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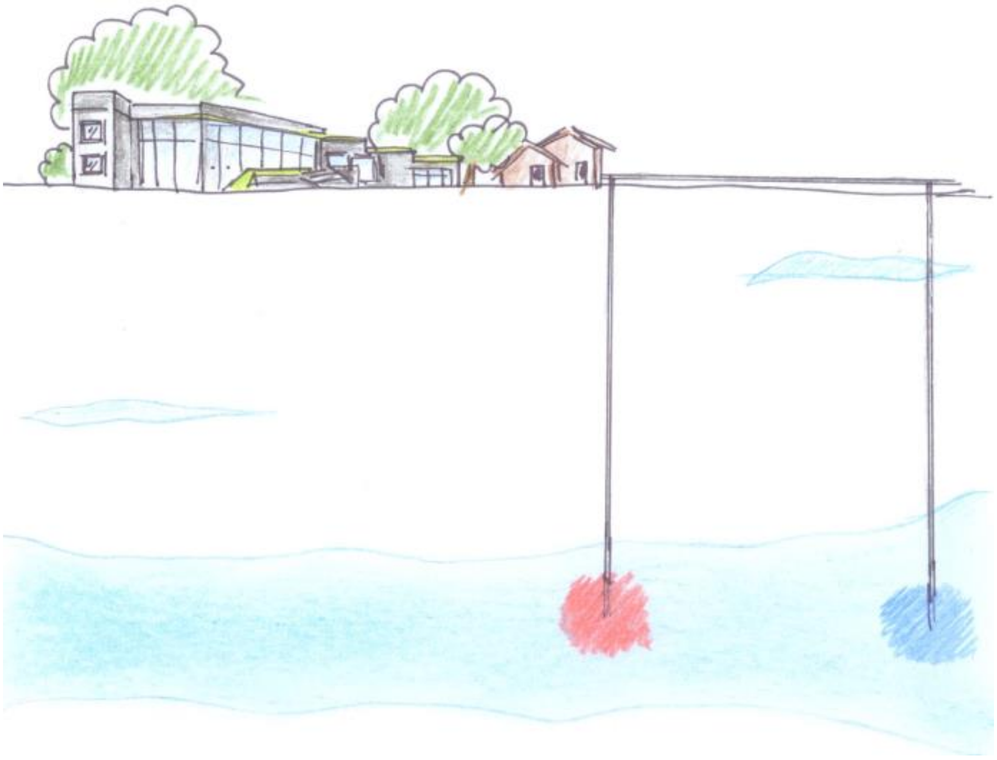
Life Cycle Assessment of an Aquifer Thermal Energy Storage system

Exploring the environmental performance of shallow subsurface space development



MSc Thesis report

Author: Alexandros Moulopoulos
Date: October 27th 2014

Colophon

Title	**Life Cycle Assessment of an Aquifer Thermal Energy Storage system -** Exploring the environmental performance of shallow subsurface space development
ECTS	45
Author Student number Email address	Alexandros Moulopoulos 3947483 amoulopoulos@gmail.com
University	Utrecht University Faculty of Geosciences Department of Innovation and Environmental Sciences
Master programme	Sustainable Development, track Energy & Materials
Supervisors	drs. C.C.D.F. (Derk) van Ree Derk.vanRee@deltares.nl Deltares dr. E. Nieuwlaar (1st reader) E.Nieuwlaar@uu.nl Utrecht University dr. R. Harmsen (2nd reader) R.Harmsen@uu.nl Utrecht University
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Acknowledgements

The present MSc report is the outcome of my 8-month internship in Deltares and forms the final part of my studies in the Sustainable Development Master programme in Utrecht University. A rigorous task which I would not have been able to complete as good as I have without the support from a number of people.

First and foremost, I offer my greatest thanks and utmost respect to my family for their love and immense support throughout the entire period of my studies. I hope I make you proud.

Second, I would like to thank all my colleagues at Deltares for making this internship a motivating and instructive experience. Most notably, Wijb Sommer for sharing his knowledge on ATES systems, Tjerk Vreeken for his assistance and willingness to oblige regarding data collection, Roy Veugen for the often endless but helpful discussions on the perks of LCA and, of course, my supervisor Derk van Ree. A naturally-inquisitive mind and exceptionally supporting person guiding me through this research, it has been very enjoyable to work with you.

Special thanks are due to my university supervisor, dr. Evert Nieuwlaar, for his expert opinion on crucial aspects of LCA and this research. I highly appreciate your thought-stimulating approach.

Last but not least, I would like to dedicate this report to all the people that have been close to me for the past two years. Thank you for being there through good and bad, I couldn’t have done it without you.

I hope you enjoy reading this report!

Alexandros Moulopoulos

October 27th 2014

Executive Summary

Thermal energy storage systems can have a significant positive contribution to the mitigation of climate change and facilitate sustainable development. For this purpose exploiting the subsurface is increasingly looked into due to the ground's inherent properties that make it a medium suitable for thermal energy storage. A number of different technologies are commercially available and widely implemented nowadays and are considered environmentally friendly solutions, especially when compared to conventional heating and cooling systems. Systems that make use of aquifers for thermal energy storage (ATES) are presently one of the most common thermal energy storage options. However, an ATES system still creates environmental impacts during its construction, use and end-of-life phases. Therefore, this report adopts a cradle-to-grave approach aiming to assess the potential life cycle environmental impacts of a combined heat and cold, shallow ATES system. To fulfil this aim the life cycle assessment (LCA) methodology as defined by the ISO standard is utilized. Given the increasing number of installed systems in the Netherlands this becomes especially relevant research and so data for this LCA was drawn from the ATES system that serves the heating and cooling demands of the Tetra building in Deltares in Delft.

Using the ReCiPe Midpoint impact assessment method the first result of this study confirms the outcome of previous research, namely that the electricity consumed during the use phase of the ATES system has the largest influence in the majority of the environmental impact categories. This is mainly due to the fossil fuels used in power plants and so switching to a renewable electricity source can reduce these impacts considerably. An additional, original finding of this research regards the preventive maintenance of the well screens of ATES systems. A certain amount of aquifer groundwater is extracted annually and used to "flush" the wells in order to prevent clogging of the well screens. Dutch legislation allows the owners of ATES systems to choose between draining this groundwater to nearby surface water or in the sewage. This study shows that the second option can incur considerable environmental impacts which in some impact categories are even larger than those of electricity use. Lastly, it is shown than when looking only from an energy perspective the use phase of an ATES system performs significantly better than a conventional heating and cooling system. However, when compared at midpoint level and accounting for more impact categories it is unclear which system is more preferable in environmental terms as their impacts appear evenly-matched.

The general conclusion that can be drawn is that, at this point and taking into account the specific assumptions and characteristics of this research, ATES systems appear to still have room for the optimization of their environmental performance and to successfully exploit their vast potential towards the transition to sustainable development.

Keywords: ATES, LCA, Environmental impacts, SimaPro, ReCiPe, Sustainability, Underground

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List of Abbreviations

ATES	Aquifer Thermal Energy Storage
CEnD	Cumulative Energy Demand
COP	Coefficient of Performance
ECES	Energy Conservation through Energy Storage
ILCD	International Reference Life Cycle Data System
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
ODP	Ozone Depletion potential
SEER	Seasonal Energy Efficiency Ratio
SPF	Seasonal Performance Factor

Chapter 1 – Introduction

1.1 Context and problem definition

Presently the built environment requires extensive amounts of materials, energy, water and land and so it accounts for the largest share of the global resource and energy demand. It has been estimated that the building sector uses about 40% of global energy, 25% of global water, 40% of global resources, and is considered responsible for approximately one third of total global greenhouse gas (GHG) emissions (UNEP, 2014). Next to that, current trends show that the world's population is expected to increase by 30% and amount to 9 billion people by 2050 (UNDESA, 2011; UNFPA, 2011). The consequence of this will be an increasing demand for buildings which is certainly going to place additional pressures on the global energy and resource system, both at an international as well as regional level, and subsequently further exacerbate the issues of global warming and environmental degradation (Xu et al., 2013). For this reason, a number of regions and individual countries have set environmental goals with the most prominent example probably being the European Union's 2020 targets. There exists therefore a necessity for the substitution of fossil fuels by renewable sources of energy that can be used to conserve on finite energy sources and reduce GHG emissions.

Renewables have shown great potential as alternative energy sources and one of the most effective ways to further exploit their potential is the development of energy storage technologies (Dincer & Rosen, 2002). Energy storage can be used to effectively conserve energy in its various forms and thus help significantly towards the mitigation of climate change. More specifically, thermal and electrical energy storage systems can facilitate the efficient use of renewable energy and help overcome the temporal mismatch between supply and demand which can ultimately lead to significant energy conservation and the reduction of GHG emissions (ECES, 2013). At the moment, however, the application of energy storage technology is limited for a number of reasons. The most important reasons are that at the current state-of-the-art energy storage systems are not economically competitive, there exist several regulatory and market barriers and lastly proven reliability and long-term performance are lacking (ECES 2013; Vail & Jenne, 1992). Nevertheless, the International Energy Agency (IEA) has initiated an international research and development programme called the Energy Conservation through Energy Storage (ECES). The purpose of ECES as stated in their 2011-2015 Strategic Plan (2011) is to "*…facilitate an integral research, development, implementation and integration of energy storage technologies to optimize energy efficiency of every kind of energy system and to enable the increasing use of Renewable Energy instead of Fossil Fuels".* Additionally, it has been stated in an ECES workshop (2014) that:

"There is not an energy problem, but an energy storage problem".

When it comes to energy consumption the major consumer, even larger than electricity production and transportation, has been identified as the need for space heating and cooling in buildings (EGEC, 2006). Many energy-saving policies are concentrating on reducing the amount of energy use in both heating and cooling as well as to the use of an energy source which is as sustainable as possible (Brouwers & Entrop, 2005). For that purpose many techniques can be employed such as the use of energy-saving equipment, high levels of insulation and advanced building management systems.

However, according to Dincer & Rosen (2002) it is thermal energy storage systems that show the largest positive contribution in this area. Among the thermal energy storage options concerning the building sector there is one that involves the use of subsurface space to store thermal energy (Energy Association, 2014). Underground thermal energy storage (UTES) is the term used to describe the use of soils, bedrock and groundwater as a storage medium for thermal energy. It has been proven that the subsurface can be a suitable medium for the long-term storage of large heat quantities due to the thermal capacity of the soil and low thermal conductivity of the rocks (Réveillère et al., 2013). The underlying principle of UTES is that during summer, heat can be captured and stored in the underground and later used during winter to heat a building. Reversely, during winter, cold can be stored and then used during the summer to cool a building. The most common types of UTES are Aquifer Thermal Energy Storage (ATES) and Borehole Thermal Energy Storage (BTES) (Lim, 2013; Bridger & Allen, 2005). Other technologies for thermal energy storage are the Cavern Thermal Energy Storage (CTES), pit storage, molten salt and also Phase Change materials (PCM) (Michel, 2009; Sharma et al., 2009).

In general, UTES systems are considered to be economical and environmentally friendly solutions to the world's energy problems that are simultaneously able to facilitate the effective utilization of renewable energy for the space heating and cooling of buildings (Dincer & Rosen, 2002; Lee, 2010; Paksoy et al., 2004). However, there remain a number of issues that need to be addressed in order for this consideration to be entirely justified especially regarding the environmental profile of these systems. Additionally, it is interesting to note that at present limited literature exists regarding the long-term environmental impacts of thermal energy storage systems in general (Oró et al., 2012; de Gracia et al., 2010; Adeoye et al., 2014) but even more so regarding ATES systems. At the same time, an increasing number of such systems is reported worldwide (Gao et al., 2009; Hähnlein et al., 2013; Sanner et al., 2003). The use of ATES systems can give rise to significant hydrological, chemical, microbiological and thermal impacts and a comprehensive evaluation of their environmental performance is necessary (Aposteanu et al., 2014; Bonte et al., 2011; IEA-ECES strategic plan, 2011). Similarly, an ATES system can be responsible for a variety of yet non-quantified environmental impacts that relate not only to the use phase of the system but also to the construction and end-of-life phases. Thus it is deemed important to perform more research in order to explore this area and produce thorough knowledge on the life cycle environmental aspects of thermal energy storage systems.

1.2 Aim of study

As was mentioned previously, although ATES systems are generally considered environmentally friendly solutions there still exist several environmental impacts that relate to their construction, use and end-of-life that still need to be properly assessed. Therefore a life cycle assessment (LCA) approach is the most suitable tool for this type of evaluation as it is especially designed to account for the impacts of production, use, and waste management of goods over their entire lifetime and at a global scale (Baumann and Tillman, 2004; Tukker, 2000). The primary aim of this study therefore is to apply the LCA approach in order to evaluate the potential environmental impacts of a shallow ATES system, identify the largest contributors to these impacts and provide a contextual comparison with a conventional heating and cooling system. This aim is also consistent with the objectives of the IEA 2011 – 2015 Strategy Plan regarding energy storage technologies.

The only similar previous research in this area involved an LCA comparison of an ATES with a BTES system focusing just on heat storage (Tomasetta, 2013). The main conclusions from that study were that electricity usage during the operation phase is the main contributor to environmental impacts and that both UTES systems show an improved environmental performance in comparison to conventional heating systems. Yet, a number of remarks were made regarding the assumptions of that study by Rijksdienst voor Ondernemend (RVO.nl). For instance, the lifetime considered was too large for an ATES system while some processes considered were not applicable to the Dutch typical procedures or were absent. Most notably, an essential maintenance process concerning the ATES well screens was missing from the study and it was important to be accounted for since it constitutes an integral operational part of any ATES system. Additionally, the previous study looked into a heat-only system. Combined heat and cold ATES systems allow for better ground temperature regeneration and therefore improve the overall performance of the system (REHAU, 2013; Paksoy et al., 2009). These systems also enable the net energy balance requirement (section 3.2) and thus present a more realistic and cost-effective option for an ATES system. Additional aims of this study are the extension of present knowledge within Deltares regarding the application of LCA to underground constructions as well as the impact evaluation of the Deltares ATES system.

To fulfil its aims, the present study examines a combined heat and cold ATES system based on data from the existing system that serves the Deltares offices in Delft. Additional focus is given on the impacts resulting from the construction and end-of-life treatment of the system thus providing a more comprehensive picture of the potential life cycle environmental impacts of a shallow ATES system. Lastly, although it was among the initial aims of this study to assess the difference in impacts between design and actual performance of the system this was deemed impossible due to lack of specific data regarding the seasonal energy consumption of the different system components. Therefore, the following analysis is performed based only on design characteristics of the Deltares ATES system.

1.3 Research questions

From the aim of the study, the main research question was derived as:

“What are the potential life cycle environmental impacts of a combined heat and cold ATES system?”

In order to answer the main research question, the analysis needed to be broken down in separate parts and so a number of sub-questions regarding the life cycle phases of an ATES system were formulated. First of all, the life cycle environmental impacts that relate to such a system needed to be identified and so the following sub-question was formed:

1. *“Which environmental impact categories are most appropriate for the life cycle assessment of an ATES system?*

In order to perform an LCA and assess the potential environmental impacts detailed information regarding energy and material inputs and outputs needed to be collected. Hence, using the Deltares ATES system as a case study a second sub-question could be added:

2. *“What are the energy and material inputs and outputs over the lifetime of an ATES system?”*

Answering the aforementioned sub-question supports the formation of the following sub-question to identify and quantify the impacts that relate to each of the life cycle phases of an ATES system:

3. *“What and how large are the environmental impacts of the construction, use and end-of-life phases of an ATES system?”*

To fulfil the second aim of this LCA regarding the identification of the dominating causes for the environmental loads in each phase of the ATES system a fourth sub-question was formulated as:

4. *“What are the dominating contributors to the life cycle environmental impacts of an ATES system?”*

A sensitivity analysis is also performed in order to address assumptions that could potentially affect the LCA results. Such an analysis can be used to provide significant insights in order to improve the environmental performance of the system. Thus, another sub-question was formulated as:

5. *“What is the sensitivity of the life cycle assessment results regarding different assumptions?”*

Examples of the different assumptions that will be assessed are the source of electricity for operating the ATES system and also different waste treatment scenarios. Finally, a sub-question to put the environmental performance of an ATES system into perspective was then formed as:

6. *“How does an ATES system compare environmentally to a conventional heating and cooling system?”*

Chapters 2 is used to present the research methodology according to the ISO standard while in Chapter 3 some background information on ATES systems is provided. In Chapter 4, the LCA methodology is applied to the Deltares case study while Chapter 5 discusses the limitations of the present study. Finally, in Chapter 6 the conclusions of the LCA are presented.

Chapter 2 – Research Methodology

In its Communication on Integrated Product Policy (IPP, 2003) the European Commission highlighted the need for the formation of a knowledge base in order to support policy decisions. The IPP further recognizes the usefulness of a holistic, evaluating assessment and promotes the adoption of "life cycle thinking". Additionally, many countries across the globe are increasingly adopting life cycle perspectives as a key aspect of their governmental programmes and policies as can be seen for example from Brazil's Policy on Solid Waste Management , Japan's 3R's and the US Preferable Purchasing Program. To examine the environmental impacts over the complete life cycle of the ATES system this research was carried out from an LCA approach. In ISO 14040 (1997) LCA was defined and internationally standardised as:

"…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".

According to the ILCD Handbook (Wolf et al., 2012) environmental LCA has been in use since the late 1980s and its strength lies with its five principles. Namely that it:

- Enables the integration of a wide range of environmental problems, such as climate change and toxicity on ecosystems and humans, into one assessment framework.
- Addresses environmental issues in a scientific and quantitative way by inventorying and analysing the amount of all related resource uses and emissions as well as monitoring impacts and achievements over time.
- Allows environmental issues to be related to any defined system, such as particular types of products and services.
- Can integrate impacts throughout the whole life cycle of the analysed system by looking over all phases. From raw material extraction, to manufacturing, distribution and use and up to the end-of-life phase (recycling and/or waste disposal). It can therefore prevent solving one problem in one stage but creating another problem in a different stage of the system's supply chain.
- Enables fair comparison of different systems/options and helps ascertain specific areas for improvement. This is achieved by comparing different options on the basis of their functional unit which by definition is an accurate and quantitative description of the functions provided by the proposed system, i.e. *"what"* does the system do or *"how well"* it does. By basing the comparison on the functional unit of different options an LCA can ensure a fair and transparent comparison.

Finally, LCA has been internationally recognized as the best available methodology to evaluate sustainable environmental performance in a consistent and transparent way (Baitz et al., 2012). The analytical phases of an LCA are shown in Fig. 1 and following that the LCA framework is presented according to the ISO 14044 standard.

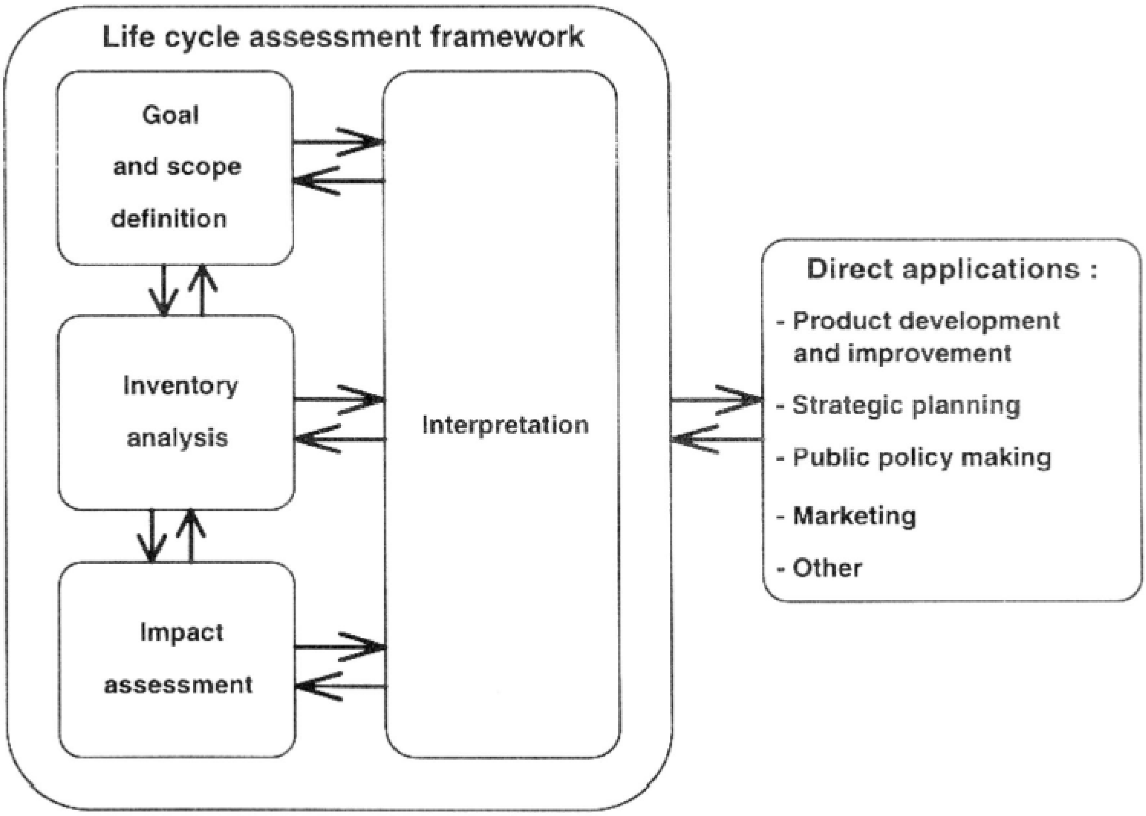

Figure 1 – LCA phases and applications (adapted from ISO 14040, 1997)

2.1 Defining the goal and scope

The goal of an LCA must state explicitly (a) the intended application, (b) the reasons for carrying out the study, (c) the intended audience to whom the results will be communicated and (d) whether the results will be used to make comparisons that might become publicly available. The scope of an LCA should include and go over:

- the product system that will be studied
- its function and functional unit
- the system boundaries
- how allocation is dealt with
- the impact assessment method(s)
- types of impacts
- the interpretation method that will be used
- data quality requirements and assumptions
- limitations of the research

All of these elements must be consistent with the goal of the study. In that regard, one of the most important and often challenging requirements of an LCA is the definition of a proper functional unit. The purpose of the functional unit is to provide reference to which input and output data will be normalized. It should define properly the function (*what*), quantity (*how much*), quality (*how well*) and timespan (*for how long*) that the system fulfils its specific function(s). Thus a proper functional unit can enable fair and transparent comparisons with other product systems that perform the same function. The system boundaries will clearly state which processes and life cycle phases are included in the study and justify the reasons why others were left out. In a comparative LCA the equivalence of systems compared must be ensured. Thus the scope should be defined in such a way that the systems can be compared, by using the same functional unit, system boundaries, data quality, allocation procedures and impact assessment methods. Should any differences exist these must be stated clearly.

Finally, the goal and scope of any LCA study must be clearly defined and consistent with the intended use. As a result of the iterative character of an LCA and unforeseen limitations (i.e. data availability) it is possible that the scope will have to be refined and revisited numerous times throughout any LCA study.

2.2 Inventory analysis

The purpose of the life cycle inventory analysis (LCI) phase is to collect qualitative and quantitative data for each process that is included in the system boundaries. Some examples of data types are energy and raw material inputs, products and by-products as wells as waste and emissions to the atmosphere. This information can be collected, measured, calculated or estimated and then used to quantify the inputs and outputs of system processes. A simplified overview of the iterative inventory analysis procedure that is followed is presented in Fig. 2.

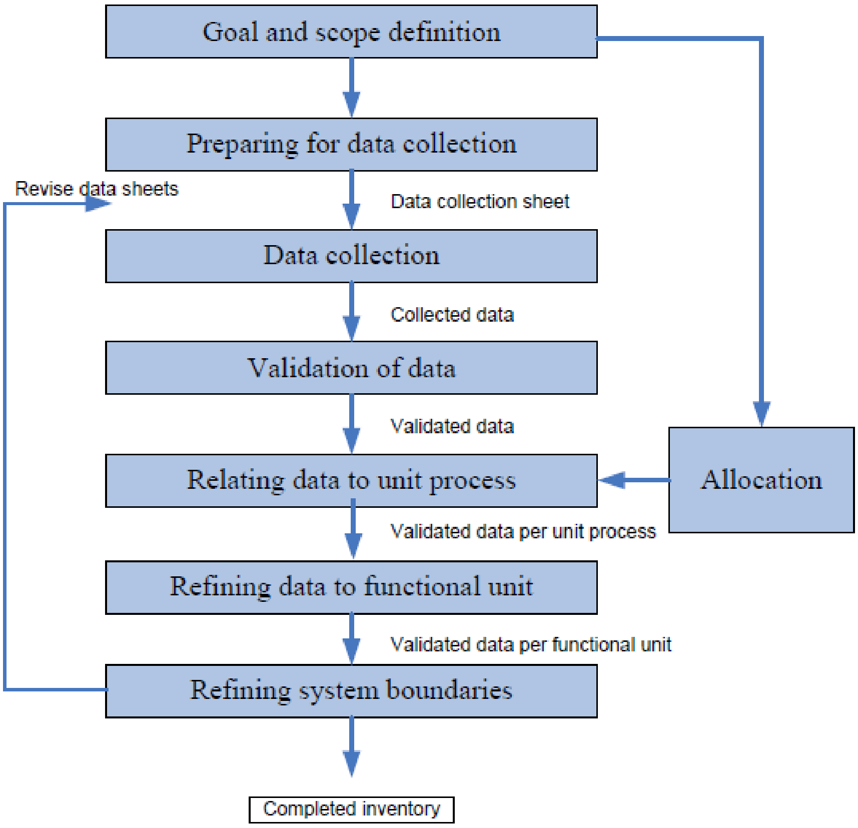

Figure 2 – LCI procedure (adapted from ISO 14044)

All calculation procedures must be clearly illustrated and explained properly and the results should be according to the functional unit of the analysis. In- and outflows of the system must also be demonstrated here, usually through a flow diagram. In the LCI the system boundaries should also be refined and explained in detail, taking into account the data availability or lack of it. In many cases some processes provide more than one function in the product system. This is defined as multifunctionality. Such an example is the provision of electricity and steam as co-products of a waste treatment facility treating different wastes. Much attention should be paid to this issue in order to avoid multifunctionality issues and to ensure that impacts are allocated properly to their respective processes. It is generally advised to avoid allocation and the main procedure for this:

1. Wherever possible, allocation should be avoided by:
    a. Subdividing the processes to subprocesses and linking them to input/output data specific to them.
    b. Expanding the system to include additional functions relating to the co-products.
2. Wherever allocation cannot be avoided, inputs/outputs of the system should be allocated according to the physical relationship between them and the system (mass allocation).
3. If a physical relationship between co-products cannot be established, then allocation should be performed proportionally to their economic value (economic allocation).

2.3 Impact assessment

According to ISO 14044 the life cycle impact assessment (LCIA) phase is:

"…aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product".

The LCIA phase is further divided into sub-phases comprising of mandatory and optional elements which are used for reporting.

Mandatory elements are:

- **Impact category definition**. Relevant environmental impacts are selected and specified according to the goal and scope definition. It is important that the selection of impact categories comes after the definition of *endpoints* or damage categories which are the final results that will be presented to the intended audience. Endpoints are the results of aggregating midpoints. *Midpoints* represent the indicators of an impact assessment. Usually, indicators chosen closer to the LCI have lower uncertainty than indicators closer to the final impact category as less of the environmental mechanism involved needs to be modelled. On the other hand, indicators closer to endpoints tend to be more easily interpreted than midpoint indicators and therefore are preferable to decision-makers of environmental policies.
- **Classification**. All LCI results are assigned to impact categories. Some of these results can contribute to several impact categories (i.e. NO_x to acidification, photochemical oxidant formation, toxicity).
- **Characterisation.** This element is defined as the calculation of category indicator results which involves the conversion of LCI results into common numerical units. This impact quantification is performed by multiplying with a characterisation factor for each impact category.

