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TNO report

Environmental Footprint of High Temperature Aquifer Thermal Energy Storage

Using Life Cycle Assessment Methodology

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Abstract

High Temperature Aquifer Thermal Energy Storage (HT-ATES) systems are a form of shallow geothermal energy application, which can be used in seasonal applications to buffer heat production and demand from a variety of heat sources. This function enables HT-ATES to improve the efficiency of large-scale heat sources by facilitating heat production to function at maximum capacity throughout the year, irrespective of fluctuations in demand. However, HT-ATES cannot be said to be free of impacts. In order to determine marginal effects of HT-ATES to heat sources, this research carries out one of the first attempts to quantify the environmental and energy footprints of ATES by means of a life cycle impact assessment (LCIA) and life cycle cumulative energy demand (CED) analysis through the investigation of two systems: a geothermal heat plant delivering heat for direct use in greenhouse farms, and a waste-to-energy incinerator delivering heat to a municipality. Analysis is carried out considering environmental effects and energy demand of the final delivery of 1 GJ of heat as the comparison basis. This is analysed using the ReCiPe midpoint method with European normalisation, and the single issue CED method – both accessible in SimaPro 8. ReCiPe midpoint assesses environmental effects within the life cycle of a product without weighing into damage categories, whereas CED analyses the life cycle for primary energy demand. Outcomes of the analysis reveal that marginal effects of HT-ATES on heat sources are unsubstantial compared to the benefits they provide, and that compared with conventional heat delivery by natural gas incinerator in the Netherlands, HT-ATES/heat source systems exhibit fossil fuel savings and climate change reduction. However, analysis also reveals that primary energy demand is higher for HT-ATES/heat source systems than for conventional means of heat delivery. This paper shows how boundary conditions may influence the extent of life cycle effects of such systems, and highlights the environmental categories in which ATES benefits or hinders heat supply.

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I would also like to thank Tom Ligthart, who supervised the LCA part of my research and Elisabeth Keijzer – both LCA experts at TNO who were able to help me by guiding me through the LCA methodology and by providing insights into my model setup as well as helping me to make use of an online LCA discussion forum which proved very useful towards data gathering. Kees van der Zalm of Visser & Smit Hanab B.V. and Paul Grootscholten of Globe Plant B.V. and GeoMEC Realisatie en Exploitatie BV who were constantly available to be approached for data and provided extensive help in verifying calculations used to make the parameters. Last but not least I extend my gratitude towards Árný Arnarsdóttir who continuously supported me personally from the side-lines throughout the long and arduous road that was my master thesis.

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1 Introduction

1.1 Background

Global energy demand continues to increase alongside trends of population growth and the increasing availability of energy demanding technologies. Meanwhile, current society is mostly based on fossil fuels – burning oil, natural gas and coals in order to generate heat and produce the electricity to meet these ends (IEA, 2013; IEA, 2014a). It has been shown that the developed world gets 80% of its energy from fossil fuels (MacKay, 2008). The scientific community has proved that burning these fossil fuels causes emissions of carbon dioxide (CO_2), which is the main greenhouse gas (GHG) responsible for the anthropogenic contribution to climate change. The resulting trend of increased CO_2 emissions has resulted in a serious global-warming problem, causing the average surface temperature of the Earth to rise in response. In this way, the climate problem can be seen as mostly an energy problem. The OECD countries have been exhibiting such trends across time (IEA, 2014a; IPCC, 2012). The vast majority of climate scientists agree that this can cause major adverse effects (IPCC, 2012).

As worldwide energy demand grows alongside the growth of global population, the need for smart, sustainable energy solutions becomes increasingly apparent. This way, demand may be met without causing the environmental harm which would otherwise be caused by the continued overuse of conventional energy resources. Limiting fossil fuel use may then also guarantee higher security of supply for existing reserves by minimizing use. These realizations are some of the many drivers behind the current energy transition – which would have the world moving away from unsustainable energy systems, towards renewable and clean options and towards much development in local and international policy (such as the European 20-20-20 targets) (Solomon & Krishna, 2011).

The Netherlands, where this project takes place, is a gas producing country. In the overall Dutch situation, fossil resources make up ~93% of primary energy supply, leaving renewables as a small minority (IEA, 2014a). Renewable energy sources are the most well-known alternative option for conventional energy production, however, in the current state of the art they are not sufficient to supply global energy demand and certainly not sufficient to supply the Netherlands from national production alone (MacKay, 2008; IEA, 2014a). In the Netherlands there is much space for improvement in terms of renewable energy realisation.

Yet another opportunity presents itself in the form of improvement of the efficiency of the current energy production system. Amongst others, this can be achieved through development of energy storage systems which may help to optimize the current energy system or even one with a higher proportion of renewables. Particular interest is created in the field of heat storage and efficiency of heat use for sustainability purposes by means of Thermal Energy Storage (TES) systems, on which this research focuses. This research will look into Aquifer Thermal Energy Storage (ATES), which is a fairly novel form of Shallow Geothermal Energy (SGE).

In the context of ATES, temperature ranges exist between technologies. Low, medium and high temperature ATES systems exist, functioning at <30 ˚C, 30-60 ˚C and >60 ˚C respectively (Drijver *et al.*, 2012). The latter of which is fairly novel, such that there are currently no other HT-ATES systems currently functioning in the Netherlands (Drijver *et al.*, 2012). TES uses groundwater to carry thermal energy between heat source and user. Underground thermal energy storage (UTES) is divided between closed-loop systems which are mainly associated with Ground Source Heat Pumps (GSHP) and heat and cold storage (Borehole Thermal Energy Storage - BTES), and open-loop systems (such as Aquifer Thermal Energy Storage - ATES) (van Heekeren & Bakema, 2015).

The implementation of UTES holds much promise for heat sources in the Netherlands where, due to proposed policy changes, the Underground Energy Taskforce expects a growth rate of approximately 30%

per year for UTES deployment (both ATES and BTES), and that without policy change, autonomous growth would still be approximately 12% per year (Bonte *et al*., 2011). It is expected that in 2015 there will be 3500 ATES systems saving up to 3000 TJ (van Heekeren & Bakema, 2015).

ATES is generally used to optimize the mismatch between energy supply and energy demand, providing both short- and long-term applications as well as applications towards heating and cooling. Temporal scale varies from immediate to seasonal use, the latter of which refers to seasonal storage, which can facilitate all-year production from associated heat sources (Paksoy, 2007). Excess heat produced from various sources could be stored in ATES which can subsequently be integrated with existing district heating systems, greenhouses or any such heat-demanding end-user for later use, essentially providing flexibility. Seasonal storage is a natural way to shift peak demand and provide thermal energy at higher efficiencies. When heat demand is lower than production, excess heat may be stored in the ATES. When demand is higher, such as in winter – extra heat can be produced from the ATES (Drijver *et al*., 2012). This could ensure that a heat source such as geothermal may operate at full capacity throughout the year, instead of turning down in summer.

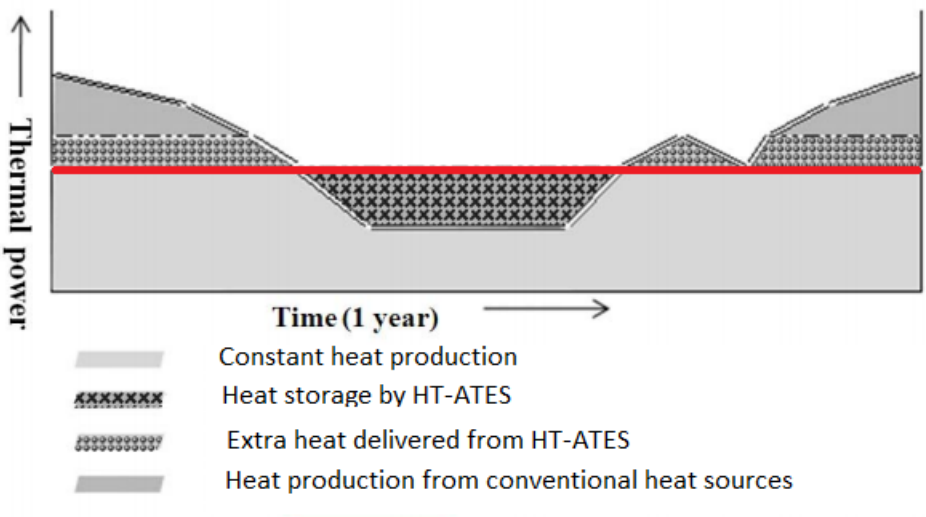

Figure 1 *Integration of HT-ATES as a buffer to constant heat production, diagram shows the relationship between available thermal power, demanded thermal power, heat storage and recovery – adapted from Drijver et al., 2012.*

ATES functions according to heat demand and production. When heat demand is lower than thermal production, excess heat can be stored in the HT-ATES. When heat demand is higher than production, heat that was previously stored can be produced from the HT-ATES, thereby facilitating seasonal use (Drijver *et al*., 2012; Cabeza, 2015).

The most common of such systems is a storage aquifer using doublets of wells separately for heating and cooling in a so-called cyclic regime. Hereby pumping up and injecting in one well is alternated during the cold and warm season. This configuration can be visualised in Figure 2.

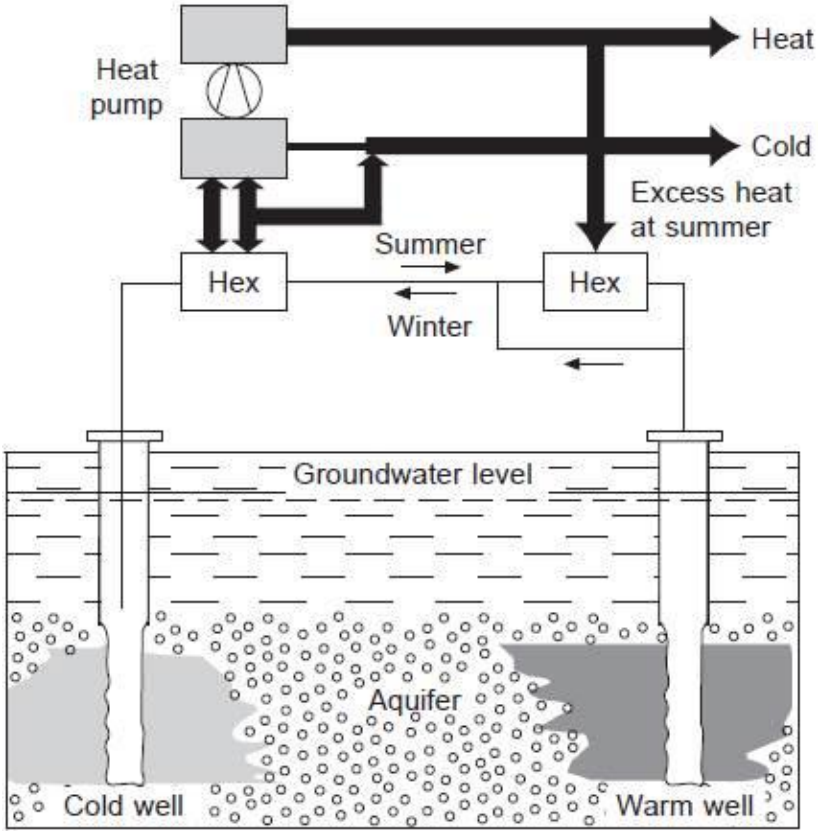

Figure 2 *ATES basic configuration* (Cabeza, 2015).

Resultant benefits of ATES use are typically: better economics due to reduced operational costs, higher efficiency of the heat source, less pollution (e.g. averted CO_2 emissions) due to re-use of stored energy rather than generation from the grid, and better system performance and reliability (Cabeza, 2015).

Regarding the setting and history of geothermal energy in the Netherlands, geothermal energy emerged later than in some other countries. This is because the production of geothermal was not competitive with relatively low gas prices due to the major natural gas reserves discovered in the middle of the previous century. Interest for geothermal energy in the Netherlands started as late as the 80's, with shallow geothermal applications whereby cooling and seasonal storage of energy for space heating was explored. The only exception is an exploratory study on geothermal energy in Asten in 1987, which was unsuccessful (Heederik & Vierhout, 1988). The increase in shallow geothermal was made easier by the fact that shallow aquifers can be found virtually anywhere in the Netherlands due to the abundance of sand and sandstone geology (ter Voorde *et al*., 2014). The setting started to pick up more significantly at the beginning of this century, when the implementation of heat and cold storage applications increased spectacularly. This was stimulated in part by rising gas prices, but also by the development of public interest in low CO_2 energy options linked to climate concerns (van Heekeren & Bakema, 2015). The result being that the Netherlands is currently the leading country in Northern Europe in terms of heat and cold storage application (Tomasetta, 2013). Realisation of such potential in heat and cold storage likely stimulated advancement in the novel high temperature storage technology. This has as yet not been realised extensively as verified by van Heekeren & Bakema (2015).

How sustainable in fact is TES in quantitative terms? This is the question which will be approached. The best approach for this would consider this question in terms of all the stages of the product or service life, from the production to the dismissal as well as all the direct and indirect effects on the environment. The consideration of impact categories would give a more complete picture of the extent of impacts caused by the use of TES, beyond only CO_2. Does the use of TES result in impacts such as freshwater eutrophication? Terrestrial acidification? Does it result in other forms of pollution and more or less so than conventional

means of heat supply? Tomasetta (2013 & 2015) shows that Life Cycle Assessment (LCA) is able to analyse the contribution of the different life stages to the overall environmental load while facilitating comparison between systems (Tomasetta, 2013; Tomasetta *et al*., 2015). This comparability makes LCA a useful instrument to determine the sustainability of UTES, which is supported by the increasing number of LCA studies being applied to environmental management problems (EC, 2010; ISO, 2006). The reports by Tomasetta conclude that in fact, LCA is able to show that UTES is more sustainable than traditional natural gas heating systems in terms of both climate (and other) impacts and energy demand performance in terms of primary energy savings (Tomasetta, 2013; Tomasetta *et al*., 2015).

However, the extent of environmental load depends upon boundary conditions such as fuel mix and heat production infrastructure, as well as system boundaries such as system specifications, lifetime and subsurface composition. Therefore the extent of sustainability is case specific. All in all, LCA is an appropriate tool to determine the sustainability of the case studies which will be analysed. The IPCC-SRREN report states that "additional LCA studies to increase the number of estimates for all geothermal energy technologies are needed" (IPCC, 2012 p.419). This highlights a very important literature gap within the geothermal field and that of LCA. The gap in literature is also that the unique combination of a heat source with added storage (buffer) system has not yet been assessed for sustainability. This will be aimed for within this research.

1.2 Study objectives

1.2.1 Research aim

This research expands the knowledge base for high temperature heat storage, focusing on the integrated use of Thermal Energy Storage systems with heat sources. Specifically, this will be done with the aim of carrying out a sustainability analysis using life cycle assessment as an instrument, basing results on the European context. LCA is based on systematic examination of the environmental impacts of products/ activities, with the aim of revealing the environmental dimensions of sustainability (Goedkoop *et al*., 2013).

Despite TES being a relatively environmentally friendly solution (Tomasetta *et al*., 2015), it would be wrong to assume that they are free of impacts. The drilling of wells, material use and energy use during the operational phase become possible sources of environmental effects. For a complete picture, sustainability will be viewed from energy and materials, as well as an environmental perspective by means of a cumulative energy demand analysis and an environmental impact assessment. Overall, this shows how ATES benefits a geothermal system or waste incinerator heat source and it reveals environmental interventions involved with the construction and operation of ATES against their heat sources.

1.2.2 Research question

- What is the added effect of HT-ATES on the environmental life cycle and cumulative energy demand of a geothermal heat doublet or Dutch waste incinerator providing heat?
  - What is the environmental benefit of ATES with a geothermal heat plant or a Dutch waste incinerator in terms of environmental load and cumulative energy demand?
  - How substantial is the impact of HT-ATES compared with heat sources?
  - How does the environmental life cycle and cumulative energy demand of ATES/heat source-coupled systems compare with conventional, natural gas?

1.3 Study objects

In order to answer the research questions, two case studies are considered for the sake of this project. Vierpolders (GeoMEC) consists of a deep (2200 m) geothermal doubl*et al*lowing for heat from the subsurface to be used directly for heating ~60 ha greenhouse farms (hereafter, the end user), operated by a collective of 9 farmers and managed by *GlobePlant* B.V (Aardwarmte Vierpolders, 2015). The

temperature from the heat-source is 80-85 °C within water from a porous sand layer and the geothermal well produces a heat capacity ~17 MW_{th} (Platform Geothermie, 2015; Aardwarmte Vierpolders, 2015).

The geothermal doublet produces ~198,000 GJ per year which could be injected into a HT-ATES for storage. The ATES efficiency at Vierpolders is 46%, therefore, after storage, the ATES is expected to produce ~91,000 GJ which may then be used to buffer elevated heat demand (of the end user) during winter months. Over the 15 year (economic) lifetime, this means that ~1,372,000 GJ heat can be produced by the ATES – enough heat for ~2700 average Dutch households for 15 years, considering that the average Dutch household had a heat demand of 34 GJ per year in 2014 (EnergieKamer.nl, n.d.; BWK, 2013).

This is to be combined with an ATES system, constituting three well doublets at ~100 m distance between each cold and warm well and storing heat in an aquifer at around 200 m depth. The wells configuration was designed so that the three warm wells are in the centre and the cold wells are in the external direction (IF Technology, 2011). Application of ATES should allow for the heat to be used all year round i.e. by storage of excess heat from the geothermal well in summer and direct use in winter – effectively buffering demand and supply. The two systems are both connected to a central heat exchanger, from where the heat is also distributed to buildings on site, as well as making it possible for hot water extracted to release its heat to the aquifer. From this point the cold water is pumped back into the cold storage aquifer.

Geological conditions are such that the concerned aquifer predominantly resides in the Maassluis Formation. This consists largely of shallow marine deposits with alternations of shell-containing sand and clay layers. Here the Maassluis Formation is overlain by fluvial sands and tidal deposits from the Waarle/ Peize Formations, and this is in turn overlain by the Kreftenheye Formation, which consists of fluvial coarse sands and gravel (Pineaud, 2014).

When discussing the aquifer itself, it becomes important to consider more explicitly the hydrogeological and hydraulic context. At Vierpolders the aquifers that constitute heat storage are situated beneath another existing aquifer. These second and third aquifers start at a depth roughly 80 meters, until 200 meters. Mean hydraulic transmissivity is 800 m^2/d and delta temperature of production is around 24 °C, resulting in a COP between 50-60 for the ATES.

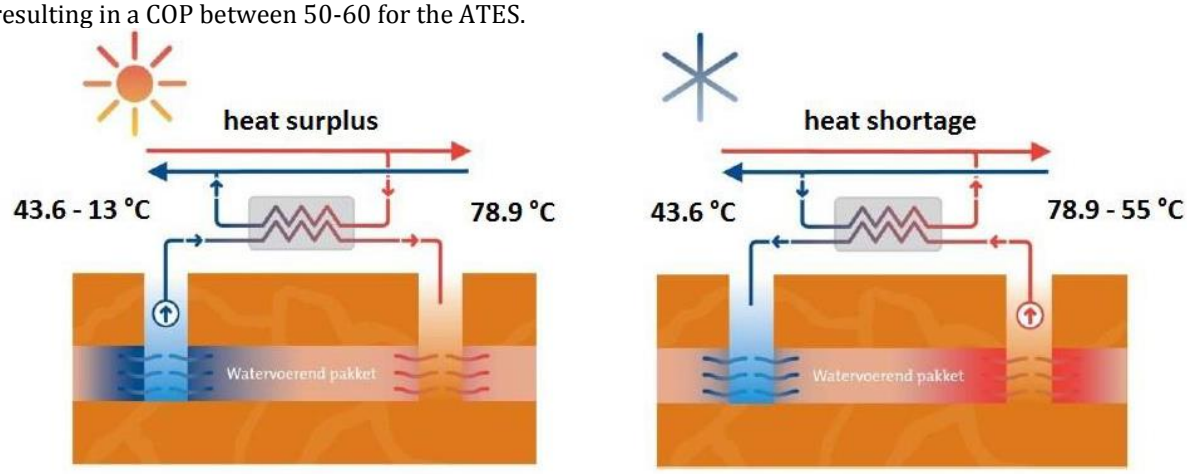

Figure 3 *Overview of GeoMEC Vierpolders HT-ATES system functioning* (IF Technology, 2011).

The second case, at Duiven (AVR), consists of a municipal waste-to-energy facility which supplies heat to the local district heating network of Duiven using residual waste and biomass (AVR, 2015b). The key difference between the two projects comes down to the scale, source of heat, and to the subsurface geology. At Duiven, a ~13 MW_{th} high temperature (~140 °C) HT-ATES system may be designed to be used in combination with waste heat from the 70 MW_{th} AVR waste incinerator to optimize the mismatch between supply and demand of heat (AVR, 2015a).

The waste incinerator would produce ~123,000 GJ waste heat per year for injection into HT-ATES for storage. The ATES efficiency at Duiven is 84%, therefore, after storage, the ATES is expected to produce 103,000 GJ to cover elevated heat demand during winter. Over the 15 year lifetime, this means that 1,545,000 GJ heat can be produced by the ATES – enough heat for ~3000 average Dutch households for 15 years (BWK, 2013).

Here, the geological conditions are similar to those of Bergerden, located nearby, for which a report regarding subsurface (hydro)geology has been produced (Pluymaekers, 2013). The storage aquifer here is contained within the Breda Formation, the shallowest point of which is found at a depth of 120 m and the base at 450 m. This stratigraphic layer is overlain by Oosterhout, then Peize-Waalre, Kreftenheye and finally Holocene layers. The sandy Breda Formation (aquifer) has a transmissivity of 350 m^2/d (Pluymaekers, 2013). In this case, delta temperature of production is 72 °C, resulting in a significantly higher COP of 201 (TNO, 2016).

ATES use at both locations could have a major impact on emissions, due to limiting environmental loads by means of reducing energy demand from the grid, as well as on costs since natural gas would no longer need to be purchased for heating purposes (Aardwarmte Vierpolders, 2015).

Table 1 *General information of the key differences between the study objects.*

	Vierpolders	Duiven
Production capacity	~11 MW_{th}	~12 MW_{th}
Injection capacity	~23 MW_{th}	~14 MW_{th}
ATES efficiency	46%	84%
Flow rate	390 m^3/h	150 m^3/h
Heat source	Geothermal	Waste incineration
End-user	Greenhouses	District heating
ATES temperature	80-85 °C	~140 °C
Aquifer depth	200 m	400-450 m
Well doublets	3	1

2 Methods and LCA setup

This report builds upon that of Tomasetta (2013) by highlighting differences and impacts between two different ATES systems, rather than comparing sustainability between BTES and ATES. This should enable a better picture of how different boundary conditions may affect the overall sustainability of an ATES system. In addition to this, consideration of the heat source which would supply heat to the ATES broadens the scope and usefulness of the applied LCA. This LCA is essentially set up as a framework, in such a way that it may be re-used to carry out LCA for ATES systems by use of input parameters. SimaPro 8 software was used.

2.1 LCA framework

The standard approach to LCA comes from the International Reference Life Cycle Data System (ILCD) handbook as well as from ISO standards (EC, 2010; ISO, 2006). The ILCD handbook is based on and conforms to the ISO 14040 and 14044 standards on LCA. ISO shows that there are four main phases of an LCA study (ISO, 2006):

a) goal and scope definition
b) inventory analysis
c) impact assessment
d) interpretation

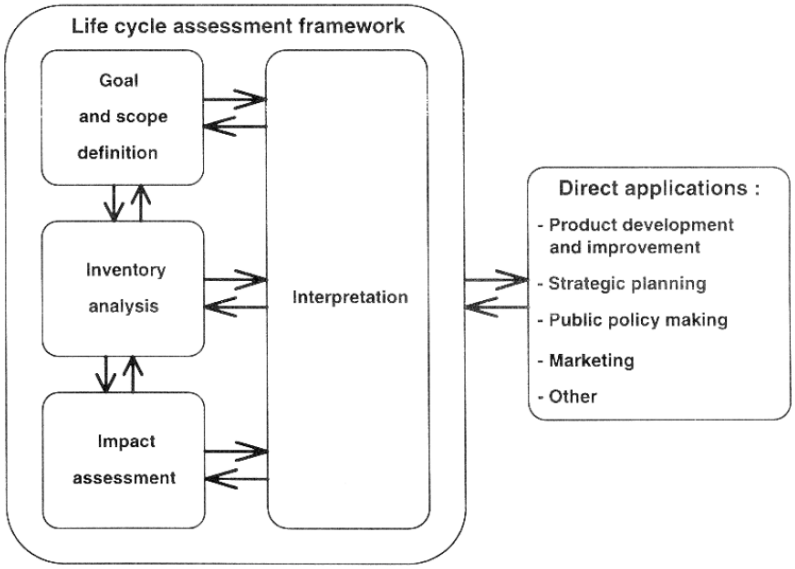

Figure 4 *Phases of an LCA* (Frischknecht *et al*., 2007).

a) Goal and scope definition

In this case, the goals are clearly outlined as aims in 1.2.1 and described further in 2.2. The scope, including system boundaries, functional unit and level of detail, depends on the subject and intended use of the study. Depth and breadth of the LCA can differ considerably depending on the goals. The scope is reasonably flexible, depending on time available for the differently prioritised case studies. Defining the functional unit for the LCA is the most important step at this stage since the rest of the LCA stages are carried out relative to the chosen functional unit (EC, 2010). Defining the goal and scope ensures that the system which is modelled does not become too distorted from reality. This ensures that the simplifications used do not overly influence the end-results. Goal and scope development are done quite

subjectively in order to describe the projects being approached. They are outlined separately from the research aims for the sake of clarity in modelling the LCA in SimaPro. Boundary conditions are then outlined to ensure that not too much of the wider, complex web of associated products is included.

b) Inventory analysis

Life Cycle Inventory (LCI) analysis is the second part. This is an inventory of input/output data with regard to the system(s) being studied. This essentially constitutes data gathering and compilation necessary for meeting the goals of the defined study. The LCI is used to compile data which allows for setting up of the model in SimaPro (EC, 2010).

c) Impact assessment

Life Cycle Impact Assessment (LCIA) is the third phase of LCA. At this stage, research strives to understand the environmental significance of the different aspects of the LCI. The LCIA is calculated using LCI data. This means for example looking at the casing material used for the ATES wells, and determining what the impact in terms of various emissions is in order to produce that casing. Hereby the first results are produced and analysed in model runs. This reveals the extent of the possible effects which ATES may result in. The impact assessment method chosen compiles these into pre-defined impact categories.

d) Interpretation

In the final phase, previously attained results are summarised and discussed as reporting shapes the deliverable. Uncertainty and sensitivity analysis, as well as consistency and completeness checks are carried out on impact assessment results. Sensitivity analysis is necessary as for example different sources assume different total lifetimes for such installations as well as uncertainty ranges for amounts of materials used and for amounts of energy used or produced (amongst other assumptions). Conclusions, recommendations and decision-making are carried out in accordance with the goals and scope definitions (EC, 2010).

