



# Further study of Life Cycle Assessment of a high density data center cooling system – Teliasonera’s “Green Room” concept

Identification of improvement possibilities using Life Cycle Assessment (LCA) and discussion about the effect of the choice of Life Cycle Impact Assessment (LCIA) methods on the results

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Shan Wang

## Abstract

The growing industry of Information and Communication Technology requires higher computing capacity of data centers. The air conditioning in data centers is a key to assure a sustainable computing environment. However, the traditional cooling systems cost large environmental footprints especially on energy consumption and greenhouse gas emissions. As a result, a green innovation of data center cooling solutions is taking place. The telecommunication company TeliaSonera is developing a high density data center cooling system - the "Green Room" and has been studying the environmental performance of this system using a Life Cycle approach. As an extension of the previous study, more aspects of the project i.e. the location of the data center, life span, alternative cooling solutions, energy recovery possibilities and uncertainty analysis is explored using Life Cycle Assessment (LCA) methodology. The comparison of locations of the Green Room indicates that the local temperature and electricity production sources are essential factors for the environmental performance of the Green Room. The analysis of the Green Room's life span reveals that the utilization phase may not always cause the most significant impact during the whole life cycle of the Green Room. If the life span changes, the manufacture phase may predominate the life cycle of the Green Room. The comparative result of alternative cooling technologies addresses that utilizing "natural coolant" (e.g. geo cooling) is a key for sustainable cooling innovation as it could significantly reduce the environmental footprint of the cooling system. Besides, heating a single building (partly) by the waste heat generated from the Green Room could save 30% of cumulative energy input and could reduce more than half of the total environmental impact. Additionally, results uncertainties caused by the choice of different LCIA methods are discussed in the end of the study.

**Key words:** Data center, Cooling system, Telecommunication, Technology and environment, Life cycle assessment (LCA), Life Cycle Impact Assessment (LCIA) method, Sustainable development

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# 1 Introduction

## 1.1 Background

Information and Communications Technology (ICT) is “a diverse set of technological tools and resources used to communicate, and to create, disseminate, store, and manage information.” (Blurton, 2002, p.1) ICT is used in a range of areas as diverse as financial services, business, media, education, transportation, healthcare, government, security and other sectors where needs information management and communication functions. The use and innovation of ICT is therefore considered as a driver for economic and social development in both developed countries and developing countries. (Steffen, 2008, pp.296-297) Within the ICT infrastructure, data center is one of the most important component which hosts servers and computers for storage, management and dissemination of data and information.(Glanz, 2012) Recent development of personal cloud computing technology, virtual business and the increasing storage requirement from companies (e.g. Facebook and Apple), has been significantly contributing to the growing demand of data centers. (Peters, 2012) The servers and other IT equipment in a data center requires a sufficient cooling system to control the temperature and humidity for an ideal computing environment. (Neudorfer, 2012) Although being widely used, traditional chiller based cooling system could consume as much as 50% of the total electricity consumption of a data center. (Peters, 2012) An innovation of data center cooling technologies is therefore taking place. In many climates, data center engineers find the cold air, cold sea water or other type of coolant which is relatively easy to obtain from nature can be used for data center cooling technologies. Such approach of data center cooling by taking advantage of outside environment conditions is known as the “Free cooling”. (McFarlane, 2012)

### 1.1.1 The Green Room concept

Teliasonera is one of the biggest telecommunication company in Scandinavia. It recently developed the “Green Room” concept, aiming to provide a cooling solution with high efficiency yet low environmental impact for data centers/telecommunication technical sites.(Lundén & Ovesson, personal communication, 2011)

As can be seen in Figure 1, the design of the Green Room consists of a main room with high density of CRAC<sup>1</sup> units including high efficient coolers and a pump room with pump racks, heat exchangers and control system. (Larsson, personal communication, 2012) Free cooling approach plays an important role in the cooling production within the “Green Room” concept. The sample of the Green Room is constructed in Stockholm, Sweden. The cooling production of this site is designed to take advantage of the nearby cold sea water as the natural coolant for most time of a year and the chiller based cooling technology is only used during summer when the sea water is not cold enough for cooling production. (Enlund, personal communication, 2012a) Moreover, according to Lundén (Personal communication, 2012), in order to reduce carbon footprint from energy consumption, the whole site is

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<sup>1</sup> CRAC = Computer Room Air Conditioner

powered by “*certified electricity*” - a type of electricity produced only from renewable energy sources such as hydropower, biomass, solar energy, wind energy, geothermal energy and wave energy. (Swedish Institute, 2011)

