Life cycle assessment of solar district heating with borehole thermal energy storage in Nunavik

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ABSTRACT

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Xiuting Wu

Nunavik, a remote subarctic region covering the northern third of Quebec, Canada, relies heavily on diesel to meet residential heating demand. Solar district heating with borehole thermal energy storage (SDH-BTES) has been regarded as one of the most promising solutions that can break the dependence on fossil fuels and develop renewable energy resource locally. Whether to develop an SDH-BTES in Nunavik is not only a technical and economic consideration, but also an environmental deliberation. Even though SDH-BTES systems are considered as an environmentally friendly technique in other regions, it is crucial to analyze its environmental performance in Nunavik, considering the harsh weather condition, inconvenient transportation and backward infrastructure there. Therefore, in this study, a cradle-to-grave life cycle assessment (LCA) of SDH-BTES in Nunavik is performed. A heating system for 20 single-family houses in Kuujjuaq, comprising a 1500 m^2 gross solar area and one hundred fifty 30–m–deep borehole heat exchangers, is modeled in SIMAPRO to analyze its environmental performance. The results are presented comparatively with the 20 conventional local household diesel furnaces. The present analyses show that SDH-BTES performs better than local diesel furnace regarding human health, climate change and resources. However, ecosystem quality impact of SDH-BTES system is remains higher than the conventional domestic diesel furnaces due to drilling process and the need to a large land occupation of underground thermal heat storage. Besides, 32418.80 kg GHG emission can be avoided per year using SDH-BTES system. In summary, the LCA results present the extent of the environmental benefits of SDH-BTES for adoption as a renewable energy shortage in Nunavik. The extent of adverse environmental impacts of the system is also characterized and estimated to provide a basis for prioritization and addressing of them.

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Abbreviations

SDH	Solar District Heating
BTES	Borehole Thermal Energy Storage
UTES	Underground Thermal Energy Storage
STST	Short Term Storage Tank
BHE	Borehole Heat Exchanger
DLSC	Drake Landing Solar Community
HR	Heat Recovery
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
IMPACT	IMPact Assessment of Chemical Toxics
CML	Institute of Environmental Sciences, Leiden University
IPCC	International Panel on Climate Change
CED	Cumulative Energy Demand
GHG	Greenhouse Gas
DALY	Disability-Adjusted Life Year
PDF	Potential Disappear Factor
TEG	Triethylene Glycol
EPT	Energy Payback Time
PV	Photovoltaic
SF	Solar Fraction

1. Introduction

1.1Background

Nunavik, a remote subarctic region of northern Quebec, is located above the 55th parallel north and extends over 560,000 square kilometers with only 12,300 inhabitants. Kuujjuaq (58.10°N, -68.42°E), the regional capital of Nunavik, is the most populated village with 2375 inhabitants. The population growth rate there has been 40% since 2000[1]. Due to high latitude, Kuujjuaq shows a subarctic climate experiencing a low annual average temperature of -5.4 °C and an annual average of 8,520 heating degree days below 18°C (HDD18). For this reason, houses in Kuujjuaq are typically built to meet the government standard for cold climate, which requires adequate insulation for the building envelope[2]. Despite this, the harsh climate condition still results in high building heating demands. The annual space heating demand of a typical single-family house located in Kuujjuaq reaches 21.6 MWh.[3]

Given the absence of a road network connecting the Nunavik villages to a major supply center such as southern Québec[4], the infrastructure construction there is relatively backward. Kuujjuaq is not connected to Quebec's electrical grid and, accordingly, relies entirely on fossil fuel to generate electricity and heat. Every single house is equipped with a diesel furnace and oil tank to supply daily heating. Although diesel furnace can satisfy the local heating demand, it is noteworthy that diesel combustion process produces significant pollution, having adverse impacts on our environment, especially climate change. Facing critical challenges related to energy need and environmental concerns that are only expected to worsen in the future, these off-gird communities have aroused wider attention. Quebec government highly supports the projects of off-grid communities and businesses to convert electricity and heat generation using fossil fuels to renewable energy sources.[5] Quebec's new 2030 Energy Policy aims to reduce fossil fuel consumption by 40% and improve living conditions for remote region. In light of this situation, there is an urgent need to call for the development of renewable energy product or system, to supply clean, locally-generated, and reliable thermal energy in Kuujjuaq and other off-grid communities. Many efforts have been made in this field, and several alternative technologies are being exam. Some in-depth research activities were taken to the hybrid wind-diesel turbine that combines current diesel generators, wind turbines, and storage systems in Nunavik, and demonstrated that hybrid wind-diesel turbine, could reduce the GHG emission by 50% approximately, which gained strong support from Hydro-Quebec[6][7]. However, the communities of Inukjuaq and Whapmagoostui-Kuujjuarapik rejected this option since they preferred hydro-power and connecting to the integrated power grid. One wind-diesel project was installed in Kuujjuaq in 1986, but despite the availability of wind and hydroelectricity resources, hybrid wind-diesel turbine is presently considered not feasible financially.[8] Besides, research and development (R&D) activities are also taken to other heating alternatives, such as wood pellets combustion, natural gas, waste gasification, etc. Yan et al. have conducted a research to compare these three technologies and illustrated that wood pellets combustion is the most suitable alternative using multi-criteria decision analysis method.[3] However, there is no wood pellet produced in Nunavik region. As a result, the wood pellets combustion approach can't break the reliance on long-distance marine transportation and satisfy heating needs locally. Although the development of renewable energy in Nunavik has encountered many hurdles, R&D activities still gain some progress. A solar panel pilot was built in Kuujjuaq in 2017, which saved more than 400 liters (105.67 gallons) of diesel between September and October[9]. Solar resource has shown its great potential in the subarctic area. However, it must be noted that solar resource is only abundant during summer while peak heating load happens in winter. In other words, the availability of solar energy is not contemporaneous with energy demand. The intermittency of solar energy resources is one of the primary and common challenges to its effectiveness and development. Hence, looking for an effective seasonal thermal energy storage (STES) has become an imperious demand for this intermittent renewable resource. Borehole thermal energy storage (BTES) is considered as a promising technology to exploit solar energy throughout the whole heating season and bridge this seasonal demand-supply gap[10]. Unlike batteries and other short-term energy storage (STES), BTES is capable of storing thermal energy from solar fields for months or years, and dispatching it on-demand to users irrespective of ambient temperatures or the present availability of sunlight. In 2007, the first community-scale SDH-BTES system in North America was built at the Drake Landing Solar Community (DLSC) in Okotoks, AB, Canada, to supply domestic space heating to 52 houses, with over 90% solar fraction realized[11]. As demonstrated at DLSC in cold climate region, solar district heating combined with borehole thermal energy storage (SDH-BTES) has attracted more and more attention. Many researches have been carried out to exam the feasibility of SDH-BTES system applied in subarctic area. Giordano et al. have verified the efficiency and viability of SDH-BTES in Kuujjuaq in their research. They revealed that solar fraction of 45 to 50%, 30% solar efficiency and heat recovery of more than 60% can be achieved by the 3rd year of operation in Kuujjuaq.[12].

Currently, application of SDH-BTES system in Nunavik is still in the research stage. There is no actual project running locally. Whether to replace the original diesel furnaces with SDH-BTES is not only a technical and economic consideration but also an environmental deliberation. To alleviate energy and environment stress in Nunavik, SDH-BTES is expected to generate sufficient thermal energy and achieve sustainability simultaneously. To this end, the Life Cycle Assessment (LCA) method can be utilized to evaluate the environmental impact of SDH-BTES, considering actual application condition in Nunavik. LCA is an established and internationally standardized method for the analysis and quantification of environmental loads and impacts through the life cycle of products and services [13]. Many researchers in their works utilized this technique. Thus, this research will conduct an LCA of SDH-BTES and evaluate its environmental performance in Nunavik.

1.2Problem statement

Although SDH-BTES is regarded as an environmentally friendly system[14], it’s critical to demonstrate its sustainability and environmental performance in Nunavik considering the climate conditions. Besides, no prior district heating system has been installed in Nunavik region, which means that the construction and installation of SDH-UTES system in Nunavik will start from ground up. Additionally, it should be noted that there are limited literatures about the long-term environmental performance of SDH-BTES system in extreme cold region. Even though SDH-BTES systems are considered to be environmentally friendly as implemented in other regions, it is crucial to conduct a research to study the extent to which the system will impact the environment in Nunavik.

To address the above problem, a life cycle assessment (LCA) approach is adopted in this thesis. It is a practical technique to investigate and evaluate the environmental impacts of a product or process from cradle to grave. It analyses the consumption of natural resources and emissions of material flows, taking into account all stages in all the life cycle processes (raw material extraction, intermediate and final manufacturing processes, packaging, transport, use, and final disposal).

1.3Objectives

Based on the background investigation of Nunavik and literature about SDH-BTES system development and LCA methodology, the general scope of this research is to utilize LCA to analyze the environmental impact of SDH-BTES system in Nunavik. Kuujjuaq community is chosen as the case study. A heating supply scenario for 20 single-family houses is modelled in this research, aiming to evaluate its environmental performance and to investigate to what extent the environmental impacts of conventional heating furnaces could be mitigated by switching to the new system.

The general objectives of this research are summarized as:

- To investigate the inputs and outputs of SDH-BTES system built in Kuujjuaq throughout its life cycle and model in SIMPAPRO.
- To evaluate the potential environmental impacts of an SDH-BTES system in Kuujjuaq.
- To identify the dominating contributors to these impacts.
- To provide a comparison with the conventional diesel furnace.

Based on the above scope and objectives, a number of research tasks are formulated:

Task 1: Identify the special characteristics of Kuujjuaq for system implementation, including weather condition, consignment condition and supportive infrastructure.

Task 2: Analyze the functional system of SDH-BTES and its effectiveness under extreme cold weather condition through evidence from a literature review, to set up the parameter of SDH-BTES system.

Task 3: Establish the research boundary and inventory of SDH-BTES system (through its life cycle) to build up an LCA model.

Task 4: Select an appropriate life cycle assessment method and evaluate the potential environmental impact of proposed project.

Task 5: Interpret the life cycle assessment results and analyze the process contributions.

Task 6: Analyze the sensitivity of the life cycle assessment results in regard to different assumptions.

Task 7: Build up an LCA model of local diesel furnace and set up a function unit to establish a comparison with the proposed SDH-BTES system.

The next chapter will provide a literature review as relate to research background on the proposed system, LCA, and case study.

2. literature review

Many renewable energy projects, such as hydro, wind, solar, geothermal, and tidal, have been studied in subarctic area. Solar district heating with borehole thermal energy storage system (SDH-BTES), which can benefit from the large availability of materials, is one of the promising avenues to provide clean and local energy and fulfill growing heating needs in Nunavik. This chapter aims to provide a review of research and development of SDH-BTES system worldwide and its feasibility in Nunavik. Additionally, based on previous research, a gap can be identified that there is a lack of particular assessment of environmental performance of SDH-BTES system in Nunavik or other extremely cold areas. Therefore, the application of life cycle assessment (LCA) is also reviewed in this chapter to provide a general picture of the environmental assessment of renewable energy systems.

2.1. Research and development of SDH-BTES

Penrod first proposed the idea that combines solar collector and borehole heat exchanger in 1956, and then he extended this idea into storing solar thermal energy underground[7]. There are a number of successful large-scale SDH-BTES projects worldwide, especially in Europe. Gao et al. reviewed and summarized the borehole seasonal solar thermal energy storage project around the world[15]. In 1984, a project equipped with 2400 m^2 roof-mounted evacuated solar collector, and 23000 m^3 borehole storage was built in Netherland to supply heating to residential buildings, achieving 65% solar fraction[16]. In 1985, a 2727m2 roof-mounted flat plate solar collector with 43000m^3 borehole storage was installed in Italy to supply heating to residential building, realizing 70% solar fraction[16]. In 1999, a plant named Neckarsulm was built in Germany with 5470 m^2 solar collectors and 63360m^3 doubled in U-shape duct borehole storage (30-m-deep). In this project, 50% solar fraction was calculated to satisfy the heating demand of a 20000 m^2 building[17][18]. In 2002, a plant named Anneberg was built in Sweden to supply heating for 50 residential units with about 120m^2 floor area each. This project was equipped with 2400 m^2 roof-mounted solar collector and 60000m^3 borehole storage (100 65-m-deep boreholes), with 70% solar fraction realized[19]. In the same year, a plant named Attenkirchen with 846 m^2 solar collector and 9350 m^3 borehole storage (double-U-loop heat exchangers with 30 m depth) was built in Germany to supply heating to 30 low energy homes, with around 50% solar fraction calculated[20]. In 2007, another SDH-BTES project was built in Germany to satisfy the heating demand of 260 houses, school and gymnasium, with 7300 m^2 vacuum tubes collector and 37500 m3 borehole storage equipped. Based on the operation data, a 50% solar fraction was realized in this project[21]. In the same year, The Drake Landing Solar Community (DLSC) was built in Okotoks, Canada, which was the first major implementation for using BTES in district heating in North America. 2293 m^2 flat plate solar collector was installed to capture solar energy and stored in a 33657 m^3 borehole thermal energy storage system, comprising 144 boreholes with a depth of 35 m. It's worthy to mention that this is the first system of this type designed to supply more than 90% space heating with solar energy and the first operating in such a cold climate (4930 HDD18) [11][22]. In 2012, The Brædstrup BTES, with a storage volume of 19000 m^3, was constructed in Denmark, which was sourced by solar thermal collectors to produce heat for a district heating network. The BTES consists of 48 boreholes with a depth of 45 m and the average storage efficiency in the period 2014-2017 was 61%. However, the Brædstrup borehole thermal energy storage system has realized a limited charge and discharge capacity due to the mismatch between the capacity of solar collectors and borehole storage[23][18][24].

Therefore, BTES is a relatively mature technology that can exploit solar energy throughout the whole heating season and bridge the seasonal demand-supply gap. According to the previous project, the solar fraction (SF) typically exceeds 50% and in some cases is over 90%.

2.2. Feasibility study of SDH-BTES in Nunavik

Challenges in cold climate have already been tackled in Europe and DLSC; some researchers are trying to apply SDH-BTES system in colder remote off-grid community, Nunavik, to replace the traditional fuel-oil-based energy device (furnace) for heating.

2.2.1. Geothermal potential in Nunavik

Comeau et al. carried out a preliminary evaluation of geothermal resources in Northern Quebec and drew a distribution map of mean thermal conductivity. Ground with low thermal conductivity is favorable to thermal energy storage systems, while a high thermal conductivity can be appropriate for geothermal heat pump systems[25].

Giordano et al. conducted research to demonstrated the potential of exploiting shallow geothermal resources in Kuujjuaq, Nunavik through electrical resistivity tomography (ERT) surveys and thermal property analyses on soil samples [26].

Miranda et al. investigated the feasibility of shallow geothermal applications such as UTES and verified that it would be feasible in locations where the rock mass hydraulic conductivity is moderate to low in order to prevent heat losses from the underground storage volume. Areas 1 and 2 are characterized by very high hydraulic conductivity; area 3, 4 and 5 by low fracture hydraulic conductivity [27].

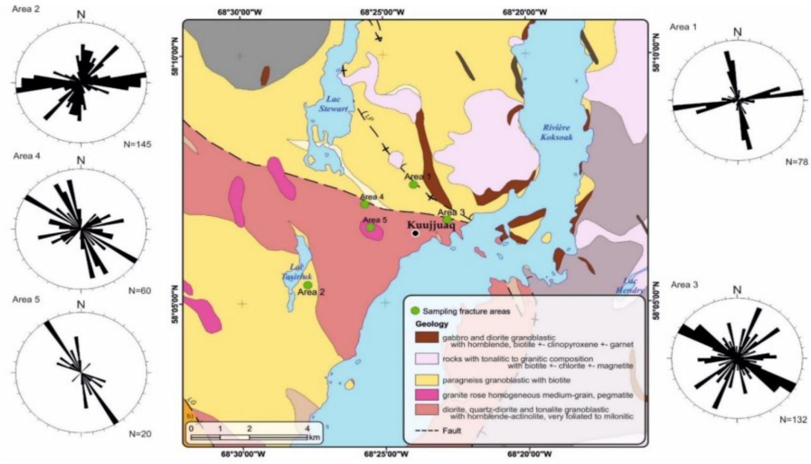


Figure 1 Geological map

2.2.2. SDH-BTES simulated in Nunavik

Giordano et al., using a pump station in Kuujjuaq as a case study, validated the technical viability of solar district heating with borehole thermal energy storage system in subarctic climates and revealed that 45 to 50% solar fraction and more than 60% heat recovery could be realized by the 3rd year of operation. They also conducted an economic analysis and demonstrated that a specific incentive program could guarantee similar net present cost and levelized cost of energy compared to the current diesel-dependent situation [28][12].

2.2.3. Economic assessment of SDH-BTES

One of the main concerns when developing SDH-BTES in subarctic communities is the high outlay for the plant, mainly due to the high cost of solar collectors and drilling activities. Mitigate the financial hurdle is one of the most significant tasks for spreading SDH-BTES around the world.

Reed et al. carried out a financial analysis for SDH-BTES system in North America and demonstrated that SDH-BTES system with subsidized support represented an attractive investment when compared with natural gas-based systems for the provision of residential space heating[29].

Welsch et al. conducted an economic assessment of borehole thermal energy storage in district heating systems in their research and verified that a combination of solar thermal collectors and BTES with a small heat and power plant (CHP) is economical even without subsidies, considering a probable increase of energy costs and the share of renewable energy in the electricity mix[30].

Renaldi et al. conducted a techno-economic analysis of a solar district heating system with seasonal thermal storage in the UK, based on the Drake Landing Solar Community in Okotoks, Canada. The results show that SDH-BTES system still needs to be supported by the government encouraging policies to make it competitive with incumbent technologies in the financial aspect. Besides, this study opens the possibility to design bespoke SDH systems for the countries in middle to high latitudes[31].

Giordano et al. conducted a 50- years life cycle cost analysis for a simulation of SDH-BTES system in Kuujjuaq, Nunavik. The result illuminated that certain interventions from the province, federation and nation were crucial to guarantee energy security in the Arctic and helped develop SDH-BTES systems, despite the significant uncertainty related to the drilling and installation cost of borehole heat exchanger in Nunavik. Net present cost (NPC) and levelized cost of energy (LCOE) of this system in the Arctic region could be further controlled and reduced by technique development, such as the air-liquid, and photovoltaic solar collectors, that could improve the overall system performance[32].

Besides, researchers have demonstrated that significant saving can be obtained by system optimization, process integration analysis and life-cycle cost assessment[33][30][34].

2.3. Life cycle assessment applied in renewable energy technology

Energy need and environmental concerns are like two critical puzzles for Nunavik and other remote regions. To cope with the climate change and fossil fuel depletion problem, renewable energy systems are expected to simultaneously provide energy and realize sustainability. Environmental assessment of facilities, equipment, and systems used for the exploitation of renewable energy sources constitutes a major challenge of the environmental scientific community. Life cycle assessment (LCA) is a strategic asset to measure the potential environmental impact of a product system throughout its life from raw material extraction, processing, manufacturing, operation, and final disposal.

Many pieces of research have been conducted to investigate the environmental performance of solar collectors, thermal energy storage systems, as well as other renewable energy systems.

2.3.1. Life cycle assessment of solar collector

Laborderie et al. simulated two types of solar thermal collectors and characterized the environmental performances using IMPACT 2002+ assessment method in SIMAPRO. The LCA results showed that solar thermal system was a good solution to reduce the environmental impacts of domestic hot water production, and highlighted the backup energy as the key factor on environmental impacts. Additionally, solar panels, water tank and pipes emerged as the major environmental components. Therefore, a technical improvement related to the main impacting components is necessary to lower the environmental impacts of the solar thermal collectors[35].

Morsink-Georgali et al. implemented a comprehensive LCA for flat plate solar thermal collectors, using the CML (2001) methodology with the Gabi software. Four alternative manufacturing scenarios were examined in the research to define manufacturing alternatives that could mitigate the negative environmental impacts. The results confirmed that minimizing the usage of aluminum metal with recycled one was able to affect the environmental footprint of a solar thermal collector significantly and the floating glass has a major contribution (50%) to the embodied energy of the solar collectors[36].

Milousi et al. evaluated the environmental performance of solar energy systems: photovoltaics (thin-film and crystalline) and solar thermal collectors (flat plate and vacuum tube), through a detailed LCA from cradle to grave via SIMAPRO. ReCiPe 2016 Midpoint Hierarchist (H) was chosen as the life cycle impact assessment method in this study. The results remarked that the production stage contributes the most significant part of the environmental impacts for both studied systems. For solar thermal collectors, flat plate and vacuum tube exhibited similar environmental impacts in most impact categories, but the vacuum tube collector has the highest values in most cases[37].

2.3.2. Life cycle assessment of thermal energy storage system

Rubino et al. carried out an LCA study for borehole thermal energy storage system using Eco-Indicator 99 impact method in SIMAPRO and demonstrated that BTES performed certainly better than a natural gas heating system in terms of fossil fuels depletion and climate change impacts, as it allowed a decrease in CO_2 equivalent emissions. Additionally, the main environmental impact of BTES was due to electricity consumption. Therefore, the source of electricity was relatively sensitive in this research, in particular to the emissions from power plants fired by fossil fuel[38].

Oró et al. developed an LCA for three different thermal energy storage (TES) systems used in solar power plants and compared the environmental impact based on the Eco-Indicator 99 (EI99) impact category in their study. From their analysis, it can be concluded that systems that use molten salts as storage material had the highest environmental impact and, therefore, should be substituted by solid media or phase change material (PCM) system[39].

Raluy et al. conducted an LCA of a centralized solar thermal system with seasonal heat storage (CSHPSS) that provided space heating and DHW for 500 dwellings of 100 m^2 located in Zaragoza, using IMPACT 2002+ method in SIMAPRO. The obtained results demonstrated the essential environmental benefits of this system, although the environmental burden provoked should not be ignored and the electrical energy consumption in the pumps should be taken into consideration due to their relevant environmental loads[40].

Aquino et al. implemented an LCA for a ground-source heat pump, including an underground thermal storage designed for space heating and cooling of an industrial building. Comprehensive ReCiPe midpoint and endpoint indicators were employed in this study. The results demonstrated that the baseline scenario without thermal storage was characterized by a lower environmental impact than the storage scenario since the cylindrical heat exchangers in the underground thermal storage reduced the measured coefficient of performance (COP)[41].

2.3.3. Life cycle assessment of SDH-BTES system

Karasu et al. performed a cradle-to-grave life cycle assessment (LCA) for an SDH-BTES project named Drake landing solar community in Okotoks, Alberta, Canada, using SIMAPRO. CML 2001 methodology is selected for the impact assessment calculations. The results demonstrated that a Drake Landing house had much lower environmental impacts than a conventional Canadian house in all studied impact categories[14].

3. Methodology

This chapter aims to introduce the operation mode of SDH-BTES system and provide general procedure of life cycle assessment.

3.1. Operation mode of SDH-BTES system

An SDH-BTES system, as demonstrated at the Drake Landing Solar Community in Okotoks, Canada, combines solar thermal collection technologies with long-term borehole thermal energy storage method. Unlike batteries and other short-term energy storage, BTES is capable of storing thermal energy from solar fields for months or years, and dispatching it on-demand to users irrespective of ambient temperatures or the present availability of sunlight.

Solar panels absorb energy from the sun to heat a water-glycol solution circulation through an insulated collector system connecting all of the panels.

Heat is transferred from the glycol-water solution to water storage tanks for short-term storage (STTS) through a heat exchanger.

A separate closed-loop system is installed to extract heat from the water-filled tanks by circulating a water-glycol solution through an array of boreholes. A borehole thermal energy storage system is installed underground with plastic pipes with a “U” bend at the bottom inserted the boreholes after drilling, the boreholes are then filled with a high thermal conductivity grout. BTES uses the underground itself as the storage material. Because of their construction principle, BTES are usually not thermally insulated to the bottom and the side; only a layer of insulation is laid beneath the topsoil to reduce the losses to the environment. The boreholes are divided into several series, allowing water to flow from the center to the outer edge of the BTES when storing heat, and from the edge towards the center when recovering heat. Therefore, the highest temperatures will always be at the center.

Underground material has a rather moderate thermal conductivity, in a range of 1–5 W/m·K, so it is possible to maintain a low heat loss if the total volume is large enough to achieve a good surface-to-volume ratio. Size is critical as heat losses are proportional to the storage surface while the storage capacity is proportional to the volume[42].

Two heat recovery (HR) indicators can be calculated as follows:

$$\eta_{BTES1} = \frac{E_{EXT}}{E_{INJ}}$$

$$\eta_{BTES2} = \frac{E_{EXT}}{E_{STO}} = \frac{E_{EXT}}{E_{INJ} - E_{LOS}}$$

where E_{EXT}, E_{INJ}, E_{STO} and E_{LOS} refer to the energy extracted during discharge, and energy injected, stored and lost during charge phase, respectively. ηBTES1 is a conventional way to calculate heat recovery, while ηBTES2 gives a sense of the impact of heat loss on the overall operation of the system.

A control mechanism is designed in SDH-BTES system to initiate and maintain the operation of collector loop whenever sufficient incident solar energy is available. The collector loop is warmed up each day through solar panels and then heat is transferred to the water tank for short-term storage using a heat exchanger and water loop when the collector loop fluid is hot enough. When space heating is required, thermal energy from water tank heats the district loop fluid using another heat exchanger. Meanwhile, if energy in water tank is insufficient to meet the anticipated heating load, heat is extracted from the borehole into the water tank to meet the requirement. On the contrary, if the temperature of stored water is insufficient to meet the heating requirement, diesel boilers is initiated to raise the temperature of the district loop as required. When heat in water tank is more than space heating requirement in the short-term, water is circulated from the water tank to the borehole, and store heat for later use. In summer when space heating requirements are low, virtually all of the solar energy collected is transferred to the borehole, while collected solar energy is not enough to meet heating demand in winter. Correspondingly, heat is extracted from the borehole. In the shoulder seasons, a proper balance between heating load and capacity to absorb solar energy is required, which means heat must be available in the district loop and there must also be sufficient capacity available in the water tank to accept large quantities of solar thermal energy. Figure 2 shows the schematic of the whole control system.