Once these standard steps are completed, the LCI, results and scope are fine-tuned in order to improve the quality of the life cycle model. This is also recommended by the ILCD. The extent of fine-tuning necessary depends on the quality of results required to create a realistic LCA, as well as on the complexity of the system. In addition to this, data availability further affects accuracy and quality. In the end, the research questions formulated are answered by means of determining if the system life cycle results in a net primary energy and environmental effects savings, or not – as well as revealing details of the environmental footprints. Such results become apparent after the final model runs.

2.2 Goal and scope

a) Goal

In this study LCA is carried out for Vierpolders HT-ATES and Duiven HT-ATES. The results are analysed to deduce how substantial the additional environmental load caused by coupling a HT-ATES is to a heat source and to visualise the primary energy demand of HT-ATES before and after considering the heat source. The HT-ATES heat-source systems will also be compared against conventional heat production from an industrial natural gas incinerator to see the difference in environmental load and cumulative energy demand.

This study looks into two Dutch cases being researched at TNO – the prospective HT-ATES system being designed to complement a geothermal well at Vierpolders (*Geo-Multi Energy Concept*, GeoMEC) and the conceptual HT-ATES at Duiven (AVR), which is to be combined with a waste incinerator. Due to time constraint, the LCA set up for the geothermal well being used in combination with this TES system on the Vierpolders site and the waste incinerator at the Duiven site are constructed as adapted inputs from an

existing inventory in the Ecoinvent database. This is rescaled relative to the reality, rather than constructing these components from detailed inventory analyses and data collection. The ATES systems on the other hand are both constructed from detailed analysis and data gathering.

This information will largely be used internally at TNO, and it will also be reviewed by the University of Utrecht. In the end, it may be published as a thesis at which point it could be shared with Visser & Smit Hanab B.V, Globe Plant, GeoMEC *Realisatie en Exploitatie* B.V and AVR B.V. These companies are the installers and operators of the study objects. The setup in SimaPro is done in a reusable way, by the use of parameters. The ILCD and SimaPro8 manuals suggest that weighting should be avoided when two products are compared in publication.

b) Scope

Both HT-ATES systems function to store heat in order to optimize the efficiency of heat delivery from their respective heat sources. This can be interpreted as heat storage and production and final delivery for direct use. Therefore the comparison basis, or functional unit, is chosen to be the delivery of 1 GJ heat using the ATES as a buffer between heat production and heat delivery. All impact assessment outcomes appear equated to this 1 GJ heat output.

Temporal scope is such that the Vierpolders HT-ATES system is a near-term project. This means that it is likely to be constructed within a short time period, or within 5 years (P Grootscholten, pers.comm. Interview, April 20, 2016). This is also reflected by the reasonably extensive studies which have already been carried out for the case as well as the completed design and license application of the ATES – the next step is construction (Aardwarmte Vierpolders, 2015; Drijver *et al*., 2012; IF Technology, 2011; Platform Geothermie, 2015; Provincie Zuid Holland, 2012; Pineaud, 2014). The Duiven HT-ATES system considers a future project – one which is as yet being conceptualised. Design has yet to shape the potential ATES and license application has not yet been approached. This will likely take longer before realisation – so more than 5 years.

Geographically speaking, the model setup in SimaPro tries as much as possible to focus on the Netherlands. This means that wherever possible, processes or materials used from the Ecoinvent database represent those that would be utilised in the Netherlands. For example instead of using a global, average electricity source to represent electricity, Dutch medium voltage electricity would be used. However, when considering the environmental impact assessment, the scope targets a European context.

The level of detail is open to first and second order processes to be included within the scope of the study. This means that the production of materials and their transport are included (1st order), as well as all processes during the life cycle (2nd order). Third order (or capital goods) processes are only considered in the form of the heat sources. However, these are included as examples adaptations from the Ecoinvent database.

Boundary conditions are such that it is assumed that the overall lifetime of both these HT-ATES systems is 15 years, in accordance with assumptions made for economic lifetime in the ATES calculation tool set up by TNO (TNO, 2016). Importantly, the lifetime of the pumps differs between the study objects. This is done because the main data sources for the case studies specify different pump lifetimes (TNO, 2016; K van der Zalm, pers.comm., Interview, April 20, 2016).

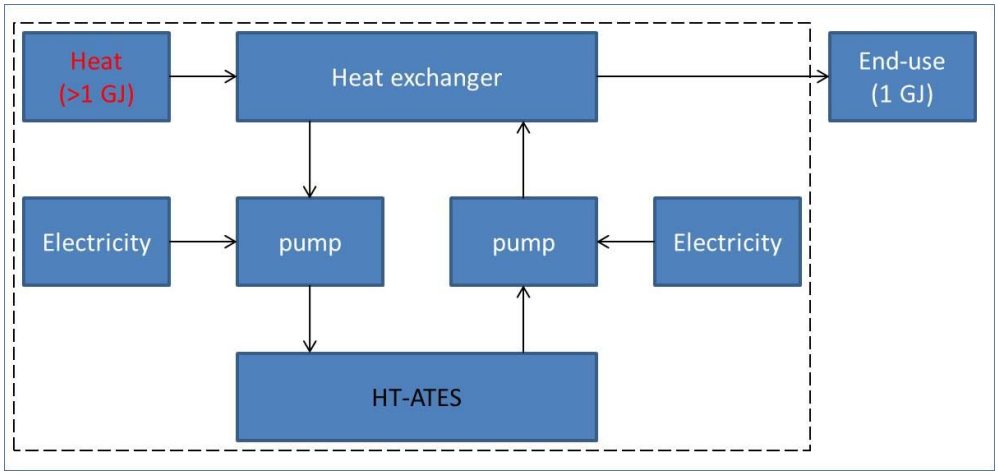

Figure 5 *General product system description and system boundaries applicable to both case studies.*

Figure 5 shows a simplified visualisation of the product system, applicable to both case studies. Focus here can be given to the scope boundaries and the main, important assemblies as they are modelled in SimaPro. That said it can be seen how the different assemblies constituting the ATES system are modelled in some detail, whereas the heat input is modelled as a bulk input. The end-user can be seen to be outside of the scope. The end-use energy quantity on the other hand is importantly less than the initial input. This is affected by factors such as the COP and roundtrip heat efficiency of the systems, which is case-specific. The following describes the systems in visual detail.

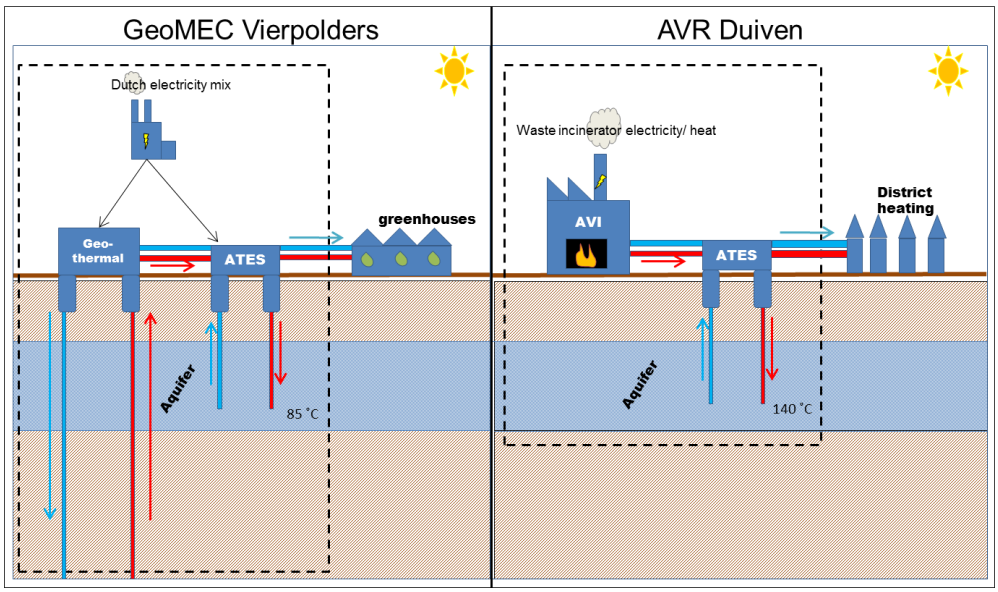

Figure 6 *System boundary and scope schematics Vierpolders followed by Duiven.*

An especially important difference highlighted by the schematic in Figure 6 is that GeoMEC utilizes electricity from the Dutch national electricity mix, whereas AVR produces its own electricity on-site by means of waste incineration. This results in a different environmental profile due to the effects of waste-to-power being different to the Dutch mix.

2.3 Inventory analysis

The Life Cycle Inventory (LCI) analysis was compiled by means of data collection and compilation. This was done by gathering relevant journal articles and company reports, as well as hosting questionnaire-based interviews and having discussions with my supervisors at TNO – Dr. Joris Koornneef and Prof. Dr.

Jasper Griffioen, and with Paul Grootscholten and Cees van de Zalm of Globe plant BV and V & S Hanab. Interviews and discussions were recorded, for the sake of reference during application of the information to SimaPro. Discussion and correspondence with GlobePlant (GeoMEC 4P *Realisatie en Exploitatie* BV) as well as Visser & Smit Hanab was sufficient in order to satisfy much of the practical data needed for both case studies seeing as that GeoMEC was at a much further stage in implementation than AVR. This meant accessibility towards information regarding the drilling and usage phases, as well as a breakdown of all of the most relevant materials used.

Literature visited for the inventory analysis consisted of journal articles, company reports and environmental product declarations examined in order to fill possible gaps in information (AVR, 2015a; AVR, 2015b; Drijver *et al*., 2012; IF Technology, 2011; Paksoy, 2007; Pineaud, 2014; Platform Geothermie, 2015; Provincie Zuid Holland, 2012; TNO, 2016). This essentially defined the current state-of-the-art of ATES technologies being considered and aids in completing the Life Cycle Inventory (LCI).

Visser & Smit Hanab were responsible for the site layout, design and installation details of the heat exchanger station, design and installation details of the heat distribution network and design of the HT-ATES system at Vierpolders (Visser & Smit Hanab B.V., 2016). Since license application procedures tend to be standardized, the provincial license application for the TES for Brielle was also scrutinized for both cases to attain technical data about installation (Provincie Zuid Holland, 2012). For Duiven which is as yet conceptual and therefore not yet as far in implementation, it was possible to make calculated assumptions based on the more certain information from Vierpolders for some physical infrastructure. Information regarding thermal and electrical energy, and operational specifics were attained from the use of an ATES calculation tool set up for AVR (TNO, 2016).

Data collected worked to describe the details of the study objects in a way that could be modelled in SimaPro. Calculations were made against information gathered from the interviewed stakeholders at Vierpolders, and from the ATES calculation tool and Joris Koornneef for Duiven. This results in calculated estimations of for example masses of materials used, dimensions of infrastructure and quantities of energy reflective of the reality. For Vierpolders, verification was achieved by telephone discussions with Cees van de Zalm, and for Duiven such verification was achieved by personal communication with Joris Koornneef.

The geothermal heat well for GeoMEC was approached by adapting a geothermal power plant from the Ecoinvent library (available in SimaPro), and rescaling this information to suit the specific case at hand. In this way the method was somewhat comparable towards that of the Duiven system, where an average industrial waste incinerator was adapted to match the waste-to-energy facility used by AVR. Heat injected into ATES from the heat sources is calculated as:

$$Heat = \frac{(summer\ injection\ T - summer\ production\ T) \times (Flow\ rate \times heat\ capacity\ water \times density\ water)}{(hours\ injection\ per\ year \times lifetime)}$$

The geothermal facility itself is adapted from a high voltage electricity producing, Hot-Dry-Rock binary cycle geothermal plant with a capacity of 3 MW_e (Weidema *et al*., 2013). This is a form of Enhanced Geothermal System (EGS) wherein fluid is circulated in a closed loop (Bertani, 2012). The plant is adapted to reflect that described by Paul Grootscholten during the interview. The plant described consists of two deep boreholes reaching 2000 m depth. One borehole is used as an injection well – which is used to stimulate the subsurface rock, and the other as a production well that supplies a heat exchanger station with geothermal fluid heated to 85 °C (P Grootscholten, pers.comm., Interview, April 20, 2016).

The entire life cycle of the HT-ATES at Duiven is also analysed, excluding analysis of the end user which in this case is the municipality. The waste incinerator is included only to the extent of factoring in as an input to the *technosphere*, from the Ecoinvent library, but using the correct amount of heat delivery. This means that both case studies use an average version of their heat sources, rather than the specific one existing. For AVR Duiven, the heat source taken from the Ecoinvent library is the treatment of municipal solid

waste by incineration in the Netherlands. This dataset inventories waste containing 92.8% average burnable municipal solid waste and 7.23% average inert municipal solid waste. The process used has a net energy production of 1.39 MJ/kg electric energy and 2.85 MJ/kg thermal energy (Weidema *et al.*, 2013).

The natural gas furnace considered as a reference case delivers heat from a low-NOx, >100 kW installation which would typically be used in the Netherlands for heat delivery (IEA, 2014b).

Technical and physical aspects of the ATES systems being analysed are described here in some detail in order to further elaborate the system boundaries. This is summarised as follows:

Table 2 *Relevant technical data for 17 MWth GeoMEC Vierpolders and 13 MWth AVR Duiven ATES systems* (Provincie Zuid Holland, 2012; IF Technology, 2011).

		Units	GeoMEC - Vierpolders	AVR – Duiven
Borehole	Number	-	6	2
	Depth	m	200	450
	Diameter	mm	900	244
	Drill energy	MWh	240	180
Well materials	Bentonite	kg	$7.82x10^5$	$7.85x10^5$
	PVC	kg	$1.14x10^4$	$3.68x10^3$
	RVS Steel	kg	$4.98x10^4$	$1.50x10^4$
Pipes materials	PVC	kg	$1.43x10^3$	$4.75x10^2$
	Chromium steel	kg	$1.66x10^4$	$3.92x10^3$
	PUR	kg	633	211
Operation	Operation	Hrs/y	4800	4891
	COP	ratio	50	201
Total result	Electricity use	GJ/ 15 y	$8.69x10^4$	$1.68x10^4$
	Heat production	GJ/ 15 y	$1.37x10^6$	$1.55x10^6$

It can already be seen that over the 15 year lifetime period, GeoMEC ATES would use about 5 times as much electricity to produce a similar amount of heat.

2.4 Impact assessment methods

The ReCiPe Midpoint (Hierarchist) method available in SimaPro8 is given special attention for the sake of assessing ATES impacts. This method was designed by Pré Consultants, CML (University of Leiden), RUN (Radboud University Nijmegen) and RIVM. Pré Consultants, the developers of SimaPro8 call ReCiPe "The most recent and harmonized indicator approach available in LCIA". ReCiPe can determine indicators at two levels:

- Eighteen midpoint indicators
- Three endpoint indicators

In this study, emphasis is given to the midpoint indicators for the sake of minimizing uncertainty, and the Hierarchist cultural perspective is adopted. This is the default ReCiPe midpoint method, using European normalisation. The degree of uncertainty and aggregation steps differs between perspectives. Importantly, ReCiPe contains the broadest set of midpoint impact categories available. ReCiPe does not include potential impacts from future extractions in the impact assessment (Goedkoop *et al.*, 2013). The term impact category is used throughout the report in a technical way, to describe midpoint categories which are modelled with midpoint indicators.

The results attained in the LCI take the form of a list of environmental interferences. In order to make sense of this list, the list is categorized into impact categories according to classification from the ReCiPe method. One substance in this case can contribute to multiple impact categories, or many substances to one impact category. The impact categories are expressed as midpoints such as in the table below.

Table 3 *ReCiPe Midpoint method impact categories details* (Goedkoop *et al*., 2013).

Impact category	Abbr.	Unit	Characterisation	Abbr.
climate change	CC	kg (CO_2 to air)	global warming potential	GWP
ozone depletion	OD	kg (CFC- 11[1] to air)	ozone depletion potential	ODP
terrestrial acidification	TA	kg (SO_2 to air)	terrestrial acidification potential	TAP
freshwater eutrophication	FE	kg (P to freshwater)	freshwater eutrophication potential	FEP
marine eutrophication	ME	kg (N to freshwater)	marine eutrophication potential	MEP
human toxicity	HT	kg (14DCB to urban air)	human toxicity potential	HTP
photochemical oxidant formation	POF	kg (NMVOC[2] to air)	photochemical oxidant formation potential	POFP
particulate matter formation	PMF	kg (PM_{10} to air)	particulate matter formation potential	PMFP
terrestrial ecotoxicity	TET	kg (14DCB to industrial soil)	terrestrial ecotoxicity potential	TETP
freshwater ecotoxicity	FET	kg (14-DCB to freshwater)	freshwater ecotoxicity potential	FETP
marine ecotoxicity	MET	kg (14-DCB[3] to marine water)	marine ecotoxicity potential	METP
ionising radiation	IR	kg (U^{235} to air)	ionising radiation potential	IRP
agricultural land occupation	ALO	m^2xyr (agricultural land)	agricultural land occupation potential	ALOP
urban land occupation	ULO	m^2xyr (urban land)	urban land occupation potential	ULOP
natural land transformation	NLT	m^2 (natural land)	natural land transformation potential	NLTP
water depletion	WD	m^3 (water)	water depletion potential	WDP
mineral resource depletion	MRD	kg (Fe)	mineral depletion potential	MDP
fossil resource depletion	FD	kg (oil)	fossil depletion potential	FDP

At the endpoint level, these categories would be agglomerated into 3 impact categories. These are much more uncertain and subjective endpoint indicators, the purpose of which is to minimise, combine and reduce the large number of midpoints for the sake of easier interpretation. The endpoints are shown in the following figure; however for these case studies this approach is not followed.

Table 4 *ReCiPe Endpoint method impact categories details* (Goedkoop *et al*., 2013).

Impact category	Abbr.	Indicator name	Unit
damage to human health	HH	disability-adjusted loss of life years	yr
damage to ecosystem diversity	ED	loss of species during a year	yr
damage to resource availability	RA	increased cost	$

A schematic summary of the functioning of ReCiPe, including the relationship between mid- and end-point indicators is illustrated in the following Figure.

[1] CFC-11: Chlorofluorocarbon
[2] NMVOC: Non Methane Volatile Organic Carbon compound
[3] 14-DCB: 1,4 dichlorobenzene

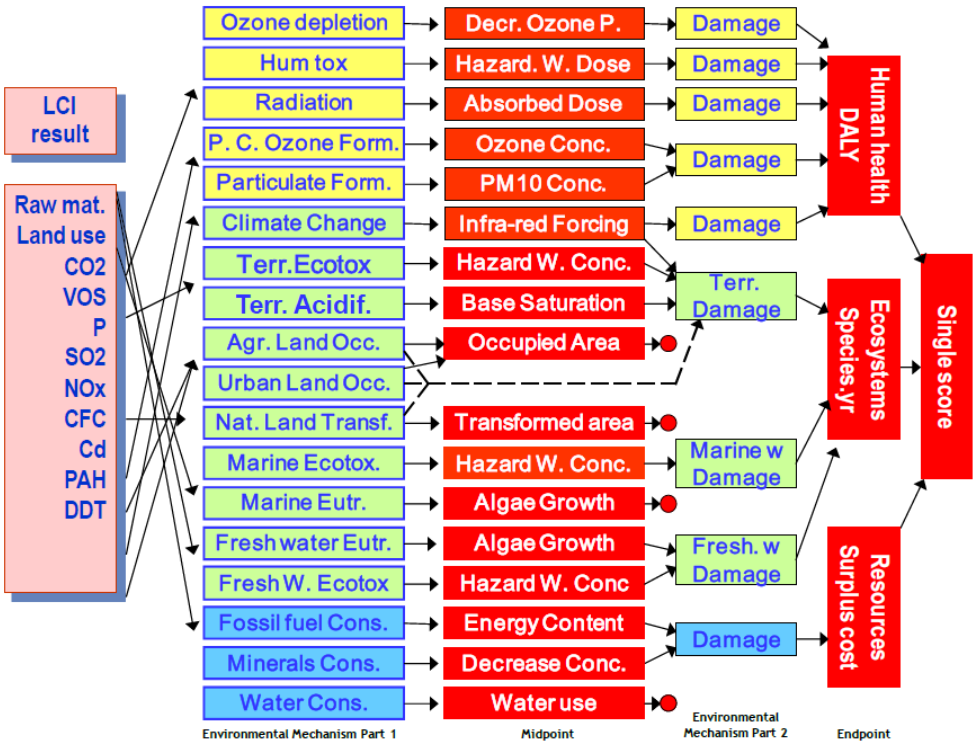

Figure 7 *Schematic overview of the functioning of ReCiPe including both mid- and end-points* (Goedkoop *et al*., 2013).

In addition to ReCiPe, the single issue method Cumulative Energy Demand (CED) is used to quantify primary energy demand. CED is a simple method based on that published by Ecoinvent version 1.01, which was expanded by Pré Consultants for energy resources available in the SimaPro database (Pré, 2015). This method does not include normalisation. Characterisation is carried out for the consumption of different types of energy, divided into 6 categories.

Table 5 *Cumulative Energy Demand method impact categories details.*

Impact category	Abbr.	Unit
Non-renewable, fossil	NR – F	MJ
Non-renewable, nuclear	NR – N	MJ
Non-renewable, biomass	NR – B	MJ
Renewable, biomass	RE – B	MJ
Renewable, wind, solar, geothermal	RE – WSG	MJ
Renewable, water	RE – W	MJ

CED states the entire demand valued as primary energy which arises from the production, use and disposal of an economic good or service (Frischknecht *et al*., 2007). The method effectively investigates energy use throughout the life cycle, including both direct uses as well as indirect energy consumption. All the while CED distinguishes between non-renewable and renewable sources of energy.

2.5 Interpretation

Impact assessment results are presented graphically in characterised and normalised form. Seeing as that characterised results have different units per impact category (See Table 3), these must be displayed in 100% stacked form. Normalised results are displayed with relative values, the units of which are the result of a point system derived from the normalisation factor. For this thesis that normalisation factor is determined according to European normalisation, which shows relevance of results in the European context.

Characterisation at the midpoint level proceeds according to the following formula:

$$I_m = \sum_i Q_{mi} m_i$$

where m_i is the magnitude of intervention (e.g., the mass of CO_2 released to air), Q_{mi} is the characterisation factor connecting intervention i with midpoint impact category m, and I_m is the indicator result for midpoint impact category m (Goedkoop *et al*., 2013).

Normalisation factors are calculated from data gathered by members of the institutions responsible for the design of ReCiPe (Sleeswijk *et al*., 2008). This compiled data from sources such as the EEA, FAO, IEA, UNECE, UNEP, UNESCO, UNFCCC and EMEP[4] with normalisation factors referring to the yearly average pollution generated by one single European inhabitant in the year 2000 (Lautier *et al*., 2010; Sleeswijk *et al*., 2008). This implies that a European inhabitant in 2000 results in a climate change effect of 8.92E-05 kg CO_2 (eq) and so on and so forth (See Table 6). Normalisation results are obtained as per the following equation:

$$N_i = \frac{S_i}{NF_i}$$

Where i is the impact category, N is the normalised result, S is the impact score of a product and NF is the normalisation factor (Lautier *et al*., 2010). This means that a normalisation value of for example 0.1 for CC would imply 10% of the CC effect of one European inhabitant in the year 2000 is caused. 0 points for WD implies that water depletion is deemed unimportant in the European, political context according to this method of normalisation.