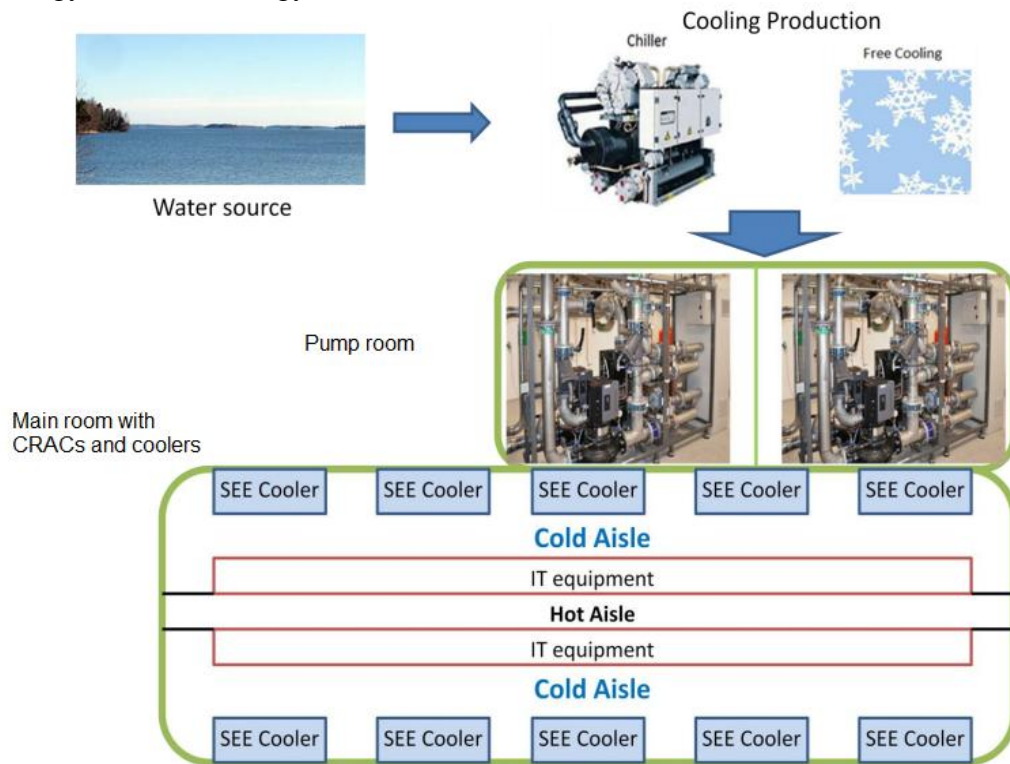


Figure 1 Overall functioning of Green Room and its main components. (Oliveira, 2012)

### 1.1.2 Life Cycle Assessment

Life Cycle Assessment (LCA) is probably the most widely used tool for studying the holistic potential environmental impact of a product. It includes the whole life cycle of the product - the raw material extraction, transportation, utilization and disposal (i.e. from cradle to grave). (ISO, 1997) In an environmental LCA study, raw material use and harmful emissions of the whole industry system of a product or service can be described in quantitative terms.

The framework of the LCA methodology usually includes:

**Goal and Scope definition:** the studied product or service is specified; the purpose and the system boundaries of the study are clearly defined.

**Inventory analysis:** the construction of the life cycle model and the environmental load calculation is executed, the related result is analyzed.

**Impact assessment:** the resource depletion and pollutant emission in inventory results are related to different environmental problems/impact categories. According to ISO 14042 (2000), the procedure of a Life Cycle Impact Assessment (LCIA) is required to follow the steps:

*Impact category definition:* this is the first step of a Life Cycle Impact Assessment. During this phase, a group of impact categories are defined, models of cause-effect chain and their endpoints are identified.

*Classification:* this step is to assign the inventory results to corresponding impact categories.

*Characterization:* the quantitative step which transfer inventory results into quantified environmental impact by using equivalency factors as reference while modeling cause effect chains. (Baumann & Tillmann, 2004)

The above steps are mandatory in an LCIA method, sometimes the below impact assessment steps can also be implemented:

*Normalization:* the characterization results are divided by the magnitude for each impact category, aiming for a better understanding of to how much extent one impact category contributes to the total environmental burden. For example in our study the results can be normalized to the environmental effects that are caused by one average European person in one year.