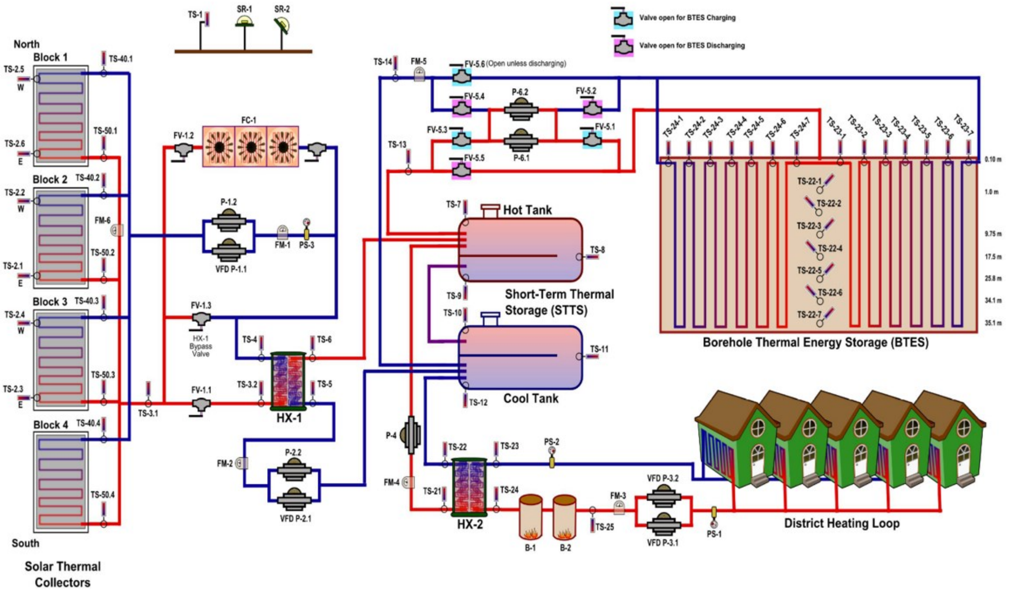


Figure 2 Schematic of SDH-BTES system

3.2. Life cycle assessment

The environmental performance of a system is not only about Greenhouse gas emission or fossil fuel depletion, but related to the whole environmental impacts from cradle to grave including many aspects concerned, such as human health, ecosystem quality and so on. Therefore, a life cycle assessment tool is applied to integrate environmental considerations into the herein research.

Life cycle assessment (LCA), a systematic method to evaluate the environmental impacts of a product system from production stage to end-of-life, can be divided into four steps:

- Goal and scope definition
- Life cycle inventory analysis (LCI)
- Life cycle impact assessment (LCIA)
- Interpretation

3.2.1. Defining goal and scope

The goal definition should contain the intended application, the reason for conducting the assessment as well as the indented audience or project stakeholder. The scope of an LCA should state explicitly the target product system, its function and function unit, boundaries of the system, allocation procedures, chosen impact assessment method, impact categories and impact indicators, applied interpretation method, requirement of data quality, any assumptions and the limitation. In that regard, it's essential to define properly the function, quantity, quality and timespan that the system realizes its specific functions or objection. The system boundaries should describe precisely which processes are considered in the assessment. Last, the goal and scope definition must be consistent with the intended application.

3.2.2. Inventory analysis

In this step, qualitative and quantitative data is collected on the basis of system boundaries to establish the inputs and outputs of each process, including energy inputs, raw material inputs, products, by-products as well as waste and emission outputs. Figure 3 presents a simplified overview of the inventory analysis procedure adapted from ISO 14044.

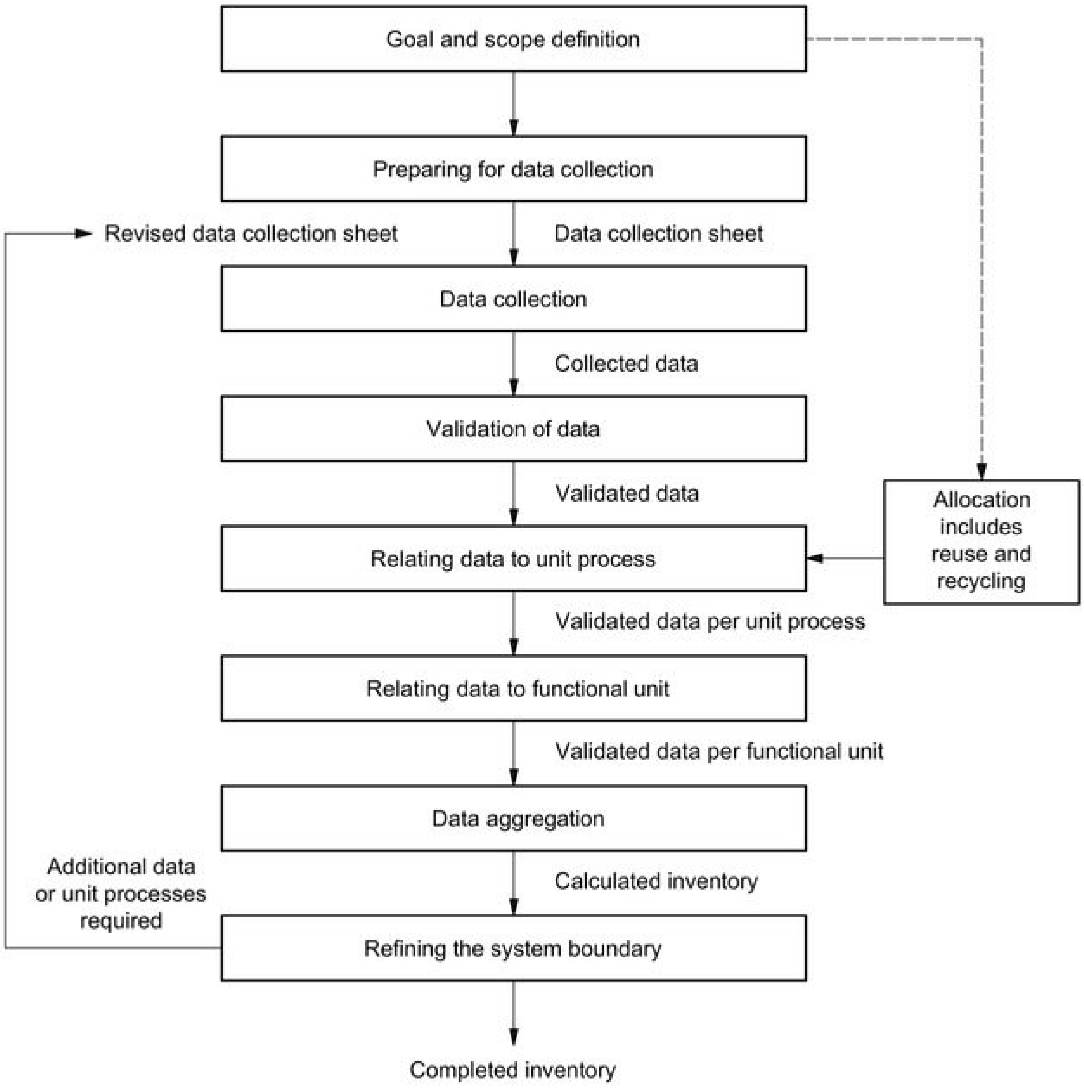


Figure 3 LCI procedure[43]

The data collected in this step can be measured, calculated or estimated to quantify the inputs and outputs of each process. Meanwhile, all calculation or estimation procedures must be illustrated and explained clearly. It’s worthy to mention that during LCI, the system boundaries should be refined, considering the data availability and data missing.

3.2.3. Impact assessment

The ISO 14040/44 standard defines an LCA as a compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system through its life cycle[44]. Life cycle assessment is defined as the phase aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system.

The basic structure of an impact assessment method encompasses classification, characterization, normalization and weighting. According to ISO 14042, LCA must at least include classification and characterization, while normalization and characterization as well as damage assessment are considered as optional elements.

Classification

The elementary flows identified in the life cycle inventory result may contribute to one or more impact categories based on the substances' ability. The classification is to allocate LCI substances to the corresponding impact categories.

The following table presents an overview of the relevant impact categories, which unit they are measured in, and what they describe, based on the EN15804 standard for LCAs in the construction sector.

Table 1 Impact category classification[45]

Impact category	Description	Unit	Source
Climate change	Indicator of potential global warming	kg CO^2-eq	GHG emission.
Ozone depletion	Indicator of emissions to	kg CFC-11-eq	/

	air that cause the destruction of the stratospheric ozone layer		
Acidification	Indicator of the potential acidification of soils and water	kg mol H+	NOx and Sox emission
Eutrophication – freshwater	Indicator of the enrichment of the fresh water ecosystem	kg PO_4-eq	Emission of nitrogen or phosphor containing compounds
Eutrophication – marine	Indicator of the enrichment of the marine ecosystem	Kg N-eq	Emission of nitrogen containing compounds.
Eutrophication – terrestrial	Indicator of the enrichment of the terrestrial ecosystem	mol N-eq	Emission of nitrogen containing compounds.
Photochemical ozone formation	Indicator of emissions of	kg NMVOC-eq	/

	gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalyzed by sunlight.		
Depletion of abiotic resources – minerals and metals	Indicator of the depletion of natural non-fossil resources.	kg Sb-eq	/
Depletion of abiotic resources – fossil fuels	Indicator of the depletion of natural fossil fuel resources.	MJ, net calorific value	/
Human toxicity – cancer, non-cancer	Impact on humans	CTUh	Toxic substances emitted to the environment.
Eco-toxicity (freshwater)	Impact on freshwater	CTUe	Toxic substances emitted to the

	organisms		environment.
Water use	Indicator of the relative amount of water used	m^3 world eq. deprived	/
Land use	Measure of the changes in soil quality	Dimensionless	/
Ionizing radiation, human health	Damage to human health and ecosystems	kBq U-235	Emissions of radionuclides.
Particulate matter emissions	Indicator of the potential incidence of disease	Disease incidence	Particulate matter emissions.

Characterization

After classification, substances are assigned to the impact category they contribute to. However, same amounts of different LCI substances allocated in the same impact category do not mean that they have same magnitude impact to the environment in this regard. In other words, different substances contribute differently to the related impact category. To distinguish their contribution quantitatively and simplify the following assessment, characterization factors determined by the impact assessment method are applied, which can express the relative contribution of a particular substance to the considered impact category. The quantities of the LCI substances are multiplied by a characterization factor. It's important to note that after characterization, the units will be changed. For example, in the climate change impact category, unit of the substance (e.g., kg) will be changed to CO_2 equivalents (kg CO_2-eq). Additionally, the impact categories cannot be compared to each other and the overall magnitude of impacts cannot be determined.

Characterization factor varies from different locations of indicators. The category indicators can be located at any point between the inventory results and endpoint in the cause-effect chain. Therefore, two types of indicator have been developed. Endpoints indicators track along the whole interact process until the end and midpoints indicators are taken somewhere along the environmental mechanism that can represent the impact on the endpoint. Based on SIMAPRO introduction, different impact assessment methods use different indicator mechanisms. Eco-indicator 99, IMPACT 2002+ and EPS2000 use endpoint indicators while CML and TRACI use midpoint indicators. Some methods, like ReCiPe have both end and midpoints, which allow the user to choose one of them. Figure 4 illustrates the location of endpoint and midpoint indicators, using Eutrophication as example. The top of the flow chart is the emission from life cycle inventory results, the midpoint indicators is located at the half-way of the flow chart and endpoint indicators are defined at the bottom.

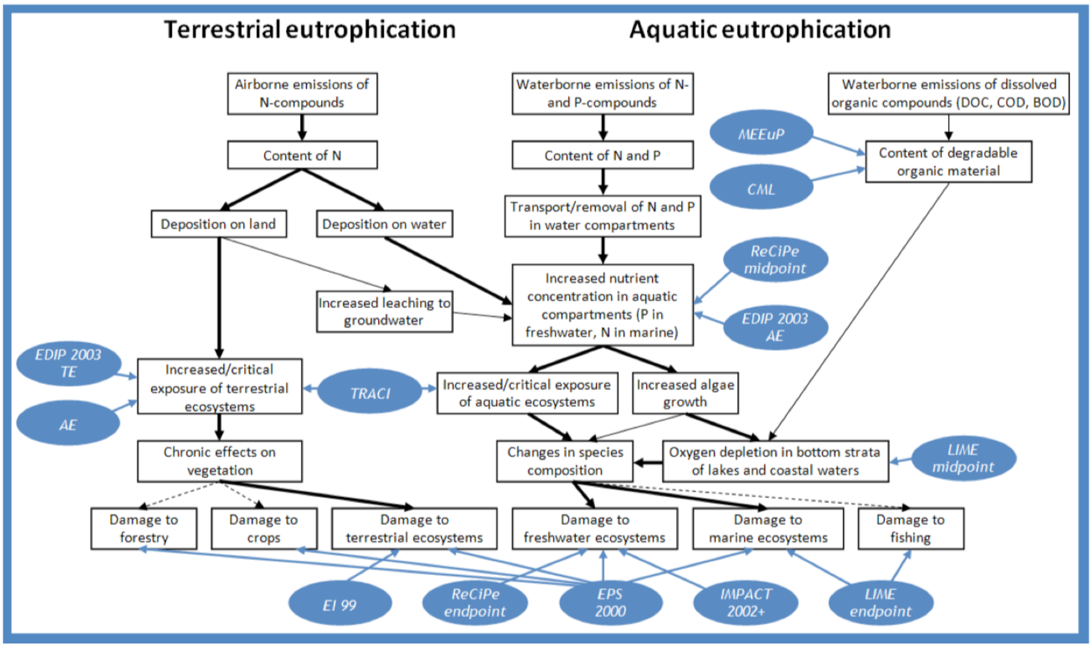


Figure 4 Overview mechanism resulting in eutrophication[46]

Normalization

As mentioned in characterization, different impact categories cannot be compared since they have different impact on the environment and also different units. For example, even though the characterization result of climate change is higher than ozone layer depletion in some cases, it’s not precise to assert that the climate change impact is higher than ozone layer depletion. To provide a clear picture of the assessment, normalization is introduced. Whether a figure is high can only be determined by comparing to its reference or a normal value. Therefore, the characterization result of climate change and ozone layer depletion should be divided by their own normal value to realize normalization. The most common normalization value is the average environmental load per year in a country or a continent, divided by the number of inhabitants[39]. After normalization, it’s more precise to compare two different impact categories quantitively. However, normalization result does not represent the significance or importance, which is a weighting issue.

Weighting

The impact category result can be multiplied by weighting factors and summed up to create a single total score, which is what we called weighting. It’s noteworthy to mention that weighting factors determination is a controversial and subjective step. Hence, it is not allowed to be used in comparative assertions disclosed to the public, based on ISO requirement. Nevertheless, weighting is still applied extensively for internal decision-making.

Damage assessment

Damage assessment, a relatively new methodology in LCA, allows the aggregation of impact category indicators into a damage category in a common unit, which is usually applied in endpoint method.

3.2.3.1. Impact assessment method

Aiming to connect the life cycle inventory to the corresponding environmental impacts and track the cause-effect chain, impact assessment method can be divided into two main schools of methods.

Classical impact assessment methods, such as CML and EDIP, use midpoint indicators to restrict the quantitative modeling to relatively early stage of the cause-effect chain, which can limit the uncertainty to some extent.

Damage oriented methods, such as Eco-indicator 99 and EPS, use endpoint indicators to track and model the whole cause-effect chain until the damage happens. Inversely, this kind of method sometimes comes with high uncertainties.

Known the basic structure of the impact assessment method, different kinds of impact category and two main classification of impact assessment method, following sections will introduce some commonly used impact assessment methods and how to choose the method appropriately.

1.Eco-indicator 99

Eco-indicator 99 uses damage-oriented method and displays the result into three main damage categories: Human health, Ecosystem quality and Resources. It's notable that damage assessment method also uses midpoint indicators and act as the basic of creating the damage categories. However, to distinguish from classical impact assessment method, midpoint indicators are called impact categories. Straightforwardly, impact categories applied in classical impact assessment method is called midpoint categories, while in damage orient method is still called impact categories. The impact categories considered in Eco-indicator 99 include Carcinogens, Respiratory organics, Respiratory inorganics, Climate change, Radiation, Ozone layer, Ecotoxicity, Acidification/ Eutrophication, land sue and resource depletion (minerals and fossil fuels). Analogously, some damage models have been established to link impact category to one or more damage categories. Figure 5 displays the methodology these model in a schematic way[47].

Human Health damage category is expressed as DALY (Disability Adjusted Life Years). Some Models have been developed considering respiratory, carcinogenic, climate change, ozone layer depletion and ionizing radiation. Four steps are applied in these models:

a) Fate analysis, linking an emission to a temporary change in concentration.

b) Exposure analysis, linking this temporary concentration to a dose.

c) Effect analysis, linking the dose to a number of health effects, like the number and types of cancers.

d) Damage analysis, links health effects to DALY, estimating the Years Lived Disabled (YLD) and Years of Life Lost (YLL).

Ecosystem Quality category is related to the percentage of disappeared species causing by the environmental load in certain area. Following steps are applied in this process:

a) Fate analysis

b) Effect analysis, linking the temporary concentration to the levels of toxicity and acidity or to the nutrients increase.

c) Damage analysis, linking the effects to the potential species disappearance.

Resource category is connected to the quality of the remaining mineral and fossil resources.

d) Resource analysis, linking the extraction to the related resource reduction

e) Damage analysis, linking the reduction to the increase extraction demand in the future.

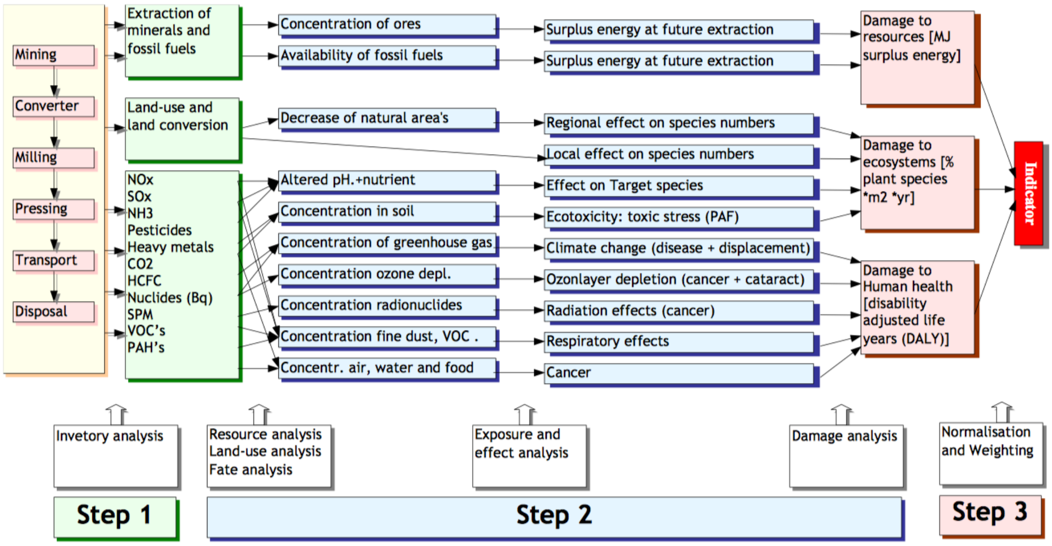


Figure 5 General representation of methodology of Eco-indicator 99[47]

2.IMPACT 2002+

IMPACT 2002+, acronym of IMPact Assessment of Chemical toxics, is a commonly used method developed by the Swiss Federal Institute of Technology- Lausanne (EPFL)[48]. It's a combination of IMPACT 2002, CML, IPCC and Eco-indicator99, which utilizes the advantages of both Classical impact assessment method and Damage oriented method. IMPACT 2002+ groups similar category endpoints into a structured set of damage categories. Meanwhile, it also adapts the midpoint categories and link each midpoint categories to one or more damage categories. Figure 6 illuminates the scheme of IMPACT 2002+ framework, which link LCI results via 14 midpoint categories (human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial eco- toxicity, terrestrial acidification/nutrification, aquatic acidification, aquatic eutrophication, land occupation, global warming, non-renewable energy, mineral extraction)to damage categories (human health, ecosystem quality, climate change, resources). Midpoint characterization factors are based on equivalency principles. Figure 7 epitomizes midpoint reference substances and damage units used in IMPACT 2002+.

It’s notable that a damage indicator result is able to represent this quality change quantitively, which, however, it’s a coarse approximation. Practically, a damage indicator result is always a simplified model of a very complex reality. The final results for these four damage categories are obtained by classification, characterization and normalization of inventory results.

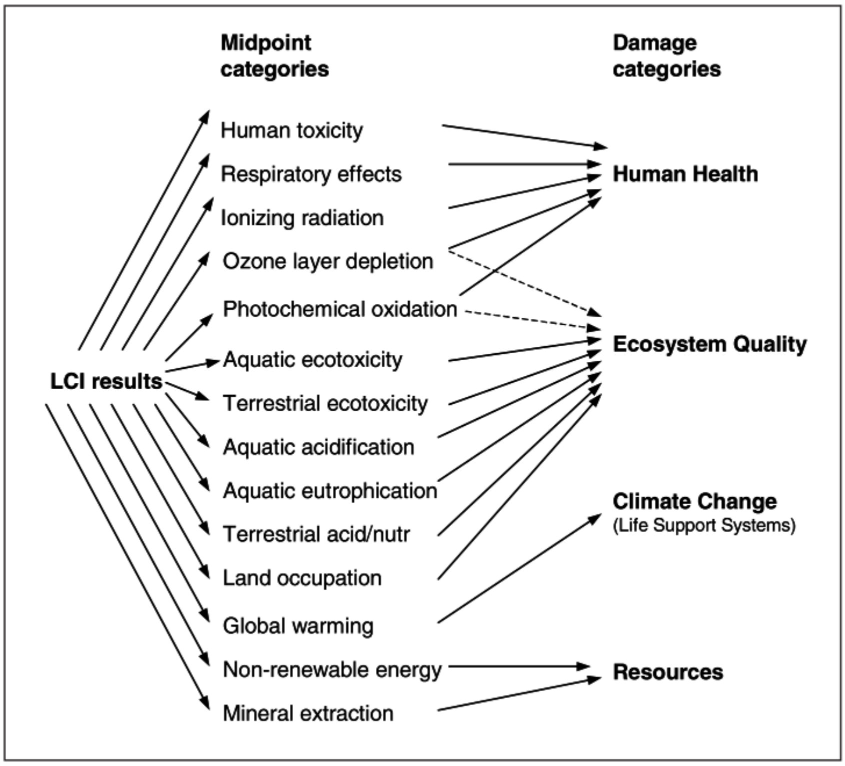
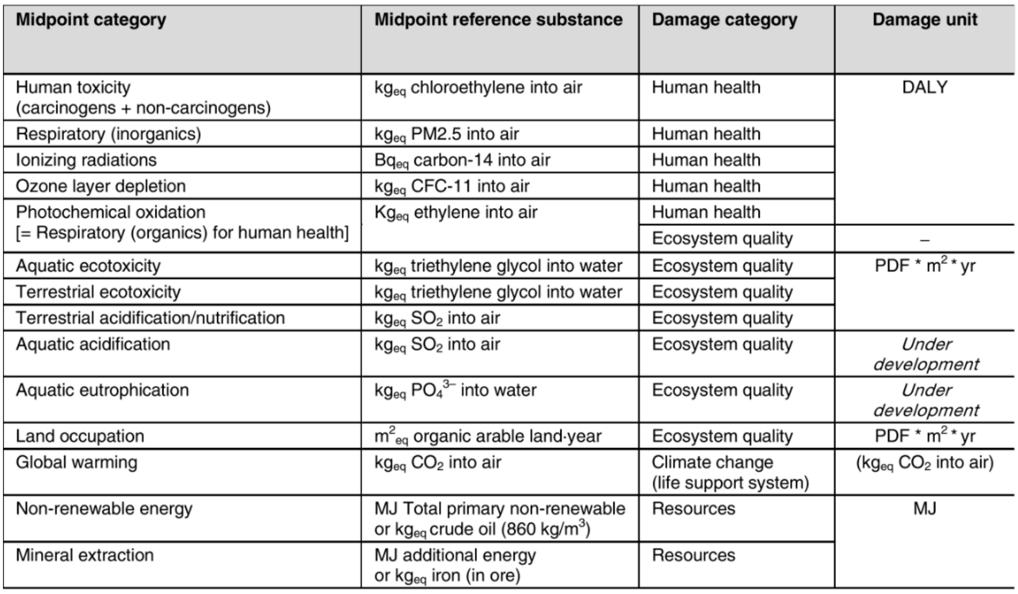


Figure 6 Overall scheme of the IMPACT 2002+ framework[48]



Midpoint category	Midpoint reference substance	Damage category	Damage unit
Human toxicity (carcinogens + non-carcinogens)	kg_{eq} chloroethylene into air	Human health	DALY
Respiratory (inorganics)	kg_{eq} PM2.5 into air	Human health	
Ionizing radiations	Bq_{eq} carbon-14 into air	Human health	
Ozone layer depletion	kg_{eq} CFC-11 into air	Human health	
Photochemical oxidation [= Respiratory (organics) for human health]	Kg_{eq} ethylene into air	Human health	
		Ecosystem quality	–
Aquatic ecotoxicity	kg_{eq} triethylene glycol into water	Ecosystem quality	PDF * m^2 * yr
Terrestrial ecotoxicity	kg_{eq} triethylene glycol into water	Ecosystem quality	
Terrestrial acidification/nutrification	kg_{eq} SO_2 into air	Ecosystem quality	
Aquatic acidification	kg_{eq} SO_2 into air	Ecosystem quality	*Under development*
Aquatic eutrophication	kg_{eq} PO_4^{3-} into water	Ecosystem quality	*Under development*
Land occupation	m^2_{eq} organic arable land·year	Ecosystem quality	PDF * m^2 * yr
Global warming	kg_{eq} CO_2 into air	Climate change (life support system)	(kg_{eq} CO_2 into air)
Non-renewable energy	MJ Total primary non-renewable or kg_{eq} crude oil (860 kg/m^3)	Resources	MJ
Mineral extraction	MJ additional energy or kg_{eq} iron (in ore)	Resources	

Figure 7 Midpoint reference substance and damage units used in IMPACT 2002+[48]

3.CED

CED, acronym of Cumulative Energy Demand, is a common used method to calculate the cumulative energy demand, which is able to represent the direct and indirect energy use expressed in MJ throughout the life cycle of a product[49]. This method is practical to provide a general view of the energy related impact during the life cycle, and is also useful to conduct a comparison of individual products. However, CED can only act as an auxiliary method to analyze the energy consumption since the result from CED cannot give a full picture for all environmental impact.

The energy resources are divided in 5 impact categories. (Non-renewable fossil, Non-renewable nuclear, Non-renewable biomass, Renewable wind, Renewable solar, geothermal and Renewable water)

4.IPCC 2013

IPCC 2013, developed by the International Panel on Climate Change, mainly focuses on the global warming issue. It is a good method to quantify the direct contributions of airborne emissions to the climate change impact, utilizing the climate change factors of IPCC with a timeframe of 20, 100 and 500 years. The mechanism of this method is to evaluate the emission of greenhouse gas result from anthropogenic activities and apply to the corresponding emissions. IPCC assesses characteristic factors based on the global warming potentials (GWPs) of different gas[50]. GWPs are index for calculating the global warming contribution of airborne emission, which can convert a particular GHG to the corresponding emission of CO_2. Therefore, the unit of IPCC results is kg CO_2 eq.

3.2.3.2. Selection of method

The best way to select an appropriate impact assessment method is to select the appropriate impact categories. It's necessary to justify this choice and clearly defend leaving out an impact category. An important way to do this is to look at existing studies, or assess the concerns on the relevant stakeholders since a study will only be accepted if the relevant stakeholders find the information about what they want to know, or understand why that information cannot be made available.[46]

3.2.4. Interpretation

The interpretation step aims to identify the most significant issues in the results obtained in LCIA as well as evaluate the completeness of the study, including uncertainty analysis and sensitivity analysis.

Uncertainty analysis is to determine the reliability of the results by identifying the data variation and correctness of the model.

Sensitivity analysis is to evaluates the influence of the most important assumptions have on the results.

4. Life cycle assessment of SDH-BTES in Kuujjuaq, Nunavik

Use Kuujjuaq as case study, a life cycle assessment of a heating scenario for 20 single-family houses is modelled is this chapter.