Table 6 ReCiPe midpoint (H) European normalisation factors per impact category (Sleeswijk *et al*., 2008; Weidema *et al*., 2013).

Abbr	Normalisation (Pt)
CC	8.92E-05
OD	45.4
TA	2.91E-02
FE	2.41
ME	9.88E-02
HT	1.59E-03
POF	1.76E-02
PMF	6.71E-02
TET	1.21E-01
FET	9.09E-02
MET	1.15E-01
IR	1.60E-04
ALO	2.21E-04
ULO	2.46E-03
NLT	6.19
WD	0
MRD	1.40E-03
FD	6.43E-04

[4] EEA (European Environment Agency); FAO (Food and Agriculture Organisation of the United Nations); IEA (International Energy Agency); UNECE (United Nations Environmental Commission for Europe); UNEP (United Nations Environment Program); UNESCO (United Nations Educational, Scientific and Cultural Organisation); UNFCCC (United Nations Framework Convention on Climate Change); EMEP (European Monitoring and Evaluation Programme)

Cumulative Energy Demand results are viewed in absolute figures (in MJ primary energy) as stacked column graphs, and also in the form of 100% stacked results in order to better see which infrastructure is responsible for proportions of energy demand categories.

Interpretation is further approached by carrying out uncertainty and sensitivity analysis as well as a general discussion. Uncertainty and sensitivity analysis determine how trustworthy the results of LCA are and how sensitive the overall situations may be to changes in certain key parameters. Applying different situations to the case studies shows how they may have been affected by different design factors. Together, this lays a foundation towards recommendations.

3 LCA results and discussion

In this chapter, results from the LCA analysis methods are presented and discussed. This is done for the ATES systems, by first excluding and then including the respective heat sources of the case studies. Results are presented first in the form of network diagrams, characterising CO_2 emission as an example of a relevant environmental intervention. This is not done for all emissions or for the impact categories, which are better represented graphically. Following this, the ReCiPe midpoint impact assessment lays out the environmental footprint, first in characterised form and then normalised to the European averages. Cumulative Energy Demand (CED) is then featured – showing cumulative primary energy required according to sources of primary energy. Special attention is given to CO_2 and to climate change, due to their European, political relevance (IPCC, 2012).

Lastly, comparisons are made to the reference case. Hereby, environmental impact assessment and CED of an industrial, natural gas incinerator are displayed and shown against the combined ATES/heat-source systems. In this way it can be discussed whether the HT-ATES and their respective heat sources are more, or less sustainable than a conventional, natural gas industrial furnace in terms of both environmental effects and energy demand.

It is important to bear in mind that the heat sources of both case studies do not 100% accurately reflect the reality as they are examples adapted from the Ecoinvent database (Weidema *et al.*, 2013). They do however give a good indication of how ATES and heat sources may interact.

3.1 GeoMEC Vierpolders impact assessment

3.1.1 GeoMEC ATES impact assessment

CO_2 characterization is considered as an example of an emission flow. Showing results in this form gives an indication of the interactions between the HT-ATES physical infrastructure.

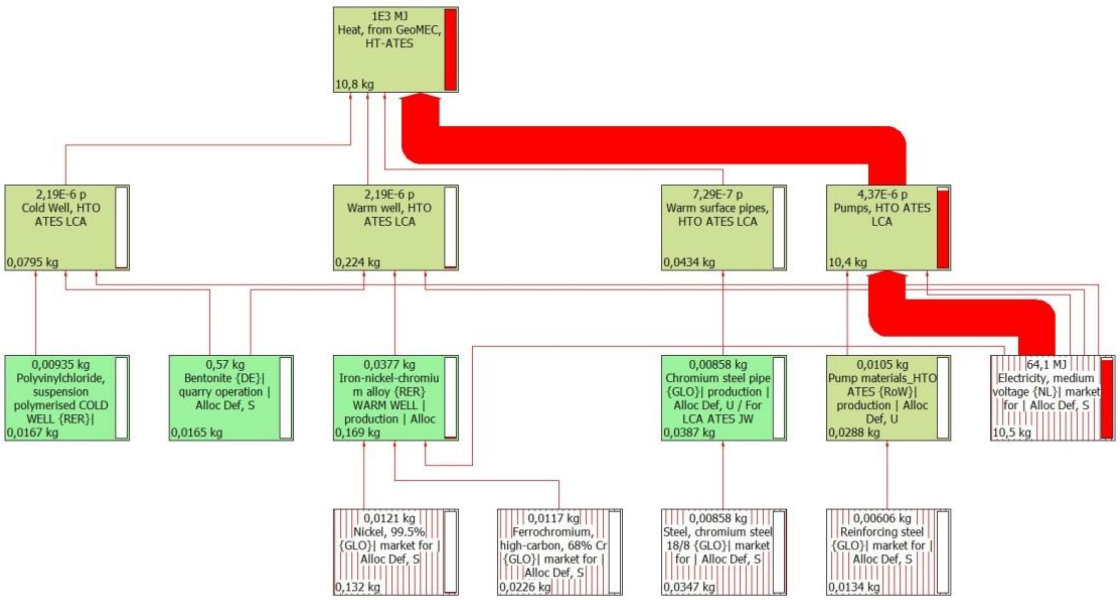

Figure 8 *GeoMEC Vierpolders ATES network diagram. CO_2 characterised impact assessment with indicators shown as values in kg CO_2 (eq) – ReCiPe midpoint (H) cut-off: 0.1%.*

Figure 8 shows how CO_2 emissions are dominated by medium voltage electricity production for the operation of the pumps. As a matter of fact, due to the electricity use during operation of the pumps,

together with the materials required for the pumps this means that they account for 96.7% of the CO_2 emitted per GJ heat. Emissions related to the remaining infrastructure are barely significant in comparison, the largest of which are the warm wells which account for 2.07% of CO_2 emissions. The remainder of ATES infrastructure together accounts for 1.23% of CO_2 emissions. Considering the wider range of impact categories, it can be seen in Figure 9 and Figure 10 that dominance of the pumps operation mostly continues, compared with the remaining infrastructure.

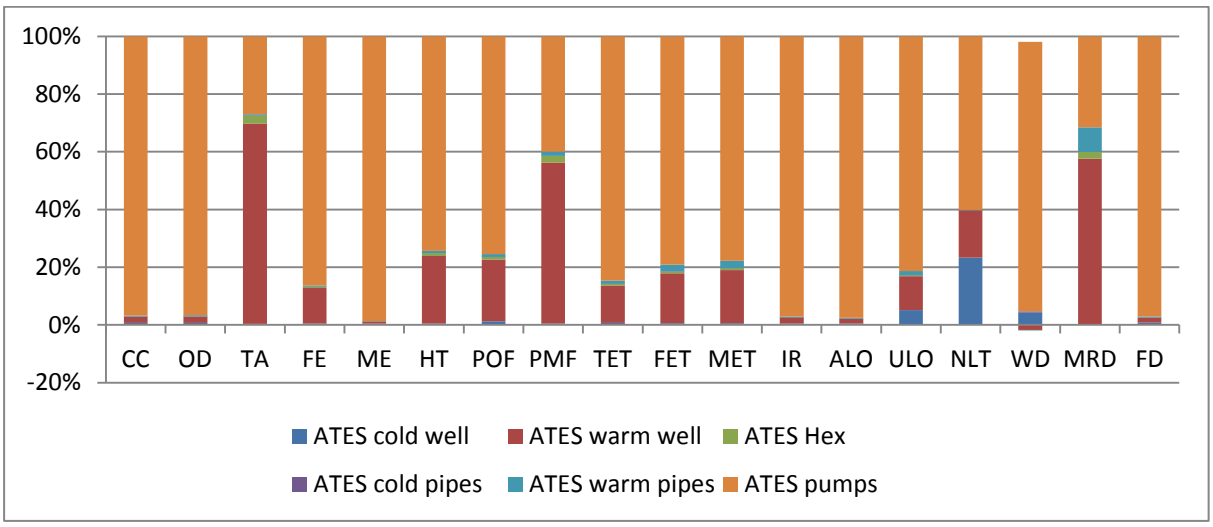

Figure 9 *GeoMEC Vierpolders ATES impact assessment featuring 100% stacked results for the 18 impact categories – Characterised results. ReCiPe midpoint (H).*

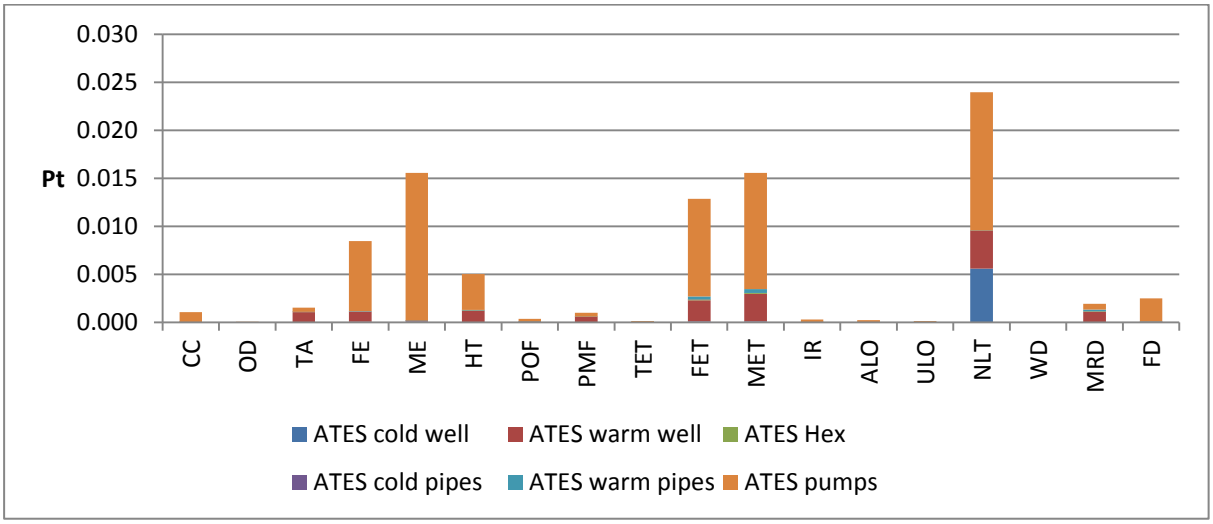

Figure 10 *GeoMEC Vierpolders ATES impact assessment featuring results normalised to European averages relative to 1 GJ heat delivery (Pt) – Normalised results. ReCiPe midpoint (H).*

The combined results of Figure 9 and Figure 10 show the impact assessment categorised into the 18 midpoint indicators of ReCiPe, each with different units (refer to Table 3). These graphs show how the different ATES components affect the overall environmental load. Load is evidently dominated by the pumps, which is due to their electricity use and by the warm wells due to their high RVS steel use. Results in Figure 9 indicate that terrestrial acidification, particulate matter formation and metal resource depletion are especially affected by the warm wells, whereas the remaining categories are mostly affected by the pumps (or electricity).

Metal depletion is obviously affected by the fact that the warm wells are constructed largely using RVS steel, however terrestrial acidification and particulate matter formation could use clarification. This is

achieved by characterizing the results according to the midpoint 'terrestrial acidification'. TA is determined by the emission to air of ammonia, nitrogen dioxide, nitrogen oxides, sulphur dioxide, sulphur monoxide and sulphur oxides – and given the encompassing unit kg SO_2 (eq). Characterising these results reveals that the production of nickel for iron-nickel-chromium alloy (RVS Steel) releases a lot of SO_2 (eq) in the form of ammonia. Regarding particulate matter, the warm wells account for 55.1% of PM10 (eq) due to the alloy production process, whereas electricity production for use by the pumps accounts for 40.7% of kg PM10 (eq). PM is also partially affected by ammonia emissions to air (with a factor 0.32), but especially so by particulates of various sizes between <10 µm - >2.5 µm (Weidema *et al*., 2013).

The added value of showing the results in a normalised form, such as in Figure 10 is that perspective can be given to the network diagrams shown when compared with the average European inhabitant. Evidently, it is especially FE, ME, FET, MET and NLT which are most relevant, however all scoring lower than 0.03 Pt. Therefore, in a European context, the five highlighted impact categories should have special attention paid to them, the highest importance of which stems from the electricity use of the pumps.

3.1.2 *GeoMEC ATES/geothermal impact assessment*

When CO_2 characterization is considered for the total GeoMEC situation, results continue to be dominated by the ATES pumps. This is a strange outcome, because in reality the geothermal doubl*et al*so requires the use of electrical pumps – pumping from a much greater depth. This highlights that there may be an issue with the method of using inputs from Ecoinvent to represent the heat sources with minimal adaptation.

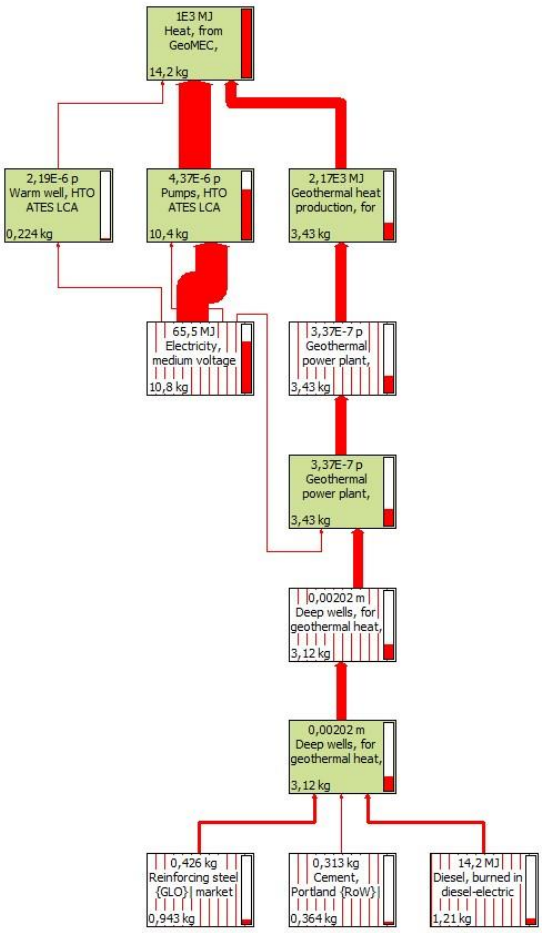

Figure 11 *GeoMEC Vierpolders ATES and geothermal installation network diagram. CO_2 characterised impact assessment with indicators shown as absolute values in kg CO_2 (eq) – ReCiPe midpoint (H) cut-off: 1.56%.*

In this case, Figure 11 depicts a surprisingly high proportion of CO_2 being allocated to operation of the HT-ATES. ATES pumps operation results in 73% of total CO_2 emissions. This is largely due to the fact that electricity at the ATES comes from a non-renewable, CO_2 intensive source – and the geothermal pumps are not accounted for. The ATES warm wells have much less relevance when regarding CO_2 flows (2%), and the contribution of the remaining ATES infrastructure is excluded from the diagram by the 1.56% cut-off value. On the other hand geothermal heat production is responsible for 24% of CO_2 emissions, which would be much higher had the geothermal pumps been accounted for. The residual 3% for the currently depicted situation is due to remaining infrastructure of the ATES (hidden by the cut-off value). The broader impact assessment results are illustrated in the following figures:

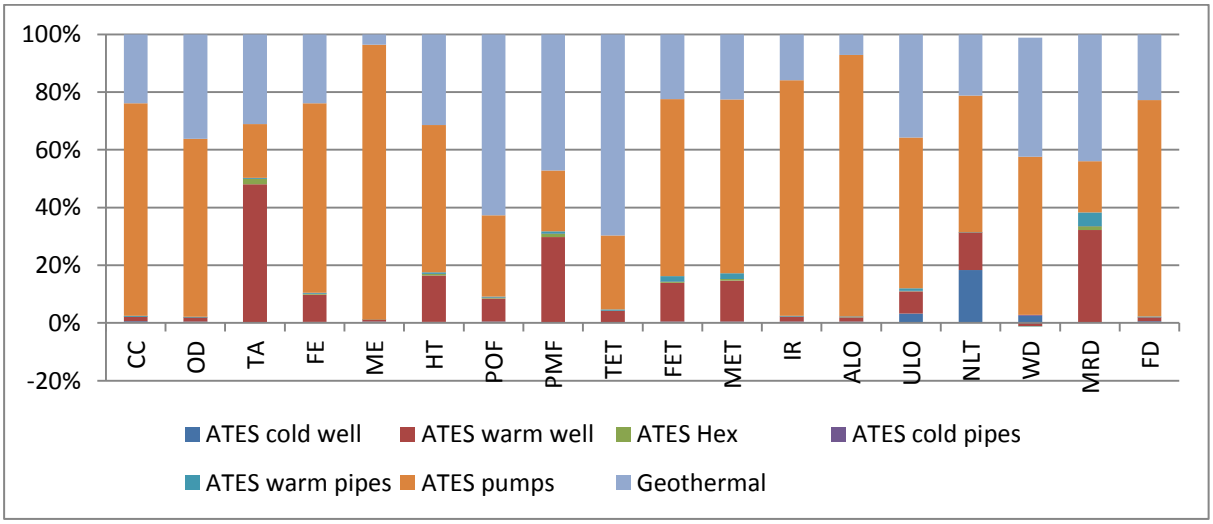

Figure 12 *GeoMEC Vierpolders ATES and geothermal installation impact assessment featuring 100% stacked results for the 18 impact categories – Characterised results. ReCiPe midpoint (H).*

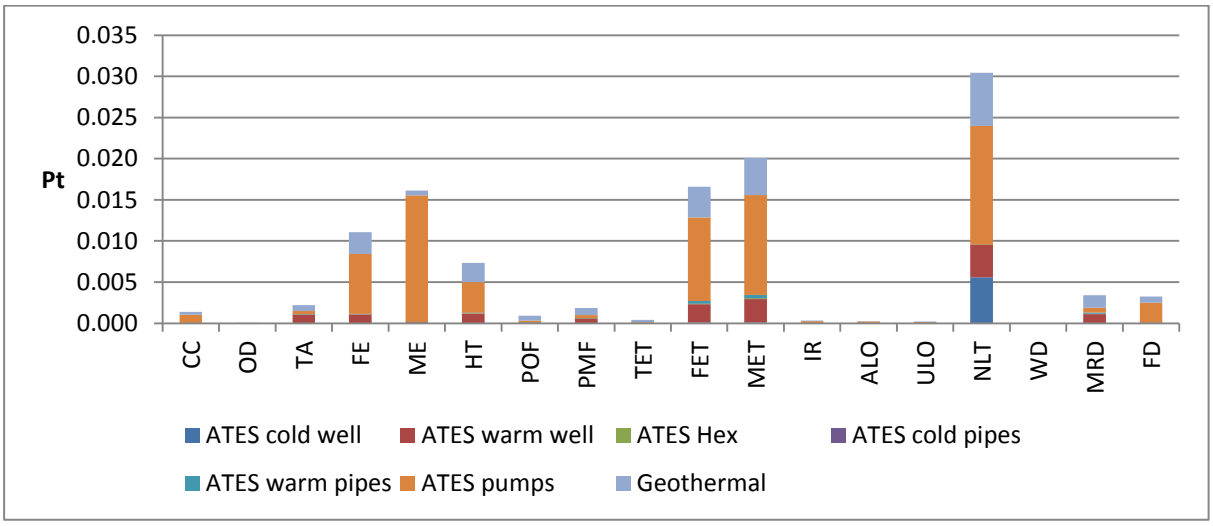

Figure 13 *GeoMEC Vierpolders ATES and geothermal installation impact assessment featuring results normalised to European averages relative to 1 GJ heat delivery (Pt) – Normalised results. ReCiPe midpoint (H).*

Figure 12 and Figure 13 show the impact assessment results of the complete GeoMEC ATES and geothermal heat coupled system characterized into the 18 impact categories resultant of the ReCiPe midpoint method. Interestingly, the trend of impact category dominance by the ATES pumps continues, despite the expectation that the ~10 times deeper geothermal wells would have resulted in higher electricity demand of their pumps – and therefore higher environmental effects of operation. Figure 12 shows that the ATES pumps are dominant in all categories apart from TA, POF, PMF, TET and MRD. For

these categories, TA is dominated by the ATES warm wells, whereas the remainder by the geothermal process.

Characterised results reveal that the warm wells of the ATES and the deep wells of the geothermal doublet result in acidification and metal resource depletion due to metal use and alloy fabrication. Diesel burned in an electricity generator set used to drill the boreholes of the geothermal installation results in POF alongside the electricity production for ATES pumps.

Normalised results produced in Figure 13 show which impact categories are most relevant in the European context. FE, ME, HT, FET, MET and NLT come out with the highest relevance, with scores >0.01. However, compared with an average European inhabitant, relevance in this case is only >1% of environmental effect. The most relevant impact category according to European normalisation, NLT, seems to be mostly determined by medium voltage electricity production used for the pumps. Analysis of the process, 'Electricity, medium voltage {NL}' shows that 12 m2a intensive forest is occupied per GJ electricity by this process and that transformation from forested land is dominated by electricity producing infrastructure (Weidema *et al*., 2013).

Closer inspection of the geothermal heat producing process used for GeoMEC reveals that the same electricity source – 'Electricity, medium voltage {NL}', is used at the adapted Hot-Dry-Rock geothermal facility as is used for the ATES. However, the majority of electricity impacts at the geothermal doublet are derived from diesel, burned in a diesel-electric generating set, used in the drilling of the boreholes (See Figure 11). This process seems to have lower values across the impact categories per GJ when compared with average, Dutch electricity. For CC and FD specifically, the diesel generator results in 89 kg CO_2 (eq) compared with 179 kg (eq) for Dutch electricity, and 30.5 kg oil (eq) for diesel compared with 59.4 kg (eq) for Dutch electricity. Regarding the most relevant categories according to normalisation – diesel outperforms Dutch electricity in FE, ME, HT, FET, MET and NLT by exhibiting lower results, whereas in some of the less relevant categories – OD, TA, POF and PMF – Dutch electricity performs better than diesel per GJ. Importantly, the electricity consumption of the pumps that would be used in the geothermal process is excluded – a large chunk of the likely effects of the total GeoMEC situation are therefore not accounted for as a result of not constructing the geothermal facility from data collection.

Overall, it can be seen that the ATES is accountable for the majority of normalised (and characterised) environmental effects of the depicted situation. ATES contributes >60% to all impact categories apart from POF, PMF, TET and MRD. These account for 37%, 53%, 30% and 56% - displaying relevance across the spectrum due to electricity use of the pumps. More data for the geothermal heat plant would have likely revealed results in which the ATES was less dominant.

3.2 GeoMEC Vierpolders Cumulative Energy Demand

3.2.1 GeoMEC ATES Cumulative Energy Demand

Following the impact assessment, the GeoMEC case study is analysed for primary energy demand – focussing first on the HT-ATES system before considering the geothermal heat plant. Results are presented illustrating responsibility of the various infrastructures in 100% stacked form, and then stacked with absolute values divided between the 6 energy categories of the CED method.

