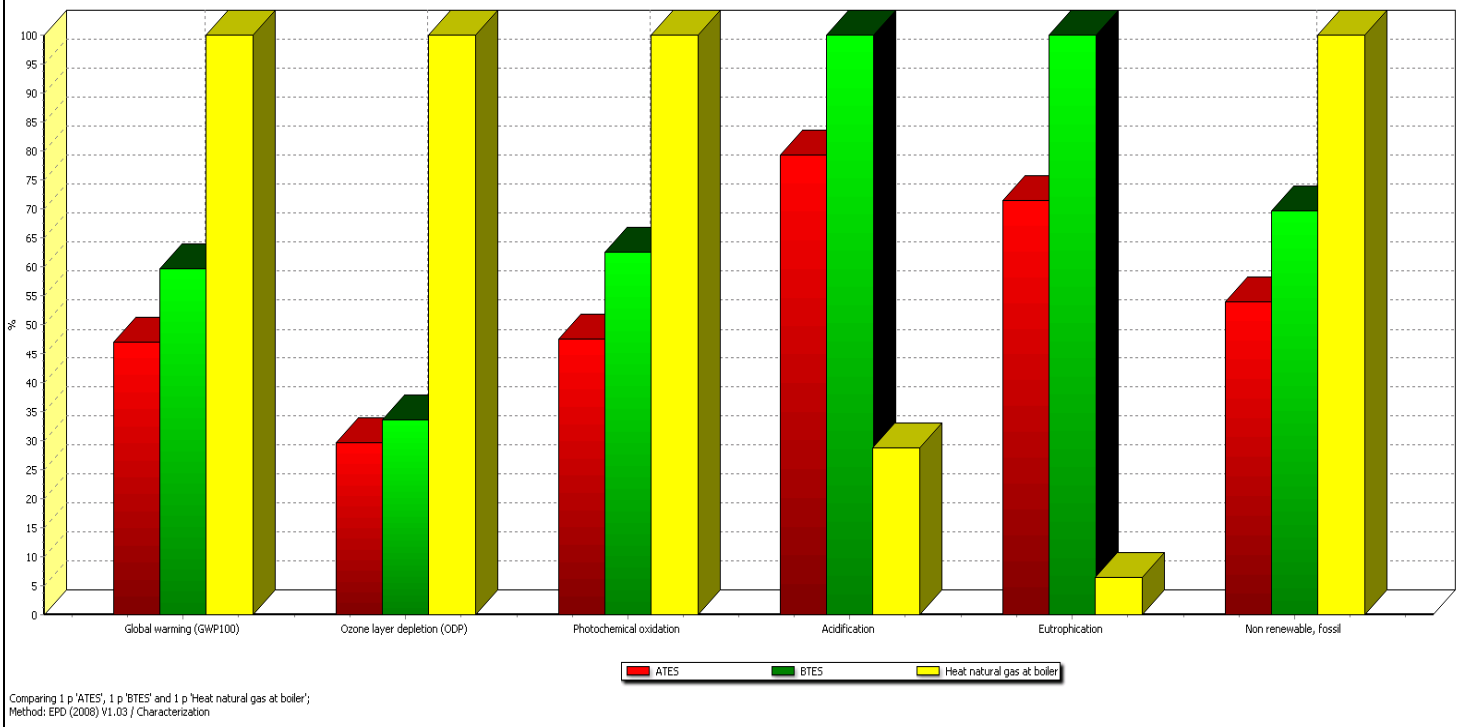

Figure 42. ATES, BTES and Natural Gas Boiler comparison. EPD (2008). Characterization.

4.2.4. Water table depth sensitivity analysis

The depth of the water table used in this report is typical of the Dutch underground conditions. It is interesting to investigate the variation of the ATES impact scores with an increased distance between the surface and the aquifer as most likely encountered in the rest of the world (Fan et al., 2010).A water table 10 m deep will add 8 meters to the head of the pump and will therefore result in an increased use of energy. The energy consumption of the pump will increase from 4kW to 5.1kW, so almost of 30% in the case of the ATES considered.