4.1. Goal and scope definition

This is the first step in conducting an LCA, which mainly describes the goal of the study and specifies the system schematic and system product as well as the system boundaries. Besides, some assumption is raised to simplify the research and the limitation are discussed at the end of this section.

4.1.1. Goal of the study

The goal of this LCA is to analyze the lifetime inventory of an assumed SDH-BTES system in Kuujjuaq and to evaluate the potential environment impacts. The total emissions throughout its entire life should be calculated to determine the total impact on the environment. Besides, this research also looks into each assembly and different life cycle phases to identify the dominating contributors to the total impacts. Additionally, a comparison with the current heating system, a common diesel furnace in each building, is provided to demonstrate that SDH-BTES system can be an environmentally friendly substitute to satisfy the heat demand in Kuujjuaq. Moreover, the underlying goal of this LCA research is to stimulate the further research in this area and dedicate to develop a renewable energy in extreme cold weather region.

In the following research, this is done by using LCA software SIMAPRO. SIMAPRO is a helpful tool to build up an LCA model assembling the material flow, process, and the whole life cycle stages, and analyze the data and calculate the total emissions.

4.1.2. General assumption

Since there is no empirical SDH-BTES project built in Nunavik or other subarctic regions, some basic hypothesis needs to be established to conduct an LCA research.

- Assumption 1: a solar district heating with borehole thermal energy storage system will be built in Kuujjuaq, Nunavik in 2022 to provide heating for 20 single-family houses there for 50 years. Figure 8 shows the detail of single-family house.

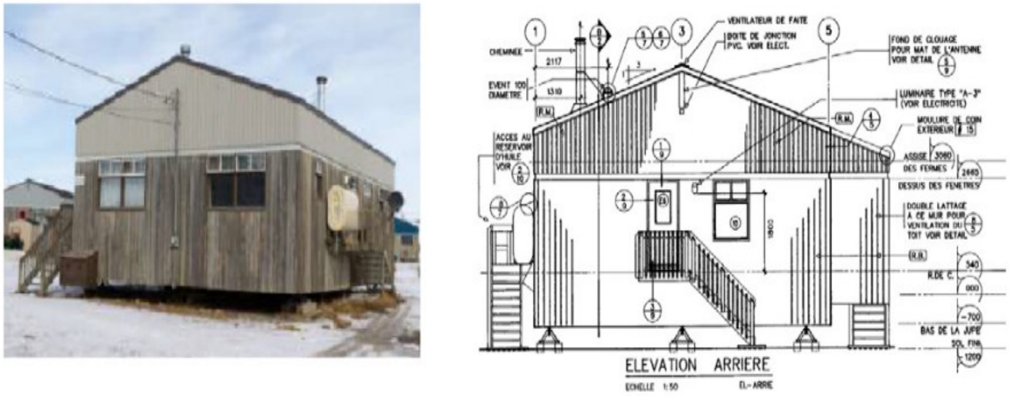


Figure 8 A typical single-family three bedrooms household (SHQ,2012,1994)

Yan et al.[3] who reviewed lots of data from KMHB conducted a RETScreen analysis to determine the heating system load of single-family houses in Kuujjuaq. They calculated that the actual heating energy demand of a single-family house is 21.6 MWh. Based on their calculation, 20 single-family houses in this study require 432 MWh heating per year.

- Assumption 2: as mentioned in literature review, Miranda et al. [27]verify that major community area is a relatively better site to develop a borehole thermal energy storage system since there is less permafrost, moderate to low fracture permeability and low fracture hydraulic conductivity. Hence, to simplify the study, SDH-BTES system is assumed to be built near a community shown in Figure 9. Figure 9 shows the surrounding of the project and the target service houses. It is assumed that the target service houses in this area are single-family houses.

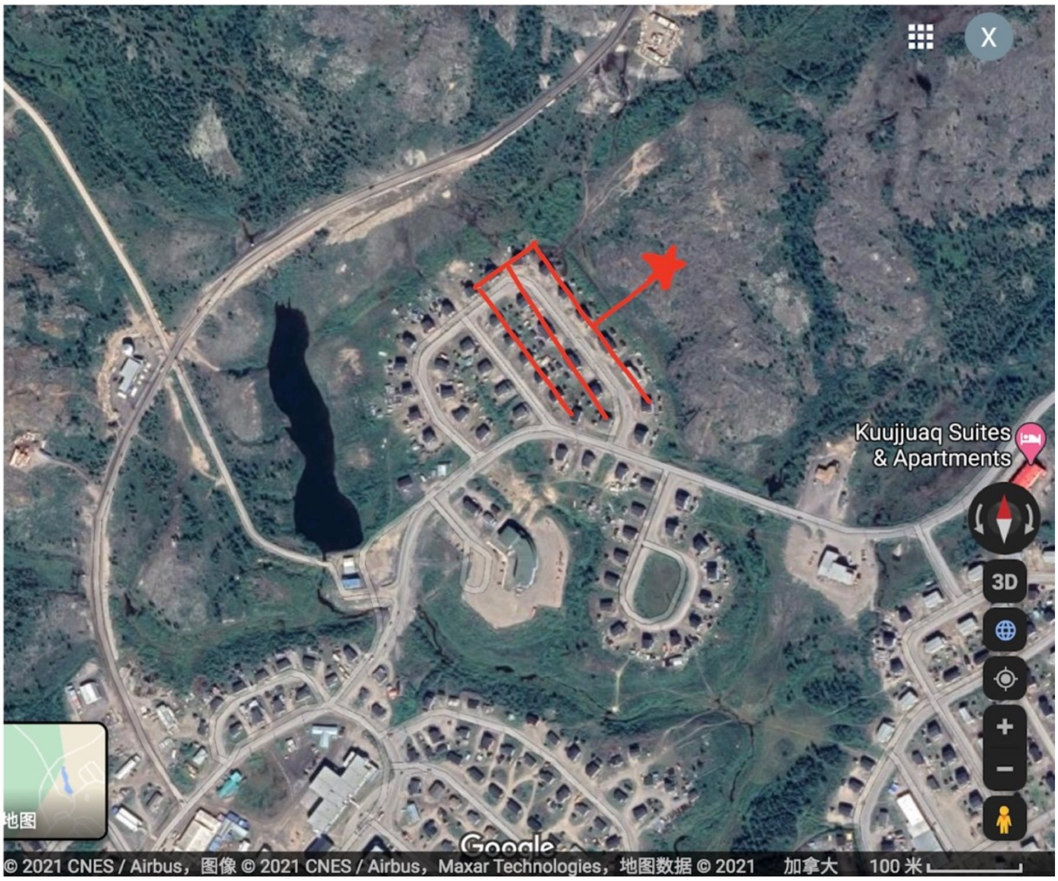


Figure 9 Site map of the project (google map)

- Assumption 3: this study is carried out on the basis of the research of Nicolò

Giordano et al., who revealed that solar fraction of 45 to 50% and heat recovery of more than 60% can be achieved by the 3rd year operation of SDH-BTES system in Kuujjuaq.[32] The main hypothesis is that SDH-BTES system can perform as efficient as the result Nicolò Giordano et al. obtained in their research.

4.1.3. System description

To satisfy the heating demand of 20 single-family houses in Kuujjuaq, an SDH-BTES system combined with an auxiliary boiler is designed to provide sufficient heating. Nicolò Giordano et al. use TRANSY to simulate 11 scenarios of SDH-BTES system in Kuujjuaq. Between them, scenario 9 received a best result in terms of heat losses both in the STST (2.3%) and in the BTES (25.2%) and provided the most heating (227 MWh) per year, although it was partly because it had the largest solar area(1500 m^2). In general, scenario 9 is the most appropriate reference for this study. Therefore, most parameter of this project will derive straightly from scenario 9. The whole system reaches a solar efficiency of 29.7%, based on the simulation result developed in the software TRNSYS[32]. Table 2 illustrates the characteristics and simulation result of scenario 9.

Table 2 Characteristics and simulation result of scenario 9

Characteristics		Simulation result	
Number of BHE (-)	150	Solar energy production (GJ[1])	1360.3

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[1] 1 MWH=3.6 GJ

Gross solar area (m^2)	1500	ηsolar [2](%)	29.7
Number of STST (–)	2	STST Losses (GJ)	31.7
STST volume (m^3)	100	Injection (GJ)	1328.5
BTES volume (m^3)	35000	Charge losses (GJ)	334.4
BHE length (m)	30	Storage (GJ)	994.1
BHE spacing (m)	3	Extraction (GJ)	719.5
Flow rate in BTES (m^3 h−1)	60	Heating from BTES (GJ)	199.9
BHE type	1-U	Heating from STST (GJ)	27.1
-	-	Total heating from system	227.0

The SDH-BTES system in this study mainly consists of five segments: solar collection field, heat storage, piping system, an auxiliary boiler and control system. Solar collection field is composed of 1500 m^2 flat plate solar collectors. Figure 10 shows the structure of the solar collector. During the charge phase, the solar collectors capture solar energy and send it to the heat storge.

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[2] Solar efficiency, based on gross area

Figure 10 Flat plate solar collector (source from https://www.onosisolar.com/solar-collectors/flat-plate-solar-thermal-collector/)

Heat storage consists of short-term heat storage and long-term heat storage, which is 2 short term storage tanks (STST) and borehole thermal energy storge (BTES), respectively. STST is two 100 m^3 water tank which can storage the heat from the solar collector temporarily. Figure 11 shows the structure of STST. Borehole thermal energy storage is a most common type of underground thermal energy storage technologies, which forms a loop to storage heat for a long term. It consists of underlying single U-tube pipes made of plastic and heat carrier fluid to prevent freezing. Figure 12 and figure 13 show the schematic of BTES and single U-pipe, respectively.

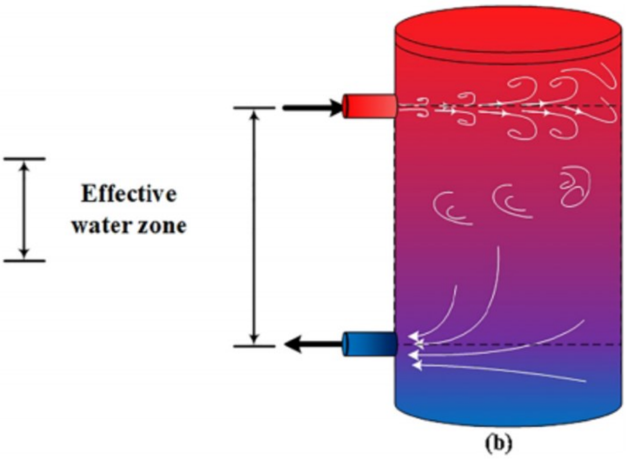

Figure 11 Schematic of water tank [51]

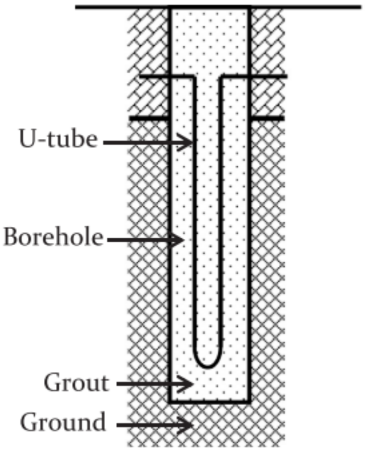

Figure 12 Schematic of borehole heat exchanger[52]

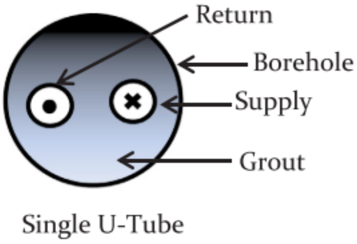

Figure 13 Single U-tube pipe[52]

Piping system includes solar collection loop and district heating loop. Solar collection loop connects the solar collector to the water tank. District heating loop is the pipe that carries hot water to the user from water tank. Based on the distance between target service community and SDH-BTES system, the length of piping is assumed to be 1000 m.

Auxiliary diesel boiler (100 KW) is equipped to generate heat when the whole system cannot provide enough thermal energy for the users. Figure 14 shows the schematic of diesel boiler.

Figure 14 Schematic of diesel boiler (source from: https://www.yd-boiler.com/products/oil-gas-boiler/)

A control system is designed to initiate and maintain the system operation, which mainly consists of 2 heat exchanger and 5 hydraulic pumps. When the solar collector loop fluid is hot enough, heat is pumped to the STTS through a heat exchanger (ex1). When space heating is required, thermal energy from the STTS heats the fluid in distribution loop through another heat exchanger (ex2). If the thermal energy in STTS is insufficient, heat is pumped from the BTES into the STTS to meet the heating load. If the energy in BTES is insufficient to meet the requirement, diesel boilers is initiated to raise the temperature of the distribution loop as required. When thermal energy in the STTS is substantial and exceeds the heating requirement in the short-term, hot water in the STTS is circulated through the BTES and store heat for long term purpose.

Figure 15 Heat exchanger

In general, the main components of SDH-BTES system in this study are solar collector, two hot water tanks, two heat exchangers, five hydraulic pumps, borehole exchangers, districting pipes and an auxiliary boiler.

4.1.4. System component summary

The main parameters of SDH-BTES system are list in Table 3.

Table 3 Main parameters of SDH-BTES system

Component	Amount	Source
Solar collector (m^3)	1500	Nicolò Giordano et al. [32]
BHE (m)	4500[3]	
100KW Boiler	1	
Oil tank (m^3)	10	
Water tank (m^3)	200[4]	
3.3 kW hydraulic	5	[11]

---

[3] One hundred and fifty unit of borehole with the length of 30 meters

[4] Two 100 m^3 water tank

pumps (-)		
Heat exchanger (-)	2	
Piping (m)	1000	Assumption

After setting up the main parameters, it’s crucial to consider the operation efficiency of the system. Since this is a hypothetical project, the input and output data can only be taken from the literature review and previous empirical project. Note that the solar efficiency is assumed as 29.7% and the solar fraction of this project is 52.5%.

Table 4 Input and output of the system

Annul operation data		Amount	Source
Output	Heating supply from Solar subsystem (MWh[5])	227	[32]
	Heating produced at auxiliary boiler (MWh)	205	
Input	Electricity consumption (MWh)	35.94	[53][54]
	Diesel consumption from diesel boiler (L)	19069.77 (205*3.6/0.0387=19069.77)	1 l diesel oil =0.0387 GJ[28]

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[5] 1 MWh = 3.6 GJ

4.1.5. System product

The product of this system is the heat delivered to buildings. To satisfy the heat demand of 20 single-family houses, SDH-BTES system need to generate 432MWh heating per year.

4.1.6. Function unit

The function of SDH-BTES system, as specified for this study, is to provide heating for 20 single-family houses. A common measure of heat is MWh. To make a comparison with the current heating system, the function unit for this study is set to be total heating (MWh) generate during the estimated life span, which is 21600 MWh for the 50 years.

4.1.7. System boundary

The boundaries of the system specify which processes should be included in the product system. This study includes acquisition of raw materials, manufacturing processes, transportation, construction, operation, and recycling of material or disposal.

The LCA of the analyzed system is divided into production stage, assembly stage, operational stage and disposal stage.

As mentioned above, this system is subdivided into several main components, which are: solar collectors, borehole, water tanks, pumps, pipeline, heat exchangers and diesel boilers as well as oil tank. The production stage will include materials used, energy consumption and transportation of material during the manufacturing process of these components.

The assembly phase will consider: transportation from the production factory to the location of the system (The transport of oil products and heavy and nonperishable materials is done by boat in Nunavik.[4] it’s assumed that the production factory of all main components is shipped by cargo ships from Montreal, so the distance is 3842.9 km), and installation of devices.

The operational phase will contain: the electrical power consumption of the pumps and the diesel consumption at the auxiliary boilers. Electricity is provided by diesel power plant in Nunavik. In the case of the diesel, it will include the extraction, processing, transportation and combustion.

At the end-of-life stage, final disposal will be considered. It is assumed that they are dumped to the landfill at the end of its useful life.

It is noted that heating devices in each building are not considered in this study.

4.1.8. Limitation

The relevancy of data is of high importance. The accessibility and availability of applicable data may affect the relevancy of the results. Results that focus on global or regional issues may not be adequate for local applications (ISO 2006). For this study the availability of data was sometimes a problem because of confidentiality of data for the previous empirical project and the limited research of SDH-BTES in Nunavik or other subarctic area. Suppliers want keep their specifications propriety since they want to ensure that they keep their share of the market by maintaining an edge over competing companies.

4.2. Life cycle inventory analysis

This chapter discusses the input and output data collection and calculation process for SDH-BTES system during life cycle stage. Input data of different component, including consumption of natural resources, energy, is collected from Ecoinvent 3.3, literature reviewed and manual in the website, while the output data is mainly collected from Ecoinvent 3.3, which encompasses the emission generation data of many processes. The LCA model is built up using SIMAPRO 8.1 software. Following research in this chapter focuses on the collection process of elementary input flow data.

4.2.1. Production stage

4.2.1.1. Solar collector

1500 m^2 Solar collector field in this project consist of 620 flat plate solar collectors with the gross area of 2.42 m^2 each. Figure 16 illustrates the structure of a flat plate solar collector with aluminum absorber. Figure 17 shows the parameter of each solar collector. Flat plate solar collector is composed of glass, absorber, insulation, back sheet, riser and header pipe, and aluminum rails.

The diagram below shows the basic construction of the collector.

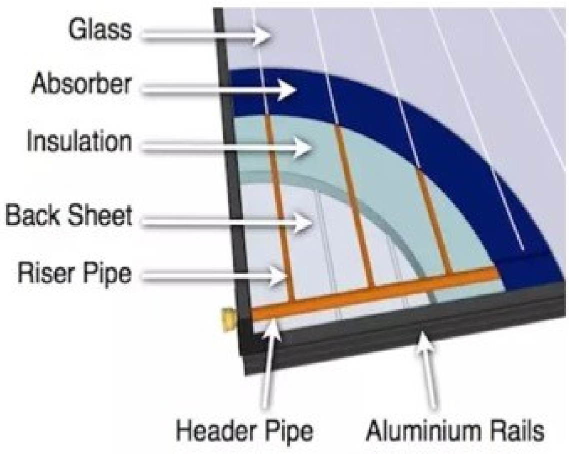


Figure 16 Basic structure of solar collector (source form: https://www.solarusagenow.com/new-page-1

Dimensions (LxWxH)*	1981 x 1222 x 80 mm
Peak Output**	1706 W
Aperature Area	2.26 m^2
Gross Area	2.42 m^2
Gross Dry Weight	38.5 kg
Fluid Capacity	1.55 L
Flow Rate	1.6 L/min (max 15L/min)
Max Operating Pressure	800 kPa / 8 bar

Figure 17 Parameter of solar collector (source form: https://www.solarusagenow.com/new-page-1)

- The cover sheets, called glazing

Toughened glass (glazing) protects the absorber from the outside environment while allowing through >90% of sunlight. “Low iron”, tempered glass is used in many collectors for mechanical strength, for safety and for higher collector efficiency.

- Absorber

A thin sheet of Aluminum is coated with a highly selective material that is extremely efficient at absorbing sunlight and converting it into usable heat. The aluminum sheet is ultrasonically welded to the copper riser pipes. Figure 18 shows the absorber grid form type.

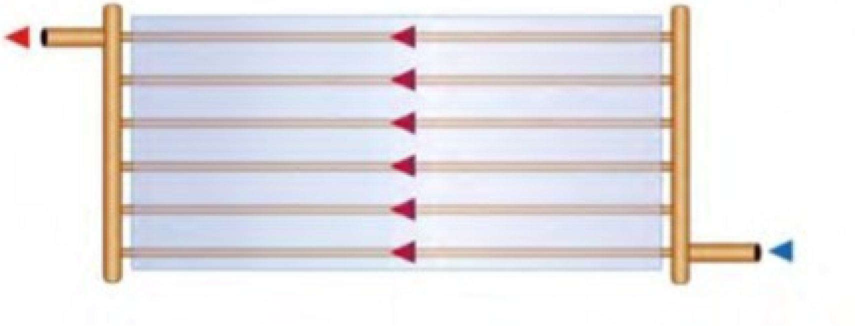


Figure 18 Absorber grid form type

- Insulation

The insulation helps reduce heat loss from the sides and back of the collector. With the average thickness of 30 to 40 mm, the insulation is made from rock wool, an ultra-light weight material.

Figure 19 Rock wool 30-40mm

- Back sheet

An aluminum alloy sheet seals the back of the panel and adds to the rigidity of the collector.

- Riser and header pipe

The header and riser pipes are brazed together to form a harp shaped heat exchanger that the solar system heat transfer fluid circulates through. The absorber sheet is ultrasonically welded to the riser pipes, thus transfers heat to the heat transfer fluid.

- Aluminum rails

Extruded from high tensile 6063 aluminum alloy, the rails form the outer framework of the collector and are designed with wings for easy mounting frame attachment.

Global environment facility has developed a research on the manufacturing of solar collector. In their research, the manufacturing process of a solar collector is divided into 12 steps. Figure 20 illustrates manufacturing processes. The first step is to cut copper header tube into the required length and then go through punching and flanging. After that, connection joints are welded at the two ends of the header tube and then connect them to the water pipes. Step 2 is to shrink the riser tubes and then weld them to the header tubes. Step 3 is a leakage test to assure complete welding between riser and header. Step 4 is to conduct a roughen treatment on riser tubes and then weld the absorber sheet on the surface of them. Step 5 is to assemble the frame and back sheet, using sheet metal bending and forming equipment. Step 6 is to place insulation inside the frame casing and complete the insulation frame assembly. Step 7 is to install the absorber above insulation and step 8 is to assemble the glass cover sheet. Step 9 is to seal the glass sheet and frame with silicon and step 10 is to apply rubber sealing for fixation of aluminum frame to frame. Step 11 is the final frame fixation using rubber to assemble frame bars to the collector. Step 12 is to pack the flat plate collector using corner covers.[55]

Figure 20 Flow chart of flat plate collector manufacturing[55]

Table 5 epitomizes the main materials and key manufacturing process of a solar collector.

Table 5 Main materials and key manufacturing process of a solar collector

Item	Detail
Main material	Glass Rock wool Copper Aluminum Rubber Silicone Steel

	HDPE
Key manufacturing process	Sheet rolling, aluminum Section bar extrusion, aluminum Welding and brazing Tempering, glass Drawing of pipes Coating

Given the exact manufacturing process of a solar collector, next is to build up the assembly in SIMAPRO. Since there is no available data of solar collector with Aluminum absorber in database, to build the target model, flat plate solar collector with copper absorber is selected and modified based on the research of Stucki et al. who update the life cycle inventories of solar collector[56]. Figure 21 illuminates the inventory of solar collector with Aluminum absorber. The arrangement of solar collectors is shown in Figure 22.

Name	Amount	Unit
Silicone product {GLO}| market for | Alloc Def, U	0.0857	kg
Water, completely softened, from decarbonised water, at user {GLO}| market for | Alloc [illegible]	1.74	kg
Propylene glycol, liquid {GLO}| market for | Alloc Def, U	1.02	kg
Brazing solder, cadmium free {GLO}| market for | Alloc Def, U	[illegible]	kg
Sheet rolling, aluminium {GLO}| market for | Alloc Def, U	1.41	kg
Corrugated board box {GLO}| market for corrugated board box | Alloc Def, U	[illegible]	kg
Synthetic rubber {GLO}| market for | Alloc Def, U	0.857	kg
Solar collector factory {GLO}| market for | Alloc Def, U	[illegible]	p
Rock wool, packed {GLO}| market for | Alloc Def, U	1.59	kg
Copper {GLO}| market for | Alloc Def, U	1.73	kg
Aluminium, wrought alloy {GLO}| market for | Alloc Def, U	5.34	kg
Steel, chromium steel 18/8, hot rolled {GLO}| market for | Alloc Def, U	[illegible]	kg
Selective coat, aluminium sheet, nickel pigmented aluminium oxide {GLO}| market for | [illegible]	[illegible]	m2
Solar glass, low-iron {GLO}| market for | Alloc Def, U	8.27	kg
Soft solder, Sn97Cu3 {GLO}| market for | Alloc Def, U	[illegible]	kg
Tap water {CA-QC}| market for | Alloc Def, U	[illegible]	kg
Tap water {Europe without Switzerland}| market for | Alloc Def, U	[illegible]	kg
Tap water {RoW}| market for | Alloc Def, U	[illegible]	kg
Polyethylene, high density, granulate {GLO}| market for | Alloc Def, U	0.00857	kg
Tempering, flat glass {GLO}| market for | Alloc Def, U	8.27	kg
Section bar extrusion, aluminium {GLO}| market for | Alloc Def, U	[illegible]	kg
Drawing of pipe, steel {GLO}| market for | Alloc Def, U	1.73	kg

Figure 21 Inventory of a solar collector

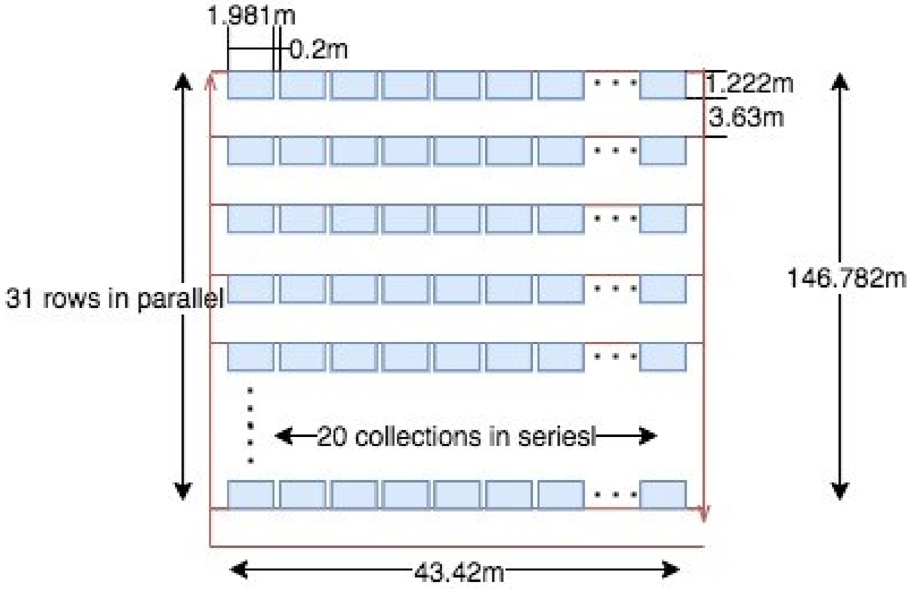


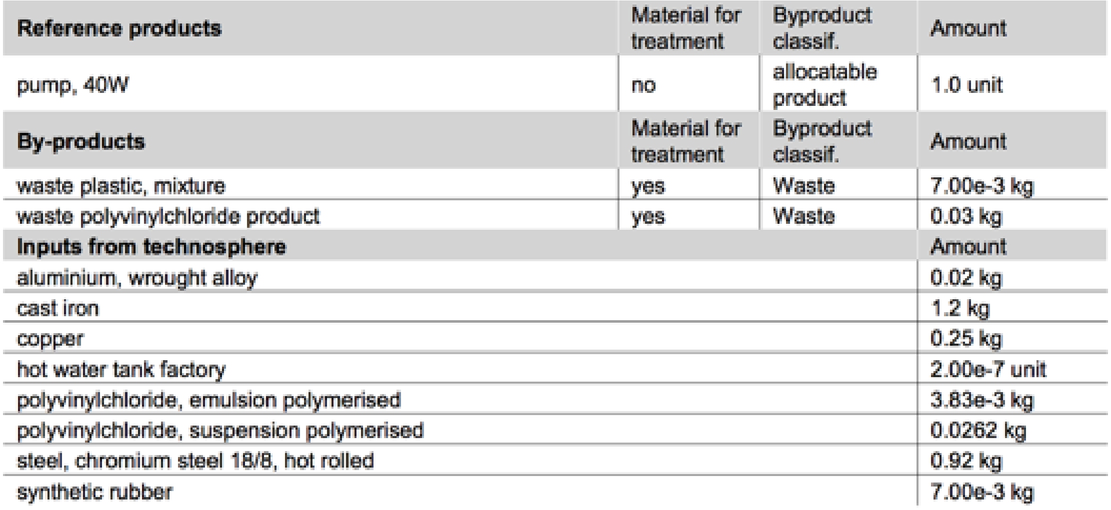
Figure 22 Arrangement of solar collector

4.2.1.2. Pump

Five hydraulic pumps are equipped in SDH-BTES system. It’s assumed that the power of these pumps is 3.3 KW. Based on the manual of pumps manufacturing, the weight of each pump is 95 kg[57]. Jungbluth established a life cycle inventory dataset of a pump with a capacity of 40 W and a gross weight of 2.4 kg in Ecoinvent. Stucki indicated that the gross weights of pumps with different capacities can be used for scaling the 40 W pump to the pumps with higher capacity. Accordingly, the target pump with the weight of 95 kg is equal to 40 units of 40W pump. Figure 24 illuminates the inventory of a 40 W pump.