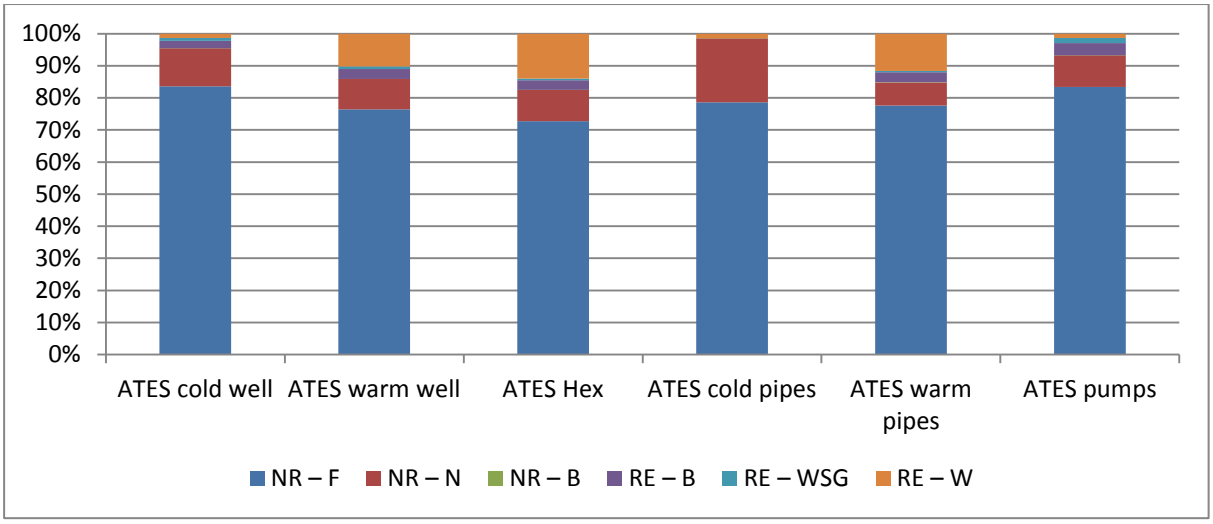

Figure 14 *GeoMEC Vierpolders ATES Cumulative Energy Demand featuring 100% stacked results for the 6 main infrastructure processes of ATES – Characterised results – 100% stacked.*

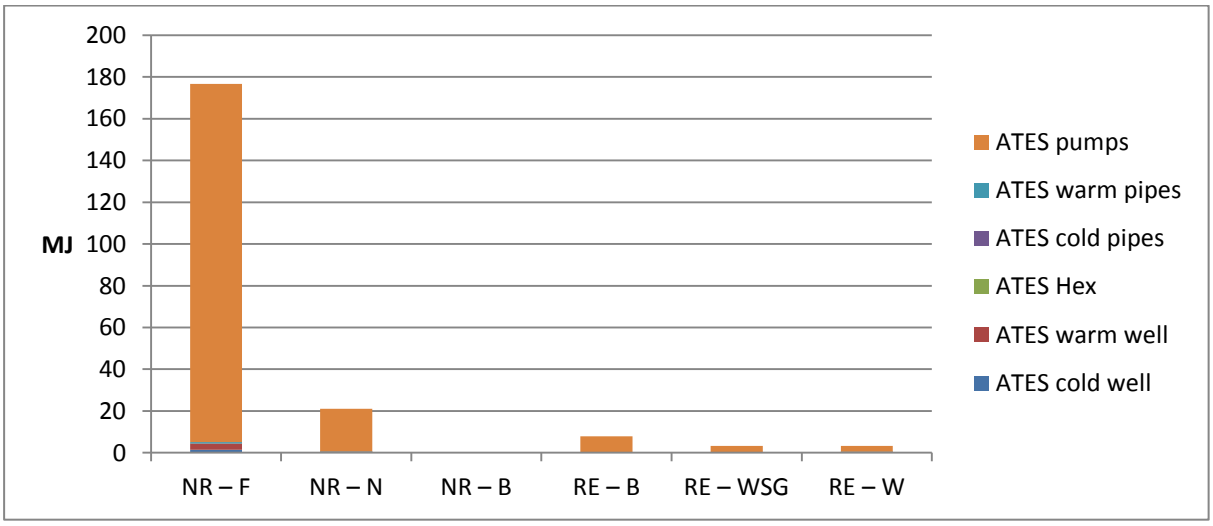

Figure 15 *GeoMEC Vierpolders ATES Cumulative Energy Demand featuring results relative to 1 GJ heat delivery of the 6 energy demand categories – Characterised results – stacked.*

The 100% stacked results in Figure 14 show how the clear majority of energy demand is attributed towards non-renewable, fossil fuels. This result is propagated across the different infrastructure of the ATES, as a result of the largely non-renewable electricity demand of the ATES pumps. This electricity is largely derived from natural gas use in the Netherlands (IEA, 2014a; IEA, 2014b) – which in SimaPro is modelled as Dutch, medium voltage electricity.

Figure 15 shows how the energy demand categories compare against each other, as determined by the ATES infrastructure. Here, the pumps are by far the most dominant factor across the energy demand categories for ATES – which features largely within the category *'Non-renewable, fossil'* due to the use of average Dutch medium voltage electricity to run them. The pumps account for ~97% of total energy demand – or 205.70 out of a sum total 212.30 MJ.

3.2.2 GeoMEC ATES/geothermal Cumulative Energy Demand

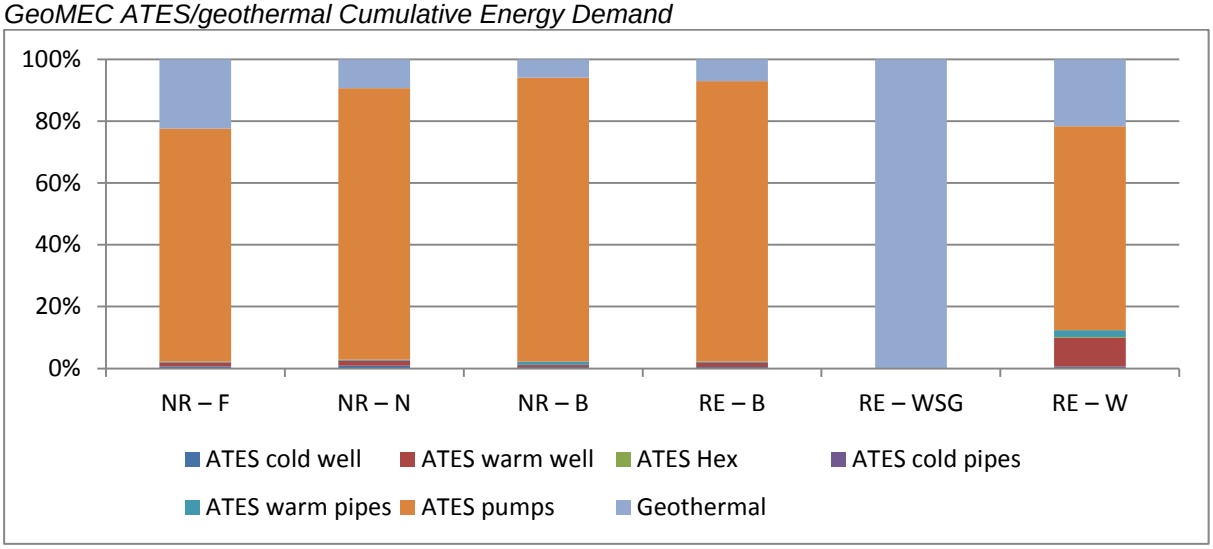

Figure 16 *GeoMEC Vierpolders ATES and geothermal installation Cumulative Energy Demand featuring 100% stacked results for the 6 energy demand categories – Characterised results.*

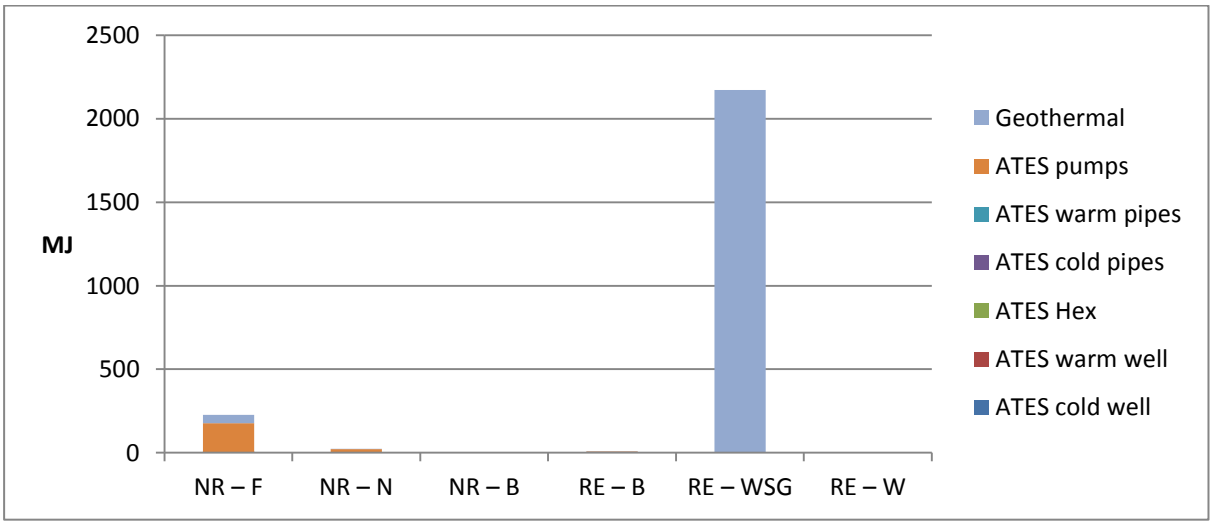

Figure 17 *GeoMEC Vierpolders ATES and geothermal installation Cumulative Energy Demand featuring results relative to 1 GJ heat delivery of the 6 energy demand categories – Characterised results.*

After including the geothermal heat plant in analysis, the 100% stacked, characterised CED results of Figure 16 continue to display huge significance for ATES pumps across the primary energy demand categories. This is for all categories apart from *'renewable, wind, solar, geothermal',* which is dominated by the geothermal heat source (99.9%). This is due to the nature of the heat source, whereas the ATES itself does not make use of renewable wind, solar or geothermal energy in large proportions according to the Dutch electricity mix adopted.

This fact is further supported by the results in Figure 17, which show that the geothermal heat source dominates energy demand. Compared against the ATES, the geothermal well is responsible for 91.3% of the total energy demand. Considering the heat source in this manner, alongside the ATES system – it becomes important to consider the ATES efficiency to determine the amount of heat delivered per heat injected. The reasonably low efficiency of the ATES, calculated to be 46% return efficiency means that a larger amount of thermal energy is injected compared with the 1 GJ delivered at the final output. This is reflected by the CED results which show primary energy demand at 2.43 GJ total, making it very interesting in terms of performance to increase the ATES efficiency.

3.3 AVR Duiven impact assessment

3.3.1 AVR ATES impact assessment

AVR results first focus on CO_2 characterisation in a network diagram in order to visualise interactions between infrastructure and resultant CO_2 emissions.

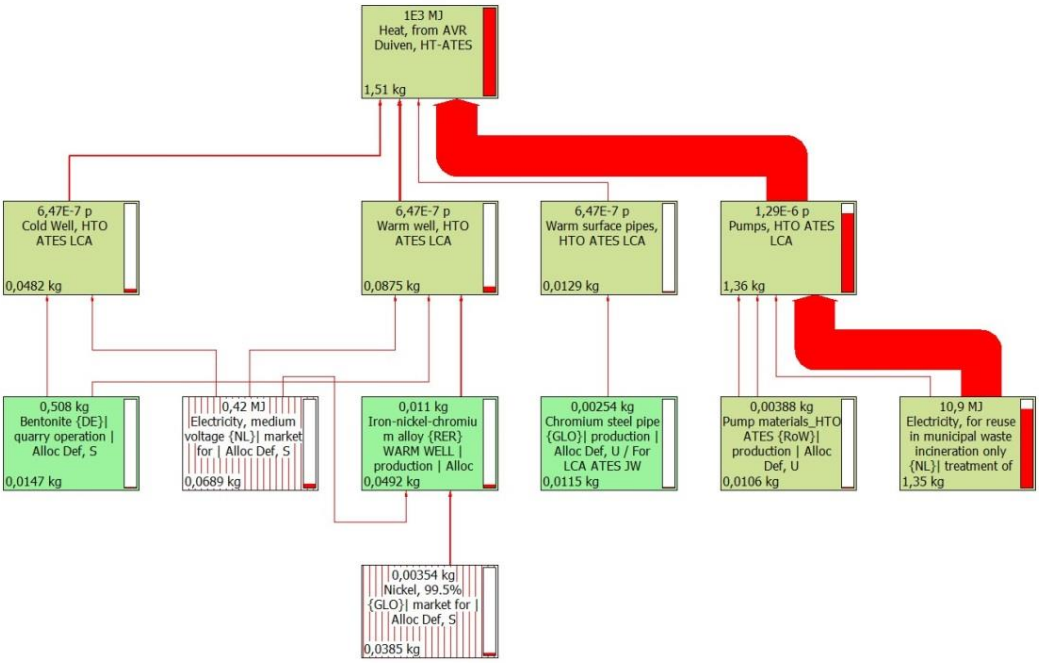

Figure 18 *AVR Duiven ATES network diagram. CO_2 characterised impact assessment with indicators shown as absolute values in kg CO_2 (eq) – ReCiPe midpoint (H) cut-off: 0.7%.*

Results in Figure 18 show that AVR Duiven HT-ATES has only 14% of the CO_2 emissions that the GeoMEC ATES has per GJ. This is especially due to lower electricity consumption at Duiven as a result of much higher coefficient of performance (COP) of 201 (as compared with 50 for GeoMEC) and more favourable subsurface temperature conditions (TNO, 2016). Of the total 1.51 kg CO_2 emitted per GJ heat delivered, the pumps are responsible for 90%, the warm well for 5.79% and the remaining infrastructure amounts to 4.21%.

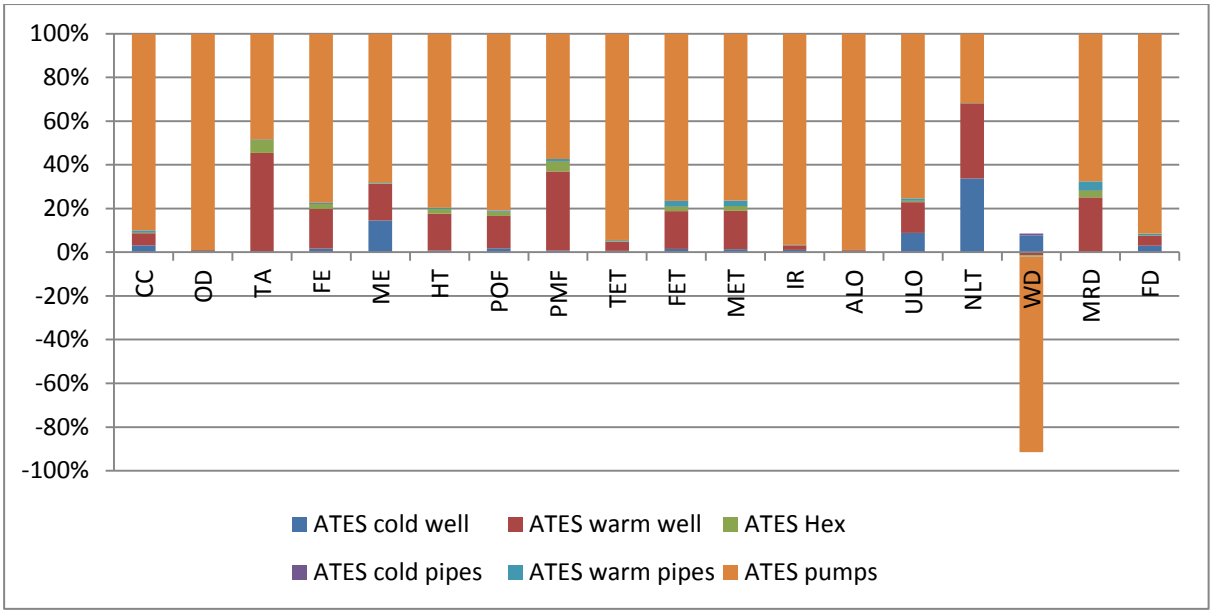

Figure 19 *AVR Duiven ATES impact assessment featuring 100% stacked results for the 18 impact categories – Characterised results. ReCiPe midpoint (H).*

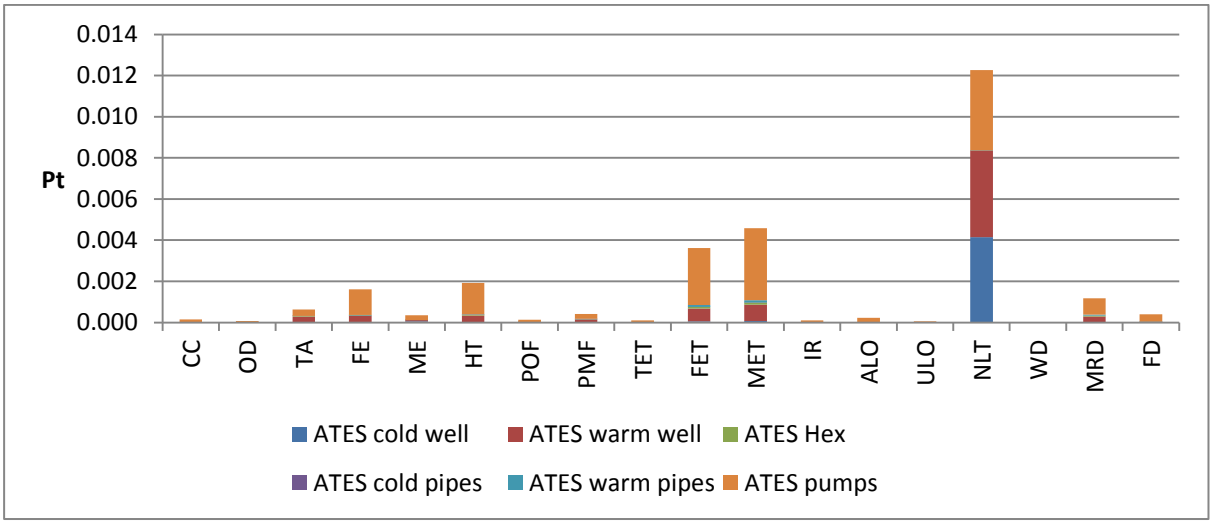

Figure 20 *AVR Duiven ATES impact assessment featuring results normalised to European averages relative to 1 GJ heat delivery (Pt) – Normalised results. ReCiPe midpoint (H).*

The combined results of Figure 19 and Figure 20 show the impact assessment categorised into the 18 ReCiPe midpoint indicators. 100% stacked, characterized impact assessment reveals a negative water depletion resultant of the pumps and the warm well. This is because of the electricity from waste process delivering electricity to the AVR ATES. A closer look at the process 'Electricity, for reuse in municipal waste incineration only' reveals that several background processes actually produce water (Weidema *et al.*, 2013). The net result of this is that more water is produced than consumed, therefore negative depletion.

Normalised impact assessment results show that on a European level, water depletion is completely irrelevant. Water depletion receives a normalisation factor of zero for the ReCiPe method with European normalisation. Focus should especially be given to NLT, just as with GeoMEC, which shows a score higher than 0.01. Apparently, the situation of Duiven is not so different to the European average. Characterised results show that negative water depletion is quite insignificant compared with other environmental effects, accounting for 6 litres of water produced per GJ delivered.

3.3.2 AVR ATES/waste incinerator impact assessment

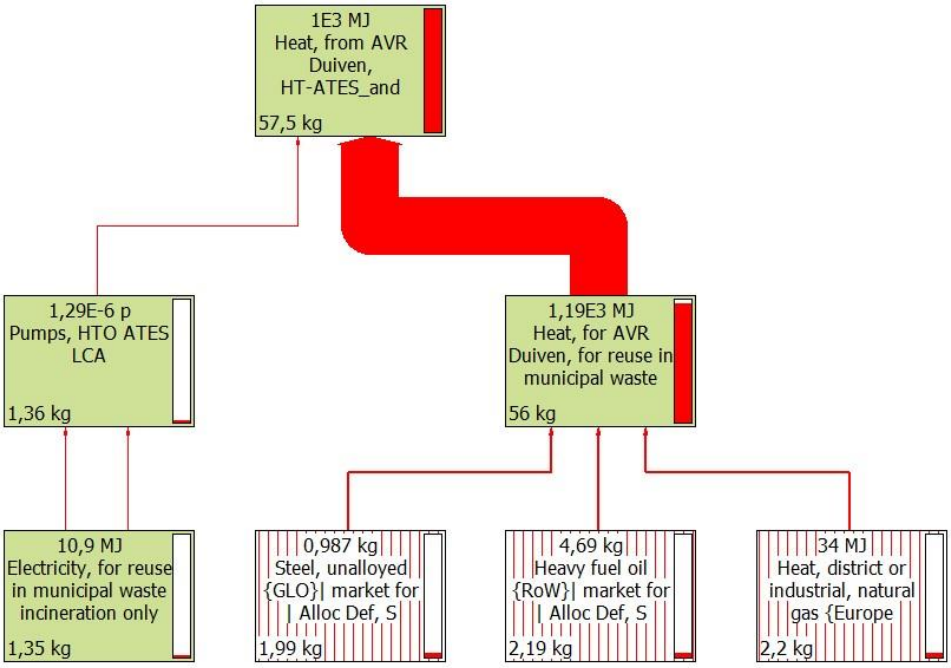

Figure 21 AVR Duiven ATES and waste incinerator network diagram. *CO_2 characterised impact assessment with indicators shown as absolute values in kg CO_2 (eq) – ReCiPe midpoint (H) cut-off:* 2.3%.

Figure 21 shows that heat from the waste incinerator is responsible for ~97% of CO_2 emissions. This result dwarfs the emissions from the ATES, unlike at GeoMEC where the ATES pumps are predominantly responsible for CO_2. The ATES system, pumps included – is collectively responsible for the other ~3% of CO_2 emissions. In this figure, several of the results are hidden by the 2.3% cut-off value due to the complete process being constructed of dozens of smaller, less significant processes.

The impact assessment analysis reveals the extent of all the other categories in the following figures.

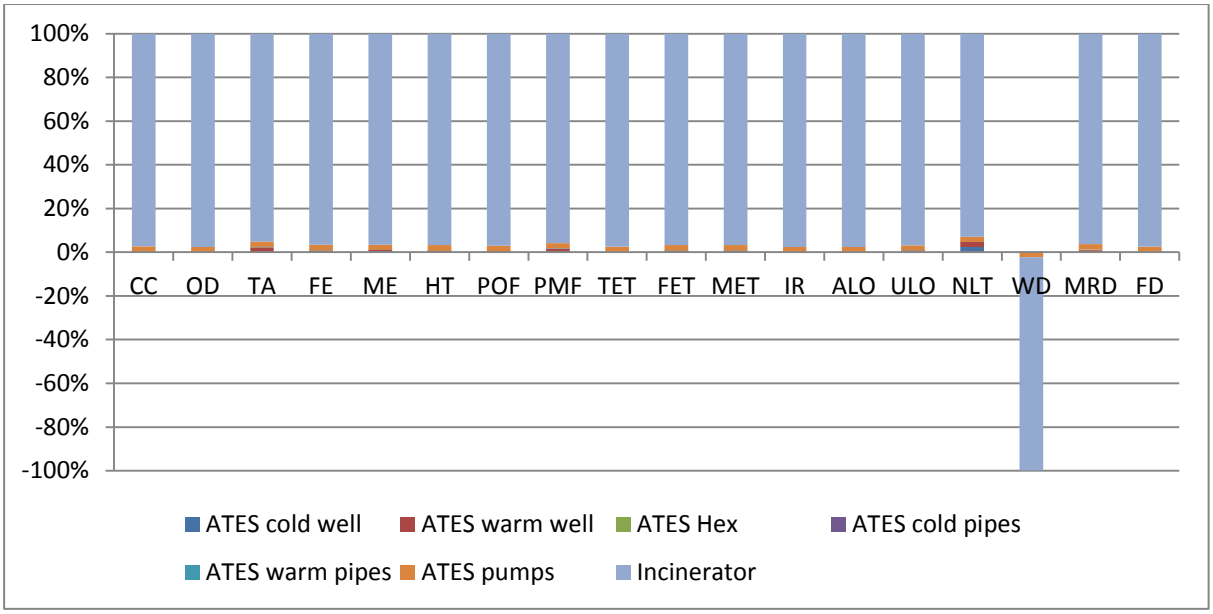

Figure 22 *AVR Duiven ATES and waste incinerator impact assessment featuring 100% stacked results for the 18 impact categories – Characterised results. ReCiPe midpoint (H).*

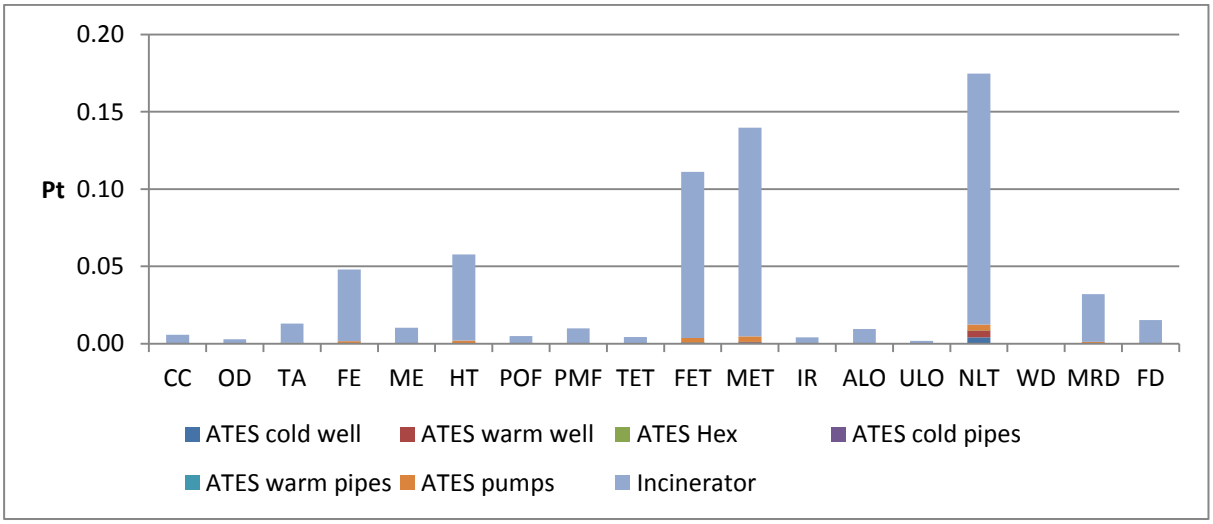

Figure 23 *AVR Duiven ATES and waste incinerator impact assessment featuring results normalised to European averages relative to 1 GJ heat delivery (Pt) – Normalised results. ReCiPe midpoint (H).*

Water depletion stands out once more in the characterised results due to its negative value. This is a result of the same factors determining the negative value within the ATES alone, due to the municipal incinerator electricity source. Due to electricity production at the incinerator using water for cooling (among other processes) – the waste incinerator process returns water to the environment, resulting in a negative depletion effect i.e. water is not depleted but rather contributed to the environment. Notice that the characterized results are displayed in 100% stacked form. Therefore, even though these results may seem large for water at this stage, their actual value is only 6 L/GJ. Normalised results in Figure 23 go further to show how irrelevant these results are in the wider context.