The optional elements of the LCIA are:

- **Normalisation.** The quantified impact from the previous step is compared to a certain reference (normal) value. An example is the average CO_2 emissions of an average European citizen in one year.
- **Damage assessment.** This is a relatively new LCA methodological step that allows the aggregation of impact category indicators into a single damage category as long as they are expressed in a common unit. For example, impact categories that refer to human health are expressed in DALYs (disability adjusted life years) and it is possible to add the DALYs from human toxicity to those caused by ozone layer depletion.
- **Weighting.** Impact categories are multiplied with a factor, and the resulting figures are used to create a single score. This step involves a high degree of uncertainty as the weighting factors are based on subjective decisions such as monetisation of environmental goods and authoritative targets and panels. In order to comply with the ISO standard weighting should be avoided when results are intended to be disclosed to the public.

2.4 Interpretation

The interpretation phase of the LCA framework is the step that identifies the most significant issues based on the results of the LCIA. It is also used to evaluate completeness of the study and check the consistency of the assumptions, methods and data used. Two further analyses can be performed here:

- Uncertainty analysis to determine how data and model uncertainties can affect the calculations and the reliability of the LCA results.
- Sensitivity analysis to determine how changes in methodological choices and assumptions can affect the results of the LCA.

Chapter 3 – Aquifer Thermal Energy Storage systems

3.1 General information

ATES (also known as open-loop systems) use underground water-bearing geological layers, commonly known as aquifers, as a heat-source or heat-sink depending on the requirement for heating or cooling. They involve the use of one or more wells which are specifically designed to withdraw or inject groundwater in order to extract and/or store large quantities of the thermal energy that is present in the groundwater and aquifer material within a certain sphere of influence. Considerable savings on electricity bills can be achieved and in most cases the payback time for these systems is shorter than five years (ECES website, 2007). Contrary to most UTES systems, including BTES, when installed in subsurface locations with suitable hydrochemical and hydrogeological conditions ATES systems can display higher heat transfer capacities which result in lower investment costs and shorter payback times (Eggen & Vangsnes, ny; Lee, 2010). The distribution of temperature in the subsurface is affected by a number of factors. According to Popiel et al. (2001), these factors can be summarized as:

a. the structural and physical properties of the ground,
b. the ground surface cover and
c. the interaction with the climate, i.e. air temperature, wind and solar radiation.

In the first few meters of the subsurface (<10m), ground and groundwater temperatures are very sensitive to weather conditions and fluctuate according to seasonal variations (Brandl, 2006; Bridger & Allen, 2005). Between 10 – 20m, this variation is alleviated and ground temperatures more or less stabilize at the average annual air temperature of the specific location while in greater depths subsurface temperatures increase gradually at an approximate rate of 1 °C per 35m (Eskilson, 1987; Bridger & Allen, 2005). Thereby, at these depths the underground offers a constant and largely stable environment for the seasonal storage of thermal energy. According to Paksoy et al. (2009), ATES systems are mostly installed in buildings with long hours of operations which also have a high level of utilization, such as academic buildings, shopping malls and office buildings. Their application can be divided in three categories: heat storage only, cold storage only or combined heat and cold storage (Hove, 1993). ATES systems are bi-directional, meaning that they can circulate groundwater to and from an aquifer to serve the heating and/or cooling purposes of a building. Systems employing both extraction and re-injection are commonly used to improve the performance of single-direction groundwater thermal systems (Dickinson et al., 2009). The basic design components of an ATES system include:

- a suitable aquifer system
- one or more injection/extraction wells
- a heat exchanger
- and an affordable or 'free' source of thermal energy, i.e. solar energy or cold from the outside air (Bakr et al., 2013).

ATES systems can be distinguished in two categories, shallow systems and deep geothermal systems. Shallow systems located up to 500m below ground level (bgl) utilize low-temperature thermal energy. Deeper than that and up to 4km bgl the systems are called deep geothermal and utilize high-temperature (45 – 90°C) energy (IF Technology, 2014).

The following figure illustrates the alternating uses of an ATES system during the winter and summer periods:

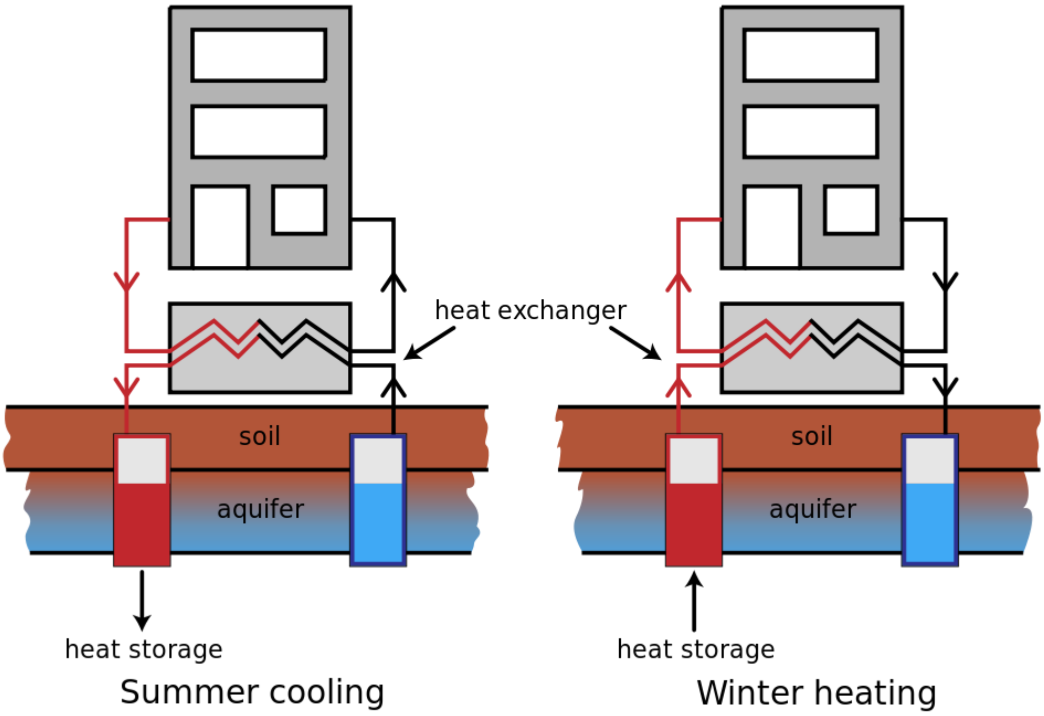

Figure 3 – ATES system operation during winter and summer (adapted from Underground Energy Storage LLC website, 2014)

The principle behind the operation of the ATES is simple. During summer, groundwater from the aquifer is pumped from the lower-temperature well (‘cold’ well) and passed through a heat exchanger within the building. Heat from the space inside the building is transferred to the stream and the water that is heated from this process is re-injected in the higher-temperature well (‘warm’ well). During winter, this process is reversed. Thereby warm groundwater is pumped from the warm well and then passed through a heat exchanger. This water is thus cooled down and then re-injected at the cold well for seasonal storage and use during the summer period. In many cases, the temperatures of the wells are sufficient for direct cooling of a building (Paksoy et al., 2009; Bridge & Allen, 2005).

In most cases the available heat delivered by a shallow ATES system is not always sufficient to cover the entire heating demands of a building. For that reason ATES systems are usually combined with other heating or heat transfer systems such as natural gas boilers and heat pumps. Heat pumps (Fig. 4) are the most standard choice and are utilized to upgrade the energy extracted from the ground and cover a larger amount of the building’s heating demand. Since heat pumps are a key element of an ATES system it is important that an understanding of their basic operation principle is acquired and therefore it will be presented in more detail here.

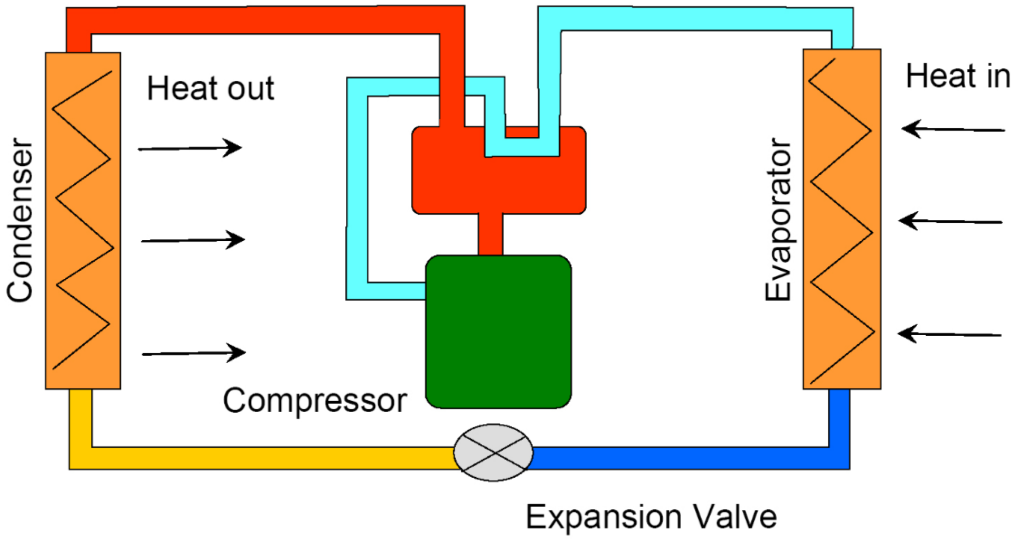

Figure 4 – Basic heat pump configuration (adapted from I-HT website, 2014)

A heat pump does not generate heat precisely but instead it is used to transfer heat from one place to another. It can transform low-temperature heat to high-temperature heat by using an additional energy input. This input is usually electricity. A heat pump comprises of four main components, the evaporator, the compressor, the condenser and the expansion valve. In the example of heating during winter, the extracted warm groundwater exchanges heat with a refrigerant that is then evaporated in the evaporator. Its pressure is increased in the compressor to allow for a further increase in the refrigerant's temperature and that heat is released to the building when it passes through the condenser and becomes liquid again. Finally, passing through the expansion valve the refrigerant returns to its original volume and the cycle begins anew. The reverse process is used for cooling in the summer and it is known as the 'air-conditioning or refrigeration principle'. Usually heat pumps are driven from electricity and a common measure of a heat pump's efficiency is the coefficient of performance (COP):

$$COP = \frac{Q}{W} \qquad (Eq. 1)$$

Where:
Q, is the thermal energy supplied or removed by the heat pump and
W, is the electricity input needed to operate the heat pump at a specific temperature.

The COP of a heat pump is influenced largely by the temperature difference between the condenser and the evaporator. Typical COP values range from 4-5 and the higher the COP the more efficient a heat pump (Blok, 2007). Another useful measure of a heat pump's efficiency is the seasonal performance factor (SPF) which can be calculated using Eq. 2:

$$SPF = \frac{useful\ energy\ output\ of\ the\ energy\ system}{energy\ input\ of\ the\ energy\ system} \qquad (Eq. 2)$$

The SPF is an average COP for a certain period, i.e. a year or a cooling season. SPF also includes other energy-consuming elements of a heat pump (i.e. circulation pumps) and its values are slightly lower than COP. The SPF also takes into account weather conditions and a building's fluctuating energy needs (Brandl, 2006).

Lastly, in an ATES system it is considered that no net extraction of groundwater from the aquifer occurs. The same amount of groundwater pumped from one well is re-injected in the other. Thus the negative impacts on the environment of an ATES system are reduced (Hendriks et al., 2008). In practice though, a small amount of groundwater (1600m^3 according to Dutch regulation) is disposed annually in a process called "flushing". This is done to prevent clogging of the screened sections of the wells by groundwater substances (heavy metals or minerals) which accumulate over time. Compared to the total amount of groundwater flowing through the aquifer this amount of groundwater is generally considered negligible which can be debatable and so an examination of the related environmental implications of this practice is necessary.

3.2 ATES in the Netherlands

In a number of European countries the application of shallow ATES systems is a standard building design option for indoors climate control. As mentioned, ATES technology is very site-specific and therefore the major precondition for the installation of such a system is the existence of an aquifer. Since aquifers can be found almost everywhere in the Netherlands this precondition is not an issue for the country and so they have become technological leaders in this area (Lee, 2010). In the Netherlands, the majority of the total ATES systems installed are shallow systems and therefore from now on only these systems will be addressed. The first systems started to be implemented in the 1980s and ever since ATES has become a viable, cost-effective and energy-efficient technology with a large commercial basis (Vail & Jenne, 1992; ECES, 1998; Snijders, 2000). In 1999 the number of ATES systems was 100 and in 2009 this increased to a total of 1000 (Bonte et al., 2011). By 2012 this number was measured at 1500 (Bloemendal et al., 2014) and now ATES systems operate in almost every major city in the Netherlands.

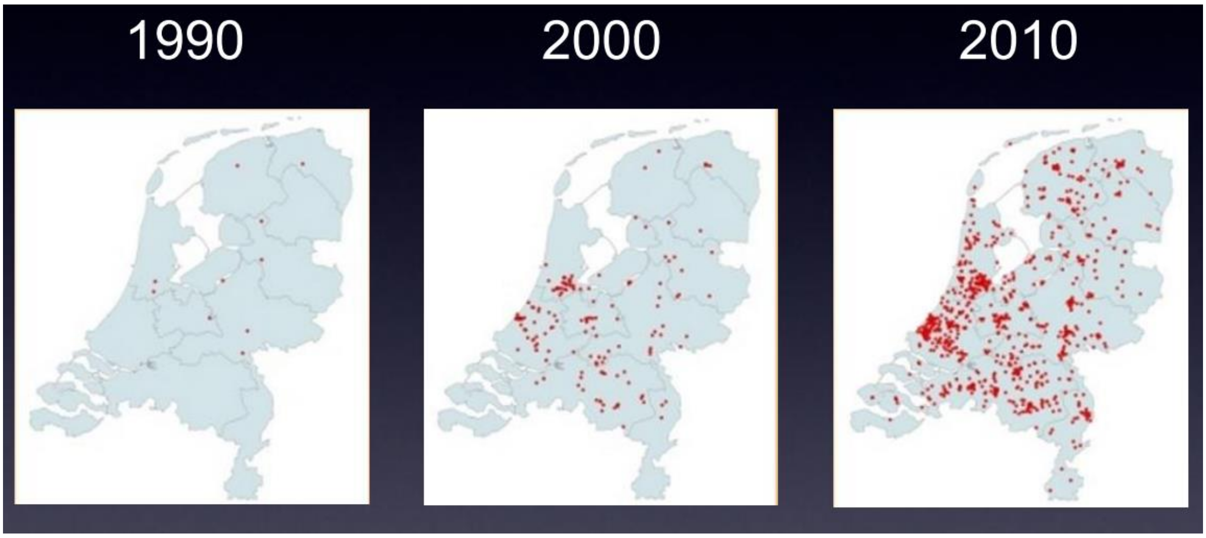

Figure 5 - ATES systems installed in the Netherlands (adapted from Worthington, 2012)

This is an impressive increase (Fig. 5) especially if one takes into account that contrary to BTES[1], ATES systems need to go through a regulatory process to obtain a permit from the government due to the fact that they utilize and interact with groundwater for their operation.

It should be mentioned that in the Netherlands a national law exists dictating that an ATES system must show an aquifer net energy balance of zero at the end of its lifespan (Staatscourant, 2011). ATES systems are most often designed to fulfil this requirement although in practice these amounts can vary from expectations. Slight cooling of the underground is allowed (no detailed quantification exists at the moment) while heating is disallowed since it can cause significant microbiological, chemical and thermal impacts (Bonte et al., 2011; Hähnlein et al., 2013). The energy balance ratio (EBR) can be calculated by using the energy balance ratio formula as described in Eq. 3:

$$EBR = \frac{Ec-Ew}{Ec+Ew} \qquad \text{(Eq. 3)}$$

In which E_c is the cumulative amount of cold that is extracted and E_w is the amount of heat extracted from the subsurface. Practically, this is checked with well temperature measurements once after 5 years of the installation time and then once every three years. In case, it is found that a system lacks a net energy balance at the end of its lifespan an additional amount of thermal energy will need to be injected (or extracted) to the ground. This, of course, can lead to a number of environmental impacts that should be taken into account when installing and operating such a system. Lastly, it has been estimated that in 2020 a total of 20.000 ATES systems should be installed in the Netherlands in order to achieve 2% energy savings according to the 2020 national targets (Goschalk & Bakema, 2009). Therefore, with such a large increase expected it becomes even more evident that thorough research needs to be made to assess the environmental impacts relating to these systems' life cycle.

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[1] More accurately, in the Netherlands BTES systems above 70kW of thermal capacity also require a permit for installation and operation (Staatscourant, 2011).

Chapter 4 – Life Cycle Assessment of the Tetra ATES system

This research can be defined as an attributional (or accounting) LCA, meaning it is meant to evaluate the environmental load of a single product system and its main contributors. The term attributional is used in the LCA research area in order to distinguish from consequential (or change-oriented) LCAs where the change from one product system to another is investigated. The present assessment was performed based on the SimaPro 8 LCA software and using the newest Ecoinvent database (v3). The following sections illustrate how the LCA framework was applied to the specific case study.

4.1 Goal and scope definition

The goal of this LCA is to evaluate the environmental impacts relating to the entire life cycle of an existing shallow ATES system, identify the major contributors to these impacts and provide a comparison with a conventional heating and cooling system. The intended application for this study is on the ATES system operating at the Deltares offices in Delft. The underlying reason for carrying out this study is to extend internal knowledge for Deltares regarding the potential environmental impacts of the installed system and their quantification. Additionally, this research is intended to cover one piece of the puzzle that is the evaluation of environmental impacts ensuing from subsurface space development and stimulate further research in this area. Moreover, a number of different parameters will be tested in order to address parts of the comments of RVO.nl regarding previous LCA on ATES systems. The intended audience for the results of the study are scientists that might use this as a basis for further research and policy-makers interested in the environmental performance of ATES systems. Decision-making based on the findings of this study alone should be avoided and always coupled with an environmental impact assessment taking into account local conditions and regulations.

In the study by Tomasetta (2013) it was shown that the majority of the environmental impacts ensue during the use phase of the system. However, in that study only heat storage UTES systems were considered. Combined heat and cold systems are more common and promising for the Netherlands as they require little extra work and costs. They also show a more positive influence on the regeneration of the thermal energy of the subsurface and thus comply better with the Dutch legislation requiring a net energy balance at the end of the system's lifetime. For that reason, this study is looking at a combined heat and cold ATES system. Additionally, this LCA looks into other important elements of an ATES system that can be distinguished within each life cycle phase and analyses their contribution to the overall environmental impacts using the updated ReCiPe assessment method which offers a more consistent set of midpoint and endpoint indicators compared to the previously used method.

The studied system serves the combined heating and cooling demands of the Tetra building of Deltares in Delft. The boundaries set for this system are according to a cradle-to-grave approach. This translates to the evaluation of impacts regarding raw material extraction, manufacturing of components, construction, use, maintenance and end-of-life treatment of the system. More detailed information on these aspects will be provided in the LCI section. In order to avoid double counting of impacts the assessment was performed by dividing into sub-systems as much as possible.

4.1.1 Tetra ATES system

The ATES system examined serves the combined heating and cooling purposes of the Tetra building complex in Delft (Fig. 6). Constructed in 2013, it comprises of a three-storey building of an approximate size of 6000 m^2, it houses 360 work places and is coupled with a 280 m^2 meeting room (Pavillion). The Tetra building has been built according to contemporary energy saving and CO_2-efficient technologies (Jeanne Dekkers website, 2014).

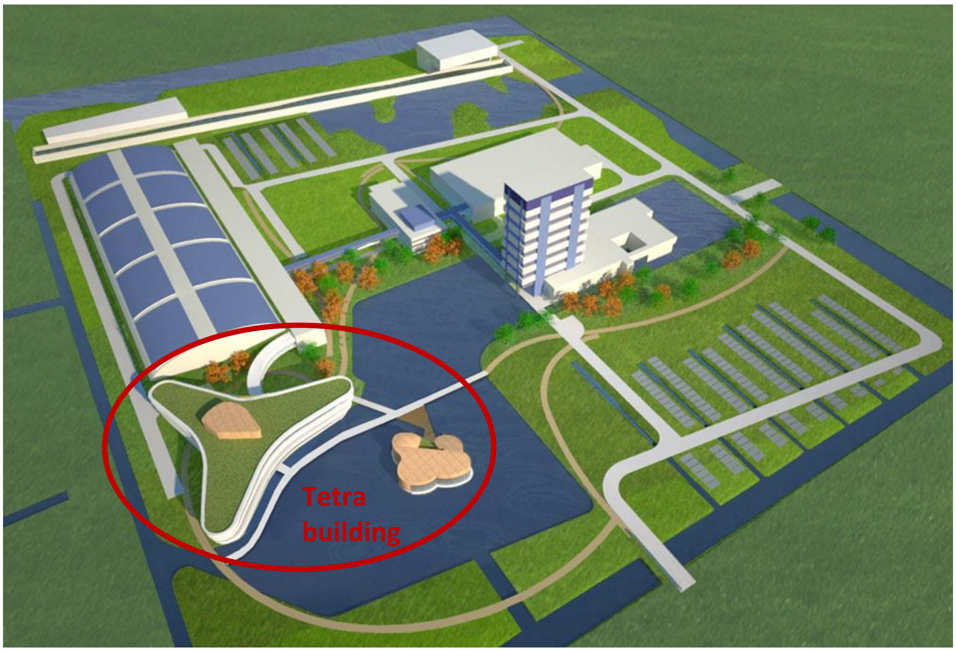

Figure 6 – Tetra building complex in the Deltares HQ in Delft (adapted from Jeanne Dekkers website, 2014)

For the operation of the ATES system, use of the second aquifer is made which is located between 42 – 80 m bgl and therefore the system belongs to the shallow subsurface space. The wells are drilled at a depth of approximately 80 m underground and at a 120 m (approx.) distance from each other. Considering the operating temperatures of the system this distance was deemed sufficient enough in order to prevent interference between the two wells. The natural groundwater temperature at this depth has been measured at 11,5 °C. An overview of the design characteristics of the entire Tetra ATES system is given in Fig. 7.

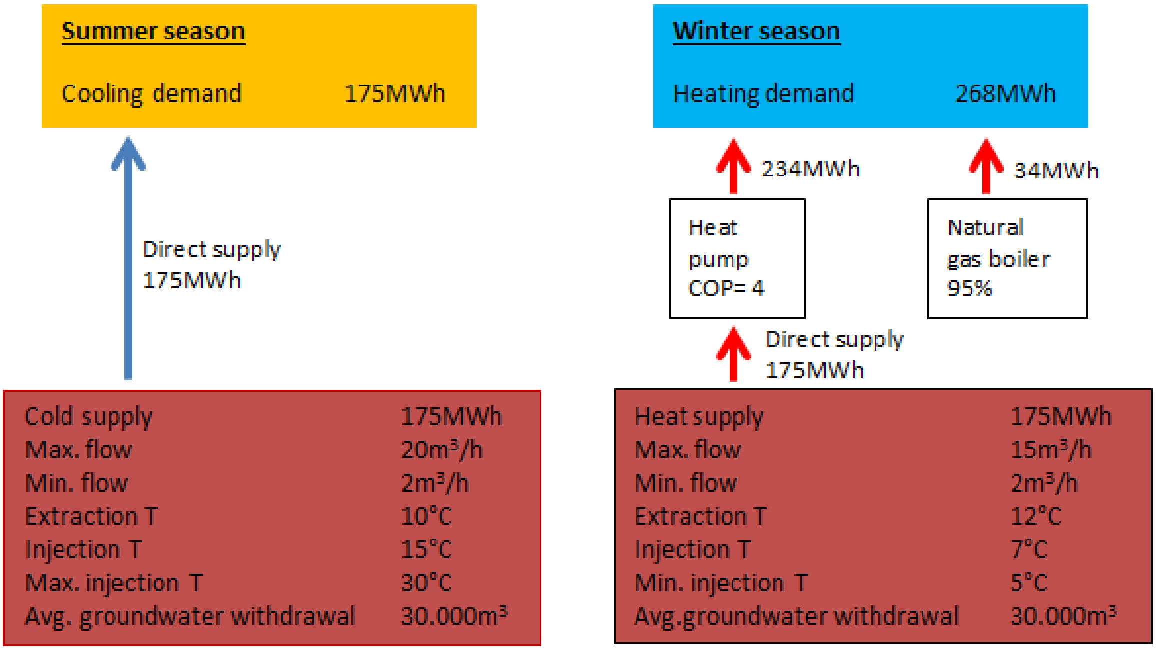

Figure 7 - Technical characteristics of the Tetra ATES system (adapted from IF Technology BV, 2011)

As can be seen from Fig. 7, the energy demand of the building has been estimated at 175MWh of cooling and 268MWh of heating per year. The system uses two wells alternatively, one for heat and one for cold storage depending on the season and intended use. A pipeline system is used to connect and distribute the extracted thermal energy from the two wells to the Tetra building. In the summer, groundwater is extracted at a temperature of 10°C and returned for heat storage at an average temperature of 15°C and a maximum of 30°C. To serve the heating demand in the winter, groundwater is extracted at a temperature of 12°C while the average return temperature is 7°C and the minimum 5°C. The temperature difference (ΔT) between injection and extraction in every season is assumed to be relatively stable at 5°C and the temperature loss between seasons resulting from thermal exchange in the subsurface is around 3°C. The cooling delivered by the aquifer is assumed to be sufficient for direct application to the building while direct heating is insufficient and so the system is coupled with a ground source heat pump.

One submersible water pump is installed in each well. These pumps extract groundwater at a maximum flow rate of 20 m^3/h from the cold well and 15 m^3/h from the warm well while the minimum flow rate is 2 m^3/h for both. The groundwater circuit (pump pit, pipelines and return wells) is air-tight and kept under a pressure equal to the pressure of the subsurface. As a result, the groundwater does not come into contact with the air or surface water. The average groundwater displacement from the aquifer is 30.000 m^3 and the maximum 50.000 m^3 per year. The flow rates are adjusted automatically depending on the thermal energy needed by the Tetra building. Similarly, switching pump functions between pumping and injection of groundwater is adjusted automatically. When the thermal energy required is lower than maximum the flow rates are reduced in order to (a) secure the desired injection temperature, (b) reduce the amount of extracted water and thus reduce the related energy usage and environmental impacts and (c) to reduce the amount of mechanical wear to the pumps. In reality, the system operates at full capacity only when the entire heating or cooling capacity is needed for the building or when the entire storage capacity is needed to store thermal energy for the next season or in order to restore the obligatory thermal energy balance of the system. Since data on the actual operation of the system was unavailable the design characteristics as presented in Fig. 7 are utilized instead.

Lastly, from Fig. 7 it can be seen that a 95% (HHV[2]) natural gas boiler is coupled with the ATES system in order to provide the additional heat needed to cover the total heating demand of the Tetra building. In the following analysis the use of the gas boiler is also taken into account albeit separately in order to allow for a clear evaluation of the differences in impacts of the ATES system.

4.1.2 Function and functional unit

The primary function of an ATES system is to deliver thermal energy in the form of heat or cold in order to allow for indoor climate regulation and thermal comfort to maintain a comfortable working environment. Therefore, the functional unit chosen for the assessment of this entire system is *the ability to serve the heating and cooling demands of a building by providing 175 MWh of cooling and 268 MWh of heating per year for a period of 15 years*. This functional unit is used to provide a reference to all inputs and outputs of the system.