Lowara 1315 Vortex
Maximum flow 44 l/s
Maximum pressure 15 m
Motor Rating 2.2 - 4.4 kW
Outlet 65 - 100 mm
Weight 95 kg

Figure 23 Hydraulic pump



Reference products	Material for treatment	Byproduct classif.	Amount
pump, 40W	no	allocatable product	1.0 unit
By-products	Material for treatment	Byproduct classif.	Amount
waste plastic, mixture	yes	Waste	7.00e-3 kg
waste polyvinylchloride product	yes	Waste	0.03 kg
Inputs from technosphere			Amount
aluminium, wrought alloy			0.02 kg
cast iron			1.2 kg
copper			0.25 kg
hot water tank factory			2.00e-7 unit
polyvinylchloride, emulsion polymerised			3.83e-3 kg
polyvinylchloride, suspension polymerised			0.0262 kg
steel, chromium steel 18/8, hot rolled			0.92 kg
synthetic rubber			7.00e-3 kg

Figure 24 Inventory of a 40W pump

4.2.1.3. Heat exchanger

Heat exchangers are unfired heat transfer equipment used in process plants. Heat exchangers are used for the transfer of heat or cold between two fluids for the purpose of heating, cooling, or condensing vapors during the process. There are several different types of heat exchangers. In this project, plate-frame type are selected. [58] Plate exchangers consist of a series of alloy plates held together by a frame. The frame can be opened to add or repair the plates. One liquid flow through alternate plates and the other liquid flow the opposite direction through the opposite plates.

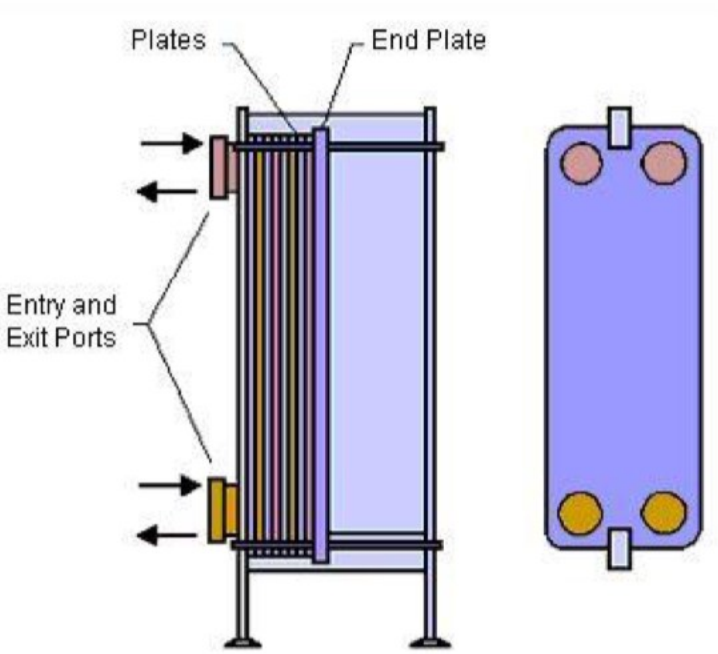
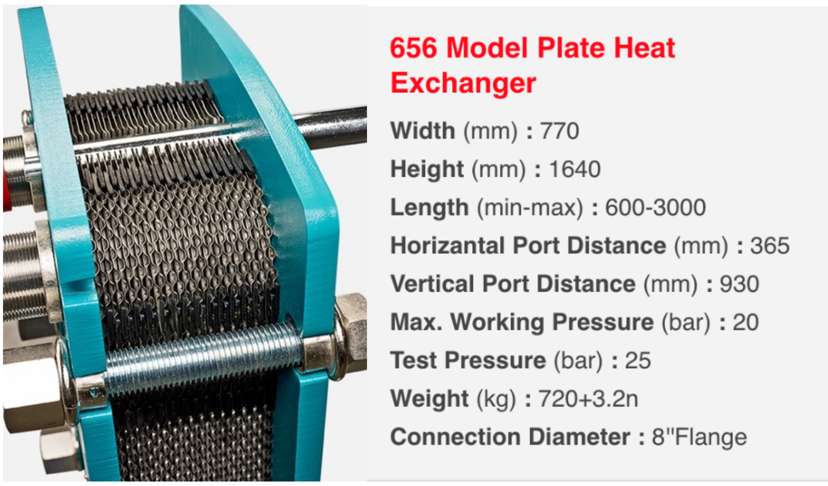


Figure 25 Plate-frame heat exchanger[59]

Adolfsson et al. [60] conducted an LCA research on heat exchanger and depicted the manufacturing process in their study. Since heat exchanger is mainly made of stainless steel, the only material considered in LCA model is stainless steel. Other parts, like gaskets, accounts for a very small mass of the heat exchanger which can be ignored. They also indicated the energy flow for manufacturing a heat exchanger is 0.8028 MJ/kg. Therefore, the production process of a heat exchanger can be simplified, only including stainless steel as material and the energy consumed during the manufacturing. The extraction and production of stainless steel are also considered in the LCA.

In this project, two 656 model plate hear exchanger are equipped. Figure 16 shows the basic parameter of heat exchanger. It’s assumed that the whole heat exchanger is made of stainless steel. Therefore, the input of a heat exchanger included 720 kg stainless steel and 578.016[6] MJ energy. Figure 27 illuminates the inventory of a heat exchanger.



656 Model Plate Heat Exchanger

Width (mm) **:** 770

Height (mm) **:** 1640

Length (min-max) **:** 600-3000

Horizantal Port Distance (mm) **:** 365

Vertical Port Distance (mm) **:** 930

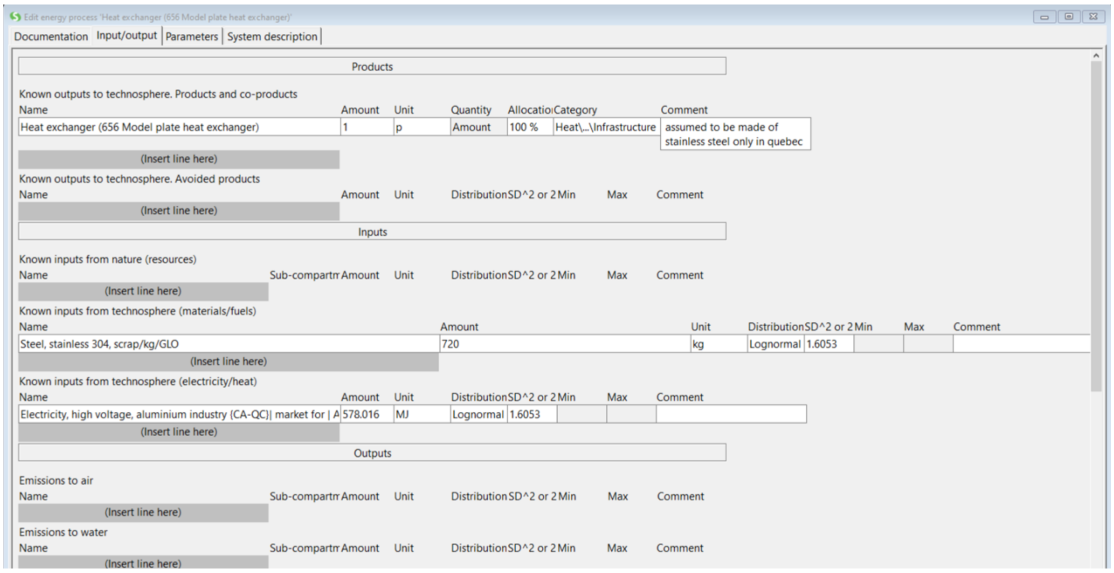
Max. Working Pressure (bar) **:** 20

Test Pressure (bar) **:** 25

Weight (kg) **:** 720+3.2n

Connection Diameter : 8"Flange

Figure 26 Plate heat exchanger (left) Basic parameter (right) [61]



Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocatio	Category	Comment
Heat exchanger (656 Model plate heat exchanger)	1	p	Amount	100 %	Heat\...\Infrastructure	assumed to be made of stainless steel only in quebec

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment

Known inputs from nature (resources)

Name	Sub-compartm	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment
Steel, stainless 304, scrap/kg/GLO	720	kg	Lognormal	1.6053			

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment
Electricity, high voltage, aluminium industry {CA-QC}| market for | A	578.016	MJ	Lognormal	1.6053			

Emissions to air

Name	Sub-compartm	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment

Emissions to water

Name	Sub-compartm	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment

Figure 27 The inventory of heat exchanger

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[6] Total energy is equal to 720kg*0.8028 MJ/kg

4.2.1.4. Pipes

Pipeline system is an essential element in SDH-BTES which connects different part of the system and distributes the heat correspondingly. The pipe consists of chromium steel pipe and tube insulation. The main manufacturing process is drawing of pipe. Figures 28 and 29 illustrate the inventory of steel pipe and insulation, respectively. The length of pipeline is assumed to be 1000 m. DN100 pipe (114.3,3.6 mm) is selected in this project, with the insulation thickness of 200 mm. The density of steel is 7850 kg/m^3, and the density of EPDM foam is 75 kg/m^3.

The volume of steel is calculated as below:

$$V = (\pi \times \left(\frac{0.1143}{2}\right)^2 - \pi \times \left(\frac{0.1143-0.0036*2}{2}\right)^2) \times 1000 \text{=1.25m3}$$

Therefore, the weight of steel is

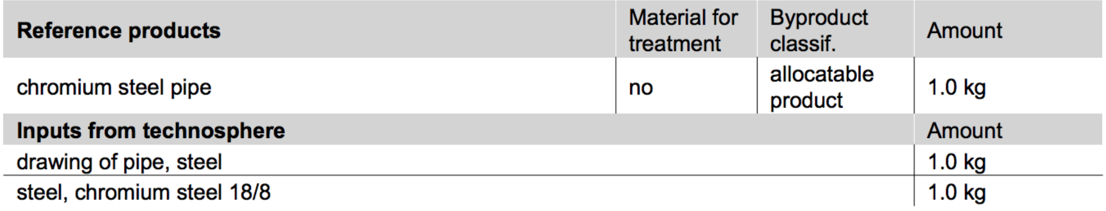
$$W = 1.25 \times 7850 = 9828.10kg$$

The volume of insulation is calculated as below:

$$V = (\pi \times \left(\frac{0.2}{2}\right)^2 - \pi \times \left(\frac{0.1143}{2}\right)^2) \times 1000 \text{=21.16m3}$$

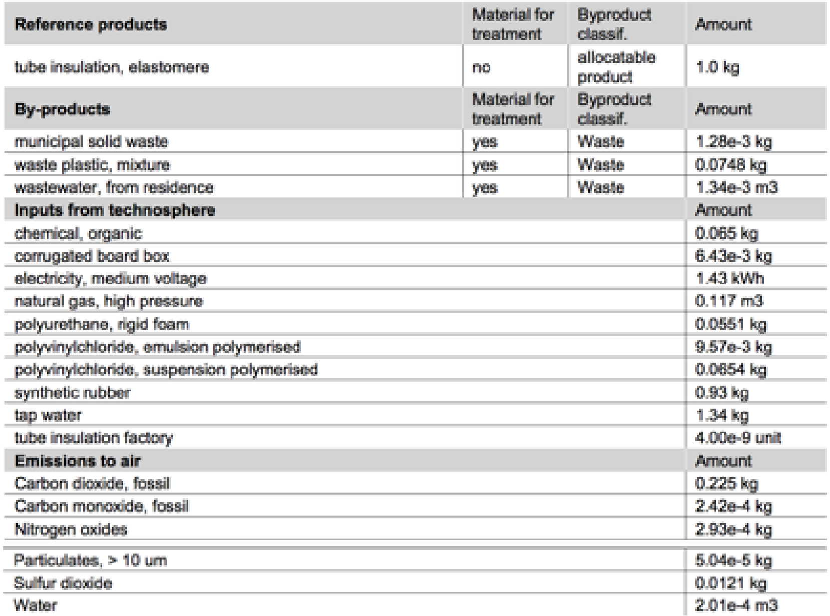
Therefore, the weight of insulation is

$$W = 21.16 \times 75 = 1586.63kg$$



Reference products	Material for treatment	Byproduct classif.	Amount
chromium steel pipe	no	allocatable product	1.0 kg
Inputs from technosphere			Amount
drawing of pipe, steel			1.0 kg
steel, chromium steel 18/8			1.0 kg

Figure 28 Inventory of chromium steel pipe



Reference products	Material for treatment	Byproduct classif.	Amount
tube insulation, elastomere	no	allocatable product	1.0 kg
By-products	Material for treatment	Byproduct classif.	Amount
municipal solid waste	yes	Waste	1.28e-3 kg
waste plastic, mixture	yes	Waste	0.0748 kg
wastewater, from residence	yes	Waste	1.34e-3 m3
Inputs from technosphere			Amount
chemical, organic			0.065 kg
corrugated board box			6.43e-3 kg
electricity, medium voltage			1.43 kWh
natural gas, high pressure			0.117 m3
polyurethane, rigid foam			0.0551 kg
polyvinylchloride, emulsion polymerised			9.57e-3 kg
polyvinylchloride, suspension polymerised			0.0654 kg
synthetic rubber			0.93 kg
tap water			1.34 kg
tube insulation factory			4.00e-9 unit
Emissions to air			Amount
Carbon dioxide, fossil			0.225 kg
Carbon monoxide, fossil			2.42e-4 kg
Nitrogen oxides			2.93e-4 kg
Particulates, > 10 um			5.04e-5 kg
Sulfur dioxide			0.0121 kg
Water			2.01e-4 m3

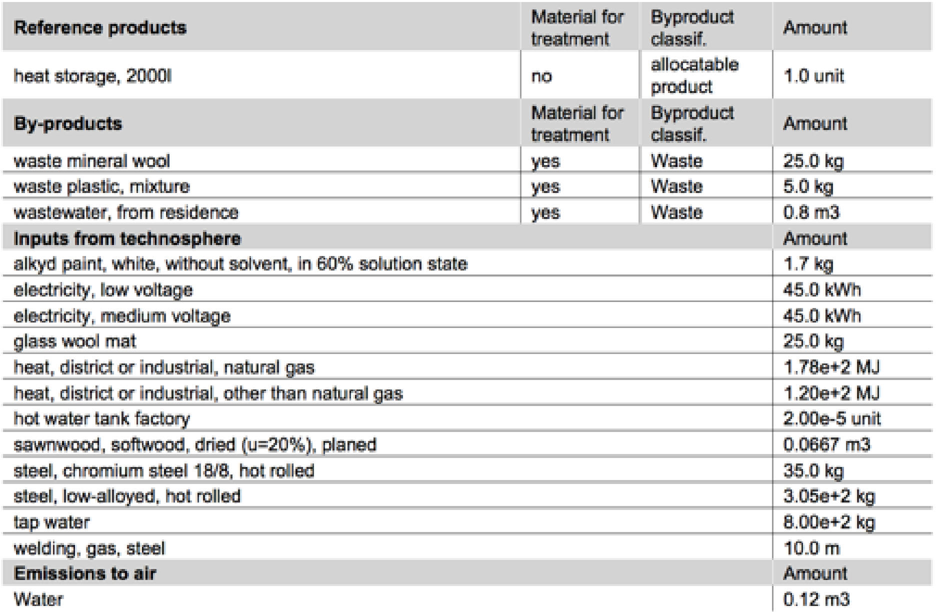
Figure 29 Inventory of tube insulation

4.2.1.5. Borehole heat exchanger

One hundred and fifty 30-m-deep single U-tube borehole heat exchangers are installed in this project, which can be considered as one hundred and fifty 60-m-length tubes at a probe. In production stage, borehole heat exchangers mainly involve the production of polyethylene U-tube pipe. The inventory will be presented later in the construction stage.

4.2.1.6. Short-term Heat storage

Short-term heat storage includes a 100m^3 hot water tank and a 100 m^3 cold-water tank which are both considered with a 2000 l heat storage (367 kg) in Ecoinvent datasets. Since the weight of a 100 m^{3}water tanks is 5000kg, the factor is calculated as 13.62 using scaling method. Figure 30 shows the inventory of 2000 l heat storage. 100 m^3 heat storage is equal to 13.62 times 2000 l heat storage.

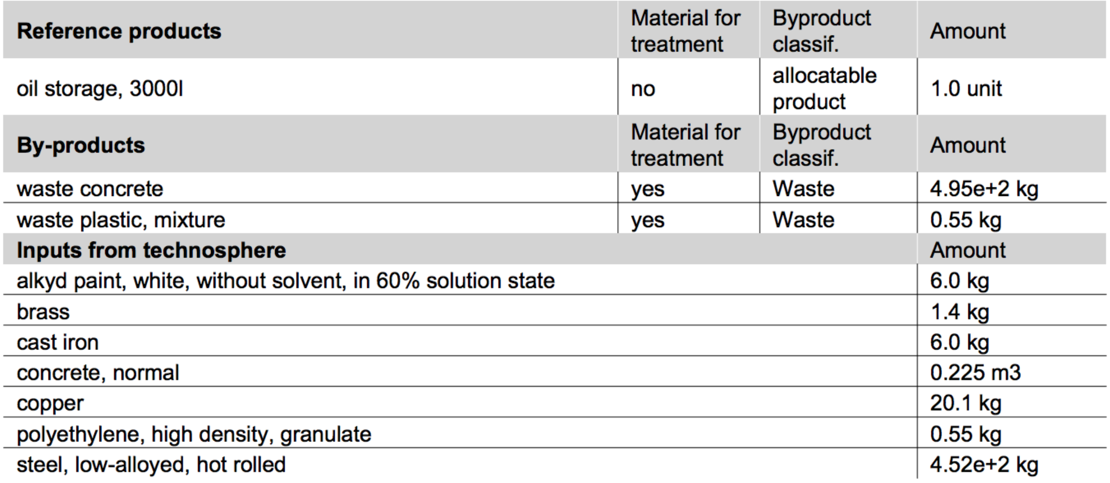


Reference products	Material for treatment	Byproduct classif.	Amount
heat storage, 2000l	no	allocatable product	1.0 unit
By-products	Material for treatment	Byproduct classif.	Amount
waste mineral wool	yes	Waste	25.0 kg
waste plastic, mixture	yes	Waste	5.0 kg
wastewater, from residence	yes	Waste	0.8 m3
Inputs from technosphere			Amount
alkyd paint, white, without solvent, in 60% solution state			1.7 kg
electricity, low voltage			45.0 kWh
electricity, medium voltage			45.0 kWh
glass wool mat			25.0 kg
heat, district or industrial, natural gas			1.78e+2 MJ
heat, district or industrial, other than natural gas			1.20e+2 MJ
hot water tank factory			2.00e-5 unit
sawnwood, softwood, dried (u=20%), planed			0.0667 m3
steel, chromium steel 18/8, hot rolled			35.0 kg
steel, low-alloyed, hot rolled			3.05e+2 kg
tap water			8.00e+2 kg
welding, gas, steel			10.0 m
Emissions to air			Amount
Water			0.12 m3

Figure 30 Inventory of 2000l heat storage

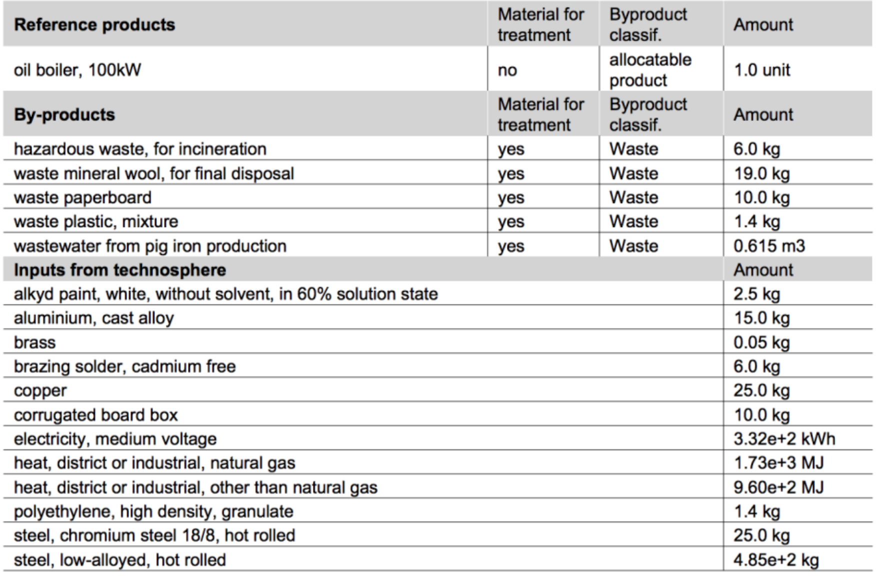
4.2.1.7. Diesel boiler

100 KW auxiliary diesel oil boiler and 10 m^3 oil tank is combined to generate heat when the thermal energy from STST and BTES is not enough. The inventory of a 100 KW oil boiler is derive directly from the Ecoinvent datasets and 10 m^3 oil tank is considered with the 3000 l oil storage in database using the same scaling method as pump and water tank. Based on literature and Ecoinvent3.3 database, the weight of a 10 m^3 oil tank is 1000 kg, while a 3000l oil tank is 486.05 kg. The factor is calculated as 2.06. Therefore, a 10m3 oil tank is equal to 2.06 units of 3000 l oil storage.



Reference products	Material for treatment	Byproduct classif.	Amount
oil storage, 3000l	no	allocatable product	1.0 unit
By-products	Material for treatment	Byproduct classif.	Amount
waste concrete	yes	Waste	4.95e+2 kg
waste plastic, mixture	yes	Waste	0.55 kg
Inputs from technosphere			Amount
alkyd paint, white, without solvent, in 60% solution state			6.0 kg
brass			1.4 kg
cast iron			6.0 kg
concrete, normal			0.225 m3
copper			20.1 kg
polyethylene, high density, granulate			0.55 kg
steel, low-alloyed, hot rolled			4.52e+2 kg

Figure 31 Inventory of 2000l oil storage



Reference products	Material for treatment	Byproduct classif.	Amount
oil boiler, 100kW	no	allocatable product	1.0 unit
By-products	Material for treatment	Byproduct classif.	Amount
hazardous waste, for incineration	yes	Waste	6.0 kg
waste mineral wool, for final disposal	yes	Waste	19.0 kg
waste paperboard	yes	Waste	10.0 kg
waste plastic, mixture	yes	Waste	1.4 kg
wastewater from pig iron production	yes	Waste	0.615 m3
Inputs from technosphere			Amount
alkyd paint, white, without solvent, in 60% solution state			2.5 kg
aluminium, cast alloy			15.0 kg
brass			0.05 kg
brazing solder, cadmium free			6.0 kg
copper			25.0 kg
corrugated board box			10.0 kg
electricity, medium voltage			3.32e+2 kWh
heat, district or industrial, natural gas			1.73e+3 MJ
heat, district or industrial, other than natural gas			9.60e+2 MJ
polyethylene, high density, granulate			1.4 kg
steel, chromium steel 18/8, hot rolled			25.0 kg
steel, low-alloyed, hot rolled			4.85e+2 kg

Figure 32 Inventory of 100KW oil boiler

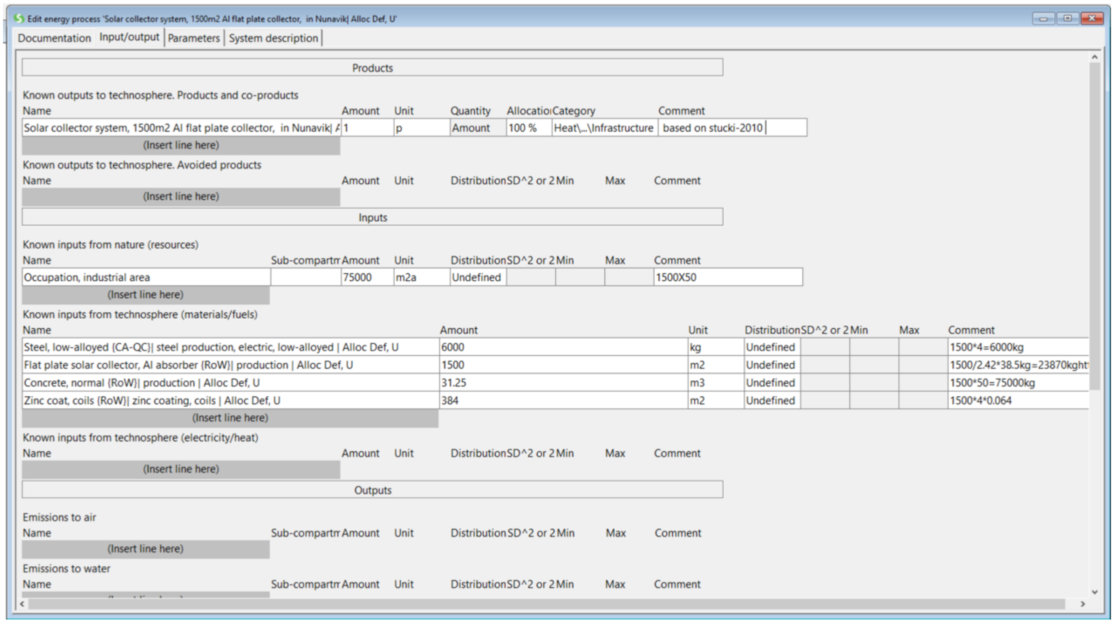
4.2.2. Construction stage

Construction stage accounts for installation of solar collectors, construction of borehole heat exchanger and transportation of all components and installation materials.