The impact assessment results in Figure 22 and Figure 23 confirm how small the effects of HT-ATES are in comparison with the waste incinerator in every impact category. It seems again that NLT is the most relevant environmental effect overall – resulting almost entirely due to the waste incinerator heat source. Following this, only FET and MET score higher than 0.1 Pt. Notice that the scores for the total situation are around 10x higher than those of the ATES in isolation.

3.4 AVR Duiven Cumulative Energy Demand

3.4.1 AVR ATES Cumulative Energy Demand

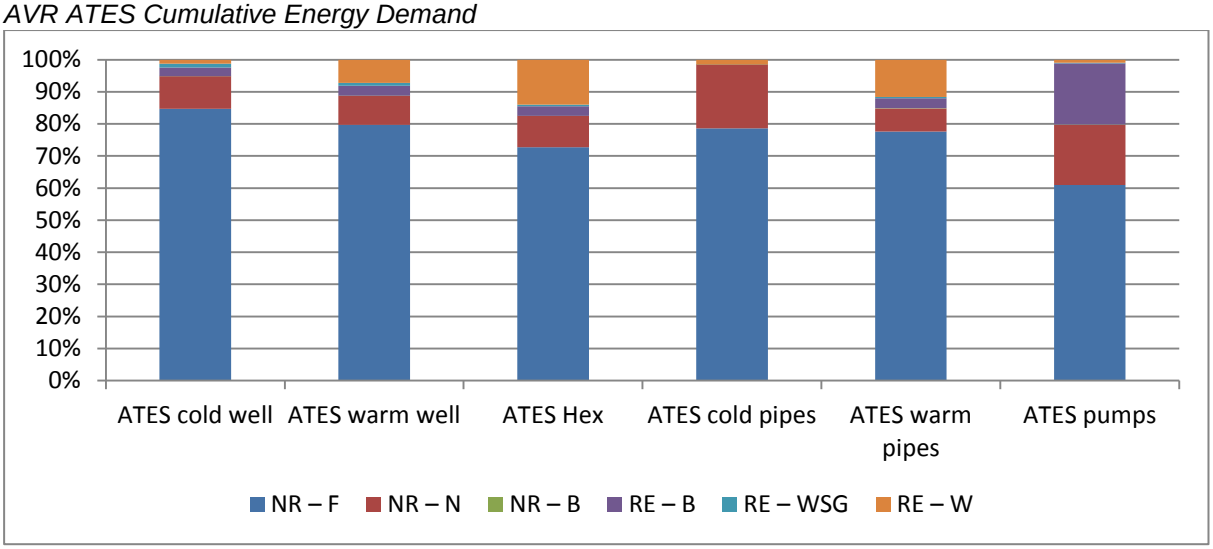

Figure 24 *AVR Duiven ATES Cumulative Energy Demand featuring 100% stacked results for the 6 main infrastructure processes of ATES – Characterised results – 100% stacked.*

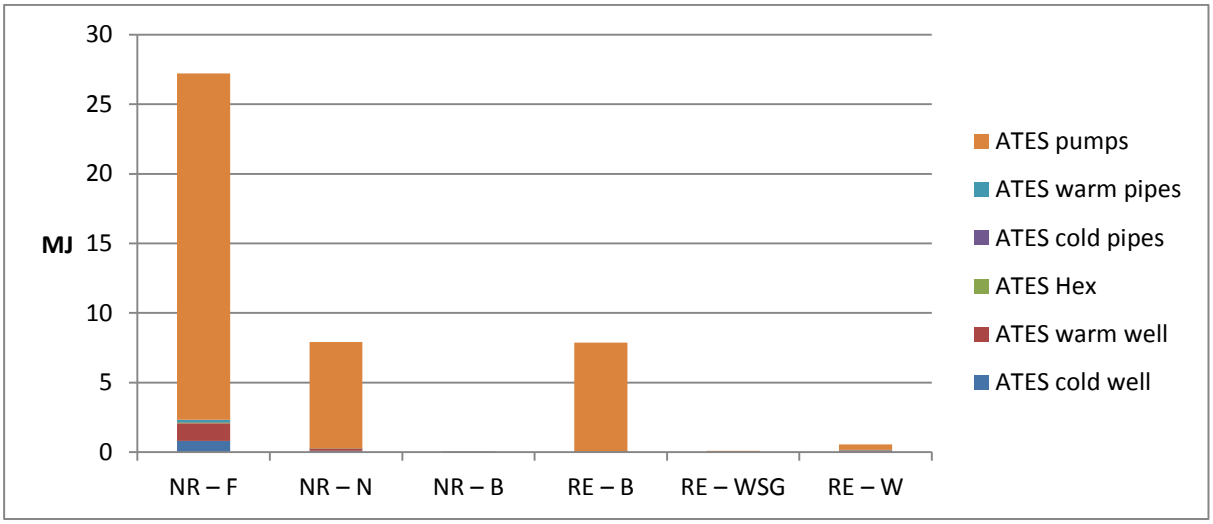

Figure 25 *AVR Duiven ATES Cumulative Energy Demand featuring results relative to 1 GJ heat delivery of the 6 energy demand categories – Characterised results – stacked.*

100% stacked results in Figure 24 show that non-renewable, fossil fuel is most dominant across the ATES infrastructure. This is because the waste incinerator process used comprises largely of non-renewable waste streams consisting of 92.8% burnable average municipal solid waste and 7.23% inert average municipal solid waste (Weidema *et al.*, 2013). Due to the Ecoinvent waste incinerator process used to represent the waste-to-energy facility used by AVR, ~40% of primary energy use of the pumps comes from incineration of renewable biomass and non-renewable, nuclear sources (Weidema *et al.*, 2013). In reality, no nuclear fuel is used for the operation of AVR, which highlights a flaw in this methodology of modelling the heat sources.

Figure 25 illustrates that in terms of total energy demand, electricity for the pumps is the controlling factor, however with a lower cumulative value than at GeoMEC. The categories, *'renewables, water'* and '*renewables, wind, solar, geothermal'* are influenced more than the other categories by the materials of the wells in Duiven. However, they too are dominated by electricity use of the pumps. In total, the Duiven ATES system demands 43.70 MJ primary energy in order to deliver the final output of 1 GJ thermal energy.

3.4.2 AVR ATES/waste incinerator Cumulative Energy Demand

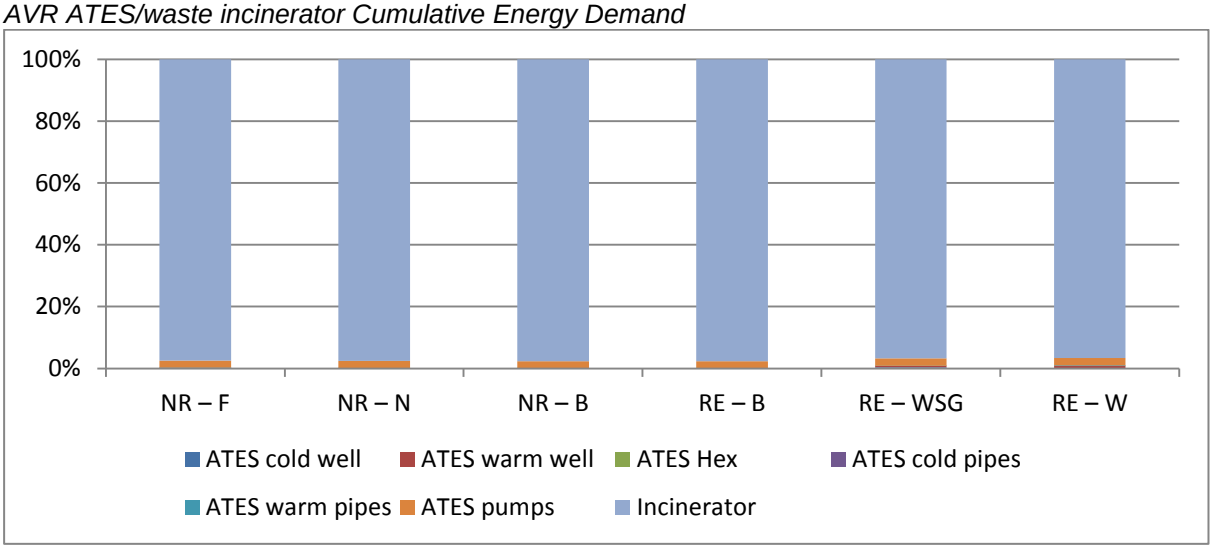

Figure 26 *AVR Duiven ATES and waste incinerator Cumulative Energy Demand featuring 100% stacked results for the 6 energy demand categories – Characterised results.*

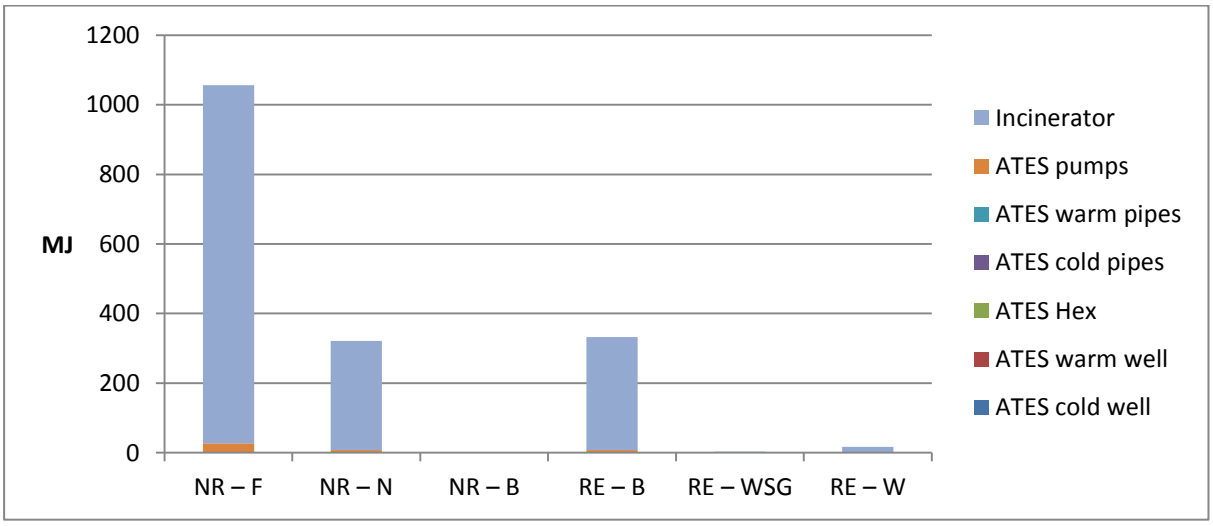

Figure 27 *AVR Duiven ATES and waste incinerator Cumulative Energy Demand featuring results relative to 1 GJ heat delivery of the 6 energy demand categories – Characterised results.*

Primary energy demand for the complete AVR system is entirely dominated by the incinerator as the heat source (See Figure 26 and Figure 27). Operation of the pumps from the ATES features especially within the category *'non-renewable, fossil'*. However, they only account for ~2% of this result (See Figure 27). Overall, fossil fuels also have the most significant contribution for the ATES/waste incinerator combination, representing 61% of demand or 1056/ 1730 MJ.

The three most relevant energy categories are, *'non-renewable, fossil'*, *'non-renewable, nuclear'* and *'renewable, biomass'* (See Figure 27). The ATES system alone showed a similar trend due to the fact that the ATES system for AVR uses electricity from a municipal waste incinerator, just like the waste incinerator, which produces its own electricity. The waste incineration process therefore results in proportionally similar outputs for both the ATES and the waste incinerator processes.

The high efficiency of the Duiven HT-ATES, calculated to have a return efficiency of 84% means that much of the thermal energy injected can subsequently be recovered. This is reflected in the 1.73 GJ cumulative energy demand compared with a delivery of 1 GJ.

3.5 Comparison to the reference situation

3.5.1 *Total impact assessment*

This section shows how the environmental footprints differ between the case studies all functioning to deliver 1 GJ of thermal energy. This accounts for both study objects with their heat sources, compared with heat delivery from an industrial natural gas incinerator.

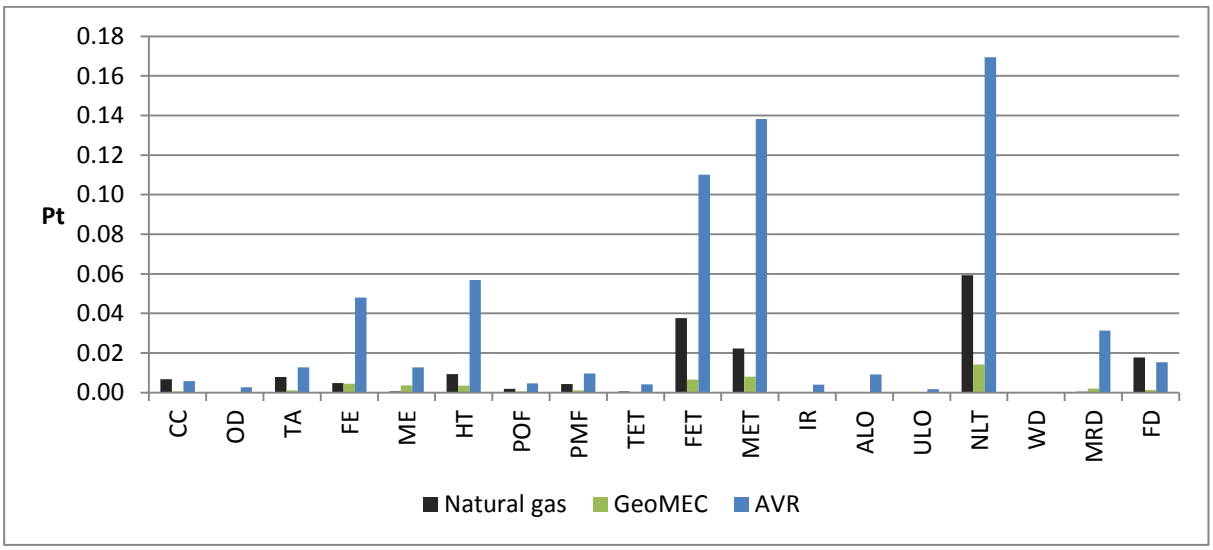

Figure 28 *GeoMEC Vierpolders, AVR Duiven and low-NOx, >100 kW natural gas industrial furnace impact assessment featuring results normalised to European averages relative to 1 GJ heat delivery (Pt) – Normalised results. ReCiPe midpoint (H).*

Figure 28 conveys that the AVR ATES/waste incinerator system has larger effects in 16 impact categories compared with the other two cases. This includes WD, in which characterised results show that AVR has a small but positive effect (negative depletion), whereas in this category, the geothermal setup at GeoMEC has the largest effect. The natural gas furnace has the largest effects under the categories climate change and fossil depletion. AVR performs worse than GeoMEC in all categories but one, WD, which has negligible impact in the European context reflected in the normalisation factor zero (Pré, 2015).

The impact assessment results for the ATES/heat source systems are evidently differently distributed according to the heat sources, with differing relevance when normalised to the European situation in Figure 28. In this case it is evident that the most relevant impact category from the previous analyses, NLT – is affected more considerably at AVR than either of the two other cases. In terms of CC though, natural gas has the largest effects.

Considering the ATES components in isolation, comparing between Figure 10 and Figure 20 reveals that the scale of the environmental effects for GeoMEC ATES is often higher than those of AVR ATES. For example, AVR produces 1.68 kg CO_2 (eq) and GeoMEC produces 11.73 kg CO_2 (eq) per 1 GJ heat delivered for the impact category CC. This has everything to do with the larger infrastructure and material use at GeoMEC, combined with higher COP (and lower electricity use) of AVR. Notice that the actual CO_2 emissions (not equivalent for CC) are featured in Figure 8 and Figure 18. Normalised results also reveal higher relevance in the European context for the GeoMEC ATES results since GeoMEC results tend to display higher normalisation scores than AVR.

Table 7 shows impact category savings of characterised results, comparing GeoMEC and AVR including their respective heat sources against the natural gas incinerator.

Table 7 *Impact assessment results comparing total Characterised situations of GeoMEC, AVR and the reference case using ReCiPe midpoint methodology to calculate savings.*

	Impact assessment			Savings		Units
Abbr.	**Natural gas**	**GeoMEC**	**AVR**	**GeoMEC**	**AVR**	**Unit**
CC	76.23	15.40	64.09	60.83	12.14	kg CO2 eq
OD	0.00	0.00	0.00	0.00	0.00	kg CFC-11 eq
TA	0.27	0.07	0.44	0.19	-0.17	kg SO2 eq
FE	0.00	0.00	0.02	0.00	-0.02	kg P eq
ME	0.01	0.16	0.10	-0.16	-0.10	kg N eq
HT	5.86	4.60	36.27	1.26	-30.41	kg 1,4-DB eq
POF	0.11	0.05	0.27	0.06	-0.16	kg NMVOC
PMF	0.07	0.03	0.15	0.04	-0.08	kg PM10 eq
TET	0.00	0.00	0.04	0.00	-0.03	kg 1,4-DB eq
FET	0.41	0.18	1.22	0.23	-0.81	kg 1,4-DB eq
MET	0.19	0.17	1.21	0.02	-1.02	kg 1,4-DB eq
IR	1.02	2.04	25.32	-1.01	-24.30	kBq U235 eq
ALO	0.19	1.12	42.58	-0.93	-42.39	m2a
ULO	0.05	0.08	0.71	-0.03	-0.67	m2a
NLT	0.01	0.00	0.03	0.00	-0.02	m2
WD	0.02	0.07	-0.28	-0.05	0.29	m3
MRD	0.37	2.43	22.86	-2.06	-22.48	kg Fe eq
FD	27.48	5.03	23.65	22.45	3.83	kg oil eq

This table suggests that GeoMEC features the best (lowest score) performance for climate change and fossil depletion, as well as featuring the highest HT savings. AVR has the worst performance for all categories apart from water depletion, fossil depletion and climate change. Natural gas has the lowest effects on agricultural land occupation and metal depletion. In terms of the most relevant category (according to normalisation) – NLT – GeoMEC has the highest savings compared with natural gas, and AVR performs worse than natural gas. It is however important to consider the environmental service provided by AVR, which works to get rid of waste. This will be discussed in further detail in section 5.2.

3.5.2 Total Cumulative Energy Demand

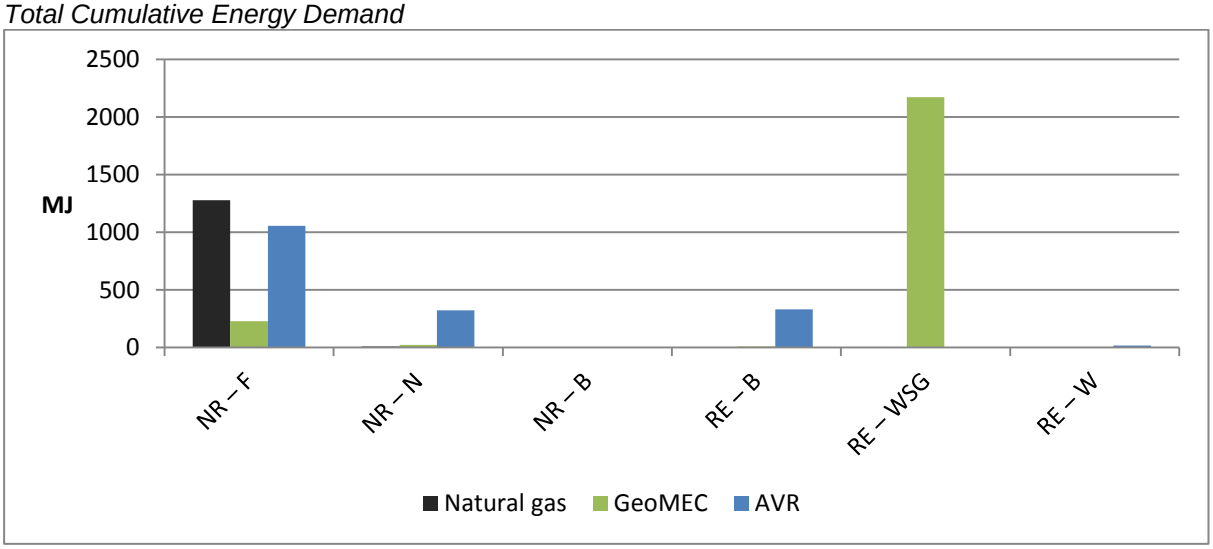

Figure 29 *GeoMEC Vierpolders, AVR Duiven and reference case Cumulative Energy Demand featuring results relative to 1 GJ heat delivery – Characterised results.*

Figure 29 shows the performance in terms of energy demand for the complete systems (including ATES and heat source), as well as performance of the reference case. In total, GeoMEC has a higher cumulative primary energy demand than both other cases especially within *'Renewable, wind, solar, geothermal'*. CED reveals a sum 2.43 GJ for GeoMEC, 1.73 GJ for AVR and 1.29 GJ primary energy for natural gas – therefore, it is the natural gas system which exhibits the lowest primary energy demand. This is especially apparent in the cumulative results as shown in Figure 29. Here, the energy demand of GeoMEC can be seen to overshadow that of both the reference case and AVR. This is because of the large amount of energy required in the geothermal process associated with the heat source.

The total primary energy value resultant of CED analysis can be broken up into energy demand from the system and the external energy requirement. Subtracting the inverse of efficiency (of the ATES) from the primary energy gives a value to external energy demand. This results in 0.26 GJ for GeoMEC and 0.54 GJ for AVR i.e. 26% and 54%. For natural gas, this value is typically ~30% (Persson & Werner, 2012). However it should be considered that GeoMEC produces heat from a sustainable source, AVR from a source providing the environmental service of waste disposal, and the reference case from a fossil fuel intensive source. Table 8 follows up by showing CED savings of cumulative results, comparing GeoMEC, AVR and the reference case.

Table 8 *Cumulative Energy Demand results comparing total situations of GeoMEC, AVR and the reference case in MJ primary energy savings.*

	Cumulative Energy Demand (MJ)			Savings (MJ)	
Impact category	**Natural gas**	**GeoMEC**	**AVR**	**GeoMEC**	**AVR**
Non-renewable, fossil	1276.42	227.60	1056.07	1048.82	220.35
Non-renewable, nuclear	10.13	23.25	321.26	-13.12	-311.13
Non-renewable, biomass	0.00	0.04	0.95	-0.04	-0.94
Renewable, biomass	1.47	8.43	332.04	-6.96	-330.57
Renewable, wind, solar, geothermal	0.77	2170.56	2.98	-2169.79	-2.21
Renewable, water	3.99	4.25	16.68	-0.26	-12.69
Total (MJ)	1292.78	2434.13	1729.99	-1141.349	-437.205

GeoMEC has the highest energy demand, followed by AVR. This is because of the large energy demand featured within RE- WSG for GeoMEC and the large demand for AVR in terms of NR- F, NR- N and RE-B. Both study objects are outperformed by the reference case by showing in total a negative savings result.

4 Uncertainty and sensitivity analysis

The complexity of Life Cycle Assessment exposes results to a degree of uncertainty. Some processes within the Ecoinvent database make use of proxies in the place of measured values, and foreground and background data inputted into SimaPro comes from estimations and discussion with experts, as well as calculated parameters. Therefore for correct interpretation of results, it is important to analyse this uncertainty, which will be done in this section.

Uncertainty can be dealt with in several ways. The one used here is the statistical way, which does not attempt to remove or reduce uncertainty, but rather to incorporate it (Finnveden *et al.*, 2009). This was done by applying the results of probability distributions and Monte Carlo simulations. Monte Carlo analysis is completed using a 95% confidence interval and carrying out 1000 runs in each case. Uncertainty is then represented as calculated error bars, the values of which stem from Monte Carlo analysis. To a certain extent, uncertainty is dealt with later by applying sensitivity analysis. Together they can be employed to aid in interpretation of the impact assessment results.

Uncertainty is considered for the ATES systems alone, by excluding the heat sources from this analysis. Importantly, uncertainty ranges for most ATES parameters were not provided for during data gathering. These parameters were provided by the data sources as fixed values, apart from COP for GeoMEC which was given a range, applied later in sensitivity analysis. This means that uncertainty results show the uncertainty associated with the impact assessment methods employed, and with the inventory from Ecoinvent used to build up the processes representing the ATES in SimaPro.