Here a secondary function could be accounted for. This function is the ability of an ATES system to store thermal energy seasonally. However, this would prohibit the ability to make comparisons with alternative heating/cooling product systems (i.e. conventional systems) and therefore this function has not been taken into account.

This functional unit was chosen as a ‘middle path’ that balances between the evaluation of the actual Tetra ATES system and the assessment of comparable shallow ATES systems. This concession comes with the inherent disadvantage of examining the potential life cycle environmental impacts of utilizing an ATES system from a demand-side point of view. What this means basically is that since the functional unit focuses on specific heating and cooling demands the generalization of this study’s quantified results with those of other buildings that employ ATES systems is prohibited (unless of course they have similar heating and cooling demands). However, this does not mean that these results cannot be used altogether. In this study the impact categories where the utilization of an ATES system has the highest impact are presented which is a finding relevant for other ATES systems as well. This study also identifies the largest contributors within each impact category as well as areas for potential improvements regarding the environmental performance of ATES systems. Thereby, these qualitative results can be generalized for other ATES systems independent from their differences to the studied system.

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[2] Higher Heating Value

4.1.3 System Boundaries

The overall system boundary for this study adopts the cradle-to-grave approach. This means that it comprises of relevant activities from the construction, use and end-of-life of the ATES system (Fig. 8).

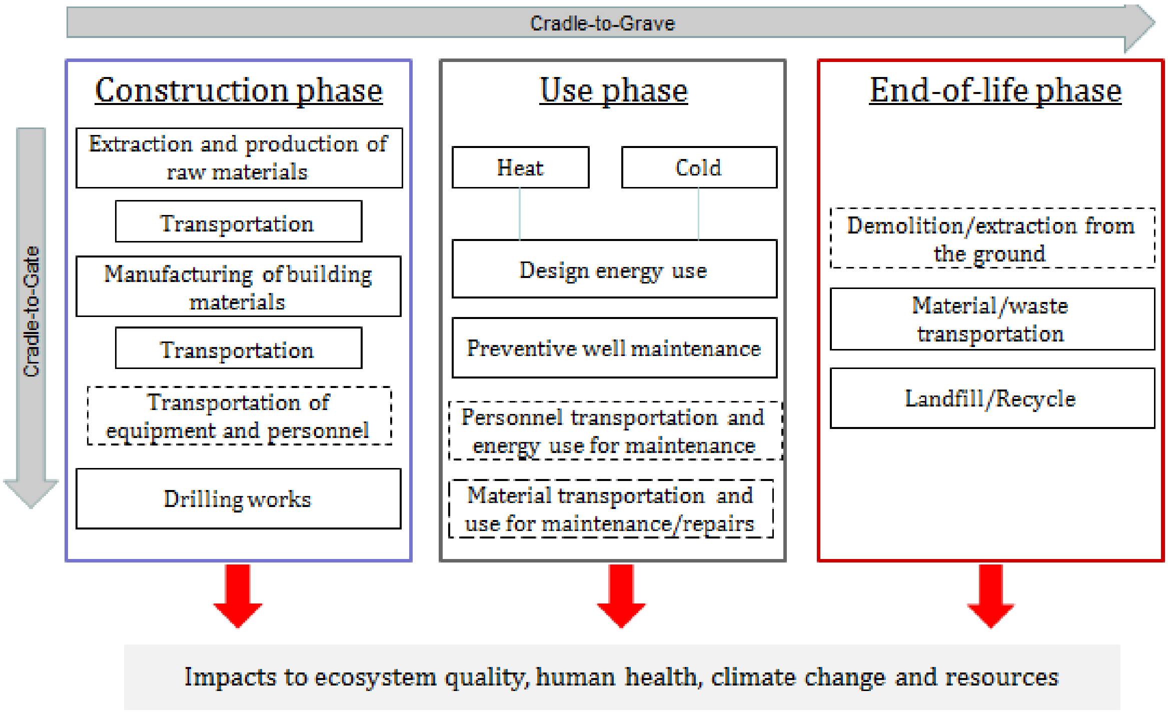

Figure 8 – Tetra ATES system boundaries

The activities included in the LCA are raw material extraction, manufacturing of system components, important material and energy requirements for construction, operation and preventive maintenance of the system and lastly disposal and treatment of system components. Transportation is also included wherever relevant. Presently it is unclear for how long the system can be utilized. The design reports have estimated 20 years of use while expert opinion from RVO.nl based on previous experience places the average lifespan at 15 years. Moreover, in a report by the Bank of America (2007) it was identified that the average lifetime of a heat pump is approximately 15 years. As it will be presented later the heat pump is a crucial component of the Tetra ATES system and therefore a use period of 15 years was adopted for the LCA. Preventive maintenance of the wells is taken into account, for the rest of the system it is assumed that no replacement of any component takes place and due to lack of additional data maintenance of mechanical and electrical components is excluded. The production of the system components is assumed to be a combination of production activities inside the Netherlands and abroad. Use and disposal are assumed to take place within the country. The main disposal option assumed for the plastic pipe system is landfilling. This choice is justified based on current practice in the country and that at the time of this study no specific law or information exists to dictate otherwise. Transportation of equipment and personnel during the construction and operation of the ATES system is not taken into account. Additionally, there is a lack of information regarding the work needed and other complex disposal options for the remaining of the system's components (i.e. heat pump) and therefore these are excluded from the study.

4.1.4 Allocation procedure

Multifunctionality issues were avoided in this LCA by dividing the inputs and outputs of the system into sub-processes. This procedure is also in line with the principles of attributional LCAs (Goedkoop et al., 2013a) which aim at evaluating a single product or product system.

4.1.5 Methods and types of impacts

The main environmental impacts that this study explores are those that relate to climate change, resource and energy consumption and also the effects on human health, ecotoxicity and land use. These impact categories are chosen for their representativeness of a broad range of potential environmental impacts and are consistent with the key sustainable development topics to be considered when managing an underground project as proposed by the ITA-AITES Working Group 15 (2010).

A) ReCiPe

To evaluate the aforementioned impacts, the ReCiPe impact assessment method was chosen. Developed in 2008 this method is a synthesis of two other LCIA methods, the "problem oriented" CML-IA and the "damage oriented" Eco-indicator 99. The benefit of using this method is that it allows the user flexibility to obtain results in both the midpoint (CML-IA) and/or endpoint (Eco-indicator 99) level. The following figure shows the structure of the method and the combination of inventory results, impact categories, environmental mechanisms and the final aggregation to a single score.

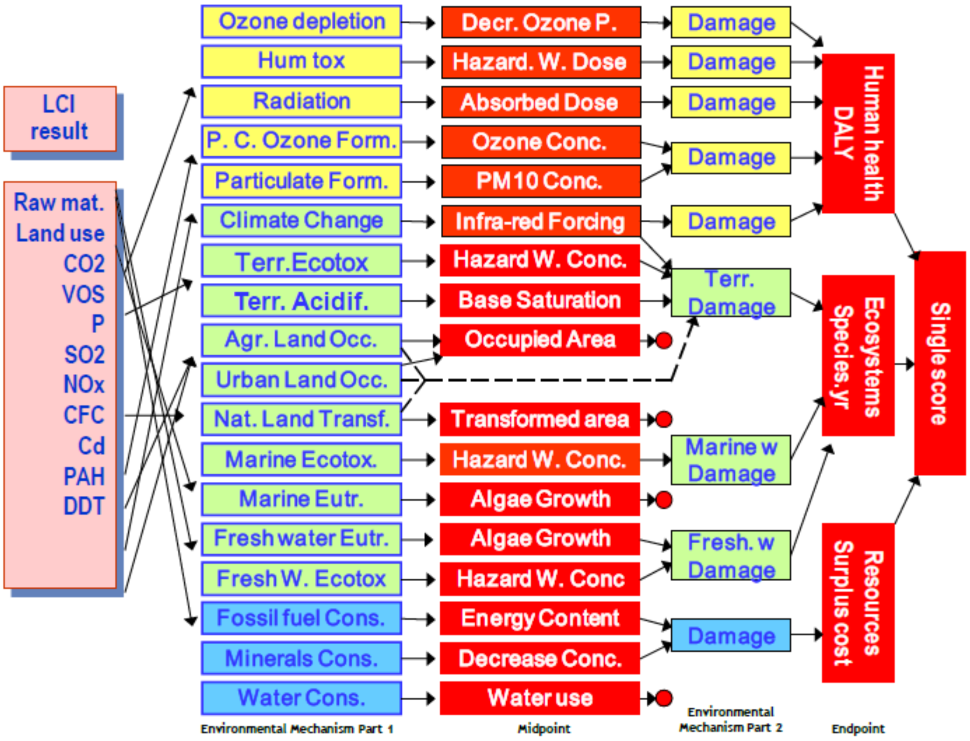

Figure 9 – ReCiPe and its midpoint and endpoint categories (adapted from SimaPro 8 Database Manual Methods, 2014)

A disadvantage of the midpoint level is that it leads to eighteen different impact categories which makes decision-making based on these results rather complex. For ReCiPe these categories and their units are shown on table 1.

Table 1 - Midpoint categories and characterisation factors (Goedkoop et al., 2013b)

Impact category	Characterisation factor unit
Climate change	kg CO_2 eq. to air
Ozone depletion	kg CFC-11[3] eq. to air
Terrestrial acidification	kg SO_2 eq. to air
Freshwater eutrophication	kg P eq. to freshwater
Marine eutrophication	kg N eq. to freshwater
Human toxicity	kg 14-DCB[4] eq. to urban air
Photochemical oxidant formation	kg NMVOC[5] to air
Particulate matter formation	kg PM_{10} to air
Terrestrial ecotoxicity	kg 14-DCB to industrial soil
Freshwater ecotoxicity	kg 14-DCB to freshwater
Marine ecotoxicity	kg 14-DCB to marine water
Ionising radiation	kg U^{235} to air
Agricultural land occupation	m^2 * yr (agricultural land)
Urban land occupation	m^2 * yr (urban land)
Natural land transformation	m^2 * yr (natural land)
Water depletion	m^3 (water)
Metal depletion	kg Fe eq.
Fossil depletion	kg oil eq.

At endpoint level, the midpoint categories are multiplied by damage factors and then aggregated to the following categories:

1. Damage to Human Health, expressed in the number of year life lost and the number of years lived disabled. These two are combined to the Disability Adjusted Life Years (DALY) index. Measured in years.
2. Damage to Ecosystem Diversity, expressed as the loss of species over a specific area in a certain time. Also measured in years.
3. Damage to Resource Availability, expressed as the surplus costs of future resource production over an infinite timeframe assuming constant annual production and a 3% discount rate. Measured in 2000US$.

The ReCiPe adopts the Cultural Theory model (Thompson et al., 1990) which is often used in policy making. In this theory three archetypes of human behaviour are described, these are:

1. **Egalitarian perspective**

   In the Egalitarian perspective the chosen timeframe is extremely long and harmful substances are taken into account if there is just an indication of their effects. Here, damage from environmental impacts is unavoidable and may result in catastrophic

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[3] Chlorofluorocarbon

[4] 1,4 dichlorobenzene

[5] Non Methane Volatile Organic Carbon compound

events. It is assumed that fossil fuels cannot be substituted and are replaced by a mix of brown coal and shale gas.

2. **Hierarchist perspective**

   The Hierarchist perspective looks at a long term perspective and substances are included if there is consensus regarding their effects available. Here it is assumed that good management can help in avoiding environmental damages. Fossil fuels are considered difficult to replace, oil and gas are replaced by shale gas while coal is replaced by brown coal.

3. **Individualist perspective**

   In the Individualist perspective the chosen timeframe is short-term and substances are included only if there is clear indication of their effects. Environmental damages are assumed to be recoverable by technological and economic development. In the example of the fossil fuels, it is assumed that they cannot be depleted and therefore are not taken into account.

These perspectives can lead to different results because of the inherent assumptions in each of them. For the main analysis the midpoint level is chosen to limit uncertainty regarding the environmental impact mechanisms as much as possible. Additionally, the Hierarchist perspective is selected as it is generally considered to be the middle one of the three perspectives. The steps of damage assessment of the impact categories and weighting are not performed in this study. Additional methods are also used to verify if the results are consistent with the ones from ReCiPe and if the method choice can influence the final outcome.

B) Cumulative Energy Demand (CEnD)

Due to the importance of energy resources and the impacts of their consumption for sustainable development the CEnD method was chosen to supplementary assess the Tetra ATES system. The aim of the CEnD method is to investigate the energy use throughout the life cycle of any product system. It is a useful method to give an overall assessment on energy-related life cycle environmental impacts. CEnD considers both direct uses as well as indirect uses (also known as embodied energy) of energy due to the use of construction materials, raw materials, etc. (Frischknecht et al., 2007). As Kasser & Pöll (1999) state, the CEnD is a method to be used in combination with more comprehensive impact assessment methods, such as the ReCiPe method used in this study. The impact categories of the CEnD method are:

Table 2 - CEnD impact categories (adapted from Frischknecht et al., 2007)

Impact category	Subcategory	includes
Non-renewable	Fossil	Hard coal, lignite, crude oil, natural gas, coal mining, peat
	Nuclear	Uranium
	Biomass	Wood and biomass from primary forests
Renewable	Biomass	Wood, food products, biomass from agriculture
	Wind	Wind energy
	Solar	Solar energy for heating and electricity
	Geothermal	Shallow geothermal energy (100-300m)
	Water	Run-of-river hydro power, reservoir hydro power

Normalization is not part of this method and therefore only characterization and single score results can be produced by this method.

4.1.6 Interpretation method chosen

A sensitivity analysis will explore the consistency of the LCA results under different assumptions, methods and data sources and types. Thereby, results will be assessed assuming different energy sources for the system, different waste scenarios and cultural perspectives. Also the different impact assessment methods mentioned in the previous section will be tested. Lastly, the new Ecoinvent database employed by SimaPro enables different system models that the user can choose from. It is interesting to examine the differences in results arising from the comparison of attributional and consequential system modelling.

4.1.7 Assumptions

A) Use phase assumptions and specifications

In order to model the Tetra ATES system as accurately as possible in SimaPro a number of assumptions had to be made. These were needed to bridge the differences between real conditions and conditions (processes) defined in the software. The main working assumptions this research is based upon are as follows:

- The system is assumed to operate with a stable temperature difference between extraction and injection of 5°C. This is assumed to be the case for both wells and is also in line with the RVO.nl practical experience on the actual operating temperature difference.
- The amount of groundwater volume withdrawn from the aquifer per year is assumed to be 30.000m^3.
- Using the above assumptions the amount of energy extracted from the subsurface can be calculated per season using the formula:

  $$Q = C_w * V * \Delta T \qquad (Eq.\ 4)$$

  Where:
  Q, is the thermal energy extracted from the subsurface
  Cw, is the specific heat capacity of water
  V, is the volume of groundwater withdrawn from the aquifer
  and ΔT, is the temperature difference between extraction and injection of the wells.
- Although both components are active during the use phase of the Tetra ATES system, the ATES and gas boiler operation have been modelled separately. This was done in order to better illustrate the contribution of each to the potential impacts and at the same time enable an overview of the whole (Tetra) ATES system's use phase environmental impacts.

B) End-of-life phase and wastewater treatment assumptions

At the moment, no specific legal provision regarding this phase exists except sealing the wells to ensure that no contamination of the aquifer is possible. Additionally, information regarding the fate of the mechanical and electrical components of the system is lacking and so these are left out from the analysis of this phase. Therefore, the only end-of-life treatment that can be evaluated regards the plastic pipeline system. Yet again here, there is no specific guideline for their end-of-life treatment and thus the most common practice is leaving the pipes in the ground. Since this process is presently not included in SimaPro, the option of landfilling the pipes was chosen to act as a substitute. It should be mentioned that although this choice can represent a realistic situation it is still possible that the impacts of this phase are slightly overestimated regarding current practice. However, this overestimation is deemed negligible and as will be seen in the analysis section it does not affect the main results significantly. Aside from that, the possibility exists for the recycling/re-use of the pipes and the difference in the resulting impacts will be assessed in the sensitivity analysis section.

Another important assumption in the end-of-life phase concerns the groundwater used by the system for preserving the wells. Groundwater carries iron, manganese, carbon dioxide and many other different minerals on its way through the soil layers. Although these substances are not harmful, they might worsen water taste or, in this case, precipitate in the pipelines. In the pumping wells changes in temperature, pressure and/or oxidation/reduction status can lead to encrustations on the well screens and in the filer materials. For this reason, the ATES well screens and pipelines are regularly preserved from clogging by “flushing” 1600m^3 of groundwater per year. The fate of the wastewater produced by this maintenance process is decided by the user of the system. By the regulating authorities it is left to the owner of the system to choose between depositing this groundwater to surface water or to the sewage. In case it is deposited in nearby surface water it can be assumed that no further treatment takes place. However, in case it is deposited in the sewage it can be assumed that this water then moves on through a wastewater treatment process, same as domestic water. Thus different impacts can occur depending on the choice for disposing the “flushing” groundwater. The impacts of each choice can be modelled by two scenarios which will also be tested and compared in the sensitivity analysis.

For the main analysis, the main configuration that will be assessed is that the ATES system falls under the landfill scenario and the assumption that the aquifer groundwater used for “flushing” the wells is sent to the sewage.

4.2 Life Cycle Inventory

To perform this study it was necessary to obtain detailed data regarding each life cycle phase of the Tetra ATES system. Thereby the LCI analysis entailed the collection of data on the system's inputs and outputs. The data collected can be distinguished in two categories, foreground and background data. Foreground data refers to the most system-specific data that was acquired. Background data is data coming from the production of generic materials, use of energy, transportation and waste types. Wherever foreground data is missing they were replaced by background data found from technical product catalogues, LCA databases and scientific literature. In order to save time and reduce the workload a cut-off criterion can be applied depending on an estimation of the environmental load of the missing process. This estimation can be performed by making a rough model of the product system in study, using background data, and identifying the missing data and their importance. For this case, foreground data (i.e. electricity use and heat distribution system) was extracted from the technical and design reports of the ATES system, Civieltechnische voorzieningen (2012) and Energieopslag (KWO) Deltares te Delft (2011). These reports were made available from Deltares. Wherever background data was used (i.e. construction materials used and transportation types) the most relevant databases accessed were the Ecoinvent by the Swiss Centre for Life-Cycle Inventories and the ELCD of the European Commissions' JRC.

In SimaPro, processes are usually divided in system processes (denoted with an S) and unit processes (U). Unit processes are transparent meaning that they provide detailed information regarding the steps that led to the specific process and also contain information on the uncertainty of the data. On the other hand, system processes include all unit processes in their record and contain no uncertainty information (Weidema, 2011). The first allow the performance of an uncertainty analysis while the latter allow for the creation of a simpler process tree and faster calculation times. Numerical results from both processes are found mostly the same (<10% difference due to rounding), but system processes make contribution analysis of single product systems less complicated and thus were chosen for this study.

Records in the newest database of SimaPro are further divided in transformation and market activities. In transformation activities all human activities that transform an input to an output different than the input are included, i.e. hard coal in the ground transformed by a hard coal mine to the marketable product of hard coal. Market activities on the other hand transfer this output to the transforming activities which then use it as an input, i.e. from hard coal at the supplier to hard coal at the consumer. In SimaPro the output of market activities is considered to be a consumption mix, *a "production-volume-weighted average of a supplier to a specific market"*. Since suppliers were unknown, most processes needed for this LCA fell more into the market category, a choice which is in line with the suggestions of PRé Consultants (2013) regarding the lack of detailed supplier information. In general, the choice between market and transformation SimaPro processes was considered depending on their relation to the actual processes in need of modelling.

Another element of the LCA methodology which appears also in the newest Ecoinvent database employed by Simapro is the separation in attributional and consequential system modelling. According to the ILCD Handbook (2010), attributional modelling depicts the environmental impacts that can be credited to the system's actual or forecasted supply chain, use and end-of-life using fact-based and measurable data of identified uncertainty. On the other hand, consequential modelling aims at identifying the long-term consequences of decisions and accounts for the interactions with other systems and from there models the analysed system around these consequences. Therefore, it does not reflect the actual supply chain but a hypothetical non-specific supply chain. Within SimaPro attributional modelling (denoted as “Alloc Def” in SimaPro) uses 1) an average supply of products as described in market activities and 2) multi-product data are allocated according to economic revenue collected. For consequential modelling 1) an unconstrained supply of products is assumed taking into account technological development and 2) multi-product data are converted to single-product data using system expansion. Attributional modelling is therefore more suitable for single product assessments (attributional or accounting LCAs) while consequential is better suited for LCA comparisons (consequential or change-oriented LCAs) where displaying the consequences of changing from one situation to another is more important. From the above and taking into account the goal of the LCA study the main analysis is performed under attributional modelling.

4.2.1 Material use

In the following table, the material input and logistics for the construction of the Tetra ATES system are presented. Links to the SimaPro processes and comments are also shown. All data on the drilling, the amount of backfill material and the length of the plastic distribution pipes were extracted from technical reports of Deltares. The exact values presented below were then calculated by combining information with data from web-available product catalogues, i.e. Marley Pipe Systems (2010), Walraven pipe data sheets (2011) and Conrad Combi 300 drilling rig specifications (Conrad website, 2014).

- Drilling

The construction process of the Tetra ATES system is centred on the drilling of the wells. For the drilling, a total of 110m^3 of water was used from the nearest fire hydrant. Similarly, the Conrad Combi 300 drilling rig was used which has a power of 200kW and an average drill rate of 9m/h. The fuel consumption for this process was calculated at 0,298t of diesel. The weight of the drilling rig is approximated at 3t and was also accounted for in the LCA.

Table 3 - Drilling the wells

Drilling	Amount (t)	SimaPro process
Diesel	0,298	*Diesel, from crude oil, consumption mix, at refinery, 200ppm sulphur EU-15 S*
Water	110	*Drinking water, water purification treatment, production mix, at plant, from groundwater RER S*

- Backfill

The amounts of used backfill material were extracted directly from the construction reports within the Deltares technical reports. At the end-of-life phase it was assumed that bentonite is used to seal up the wells. During construction of the wells the total amount of soil extracted was approximated using the cylinder volume formula:

$$V = \pi * radius^2 * depth$$

With an approximate borehole diameter of 500mm and a total well depth of 160m the extracted soil was calculated at 31,6m^3. From the Mikolit product catalogue the density of saturated backfill material is 1,8 t/m^3 while the density of sand mixed with gravel was found to be 1,65t/m^3 (Simetric website, 2011). Therefore, the occupied volume within the wells can be calculated as the sum of these materials which is 25,2m^3. The ground volume occupied by the installed pipes is assumed to be minimal compared to the backfill material. Therefore, to seal the wells 6,4m^3 or 11,5t of bentonite need to be used. This result is calculated based upon the density value chosen from the specific source. Since this value can differ with temperature and pressure variations as well as source this conversion is only used as an approximation. The reported and calculated amounts and associated SimaPro processes are shown in the table below.

Table 4 - Backfill material

Backfill material	Amount (t)	SimaPro process
Mikolit 300	1,5	*Bentonite {GLO}|market for|Alloc Def S*
Mikolit 00	10	*Clay {GLO}|market for|Alloc Def S*
Sand	11	*Sand {GLO}|market for|Alloc Def S*
Gravel	20	*Gravel (crushed) {GLO}|market for|Alloc Def S*
Bentonite (for sealing the wells)	11,5	*Bentonite {GLO}|market for|Alloc Def S*

- Pipes

The piping system that connects the wells and the Tetra building is a combination of PVC and HDPE pipes. The PVC pipes were used for the well construction while the HDPE pipes were mostly used to connect the electrical cables between the wells and the building. Depending on the intended use different varieties of these pipes were used. The processes *"HDPE pipes E"* and *"PVC pipes E"* were chosen for the HDPE and PVC pipes respectively.

Table 5 - Pipes in the ATES system

Pipe material	Length (m)	Specific weight (kg/m)	Weight (kg)
HDPE			
90mm	15	2,11	31,6
125mm	206	4,06	836,4
PVC			
40mm	8	0,35	2,8
160mm	90	5,47	492,3
315mm	70	20,9	1463

- Pumps

In this analysis two groundwater pumps and one heat pump are taken into account as use phase products that need to be included in the ATES assembly. To account for their production and inclusion in the LCA the process *"Pump and pumping manufacturing equipment"* was chosen for the water pumps and *"Heat pump, 30kW {GLO}|market for|Alloc Def S"* for the heat pump.

4.2.2 Energy use

- During the construction phase the consumption of 1000kWh of electricity was needed approximately in order to pump clean and test the wells.

- During the operational phase the main consumers of electricity are the groundwater pumps and the heat pump. For the following calculations the design values as presented in Fig. 7 are used. The electricity input of the water pumps can be calculated using the average groundwater withdrawal volume and the energy requirements for the operation of the water pumps:

$$\textit{Annual electricity input of water pumps} = \textit{water volume pumped/yr} * \textit{energy req. for pumping} = 30000m^3/yr * 0{,}2\ kWh/m^3 = 6MWh$$

It is important to note that this electrical input is used to pump the groundwater from the aquifer system to the surface per season and therefore the annual electricity consumption of the water pumps is 12MWh. During the cooling season, the amount of thermal energy delivered is sufficient for direct cooling of the building and therefore no heat pump is needed (in practice, this can differ greatly depending on climate variation). During the heating season, the thermal energy from the aquifer is passed through a heat pump in order to upgrade its thermal content. Therefore, for a heat pump with a COP value of 4 the electrical input in order to cover the heat demand of the building is calculated using Eq. 1:

$$\textit{Annual electricity input of heat pump} = \frac{Thermal\ output/yr}{COP} = \frac{234MWh/yr}{4} = 58{,}5MWh/yr$$

It is also important to mention here that there is a difference between using the COP and the SPF value of a heat pump to calculate the electrical input (section 3.1). For this calculation it would be more accurate to use the SPF value as it accounts for climate variation and other energy-consuming elements of a heat pump. By taking these elements into account the SPF value would be lower than the COP and so the electrical input would be higher. However, detailed data on the electricity use of the heat pump was unavailable and so estimating the actual SPF of the system was impossible. As a substitute the COP was used instead.

- To serve the instantaneous heat demands of the Tetra building a natural gas boiler is used. The efficiency of this boiler is 95% (HHV). Therefore, the fuel input to cover to remaining heating demand is:

$$\textit{Annual fuel input of gas boiler} = \frac{Heat\ output/yr}{boiler\ efficiency} = \frac{34MWh/yr}{95\%} = 35{,}78MWh^{6}/yr * 3{,}6 = 128\ GJ/yr\ \textit{of natural gas}$$

- In order to preserve the wells and ensure the operational integrity of the water pumps 1600m^3 of groundwater need to be pumped annually. Using the same energy requirement of the water pumps as before it was calculated that the annual electricity consumption for the preservation of the wells is:

$$1600m^3 * 0{,}2kWh/m^3 = 0{,}32MWh$$

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[6] Primary energy

The energy requirements of the system are presented in table 6 while the cumulative energy demands for a period of 15 years can be found in table 8.