In this project, 620 solar collectors are installed south facing at an angle equal to the latitude, with no shade, such as buildings, trees and snow[28]. Concrete and zinc coated steel are two basic materials used to install the solar collectors, with the consumption of 50 kg/m^2 and 4 kg/m^2, respectively[56]. Since the Ecoinvent dataset for zinc coatings refers to the surface area (m^2) of coated steel, 0.064 m^2 surface per kg steel is assumed[62]. Figure 33 depicts the installation mode of solar collectors and Figure 34 presents the inventory of 1500m^2 solar collectors, including installation.

Figure 33 Solar collectors' installation (source from:

https://sunearthinc.com/solar-hot-water-collectors/



Edit energy process 'Solar collector system, 1500m2 Al flat plate collector, in Nunavik| Alloc Def, U'

Products

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocatio	Category	Comment
Solar collector system, 1500m2 Al flat plate collector, in Nunavik| A	1	p	Amount	100 %	Heat\...\Infrastructure	based on stucki-2010

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment

Inputs

Known inputs from nature (resources)

Name	Sub-compartm	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment
Occupation, industrial area		75000	m2a	Undefined				1500X50

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment
Steel, low-alloyed {CA-QC}| steel production, electric, low-alloyed | Alloc Def, U	6000	kg	Undefined				1500*4=6000kg
Flat plate solar collector, Al absorber {RoW}| production | Alloc Def, U	1500	m2	Undefined				1500/2.42*38.5kg=23870kght
Concrete, normal {RoW}| production | Alloc Def, U	31.25	m3	Undefined				1500*50=75000kg
Zinc coat, coils {RoW}| zinc coating, coils | Alloc Def, U	384	m2	Undefined				1500*4*0.064

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment

Outputs

Emissions to air

Name	Sub-compartm	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment

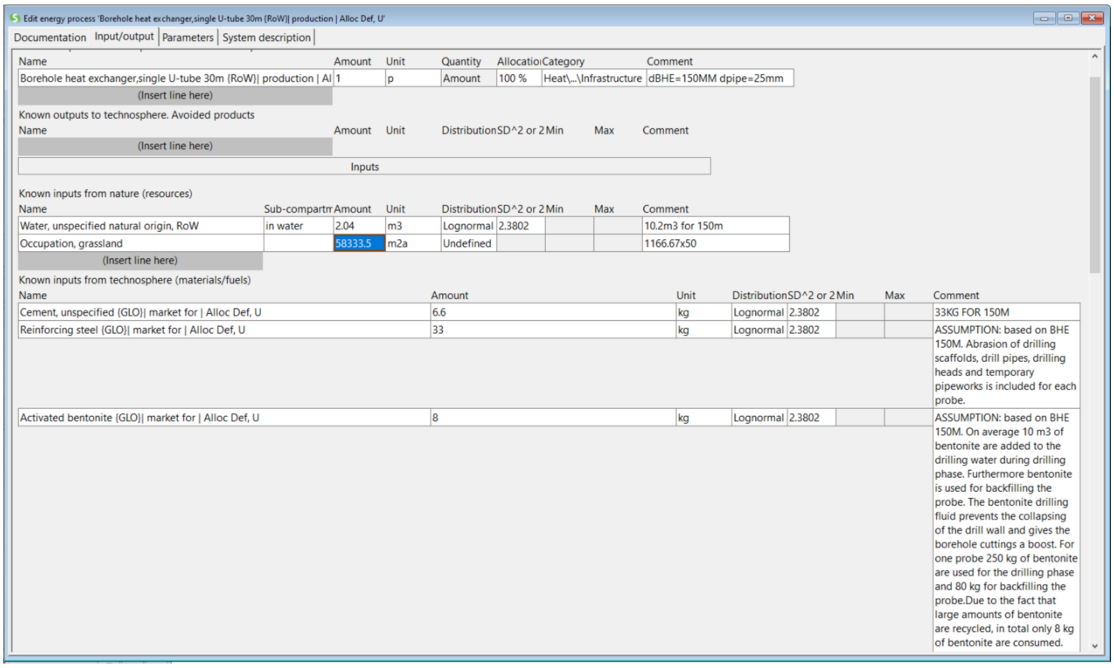
Emissions to water

Name	Sub-compartm	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment

Figure 34 Inventory of 1500m2 solar collector, including installation

Boreholes are constructed by first drilling a hole to 30 m in depth. Once the hole is drilled, a U-tube heat exchanger is installed and inserted into the drilled hole. This allows the fluid to flow down to the bottom of the borehole and then return to the surface in a continuous loop. Once the piping is installed the remaining volume of the drilled borehole is filled with grout to provide structural support of the drilled hole and to increase thermal conductivity between heat transfer pipes and the ground. During the construction process, a certain amount of reinforcing steel is consumed for the temporary pipework and abrasion of drilling scaffolds, etc. Activated bentonites are used for the drilling phase and backfilling the probe. The drill pipes are operated hydraulically by the Unimog engine. In the same way the pump is operated, which is used for rinsing during drilling phase and for pumping down the bentonite-cement suspension. Data regarding diesel consumption is derived from Rohner, who calculated that 2.5 liters of diesel per meter probe are used in case of hydraulic-circulation drilling, 3.5 liters per meter of probe are used in case of hammer drilling.

It’s assumed that 40 % of probes are installed with hydraulic-circulation drilling, 60 % with hammer drilling. Therefore, approximately 3.1 liters of diesel per meter are used on average. To enhance the heat storage capacity, 1m XPS insulation is laid on the surface of borehole heat exchanger. Figure 35 illustrates the inventory of borehole heat exchanger equipped in this project.



Name	Amount	Unit	Quantity	Allocatio	Category	Comment
Borehole heat exchanger,single U-tube 30m {RoW}| production | Al	1	p	Amount	100 %	Heat\...\Infrastructure	dBHE=150MM dpipe=25mm
(Insert line here)						

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment
(Insert line here)							

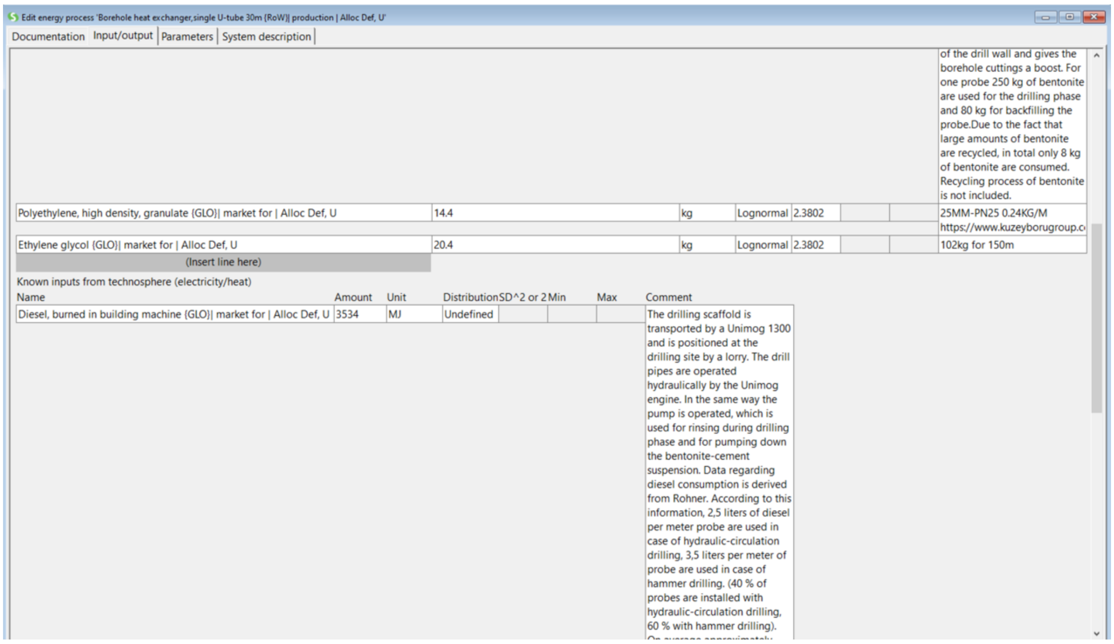
Inputs

Known inputs from nature (resources)

Name	Sub-compartm	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment
Water, unspecified natural origin, RoW	in water	2.04	m3	Lognormal	2.3802			10.2m3 for 150m
Occupation, grassland		58333.5	m2a	Undefined				1166.67x50
(Insert line here)								

Known inputs from technosphere (materials/fuels)

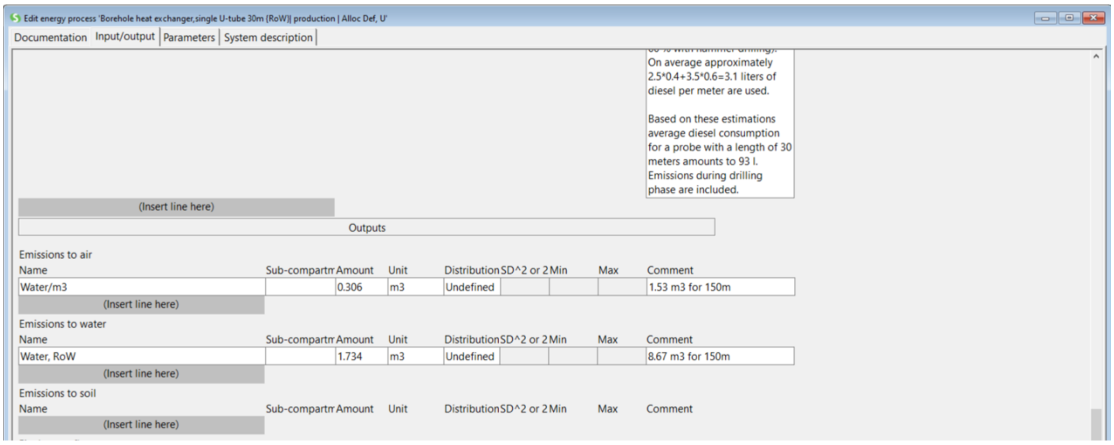
Name	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment
Cement, unspecified {GLO}| market for | Alloc Def, U	6.6	kg	Lognormal	2.3802			33KG FOR 150M
Reinforcing steel {GLO}| market for | Alloc Def, U	33	kg	Lognormal	2.3802			ASSUMPTION: based on BHE 150M. Abrasion of drilling scaffolds, drill pipes, drilling heads and temporary pipeworks is included for each probe.
Activated bentonite {GLO}| market for | Alloc Def, U	8	kg	Lognormal	2.3802			ASSUMPTION: based on BHE 150M. On average 10 m3 of bentonite are added to the drilling water during drilling phase. Furthermore bentonite is used for backfilling the probe. The bentonite drilling fluid prevents the collapsing of the drill wall and gives the borehole cuttings a boost. For one probe 250 kg of bentonite are used for the drilling phase and 80 kg for backfilling the probe.Due to the fact that large amounts of bentonite are recycled, in total only 8 kg of bentonite are consumed.



Name	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment
							of the drill wall and gives the borehole cuttings a boost. For one probe 250 kg of bentonite are used for the drilling phase and 80 kg for backfilling the probe.Due to the fact that large amounts of bentonite are recycled, in total only 8 kg of bentonite are consumed. Recycling process of bentonite is not included.
Polyethylene, high density, granulate {GLO}| market for | Alloc Def, U	14.4	kg	Lognormal	2.3802			25MM-PN25 0.24KG/M https://www.kuzeyborugroup.c
Ethylene glycol {GLO}| market for | Alloc Def, U	20.4	kg	Lognormal	2.3802			102kg for 150m
(Insert line here)							

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment
Diesel, burned in building machine {GLO}| market for | Alloc Def, U	3534	MJ	Undefined				The drilling scaffold is transported by a Unimog 1300 and is positioned at the drilling site by a lorry. The drill pipes are operated hydraulically by the Unimog engine. In the same way the pump is operated, which is used for rinsing during drilling phase and for pumping down the bentonite-cement suspension. Data regarding diesel consumption is derived from Rohner. According to this information, 2,5 liters of diesel per meter probe are used in case of hydraulic-circulation drilling, 3,5 liters per meter of probe are used in case of hammer drilling. (40 % of probes are installed with hydraulic-circulation drilling, 60 % with hammer drilling).



On average approximately 2.5*0.4+3.5*0.6=3.1 liters of diesel per meter are used.

Based on these estimations average diesel consumption for a probe with a length of 30 meters amounts to 93 l. Emissions during drilling phase are included.

Emissions to air

Name	Sub-compartm	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment
Water/m3		0.306	m3	Undefined				1.53 m3 for 150m

Emissions to water

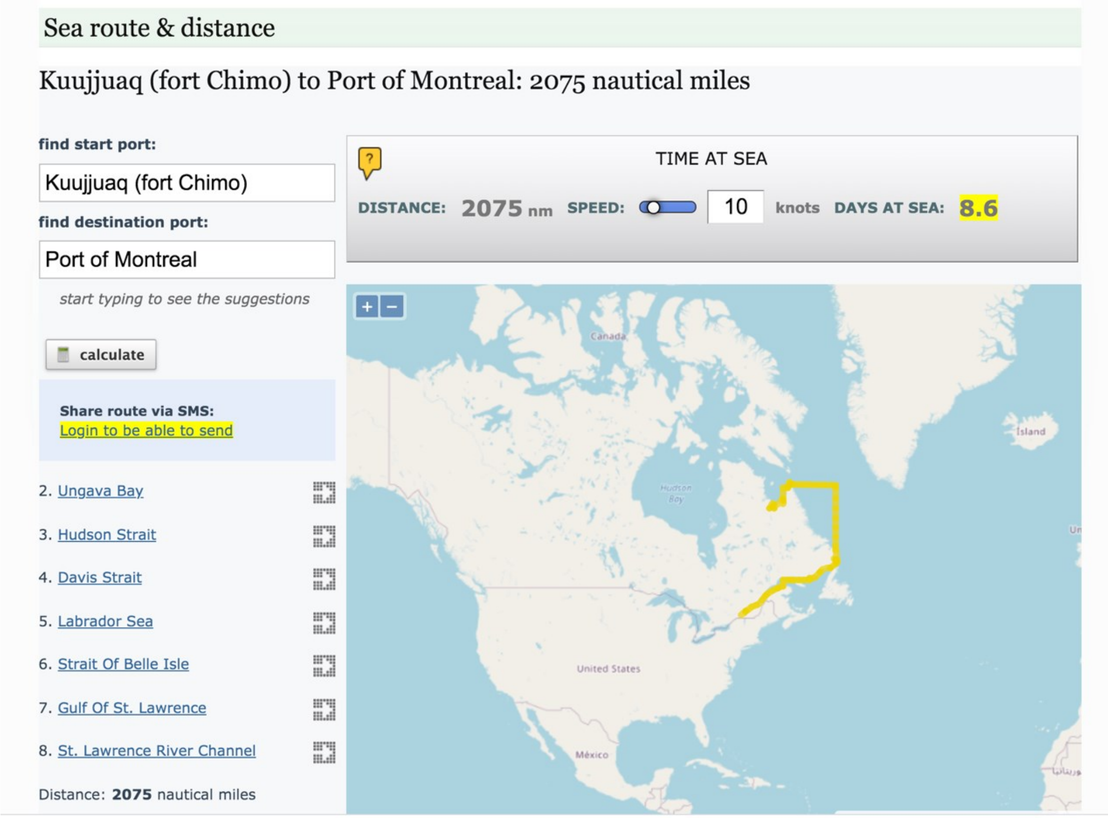
Name	Sub-compartm	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment
Water, RoW		1.734	m3	Undefined				8.67 m3 for 150m

Emissions to soil

Name	Sub-compartm	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment

Figure 35 Inventory of borehole heat exchanger, including construction stage

All components and materials are assumed to be transported by a cargo ship from Montreal to Kuujjuaq. Figure 36 indicates the distance between port of Montreal and Kuujjuaq, which is 2075 nautical miles (3842.9 km).



Kuujjuaq (fort Chimo) to Port of Montreal: 2075 nautical miles

find start port: Kuujjuaq (fort Chimo)

find destination port: Port of Montreal

start typing to see the suggestions

Share route via SMS:
Login to be able to send

DISTANCE: 2075 nm SPEED: 10 knots DAYS AT SEA: 8.6

2. Ungava Bay
3. Hudson Strait
4. Davis Strait
5. Labrador Sea
6. Strait Of Belle Isle
7. Gulf Of St. Lawrence
8. St. Lawrence River Channel

Distance: **2075** nautical miles

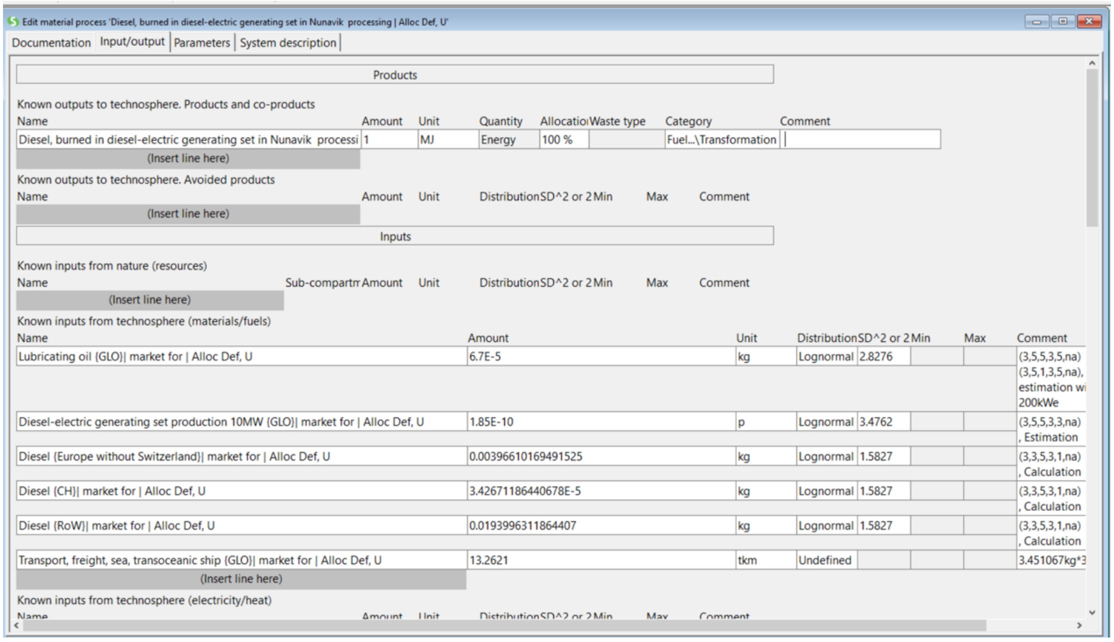
Figure 36 Distance (http://ports.com/sea-route/)

4.2.3 Operation stage

4.2.3.1. Electricity consumption

This project is assumed to start in 2022 and end in 2072. Since Kuujjuaq is off-grid community, electricity is generated from local diesel plant.

The operation scenario of the SDH-BTES system in Kuujjuaq is based on the actual operation situation of Drake landing solar community. Mesquita et al. summarized the 10 years operation data of SDH-BTES system in Okotoks, Alberta from 2007 to 2017, which generated 2370 GJ per year to satisfy 52 houses heating load[53]. During operation, electricity consumption is mainly from the pumps. The average annual electricity from 2007 to 2012 is 197.2 GJ.[54] However, the total heating load for the target users in this project is 432 MWh (1555.2GJ). To simplify the research, the electricity consumption of this project is estimated to 65.62% of Drake landing solar community, which is 129.4 GJ (35.94 MWh). Figure 37 shows the inventory of diesel-electric generating process, including the inventory of a diesel-electric generation plant.



Edit material process 'Diesel, burned in diesel-electric generating set in Nunavik processing | Alloc Def, U'

Products

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocatio	Waste type	Category	Comment
Diesel, burned in diesel-electric generating set in Nunavik processi	1	MJ	Energy	100 %		Fuel...\Transformation	

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment

Inputs

Known inputs from nature (resources)

Name	Sub-compartm	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment
Lubricating oil {GLO}| market for | Alloc Def, U	6.7E-5	kg	Lognormal	2.8276			(3,5,5,3,5,na) (3,5,1,3,5,na), estimation wi 200kWe
Diesel-electric generating set production 10MW {GLO}| market for | Alloc Def, U	1.85E-10	p	Lognormal	3.4762			(3,5,5,3,3,na) , Estimation
Diesel {Europe without Switzerland}| market for | Alloc Def, U	0.00396610169491525	kg	Lognormal	1.5827			(3,3,5,3,1,na) , Calculation
Diesel {CH}| market for | Alloc Def, U	3.42671186440678E-5	kg	Lognormal	1.5827			(3,3,5,3,1,na) , Calculation
Diesel {RoW}| market for | Alloc Def, U	0.0193996311864407	kg	Lognormal	1.5827			(3,3,5,3,1,na) , Calculation
Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, U	13.2621	tkm	Undefined				3.451067kg*3

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment

Figure 37 Inventory of diesel-electric generating process

4.2.3.2. Direct diesel consumption

Diesel consumption includes electricity consumed during operation and diesel consumed directly from the auxiliary diesel boiler. As mentioned in the system description, diesel consumed from the auxiliary diesel boiler is 205 MWh. The extraction, processing, transportation and combustion of diesel are considered in the LCA model. Therefore, a heat production process using diesel is selected in this project.

4.2.3.3. Maintenance

During the operation of the project, some components need to be replaced to maintain the system efficiency. Lifetime assumption of each component is listed in Table 6. The assumption is based on the manual of each component and also considers the harsh weather condition in Kuujjuaq.

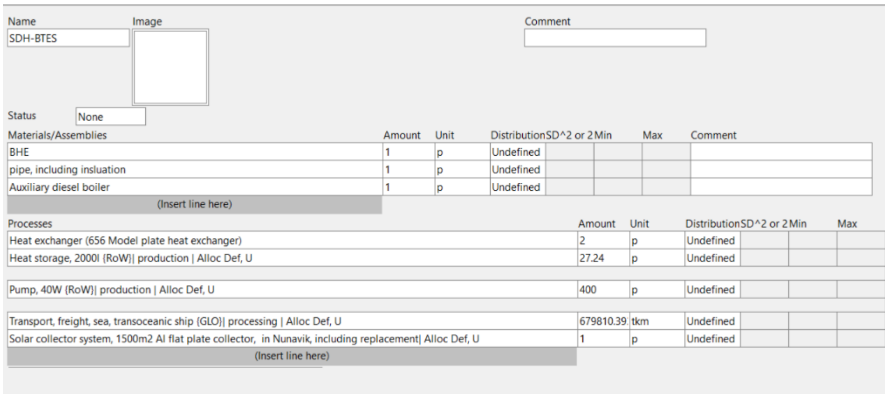
Table 6 Life time assumption of components

Component	Expected lifetime	Replacement
Boiler	15 years	3 times
Water tankx2	50 years	0 time
Oil tank	25 years	1 time
Hydraulic pumpsx5	25 years	1 time
Heat exchangerx2	50 years	0 times
1500m2 Solar panel	25 years	1 time
BHE	50 years	0 times
Piping	50 years	0 times

Replacement of facility results in extra consumption. Hence, during the life cycle stage, two sets of 1500 m^2 solar collectors, two pieces of water tanks, four pieces of boilers, ten pieces of pumps, two pieces of oil tanks, two pieces of heat exchangers, 1000-m-length pipeline and 150 borehole heat exchangers are considered in the SDH-BTES system. Table 7 epitomizes the amount of different components considered and the total weight to be transported. Figure 38 illuminates the assembly of the SDH-BTES system, including the replacement and transportation.

Table 7 Total weight of different components

Component	**Amount**	**Weight**	**Source**
Solar collectors (including	1440p	128740kg	Ecoinvent 3.3
Pump	10p	950kg	
Heat exchanger	2p	1440kg	
Steel pipe	1000m	9828.1kg	
Pipe insulation	1000m	1586.62kg	
Borehole	4500m	36626.67kg	
Water tank	2p	10000kg	
Oil boiler	4p	3800kg	
Oil tank	2p	2000kg	
Total	-	194971.39kg	-



Name: SDH-BTES

Image

Comment

Status: None

Materials/Assemblies	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment
BHE	1	p	Undefined				
pipe, including insluation	1	p	Undefined				
Auxiliary diesel boiler	1	p	Undefined				

Processes	Amount	Unit	Distribution	SD^2 or 2	Min	Max
Heat exchanger (656 Model plate heat exchanger)	2	p	Undefined			
Heat storage, 2000l {RoW}| production | Alloc Def, U	27.24	p	Undefined			
Pump, 40W {RoW}| production | Alloc Def, U	400	p	Undefined			
Transport, freight, sea, transoceanic ship {GLO}| processing | Alloc Def, U	679810.39	tkm	Undefined			
Solar collector system, 1500m2 Al flat plate collector, in Nunavik, including replacement| Alloc Def, U	1	p	Undefined			

Figure 38 Assembly of SDH-BTES system, including transportation

4.2.4. Disposal

To simplify the study, at the end-of-life stage, it is assumed that all materials are dumped to the landfill. This involves energy consumption and environmental waste generated as a result of landfill disposal. And the transport of waste is also considered. All of Nunavik's villages have a northern landfill on their territory that meets the requirements of the regulation respecting the Landfilling and Incineration of Residual Materials. Nunavik Residual Materials Management Plan indicates the landfill site in Kuujjuaq. Truck is selected to carry the waste. The distance between SDH-BTES with landfill site is 9.5 km.

Figure 39 Landfill site in Kuujjuaq

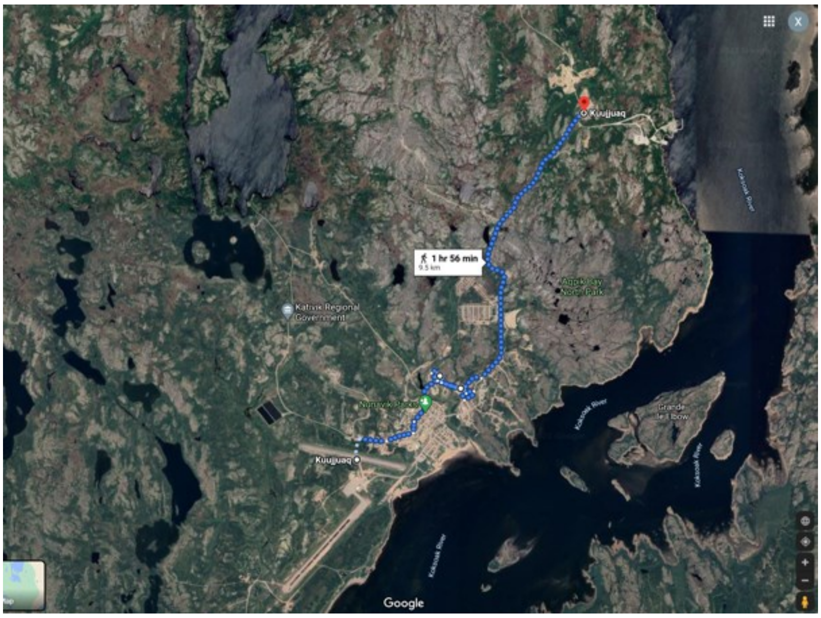
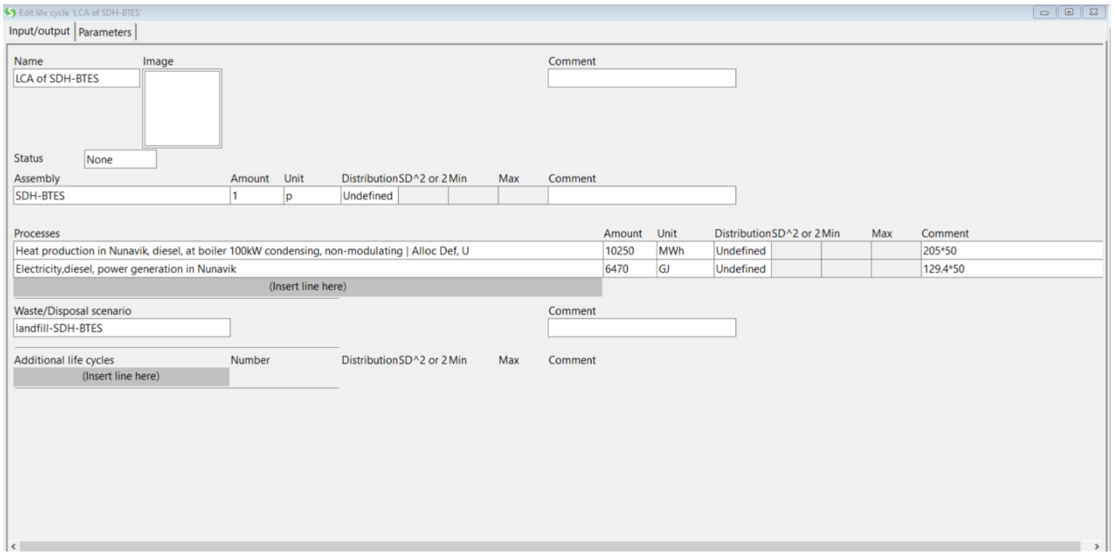


Figure 40 Distance between landfill site and project site

4.2.5. Life cycle inventory

Based on input data collected and the emission data from database, life cycle model of SDH-BTES can be established in SIMAPRO. Figure 41 presents the LCA model of SDH-BTES, including the assembly of SDH-BTES, the operation process and disposal scenario.