Figure 43 shows the comparison among ATES featuring a 2 m and a 10 m deep water table and BTES. Even with different underground conditions, ATES impacts are smaller than for BTES. As far as the two ATES systems are concerned, a deeper water table slightly affects all the Impact categories even if the Carcinogens, Respiratory inorganics, Climate change and Fossil fuels categories variation is more substantial. In spite of this, the possible impacts caused by ATES remain less important than the possible impacts caused by BTES, even in case of a deeper water table. This result refers to the application of E-I 99 impact method.

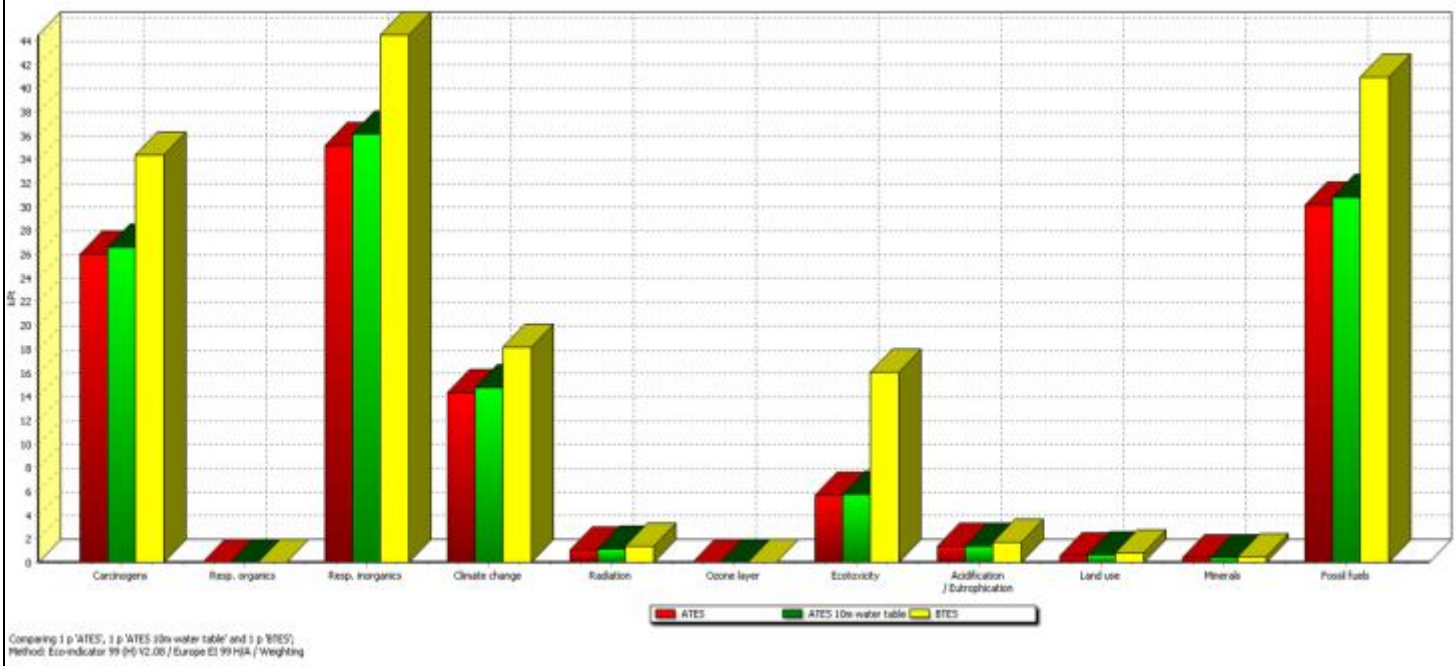

Figure 43. ATES with different water table depths (2 and 10 m) and BTES comparison. E-I 99 H/A. Impact categories.