Table 6 – Tetra ATES system energy inputs and outputs

Energy input	Amount	Unit	SimaPro process	Energy output
Groundwater pumps				
Electricity	12	MWh	*Electricity, low voltage {NL} |market for | Alloc Def, S*	175 MWh for heating, 175 MWh for cooling
Electricity	0,32	MWh	*Electricity, low voltage {NL} |market for | Alloc Def, S*	-
Heat pump				
Electricity	58,5	MWh	*Electricity, low voltage {NL} |market for | Alloc Def, S*	234 MWh for heating
Gas boiler				
Natural gas	128	GJ	*Heat, district or industrial, natural gas {Europe w/o CH} | heat production, at boiler condensing modulating >100kW | Alloc Def, S*	34 MWh for heating
Cleaning and testing the wells (only once)				
Electricity	1000	kWh	*Electricity, low voltage {NL} |market for | Alloc Def, S*	-

4.2.3 Waste

As mentioned earlier no standard procedure exists for the treatment at the end-of-life of ATES systems. The only condition that could be identified was the sealing of the boreholes and it has already been taken into account in the material use section (4.2.1). The plastic pipes are left in the ground and filled with backfill material (most often bentonite) to ensure that no aquifer contamination takes place. Therefore, a waste scenario was developed to emulate the impacts from landfilling the total amount of HDPE and PVC pipes. Since further information on the fate of the heat pump and water pumps as well as other smaller components of the ATES system were absent these components are not taken into account in the waste scenario. In the landfill scenario in SimaPro, the *"Waste polyethylene/polypropylene product (waste treatment) {CH}|treatment of waste polyethylene/polypropylene product, collection for final disposal|Alloc Def S"* waste treatment process was chosen for the HDPE pipes and the *"Waste polyvinylchloride product (waste treatment) {CH}|treatment of waste polyvinylchloride product, collection for final disposal|Alloc Def S"* for the PVC pipes.

Use of water resources has only recently been addressed in LCA and the assessment still lacks wide application (Pfister et al., 2010) and therefore in this research it proved to be a difficult process to model accurately. Since SimaPro works by modelling inputs and outputs it was necessary that a process was used to model the extraction of groundwater from the aquifer. However, the software at the moment does not include a material process that can accurately model the extraction of unprocessed groundwater from an aquifer which can then be sent directly to the sewage. The closest existing process that could be identified to represent the extraction of groundwater is *"Drinking water, water purification treatment, production mix, at plant, from groundwater RER*

S” but a number of additional emissions and materials are included which affect the final outcome of the analysis. Therefore, the process ‘Aquifer Groundwater’ was created to model the extraction of groundwater from the aquifer. To model this process *“Water, well, in ground, NL”* was chosen as a resource input from nature. Subsequently, the waste treatment process could be chosen. The choice in this case is *“Waste water treatment, domestic waste water according to the Directive 91/271/EEC concerning urban waste water treatment, at waste water treatment plant EU-27 S”*.

Table 7 – Waste output of the Tetra ATES system

Waste	Amount (kg)
HDPE pipes	868
PVC pipes	1958
Wastewater	1600

4.2.4 Summary of LCI

The following table presents the overall life cycle inventory of the ATES system. Logistics calculations regarding the transportation of materials are included here. Since an exact value was unavailable, in all calculations the transport distance was assumed to be 50km. The SimaPro processes chosen to represent transportation of materials and equipment were *"Transport, freight, lorry>32 metric ton, EURO5 {GLO}|market for|Alloc Def S"* and *"Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {GLO}|market for|Alloc Def S"*. All values in table 8 are presented in reference to the functional unit (section 4.1.2).

Table 8 - LCI and logistics of the Tetra ATES system

Input name	Amount	Unit	Comments
Material input			
Diesel	0,298	t	Fuel for the drilling machine
Water	110	t	Needed during the drilling
Transport	165	tkm	Drill rig weight * diesel fuel
Bentonite	1,5	t	Substituting Mikolit 300
Clay	10	t	Substituting Mikolit 00
Sand	11	t	Backfill material
Gravel	20	t	Backfill material
Bentonite	11,5	t	Sealing the wells at the end-of-life
Transport	2700	tkm	-
HDPE	0,84	t	206m of 125mm HDPE pipe
	0,03	t	15m of 90mm HDPE pipe
Transport	43,5	tkm	-
PVC	0,5	t	90m of 160mm PVC pipe
	1,5	t	70m of 315mm PVC pipe
	0,003	t	8m of 40mm PVC pipe
Transport	100	tkm	-
Energy input			
Electricity	184,8	MWh	Water pump energy consumption of 12,32 MWh/yr for 15 years
Electricity	877	MWh	Heat pump energy consumption of 58,5 MWh/yr for 15 years
Heat	1,9	TJ	Natural gas input in boiler for 15 years
Electricity	1	MWh	Energy consumption for cleaning and testing the wells
Waste			
HDPE pipes	0,87	t	Landfill
PVC pipes	1,96	t	Landfill
Wastewater	24000	m^3	Groundwater used for the maintenance of the well screens for 15 years

4.3 Life Cycle Impact Assessment results

In this section results from the impact assessment will be presented. All results are presented taking into account the long-term emissions of each process.

4.3.1 Characterization

In Fig. 10 the characterization results per impact category of each life cycle phase of the Tetra ATES system can be observed. It can be easily noticed that the entire system's use phase (red and purple bars in Fig. 10) is the dominant life cycle phase regarding impacts in the majority of the impact categories. In this study the operation of the ATES system refers to the electricity used to drive the groundwater pumps and the heat pump it can already be inferred that electricity use is the largest contributor to the environmental impacts of the Tetra ATES system. It is also apparent that using a natural gas boiler has a noteworthy effect in each category (boiler production and operation are both included due to the SimaPro process chosen). The end-of-life phase shows significant importance in some impact categories where it is even on par with the impacts resulting from the use phase. The most notable influence of the end-of-life phase appears in Climate change, Terrestrial acidification, Marine eutrophication, Photochemical oxidant formation and Particulate matter formation. Lastly, the Ozone depletion impact category is the only category where the construction phase appears as the dominant life cycle phase. Tables with detailed environmental impact scores per impact category can be found in Appendix A.

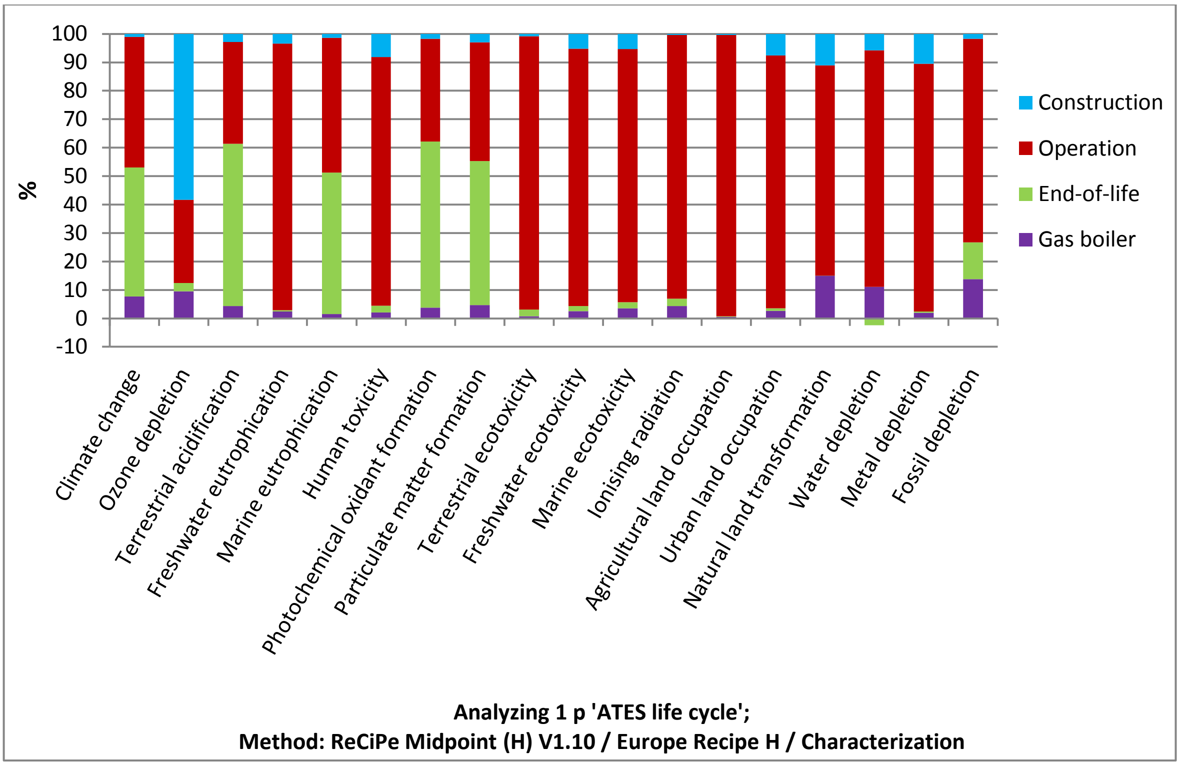

Figure 10 – Characterization results of the Tetra ATES system

It must also be noted that in the Water depletion impact category, the end-of-life phase shows a negative percentage which is meant to indicate that it has a positive influence to the specific impact category. The positive impact occurs because after the wastewater treatment, the clean outflow is deposited back in surface water and therefore the impact of water depletion is mitigated to a certain extent. The relative contribution of each life cycle phase in each impact category can be seen on table 9.

Table 9 – Life cycle phase relative contribution per impact category (%)

Impact category	Construction	Operation	End-of-life	Gas boiler
Climate change	1,1	45,8	45,3	7,8
Ozone depletion	58,3	29,3	3,0	9,5
Terrestrial acidification	2,9	35,7	57,0	4,4
Freshwater eutrophication	3,4	93,7	0,5	2,4
Marine eutrophication	1,3	47,4	49,7	1,5
Human toxicity	8,2	87,4	2,3	2,1
Photochemical oxidant formation	1,7	36,1	58,4	3,8
Particulate matter formation	3,0	41,7	50,6	4,7
Terrestrial ecotoxicity	0,8	96,1	2,4	0,7
Freshwater ecotoxicity	5,2	90,4	1,8	2,6
Marine ecotoxicity	5,3	89,1	2,1	3,5
Ionising radiation	0,4	92,6	2,6	4,3
Agricultural land occupation	0,4	98,9	0,2	0,5
Urban land occupation	7,5	88,9	0,9	2,6
Natural land transformation	11,1	73,8	0,1	15,0
Water depletion	5,8	83,1	-2,4	11,1
Metal depletion	10,5	87,1	0,5	1,9
Fossil depletion	1,8	71,5	12,9	13,8

From the characterization results the importance of the impacts cannot be compared as each impact category is defined in its own unit. Therefore, the next step of normalization is used to put these impacts into perspective and show how important these impacts are when compared to each other.

4.3.2 Normalization

For this step, SimaPro divides each characterization result with a specific normalization factor which is used as a reference value. In LCA the reference value for normalization is dependent on the normalization set chosen when performing the analysis and for this study the European normalization set was chosen. Therefore, the reference values of this study are the annual average environmental impacts of an average European citizen per impact category (as defined in ReCiPe). From the normalized impact categories, 7 can be identified to have the largest significant impact (Fig. 11) when compared to their reference value. The impact categories where the Tetra ATES system has the largest normalization scores are, in descending order, Natural land transformation, Marine ecotoxicity, Freshwater eutrophication, Freshwater ecotoxicity, Human toxicity, Fossil depletion and Climate change. The remaining categories should not be interpreted as less important as this is an issue of weighting which is outside the scope of this study.

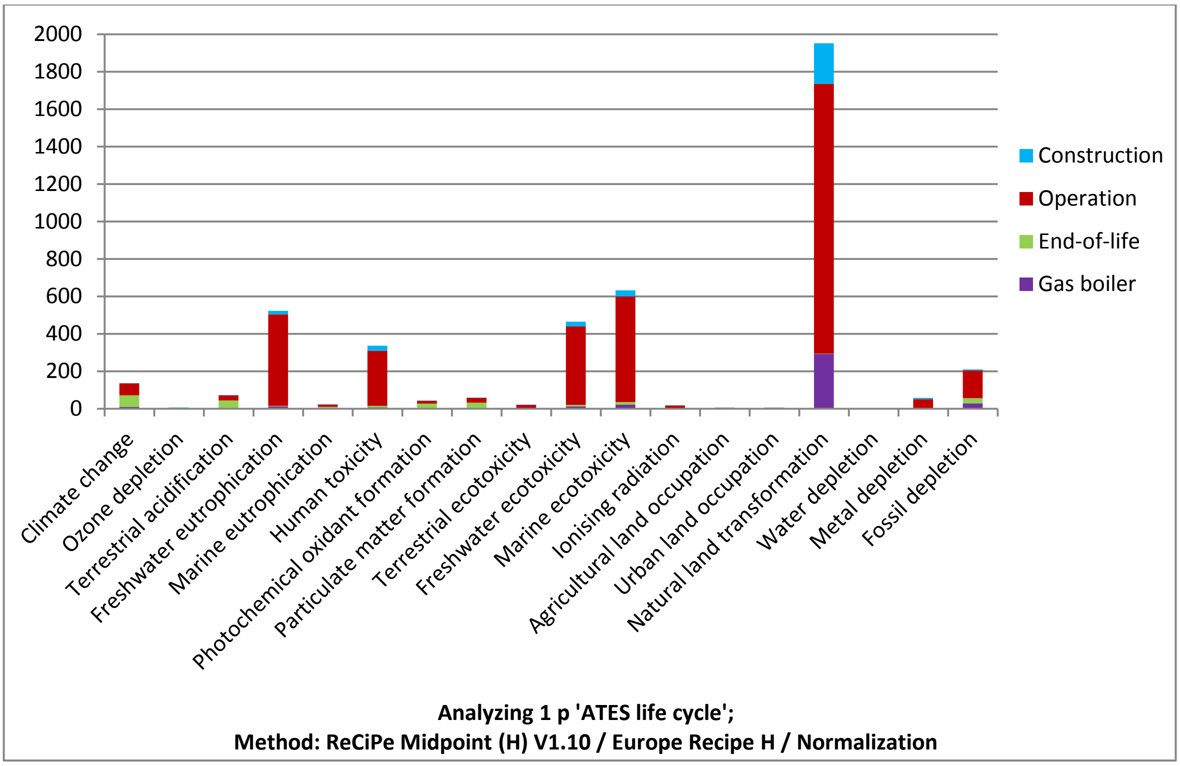

Figure 11 - Normalization[7] results of the Tetra ATES system

It should be noted that the results shown here express the total potential impacts of the system for a period of 15 years. Hence, to compare the annual impact of the system's impacts one should divide by the use period.

In the ReCiPe method the normalization factor of water depletion is unavailable and therefore set to zero. For that reason, in Fig. 11 only 17 out of the 18 impact categories appear. As mentioned before, water depletion is a relatively new research field for the practitioners and developers of LCA and its inclusion in the LCA methodology remains a challenge. A possible reasoning for choosing a zero value is the inherent problem to distinguish between water depletion significance as water can be a scarce resource in one region and an abundant in another. Moreover it should be noted that at its present form ReCiPe as well as the other impact assessment methods do not consider extensively the use of the subsurface in their environmental modeling. Therefore, Agricultural and Urban land occupation as well as Natural land transformation are rather limited to the aboveground surface and possible interactions with other subsurface uses are not included.

From the above results a general picture can be acquired of the environmental impacts of each life cycle phase of the Tetra ATES system. However, these results don't help identify and quantify the individual processes that contribute the most per impact category. For this reason, a contribution analysis for each impact category is performed to identify the most dominant aspects of the Tetra ATES system.

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[7] Strictly speaking since normalization values are expressed per year (i.e. CO_2-eq/yr) the unit of the y-axis is a year (yr).

4.3.3 Contribution analysis

Presenting a detailed contribution analysis for 18 impact categories can be a lengthy, complex procedure and so in this section only rounded comparative figures will be presented in order to give an indication of the top contributors per impact category (detailed scores can be found in Appendix A). The cut-off criteria applied for the contribution analysis is 0,1% in order to account for all the important processes of the Tetra ATES system. The following presentation of the contribution analysis results is separated by grouping the affected impact categories according to the largest contributor.

A) Electricity use

The single largest contributor to the majority of the life cycle environmental impacts of the Tetra ATES system is identified as the electricity that is consumed for the operation of the water pumps to withdraw groundwater from the aquifer and the electricity input for the heat pump to transfer and upgrade the heat from the aquifer to the building. From these two electricity inputs, the energy required to operate the heat pump is the largest with a demand of 58,5MWh/yr (82,4% of the total electricity input).

In the following figures, a quantification of the impact of the electricity usage per impact category can be seen. Regarding Climate change and the emission of CO_2-eq it can be observed from Fig. 12 that electricity use contributes the most with almost 700 tons of CO_2-eq emissions but interestingly enough it is followed closely by the wastewater treatment process with 684 tons of CO_2-eq emissions. The rest of the impacts are attributed to the use of natural gas for the boiler and the production of the PVC pipes that contribute to the CO_2-eq emissions of the Tetra ATES system with 118 and 6 tons CO_2-eq respectively.

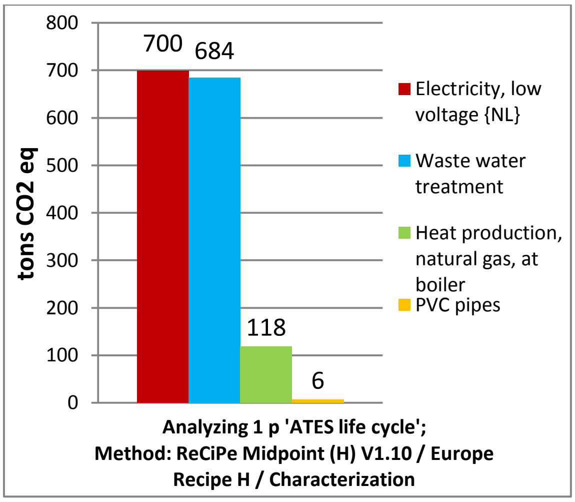


Figure 12 - Climate change

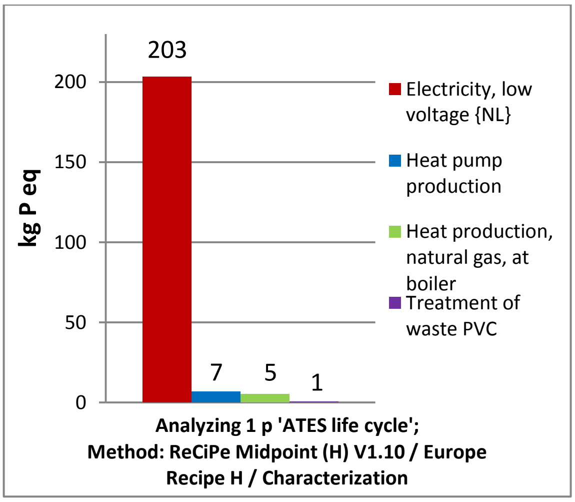


Figure 13 - Freshwater eutrophication

The prevalence of electricity consumption as the largest contributor in the majority of the impact categories can be better observed in the following Fig. 13 - 24. In these impact categories the impact of electricity usage is so high that it dwarves the impacts of other system components. The other contributors that can be identified are natural gas consumed for the boiler, the production of the heat pump and the wastewater treatment process.

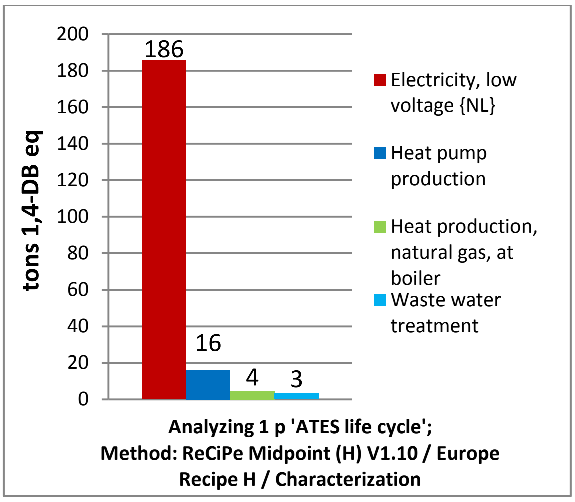


Figure 14 - Human toxicity

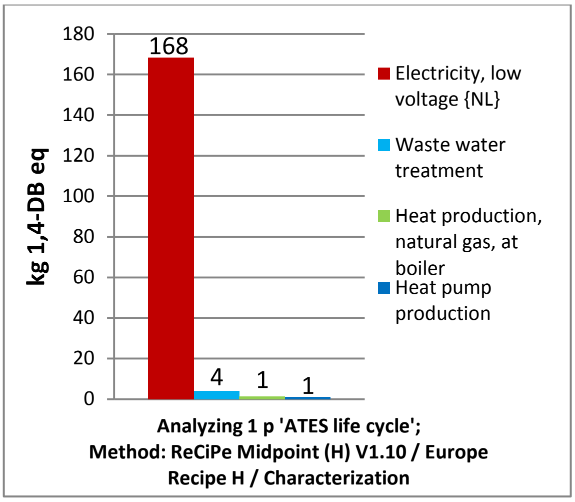


Figure 15 - Terrestrial ecotoxicity

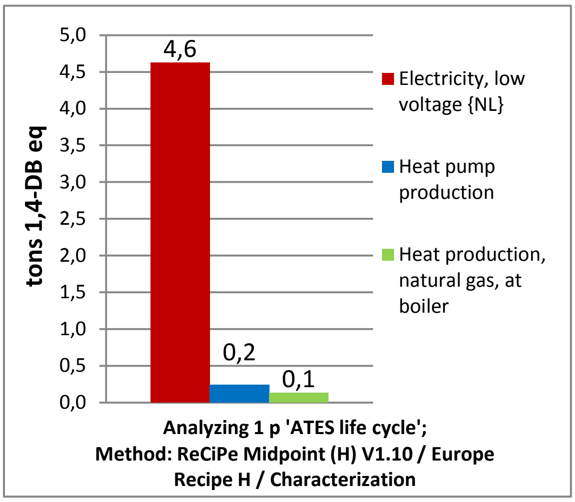


Figure 16 - Freshwater ecotoxicity

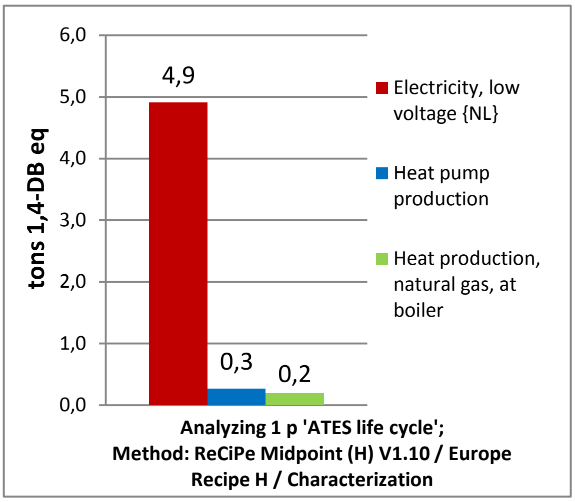


Figure 17 - Marine ecotoxicity

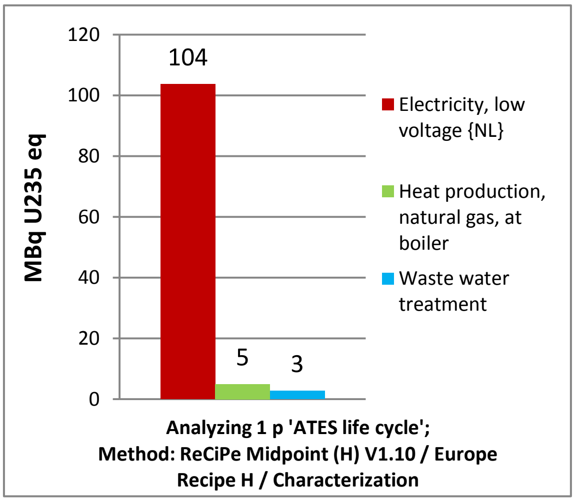


Figure 18 - Ionising radiation

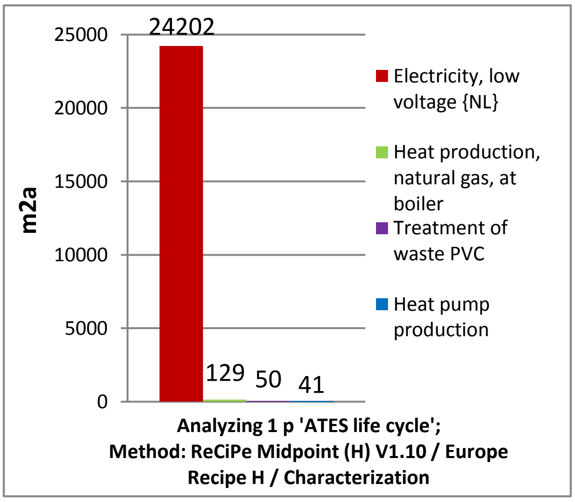


Figure 19 - Agricultural land occupation

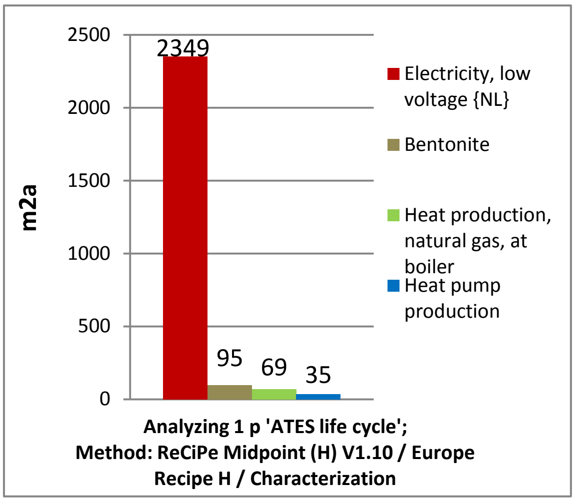


Figure 20 - Urban land occupation

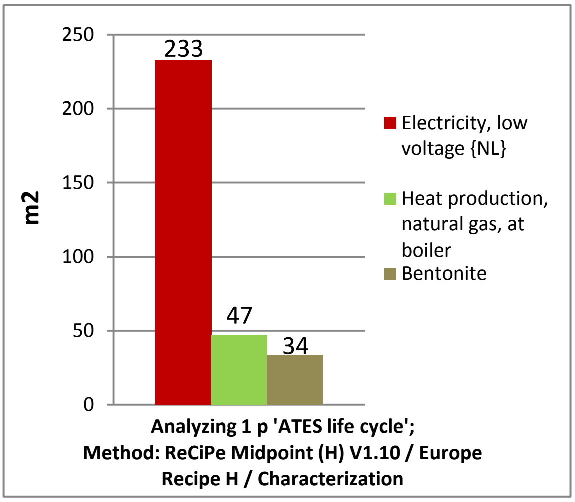


Figure 21 - Natural land transformation

In Figures 20 and 21 it is worthy to mention that bentonite appears as a top contributor as well. Although, it has a minor impact compared to the impacts of the entire system it still shows the influence that the practice of sealing the wells can have to the environment and indicates a potential opportunity for improvement. Since bentonite is a resource-intensive and costly sealing material it might be preferable to use other suitable sealing materials. Of course, the first priority when sealing the wells is the certainty that leakage and aquifer contamination will be prevented and therefore additional practical considerations such as resistance to water flow need to be made.