Name: LCA of SDH-BTES

Comment:

Status: None

Assembly	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment
SDH-BTES	1	p	Undefined				

Processes	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment
Heat production in Nunavik, diesel, at boiler 100kW condensing, non-modulating | Alloc Def, U	10250	MWh	Undefined				205*50
Electricity,diesel, power generation in Nunavik	6470	GJ	Undefined				129.4*50

Waste/Disposal scenario: landfill-SDH-BTES

Comment:

Additional life cycles	Number	Distribution	SD^2 or 2	Min	Max	Comment

Figure 41 LCA model of SDH-BTES

The Main materials of the considered components are showing in Table 8.

Table 8 Main materials of the considered components

Main materials of the considered components					
Materials	Solar collectors	Hot water tanks	pumps	Heat exchanger	Total
Glass	24.81ton				24.81ton
Aluminium	16.02ton				16.02ton
Copper	5.19ton				5.37ton
Steel	12.42ton	9.26ton	368kg	1.44ton	28.13ton
Rock wool	4.77ton				4.85ton
Glass wool		680.99kg			0.68ton
Cast iron			480kg		0.48ton
HDPE	25.71kg				2.19ton
Synthetic rubber	2.57ton				3.03ton
Silicone	0.26ton				0.26ton

Main materials of the considered components					
Materials	pipes	BHE	Oil tank	boiler	Total
Copper			82.81kg	99.96kg	/
Cement		990kg			
Stainless steel	9828.1kg		1.86ton	2.04ton	/
Reinforcing steel		4.95ton			4.95ton
Rock wool				75.96kg	/

HDPE		2.16ton	2.27kg	5.60kg	/
XPS		24.27ton			24.27ton
PUR	87.26kg				0.03ton
Synthetic rubber	1473.82kg				/

4.3. Life cycle impact assessment

4.3.1. Selection of method

Once the inventory is established, life cycle impact assessment of SDH-BTES should be conducted to evaluate the impact quantitatively. There is a plethora of impact assessment methods available and there are no standard criteria to judge which method is better. Based on the tutorial of SIMAPRO, the best way to select a method is to look at the previous research or the concerns of the project stakeholder.

According to the literature review, IMPACT 2002+ and Eco-indicators 99 are two common methods used to assess the general environmental impact of thermal energy storage system. IMPACT 2002+ is selected in this research since Eco-indicators 99 has been superseded in SIMAPRO 8.1. Besides, some single-issue methods are also essentials to provide supplementary information. IPCC 2013 is used to evaluate the greenhouse gas emission, generating characterization values of the kg of CO^2-equivalent within 100 years. CEM is used to obtain the involved energy consumption during the life cycle stage.

4.3.2. LCA results

4.3.2.1. IMPACT 2002+

IMPACT 2002+ is able to provide a broad picture of the environmental impact of the project. Figure 42 shows the main processes involved in the life cycle of SDH-BTES system installed in Nunavik. The width of the red arrows is proportional to the magnitude of the impact. Note that the assembly of SDH-BTES represents the production and construction stage of the whole system, including solar filed, thermal heat storage and auxiliary boiler. The operation stage mainly consists of the energy consumption throughout this stage, including electricity used to operate the pumps and diesel used at auxiliary boiler. The end-of-life stage is represented by landfill disposal. Conspicuously, the majority impact comes from process named heat production at boiler, occupying exactly 56.1%, while final landfill disposal is less significant comparing to other phases, with mere 0.0138%. As far as the disposal scenario is concerned, it's worthy to note that the waste treatment is assumed to be sanitary landfill, which is a modern engineering landfill where waste is allowed to decompose into biologically and chemically inert materials in a setting isolated from the environment, and the impact of the remaining wells in the underground are not able to simulate within SIMAPRO. In that case, the actual impact of the final disposal will more than the simulation results.

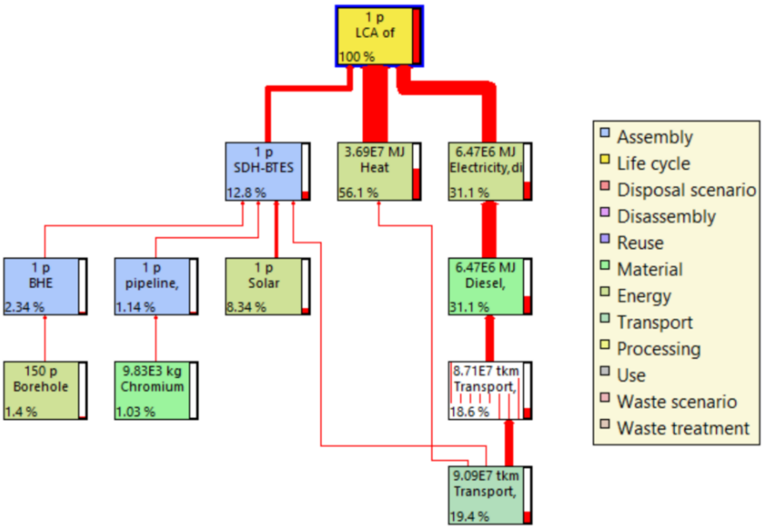


Figure 42 Network of SDH-BTES. IMPACT 2002+.single score Cut off:1%

Characterization

The characterization results per impact category can be observed in Figure 43. As mentioned above, SDH-BTES (blue bar) involves both production and construction of all components, including replacement happen in operation stage, while electricity consumption and heat production process are combined to represent operation stage (grey and orange bars). Therefore, it can be easily noticed that the operation phase is the most dominant life cycle phase regarding to the majority of impact categories, which can be explained by the diesel combustion emission in this phase. It's also apparent that production and construction phase show its prominent influence in carcinogens (31023.01 kgC2H3Cleq), non-carcinogens (46670.4 9kgC2H3Cleq), land occupation (132894.80 m2org.arable), Aquatic eutrophication (719.54kg PO4 P-lim) and mineral extraction (1049810.54 MJ surplus) impact categories. Analyzing the components of SDH-BTES system (Figure 44), it can be found that solar collectors are the highest contributor of most impact categories.

Table 9 Characterization result

Impact category	**Unit**	**Total**	**Production and construction**	**Operation-**	**End-of-life**
Carcinogens	kg C2H3Cl eq	59490.41	31023.01	28454.55	12.85
Non-carcinogens	kg C2H3Cl eq	63394.12	46670.49	16699.88	23.75
Respiratory inorganics	kg PM2.5 eq	15975.23	1439.06	14535.05	1.12
Ionizing radiation	Bq C-14 eq	41912604.92	5750010.04	36153476.34	9118.54
Ozone layer depletion	kg CFC-11 eq	0.90	0.07	0.83	0.00
Respiratory organics	kg C2H4 eq	4810.59	356.65	4453.59	0.26
Aquatic ecotoxicity	kg TEG water	307381191.28	129391747.66	177359440.95	0.35
Terrestrial ecotoxicity	kg TEG soil	88787314.70	44824824.54	43949253.40	630002.66
Terrestrial acid/nutri	kg SO2 eq	379275.79	20872.47	358381.00	13236.75
Land occupation[7]	m2org.arable	144784.07	132894.80	11797.99	22.32
Aquatic acidification	kg SO2 eq	68328.69	7158.75	61160.50	91.28
Aquatic eutrophication	kg PO4 P-lim	1089.27	719.54	368.74	9.44
Global warming	kg CO2 eq	5479101.95	718113.88	4757560.24	1.00
Non-renewable energy	MJ primary	81082793.11	10414608.95	70656361.47	3427.83

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[7] Area of land occupied multiply years occupied

Mineral extraction	MJ surplus	1077984.67	1049810.54	28148.63	11822.69

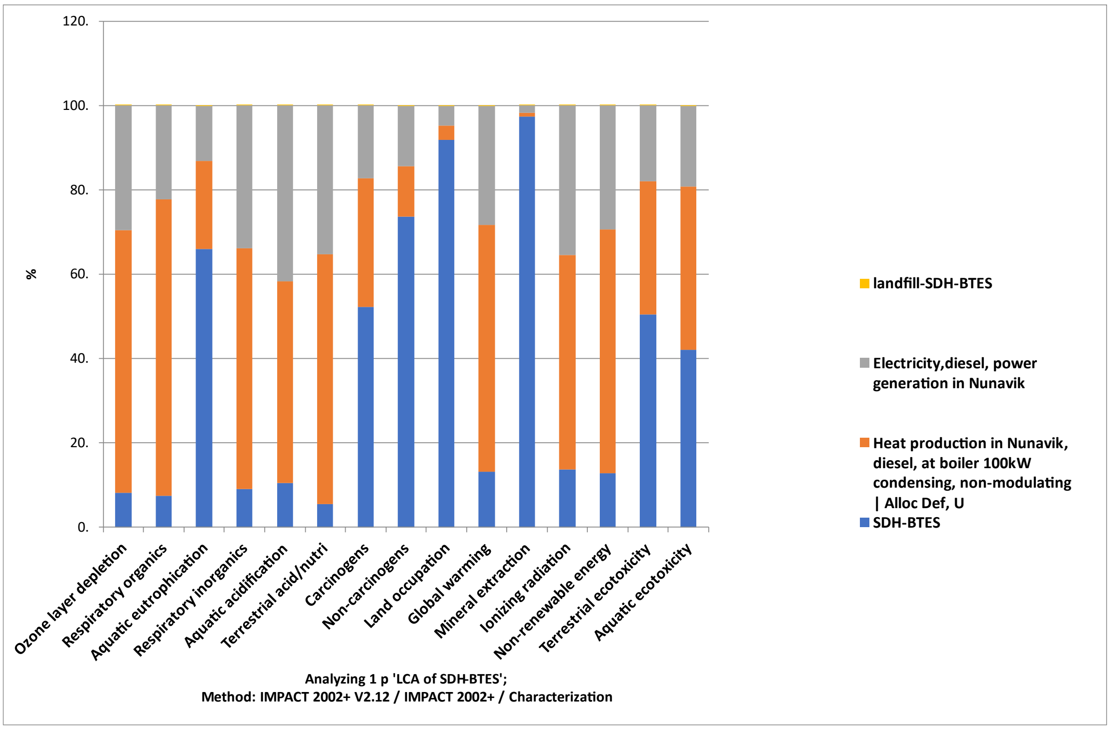


Figure 43 Characterization results of the SDH-BTES LCA project

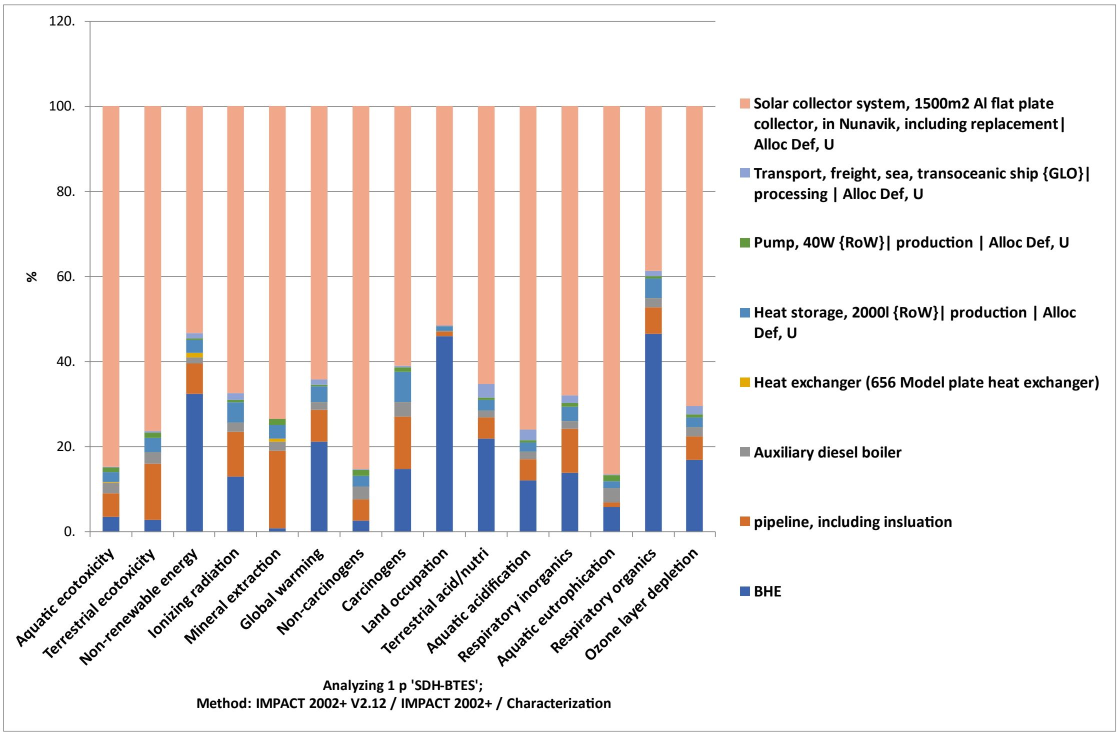


Figure 44 characterization result of production and constriction stage of SDH-BTES, IMPACT 2002+

Damage assessment

The damage assessment is a relatively new step which is applied to endpoint method. In this step, different impact categories are combined into a damage category with a common unit. As mentioned above, IMPACT 2002+ introduces four damage categories. Following table epitomizes the calculated impact of different phase to corresponding damage categories. As seen in Figure 45, operation stage has a significant impact on all damage categories.

Table 10 Damage assessment result

Damage category	**Unit**	**Total**	**Production and construction**	**Operation**	**End-of-life**
Human health	DALY	11.55	1.23	10.32	0.00
Ecosystem quality	PDF*m2*yr	1269999.65	527622.53	742118.08	259.03
Climate change	kg CO2 eq	5479101.95	718113.88	4757560.24	3427.83
Resources	MJ primary	82160777.79	11464419.49	70684510.09	11848.20

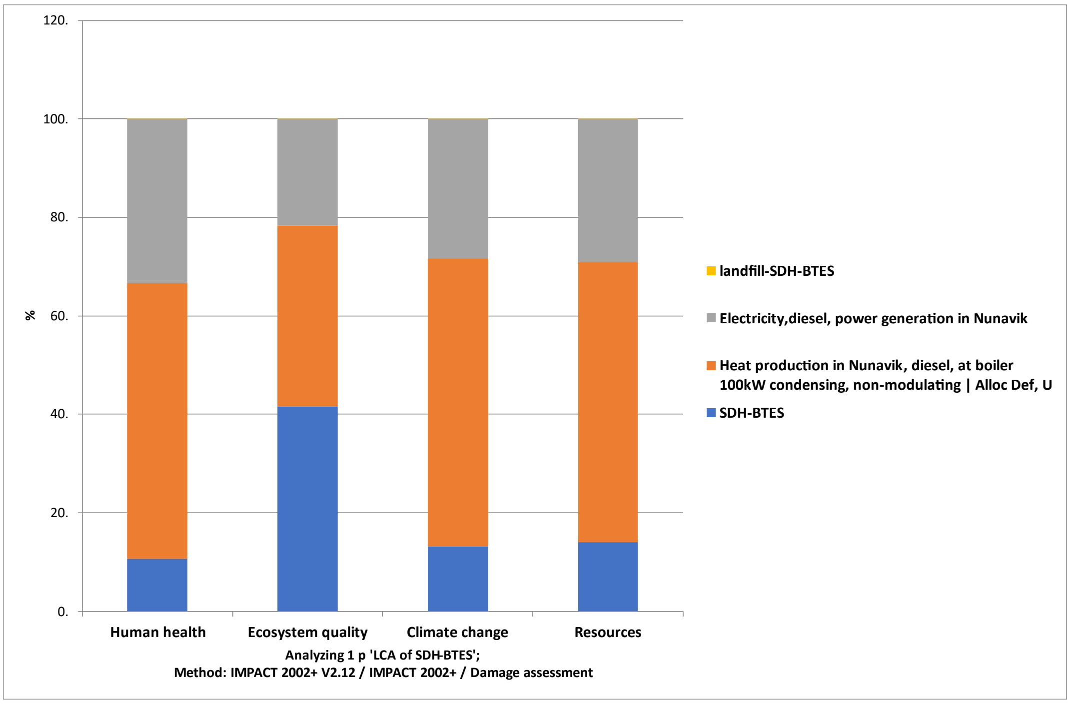


Figure 45 Damage assessment result (%)

Normalization

However, with the characterization results, the importance of these four impact categories cannot be compared since they have different units. Therefore, the normalization is conducted to represent how significant of these impacts compared to their annual average data. To realize normalization, SIMAPRO divides each characterization result with a factor named reference value. Figure 46 presents the normalization results of different impacts. In descending orders, the impact categories with largest scores are human health, climate change, resource and ecosystem quality. In other words, the life cycle of SDH-BTES system has greatest influence on the human health aspect. In spite of that, it's not accurate to say human health categories is most significant among other impacts. To establish the comparison, weighting is carried out in the next step.

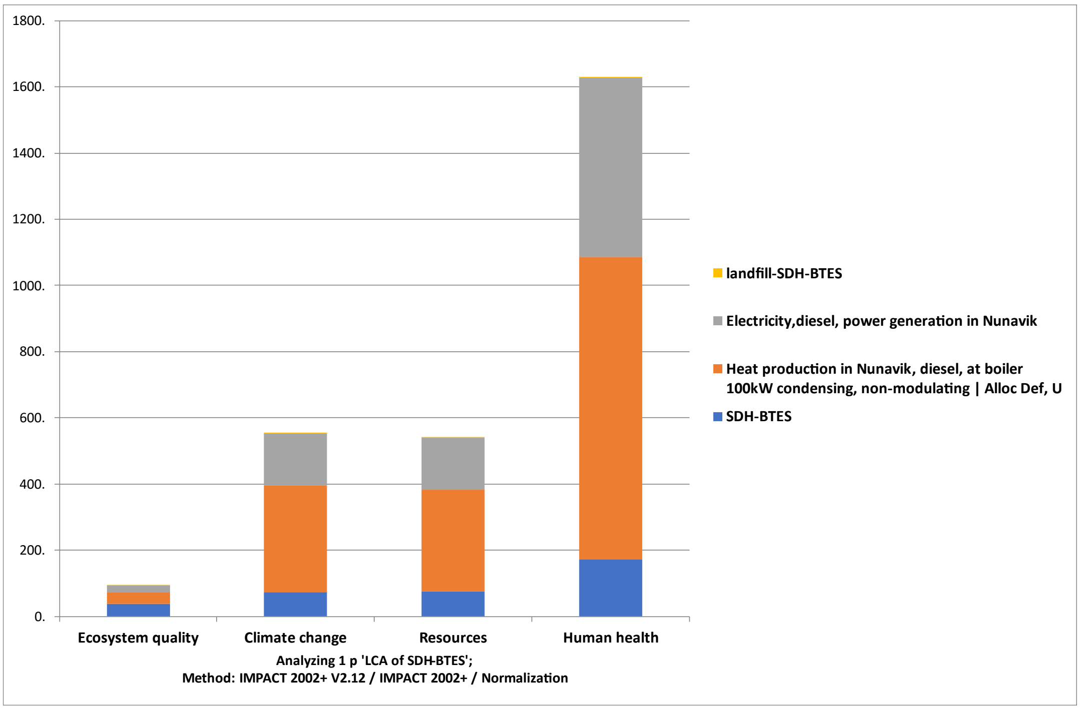


Figure 46 Normalization results

Weighting

In this step, impact categories results are multiplied by weighting factors, and are added to come up with a single score or total score. Following table epitomizes the weighting results of different stages to different categories. Figure 47 intuitively demonstrates that human health is the most significant impact accounting for 58% of the total score, with about 1.63 kpts, while ecosystem quality is the least significant categories accounting for 0.09 kpts. To state explicitly, the life cycle of SDH-BTES system generates 2.81 kpts impact in total to the environment, affecting human health most. As far as different stages, it's worthy to point out that operation stage is dominant on all categories. Compared to other stage, disposal is far more less significant. Nevertheless, it’s also important to notice that disposal mainly contribute to the climate change, since the decomposition of organic waste in landfills produces a gas which is composed primarily of methane, a greenhouse gas contributing to climate change. Hence, a conclusion can be established based on the results. Diesel used to operate the system, including electricity generated by local diesel power plant and diesel combusted directly at auxiliary boiler, is the major inducement for all impacts.

Table 11 Weighting result

Damage category	**Unit**	**Total**	**Production and construction**	**Operation-diesel consumption**	**Operation-Electricity consumption**	**End-of-life**
Total	kpt	2.81	0.36	1.58	0.88	0.00
Human health	kpt	1.63	0.17	0.91	0.54	0.00
Ecosystem quality	kpt	0.09	0.04	0.03	0.02	0.00
Climate change	kpt	0.55	0.07	0.32	0.16	0.00
Resources	kpt	0.54	0.08	0.31	0.16	0.00

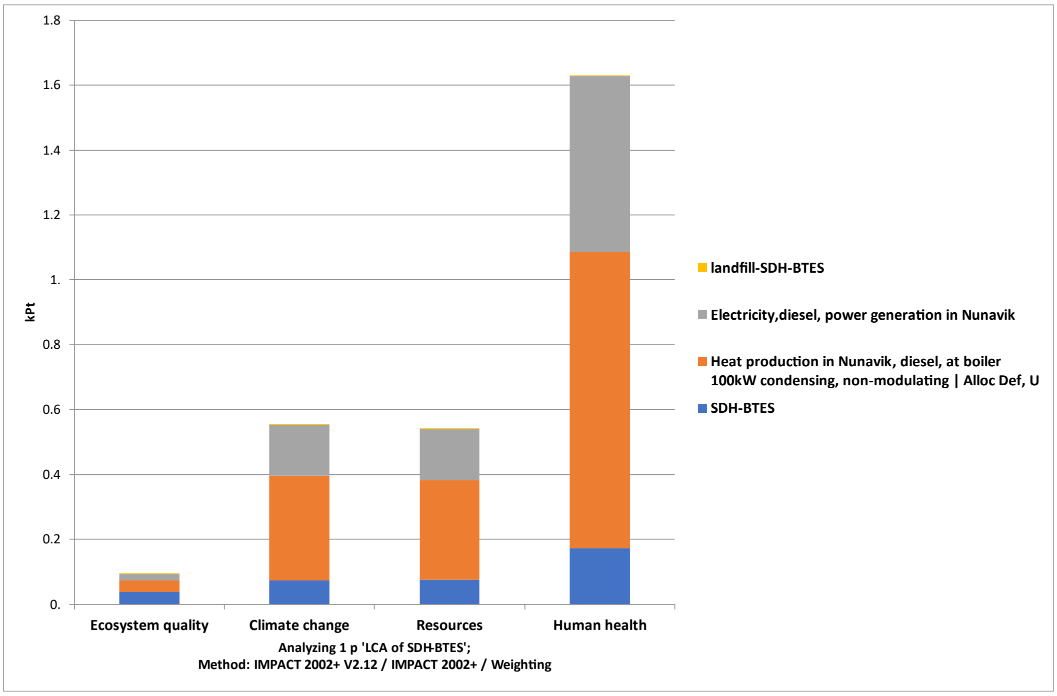


Figure 47 Weighting result kpt

Contribution analysis

With a general picture of the environmental impacts of each life cycle phase established, a contribution analysis should be performed to identify and quantify major elements contribution and individual process that contribute the most per damage category. Table 12 illustrates the contribution value per unit of total thermal energy demand of different component of the system. SDH-BTES system is divided into four main components, including solar subsystem, auxiliary subsystem, transportation and disposal. According to the data, solar subsystem accounts for 43.47% of the total environmental impact, while auxiliary diesel boiler system makes up 56.35%. Note that the contribution of the transportation and disposal is almost negligible, with 0.16% and 0.02% respectively. Focusing on the solar subsystem, electricity consumed in the pump during operation provokes highest environmental impact (71.53%) due to the diesel power generation, followed by solar collectors (19.19%). As for the auxiliary boiler subsystem, heat produced by diesel causes highest impact, accounting for more than 99%. In general, diesel consumed at the auxiliary boiler is the highest contribution aspect among the whole system, followed by the electricity consumption. Combined with the results obtained above, it's worthy to mention that, due to the low solar fraction of the system (52.5%), diesel still have a great impact on the environment. Breaking the dependence of diesel remains one of the main obstacles to overcome. Despite of this, SDH-BTES system still plays an important role in sustainability.

Table 12 Major element contribution value of IMPACT 2002+ (points) per unit of total thermal energy demand

Elements	**mPts IMACT/MWh**	
Solar collectors	10.87	19.19%
Water tanks	0.57	1.00%
Pipe	1.49	2.62%
Pumps	0.12	0.21%
Heat exchangers	0.04	0.06%
Borehole heat exchanger	3.05	5.38%
Pump electricity	40.52	71.53%
SDH-BTES subsystem	**56.65**	**43.47%**

Boiler	0.18	0.25%
Oil tank	0.12	0.17%
Diesel consumption	73.12	99.58%
Auxiliary subsystem	**73.43**	**56.35%**
Transportation	**0.21**	**0.16%**
Disposal	**0.03**	**0.02%**
Total	**130.32**	**100.00%**

Next, a contribution analysis for each damage category is performed to evaluate the most dominant processes of the system. The cut-off criteria applied for this analysis is 1% to account for the most significant processes. The completed data is attached in the appendix. Figure 48-51 illustrate the major processes contribute to each damage category. In terms of human health and climate change, heat production process at diesel boiler is identified as a major contribution, with around 50%, which can be explained that diesel combustion produces greenhouse gas and other airborne emission, like SOx, may affect human respiratory and even lead to cancer. To explain more explicitly and statistically, IPCC method combined with other airborne emission collected from inventory will be introduced in next step. In respect to ecosystem quality and resource category, the inducement is inconspicuous.