4.2.5. Electricity production sensitivity analysis

The electricity production European countries mix is the process responsible for the majority of the impacts within all the impact methods used. For this reason a sensitivity analysis using electricity produced using photovoltaic panels is performed. The results are shown in *Figure 44,Figure 45* and *Figure 46*. As expected, this choice lowers all the Impact categories scores and roughly halves the overall impacts, making UTES an even more attractive alternative to a heating system using natural gas.

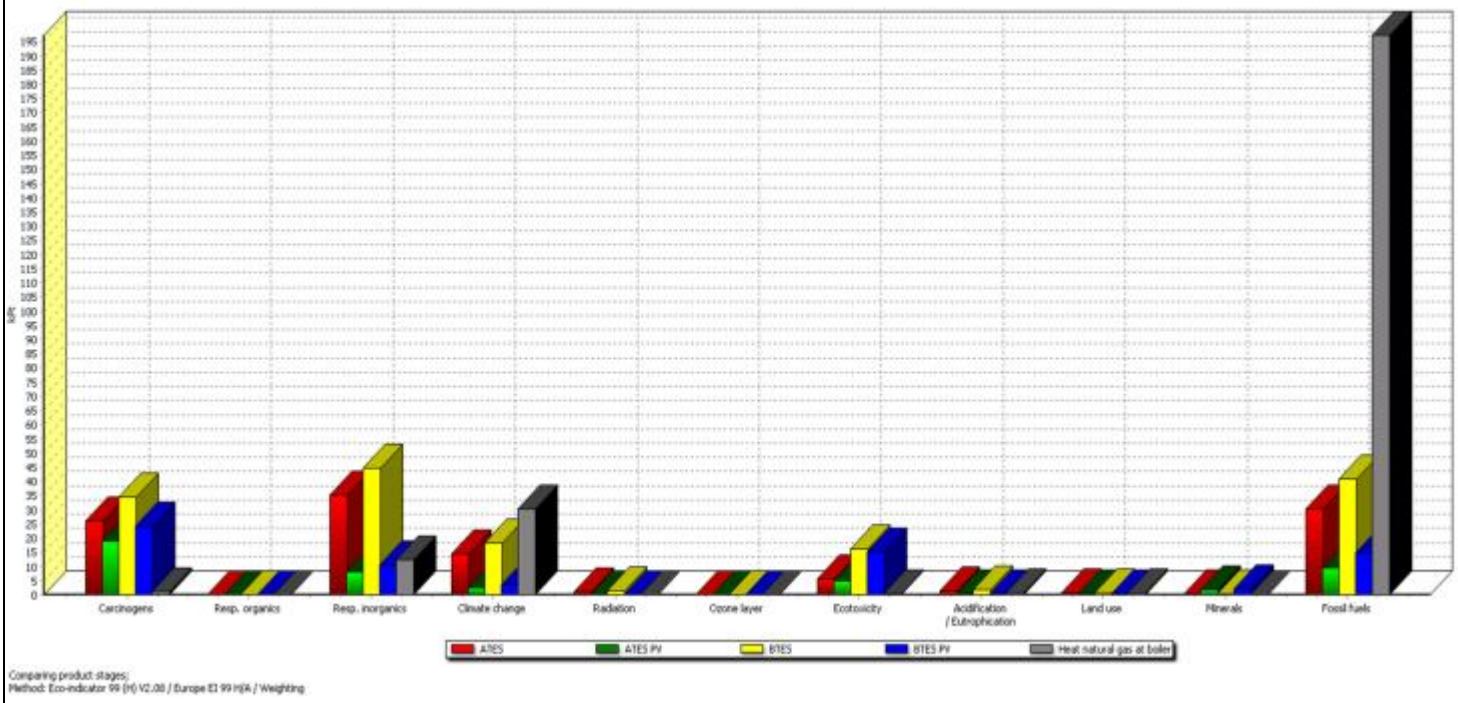

Figure 44. UTES using EU electricity production mix, UTES using PV electricity production and Natural Gas Boiler comparison. E-I 99 H/A. Impact categories.