4.1 Uncertainty analysis

The following shows the uncertainty analysis results of GeoMEC Vierpolders ATES system in isolation. Results are displayed for both the impact assessment and CED.

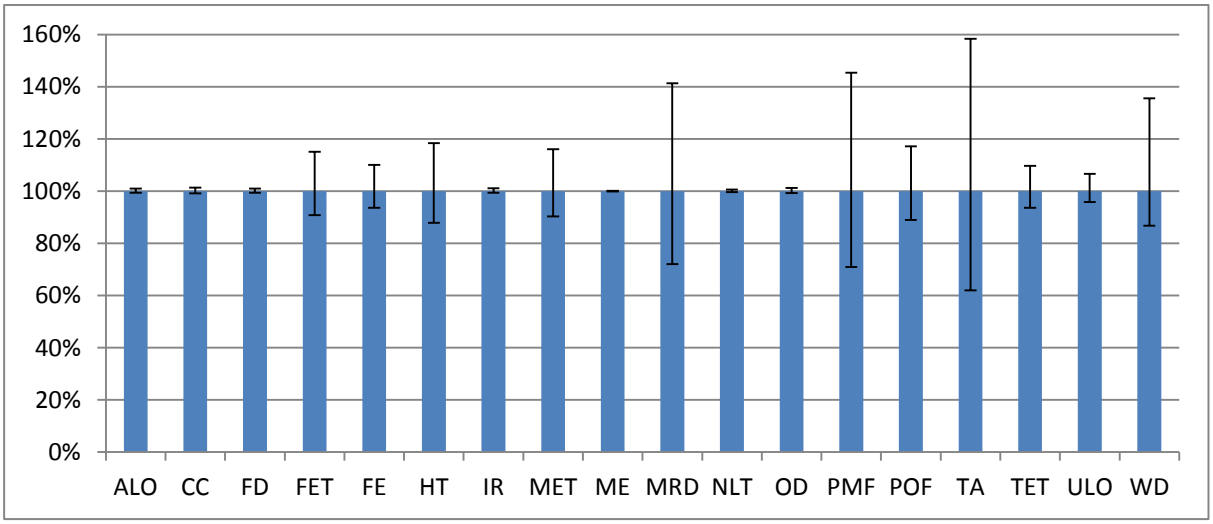

Figure 30 *GeoMEC Vierpolders ATES impact assessment uncertainty analysis featuring 100% stacked results for the mean values of the 18 impact categories – Characterised results. Mean values revealed in Monte Carlo.*

Results are shown in 100% stacked form in order that error bars may be viewed per impact category. This shows that it is especially metal depletion, particulate matter formation, terrestrial acidification and water depletion that show the highest uncertainties. Comparing these results against those of Figure 9 and Figure 10, where the impact assessment results for the GeoMEC ATES are shown indicates that it is especially the less substantial impact categories which have higher uncertainty ranges. Uncertainty was also considered for CED as follows:

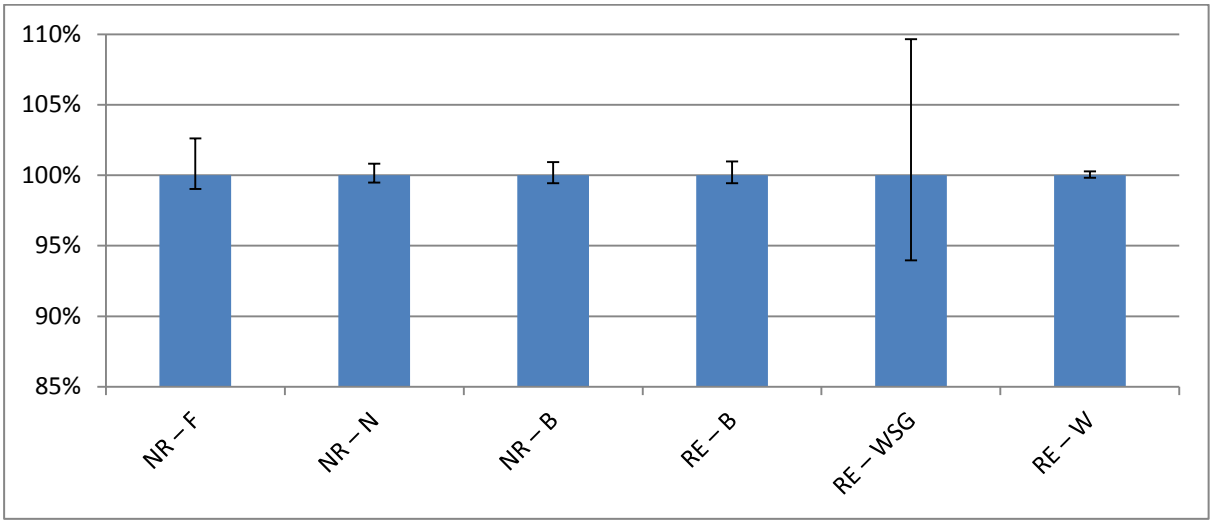

Figure 31 *GeoMEC Vierpolders ATES CED uncertainty analysis featuring 100% stacked results for the mean values of the 6 energy demand categories – Characterised results. Mean values revealed in Monte Carlo.*

When considering the uncertainty of energy demand, it is apparent that especially *'renewable, wind, solar, geothermal'* has an uncertainty range nearing >+/- 10%. However, this category only constitutes ~1.5% of the primary energy demand as shown by Figure 15.

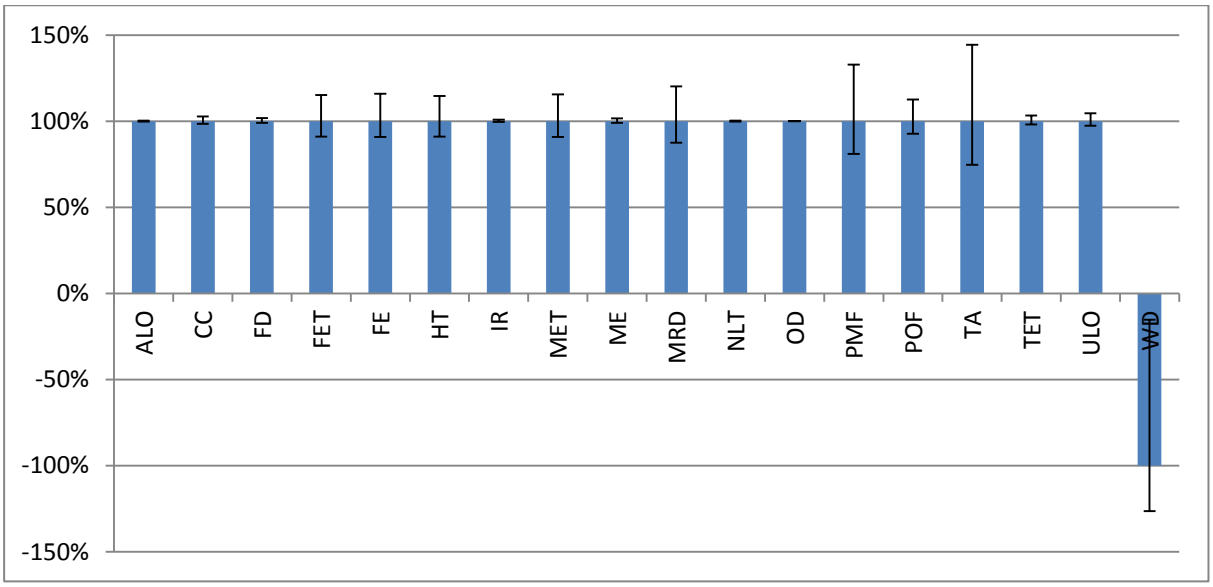

Figure 32 *AVR Duiven ATES impact assessment uncertainty analysis featuring 100% stacked results for the mean values of the 18 impact categories – Characterised results. Mean values revealed in Monte Carlo.*

Figure 32 shows the uncertainty analysis results of AVR Duiven ATES system in isolation. It shows that especially metal depletion, particulate matter formation, terrestrial acidification and water depletion show the highest degrees of uncertainty. This is consistent with GeoMEC. Comparing these results against those of Figure 19 and Figure 20, where the impact assessment results for the ATES are shown indicates once more that it is mostly the less substantial impact categories which have higher uncertainty. However, metal depletion is more important for AVR so these results should be taken with care.

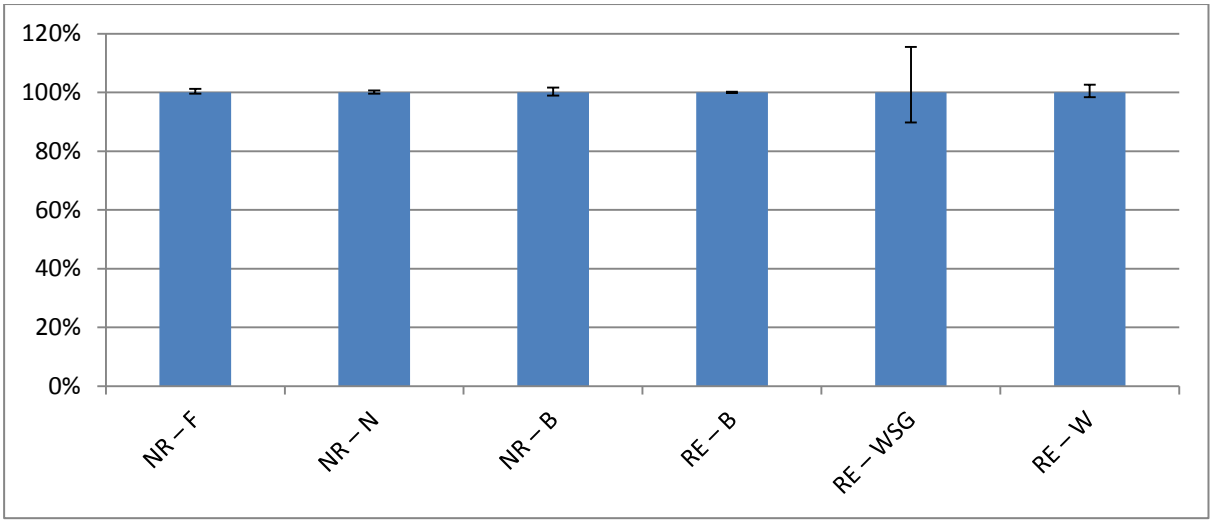

Figure 33 *AVR Duiven ATES CED uncertainty analysis featuring 100% stacked results for the mean values of the 6 energy demand categories – Characterised results. Mean values revealed in Monte Carlo.*

When considering CED uncertainty, it is especially *'renewable, wind, solar, geothermal'* which has a large uncertainty range (>10%). However, this category only constitutes 1.3% of the mean primary energy demand for the AVR ATES.

For practical reasons parameters and inputs were kept as simple as possible because the more parameters that are used, the higher the degree of uncertainty that follows. This is because results between the impact categories are dependent on the input parameters discovered during data gathering. When factoring uncertainty, on the one hand, inputs from the Ecoinvent database used to construct the LCA project intrinsically have uncertainty values defined in ranges of normal, uniform, lognormal or triangle uncertainty. The parameters which were manually inputted on the other hand are such that some of them have uniform uncertainty values and others are entirely certain. For example, the number of wells at Vierpolders is 6. This needs no uncertainty range because it is concretely defined in the design of the project. Uncertainty therefore largely comes from the Ecoinvent database.

It is expected that uncertainty results will be broader for the total systems than it would have been for the ATES systems in isolation. This has a lot to do with the possibility that the less-specific heat sources may have been miss-specified by making use of average situations. This may have resulted in data and model uncertainty as data can show variability, among other types of uncertainty (Finnveden *et al*., 2009). The uncertainty of the systems including heat sources is elaborated in Appendix 1: Uncertainty of total systems. Uncertainty for the total systems is done separately, in the appendices because the ATES systems themselves are comparatively more important for the scope of this research, and because the heat sources are mostly present as 'standard layouts' in the Ecoinvent library.

4.2 Sensitivity analysis

Sensitivity analysis is carried out on the most important parameters used to describe the case studies in SimaPro by means of parameter variation and scenario analysis. In this way it can be seen how sensitive impact assessment results are towards changes in the ATES infrastructure by means of parameters. This says something about sensitivity towards boundary conditions (increasing reliability). Parameters chosen are COP, operating hours per year, flow rate and lifetime. Sensitivity is measured by subjecting the parameters to high and low scenarios and then calculating the % change per impact category – compared with the default value – according to that high or low scenario. The degree of sensitivity calculated is represented in Δ% form, emphasized by shades of green and red (green for high scenario and red for low) – the darker the colour, the higher the % relative to the other parameter categories. Positive values mean that there is a lower % effect per impact category, and negative values mean that there is a higher resultant environmental effect per category.

For GeoMEC, parameter ranges chosen for the high and low scenarios were partially due to a range given by the data providers for COP, but otherwise by increasing and decreasing parameters compared with the default situation with a reasonable amount as consulted with Joris Koornneef (J Koornneef, pers.comm., Meeting, July 25, 2016):

Table 9 *GeoMEC ATES chosen sensitivity parameters and justification*

	Unit	Default value	High	Low	Factor or justification
COP	-	50	60	40	Range provided by interview discussion during data collection (K van der Zalm, pers.comm., Interview, April 20, 2016)
Operating hours	Hrs/y	4800	6000	3600	+/- 1200 hrs (J Koornneef, pers.comm., Meeting, July 25, 2016)
Flow rate	m^3/hr	390	440	340	+/- 50 m^3/h (J Koornneef, pers.comm., Meeting, July 25, 2016)
Lifetime	yrs	15	20	10	+/- 5 yrs (J Koornneef, pers.comm., Meeting, July 25, 2016)

Table 10 *GeoMEC sensitivity analysis using conditional formatting to highlight significance. More significant high scenario uncertainty is darker green and more significant low scenario uncertainty is darker red (See* **Table 3** *for abbreviations of impact categories).*

	CC	OD	TA	FE	ME	HT	POF	PMF	TET	FET	MET	IR	ALO	ULO	NLT	WD	MRD	FD
COP high	16%	16%	4%	14%	16%	12%	13%	7%	14%	13%	13%	16%	16%	13%	10%	16%	5%	16%
COP low	-24%	-24%	-7%	-21%	-25%	-18%	-19%	-10%	-21%	-20%	-19%	-24%	-24%	-20%	-15%	-24%	-7%	-24%
Hours high	1%	1%	15%	3%	0%	6%	5%	12%	3%	4%	5%	1%	1%	4%	8%	1%	14%	1%
Hours low	-1%	-1%	-24%	-5%	0%	-9%	-8%	-20%	-5%	-7%	-8%	-1%	-1%	-6%	-13%	-1%	-24%	-1%
Flow rate high	0%	0%	8%	2%	0%	3%	3%	7%	2%	3%	3%	0%	0%	2%	5%	0%	8%	0%
Flow rate low	-1%	-1%	-11%	-2%	0%	-4%	-4%	-9%	-2%	-3%	-3%	0%	0%	-3%	-6%	-1%	-10%	0%
Lifetime high	1%	1%	18%	3%	0%	6%	6%	15%	4%	5%	6%	1%	1%	5%	10%	1%	17%	1%
Lifetime low	-2%	-2%	-37%	-7%	-1%	-13%	-12%	-30%	-8%	-10%	-11%	-1%	-1%	-9%	-20%	-1%	-34%	-1%

For AVR, parameter ranges chosen for the high and low scenarios were based on comparability towards the GeoMEC case by matching the high and low scenario values with those of GeoMEC, or by adapting them with similar ranges. For AVR this meant:

Table 11 AVR *ATES chosen sensitivity parameters and justification*

	Unit	Default value	High	Low	Factor or justification
COP	-	201	242	161	+/- 20% (J Koornneef, pers.comm., Meeting, July 25, 2016)
Operating hours	Hrs/y	4891	6000	3600	Range chosen for comparability with GeoMEC
Flow rate	m^3/hr	150	200	100	+/- 50 m^3/h (J Koornneef, pers.comm., Meeting, July 25, 2016)
Lifetime	yrs	15	20	10	+/- 5 yrs (J Koornneef, pers.comm., Meeting, July 25, 2016)

Table 12 *AVR sensitivity analysis using conditional formatting to highlight significance. More significant high scenario uncertainty is darker green and more significant low scenario uncertainty is darker red (See* **Table 3** *for abbreviations of impact categories).*

	CC	OD	TA	FE	ME	HT	POF	PMF	TET	FET	MET	IR	ALO	ULO	NLT	WD	MRD	FD
COP high	15%	16%	8%	11%	11%	12%	13%	9%	16%	12%	12%	16%	16%	12%	5%	18%	10%	15%
COP low	-22%	-25%	-12%	-17%	-17%	-17%	-20%	-14%	-23%	-18%	-18%	-24%	-25%	-19%	-8%	-27%	-16%	-23%
Hours high	-20%	-22%	-11%	-16%	-15%	-16%	-18%	-13%	-21%	-16%	-16%	-22%	-22%	-17%	-7%	-25%	-14%	-21%
Hours low	23%	26%	12%	18%	18%	18%	21%	15%	25%	19%	19%	25%	26%	19%	8%	29%	17%	24%
Flow rate high	-30%	-33%	-16%	-23%	-22%	-23%	-27%	-19%	-31%	-24%	-24%	-32%	-33%	-25%	-11%	-36%	-21%	-30%
Flow rate low	30%	33%	16%	23%	22%	23%	26%	19%	31%	24%	24%	32%	33%	25%	11%	36%	21%	30%
Lifetime high	3%	0%	13%	6%	8%	5%	5%	11%	1%	6%	6%	1%	0%	6%	17%	-2%	8%	2%
Lifetime low	-5%	0%	-26%	-11%	-16%	-10%	-10%	-21%	-3%	-12%	-12%	-2%	-1%	-12%	-34%	4%	-16%	-4%

Results of the sensitivity analysis show how various important parameters affect the environmental footprint as a whole – as determined by ReCiPe midpoint. Percentage change seems to be quite high in general, which would likely be much less so if the larger, complete systems had been analysed in the place of focusing the ATES systems. Outcomes of the sensitivity analysis reveal clearer impact category sensitivity trends for GeoMEC ATES than for AVR ATES, as represented by the darker colours throughout COP as well as TA, PMF, NLT and MRD impact categories. For AVR, it appears that there are higher degrees of sensitivity for parameters that are not so strongly affected in GeoMEC. For example CC, OD, POF, TET, IR, ALO, WD and FD all seem to be strongly affected by all parameters apart from lifetime, whereas NLT appears to be mostly affected by lifetime – more so than GeoMEC.

Table 10 shows the results for GeoMEC. Sensitivities >10% across the impact categories are deemed relevant enough for discussion. Evidently, both high and low scenarios for COP have relatively large effects on the results. This is shown by the high (>10%) values (both positive and negative) reflected by the darker colours. COP has such sensitivity across all of the impact categories apart from TA and MRD, as well as the high COP scenario for PMF. For operating hours, especially TA, PMF and MRD are significantly affected, whereas NLT is mostly affected by the low scenario. Flow rate has an especially significant effect (within the low scenario only) on TA and MRD. Lifetime especially affects TA, PMF, NLT and MRD, whereas HT, POF, FE and MET are especially triggered by the low scenario.

Table 12 shows the sensitivity analysis results for AVR. Here we see that the only less significantly affected impact category is NLT, as well as the high scenarios for TA and PMF. For operating hours all of the impact categories apart from NLT are significantly affected for both high and low hours. Flow rate affects all categories significantly for both high and low flow rate. Lifetime especially affects TA, PMF and NLT, whereas especially the low lifetime scenario affects FA, ME, HT, POF, FE, MET, ULO and MRD.

Strangely, the high and low operation hours scenarios and the high and low flow rate scenarios affect GeoMEC and AVR in opposite manners. Where the high scenario results in positive (good) results for GeoMEC, it results in negative (bad) results for AVR. It would have been expected that high operation hours per year would have a positive impact due to more efficient use of the ATES per GJ heat delivered, whereas increased flow rate means that less thermal energy is produced and pumps work less hard – therefore lower impacts overall, but lower energy profitability. Calculation behind these strange results was double-checked, however reasons behind this behaviour was inconclusive.

5 General discussion

In this section the results and their implications are reflected upon and discussed by approaching them from the perspective of an overview. The main topics discussed take the form of a critical reflection of results, possible alternative situations, implications of uncertainty and sensitivity results, minor case specific factors, limitations of the approach – and subsequent recommendations and future study opportunities.

5.1 Critical reflection

Research featured in the IPCC-SRREN report shows that the majority of impacts associated with geothermal LCA are dominated by initial material and energy inputs during construction of the wells, power plant and pipe lines, rather than being a consequence of usable energy production (IPCC, 2012). Although this might be true for the deep geothermal installation at Vierpolders, this research disproves this hypothesis when regarding ATES (SGE) by pointing out that in fact, the operation phase of ATES constitutes the largest environmental effects due to impacts associated with electricity used for the pumps. This of course also has to do with the fact that ATES works as an energy buffer, rather than being an energy source, so energy use is not compensated by production. Results from Tomasetta also show that the use phase is responsible for the majority of (endpoint) LCIA results (Tomasetta, 2013; Tomasetta *et al*., 2015).

It is considered to be common knowledge that geothermal energy is one of the most effective low carbon dioxide emitting, large-scale energy sources available to us (IPCC, 2012). The IPCC-SRREN report does show that the main GHG normally emitted by geothermal operations is CO_2. This is because geothermal fluids contain variable quantities of gas which mostly comprises of CO_2 (IPCC, 2012). Gas composition and quantity depend on geological conditions encountered in different fields. CO_2 emissions however, are also dependent on the type of technology being applied. This study concerns direct heating applications in open-loop (ATES) systems, where CO_2 emissions are typically negligible (IPCC, 2012; Hendriks *et al*., 2010).

Overall, the geothermal heat source has been shown to have lower midpoint results across the impact categories than the waste incinerator heat source. This is due to emissions associated with the incineration of waste at AVR as seen in the process construction within SimaPro (Weidema *et al*., 2013). The incineration of various waste streams in the average Dutch waste incineration system includes the emission (to air) of substances resultant of incomplete combustion (Pré, 2015; Jones & Harrison, 2016). The geothermal facility on the other hand has very minor emissions, the majority of which in this case are associated with diesel generators that were used for the drilling operation of the geothermal boreholes (Weidema *et al*., 2013). This shows that the geothermal facility has lower environmental effects than the waste incinerator overall, however, seeing as that the majority of effects are associated with the drilling of the doublet, rather than operation of pumps at the geothermal facility – this suggests that a large proportion of effects may be missing from the geothermal process employed.

Considering the results as they were modelled alongside their heat sources, climate change and fossil depletion environmental interventions are lower for the total situations of both GeoMEC and AVR than they are for an industrial natural gas incinerator – so both study objects exhibit savings for these categories. GeoMEC saves 60.8 kg CO_2 (eq) and 22.5 kg oil (eq), and AVR saves 12.1 kg CO_2 (eq) and 3.8 kg oil (eq) per GJ heat delivered. However, when more impact categories are taken into account, the study objects sometimes perform more poorly than natural gas. This is especially so for the AVR ATES/incinerator system. GeoMEC ATES/geothermal performs worse in terms of ME, IR, ALO, WD and MRD (See Table 3 for impact category abbreviations). On the other hand, the AVR ATES/incinerator system performs more poorly for all categories apart from CC, OD, WD and FD (See Table 7).

Reviewing results in normalised form reveals that, compared with European average annual emissions per inhabitant, relative to 1 GJ heat – GeoMEC ATES/geothermal system outperforms natural gas in every category, where the AVR ATES/incinerator system is outperformed in half of the impact categories by natural gas: FE, ME, HT, PMF, FET, MET, ALO, NLT and MRD. Combining all the categories, relative to European averages, AVR is shown to be -0.46 Pt worse and GeoMEC is 0.13 Pt better in total when compared with natural gas. The scores for the total situations are around 10x higher than those of the ATES in isolation, which highlights how small the marginal effect of ATES is on the heat sources.

The largest responsibility across the impact categories evident from characterised results is due to the ATES pumps for GeoMEC in both the ATES-only and the total (including geothermal well) situations. This trend of ATES pump (operation) dominance is interrupted in the categories TA, POF, PMF, TET and MRD – where ATES warm wells and geothermal facilities together display dominance. Once the entire infrastructure is considered, the geothermal wells display dominance in only POF, PMF and TET. Closer inspection of the geothermal heat producing process used for GeoMEC revealed that the ATES and geothermal doublet make use of the same electricity source – 'Electricity, medium voltage {NL}', which in the doublet is used at the adapted Hot-Dry-Rock geothermal facility. However, the majority of electricity impacts at the geothermal doublet are derived from diesel, burned in a diesel-electric generating set used to drill the geothermal boreholes. It is apparent that this process has lower values across the impact categories per GJ when compared with average, Dutch electricity. For CC and FD specifically, the diesel generator results in 89 kg CO_2 (eq) compared with 179 kg (eq) for Dutch electricity, and 30.5 kg oil (eq) for diesel compared with 59.4 kg (eq) for Dutch electricity. Regarding the most relevant categories according to normalisation – diesel outperforms Dutch electricity in FE, ME, HT, FET, MET and NLT by exhibiting lower results, whereas in some of the less relevant categories – OD, TA, POF and PMF – Dutch electricity performs better than diesel per GJ.