*Grouping:* the characterization results are sorted (and possibly ranked) into some groups, for example, “impact with high/medium/low priority” or “global/regional/local impact”.

*Weighting:* in this procedure each environmental impact is quantified by adding a weight factor in order to show its relative importance against all the other environmental impact. Moreover, all the weighted scores can be added up to give a total single impact score for the systems, known as the *Single Score* result. (Colin McMillan, 2011) The single score result can provide an easy-to-understand result for the life cycle of a subject, although ISO standard advices that weighting and single score result shall not be used for public comparisons due to the subjectivity of weighting. (ISO, 2006)

### 1.1.3 Literature review

Recent researches indicate that data center sustainability plays an important role of the sustainable development of ICT industry. According to Malmmodin et al. (2010, p.782) , in 2007 about 25.4% of the electricity consumption from global ICT industry was consumed by data center operation, the corresponding greenhouse gas emissions is estimated as 17.4%. Moreover, according to Kant (2009, pp. 2939-2965) and Uddin and Rahman (2012, p.4083), the cooling system may cost 25% to 50% of total electricity consumption in many data centers including CRAC units, pumps, chillers and cooling towers. Green innovation of data center cooling system is therefore

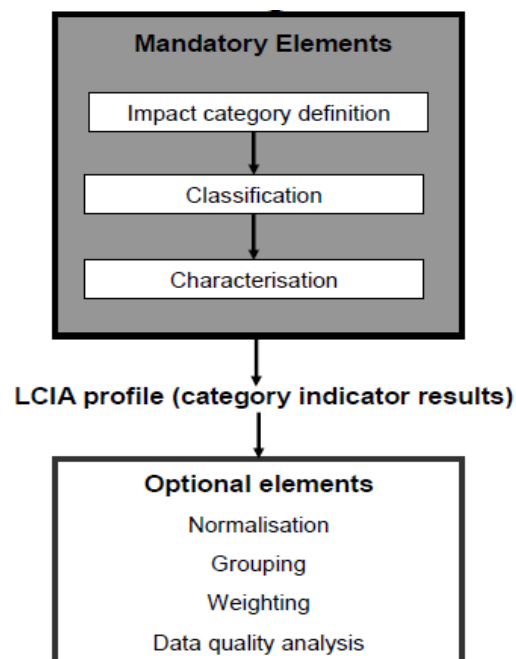


Figure 2 Life Cycle Impact Assessment steps (ISO 14042 2000)



considered as a significant perspective in data center design. In current development of data centers, capitalizing free cooling technology is considered as a key for improving the energy efficiency. (Google, 2012) Intel (2008, p.4) did a “proof of concept” test of free cooling by using outdoor cold air to cool a 10-megawatt data center. The result shows when using free cooling, the power consumption may reduce 74%. According to the local climate of the tested data center, the cold air can be obtained in maximum 91% time of the year. It is therefore estimated that 67% of electricity consumption could be saved from cooling production in a year.

Researches address that the geographic location is crucial for green data center design. The local temperature of a data center may significantly influence the cooling demand of a data center. (Curry et al., 2012, p.3) At the same time, locations where close to renewable energy sources (hydropower, wind, solar etc.) are preferable for reducing the emissions from the power generation site. (Uddin & Rahman, 2012, p.4083) An air management and energy efficiency investigation of a data center in Finland suggested that the waste heat produced from a data center may be collected and used for heating or water heating, which is also an option for enhancing energy efficiency of a data center. (Lu et al., 2011, p.3372)

Additionally, the Green Grid (2009, p.50) proposed energy policies for green data centers in European countries including the requirements of the energy consumption of the cooling equipment as well as the banned refrigerants which depletes the ozone layer.

An LCA study of the Green Room proposed by Teliasonera is finished. (Oliveira, 2012). It accounted for the usage of raw material and energy, including 6.4 tons of stainless steel, 2.1 tons of copper, and 165kg of refrigerant (R134a) are used; and more than 9000MWh of electricity will be consumed 20 years - the preliminary assumption of the life span of the Green Room. The impact assessment results was mainly calculated by ReCiPe. According to the single score result 77% of the total environmental impact is attributed to the utilization phase of the life cycle of the Green Room. Moreover, extraction/manufacture phase is shown as the second most important phase, whereas the impact of transportation phase is minimal. Most of the potential impact comes from the human toxicity, climate change and fossil depletion impact categories which mainly reflects the situation of energy consumption and raw material extraction/manufacture. (Oliveira, 2012)

## **1.2 Objectives**

While the previous study offered comprehensive environmental assessment of the Green Room, this study aims to explore more perspectives of the Green Room concept from broader horizons. We are particularly interested in understanding how the results change if:

- 1) the Green Room is installed in different locations;
- 2) the Green Room is utilized for shorter time period;
- 3) the cooling technology of the Green Room is changed to other cooling solutions;
- 4) the waste heat generated from the servers and other equipment is recycled and reused for other occasions.