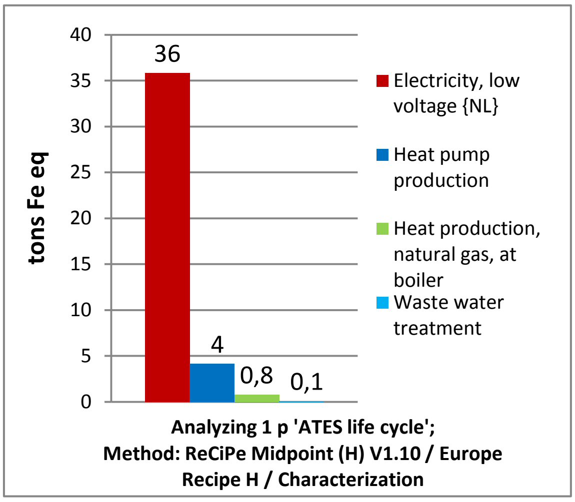


Figure 22 - Metal depletion

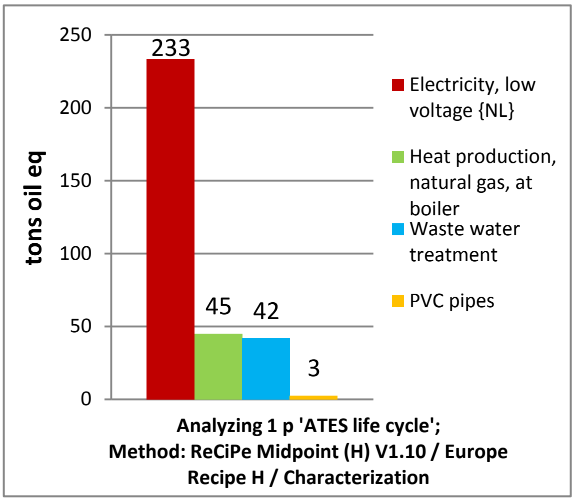


Figure 23 - Fossil depletion

A similar picture can be seen in Fig. 22 and 23 presented above. Electricity use, heat pump production, wastewater treatment and consumption of natural gas are the main contributors in the Metal and Fossil depletion impact categories. Only for the latter, the construction of the PVC pipes appears as an additional top contributor albeit with a really small impact when compared to the rest.

In the Water depletion impact category, electricity use is once more the dominating contributor followed by the use of natural gas for the operation of the boiler. It is also interesting to see that the direct depletion of groundwater by the Tetra ATES system is partly counterbalanced by the wastewater treatment process according to SimaPro. As it was mentioned in the characterization section, a negative value in an impact category indicates that the specific impact is reversed. Therefore it can be seen in Fig. 24 that from the total of groundwater that the system withdraws in 15 years for preserving the wells, approximately 92% of it is returned to the water tables.

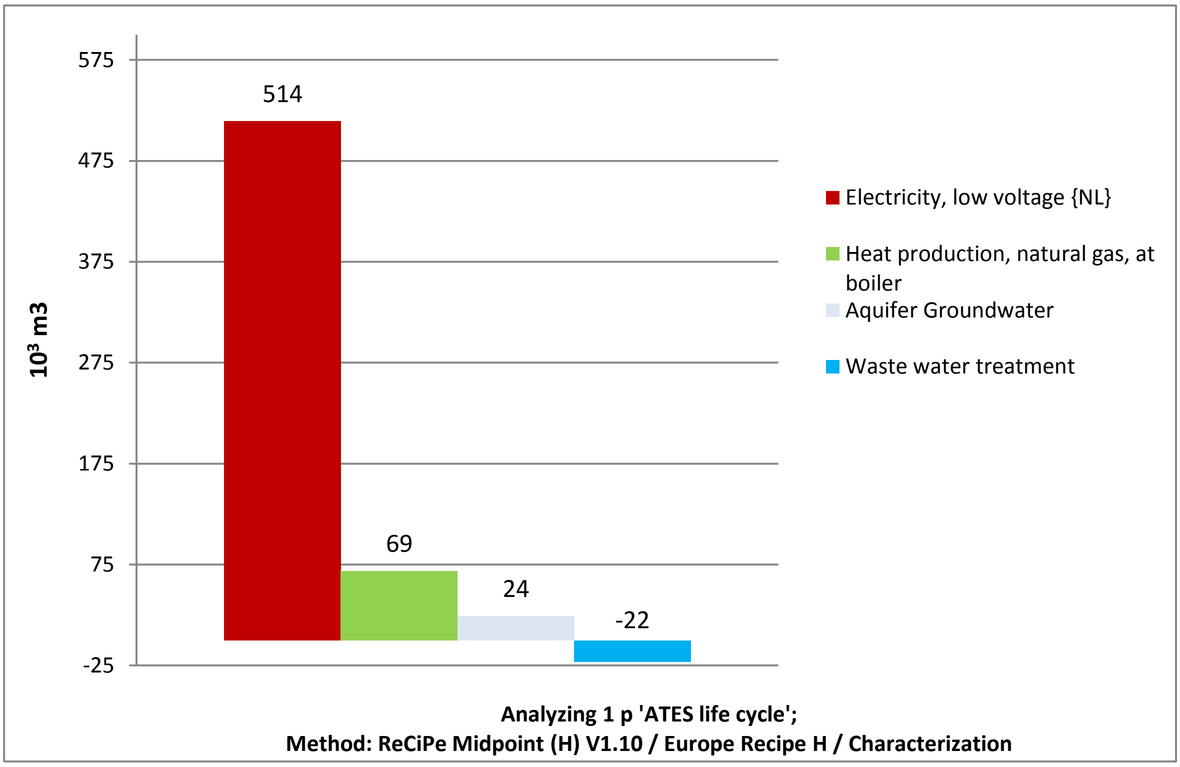


Figure 24 - Water depletion

The importance of aquifer groundwater must be pointed out at this point as its presence fulfills a number of vital environmental functions. Besides being the natural habitat for flora and fauna aquifers also serve the freshwater drinking requirements of humans, among other uses (Boulton, 2005; Danielopol et al., 2003). According to the European Commision's Groundwater Directive (2008), aquifers are the largest reservoir of freshwater on the planet. Additionally, 75% of Europe's inhabitants and 50% of the global population are directly dependent on groundwater to satisfy their freshwater requirements (Danielopol et al., 2008; Hähnlein et al., 2013). Therefore, if one takes into account the amount of predicted ATES systems for the Netherlands and also accounts for a global increase it becomes obvious how important the good management of ATES systems is in order to preserve aquifer groundwater quality and quantity.

B) Wastewater treatment

Aside from the dominating impact of the electricity usage it is interesting to see that the wastewater treatment process dominates the impacts in a number of the remaining impact categories as well. Asides from its significantly large impact in the Climate change and particularity in the Water depletion impact categories which were evaluated previously, the wastewater treatment process appears as the biggest contributor in the Terrestrial acidification, Marine eutrophication and Photochemical oxidant and Particulate matter formation impact categories (Fig. 25 – 28).

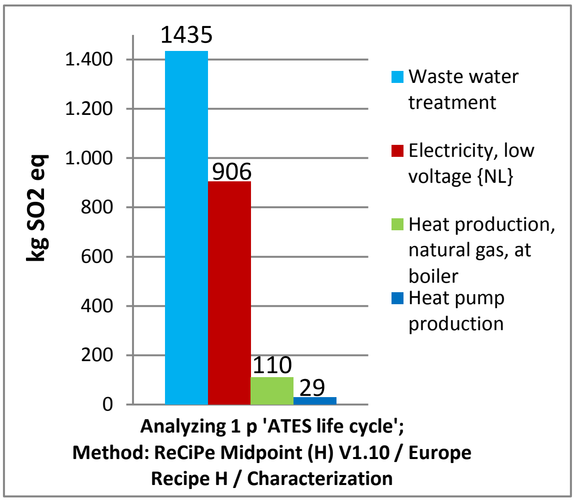


Figure 25 - Terrestrial acidification

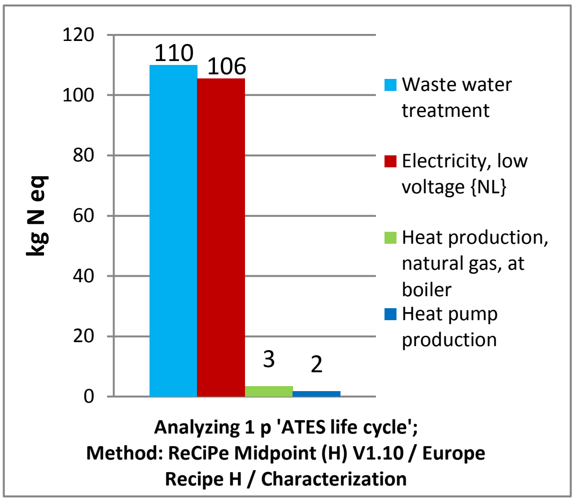


Figure 26 - Marine eutrophication

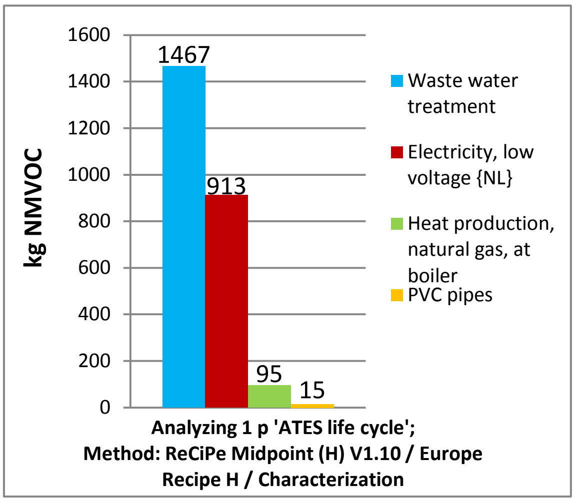


Figure 27 - Photochemical oxidant formation

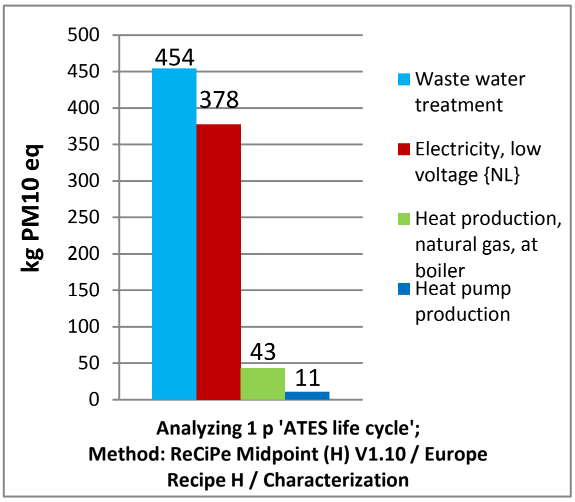


Figure 28 - Particulate matter formation

The rest of the top contributors identified remain the same, with electricity being the second biggest and followed by the heat pump production, the consumption of natural gas and the production of the PVC pipes.

C) Heat pump production

The only impact category where the largest contributor is different from electricity consumption or wastewater treatment is Ozone depletion (Fig. 29). Here the biggest impacts are credited to the production of the heat pump.

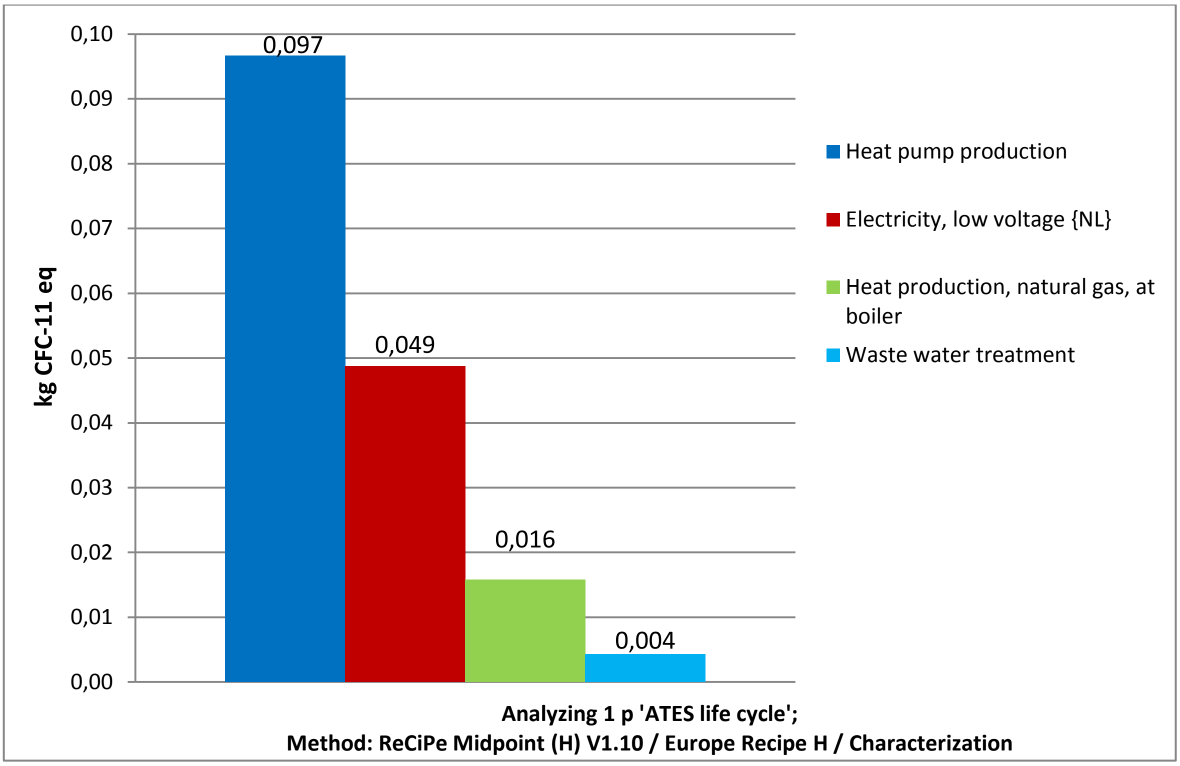


Figure 29 - Ozone depletion

This can probably be explained by the presence of CFCs in the heat pump. CFCs are typically used in heat pumps as heat transfer mediums due to their thermodynamic properties although in recent years they are slowly phased out because of their harmful environmental impacts. These days CFCs are replaced by water, hydrocarbons or ammonia as working fluids. It was found that the SimaPro process used to represent the production of the heat pump (*"Heat pump, 30kW {GLO}|market for|Alloc Def S"*) contains a number of emissions of CFCs in the atmosphere. However, it is important to distinguish that this is not the case for the specific heat pump utilized by the Tetra ATES system. The heat pump used by the Tetra system (Trane CGWH 115) employs R407C, a substitute refrigerant commonly used for the residential and light commercial air conditioning and heating appliances (Tecumseh, 2009). R407C is a non-ozone depleting mix of three hydrofluorocarbons (HFC) refrigerants, R32, R125 and R134a. According to DuPont, this refrigerant has an Ozone Depletion potential (ODP) of zero. Therefore, the above results regarding the heat pump are not relevant for the specific case of the Tetra ATES system. Nonetheless, results from Fig. 29 can still be relevant for other cases of ATES systems employing older heat pumps that still utilize ozone-depleting refrigerants.

4.4 Interpretation of results

4.4.1 Sensitivity analysis

In this section the sensitivity of the main analysis results will be examined by evaluating the system under different assumptions, methods and modelling choices. The functional unit of the LCA has been retained identical for all comparisons.

Renewable sources of energy

The first assumption to test is changing the electricity source for powering the water pumps and heat pump. As it was presented the electricity use during the operation of these two system components is the largest contributor to environmental impacts mainly because the energy mix of the country is dominated by the use of fossil fuels. In SimaPro it was found that the production mix of high voltage electricity for the Netherlands accounts for a share of fossil fuel (oil, coal, natural gas) electricity generation that amounts to about 65%. Nuclear, wind and hydro are calculated at 3,2%, 3,4 % and 0,1% respectively. Imports from Germany, Belgium and Norway are responsible for 20% of the electricity production mix while the remaining 8% is assumed to come from co-generation plants, municipal solid waste treatment and the treatment of blast furnace and coal gas in power plants. It should be noted that the values used in this SimaPro process are an extrapolation to 2013 of 2008 data.

Therefore to test the assumption regarding an alternative electricity source, in this sensitivity analysis the change will concern shifting from the Dutch national mix to 100% electricity provision from a renewable source of energy. First of all, the renewable energy is assumed to originate entirely from three separate options, namely hydropower (river) plants, photovoltaic (PV) panels and from offshore wind turbines. The processes chosen to represent these options are *"Electricity, high voltage {NL}|electricity production, hydro, run-of-river|Alloc Def S"*, *"Electricity, high voltage, {NL}|electricity production, wind, 1-3MW turbine offshore|Alloc Def S"* and *"Electricity, low voltage, {NL}|electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted|Alloc Def S"*. An additional option was added to reflect the possibility of buying a "green" electricity mix from private company providers and to evaluate the impacts from such a choice. The scenario developed (RES mix) for this LCA followed the "model contract" option provided by Greenchoice (2013). In this contract offer the client is provided with 100% renewable electricity comprising of 44,2% Dutch biomass, 0,8% Dutch solar power, 40% Dutch wind power and 15% European wind power. The SimaPro processes chosen to represent these electricity sources are shown in table 10.

Table 10 - SimaPro processes chosen for the RES mix scenario

Renewable energy source	SimaPro process
Dutch biomass	*Electricity, low voltage {CH}|treatment of biogas, burned in micro gas turbine 100kWe|Alloc Def, S*
Dutch solar power	*Electricity, low voltage, {NL}|electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted|Alloc Def S*
Dutch wind power	*Electricity, high voltage, {NL}|electricity production, wind, 1-3MW turbine offshore|Alloc Def S*
European wind power	*Electricity, high voltage {CH}|wind power, import from Germany|Alloc Def, S*

The production amount of each process has been allocated according to the Greenchoice “model contract” and the characterization results of this comparison are presented in the following figure.

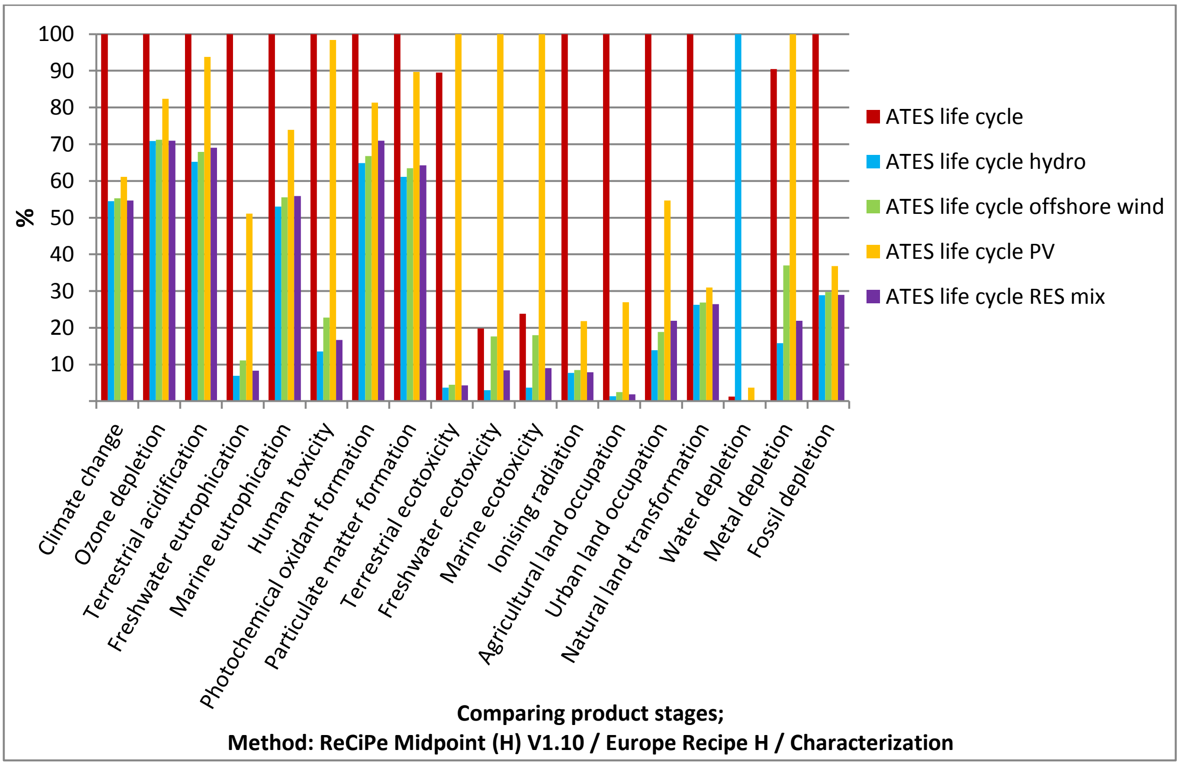


Figure 30 – Tetra ATES life cycle characterization results of different sources of energy

Among the examined options, the 100% hydro- and wind-powered options as well as the RES mix option are the ones with the lowest contribution to the majority of the impact categories. When powered with electricity generated from hydro plants the ATES system shows the lowest impact of all. The only impact category that this option scores worst is Water depletion. From all the examined options, the national mix-powered system scores the highest and is responsible for the largest environmental impacts in the majority of the categories. An interesting finding however is the impacts from the 100% PV-powered system. Among the tested options it is the second-worst and in some cases it scores even worse than when the system is powered by the Dutch national mix. The categories where the 100% PV-powered system scores worse are Terrestrial, Freshwater and Marine ecotoxicity as well as Water and Metal depletion. Additionally, in the Human toxicity category the difference with the national mix-powered system is quite small.

The reason why the 100% PV-powered system scores worse in the toxicity-related impact categories is most probably due to the production process of the PV panels. Production of PV panels is a resource-intensive procedure that requires significant amounts of chemicals and other toxic materials that are often hazardous for the environment. Similarly, for their construction some amount of water is needed which explains the difference in the Water depletion impact category. Also there exists competition for land use which can explain the large scores for Agricultural and Urban land occupation and Natural land transformation. At the same time, a wide variety of metals and minerals are used for the production of PV panels (Minerals Education Coalition, 2010) which can explain the large impact in the Metal depletion category. A similar explanation can be given for the 100% wind-powered option regarding the differences from the rest of the options in Freshwater and Marine ecotoxicity and Metal depletion impact categories. From the above it can be said that using a renewable electricity source significantly reduces the environmental impacts of an ATES system. Positively enough, at present there exist a few companies that can provide 100% renewable electricity (mix or single source) and so a switch from the national country mix to renewables appears to be feasible.

Cultural perspectives

In the table below the differences in impact for the Egalitarian and Individualist perspectives are shown. Since the Hierarchist perspective is considered middle point to the other two, results here are compared to results from the Hierarchist perspective.

Table 11 - Comparison of the differences in contribution to impact categories between the cultural perspectives (%)

Impact category	Egalitarian				Individualist			
	Construction	**Operation**	**End-of-life**	**Gas boiler**	**Construction**	**Operation**	**End-of-life**	**Gas boiler**
Climate change	-0,24	-0,56	0,84	-0,04	0,49	1,38	-2,05	0,17
Ozone depletion	x	x	x	x	x	x	x	x
Terrestrial acidification	-0,17	-0,20	0,59	-0,22	0,09	-0,019	-0,21	0,1345
Freshwater eutrophication	x	x	x	x	x	x	x	x
Marine eutrophication	x	x	x	x	x	x	x	x
Human toxicity	-1,25	0,49	-0,51	1,28	4,29	-29,34	24,29	0,75
Photochemical oxidant formation	x	x	x	x	x	x	x	x
Particulate matter formation	x	x	x	x	x	x	x	x
Terrestrial ecotoxicity	6,67	-9,40	2,14	0,59	-0,0001	0,0003	0,0001	-0,0003
Freshwater ecotoxicity	0,01	-0,06	0,04	x	-0,0036	0,0039	-0,0004	0,0001
Marine ecotoxicity	-0,22	0,72	0,17	-0,67	-0,92	0,24	0,65	0,0354
Ionising radiation	x	x	x	x	-0,07	2,95	-1,19	-1,68
Agricultural land occupation	x	x	x	x	x	x	x	x
Urban land occupation	x	x	x	x	x	x	x	x
Natural land transformation	x	x	x	x	x	x	x	x
Water depletion	x	x	x	x	x	x	x	x
Metal depletion	x	x	x	x	x	x	x	x
Fossil depletion	x	x	x	x	x	x	x	x

A positive value indicates that the particular perspective has a larger environmental impact compared to the Hierarchist while a negative value indicates that it has a smaller impact. In 8 out of the 18 impact categories no difference can be observed which leaves 10 categories where a difference can be observed and in most cases these are quite small. Basically, this means that for most impact categories changing perspectives does not have a huge effect in impacts. However, there are some differences where this can change and are worth looking into. The most notable differences exist in the results regarding toxicity. To understand the difference in impacts better the normalized values are shown in Fig. 31.

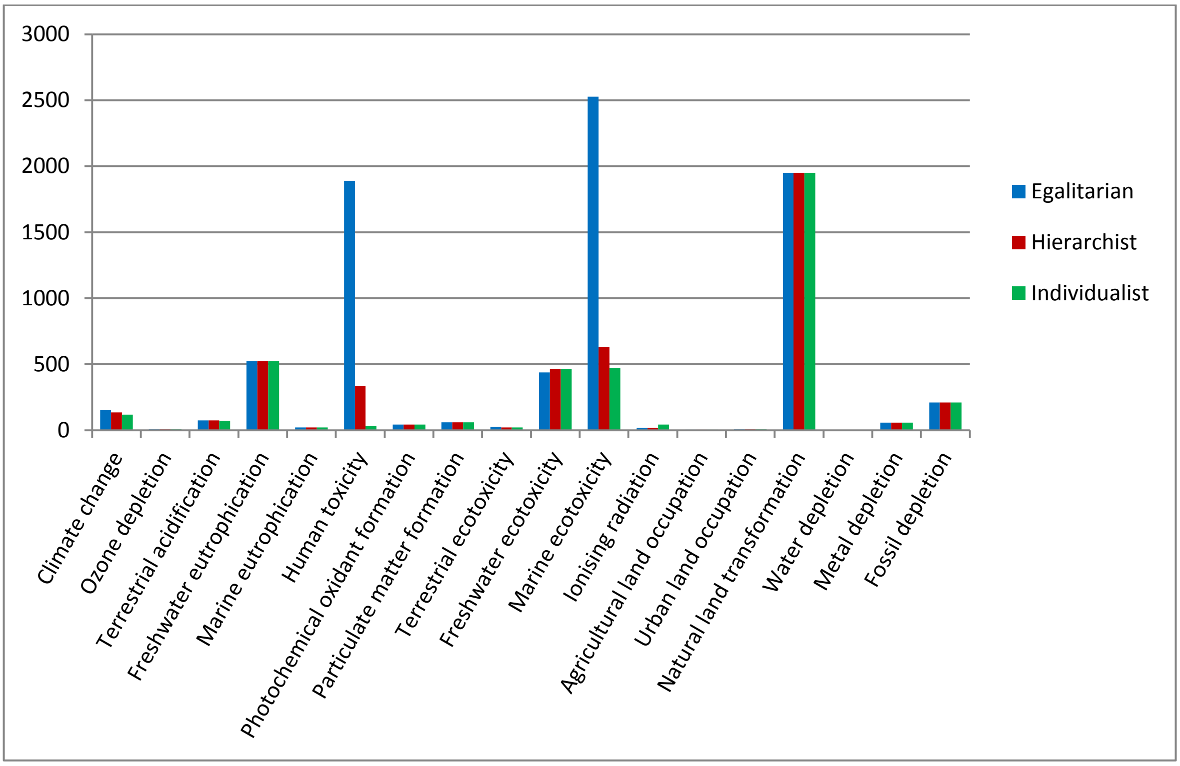


Figure 31 - Normalized values of the different perspectives for the Tetra ATES system

A great difference in impacts can be observed for the Egalitarian perspective for the Human toxicity and Marine ecotoxicity impact categories. Similar for the Individualist perspective, the impact in Human toxicity is much smaller and almost equal for Marine ecotoxicity. These differences in results can be attributed to the inherent assumptions within each perspective (section 4.1.5A).