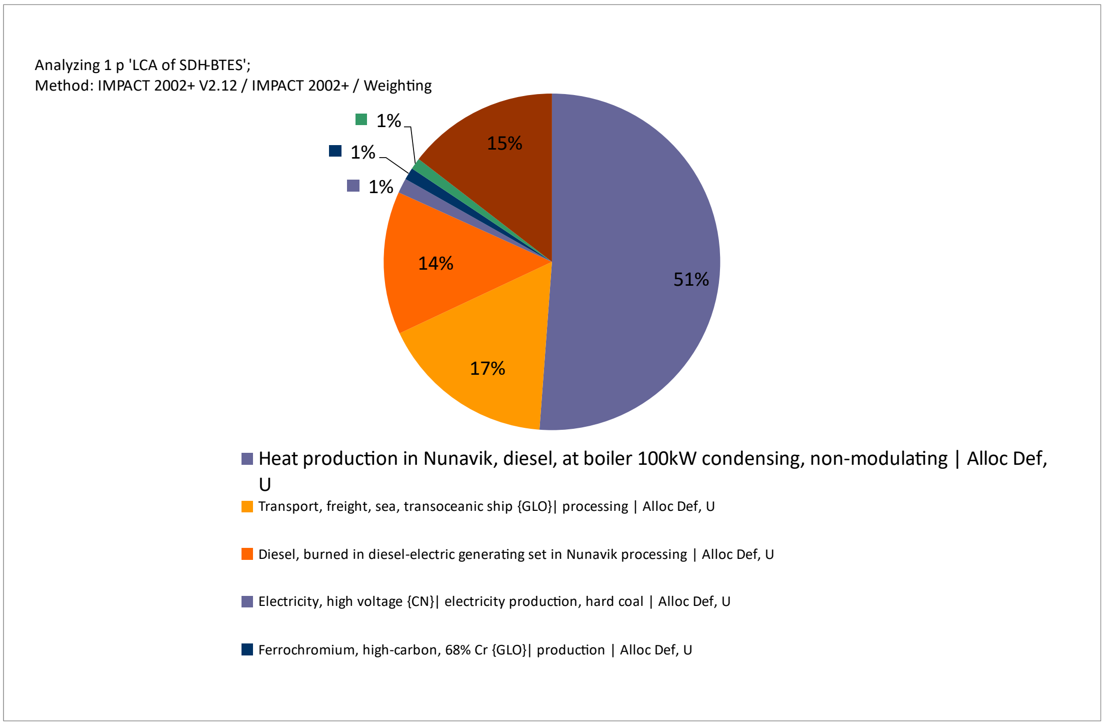


Figure 48 Process Contribution-Human health -cut off 1%

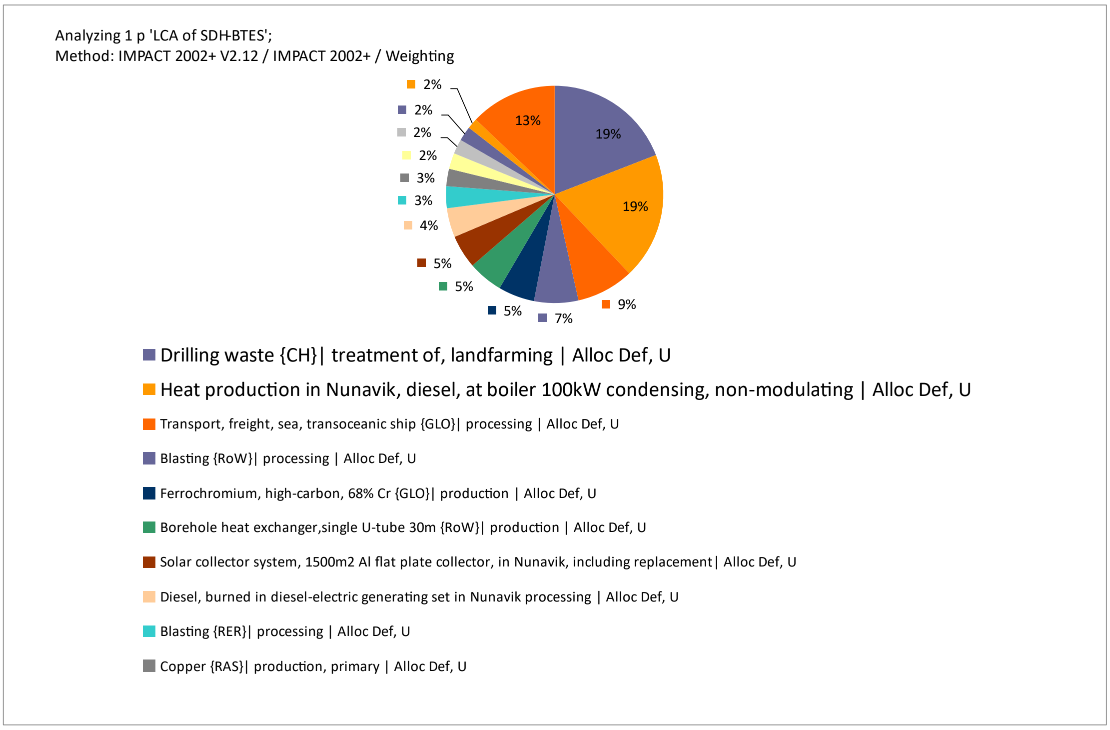


Figure 49 Process Contribution-Ecosystem quality-cut off 1%

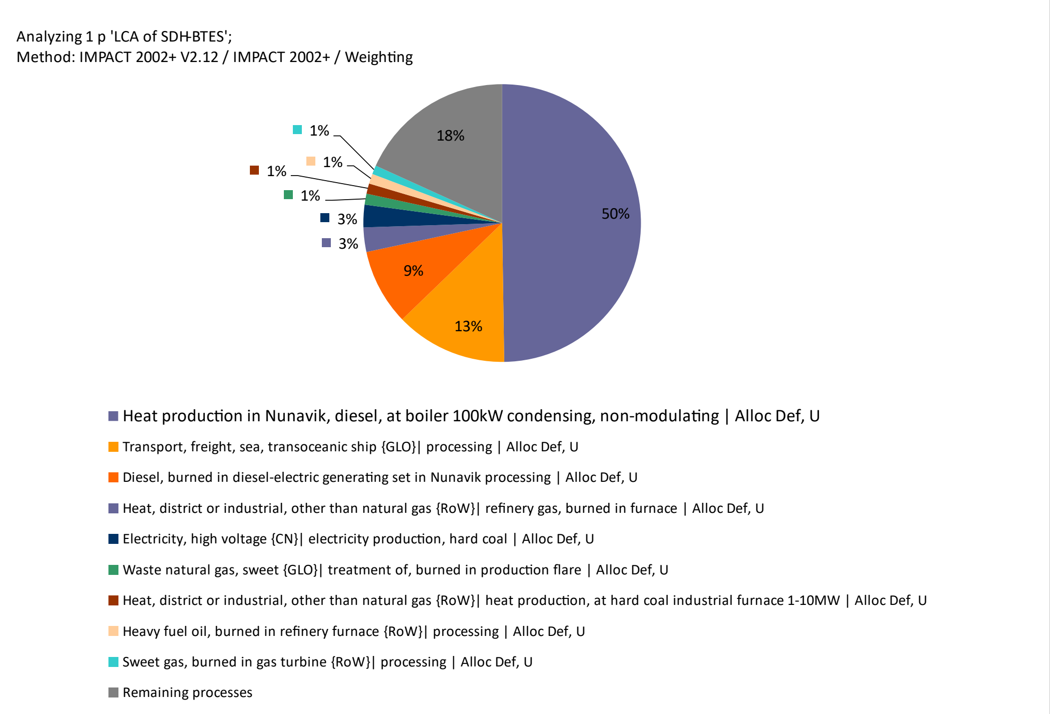


Figure 50 Process Contribution-Climate change-cut off 1%

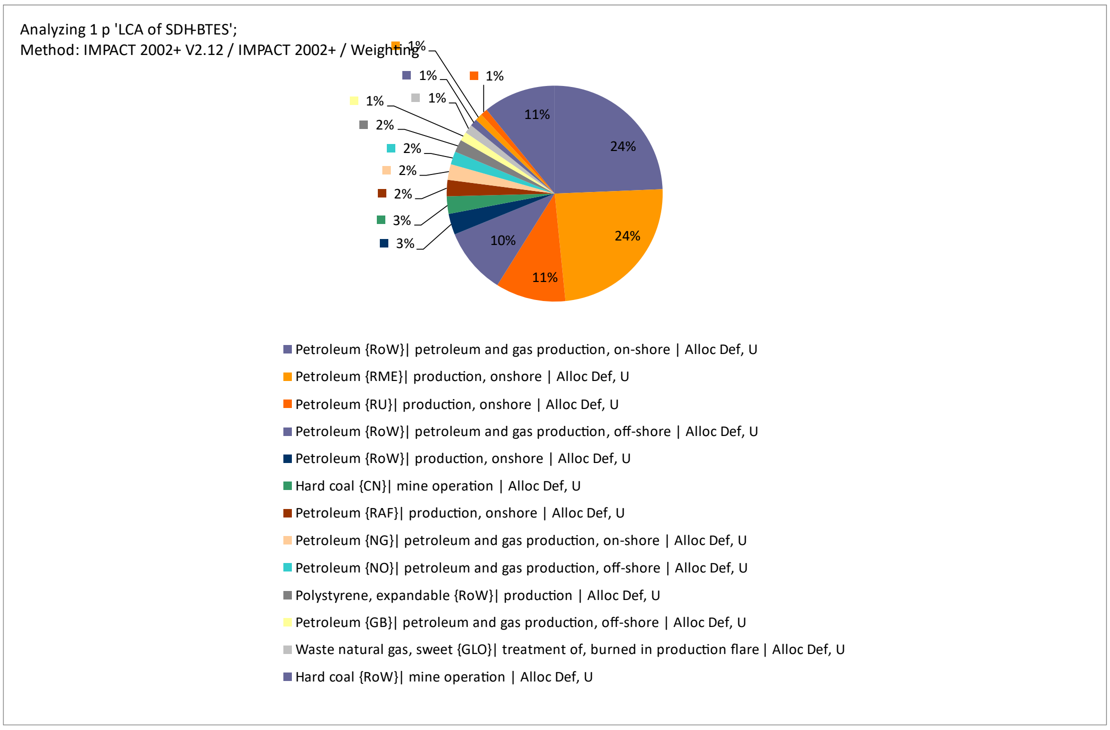


Figure 51 Process Contribution-Resource-cut off 1%

4.3.2.2. Greenhouse gas emission and other airborne emission

Greenhouse gases are gases in the atmosphere such as water vapor, carbon dioxide, methane and nitrous oxide that can absorb infrared radiation, trapping heat in the atmosphere which will cause global warming. In this work, IPCC2013 with a timeframe of 100 years is utilized to calculate the characterization of different greenhouse gases based on their global warming potential. Table 13 illuminates the CO_2 equivalent emission per unit of total thermal energy demand. As can be seen from the figures, greenhouse gas emission is mainly associated to the Auxiliary boiler subsystem and SDH-BTES subsystem, accounting for 58.18% and 41.39% respectively. Focusing on the contribution of each element, it's apparent that diesel consumed at the boiler provokes the highest emission (150.31 kg CO_2 eq/MWh), followed by the electricity consumed at the pump (72.77 kg CO_2 eq/MWh). It can be explained that both the original fuel of the boiler and electricity generated in Nunavik are diesel, which produce 10,180 grams of CO_2 emissions per gallon of diesel consumed. The solar collectors present a third highest emission, causing 22.65 kg CO_2 eq/MWh. Note that the contribution of transportation and disposal is almost negligible, accounting for merely 0.15% and 0.28%, respectively.

Table 13 CO_2 equivalent emission result from IPCC2013 per unit of total thermal energy demand

Elements	**Kg CO_2 eq/MWh**	
Solar collectors	22.65	21.09%
Water tanks	1.29	1.20%
Pipe	2.63	2.45%
Pumps	0.16	0.15%

Heat exchangers	0.00	0.00%
Borehole heat exchanger	7.88	7.34%
Pump electricity	72.77	67.78%
Solar subsystem	**107.37**	**41.39%**
Boiler	0.35	0.23%
Oil tank	0.24	0.16%
Diesel	150.31	99.61%
Auxiliary subsystem	**150.90**	**58.18%**
Transportation	**0.40**	**0.16%**
Disposal	**0.72**	**0.28%**
Total	**259.40**	**100.00%**

In addition to greenhouse gases, NOx and SOx emission are also essential to be considered due to their adverse effects to the human health and ecosystem. Having a negative effect on respiratory conditions, NOx and SOx may result in inflammation of the airways deeply and reducing lung function; and further contribute to the formation of fine particles and ground level ozone, both of which are associated with adverse health effects. Besides, high level of NOx and SOx impact vegetation, including forests and agricultural crops. According to the airborne emissions collected from inventory, NOx is mainly provoked by the auxiliary boiler subsystem (62.21%), while

SOx is resulted from Solar subsystem (78.66%). Analyzing the inducement of these emissions, it's apparent that electricity consumed at the pump and diesel used at the boiler provoked the highest NOx and SOx emissions. Therefore, these airborne emissions mostly caused by diesel. Besides, solar collectors also present a high contribution regarding to SOx emission, accounting for 22.81% of the SDH-BTES subsystem. This fact can be explained that the copper and aluminum used in solar collectors provoke a large amount of SOx emission.

Table 14 Other relevant airborne emissions per unit of total thermal energy demand

Elements	**kg NOx/MWh**		**kg SOx/MWh**	
Solar collectors	0.07	6.14%	0.19	22.81%
Water tanks	0.00	0.28%	0.00	0.53%
Pipe	0.01	0.59%	0.01	1.34%
Pumps	0.00	0.05%	0.00	0.20%
Heat exchangers	0.00	0.00%	0.00	0.00%
Borehole heat exchanger	0.04	3.17%	0.02	1.83%
Pump electricity	1.01	89.77%	0.60	73.28%
Solar subsystem	**1.12**	**37.62%**	**0.82**	**78.66%**
Boiler	0.00	0.05%	0.00	1.15%
Oil tank	0.00	0.04%	0.00	0.75%
Diesel	1.85	99.91%	0.21	98.09%
Auxiliary subsystem	**1.85**	**62.21%**	**0.22**	**20.86%**
Transportation	**0.01**	**0.17%**	**0.00**	**0.46%**

Disposal	**0.00**	**0.01%**	**0.00**	**0.01%**
Total	2.98	100.00%	1.04	100.00%

4.3.2.3. Cumulative Energy Demand (CED)

In respect to the direct and indirect energy use throughout the life cycle of SDH-BTES system, fossil fuel consumption presents significantly higher value (96.06%), which primarily happen at operation stage due to a large amount of diesel consumption. Focusing on the CED of each component, it's apparent that auxiliary boiler subsystem requires highest energy during life cycle stage (56.97%), followed by Solar subsystem (42.86%). Analyzing the values corresponding to the auxiliary subsystem, diesel undoubtedly ranks the first place (0.60). As for the solar subsystem, in addition to the electricity, solar collectors and borehole heat exchanger also require high value of energy, with 0.08 and 0.05 respectively. This fact can be explained that, in addition to electricity generation, the rest of the energy is mainly used for the manufacturing and construction processes of solar collectors and borehole heat exchangers.

The CED allows an estimation of Energy Payback Time (EPT), which is the period of time that the system has to be in operation to save the amount of primary energy spent for the whole system, including production, construction, operation and disposal. To calculate the EPT, the CED of the Solar subsystem is divided by the energy produced by this subsystem. The obtained payback time is 13.78 years.

$$\frac{11265936.4\mathrm{MJ}}{227\mathrm{Mwh} * 3600\mathrm{MJ/Mwh}} = 13.78 \text{ years}$$

Table 15 Cumulative energy demand of each life cycle stage

Impact category		**Total MJ**	**Production & construction stage MJ**	**Operation stage-Heat production at diesel boiler MJ**	**Operation stage-Electricity consumed in pump MJ**	**End-of-life MJ**
Total		82717949.44	11558924.85	46962930.76	24183794.25	12299.57
Non-renewable, fossil	96.06%	79455000.22	9759608.53	46544350.63	23139913.49	11127.58
Non-renewable, nuclear	1.97%	1627205.09	654732.77	268047.85	703729.54	694.92
Non-renewable, biomass	0.00%	2358.91	1684.33	226.04	448.24	0.30
Renewable, biomass	0.58%	479149.05	342333.80	47799.97	88807.80	207.47
Renewable, wind, solar, geothe	0.11%	94400.26	33714.30	15761.76	44878.90	45.31
Renewable, water	1.28%	1059835.91	766851.12	86744.52	206016.29	223.98

Table 16 CED per unit of total thermal energy demand of each component

Elements	**MJ CED/MJ**	
Solar collectors	0.08	17.85%
Water tanks	0.00	1.09%
Pipe	0.01	2.48%
Pumps	0.00	0.14%
Heat exchangers	0.00	0.34%
Borehole heat exchanger	0.05	9.89%
Pump electricity	0.31	68.22%

Solar subsystem	**0.46**	**42.86%**
Boiler	0.00	0.21%
Oil tank	0.00	0.13%
Diesel	0.60	99.66%
Auxiliary subsystem	**0.61**	**56.97%**
Transportation	**0.00**	**0.16%**
Disposal	**0.00**	**0.01%**
Total	**1.06**	100.00%

4.4. Interpretation

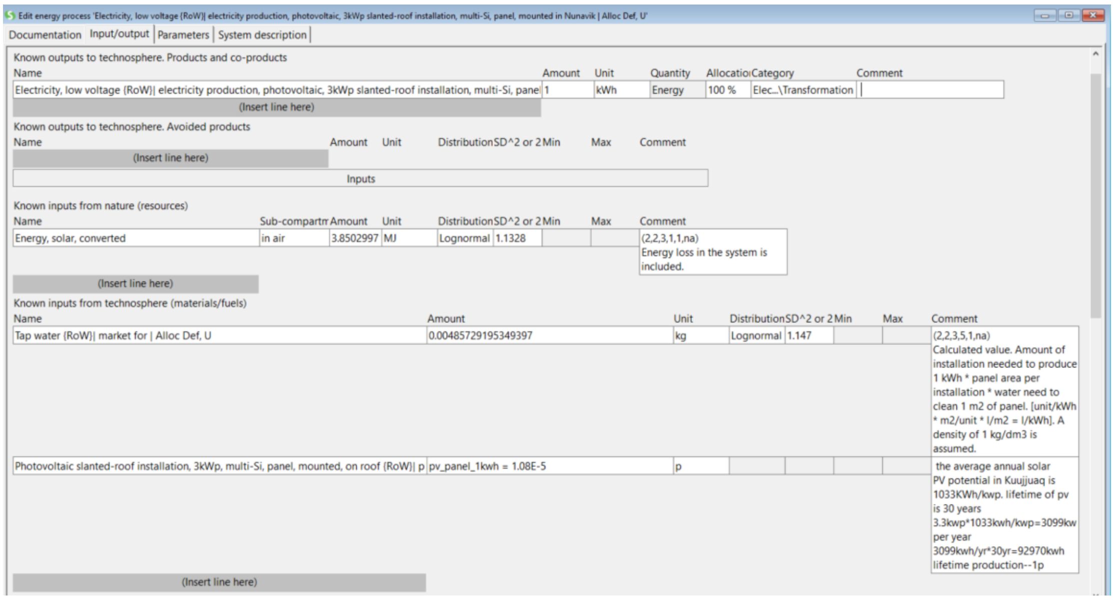
4.4.1. Sensitivity analysis

In this chapter, the sensitivity of the results will be examined by assessing the SDH-BTES system under different assumptions.

4.4.1.1. Sources of electricity

Lacking renewable electricity source, Kuujjuaq, an off-grid community, depends heavily on fossil fuel. To get rid of this situation, some green energy pilots are testing locally. One of the promising ways to substitute diesel power plant is photovoltaic (PV) panels, with average 1,033 kWh/kW annual solar PV potential in Kuujjuaq [63]. Hence, the first assumption to test is changing the electricity source to photovoltaic

(PV) panels. Process named ‘Electricity, low voltage, {ROW}| electricity production, photovoltaic, 3kwp slanted-roof installation, multi-si, panel, mounted| Alloc Def S’ is used to create a new electricity production process in Nunavik. The lifetime of a PV panel is 30 years. Figure 52 illuminates the input and output of the process.



Edit energy process 'Electricity, low voltage {RoW}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted in Nunavik | Alloc Def, U'

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocatio	Category	Comment
Electricity, low voltage {RoW}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel	1	kWh	Energy	100 %	Elec...\Transformation	

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment

Known inputs from nature (resources)

Name	Sub-compartm	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment
Energy, solar, converted	in air	3.8502997	MJ	Lognormal	1.1328			(2,2,3,1,1,na) Energy loss in the system is included.

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment
Tap water {RoW}| market for | Alloc Def, U	0.00485729195349397	kg	Lognormal	1.147			(2,2,3,5,1,na) Calculated value. Amount of installation needed to produce 1 kWh * panel area per installation * water need to clean 1 m2 of panel. [unit/kWh * m2/unit * l/m2 = l/kWh]. A density of 1 kg/dm3 is assumed.
Photovoltaic slanted-roof installation, 3kWp, multi-Si, panel, mounted, on roof {RoW}| p	pv_panel_1kwh = 1.08E-5	p					the average annual solar PV potential in Kuujjuaq is 1033KWh/kwp. lifetime of pv is 30 years 3.3kwp*1033kwh/kwp=3099kw per year 3099kwh/yr*30yr=92970kwh lifetime production--1p

Figure 52 Electricity production, photovoltaic, 3kwp slanted-roof, panel, Nunavik

Next, impact assessment is conducted to test the sensitivity of different electricity source. As shown in Figure 53, powered with electricity generated from PV panels demonstrates its relatively better environmental performance. The only impact category score worst is Mineral extraction, which is probably due to the production process of the PV panels. PV panels production is a resource-intensive procedure that requires significant amounts of metals and minerals. Table 17 shows that using PV panel can improve the system by 29%. In general, it can be said that powered by PV panels can reduce the environmental impacts of an SDH-BTES system since it can partly break the dependence of diesel.

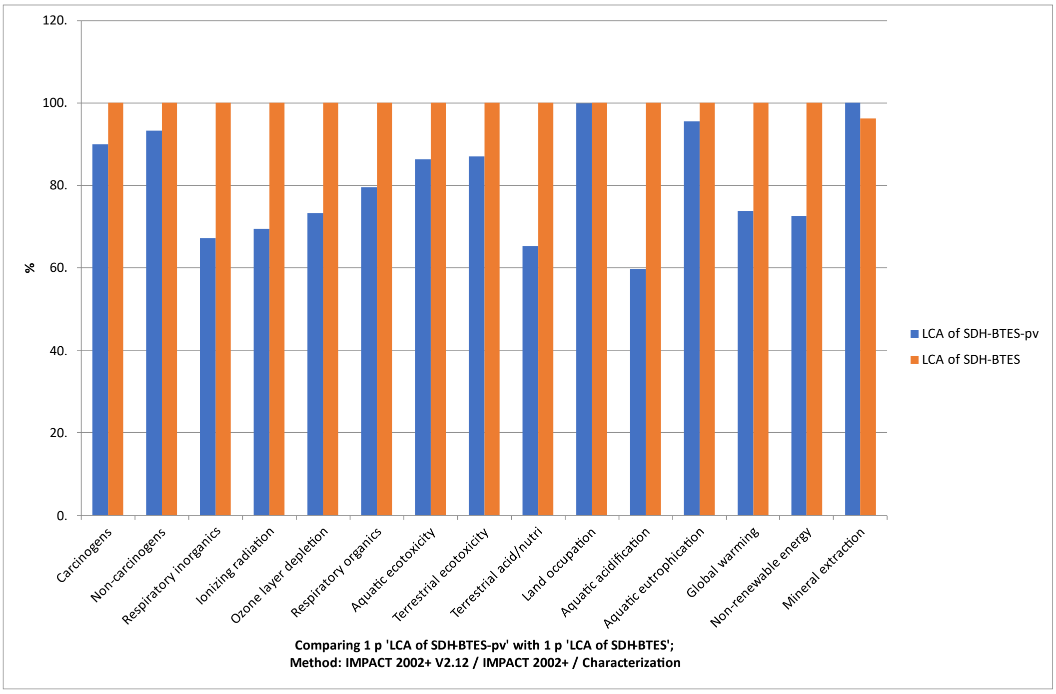


Figure 53 Impact assessment results of different sources of energy, IMPACT 2002+, characterization

Table 17 Single score of different sources of energy

Damage category	Unit	LCA of SDH-BTES	LCA of SDH-BTES-pv
Total	kpt	2.81	1.99
Human health	kpt	1.63	1.10
Climate change	kpt	0.55	0.41
Resources	kpt	0.54	0.40
Ecosystem quality	kpt	0.09	0.08

4.4.1.2. End-of-life scenario

As stated in section 4.2.4, the final disposal scenario is assumed that all wastes will be sent to landfill site directly at the end of the project. Another possibility is that some of them can be recycled or reused: 30% steel, 30% PVC, 30% aluminum, 30% glass. Besides, the worst scenario is incineration. As it can be observed from Figure 54, landfill combined with recycle scenario is most sustainable, while incineration scenario performs the worst. However, when testing in the whole life cycle of project (Figure 55), no significant difference can be seen in different disposal scenarios. Therefore, in this project, disposal scenario is less sensitive.