The realisation of the high contribution of ATES pumps highlights the flaws in the methodology used to incorporate the geothermal heat source at Vierpolders. In actual fact, simply due to the deeper wells of the geothermal doublet, more electricity would be expected to be required as compared to the ATES boreholes for the sake of pumping geothermal fluid (Hähnlein *et al*., 2013). This means that the outcomes should actually have resulted in the ATES at GeoMEC constituting a smaller proportion of the overall effects, due to the majority of effects being determined largely by the use of electricity – for which the ATES and the geothermal doublet would utilize the same source. This fault comes down to an error in modelling the geothermal heat source. The geothermal heat source was adapted from a Hot-Dry-Rock geothermal power plant which used self-produced electricity for pumps operation (Weidema *et al*., 2013). This low-effect geothermal electricity has failed to be incorporated into the method, resulting in an underestimation of environmental effects from the GeoMEC heat source.

For the ATES system at AVR, the pumps are dominant across all impact categories save for NLT, where responsibility is divided fairly equally between ATES pumps, the warm well and the cold well. When the heat source is considered, impact categories are almost entirely dominated by the waste incinerator. Normalised results show that in perspective, natural land transformation is the most relevant factor across the impact categories for both case studies, followed by marine ecotoxicity and then freshwater ecotoxicity. Dominance by the waste heat thermal provider is due to the large effects of the operation of the incinerator, which burns waste (Pavlas *et al*., 2010). Although it is plausible that the waste incinerator would have larger effects than the ATES at Duiven, the heat source is modelled too inaccurately to draw solid conclusions. This verifies that the methodology used to compile the waste incinerator at Duiven too, was flawed.

In terms of the Cumulative Energy Demand, both study objects result in a higher total CED compared with natural gas. GeoMEC energy demand exceeds that of natural gas by a total 1.14 GJ, whereas AVR by 0.44 GJ. This is especially due to the high renewable, geothermal primary energy demand of the geothermal facility at GeoMEC, and the combined nuclear and biomass energy demand featured within the waste incineration process at AVR.

It can be calculated from results in Table 8 that ~19% of cumulative energy demand for AVR comes from a (non-renewable) nuclear source and another 19% from (renewable) biomass. It is important to remember that this is not necessarily true for the actual situation at Duiven, in which the waste incinerator uses a much higher proportion of (renewable) biomass in the incineration process in reality (AVR, 2015b). This comes from the renewable waste stream used to fuel the incinerators from the local region and from Germany (AVR, 2015b). CED results highlight how outcomes of the total situations are highly dependent on assumptions used in the compilation of the heat source processes.

5.2 Alternative scenarios

As an alternative to the AVR ATES/incinerator system, the case study can be approached ignoring environmental effects from the heat source because an environmental service is provided for by the waste treatment process (Pavlas *et al*., 2010; Eriksson *et al*., 2007; Ekvall *et al*., 2007). The service provided consists of AVR producing construction material from paper waste, recuperating precious metals by purifying flue gases and industrial waste water, paving stones from bottom ash as well as producing thermal and electrical energy from waste incineration (AVR, 2016).

Considering these services the total environmental footprint of Duiven could be seen to be equivalent to that of its ATES system alone. The result of this is that, in the context of CC, this would result in 2.62% of the total results expected in the normal situation. Categories such as NLT cannot be overlooked because, seeing as that the physical infrastructure of the AVR incinerator would still be required in this scenario, land occupation factors cannot be ignored along with factors such as CO_2 emissions associated with the waste incineration process. For the energy demand analysis, the waste incinerator for Duiven also cannot be ignored as the environmental service of waste treatment is less relevant from an energy demand perspective.

Another interesting scenario considers exchanging the Dutch average, medium voltage electricity used for the ATES pumps with electricity produced from a renewable source. Wind power is chosen as an appropriate substitution with the process 'Electricity, high voltage {NL} electricity production, wind, >3MW turbine, onshore'. High voltage was considered in the place of medium voltage because SimaPro did not have other possibilities for this (Weidema *et al*., 2013). The result is an overall decrease in single score (ReCiPe midpoint bioboost) impact assessment of GeoMEC to 0.73 Pt per GJ. Changes are not uniform across the impact categories (See Appendix 2: ReCiPe midpoint shadowprices bioboost). The most relevant impact category according to characterisation becomes human toxicity with 80% of original situation. Fossil resource depletion also decreases to 6% of the original situation. FET, MET and MRD effects increase greatly (See Appendix 3: ReCiPe midpoint (H) impact assessment GeoMEC ATES with wind power). Overall, the use of wind energy for the pumps results in 10.82 kg CO_2 (eq) savings per GJ compared to the GeoMEC ATES situation using Dutch, medium voltage electricity for operation.

CED results of the alternative GeoMEC scenario would have a cumulative demand of 81 MJ for the GeoMEC HT-ATES system – a decrease from 212.25 MJ. The most substantial demand comes from the category, '*renewable wind, solar, geothermal'* due to the electricity source with a value of 68.28 MJ. *'Non-renewable, fossil'* decreases to 10.51 MJ from 176.63 MJ and '*non-renewable, nuclear'* decreases from 21.08 MJ to 1.18 MJ demand. Overall, switching to a renewable source of electricity such as from wind turbines has a positive effect on both the environmental load and on primary energy demand by reducing both elements.

For both situations, the vast majority of ATES environmental effects can be allocated to the operational phase. For the ATES this is clearly related to the electricity used during the 15 year period of life – allocated to the pumps. This is exacerbated in particular by emissions from fossil fuel fired power plants that supply the electricity for GeoMEC and waste incineration which supplies the electricity for AVR. When the electricity source at GeoMEC is changed from the Dutch average, medium voltage electricity mix

to electricity from renewable wind turbines – the environmental effects overall clearly dip (See Appendix 8.3). However, for categories such as FET, MET and MRD, characterised results are much higher for renewables than they are for average Dutch electricity. Considering the other life cycle phases of the ATES systems shows that the effects of drilling, installation and materials used are practically negligible when compared with the electricity use of pumps. This is true for every impact category apart from HT and MRD, which are mostly dominated by materials used for the warm wells that use large amounts of RVS steel in their construction.

5.3 Implications of uncertainty and sensitivity

The degree of uncertainty of impact assessment and CED results has much to do with the analysis methods chosen within SimaPro. This is because each impact category is associated with a coefficient of variation and often makes use of a linear dependence on certain emissions i.e. kg SO_2 (eq) with acidification (Finnveden *et al*., 2009). The Monte Carlo method is used to analyse uncertainty as the Ecoinvent database already contains probability distributions and the ReCiPe method contains algorithms for conducting Monte Carlo analysis (Huijbregts *et al*., 2001; Weidema *et al*., 2013).

Comparing the two case studies against one-another, we see that COP and lifetime affects them both in a similar fashion. However, in terms of operating hours the difference in high and low scenarios affects the study objects in an opposite manner. Where the low scenario affects GeoMEC negatively (smaller effects) and the high scenario affects it positively, the low scenario is the one that affects AVR positively. When considering flow rate on the other hand, results show that GeoMEC is surprisingly insignificantly affected by both high and low scenarios, whereas for AVR flow rate has the highest average percentage of sensitivity for all of the impact categories across the parameters, and for both the high and low scenarios.

For almost all of the impact categories for both GeoMEC and AVR, there exists a tendency for higher sensitivity as a result of the low scenarios than the high scenarios. This is true for all the parameter scenarios apart from the flow rate of AVR, which is equally affected for both high and low scenarios across the impact categories e.g. -33 and +33% for high flow rate and low flow rate for OD. Interestingly for both cases, lifetime changes do not substantially affect CC (no more than 5%).

5.4 Further discussion

For the GeoMEC Vierpolders case study it should be mentioned that in order to deal with calcium carbonate ($CaCO_3$) precipitation that would occur due to elevated subsurface temperatures around the warm wells, the site operators have suggested that hydrochloric acid (HCl) may be used. HCl is to be flushed through the warm wells along with groundwater such that chloride concentrations would increase by ~10% (K van der Zalm, pers.comm., Interview, April 20, 2016). To negate impacts from the use of HCl, a 2 m^3 polyethylene storage tank is used in conjunction with a collecting basin around it. Excess HCl collects in this system, the material use of which would result in insignificant impacts with regards to the ATES as a whole. Effects associated with the 2 m^3 storage tank would be negligible, so they are ignored in this thesis.

Relevance in this study stems from both an environmental and an energy efficiency perspective. In combination with this, the changes happening in the EU in terms of the importance of renewables and efficiency improvements within the energy transition creates relevance. This research contributes to a knowledge base which is currently demanding expansion. LCA of the various existing types of geothermal installations is still very limited. Thereby, this research fills a research and literature gap by expanding the scientific knowledge base. Contribution is also made to knowledge about environmental footprint reduction and energy efficiency improvement.

This research is relevant for TNO, from where the research internship was followed in order to complete the thesis. Presence at TNO enabled direct exposure to sources of data and expertise in the fields of

geothermal, subsurface energy storage and LCA. Similarly, this research is relevant for Utrecht University as well as heat users who may be considering the use of heat storage.

The reusable setup of the LCA in combination with a spreadsheet calculation tool can be useful to assess whether a business case exists in an ATES-related project with aims in decarbonising heat production, or in reducing flows of other specific emissions pathways. This report can be used as a tool to raise TNO's profile in environmental impact assessment of energy systems as it produces an effective means to assess environmental effects of subsurface energy storage.

5.5 Limitations

Limitations to the study mainly have to do with SimaPro in the form of limitations in the LCA methodology employed and in terms of data and information limitations.

Data was limited for the waste incinerator used by AVR at Duiven, and for the ATES system used by AVR as well – which due to being conceptual did not have any information on its physical design and infrastructure and was therefore modelled based on that of GeoMEC. Data was also limited for the geothermal doublet being used by GeoMEC because the initial focus of the research strictly focused on the HT-ATES systems, excluding impact assessment of their respective heat sources. The result of this is that data was gathered in as much detail as possible for the ATES, but in fleeting detail for the heat sources. Once it became apparent that the heat sources would be considered, it was decided to model them as basic inputs from the Ecoinvent library – a method which was found to be flawed as it depicted situations which were too far from the reality. The flaws resultant of this application of the heat-source methodology shows that it is necessary to construct all aspects of the study objects by means of extensive data gathering, in a case-specific manner.

Comparison with international scientific literature was attempted, however, due to the novelty of this ATES LCA project – no comparable literature was found aside from that of Tomasetta *et al* (2013 & 2015). Other scientific literature exists in the form of geothermal LCA and overview papers (Hähnlein *et al*., 2013; Axelsson, 2010; Lund, 2010), as well as some LCA literature on different types of TES (Ferguson, 2013; Oró *et al*., 2012; Denholm & Kulcinski, 2004; Xu *et al*., 2014). Conclusions of these papers tend to agree with the outcomes of this study as they verify that life cycle greenhouse gas emissions are lower for storage systems combined with renewables than with fossil fuels, but also that geothermal is a better choice than conventional fossil fuels in terms of subsurface energy footprints (Denholm & Kulcinski, 2004; Ferguson, 2013; Lund, 2010).

The current state of the art of the impact assessment methodologies has a loophole in that not all of the possible interventions which may occur in the subsurface of situations considered are necessarily covered. LCA results inherently depend on the environmental conditions and the system boundaries in which analysis has been carried out. This means that results of the impact assessment are limited to for instance 18 ReCiPe midpoint impact categories in the ReCiPe midpoint (Hierarchist) method or 6 energy categories in the CED method – such as in this case – rather than on specific impacts or emissions which may be of particular importance to an individual stakeholder. This shortcoming can be seen in the discussion of the possible effects of HCl at GeoMEC in section 5.4.

Paradoxically, due to the large number of impact categories which are included, their full discussion would result in an overly long thesis report. Therefore, it was necessary to select key categories which displayed the most relevant or substantial results, and to discuss these in detail. This means that, although displayed in the graphical results – some impact categories are only fleetingly discussed, whereas these results could prove to be especially important dependent on the reader.

The normalisation method followed also has its limitations. Since European normalisation is followed for the impact assessment, results are placed into the context of yearly average pollution by a European inhabitant in the year 2000 – which determines relevance.

Lastly, the two case studies have more than one significant variable between them. They have different subsurface conditions, resulting in largely different ATES circumstances. Besides the difference in number and depth of wells, the two case studies are separated by far more favourable conditions at Duiven than at Vierpolders for the operation of ATES. Therefore comparisons between them do not result in the conclusion that one system functions better than the other in general terms, but rather in terms specific to their boundary conditions. Not only do the storage systems differ in number and depth of wells, but so does the subsurface of the two locations. On top of this, the heat sources present another important variable as they function in a vastly different manner to one another.

5.6 Recommendations and future study

Sensitivity analysis shows that environmental effects are particularly affected by COP and operating hours for GeoMEC, and COP, operating hours and flow rate for AVR. This means that in order to improve the environmental profiles of the study objects, higher COP should be strived for at Vierpolders. Increased operating hours would also be beneficial because, despite it resulting in more electricity use for the pumps, it also results in larger amounts of energy production and injection to the ATES (which would still have the same efficiency). At Duiven, higher COP, but especially higher operating hours and flow rates would achieve the most environmentally friendly results. It is recommended to improve efficiency of ATES in this regard as much as possible to ensure lower effects coming especially as a result of electricity consumption. Increased efficiency should also result in lower cumulative energy demand, and therefore higher energy recovery. At GeoMEC low ATES efficiency of 46% means that in order to produce 1 GJ heat from ATES, 2.17 GJ of geothermal heat is required from the source, with an additional external demand amounting to 2.43 GJ primary energy demand. High ATES efficiency of 86% for AVR means a better ratio of energy injected to energy produced, resulting in a lower environmental footprint as a result of the HT-ATES system. For the production of 1 GJ at AVR, 1.16 GJ is required from the heat source, with a cumulative primary energy demand of 1.73 GJ. If the ATES efficiency at GeoMEC were to be increased to even 60%, this would result in 0.5 GJ more energy recovery per GJ delivery or ~1/3 more.

As this is one of the first ATES LCA analyses, the possibility for future study is great. To begin with, future studies could look into comparing the ATES systems against a natural gas fuelled boiler that would normally be used in the place of the ATES to satisfy excess heat demand during winter. Here the ATES-specific savings could be compared against natural gas as well, rather than comparing only the total situations against heat sources. In addition to this, the same ATES system could theoretically be modelled in combination with a waste incinerator and with a geothermal well to see which it complements better. This could be done using the LCA project and calculation tool set up during research. Furthermore, future study could model the heat sources of the case studies in a more complete manner. This would mean carrying out case-by-case, in-depth inventory analysis to complete the heat sources, which would result in increased reliability of results incorporating the heat sources. Lastly, subjecting the results to global normalisation, Dutch normalisation (where possible) or even calculating a more recent normalisation would result in more interesting and relevant results, dependent on the context and interest of the reader.

6 Conclusions

This research looks at two High Temperature Aquifer Thermal Energy Storage (HT-ATES) systems which store heat produced at a geothermal heat plant (GeoMEC) and a municipal waste-to-energy facility (AVR) in the Netherlands. The sustainability of these two systems is assessed as they are not free of environmental effects. This assessment aims to show how substantial these effects are in comparison with those of the heat sources, as well as showing how much primary energy is demanded for the total systems, irrespective of their energy-saving function. The thesis is approached from the angle of the research question: "What is the added effect of HT-ATES on the environmental life cycle and cumulative energy demand of a geothermal heat doublet or Dutch waste incinerator providing heat?" This question is broken down into three research sub-questions:

- What is the environmental benefit of ATES with a geothermal heat plant or a Dutch waste incinerator in terms of environmental load and cumulative energy demand?
- How substantial is the impact of HT-ATES compared with heat sources?
- How does the environmental life cycle and cumulative energy demand of ATES/heat source-coupled systems compare with conventional, natural gas?

The research carried out enables the first research sub-question to be answered with conviction, however the second cannot be answered due to the methodological challenge of heat-source inclusion and the third research sub-question is also answered with some scepticism.

The difference in energy injected and produced for the HT-ATES systems is 26% and 54% for GeoMEC and AVR, respectively. ATES pays off because the initial energy investment of the HT-ATES systems is low compared to that during operation: this makes it sensible to consider the addition of ATES at Vierpolders and at Duiven. This outcome is more so for AVR than GeoMEC because of the smaller comparable size of the ATES compared with heat source for AVR. Compared with natural gas, both systems exhibit a higher total energy demand per GJ heat delivery. In terms of impact assessment, the outcomes suggest that both cases show savings in terms of fossil fuels, when compared with a natural gas incinerator. Therefore HT-ATES is very interesting in terms of environmental yield because of the large amount of energy saved as a result of high delta T. These outcomes are limited by the methodology which works to relativize the heat sources, and should be considered in the answer to the third research sub-question. An interesting question becomes how you can further optimize the operation phase in order to improve yield of the system by means of, for instance, increasing the efficiency of the ATES.

The method used to compile the heat sources shows that it is not representative to simply take a process from the Ecoinvent database and to model this with minor adaptations. The flaws resultant of this application of the heat-source methodology shows that it is necessary to construct all aspects of the study objects by means of extensive data gathering in a case-specific manner. This means that results considering the total systems (ATES/heat source), should be viewed as relative cases, rather than accurate representations of the reality. Having looked extensively at the possibility of adapting existing Ecoinvent heat sources as inputs to the total systems in use, it can be concluded that there are too many uncertainties and assumptions to use this method accurately. This problem forms the basis for future research. Therefore, the findings indicate that the higher the environmental footprint of a heat source, the less substantial the comparative footprint of HT-ATES. In terms of energy demand, the buffer function carried out by HT-ATES is recommendable due to the low environmental footprint and energy investment and the high energy savings.

Overall, this research contributes new understanding towards the life cycles of HT-ATES and how this may be modelled. This fits into the study of energy storage by filling in a literature gap which shows how ATES helps to take a step in optimizing the current energy system, and how it can reduce fossil fuel dependency.

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8 Appendices

8.1 Appendix 1: Uncertainty of total systems

8.1.1 GeoMEC ATES/geothermal facility

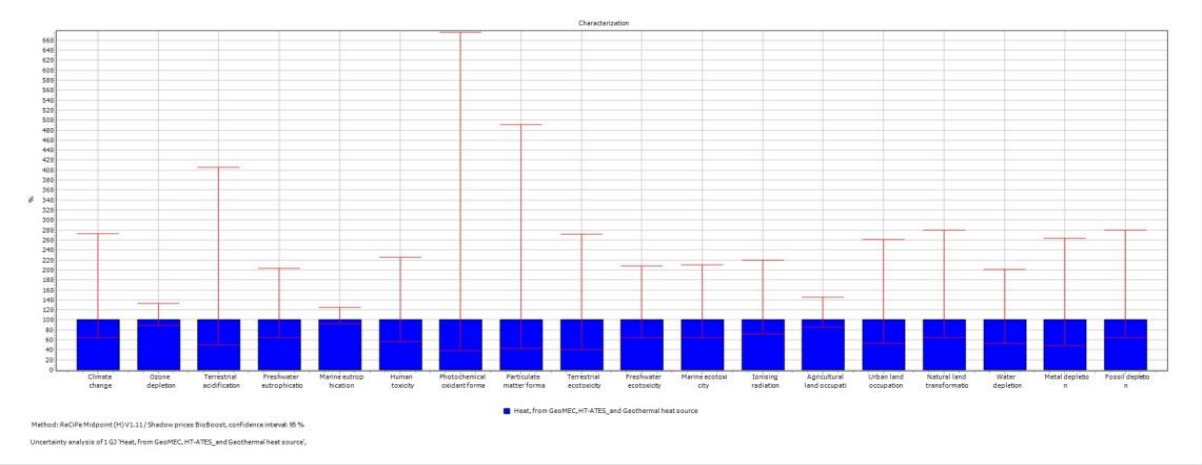

Figure 34 *GeoMEC ATES/geothermal doublet. Uncertainty analysis of 1 GJ heat. ReCiPe midpoint (H). Characterised results*

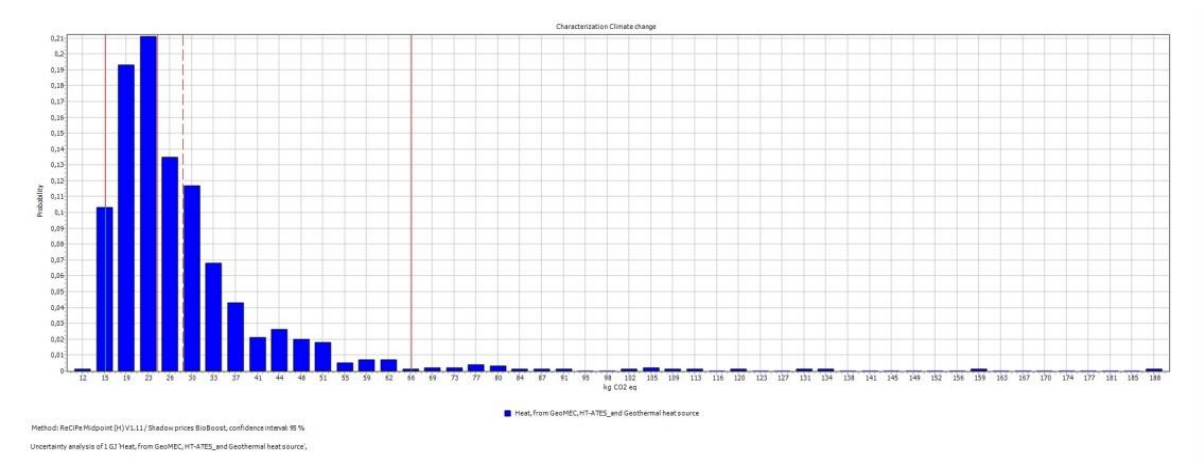

Figure 35 *GeoMEC ATES/geothermal doublet. Uncertainty distribution ReCiPe midpoint (H)*

Uncertainty overall is largely determined by the heat source, and less so by the ATES. This is because of the sheer scale of the heat source compared with the ATES. When interpreting the results of uncertainty analysis, it can be seen that many categories pertain a large degree of uncertainty. This is especially so for the category POF. Referring to Figure 13, which shows the normalised impact assessment results of GeoMEC ATES and geothermal well coupled system, reveals that in fact CC, HT, WD, MRD and FD are the 5 most relevant impact categories. These categories have significant uncertainty, but nowhere near that of categories such as POF. Distribution for GeoMEC is lognormal.

8.1.2 AVR ATES/waste incinerator

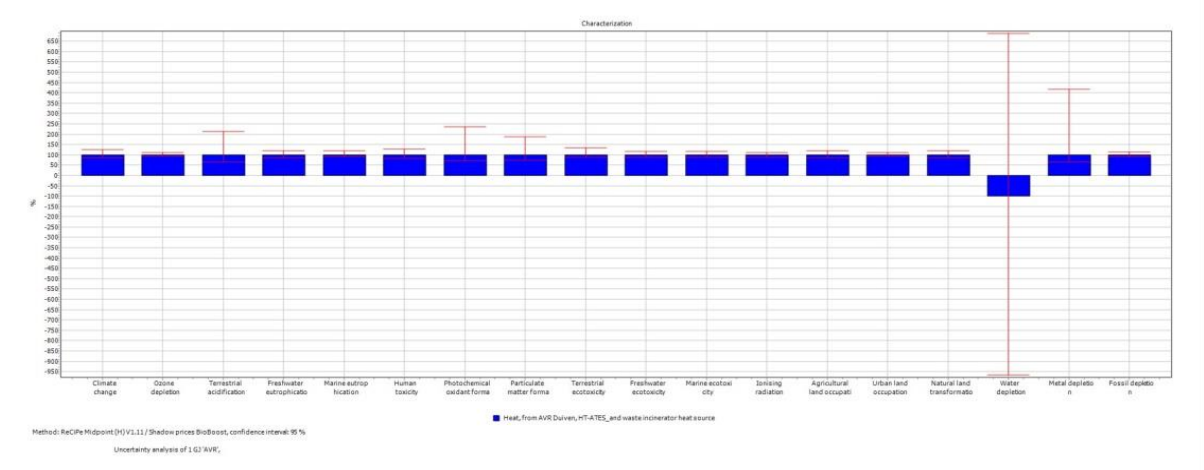

Figure 36 *AVR ATES/waste incinerator. Uncertainty analysis of 1 GJ heat. ReCiPe midpoint (H). Characterised* results

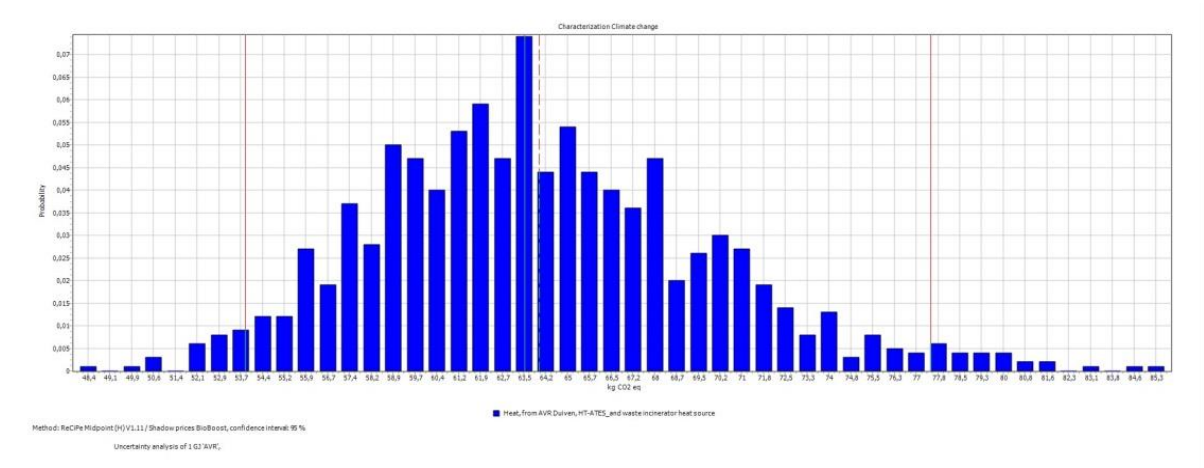

Figure 37 *AVR ATES/waste incinerator. Uncertainty distribution. ReCiPe midpoint (H)*

Uncertainty for the AVR ATES and waste incinerator system is also largely determined by the heat source due to the larger size of this installation. Figure 36 and Figure 37 generally show a smaller uncertainty than GeoMEC, with reasonably normal distribution. However, the negative water depletion featured in the impact assessment in Figure 22 displays an enormous degree of uncertainty in Figure 36. This suggests that the method used within SimaPro to calculate water depletion might not be trustworthy. Despite this, referring to the normalised results in Figure 23 shows that water depletion may be unsubstantial enough to be ignored.