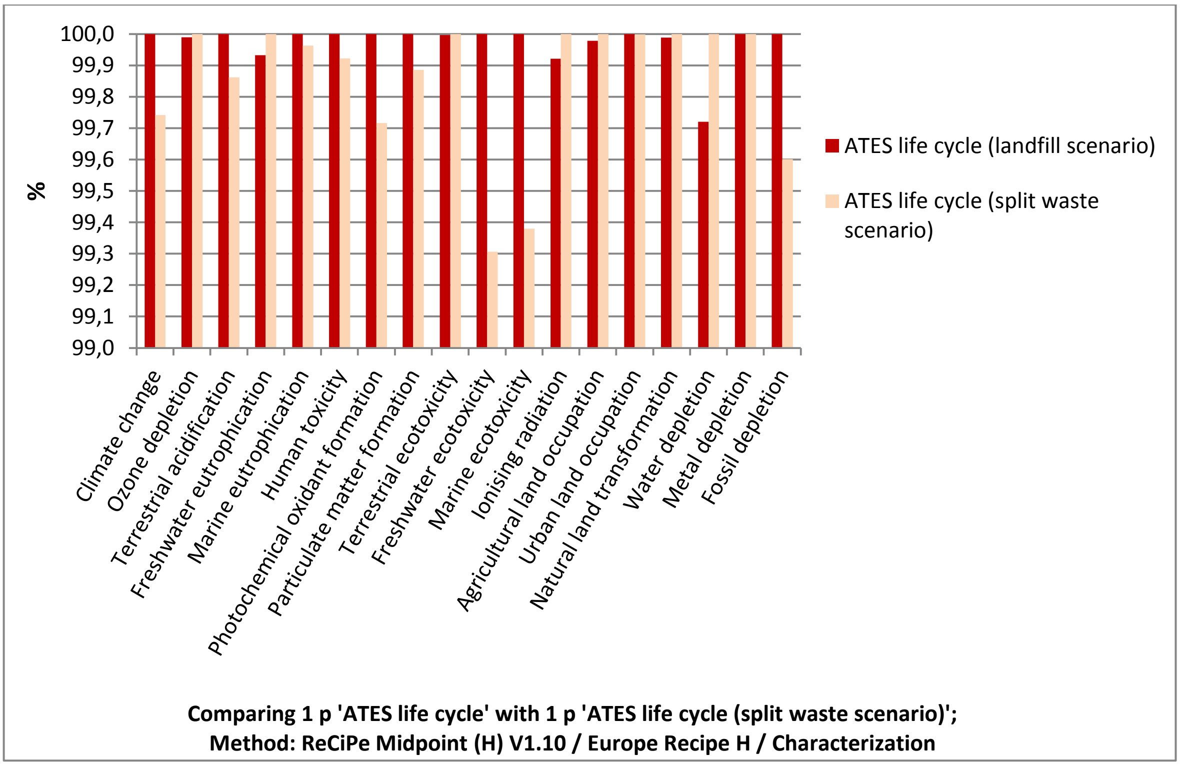
The Egalitarian perspective is the most precautionary one, taking the longest timeframe in consideration and impact types (i.e. harmful substances) are taken into account even if just an indication of their effects exists. Coupled with the fact that it is assumed that environmental damage is irreversible, this can explain why toxicity impacts are presented so large compared to the other perspectives. On the other hand, in the Individualist perspective the defined timeframe is short-term, only undisputed impact types are considered and in general it is assumed that technological development can help recover environmental damages. Additionally, fossil fuels are considered to be infinite and so their impact is not taken into account which can explain the large difference (29%) in the operation phase for the Human toxicity impact category.

End-of-life treatment

In this analysis two hypotheses regarding the end-of-life treatment are tested. The first one has to do with a different choice of waste scenario and the second compares the impacts under different assumptions regarding the treatment of the aquifer groundwater used for the preventive maintenance of the well screens.

A) Landfill vs. split waste scenario

As stated in section 4.1.7B, the basic configuration for this LCA involves the landfilling of the pipeline system. Another possibility is that these pipes can be extracted from the ground and recycled or re-used. Especially given their longer lifetime (25 years according to the Bank of America 2007 report) when compared to the ATES system this is a realistic scenario. However, an issue arises regarding the amount of pipes that could be recycled/re-used. Compared to horizontal pipelines, vertically-placed pipes are difficult to extract from the ground and even more so when backfill material has been used to pack them tight within the ground. Therefore, it is common practice that these pipes are left in the ground as it presents additional costs and effort to remove them. However, it possible to extract and recycle the ones that are within easier reach. So, for the second option only the extraction and recycling of the horizontal HDPE pipes is assumed. Therefore, the alternative waste scenario (split waste scenario) is modeled similarly to the landfill scenario with the exception that the entire amount of HDPE pipes is assumed to undergo the *"PE (waste treatment) {GLO}|recycling of PE|Alloc Def, S"* treatment. Impacts from the process of extracting the pipes from the ground could not be modeled and therefore were left out of the comparison.



Comparing 1 p 'ATES life cycle' with 1 p 'ATES life cycle (split waste scenario)';
Method: ReCiPe Midpoint (H) V1.10 / Europe Recipe H / Characterization

Figure 32 - Characterization results of the waste scenario comparison

In Fig. 32, the difference in impacts under the different waste scenarios is presented (vertical axis starts at 99%). As expected, an improvement in environmental impacts is observed when recycling the HDPE pipes instead of landfilling them. Although it has a small contribution compared to the total impacts of the Tetra ATES system, this difference could increase and potentially play a more significant role if the entirety of the pipeline system is recycled and should more system components be added to the recycling scenario. The largest differences can be observed in the Freshwater and Marine ecotoxicity impact categories at 0,7% and 0,6% respectively. Although it wasn't feasible to evaluate the environmental impacts that could originate from the extraction of the pipes from the ground it remains interesting for future research to see the degree at which these impacts could counterbalance the positive effects from recycling.

B) Wastewater treatment

For this comparison the assumptions tested regard the option of the systems' owner to deposit the groundwater that is used for the preservation of the wells. The initial scenario that is used illustrates the impacts of "flushing" the wells and draining the utilized groundwater to the sewage. From there, same as domestic wastewater, it follows through a wastewater treatment process and the clean outflow ends up in surface water. The alternative scenario (surface deposit scenario) assumes that groundwater is withdrawn from the aquifer but instead of drained in the sewage it is deposited directly in nearby surface water. In SimaPro, groundwater is generally modeled as cleaner than surface water and therefore it could be said that no significant local impacts can be expected from the deposition of groundwater to nearby surface water. Especially, if one considers the inclusion of a water filter that could solve this issue relatively easy (and cost-effectively). However, since this assumption can be debated the relevant results from this assumption should be treated cautiously.

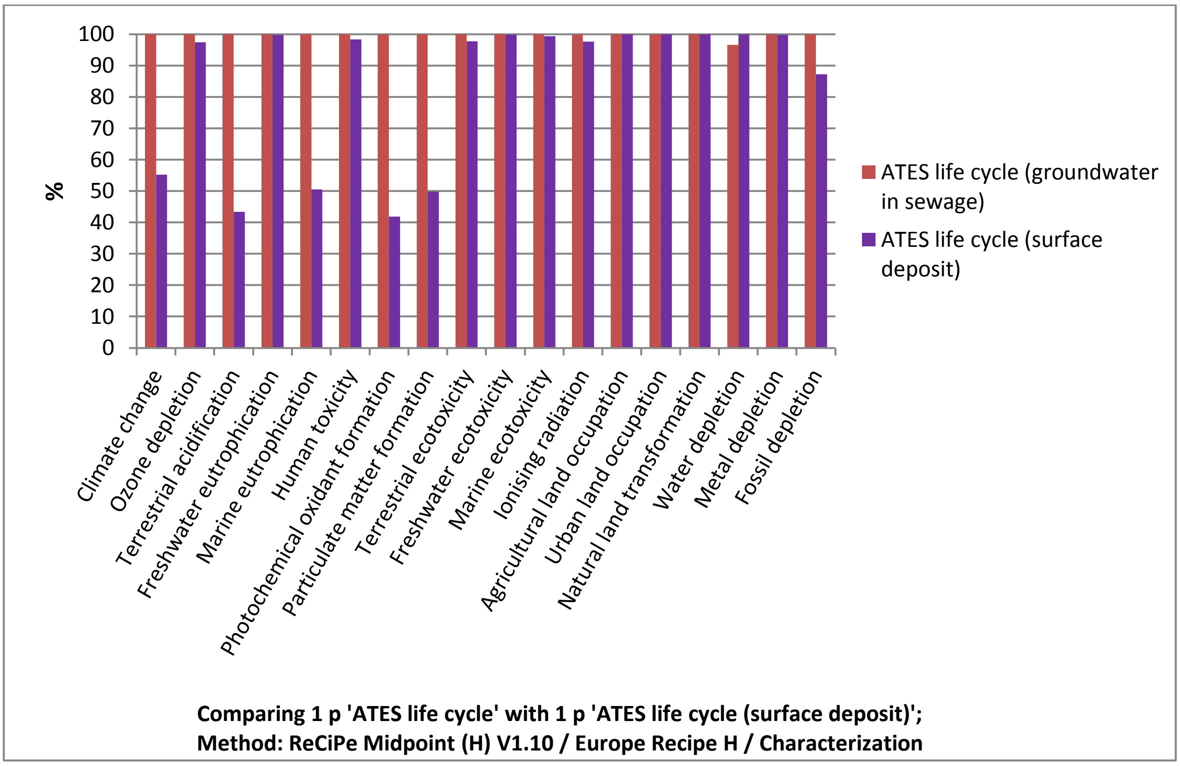


Figure 33 - Characterization results of the wastewater scenario comparison

Significant differences in impacts can be observed from the comparison of the different wastewater scenarios (Fig. 33). The largest ones are occurring in the Climate change, Terrestrial acidification, Marine eutrophication, Photochemical oxidant formation and Particulate matter formation impact categories. A great variety of substances such as nutrients, chemicals (i.e. H_2SO_4 and H_3PO_4) and of course energy goes into the waste water treatment process which can be deemed responsible for the additional impacts.

An interesting finding of this comparison is that in the first scenario water depletion is less than in the surface deposit scenario. Counter-intuitively since both streams end up in surface water, this is the only impact category where the first scenario scores better than the second. These results however make sense since SimaPro works with inputs and outputs and in the second scenario no wastewater output was assigned since no relevant process could be found. Based on the quote from Goedkoop et al. (2013b) which state that *"…if water is consumed but also released very close to the point of consumption, one may argue that the water is not lost and thus water use does not result in any shortage"* it can be argued that this result is incorrect. In fact, in the contribution analysis it was shown that about 8% of the extracted groundwater is lost during the wastewater treatment process. Since no water loss is expected when deposited straight to nearby surface water it can be argued that the initial scenario scores worse in the Water depletion impact category as well.

CEnD

Results from the CEnD impact assessment method (Fig. 34) further verify the main results from the ReCiPe method. It is shown that the electricity used for the operation of the water pumps and heat pump is the main contributor to direct and indirect energy consumption. From the CEnD results, it can be reported that the potential total direct and indirect (embodied) energy usage of the Tetra ATES system for a 15-year period is approximately 16,4TJ (for detailed information please refer to Appendix B).

Approximately 73% (11,9TJ) of the total energy is consumed for the operation of the ATES system (groundwater pumps and heat pump) while 25% (4,2TJ) is expended from the construction/operation of the natural gas boiler and during the end-of-life of the entire system (12,9% and 12,8% respectively).

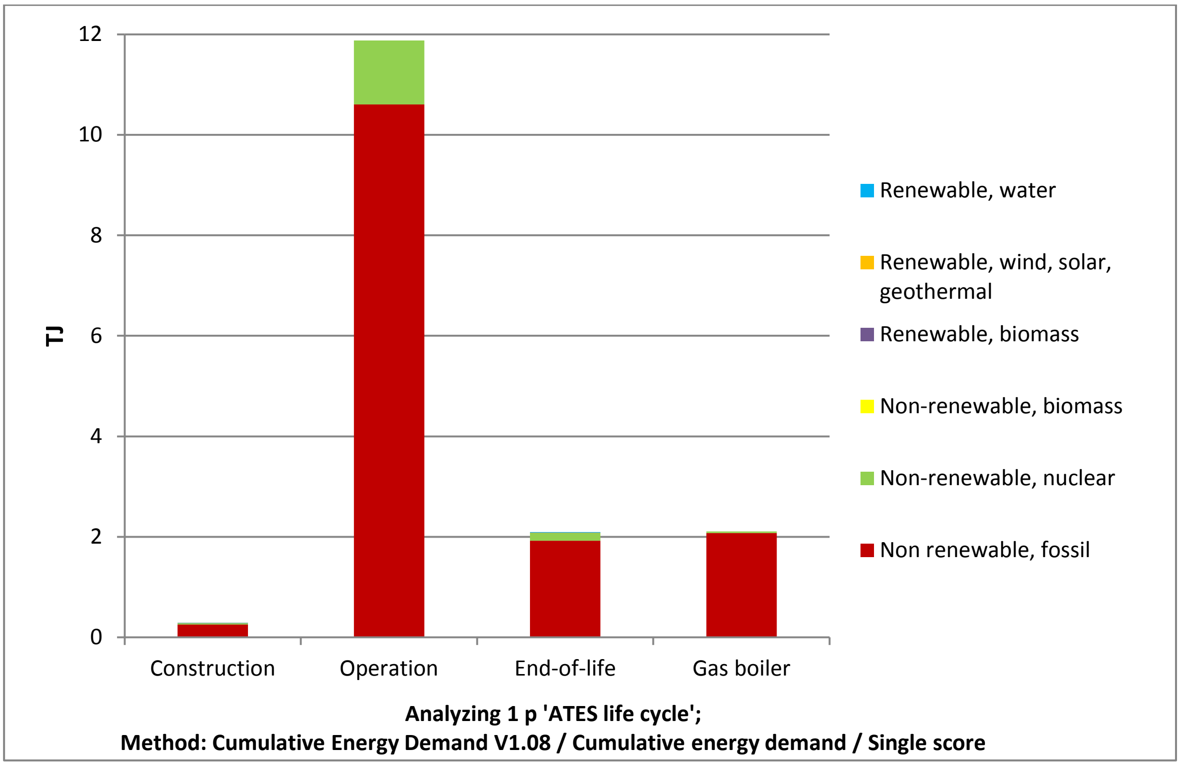


Figure 34 – CEnD Single score results of the Tetra ATES system

Consumption of renewable energy by the Tetra ATES system is particularly small. From Fig. 34 it remains evident how large the influence of non-renewable sources of energy (fossil fuels, nuclear) is regarding the life cycle environmental impacts of the Tetra ATES system.

It is important to keep in mind that a number of important environmental impacts are not shown with the following method. For instance, the impacts from the production of wastewater are not represented adequately. These results must therefore be coupled with the main analysis results from section 4.3 in order to get a complete impression of the overall environmental impacts of the Tetra ATES system.

System modelling

In the new Ecoinvent database (v3) which is incorporated in SimaPro, the user can choose between two different system model options, attributional and consequential modelling. As mentioned in section 4.2 the main differences between these two options are the way they handle multi-functionality and also their consideration of average or marginal suppliers and of technological development. More specifically, in the default attributional model option the 1) use of an average supply of products as described in markets activities is assumed and 2) allocation of multi-product data is performed according to economic revenue collected (based on their ‘true value’, which is a correction for market imperfection and distortions where the revenue does not reflect the true functional value of products and co-products). In the new consequential model option the focus is on long-term consequences of decisions and it is assumed that 1) an unconstrained supply of products exists that accounts for technological development and 2) multi-product data are converted into single-product data using system expansion. The ILCD Handbook (2010) recommends an in-between model of these two system model options. Additionally, the results of choosing a system model can be significantly different as, for instance, data from average production can be largely different from data from modern, marginal suppliers. For that reason, it was deemed interesting to compare the sensitivity of the results under the two system models available in SimaPro. As stated in Weidema (2011), with this new database structure it becomes possible to compare different modelling results of the same product while maintaining the same data. For this comparison, an identical consequential Tetra ATES system model was created by replacing all attributional processes (*Alloc Def*) with consequential processes (*Conseq*). Performing a full LCA using consequential data can be a whole study in itself and so in this section only the results of the comparison will be shown. Only market activities are used in this analysis.

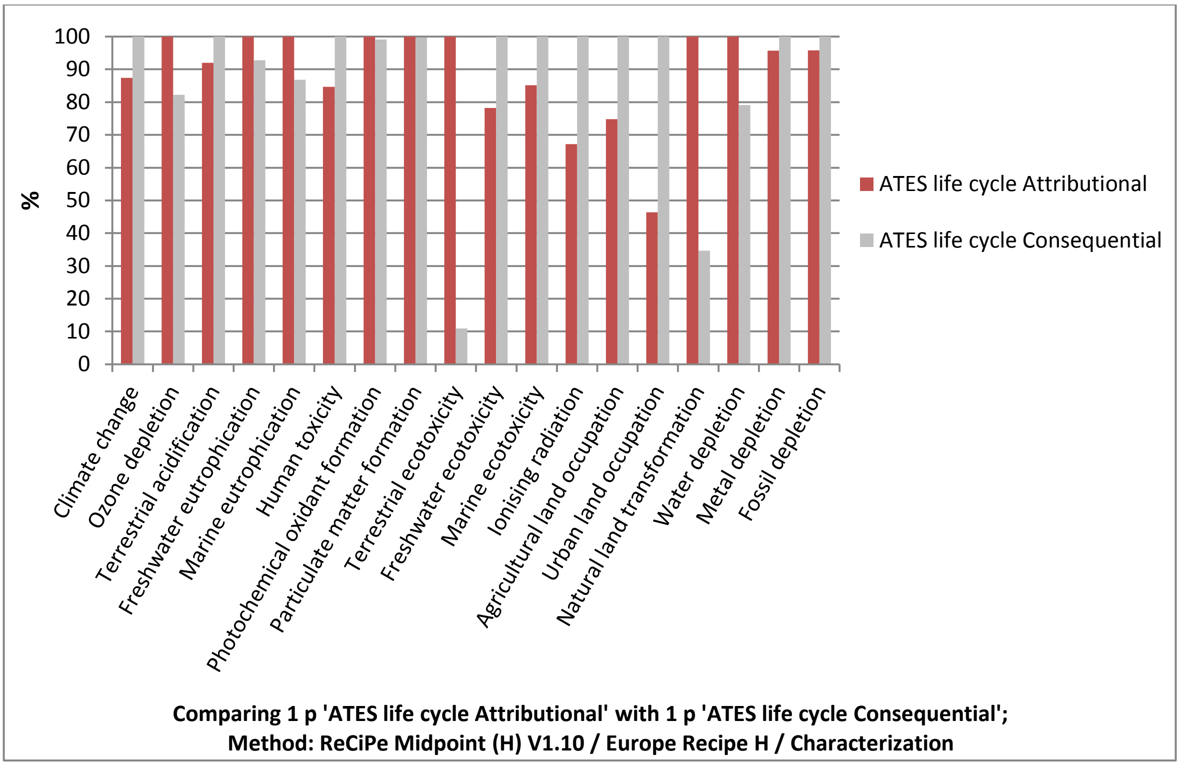


Figure 35 - Characterization results of the system model comparison

From Fig. 35 it is important to notice how large the differences can be between the two system model options. While the attributional model scores worse in 8 categories (Particulate matter formation included), the consequential model scores worse in 10. In some cases the consequential model shows a large positive difference, almost 70% for Natural land transformation and 90% for Terrestrial ecotoxicity. In other cases, such as Climate change, Freshwater and Marine ecotoxicity, Ionising radiation and Urban and Agricultural land occupation, the attributional model scores significantly better (15 – 55%). Additionally interesting are the normalization results of the system model comparison (Fig. 36).

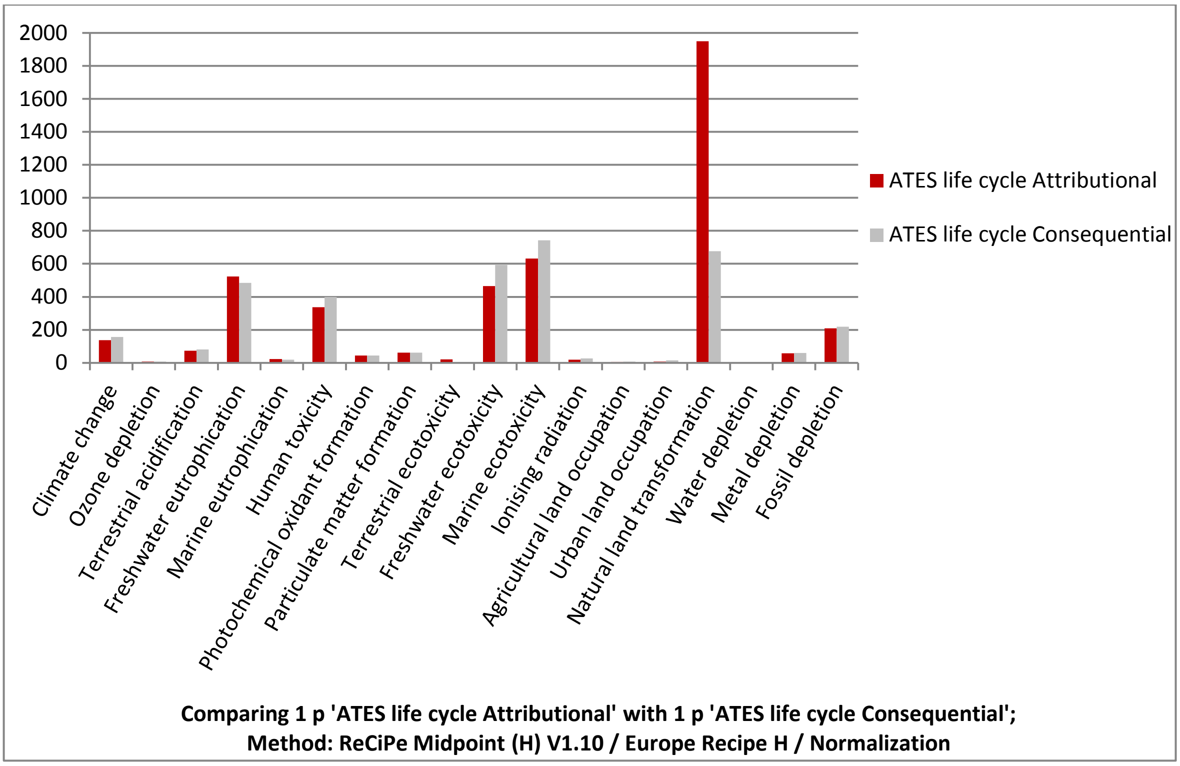


Figure 36 - Normalization results from the system model comparison

When compared to the European reference value the results show significant differences. This is especially relevant for the impact category of Natural land transformation. As it was presented earlier in section 4.3.2, the impact of the Tetra ATES system in this category is the largest by a substantial margin from all other impact categories. When using consequential modelling this image is altered and Natural land transformation shows a major reduction by approximately 65%. However, the overall image of the life cycle environmental impacts of the Tetra ATES system does not alter that much and the main impact categories affected the most remain the same. More detailed tables and a brief analysis of the characterisation and normalization results of the consequential LCA can be found in Appendix C.

The above results demonstrate the importance of making a choice regarding the adopted system model when performing an LCA. This choice can be based on various parameters as the different system models are relevant for different purposes depending on the user’s and target audience’s interest.

4.4.2 Comparison with a conventional heating and cooling system

In order to test the notion that ATES systems are environmentally friendly it was important that a comparison with a reference system was made. For this comparison, the reference system is assumed to provide space heating and cooling using traditional means. Therefore, for the reference system heating during the winter is entirely provided using a 95% (HHV) natural gas boiler and cooling in the summer by air-conditioning. In order to ensure a fair comparison the reference system is modelled using the same functional unit (as defined in section 4.1.2). This basically means that the gas boiler is used to provide 268MWh of heat while the air-conditioner is assumed to provide 175MWh of 'cold'. The fuel consumption of the natural gas boiler is calculated as:

$$\textit{Annual fuel input of gas boiler} = \frac{Heat\ output/yr}{boiler\ efficiency} = \frac{268MWh/yr}{95\%} = 282MWh/yr * 3{,}6 = 1015\ GJ/yr\ \textit{of natural gas}$$

Since no process was available in SimaPro to model the provision of cooling from conventional air-conditioning units this process was modelled instead using the electricity input needed to cover the 175MWh cooling demand of the Tetra building. To derive this input it is assumed that the reference system utilizes a modern air-conditioner. According to Energy Star (2014), a conventional central air-conditioning unit is assigned a Seasonal Energy Efficiency Ratio (SEER) of 13. SEER can be calculated as follows:

$$SEER = \frac{Output\ cooling\ energy\ in\ BTU\ over\ a\ season}{input\ electrical\ energy\ in\ Wh\ during\ the\ same\ season} \qquad (Eq.\ 5)$$

From Eq. 5 it is calculated that for a central air-conditioner with a SEER of 13 to provide 175MWh of cooling, the following annual electrical input is needed:

$$\textit{Air-conditioner electrical input} = \frac{175MWh}{13} = \frac{597.124.786BTU}{13} = 46MWh$$

Table 12 shows the energy inputs of the reference system throughout the 15-year period examined in order to cover the heating and cooling demands of the Tetra building.

Table 12 - Energy inputs of the reference system

Energy input	Amount	Unit	SimaPro process	Comments
Gas boiler				
Natural gas	15,2	TJ	*Heat, district or industrial, natural gas {Europe w/o CH} | heat production, at boiler condensing modulating >100kW | Alloc Def, S*	Natural gas input in boiler for a period of 15 years
Air-conditioner				
Electricity	690	MWh	*Electricity, low voltage {NL} |market for | Alloc Def, S*	Energy consumption of 46MWh/yr for a period of 15 years

From table 12, it can be seen that by utilizing an ATES system there be can significant variation in the energy requirements for space heating and cooling. Most notably, when using the ATES system in the Tetra building natural gas savings of 13,3TJ can be accomplished in 15 years which amount to

838tons of CO_2-eq approximately. Additionally, when comparing tables 8 and 12 it is rather obvious that there are significant deficiencies in the present comparison of the Tetra ATES and the reference system. No data was available regarding the construction and end-of-life phase of the reference system and so these were left out. Only the use phase could be determined for the reference system and so comparing with the entire Tetra ATES system as modelled previously would make an incomplete comparison. Nevertheless, the results of comparing an ATES system with a conventional heating and cooling system are still interesting to present as they can illustrate the potential differences in the environmental impacts of the use phase between the two options. For this reason a comparison of the use phase of the two systems is presented. For this analysis the impacts of the construction and end-of-life phase of the Tetra ATES system are also left out and so the system is modelled as ATES use phase. Since significant aspects of the ATES system and Reference system are left out it must be noted that by no means should the following results be taken independently to reach a final definitive deduction and further research with a more complete dataset regarding the excluded life cycle phases and including additional assessment steps should be pursued.