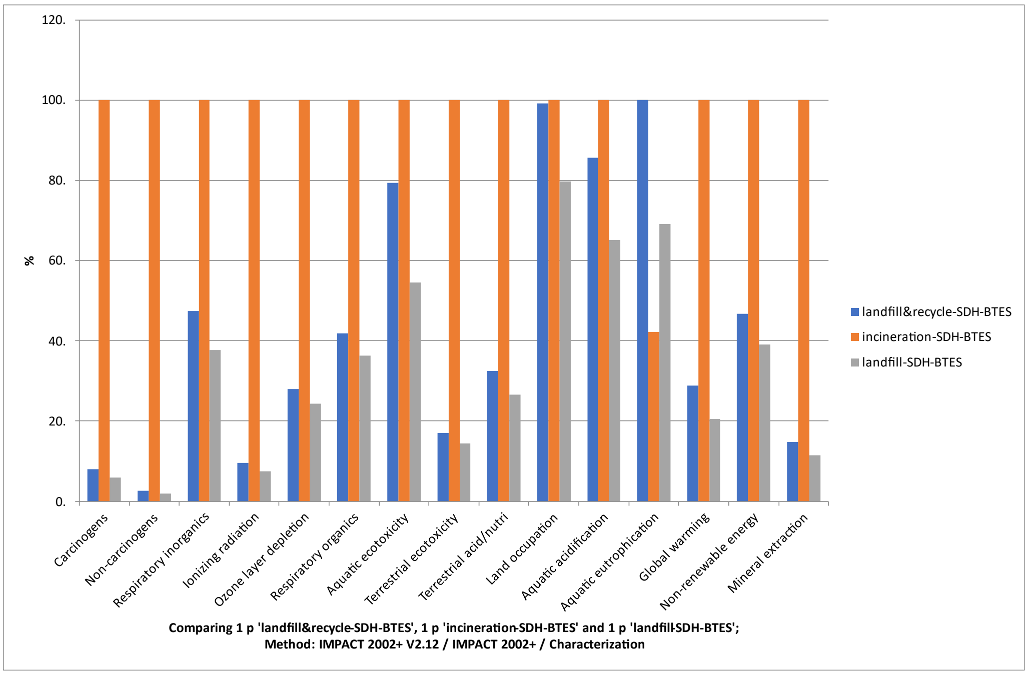


Figure 54 Comparison results, disposal scenario, IMPACT 2002+, charaterization

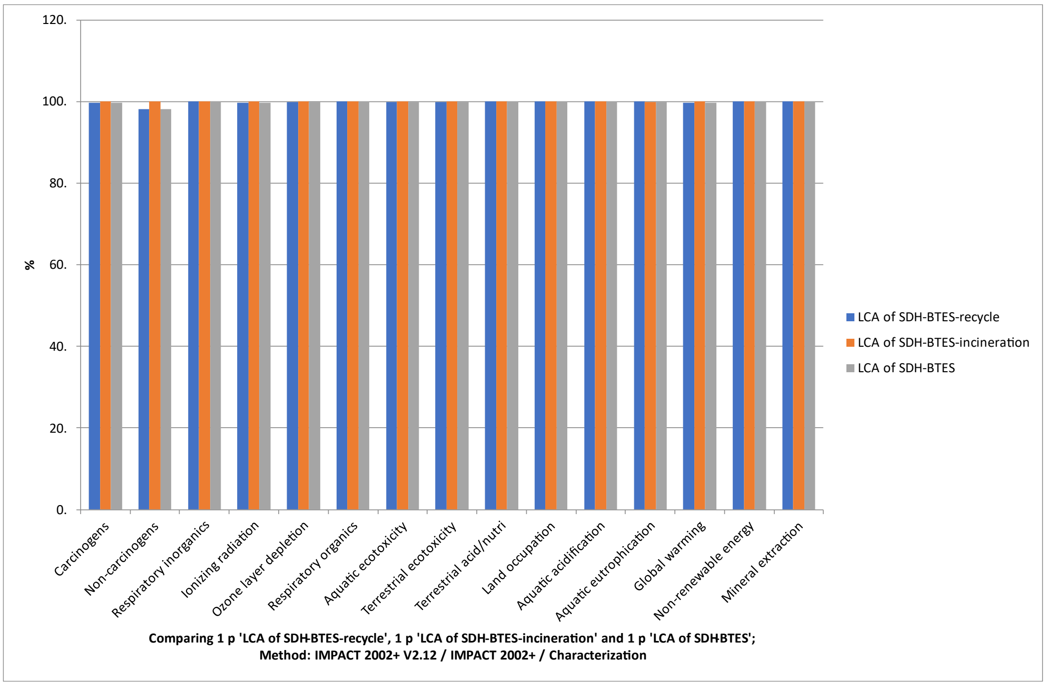


Figure 55 Comparison results, LCA of SDH-BTES, different disposal scenario, IMPACT 2002+, charaterization

Table 18 Sensitivity result of PV panel

Damage category	Unit	LCA of SDH-BTES	LCA of SDH-BTES-incineration	LCA of SDH-BTES-recycle
Total	kpt	2.81	2.82	2.81
Human health	kpt	1.63	1.63	1.63
Climate change	kpt	0.55	0.56	0.55
Resources	kpt	0.54	0.54	0.54
Ecosystem quality	kpt	0.09	0.09	0.09

4.4.1.3. Length of pipeline

Another assumption to test is the length of pipeline. To test the sensitivity of pipeline, another scenario is simulated with the pipe length of 2000 m, 2times of the basic scenario. Based on the results, changing the total length of pipeline to 2000 m make no obvious difference to the life cycle impact.

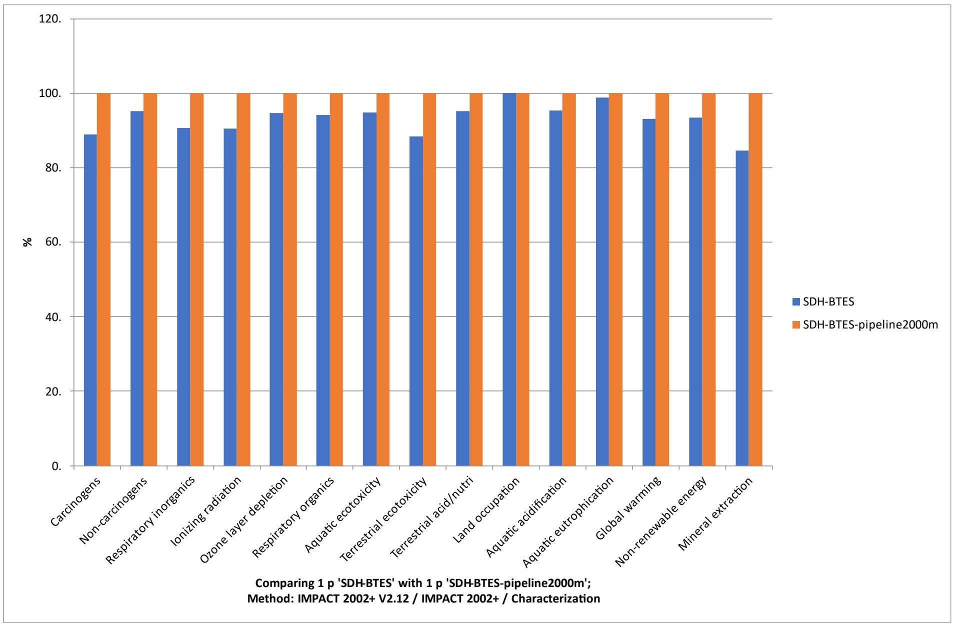


Figure 56 Comparison results, production & construction stage, IMPACT 2002+, characterization

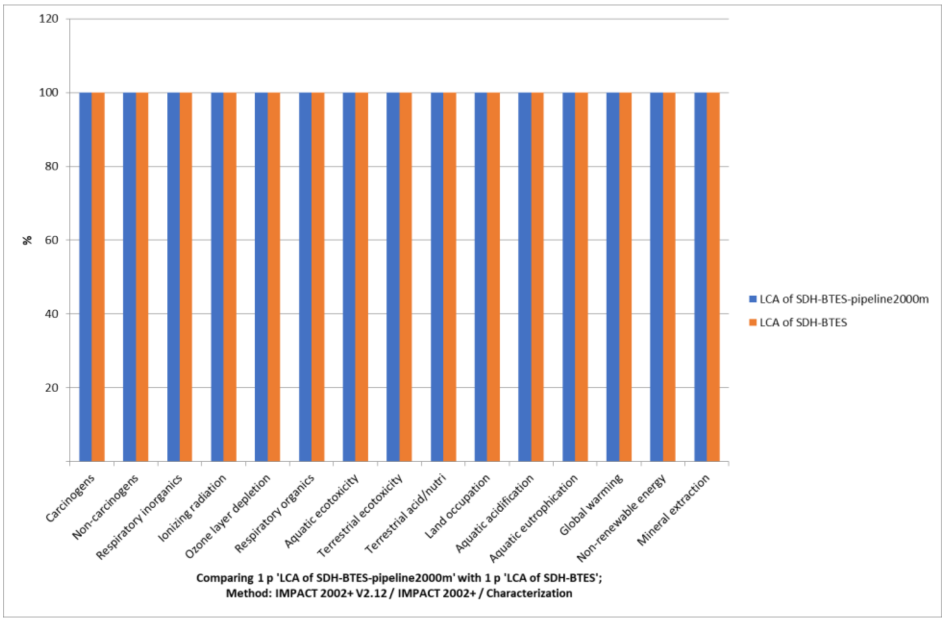


Figure 57 Comparison results, LCA of SDH-BTES, different pipeline length, IMPACT 2002+, characterization

Table 19 Sensitivity result of pipeline

Damage category	Unit	LCA of SDH-BTES	LCA of SDH-BTES-2000m pipeline
Total	kpt	2.81	2.81
Human health	kpt	1.63	1.63
Climate change	kpt	0.55	0.55

Resources	kpt	0.54	0.54
Ecosystem quality	kpt	0.09	0.09

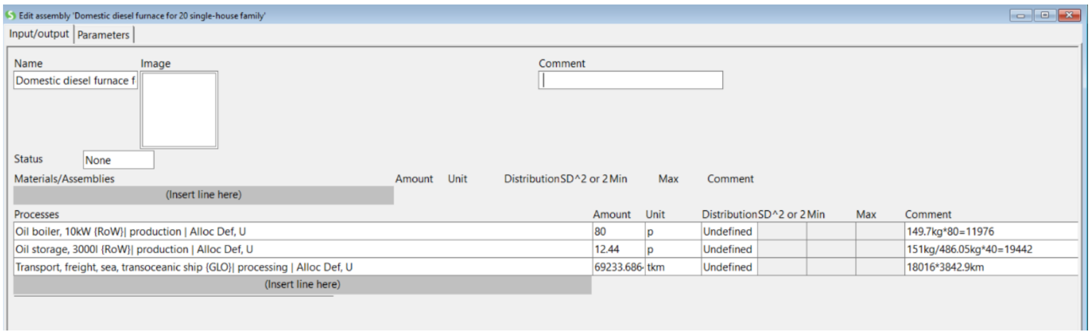
4.4.2. Comparison between SDH-BTES and conventional heating system in Kuujjuaq, Nunavik

In order to test the notion that SDH-BTES system is environmentally friendly or decide its feasibility in environmental aspect, it's essential to conduct a comparison between SDH-BTES system with the conventional heating system in Kuujjuaq, Nunavik. SDH-BTES system is assumed to satisfy 20 single-house families heating demand and the lifetime of the project is 50 years. Accordingly, conventional heating system selected to conduct the comparison is also supply heating for 20 single-house families for 50 years.

4.4.2.1. Life cycle inventory analysis of conventional heating system in Kuujjuaq

As mentioned above, Kuujjuaq is not connected to Quebec's electrical grid and accordingly, relies entirely on diesel fuel to generate the electricity and heat using diesel power plants and furnaces. Every single house is equipped with a diesel furnace to supply daily heating. A local domestic diesel furnace mainly consists of a diesel boiler and an oil tank (pipeline is ignored). It’s assumed that all 20 single-house families are equipped with the same type of diesel furnace, which is 10 KW oil boiler and 1500 l oil tank. The lifetime assumptions of oil boiler and oil tank are 15 years and 25 years, respectively, same as SDH-BTES system. Therefore, the production and construction stage of 20 domestic diesel furnaces scenario is composed of eighty 10KW oil boilers, forty 1500 l oil tanks, and transportation from Montreal to

Kuujjuaq, including the replacement during operation stage. Based on manufacturing manual and Ecoinvent3.3 database, the weight of 1500 l oil tank is 151 kg and 3000l oil tank is 486.05 kg. The scaling factor is calculated as 0.31. Therefore, a 1500l oil tank is equal to 0.31 units of 3000 l oil storage. Figures 59 and 60 show the inventory and life cycle stage of 20 domestic diesel furnaces. To satisfy thermal demand of 20 single-house family, 2,046,315 liters diesel are consumed at boiler to generate 77,760,000 MJ energy for 50 years.



Edit assembly 'Domestic diesel furnace for 20 single-house family'

Name: Domestic diesel furnace f

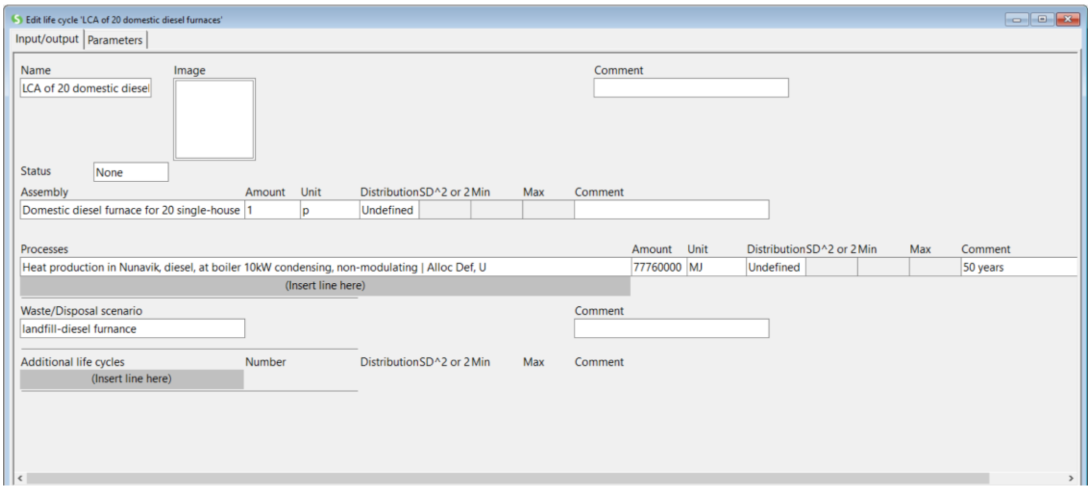
Status: None

Materials/Assemblies

Materials/Assemblies	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment

Processes	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment
Oil boiler, 10kW {RoW}| production | Alloc Def, U	80	p	Undefined				149.7kg*80=11976
Oil storage, 3000l {RoW}| production | Alloc Def, U	12.44	p	Undefined				151kg/486.05kg*40=19442
Transport, freight, sea, transoceanic ship {GLO}| processing | Alloc Def, U	69233.686	tkm	Undefined				18016*3842.9km

Figure 58 Inventory of 20 domestic diesel furnaces scenario



Edit life cycle 'LCA of 20 domestic diesel furnaces'

Name: LCA of 20 domestic diesel

Status: None

Assembly	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment
Domestic diesel furnace for 20 single-house	1	p	Undefined				

Processes	Amount	Unit	Distribution	SD^2 or 2	Min	Max	Comment
Heat production in Nunavik, diesel, at boiler 10kW condensing, non-modulating | Alloc Def, U	77760000	MJ	Undefined				50 years

Waste/Disposal scenario: landfill-diesel furnance

Additional life cycles	Number	Distribution	SD^2 or 2	Min	Max	Comment

Figure 59 Life cycle stage of 20 domestic diesel furnaces

4.4.2.2. Comparation between SDH-BTES and local furnaces

To further analyze the substantiality of SDH-BTES system built in Nunavik, a comparation is conducted between SDH-BTES system and 20 domestic diesel furnaces. The impact assessment results of SDH-BTES system and 20 domestic diesel furnaces are illustrated in Table 20. As it can be observed from Table 21 and Figure 60, SDH-BTES system performs better than local diesel furnace regarding to human health, climate change and resources. In general, using SDH-BTES system to supply heating can improve environmental impact by 21%. However, ecosystem quality impact of SDH-BTES system is slightly higher than the conventional domestic diesel furnaces, which can be explain by drilling process of BHE.

Table 20 Comparation results, IMPACT 2001+, single score

Damage category	Unit	LCA of SDH-BTES	LCA of 20 domestic diesel furnaces
Total	kpt	2.81	3.56
Human health	kpt	1.63	2.03
Climate change	kpt	0.55	0.72
Resources	kpt	0.54	0.73
Ecosystem quality	kpt	0.09	0.08

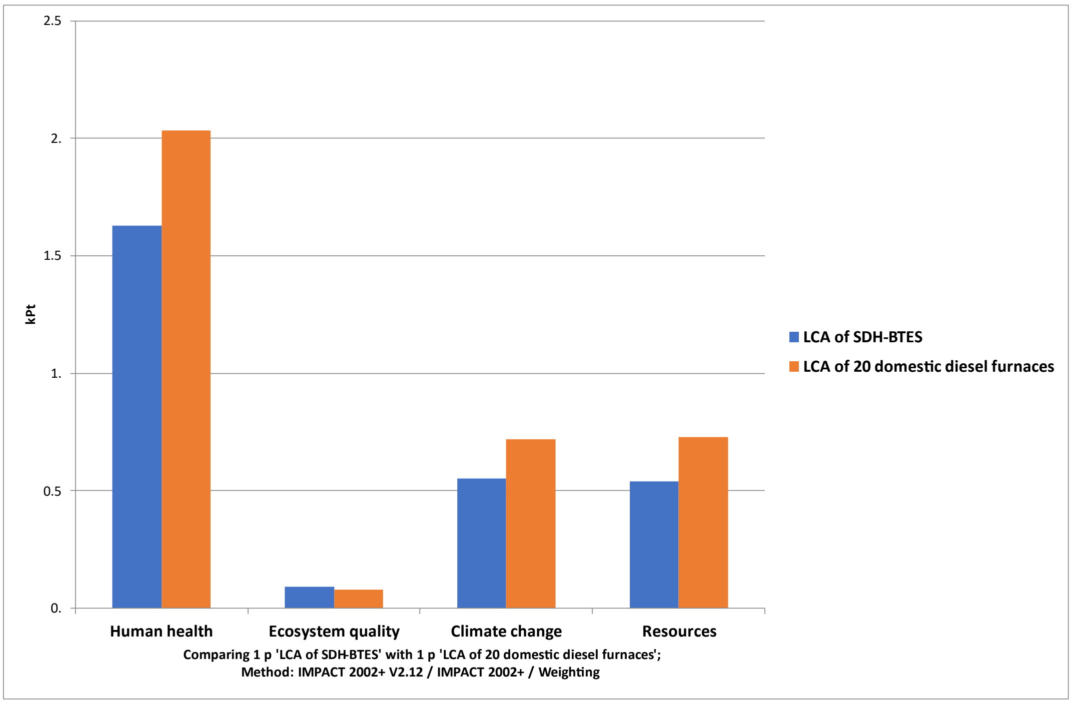


Figure 60 Comparation between SDH-BTES with 20 local furnaces using IMPACT

2002+

For the greenhouse gas emission and other airborne emission, Table 18 epitomizes the comparison results between SDH-BTES and conventional heating system. It appears that the conventional heating system in Nunavik produces 144477.60 kg CO_2 eq/year while the SDH-BTES system produces only 112058.80 kg CO_2 eq/year, which means 32418.8 kg GHG emission can be avoided per year. Besides, SDH-BTES system also improves its environmental performance regarding to NOx emission, reducing 478.01 kg per year. However, it's worthy to note that SDH-BTES system scores worse at SOx emission, increasing by 193.21 kg per year.

Table 21 Comparison results, greenhouse gas emission and other airborne emission

Airborne emission	Unit	LCA of 20 domestic diesel furnaces	LCA of SDH-BTES	Saving (%)
IPCC GWP 100a	kg CO2 eq/yr	144477.60	112058.80	22.44%
NOx	Kg/yr	1762.84	1284.83	27.12%
SOx	Kg/yr	253.29	446.50	-76.28%

Analyzing the cumulative energy demand, conventional heating system consumes a plethora of fossil fuel (2195605.05 MJ/yr), which is 1.4 times that of SDH-BTES. As shown in Table 22, developing SDH-BTES system is able to save fossil fuel, but it also consumes large amounts of other types of resource. Since it’s outside the scope of this study to interpret the significance of different energy resources, a simple weighting result is applied to provide a general picture of the comparison. Figure 61 illustrates the weighting results of CED, it can be noted that conventional heating system in Nunavik (111 TJ) consumes more energy than SDH-BTES system (82.7 TJ).

Table 22 Comparison results, Cumulative energy demand

Impact category	Unit	LCA of SDH-BTES	LCA of 20 domestic diesel furnaces	Saving (%)
Non renewable, fossil	MJ/yr	1589100.00	2195605.05	27.62%
Non-renewable, nuclear	MJ/yr	32544.10	15443.32	-110.73%
Non-renewable, biomass	MJ/yr	47.18	20.99	-124.77%
Renewable, biomass	MJ/yr	9582.98	2998.11	-219.63%
Renewable, wind, solar, geothe	MJ/yr	1888.01	916.05	-106.10%
Renewable, water	MJ/yr	21196.72	5320.36	-298.41%

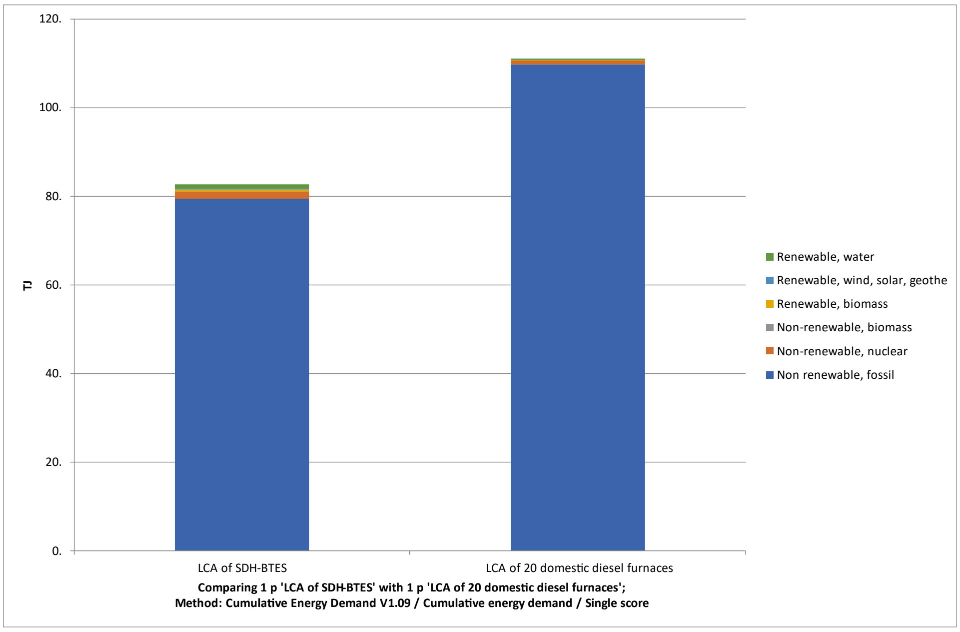


Figure 61 Comparation result, Cumulative energy demand, weighting

5. Discussion and conclusions

5.1. Conclusions

The life cycle assessment (LCA) of a solar district heating with borehole thermal energy storage (SDH-BTES) has been developed using software SIMPARO 8.1 in this research. The aim of this system was to provide thermal heating energy to 20 single-family houses located in Kuujjuaq, Nunavik for 50 years. The estimates, per unit of thermal energy demand, about the IMPCAT2002+, the greenhouse gas emissions (kg of CO_2- equivalent), nitrogen oxides emission and sulfur oxides emission, as well as the value of CED, was carried out to provide benchmarks for evaluations of environmental burden that could be provoked by the analyzed system:

1. SDH-BTES system provoked 130.32 mpts impact per MWh of thermal energy demand.
2. SDH-BTES system generated 259.40 kg of CO_2- equivalent per MWh, 2.98 kg of NOx per MWh and 1.04 kg of SOx per MWh of thermal energy demand.
3. SDH-BTES system consumed 1.05 MJ CED per unit of total thermal energy demand. The CED allows estimating the Energy Payback Time (EPT) of the analyzed system, which is relevant for the assessment of systems driven by renewable energies. The EPT of solar subsystem is 13.78 years.

SDH-BTES system provoked 2.81 kpts impact in total, of which the Human health category accounts for 1.63 kpts, climate change accounts for 0.55 kpts, resource category accounts for 0.54 kpts and ecosystem quality accounts for 0.09kpts. Looking into different phases of the proposed project, the operation phase provoked 2.45 kpts impact in total, while production and construction phase caused 0.36 kpts impact. The contribution of disposal phase is less significant comparing to other phases (0.001 kpts). The operation phase is associated with major inducement for all damage categories.

Focusing on different component of system, solar subsystem accounts for 43.47% of the total environmental impact, while auxiliary diesel boiler system makes up 56.35%. The contribution of the transportation and disposal is almost negligible over the service life of the system, with 0.16% and 0.02% respectively. In general, diesel consumed in the auxiliary boiler is the highest contributor among the component of the system, followed by the electricity consumption, which is also generated by diesel combustion. It's worthy to mention that due to the partial contribution of solar energy in the proposed system (52.5%), diesel still remains as a source of energy in the proposed system. In this regard, based on the sensitivity analysis, it was concluded that changing the electricity source to photovoltaic (PV) panels can reduce the total impact by 0.82 kpts, thereby further improving the environmental performance.

Despite the partial solar contribution, SDH-BTES system could still plays an important role in renewable energy development in Nunavik. By comparing the proposed system with the conventional heating system in Nunavik (i.e. local diesel furnace), SDH-BTES system can perform better in regard to human health, climate change and resource efficiency targets. However, ecosystem quality impact of SDH-BTES system remains higher than the conventional domestic diesel furnaces due to requiring a large land occupation for underground thermal heat storage. Overall, 32418.8 kg of GHG emission can be avoided per year using SDH-BTES system and along with mitigation of 478.01 kg NOx emission per year. However, SDH-BTES system presents a higher SOx emission potential, with an increase of 193.21 kg per year. As for CED, 27.62% fossil fuel savings per year can be achieved using SDH-BTES system in Nunavik over 50 years.

This research highlighted the importance of increasing the solar fraction of the system (and reducing the share of auxiliary diesel system), which can be realized by reducing the heat loss of the STTS and BTES system, incorporating heat recovery of BTES system as well as improving the efficiency of solar panel. Besides, reducing the electrical energy consumption of the pumps, considering the environmental burden provoked by the production of electricity is also recommended. It is also recommended that the solar collectors are sourced from manufacturing facilities using environmentally friendly materials.

In summary, SDH-BTES is a promising technology committing to supply clean, locally-generated and reliable heat in off-grid communities. The conducted LCA and results demonstrated the extent of the environmental benefits of SDH-BTES as renewable energy shortage alternative for Nunavik and its contribution to local energy security. It has also characterized and estimated the extent of environmental impacts provoked by this system to provide a basis for prioritization and addressing of them.

5.2. Limitation and future work

Regarding this research and its findings, it should be noted that there is some limitation that need to be mentioned. LCA is an analytical tool used to show the potential environmental impacts of a product system and therefore local impacts are not amply represented. This is especially essential for SDH-BTES system since it include an underground thermal storage which may cause geological impacts and interaction with underground water. For future studies, it is recommended to perform a detailed analysis regarding the environmental impact caused by drilling process and final disposal of boreholes.

Besides, there are some limitations regarding the inventory data that was used in this research. Details of some of the process could not be established completely based on the real manufacturing processing data and substitute/similar processes had to be chosen. Updating the SIMAPRO database is a long-lasting challenge, which remains an area open for further development.

Additionally, since there is no empirical SDH-BTES project built in Nunavik or other subarctic regions in Canada, this research is performed under some (hypothetical) assumptions. Practically, the actual conditions and performance efficiency can differ in real application, in particular to permafrost. Although Kuujjuaq is located in the discontinuous but widespread permafrost zone, permafrost is rather scattered in the area. Its presence is strongly dependent on local geological conditions. Hence, it's essential to conduct future research to collect supplementary (field) data to re-examine these assumptions and evaluate the potential impact caused by permafrost.

Lastly, since Diesel has been the major energy resource for a long time in Nunavik, developing a renewable energy may encounter various problem, especially social issues. A more detailed social impacts study would be required to take into account every consequence of the final solution to be implemented.

APPENDIX

LCIA results.xlsx

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