8.1.3 Reference situation

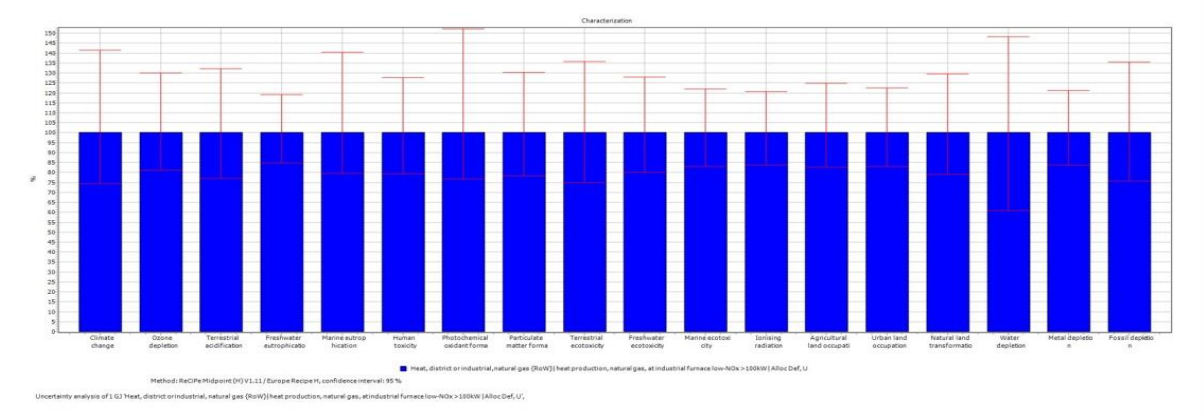

Figure 38 *Low NOx natural gas heat production. Uncertainty analysis of 1 GJ heat. ReCiPe midpoint (H). Characterised results*

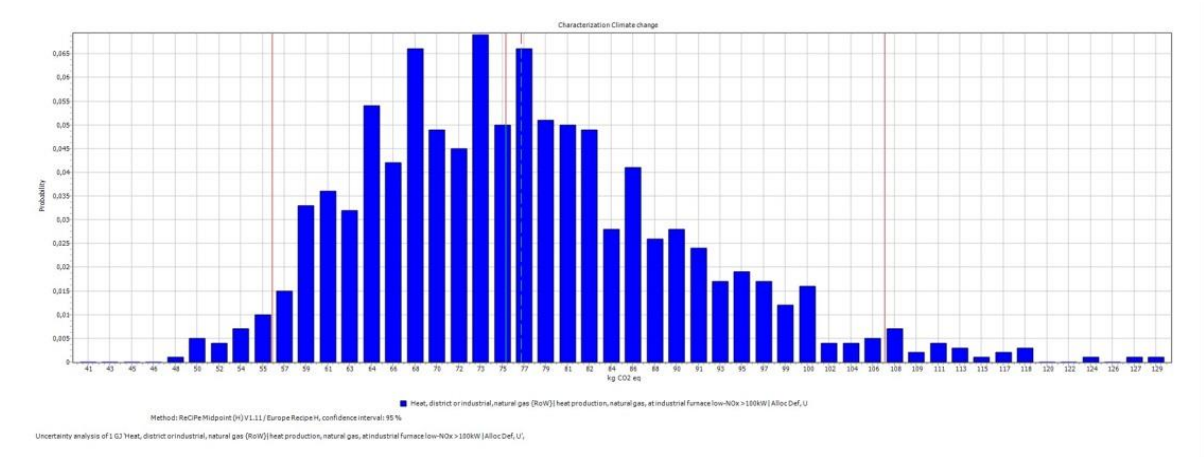

Figure 39 *Low NOx natural gas heat production. Uncertainty distribution. ReCiPe midpoint (H)*

Error bars calculated for the reference case show a fairly normal distribution with fairly evenly distributed uncertainty between the impact categories. Climate change, human toxicity and fossil depletion are the three most relevant categories as revealed in the normalised impact assessment in Figure 28 where the reference case is included. These categories all feature error bars of ~+/- 30%.

8.2 Appendix 2: ReCiPe midpoint shadowprices bioboost

8.2.1 GeoMEC ATES and ATES/geothermal facility

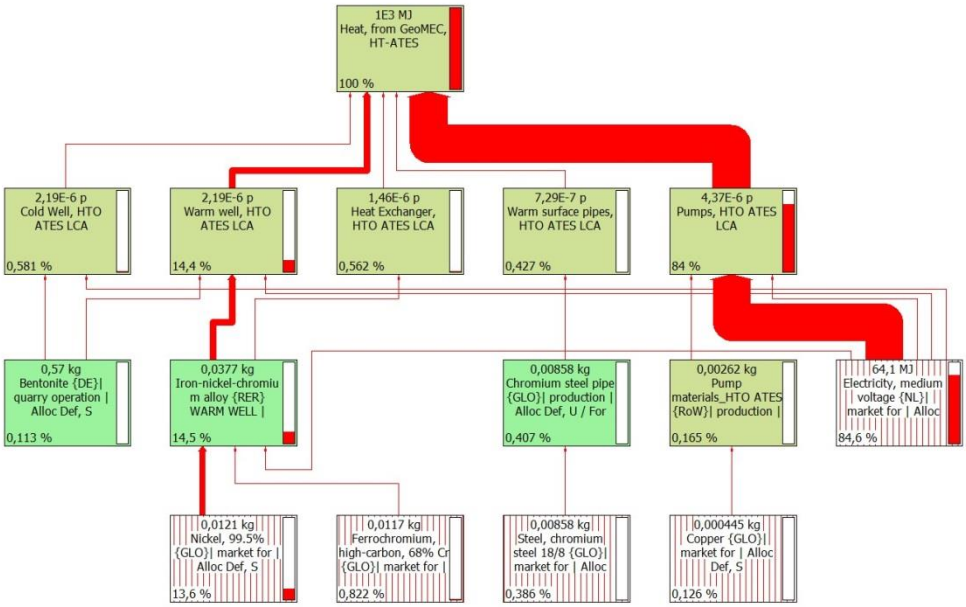

Figure 40 *GeoMEC Vierpolders ATES network diagram. Single score impact assessment with indicators represented in% form, rather than absolute values – ReCiPe midpoint (H) cut-off: 0.1%*

Figure 40 shows single score network summed values for GeoMEC ATES with indicators represented in % form i.e. percentage of the total single score. This gives a general idea of where impacts are coming from by compiling midpoint indicators into a single result. Here the cumulative result is 3.35 Pt. In this case predominantly due to the use phase of the pumps, followed by the large material input required in the warm wells largely attributed to the Iron-nickel alloy production (or RVS steel).

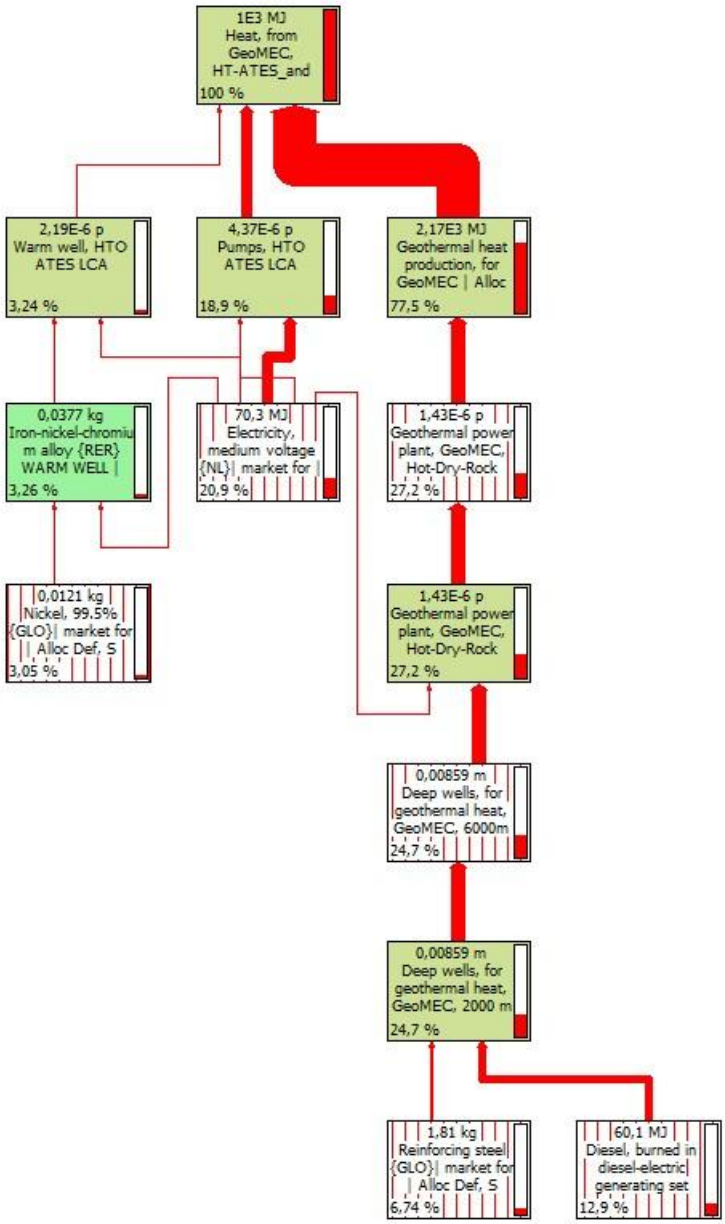

Figure 41 *GeoMEC Vierpolders ATES/geothermal installation network diagram. Single score impact assessment with indicators represented in % form, rather than absolute values – ReCiPe midpoint (H) cut-off: 2.76%*

Figure 41 shows the general single score network for the full GeoMEC system – ATES including heat source. Indicators are represented in % form. This gives a general idea of where impacts are concentrated. In this case again due to the use phase of ATES pumps – but also due to the operation of the geothermal facility. We can see that in the case of the full system, pumps electricity of the ATES now accounts for ~19% of the single score, whereas geothermal heat production accounts for 77.5% of the single score. Cumulative points amount to 14.9 Pt for the complete system, therefore ATES accounts for 22.5% of the single score impact assessment outcome.

8.2.2 AVR ATES and ATES/waste incinerator

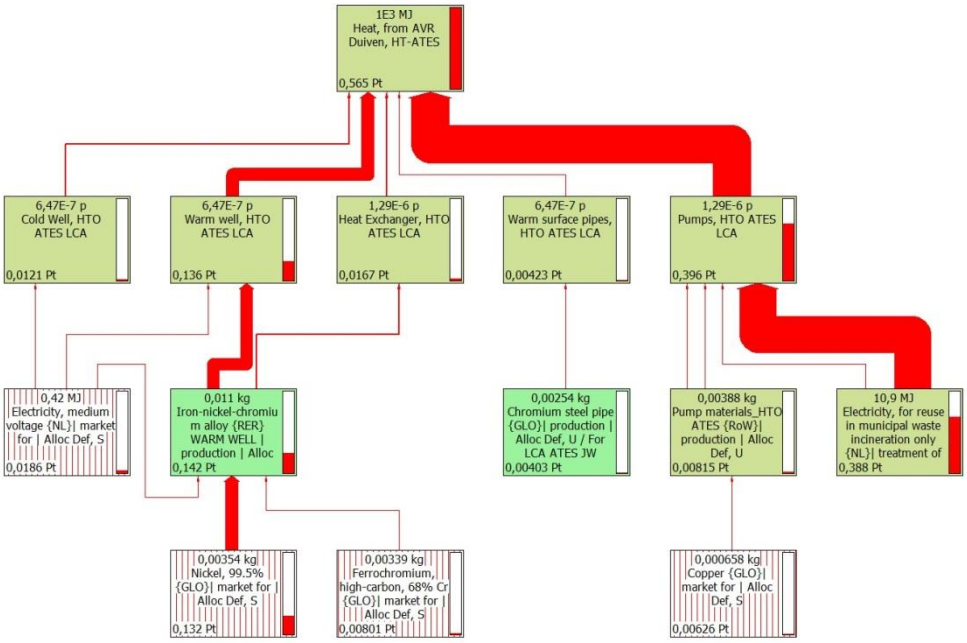

Figure 42 *AVR Duiven ATES network diagram. Single score impact assessment with indicators represented in % form, rather than absolute values – ReCiPe midpoint (H) cut-off: 0.7%*

Figure 42 shows single score networked values for AVR HT-ATES with indicators represented in % form. The results are distributed in a similar fashion to those of GeoMEC, being dominated by electricity for the pumps, followed by materials from the warm well. In the case of Duiven however, electricity comes from a different source – electricity for reuse in municipal waste incineration. This means that Duiven supplies its own electricity from the same facility that functions as a heat source for operation of the ATES. The second most important source of impacts is also the warm well here. It should be remembered that Duiven only has one warm well for the ATES, but also that the total length of casing (and drilling depth) is similar to GeoMEC (600 m as opposed to 450 m for AVR). The cumulative single score result is 0.57 Pt – 17% of GeoMEC per GJ heat delivered. 70% of this is due to the pumps and 24% due to the warm well, whereas the remaining 6% is attributed to the outstanding infrastructure.

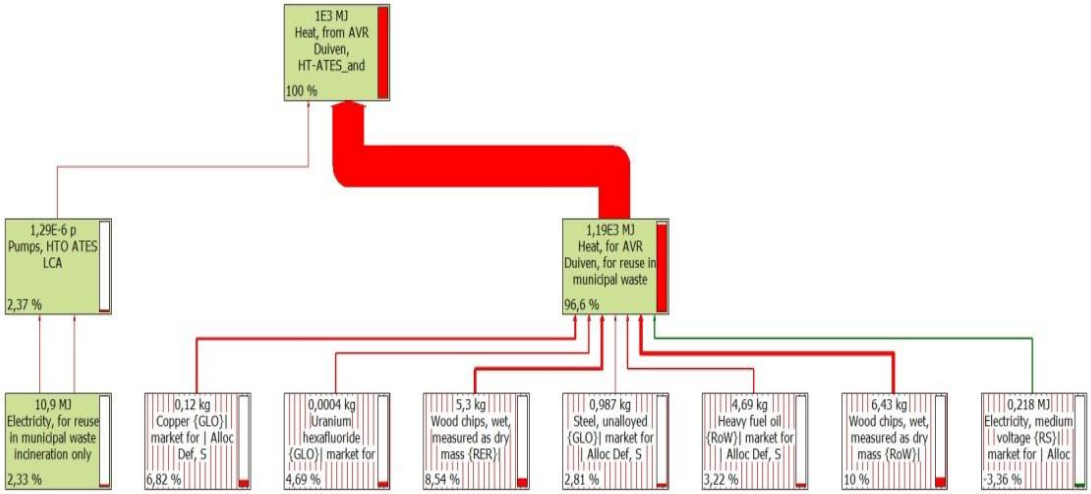

Figure 43 *AVR Duiven ATES/waste incinerator network diagram. Single score impact assessment with indicators represented in % form, rather than absolute values – ReCiPe midpoint (H) cut-off: 2.3%*

When considering the total HT-ATES/incinerator system, Figure 43 shows how single score impacts associated with the waste incineration facility completely dwarf impacts from the Duiven ATES system.

The incinerator accounts for 96.6% of these results. The ATES system as a whole accounts for the remaining 3.4% (2.4% being due to the pumps electricity). Cumulative results amount to 16.7 Pt for the complete system, therefore ATES accounts for only ~3.3% of the single score outcome. Therefore the environmental life cycle of the HT-ATES has a much more substantial impact on the environmental life cycle at Vierpolders than at Duiven – this is confirmed in impact assessment results. Discussing the single score results overall, it is right and proper to point out that the single score points for ATES before the inclusion of the heat source are much lower than when the source is included. Looking at the total AVR system vs. total GeoMEC system (including heat sources) – we can see that AVR has 12% more points than GeoMEC.

8.3 Appendix 3: ReCiPe midpoint (H) impact assessment GeoMEC ATES with wind power

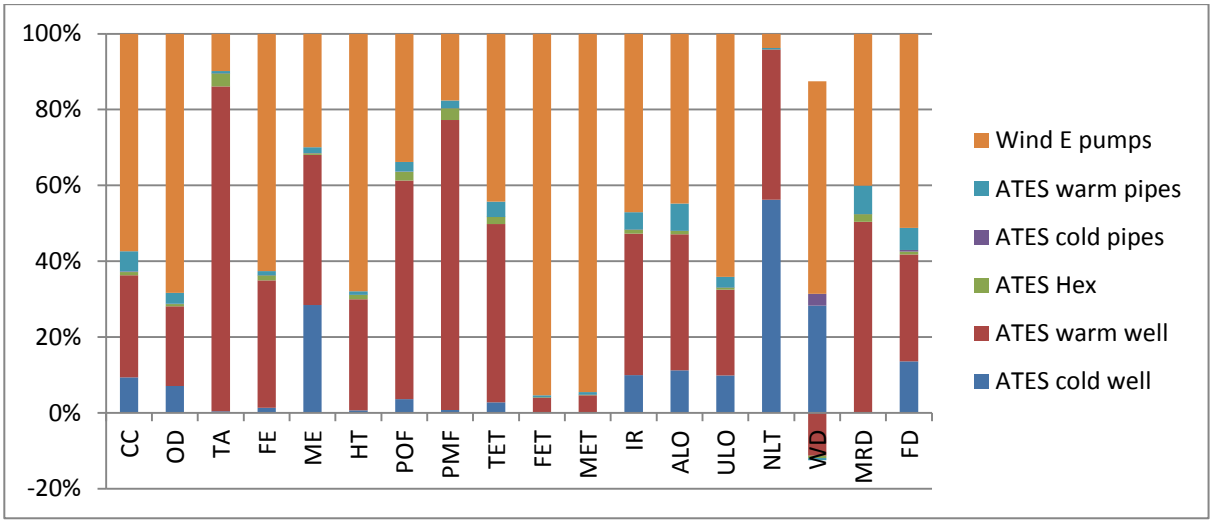

Figure 44 *GeoMEC Vierpolders ATES impact assessment for wind electricity featuring 100% stacked results for the 18 impact categories – Characterised results. ReCiPe midpoint (H).Compare with Figure 9*

Distribution of characterised results means that the pumps now take up less responsibility for factors such as CC (See Discussion, Alternative scenarios).

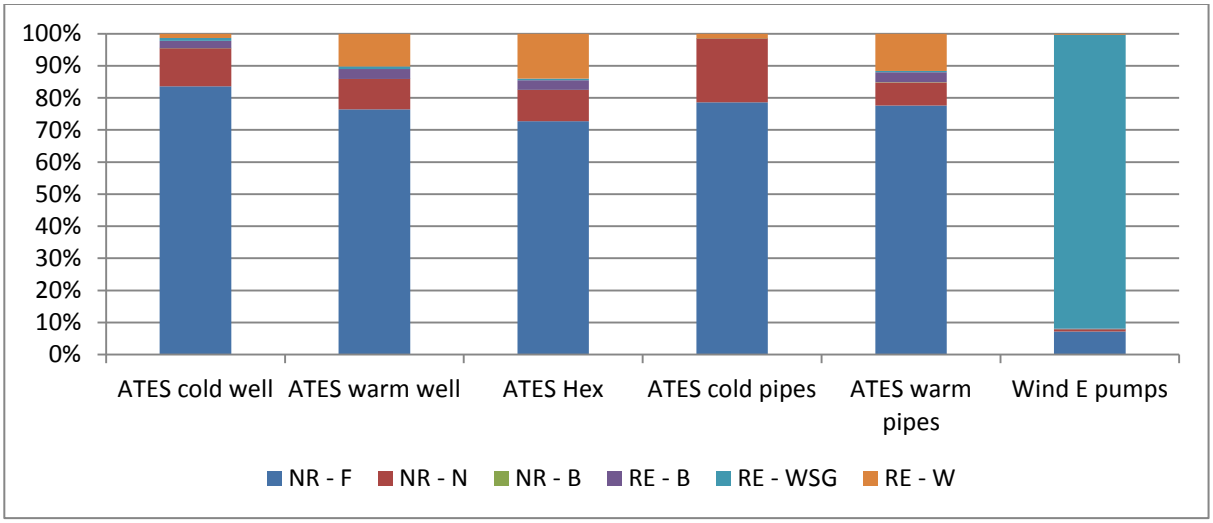

Figure 45 *GeoMEC Vierpolders ATES Cumulative Energy Demand with wind electricity featuring 100% stacked results for the 6 main infrastructure processes of ATES – Characterised results – Compare with Figure 14*

Notice how pumps are now dominated by RE – WSG, under which wind power falls.

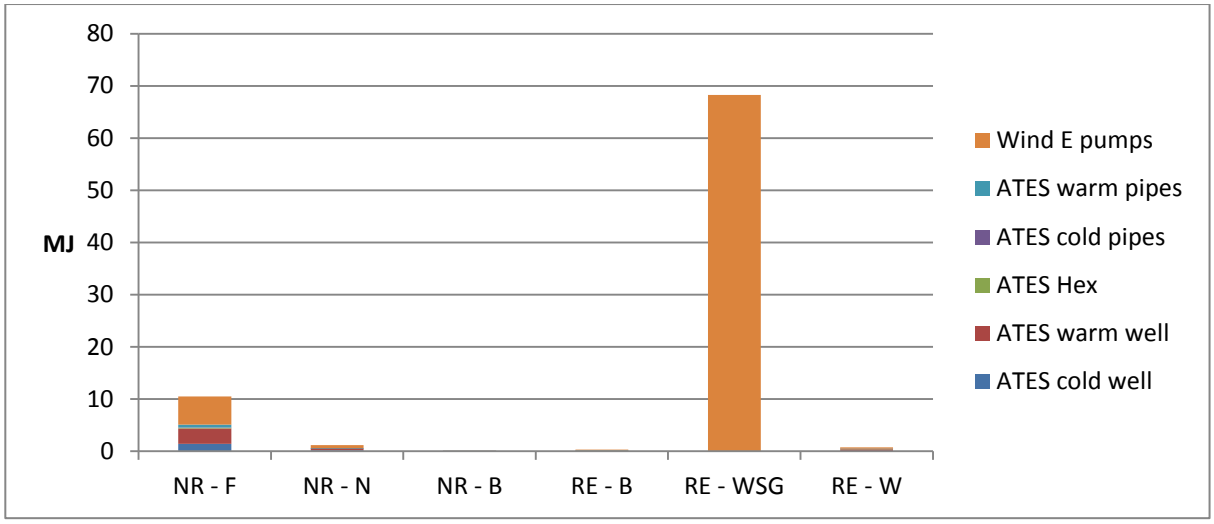

Figure 46 *GeoMEC Vierpolders ATES Cumulative Energy Demand with wind electricity featuring results relative to 1 GJ heat delivery of the 6 energy demand categories – Characterised results – Compare with Figure 15*

Figure 46 reveals a complete shift in primary energy demand for the GeoMEC ATES. Rather than domination within NR – F due to Dutch average electricity as was the case in Figure 15, RE – WSG now becomes the most important factor as determined by the pumps. According to the results, this also results in a lower total energy demand for the pumps in order to supply them with electricity for operation (See General discussion, section 5.2, page 52).