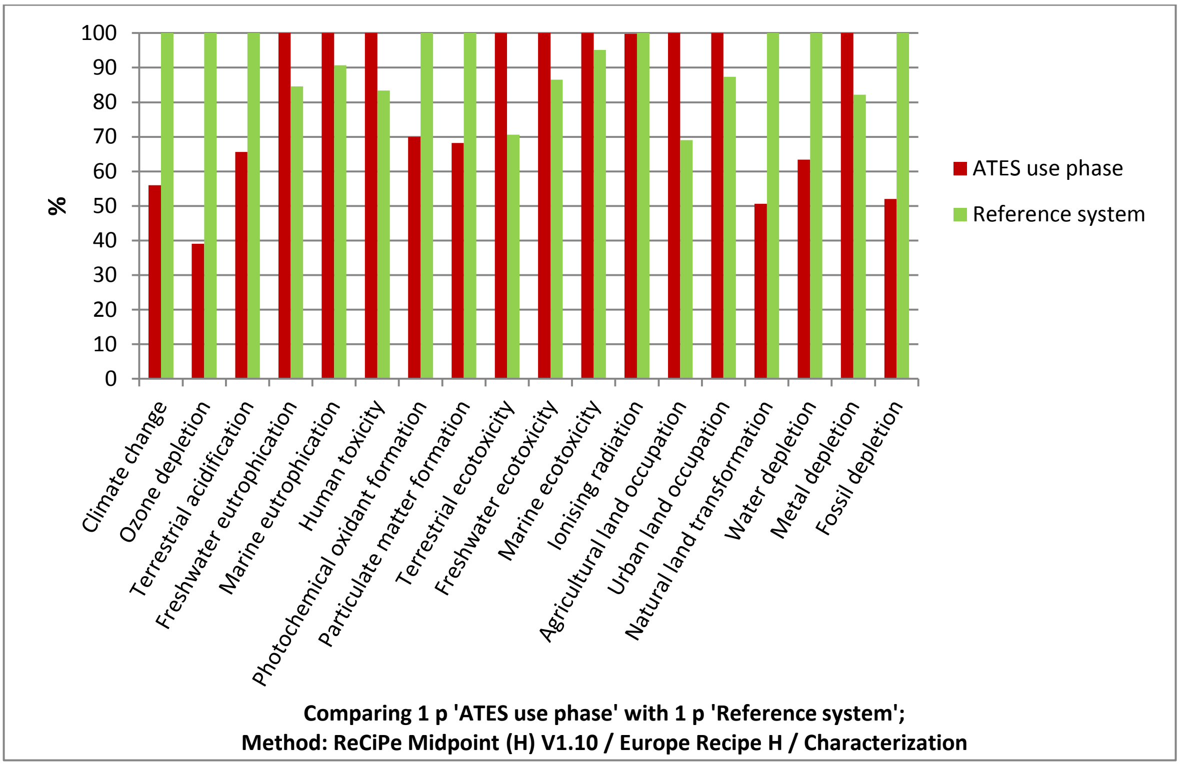


Figure 37 - Characterisation results of the ATES use phase and Reference system comparison

Fig. 37 shows an evenly-divided image regarding the environmental impacts of the use phase of both systems. In half of the impact categories the Tetra ATES system is shown to score worse than the Reference system. These categories are Freshwater and Marine eutrophication, Human toxicity, Terrestrial, Freshwater and Marine ecotoxicity, Agricultural and Urban land occupation and Metal depletion. In the remaining impact categories of Climate change, Ozone depletion, Terrestrial acidification, Photochemical oxidant and Particulate matter formation, Ionising radiation, Natural land transformation, Water and Fossil depletion it is the Reference system that scores worse. In table 13 the relative contribution of each system per impact category can be seen in more detail. Here it can be observed that Ionising radiation is an impact category where the ATES system also scores quite highly and the difference to the Reference system is very small.

Table 13 - ATES use phase and Reference system relative contribution (%) per impact category

Impact category	ATES use phase	Reference system
Climate change	55,95	100
Ozone depletion	39,05	100
Terrestrial acidification	65,64	100
Freshwater eutrophication	100	84,57
Marine eutrophication	100	90,73
Human toxicity	100	83,39
Photochemical oxidant formation	70,01	100
Particulate matter formation	68,18	100
Terrestrial ecotoxicity	100	70,65
Freshwater ecotoxicity	100	86,56
Marine ecotoxicity	100	95,12
Ionising radiation	99,77	100
Agricultural land occupation	100	69,01
Urban land occupation	100	87,36
Natural land transformation	50,63	100
Water depletion	63,38	100
Metal depletion	100	82,13
Fossil depletion	52,02	100

From the above, it appears that by using the ATES system the Tetra building does not improve its environmental performance significantly when compared to using a conventional heating and cooling system. Based on these results, one could even argue that the Reference system is equally environmentally friendly compared to the Tetra ATES system which contradicts the idea and purpose behind the development of the ATES technology. It is worthy to note nonetheless a few of the impact categories where the use phase of the Reference system scores worse. Climate change and Ozone depletion as well as Water and Fossil depletion are major environmental concerns of the modern world and so it could be certainly counter-argued whether the Reference system is indeed as good as the ATES system in environmental terms.

Since it is outside the scope of this study to interpret the importance of impact categories no further evaluation of these results will be made. However, it should be noted that these are results of the ReCiPe Midpoint impact assessment method. By using a different method such as the ReCiPe Endpoint method, where the additional steps of weighting and single score are included, the results produced can be very different from the ones presented here. For illustration purposes the results from using the ReCiPe Endpoint method are shown in Appendix D. Nevertheless using a different impact assessment method can provide significant additional insights. Since in the use phase the examined processes relate to energy use it is suitable to see also how these two systems compare regarding their different energy inputs. Thus the comparison between the use phase of the Tetra ATES system and the Reference system is further evaluated using the CEnD method (Fig. 38).

The first thing to notice from the CEnD impact assessment method results is that only non-renewable sources of energy are presented. Renewables such as water, biomass, solar, wind and geothermal are not applicable for this comparison as the use phase of both systems is modelled using the national electricity mix and natural gas to power the gas boilers (table 12).

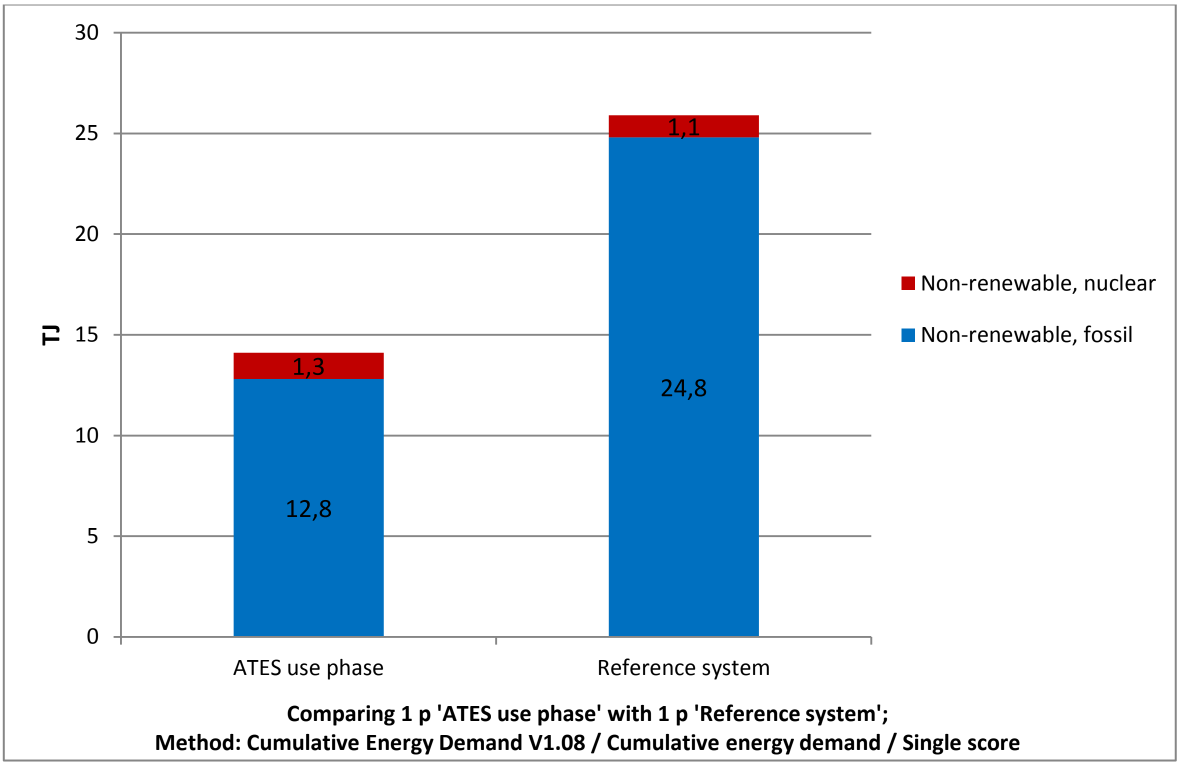


Figure 38 - ATES use phase and Reference system Single score results under the CEnD method

The total energy use of the Tetra use phase is measured at 14,1TJ[8] in a 15-year period while the energy that would be consumed should the Tetra building use conventional means for heating and cooling is 25,9TJ. This shows that by utilizing the ATES system the Tetra building saves approximately 45% in total energy use.

The "take-home" message from this analysis should be that depending on the life cycle impact assessment method used a variety of results can be presented and so it is important to understand where these results come from. From an energy perspective and using the CEnD method it is clear that the Tetra ATES system performs much better in terms of energy consumption, especially so since it exploits a renewable energy source (low-enthalpy shallow geothermal energy), which is important for the mitigation of climate change. On the other hand, using the ReCiPe Midpoint impact assessment method it is shown that there are significant differences when accounting for more impact categories (i.e. regarding eutrophication and toxicity impact categories) where the use of an ATES system shows a diminished environmental performance. It therefore remains crucial to understand and include as many as possible environmental impacts in order to properly and thoroughly assess the life cycle environmental performance of any product or product system.

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[8] The divergence of 0,1TJ when compared to the results of the sensitivity analysis should be attributed to rounding of SimaPro.

Chapter 5 – Discussion

Regarding this research and its findings it should be noted that there are some limitations and concessions that need to be accounted for. Starting with the research methodology, LCA is an analytical tool used to show the potential environmental impacts of a product system and therefore local impacts are not amply represented. This is especially important for ATES systems as they interact with the aquifer groundwater in the subsurface and therefore can have a range of potential local chemical, microbiological and thermal environmental impacts (Bonte et al., 2011; Hähnlein et al., 2013) that cannot be identified with an LCA. These impacts are currently under research from the scientific community and their findings should always be taken into account. Additionally, the interaction of human activities with the subsurface are incompletely addressed in the existing impact assessment methods and thus the environmental impacts examined cannot be guaranteed to fully reflect the entirety of possible impacts. For example, the Land transformation impact category could be expanded to account also for competing uses of the underground or the Water depletion impact category to address the use of water resources in a more consistent manner.

Moreover, it is important to see how the methodological choices can influence the outcome of an LCA. For instance, the goal and scope definition or the choice of a functional unit can vary from one study to another and so the results can differ to a large extent. Also, the possibility to select between different allocation methods, system boundaries and impact assessment methods can lead to data and result inconsistencies. In this study an illustration of the differences in results under different allocation methods is presented by the system modelling comparison in the sensitivity analysis section. Furthermore, to complete the puzzle of sustainable subsurface development social aspects could also be included in future work. Further harmonisation of the LCA methodology beyond the ISO standard is therefore recommended.

On a similar note, there are some additional limitations regarding the inventory data that was used to perform this research. Some of the real processes of the system could not be linked with SimaPro processes and substitutes (technological or geographical) had to be chosen. Inventorying all processes and materials to update the SimaPro database is certainly a challenging and long-lasting procedure and therefore this field remains an area open for further development.

Lastly, this research was performed using the design characteristics of the Tetra ATES system. In practice, the actual operational conditions and performance can differ significantly and so it is an interesting field to perform future research with supplementary data on the system's actual performance and compare that to the design values. Although this research attempted to be as complete as possible still a lot more information could be useful in order to provide a complete life cycle assessment of ATES systems. Nevertheless, it is the hope of the author that this analysis can be used as a basis to encourage the completion of additional assessments on ATES and other energy storage systems that incorporate different data and impact assessment methods and examine more considerations and assumptions.

Chapter 6 – Conclusions

Adopting a cradle-to-grave approach this study aimed at assessing the life cycle environmental impacts of a combined heat and cold shallow ATES system using the LCA methodology. The outcomes of this study can thus be used to provide an answer to the main research question:

"What are the potential life cycle environmental impacts of a combined heat and cold ATES system?"

To effectively answer the main research question a set of sub-questions was formed studying the impacts of an existing ATES system in the Netherlands for a 15-year use period. A short recap of the answers to the formulated sub-questions will be presented here followed by some final, general conclusions and remarks. The first sub-question that needed to be addressed was:

1. "Which environmental impact categories are most appropriate for the life cycle assessment of an ATES system?

Following the suggestions of the ITA-AITES Working Group 15 (2010) on research regarding the exploitation of the underground the most appropriate environmental impact categories for the LCA of ATES systems were found to be climate change, resource depletion, energy consumption, ecotoxicity, land use and effects on human health. These impact categories represent a broad range of important environmental impacts and are consistent with key sustainable development themes. Utilizing the updated ReCiPe Midpoint (H) impact assessment method it was made possible to address the entirety of these impact categories (table 1) in a consistent and thorough manner.

2. "What are the energy and material inputs and outputs over the lifetime of an ATES system?"

Calculations and assumptions on the life cycle energy and material inputs and outputs of the ATES system are listed in section 4.2 while table 8 presents a summary of the LCI. The most important material inputs of the system regard the heat pump and bentonite for the sealing of the wells along with the PVC and HDPE pipes for the ATES distribution system. The plastic pipes along with the groundwater used for the preventive maintenance of the well screens were shown as the most important material outputs of the system. The largest energy input of the ATES system was found to be the electricity used for the operation of the heat pump. Additional energy inputs are the natural gas consumed by the gas boiler and the electricity used to drive the groundwater pumps. Lastly, the energy output of the ATES system is the thermal energy delivered to satisfy the heating and cooling demands of the Tetra building.

3. *"What and how large are the environmental impacts of the construction, use and end-of-life phases of an ATES system?"*

The results of the LCIA display the impact of each life cycle phase of an ATES system per impact category. In the majority of the impact categories the use phase shows the largest influence, even without adding the use of the natural gas boiler. The affected impact categories are Freshwater eutrophication, Human toxicity, Terrestrial, Freshwater and Marine ecotoxicity, Ionising radiation, Agricultural and Urban land occupation, Natural land transformation and also Water, Metal and Fossil depletion. The end-of-life phase follows by showing large influence in the Terrestrial acidification, Marine eutrophication and Photochemical oxidant and Particulate matter formation impact categories. In the Climate change impact category the aforementioned life cycle phases are almost equal in impact. Lastly, the construction phase appears as the most important phase only in the Ozone depletion impact category. The normalization results showed that the Tetra ATES system scores the largest in the Natural land transformation, Marine ecotoxicity, Freshwater eutrophication, Freshwater ecotoxicity, Human toxicity, Fossil depletion and Climate change impact categories (in descending order of impact).

4. "What are the dominating contributors to the life cycle environmental impacts of an ATES system?"

The findings of this study regarding the dominant contributors to environmental impacts provide some interesting insights. First, it is shown that in the impact categories where the use phase has the prime impact it is the electricity consumption during this phase that contributes the most. This result is consistent and confirms the outcome of previous research by Tomasetta (2013). The largest share of the electricity use is credited to the operation of the heat pump and the rest is consumed for the operation of the groundwater pumps. The second important finding of this study, which is also new compared to previous studies, relates to the process followed concerning the preventive maintenance of the well screens. In the impact categories dominated by the end-of-life phase it was identified that the major contributor to environmental impacts is the wastewater treatment process. The groundwater used to "flush" the well screens is deposited in the sewage and although it is generally considered clean water it still follows the same process as domestic wastewater on to a wastewater treatment process. This process is shown in this study to have substantial environmental impacts. Lastly, the dominating contributor in the Ozone depletion category is the production of the heat pump due to the utilization of CFCs for its operation. As it is explained in section 4.3.3C this is not relevant for the specific case study but the results nevertheless remain applicable as this could be the case for other ATES systems employing a heat pump.

5. "What is the sensitivity of the life cycle assessment results regarding different assumptions?"

A sensitivity analysis examined the consistency of the LCA results under a variety of different factors. Looking at the electricity source that powers the ATES system it was found that switching to a fully renewable electricity source can reduce considerably the entirety of environmental impacts. However, this choice should be carefully considered as not all options tested show the same improvement in environmental performance. The best, and also realistic, option tested is the adoption of a 100% renewable electricity mix where offshore wind and biomass electricity production hold the largest shares, followed by solar PV electricity generation. When examined from different cultural perspectives, the results of the LCA remained largely the same. Testing different end-of-life scenarios showed that improvements can be achieved if the system components are recycled, albeit with the present restricted dataset these improvements were small. When testing the option for the disposal of the groundwater used for the maintenance of the wells screens it was found that choosing to dispose it in nearby surface water scores much better than when disposing it in the sewage and so an opportunity exists here for the optimization of the environmental performance of ATES systems. This difference is especially large in the Climate change, Terrestrial acidification, Marine eutrophication, Photochemical oxidant formation and Particulate matter formation impact categories. Additionally, the results of the main analysis were verified by a supplementary assessment using the CEnD impact assessment method that examines the direct and indirect energy consumption of the system. Lastly, the new version of SimaPro enables the utilization of different system modelling options, namely attributional and consequential modelling. It was observed that due to the intrinsic assumptions within each option significant differences can be found in the characterization results although the overall image does not change considerably in the normalization results. Nevertheless, this analysis points out the importance of carefully considering the choice of a system model that is relevant to the user's and target audience's interests.

6. "How does an ATES system compare environmentally to a conventional heating and cooling system?"

In general, ATES systems are considered environmentally friendly solutions towards the mitigation of climate change and sustainable development (Dincer & Rosen, 2002; Lee, 2010; Paksoy et al., 2004). This is certainly the case when one looks into the energy used to operate an ATES system and compare that to the energy consumed by a conventional heating and cooling system (natural gas boiler and air-conditioner). Utilizing the CEnD method it was found that by using the ATES system the Tetra building achieves 45% in total energy savings compared to using a conventional system to serve its heating and cooling demands. Interestingly enough when using a more complete impact assessment method that examines a variety of environmental impacts it was found that the impacts are almost evenly divided between the two options. Since it is outside the scope of this study to interpret the importance of the impact categories no further evaluation of these results is made. However, it should be noted that the aforementioned results derive from the ReCiPe Midpoint impact assessment method which limits the analysis to the midpoint level and so the steps of weighting and single score are not available. Although largely subjective, by using these steps the impacts could be presented according to their importance to the target audience and the end results could differ significantly.

From this research the general conclusion that can be drawn is that, at this point and taking into account the specific assumptions and characteristics of this research, ATES systems appear to still have room for the optimization of their environmental performance and to successfully exploit their vast potential towards the transition to sustainable development. Nevertheless, when compared with conventional systems at the use phase ATES systems can still offer an environmentally friendly solution to the service of the space heating and cooling demands of buildings. Significant improvement opportunities for their environmental performance were shown to lie with the electricity source of the system and also the choice of disposing the groundwater used for the preventive maintenance of the well screens. Albeit smaller, even further improvements can be achieved by recycling or re-using components of the ATES system.

As a last note it should be said that the use of the subsurface can offer significant opportunities for sustainable development. However, as alternative uses are increasingly competing it remains an interesting field of research to identify those options that offer the greatest benefits at the lowest environmental costs.

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Appendices

Appendix A – detailed Environmental impacts of Tetra ATES system

Cut-off criterion 0,1%.

Table 14 – Characterisation results of the Tetra ATES system

Climate change	Unit	Total	Construction	Operation	End-of-life	Gas boiler
Total of all processes	kg CO2 eq	1525696,60	16680,11	699156,28	691503,58	118356,60
Remaining processes	kg CO2 eq	1718,47	1718,47	x	x	x
Electricity, low voltage {NL}	kg CO2 eq	699812,77	656,48	699156,28	x	x
Waste water treatment	kg CO2 eq	684091,86	x	x	684091,86	x
heat production, natural gas, at boiler	kg CO2 eq	118356,60	x	x	x	118356,60
PVC pipes	kg CO2 eq	6467,35	6467,35	x	x	x
Heat pump production	kg CO2 eq	5678,85	5678,85	x	x	x
treatment of waste PVC	kg CO2 eq	4769,72	x	x	4769,72	x
treatment of waste HDPE	kg CO2 eq	2642,01	x	x	2642,01	x
HDPE pipes E	kg CO2 eq	2158,95	2158,95	x	x	x
Ozone depletion	Unit	Total	Construction	Operation	End-of-life	Gas boiler
Total of all processes	kg CFC-11 eq	0,166	0,097	0,049	0,005	0,016
Remaining processes	kg CFC-11 eq	x	x	x	x	x
Heat pump production	kg CFC-11 eq	0,097	0,097	x	x	x
Electricity, low voltage {NL}	kg CFC-11 eq	0,049	x	0,049	x	x
heat production, natural gas, at boiler	kg CFC-11 eq	0,016	x	x	x	0,016
Waste water treatment	kg CFC-11 eq	0,004	x	x	0,004	x
treatment of waste PVC	kg CFC-11 eq	0,001	x	x	0,001	x
Terrestrial acidification	Unit	Total	Construction	Operation	End-of-life	Gas boiler
Total of all processes	kg SO2 eq	2530	72,90	905	1440	110
Remaining processes	kg SO2 eq	3,90	3,44	x	0,47	x
Waste water treatment	kg SO2 eq	1430	x	x	1430	x
Electricity, low voltage {NL}	kg SO2 eq	906	0,85	905	x	x
heat production, natural gas, at boiler	kg SO2 eq	110	x	x	x	110
Heat pump production	kg SO2 eq	29,40	29,40	x	x	x
PVC pipes	kg SO2 eq	26,20	26,20	x	x	x
treatment of waste PVC	kg SO2 eq	9,46	x	x	9,46	x
HDPE pipes	kg SO2 eq	7,61	7,61	x	x	x
Bentonite	kg SO2 eq	2,90	2,90	x	x	x
Gravel	kg SO2 eq	2,54	2,54	x	x	x
Freshwater eutrophication	Unit	Total	Construction	Operation	End-of-life	Gas boiler
Total of all processes	kg P eq	217	7,43	203	1,11	5,20
Remaining processes	kg P eq	0,30	0,30	x	0,01	x
Electricity, low voltage {NL}	kg P eq	203	0,19	203	x	x
Heat pump production	kg P eq	6,94	6,94	x	x	x
heat production, natural gas, at boiler	kg P eq	5,20	x	x	x	5,20
treatment of waste PVC	kg P eq	0,62	x	x	0,62	x

Waste water treatment	kg P eq	0,48	x	x	0,48	x
Marine eutrophication	Unit	Total	Construction	Operation	End-of-life	Gas boiler
Total of all processes	kg N eq	222	2,96	106	111	3,43
Remaining processes	kg N eq	0,64	0,60	x	0,04	x
Waste water treatment	kg N eq	110	x	x	110	x
Electricity, low voltage {NL}	kg N eq	106	0,10	106	x	x
heat production, natural gas, at boiler	kg N eq	3,43	x	x	x	3,43
Heat pump production	kg N eq	1,74	1,74	x	x	x
PVC pipes	kg N eq	0,53	0,53	x	x	x
treatment of waste PVC	kg N eq	0,45	x	x	0,40	x
Human toxicity	Unit	Total	Construction	Operation	End-of-life	Gas boiler
Total of all processes	kg 1,4-DB eq	212000	17300	185000	4900	4450
Remaining processes	kg 1,4-DB eq	337	337	x	x	x
Electricity, low voltage {NL}	kg 1,4-DB eq	186000	174	185000	x	x
Heat pump production	kg 1,4-DB eq	16000	16000	x	x	x
heat production, natural gas, at boiler	kg 1,4-DB eq	4450	x	x	x	4450
Waste water treatment	kg 1,4-DB eq	3450	x	x	3450	x
treatment of waste PVC	kg 1,4-DB eq	1170	x	x	1170	x
PVC pipes	kg 1,4-DB eq	864	864	x	x	x
treatment of waste HDPE	kg 1,4-DB eq	274	x	x	274	x
Photochemical oxidant formation	Unit	Total	Construction	Operation	End-of-life	Gas boiler
Total of all processes	kg NMVOC	2520	42,70	913	1470	95,40
Remaining processes	kg NMVOC	5,21	4,47	x	0,74	x
Waste water treatment	kg NMVOC	1470	x	x	1470	x
Electricity, low voltage {NL}	kg NMVOC	913	0,86	913	x	x
heat production, natural gas, at boiler	kg NMVOC	95,40	x	x	x	95,40
PVC pipes	kg NMVOC	14,50	14,50	x	x	x
Heat pump production	kg NMVOC	10,60	10,60	x	x	x
treatment of waste PVC	kg NMVOC	6,43	x	x	6,43	x
HDPE pipes	kg NMVOC	5,20	5,20	x	x	x
Bentonite	kg NMVOC	4,48	4,48	x	x	x
Gravel	kg NMVOC	2,55	2,55	x	x	x
Particulate matter formation	Unit	Total	Construction	Operation	End-of-life	Gas boiler
Total of all processes	kg PM10 eq	905	26,90	377	458	42,60
Remaining processes	kg PM10 eq	1,89	1,69	x	0,20	x
Waste water treatment	kg PM10 eq	454	x	x	454	x
Electricity, low voltage {NL}	kg PM10 eq	378	0,35	377	x	x
heat production, natural gas, at boiler	kg PM10 eq	42,60	x	x	x	42,60
Heat pump production	kg PM10 eq	10,60	10,60	x	x	x
PVC pipes	kg PM10 eq	9,23	9,23	x	x	x
treatment of waste PVC	kg PM10 eq	3,65	x	x	3,65	x
HDPE pipes	kg PM10 eq	2,64	2,64	x	x	x