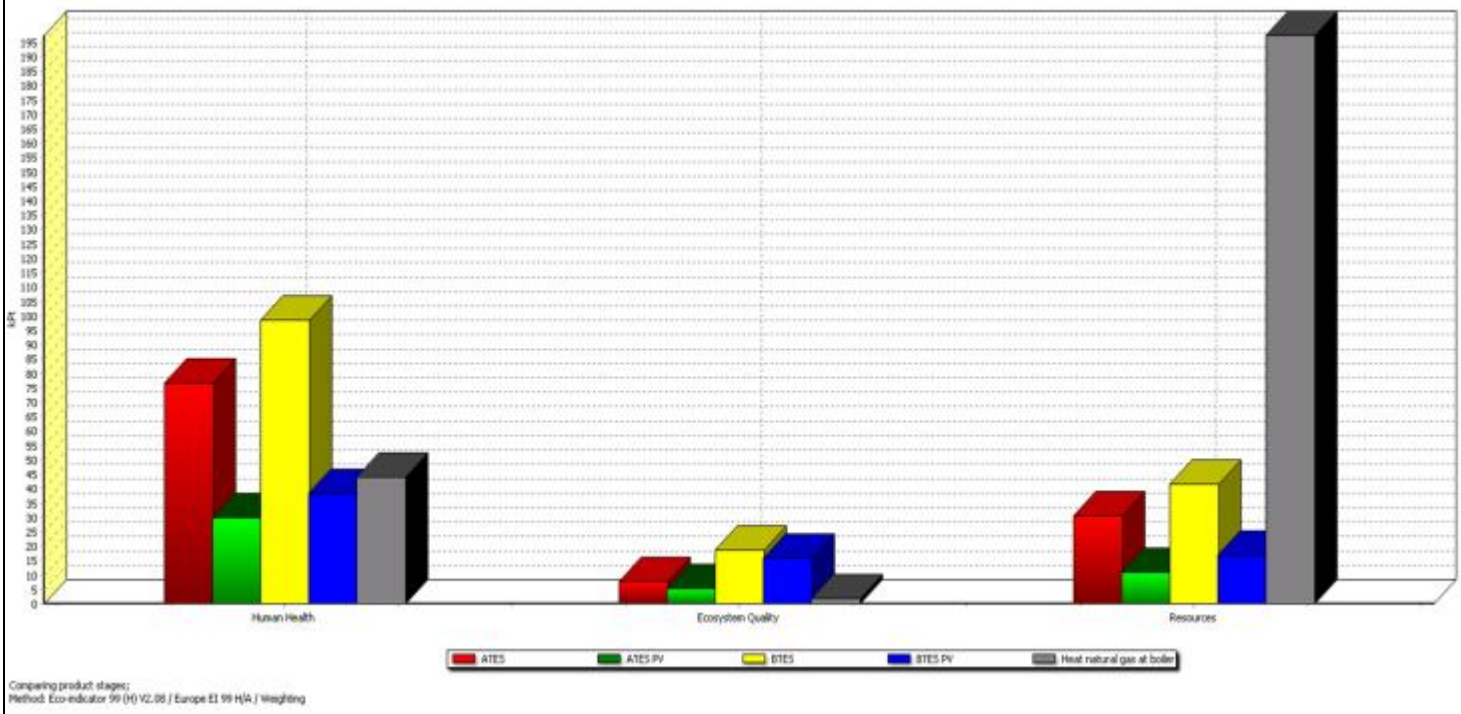

Figure 45. UTES using EU electricity production mix, UTES using PV electricity production and Natural Gas Boiler comparison. E-I 99 H/A. Damage categories.