Bentonite	kg PM10 eq	1,40	1,40	x	x	x
Gravel	kg PM10 eq	1,06	1,06	x	x	x
Terrestrial ecotoxicity	Unit	Total	Construction	Operation	End-of-life	Gas boiler
Total of all processes	kg 1,4-DB eq	175	1,48	168	4,18	1,25
Remaining processes	kg 1,4-DB eq	0,15	0,14	x	0,01	x
Electricity, low voltage {NL}	kg 1,4-DB eq	168	0,16	168	x	x
Waste water treatment	kg 1,4-DB eq	3,94	x	x	3,94	x
heat production, natural gas, at boiler	kg 1,4-DB eq	1,25	x	x	x	1,25
Heat pump production	kg 1,4-DB eq	1	1	x	x	x
treatment of waste PVC	kg 1,4-DB eq	0,23	x	x	0,23	x
PVC pipes	kg 1,4-DB eq	0,18	0,18	x	x	x
Freshwater ecotoxicity	Unit	Total	Construction	Operation	End-of-life	Gas boiler
Total of all processes	kg 1,4-DB eq	5110	265	4620	92,80	130
Remaining processes	kg 1,4-DB eq	8,55	8,55	x	x	x
Electricity, low voltage {NL}	kg 1,4-DB eq	4620	4,34	4620	x	x
Heat pump production	kg 1,4-DB eq	242	242	x	x	x
heat production, natural gas, at boiler	kg 1,4-DB eq	130	x	x	x	130
treatment of waste PVC	kg 1,4-DB eq	47,70	x	x	47,70	x
treatment of waste HDPE	kg 1,4-DB eq	36,90	x	x	36,90	x
Bentonite	kg 1,4-DB eq	10,70	10,70	x	x	x
Waste water treatment	kg 1,4-DB eq	8,23	x	x	8,23	x
Marine ecotoxicity	Unit	Total	Construction	Operation	End-of-life	Gas boiler
Total of all processes	kg 1,4-DB eq	5500	291	4900	115	195
Remaining processes	kg 1,4-DB eq	10,10	10,10	x	x	x
Electricity, low voltage {NL}	kg 1,4-DB eq	4910	4,60	4900	x	x
Heat pump production	kg 1,4-DB eq	267	267,00	x	x	x
heat production, natural gas, at boiler	kg 1,4-DB eq	195	x	x	x	195
treatment of waste PVC	kg 1,4-DB eq	41,80	x	x	41,80	x
Waste water treatment	kg 1,4-DB eq	37,10	x	x	37,10	x
treatment of waste HDPE	kg 1,4-DB eq	35,90	x	x	35,90	x
Bentonite	kg 1,4-DB eq	9,72	9,72	x	x	x
Ionising radiation	Unit	Total	Construction	Operation	End-of-life	Gas boiler
Total of all processes	kBq U235 eq	112000	439	104000	2950	4850
Remaining processes	kBq U235 eq	155	151	x	4,19	x
Electricity, low voltage {NL}	kBq U235 eq	104000	97,20	104000	x	x
heat production, natural gas, at boiler	kBq U235 eq	4850	x	x	x	4850
Waste water treatment	kBq U235 eq	2640	x	x	2640	x
treatment of waste PVC	kBq U235 eq	302	x	x	302	x
Heat pump production	kBq U235 eq	191	191	x	x	x
Agricultural land occupation	Unit	Total	Construction	Operation	End-of-life	Gas boiler
Total of all processes	m2a	24500	98,30	24200	50,60	129
Remaining processes	m2a	35	34,20	x	0,84	x
Electricity, low voltage {NL}	m2a	24200	22,70	24200	x	x

heat production, natural gas, at boiler	m2a	129	x	x	x	129
treatment of waste PVC	m2a	49,70	x	x	49,70	x
Heat pump production	m2a	41,40	41,40	x	x	x
Urban land occupation	Unit	Total	Construction	Operation	End-of-life	Gas boiler
Total of all processes	m2a	2640	199	2350	23,80	68,80
Remaining processes	m2a	4,84	2,46	x	2,38	x
Electricity, low voltage {NL}	m2a	2350	2,20	2350	x	x
Bentonite	m2a	95,40	95,40	x	x	x
heat production, natural gas, at boiler	m2a	68,80	x	x	x	68,80
Heat pump production	m2a	34,80	34,80	x	x	x
Transport, freight, lorry	m2a	27,30	27,30	x	x	x
treatment of waste PVC	m2a	21,50	x	x	21,50	x
Gravel	m2a	19,40	19,40	x	x	x
Sand	m2a	10,10	10,10	x	x	x
Clay	m2a	3,81	3,81	x	x	x
Transport, freight, lorry	m2a	3,56	3,56	x	x	x
Natural land transformation	Unit	Total	Construction	Operation	End-of-life	Gas boiler
Total of all processes	m2	315	35	233	0,22	47,30
Remaining processes	m2	0,44	0,22	x	0,22	x
Electricity, low voltage {NL}	m2	233	0,22	233	x	x
heat production, natural gas, at boiler	m2	47,30	x	x	x	47,30
Bentonite	m2	33,90	33,90	x	x	x
Gravel	m2	0,36	0,36	x	x	x
Heat pump production	m2	0,32	0,32	x	x	x
Water depletion	Unit	Total	Construction	Operation	End-of-life	Gas boiler
Total of all processes	m3	603000	35700	514000	-15100	68700
Remaining processes	m3	1060	1000	x	55,20	x
Electricity, low voltage {NL}	m3	514000	482	514000	x	x
heat production, natural gas, at boiler	m3	68700	x	x	x	68700
Aquifer Groundwater	m3	24000	24000	x	x	x
Heat pump production	m3	9270	9270	x	x	x
treatment of waste PVC	m3	6410	x	x	6410	x
Gravel	m3	979	979	x	x	x
Waste water treatment	m3	-21500	x	x	-21500	x
Metal depletion	Unit	Total	Construction	Operation	End-of-life	Gas boiler
Total of all processes	kg Fe eq	41100	4320	35800	199	801
Remaining processes	kg Fe eq	136	131	x	4,37	x
Electricity, low voltage {NL}	kg Fe eq	35800	33,60	35800	x	x
Heat pump production	kg Fe eq	4150	4150	x	x	x
heat production, natural gas, at boiler	kg Fe eq	801	x	x	x	80
Waste water treatment	kg Fe eq	97,70	x	x	97,70	x
treatment of waste PVC	kg Fe eq	97,20	x	x	97,20	x
Fossil depletion	Unit	Total	Construction	Operation	End-of-life	Gas boiler

Total of all processes	kg oil eq	326000	5740	233000	42200	45100
Remaining processes	kg oil eq	523	508	x	15,20	x
Electricity, low voltage {NL}	kg oil eq	233000	219	233000	x	x
heat production, natural gas, at boiler	kg oil eq	45100	x	x	x	45100
Waste water treatment	kg oil eq	41800	x	x	41800	x
PVC pipes	kg oil eq	2620	2620	x	x	x
HDPE pipes	kg oil eq	1550	1550	x	x	x
Heat pump production	kg oil eq	504	504	x	x	x
treatment of waste PVC	kg oil eq	386	x	x	386	x
Diesel, from crude oil	kg oil eq	339	339	x	x	x

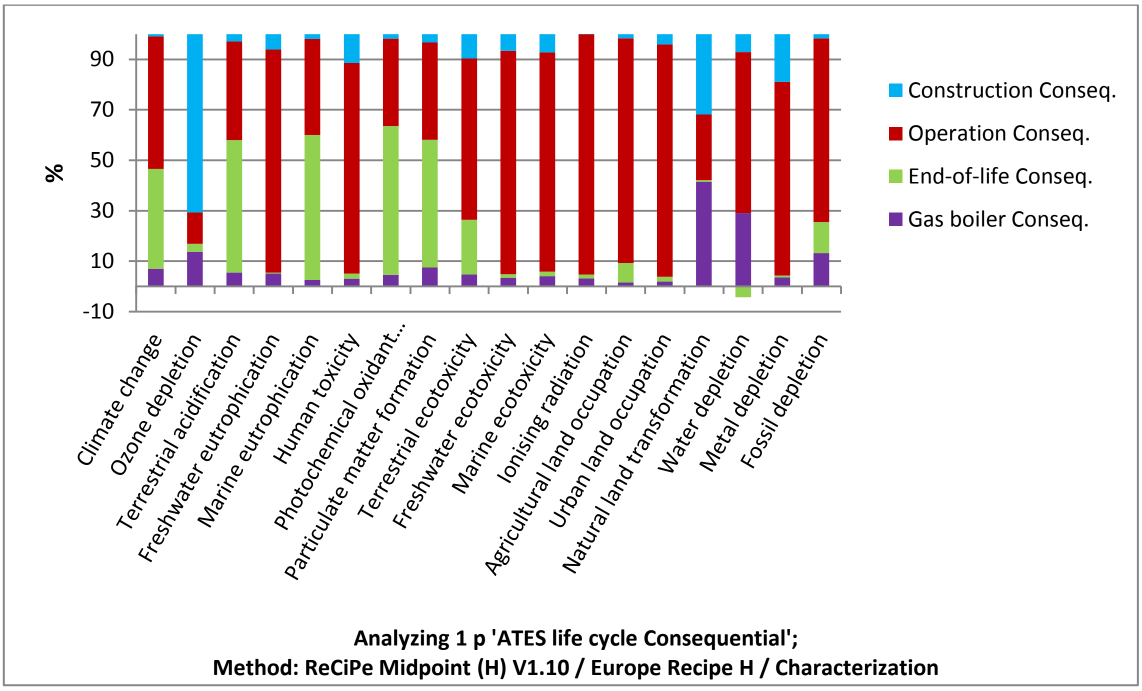
Appendix B – detailed CEnD Single score results

Table 15 – CEnD Single score results for the Tetra ATES system

Impact category	Unit	Total	Construction	Operation	End-of-life	Gas boiler
Total	TJ	16,37	0,29	11,87	2,10	2,11
Non-renewable, fossil	TJ	14,86	0,26	10,60	1,92	2,08
Non-renewable, nuclear	TJ	1,48	0,02	1,27	0,15	0,03
Non-renewable, biomass	TJ	0	0	0	0	0
Renewable, biomass	TJ	0,00169	0,00168	0	5,36E-06	0
Renewable, wind, solar, geothermal	TJ	0,00918	0,00026	0	0,0089	0
Renewable, water	TJ	0,01544	0,00334	0	0,0121	0

Appendix C – Tetra ATES system consequential LCA (main) results

From Fig. 39 and table 16, it becomes apparent that there are significant differences regarding the relative contribution within the life cycle phases of the Tetra ATES system depending on the system modelling (consequential vs. attributional data).



Analyzing 1 p 'ATES life cycle Consequential';
Method: ReCiPe Midpoint (H) V1.10 / Europe Recipe H / Characterization

Figure 39 - Characterization results of Tetra ATES system (consequential)

Table 16 - Life cycle phase relative contribution per impact category (%) (Consequential)

Impact category	Construction Conseq.	Operation Conseq.	End-of-life Conseq.	Gas boiler Conseq.
Climate change	0,97	52,46	39,55	7,02
Ozone depletion	70,71	12,43	3,13	13,73
Terrestrial acidification	2,95	39,10	52,54	5,42
Freshwater eutrophication	6,09	88,47	0,40	5,04
Marine eutrophication	1,99	38,06	57,44	2,51
Human toxicity	11,49	83,49	1,94	3,07
Photochemical oxidant formation	1,82	34,66	58,91	4,61
Particulate matter formation	3,36	38,50	50,65	7,48
Terrestrial ecotoxicity	9,71	63,87	21,70	4,73
Freshwater ecotoxicity	6,68	88,54	1,40	3,38
Marine ecotoxicity	7,33	86,87	1,78	4,02
Ionising radiation	0,10	95,21	1,54	3,15
Agricultural land occupation	1,73	88,97	7,73	1,57
Urban land occupation	4,07	92,12	1,89	1,92
Natural land transformation	31,94	25,94	0,64	41,49

Water depletion	7,12	63,78	-4,33	29,09
Metal depletion	18,91	76,72	0,84	3,53
Fossil depletion	1,72	72,77	12,32	13,20

Table 17 shows the differences when comparing consequential to attributional LCA results.

Table 17 - Relative contribution comparison of the system models

Impact category	Construction	Operation	End-of-life	Gas boiler
Climate change	0,13	-6,66	5,75	0,78
Ozone depletion	-12,41	16,87	-0,13	-4,23
Terrestrial acidification	-0,05	-3,4	4,46	-1,02
Freshwater eutrophication	-2,69	5,23	0,1	-2,64
Marine eutrophication	-0,69	9,34	-7,74	-1,01
Human toxicity	-3,29	3,91	0,36	-0,97
Photochemical oxidant formation	-0,12	1,44	-0,51	-0,81
Particulate matter formation	-0,36	3,2	-0,05	-2,78
Terrestrial ecotoxicity	-8,91	32,23	-19,3	-4,03
Freshwater ecotoxicity	-1,48	1,86	0,4	-0,78
Marine ecotoxicity	-2,03	2,23	0,32	-0,52
Ionising radiation	0,3	-2,61	1,06	1,15
Agricultural land occupation	-1,33	9,93	-7,53	-1,07
Urban land occupation	3,43	-3,22	-0,99	0,68
Natural land transformation	-20,84	47,86	-0,54	-26,49
Water depletion	-1,32	19,32	1,93	-17,99
Metal depletion	-8,41	10,38	-0,34	-1,63
Fossil depletion	0,08	-1,27	0,58	0,6

A green cell (positive value) indicates a largest contribution for the attributional LCA while a red cell (negative value) indicates a larger contribution for the consequential LCA. It can be seen that the contribution to impacts of the consequential LCA are generally larger for the construction phase and for the use of the gas boiler. On the other hand, the attributional LCA shows largest impacts for the operation (electricity use) of the ATES system. A possible interpretation for that is that the consequential data takes into account the technological developments regarding the production of electricity in the Netherlands (both processes used were the specific country mixes) and so it accounts for an impact reduction due to these developments. For example, when looking at the SimaPro data it is found that a different electricity mix is adopted for the consequential data which has an influence in the results. An overall conclusion regarding the use phase cannot be drawn at this point since it can be seen that the two components (electricity use for pumps and natural gas for boiler) contribute differently. Additionally, a single overall conclusion on which system model is better for this analysis cannot be drawn either and so the choice on the system model depends on the LCA user's intent. Table 18 displays in detail the characterization results of the consequential LCA and it is followed by the respective normalization results.

Table 18 - Characterization results of consequential LCA

Impact category	Unit	Total	Construction Conseq.	Operation Conseq.	End-of-life Conseq.	Gas boiler Conseq.
Climate change	kg CO2 eq	1745789,70	16890,39	915792,90	690539,50	122566,91
Ozone depletion	kg CFC-11 eq	0,14	0,10	0,02	0,00	0,02
Terrestrial acidification	kg SO2 eq	2752,21	81,13	1076,08	1445,88	149,11
Freshwater eutrophication	kg P eq	201,09	12,26	177,90	0,81	10,13
Marine eutrophication	kg N eq	192,99	3,84	73,45	110,86	4,85
Human toxicity	kg 1,4-DB eq	250423,93	28775,72	209081,28	4868,95	7697,98
Photochemical oxidant formation	kg NMVOC	2501,35	45,53	867,05	1473,58	115,19
Particulate matter formation	kg PM10 eq	902,24	30,34	347,40	457,01	67,49
Terrestrial ecotoxicity	kg 1,4-DB eq	19,16	1,86	12,24	4,16	0,91
Freshwater ecotoxicity	kg 1,4-DB eq	6530,71	436,28	5782,48	91,36	220,60
Marine ecotoxicity	kg 1,4-DB eq	6464,74	473,98	5615,93	114,87	259,97
Ionising radiation	kBq U235 eq	166417,59	168,59	158443,66	2569,36	5235,97
Agricultural land occupation	m2a	32702,19	564,32	29095,52	2528,68	513,67
Urban land occupation	m2a	5693,73	231,76	5244,99	107,62	109,37
Natural land transformation	m2	109,35	34,93	28,36	0,70	45,37
Water depletion	m3	477070,93	35525,14	318064,89	-21591,45	145072,35
Metal depletion	kg Fe eq	42971,03	8125,96	32968,21	359,28	1517,58
Fossil depletion	kg oil eq	340521,53	5858,85	247794,56	41935,57	44932,56

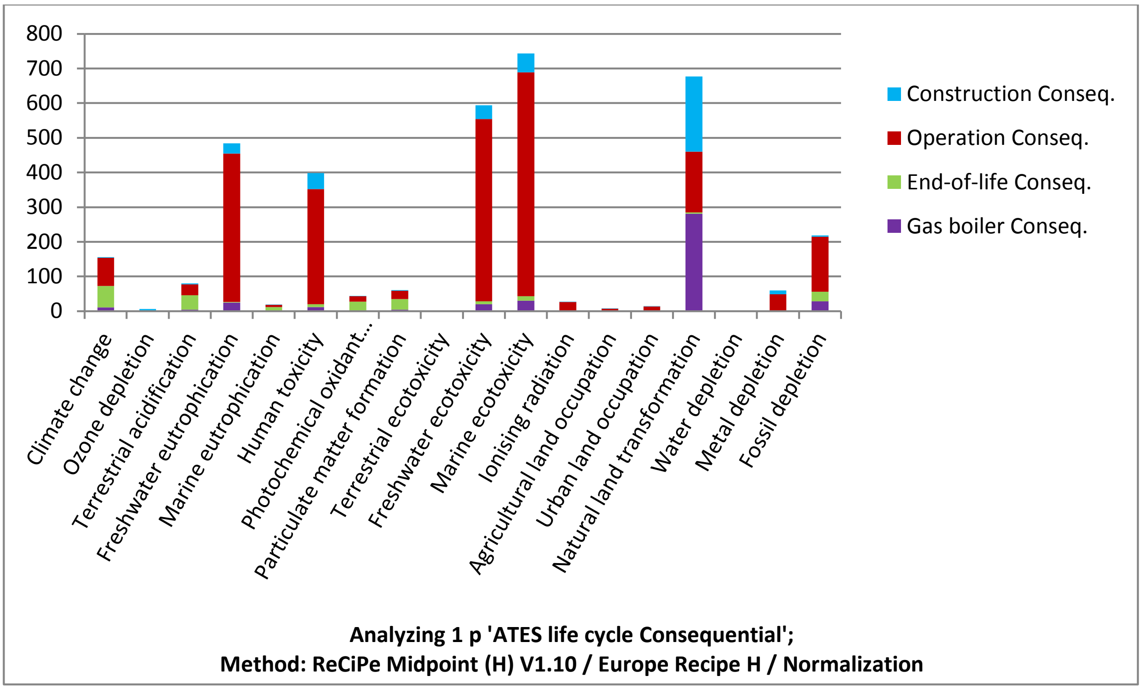


Figure 40 - Normalization results of Tetra ATES system (consequential)

Table 19 - Normalization results of consequential LCA

Impact category	Construction Conseq.	Operation Conseq.	End-of-life Conseq.	Gas boiler Conseq.
Climate change	1,51	81,69	61,6	10,93
Ozone depletion	4,39	0,77	0,19	0,85
Terrestrial acidification	2,36	31,31	42,08	4,34
Freshwater eutrophication	29,54	428,74	1,95	24,41
Marine eutrophication	0,38	7,26	10,95	0,48
Human toxicity	45,75	332,44	7,74	12,24
Photochemical oxidant formation	0,8	15,26	25,94	2,03
Particulate matter formation	2,04	23,31	30,67	4,53
Terrestrial ecotoxicity	0,23	1,48	0,5	0,11
Freshwater ecotoxicity	39,66	525,63	8,3	20,05
Marine ecotoxicity	54,51	645,83	13,21	29,9
Ionising radiation	0,03	25,35	0,41	0,84
Agricultural land occupation	0,12	6,43	0,56	0,11
Urban land occupation	0,57	12,9	0,26	0,27
Natural land transformation	216,2	175,55	4,3	280,82
Water depletion	0,	0,	0,	0,
Metal depletion	11,38	46,16	0,5	2,12
Fossil depletion	3,77	159,33	26,96	28,89

Appendix D – Comparison of the use phase of the Tetra ATES system with a Reference system using the ReCiPe Endpoint (H) method

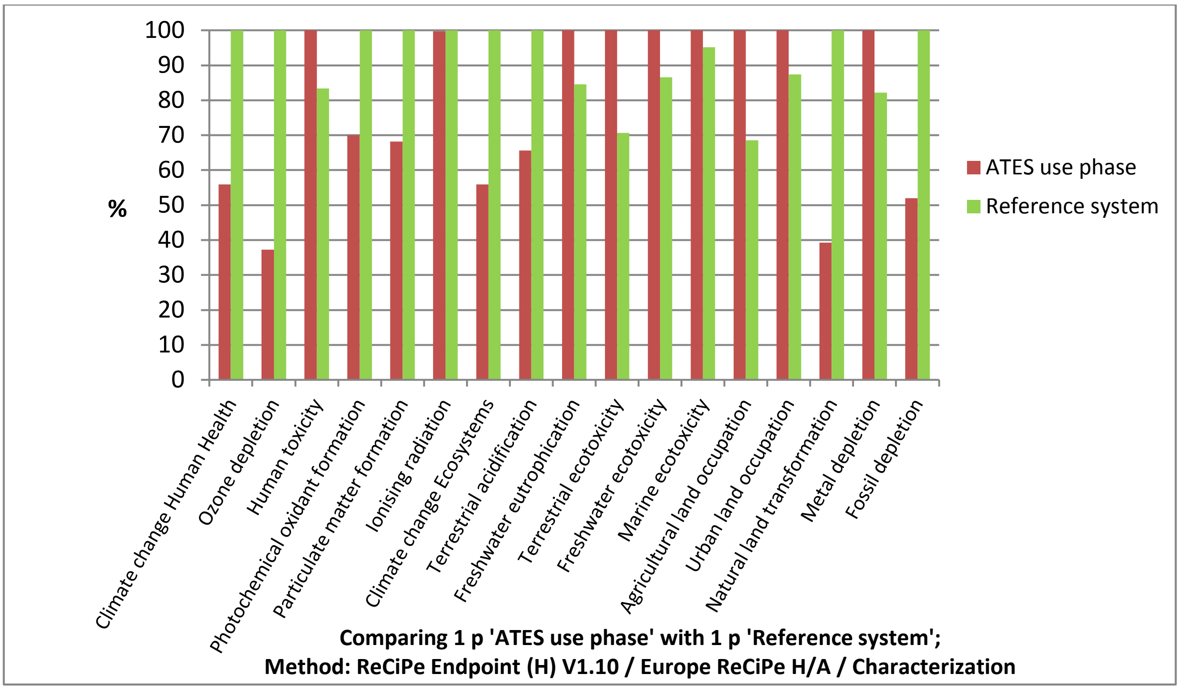


Figure 41 – ReCiPe Endpoint (H) characterisation results of the ATES use phase and Reference system comparison

Comparing Fig. 41 to Fig. 37 the characterisation results are similar for both methods and so the two systems are shown to be evenly-matched in environmental impacts. In the Damage assessment step, the individual impact categories are aggregated to similar categories and the results are presented in Fig. 42.

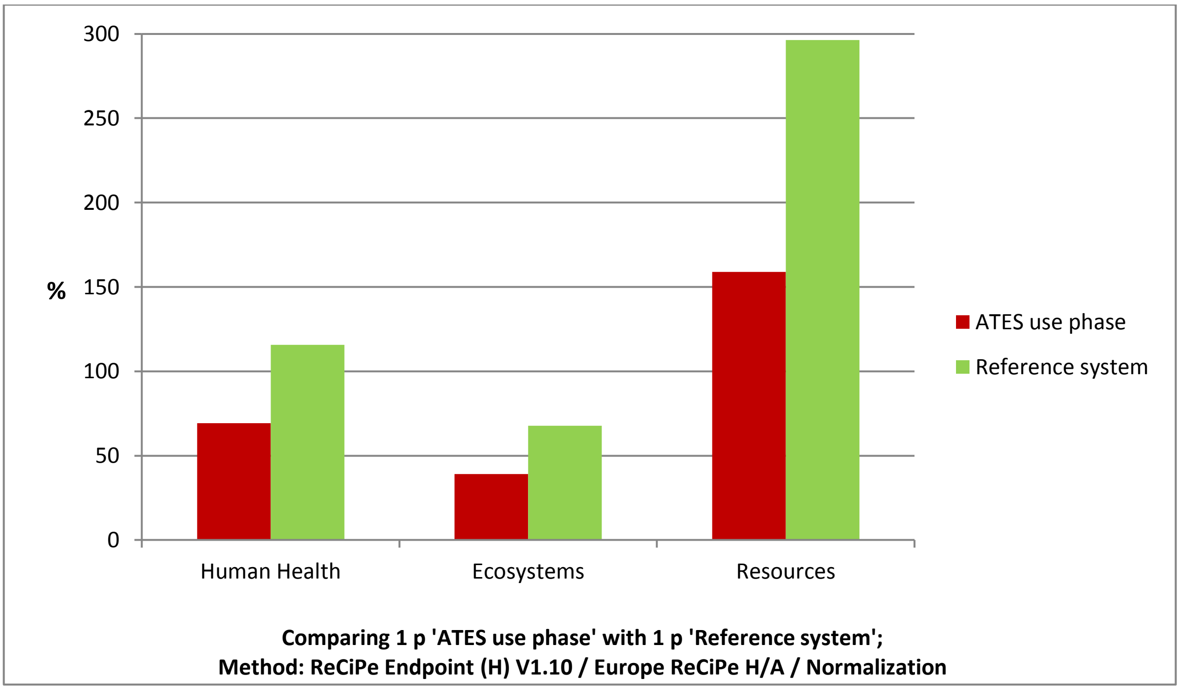


Figure 42 - ReCiPe Endpoint (H) damage assessment results of the ATES use phase and Reference system comparison

Lastly, when weighted and aggregated even further the single score results per impact category of the ReCiPe Endpoint impact assessment method as are follows in Fig. 43.

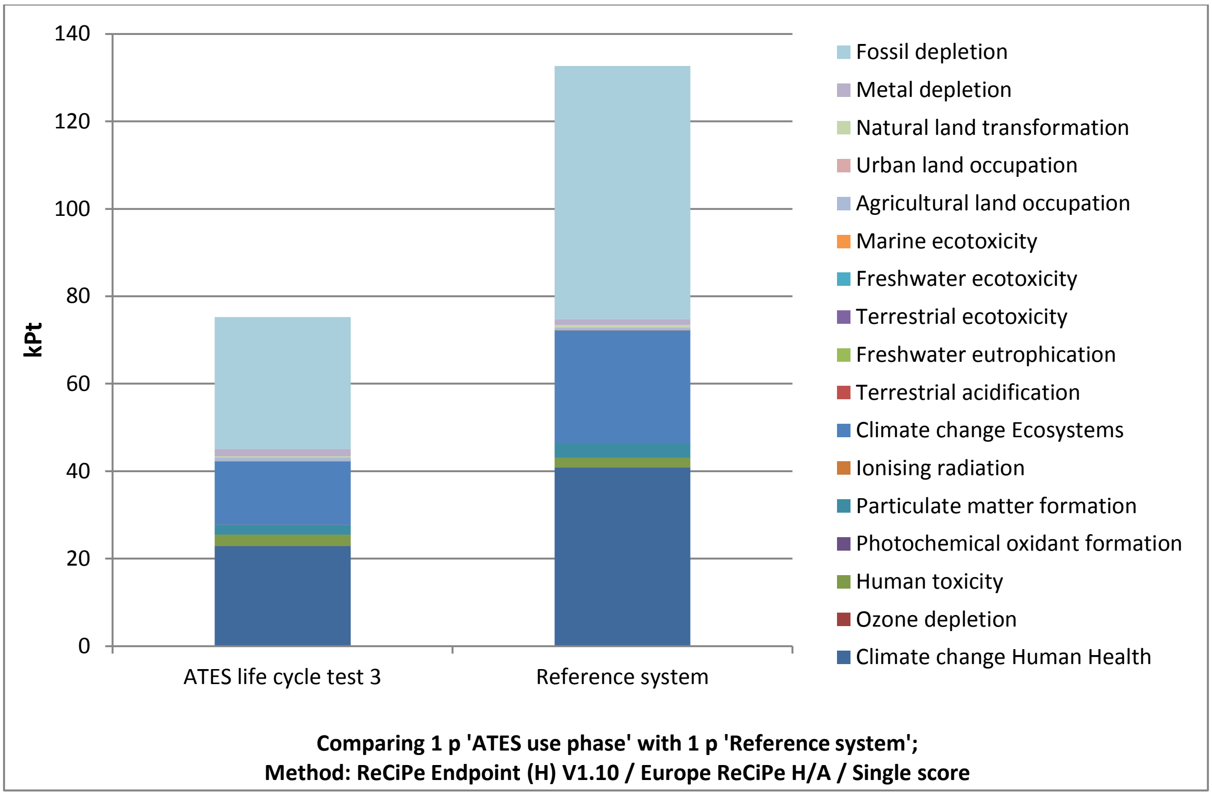


Figure 43 - ReCiPe Endpoint (H) single score results of the ATES use phase and Reference system comparison

From the above figures it becomes apparent how the additional aggregation steps of Damage assessment and Single score can present less complex results than those of the characterisation step. In both these steps the Reference system appears to score worse than the Tetra ATES system.