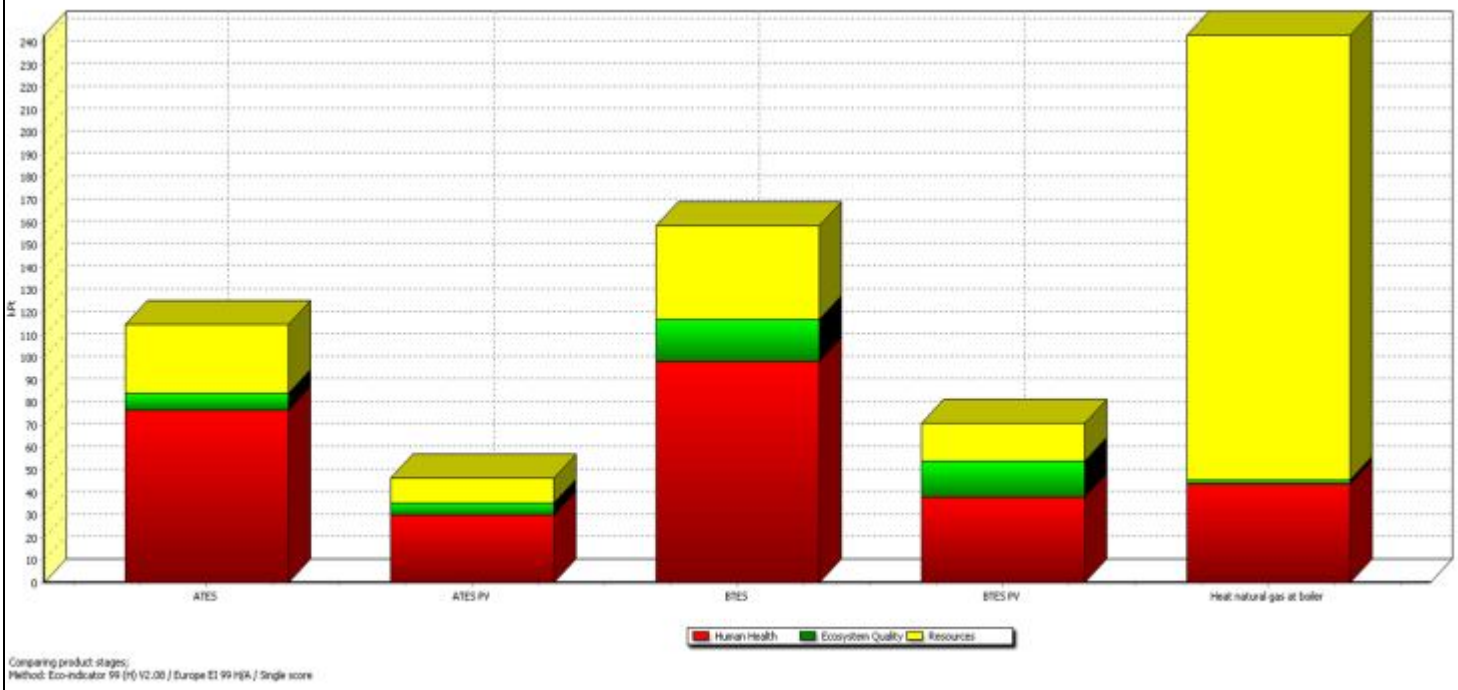

Figure 46. UTES using EU electricity production mix, UTES using PV electricity production and Natural Gas Boiler comparison. E-I 99 H/A. Single score.

5. ***Conclusions***

UTES technologies represent a possible solution to energy depletion as they allow to buffer the seasonal difference between energy supply and energy demand, exacerbated with renewable energy production. However, the speed of development and implementation of UTES – accelerated by the urge to reduce climate change footprints and by the attraction of sustainable and financially convenient solutions - has not been counterbalanced by an understanding of the systems deep enough to consider impacts on other sectors and - as a consequence - by responsible policy making. As noted, UTES not only poses potential threats to groundwater resources and the subsequent drinking water supply, but also generates conflicts with other potential users of the underground.

According to the LCA results using Eco-Indicator 99 impact method, UTES might represent better solutions compared to buildings traditional heating systems like natural gas and ATES seem to be more sustainable compared to BTES. UTES potential impacts become definitely less important when electricity produced only from renewable energy sources like photovoltaic panels is considered instead of a European countries mix, as the main calculated impacts of UTES are due to the electricity consumption, in particular to the emissions from fossil fuels fired power plants. Nevertheless, it is right and proper to point out that the present state of the art of the impact assessment methods does not include the totality of the impacts of these relatively new technologies installed in the underground. When changing the impact method from E-I 99 to IMPACT 2002+, the results seems to change as the traditional heating system is associated to a lower single score. In this case, in addition to the considerations about the incompleteness of the impact methodologies, it turns out that the different results are probably due to the different system boundaries of the traditional heating system coupled with the assumptions and approximation necessary to build the UTES life cycle model. The second impact method used for the sensitivity analysis is EPD: this is a midpoint methodology therefore a single score visualisation is not possible. UTES performs better than the traditional heating system in four out of six impact categories. A common output for all the three methods used is that ATES always performs better than BTES. This leads to the conclusion that a comparison between two similar systems like ATES and BTES might generate more consistent results than a comparison within systems with the same function but very different features, especially for relatively new fields for LCA application.

In general, it is possible to state that UTES performs certainly better than a natural gas heating system in terms of fossil fuels depletions and potential climate change impacts, as it allows a decrease in CO_2 equivalent emissions. Nevertheless, these results are related to the boundaries and assumptions chosen in this study and might change in case of specific systems with different characteristics and with different geological and climate conditions. Moreover, it is important to underline that the LCA results are relative only to one single ATES or BTES system and do not consider the high forecasted number of future installations that might raise additional problems in terms of temporary water stock depletion for ATES and space resource depletion for BTES.

When analysing the total energy requirements with the Cumulative Energy Demand method, UTES performs better than a natural gas heating system: ATES receive the first place in terms of performances again, with an energy demand 23% lower than BTES and 40% lower than natural gas. The life cycle energy savings of UTES are much lower than the primary energy savings suggested in many papers, because primary energy savings calculations consider only the operational phase of the systems. The life cycle energy savings of the considered ATES system accounts only for 30% against 77% of primary energy savings. Similarly, the life cycle energy savings of the considered BTES system accounts only for 10% against 70% of primary energy

savings. Nevertheless the total energy demand for natural gas is even higher than the thermal energy return. Moreover, almost the totality of the energy consumed by the traditional heating system has obviously fossil origins while the electricity consumed by the UTES systems can also derive from renewable sources. The outcome seems to change when considering exergy instead of energy: more exergy is consumed than retrieved. Compared to UTES the natural gas system consumes more exergy from fossil resources but less nuclear exergy and especially less exergy associated to hydropower. Nevertheless the comparison among different exergy indicators is discouraged, especially among non renewable and renewable ones as the latter account for exergy deriving from outside the system Earth. Therefore it is not possible to state which system performs better in terms of exergy consumption. The reduction of energy and exergy consumption is one important prerequisite for sustainable development as several environmental problems, e.g. climate change, resource depletion or nuclear waste disposal, are linked to the energy use. Energy consumption is also easily understandable for decision-makers such as consumers, politicians or managers of private enterprises. But energy/exergy use does not give a complete picture for all environmental impacts in the life cycle of goods and services and the environmental impacts vary among different energy resources.

In conclusion, this LCA study sets a basic framework to investigate UTES sustainability but this methodology is still incomplete. This makes the quantification of the real risks connected to this option more problematic. It is still unclear whether – in a future perspective - UTES should represent only a transitional expedient or a final solution. For this reason further research in terms of databases improvement and impact method models development is strongly recommended. The list of included impacts should be extended and a methodology to quantify the uncertainty associated to the models used in the impact methods should be developed. Moreover the underground knowledge is still incomplete compared to the long-term exploited surface and it should be improved. For instance, more insights on the underground microbiological populations and hydrogeological transport and chemical mechanisms are needed.

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