Another objective of this study is to understand the uncertainty caused by the choice of the Life Cycle Impact Assessment methods as well as its impact to the final results of the Green Room LCA study.

The whole report of the study is divided into five individual study topics. Each topic is discussed in each study respectively, using LCA as a tool and following the LCA methodological framework. The condensed conclusion and limitation of the whole study will be presented in the end of the main report.

## **1.3 Methodology in general**

The study uses Simapro 7.2 (Pré 2012) software as LCA tool and benefits from the existing model and results of the LCA study of the Green Room by Oliveira (2012), in which the tested “Green Room” example refers to the site constructed in Stockholm, Sweden, powered by Swedish certified electricity. In this project our discussion will continue using the same site (i.e, the data center located in Stockholm and powered by Swedish certified electricity) as the “base case” but in some cases it may refer to data centers under other geographic and/or energy supply conditions which will be described in the related studies.

Most of the data used in the study is from Ecoinvent database v 2.0 (Swiss Center for Life cycle inventories, 2012) as implemented in Simapro software. The data which not included in ecoinvent are directly collected from personal contacts in Teliasonera, published statistic report as well as estimations. Following Oliveria’s study, ReCiPe (Goedkoop et al., 2009) is chosen as the major Life Cycle Impact Assessment methodology in our study. Cumulative Energy Demand (Frischknecht, 2004 & VDI, 1997) is utilized as a complementary assessment method especially for analyzing the energy perspective of the study. The LCA studies in study topic 1-4 follow the framework of the LCA methodology, i.e. goal and scope definition, inventory analysis and impact assessment. Characterization results and Single Score results are used for the analysis and discussion of this study. More detailed information regarding specific study procedure or methods will be described under each study topic.

## **2 The Studies**

### **2.1 Study One: Environmental impact comparison based on the Green Room being installed in different locations**

#### **2.1.1 Introduction**

As an international company, Teliasonera aims to internationally promote the Green Room concept high efficient cooling system for ICT technical site/data centers. Concerning this subject, the location of the site - a key factor influencing the total environmental impact of the Green Room - needs to be investigated.

Firstly, the colder the local climate is, the larger possibility to obtain the free coolant from nature, such as cold air or cold water. As a result, the demand for chiller based cooling is reduced and correspondingly saving electricity. Recently many ICT corporations choose cold areas in the world as locations of their new technical sites,

for example, the north part of Europe. In 2011 Google's new data center was constructed in an old paper mill in Hamina, Finland, taking advantage of its already built tunnel to pump the nearby cold sea water as its coolant. (Google, 2011) Similarly, Facebook is currently constructing their new data center in Luleå Sweden. (Waugh, 2011) Thanks to the cold weather in Stockholm, TeliaSonera is able to use neighborhood sea water as the coolant for the Green Room cooling system approximately 8 to 9 months in a year.

Secondly, the national electricity generation sources vary depending on the country, since every country has its unique energy context related to the energy demand, infrastructure, resources, economy and many other perspectives. Hence from environmental point of view, different electricity generation sources plays a vital role on the total environmental impact of a product/service's life cycle especially in energy intensive industries, resulting from the huge differences of the environmental impacts between generating electricity by non-renewable energy sources (i.e. fossil fuels and nuclear power) and renewable energy sources. Moreover, it is noteworthy that there is certified electricity available in the market in many countries. Using this type of electricity may significantly reduce the environmental impact in the energy intensive industry and therefore being utilized by many corporations. As an example, the electricity purchased by TeliaSonera in Sweden and Finland is 100% generated from renewable sources. (TeliaSonera AB, 2010, p.45). The new Facebook data center located in Luleå will also derive the electricity from a nearby hydropower plant as its sustainable energy supply. (Waugh, 2011). Shehabi et al.(2010, pp.995-996) investigated some data centers spreading in different regions in the US and showed that the location difference of data centers influences 1) the electricity demand due to the different local temperature; 2) the greenhouse gas emissions since the local primary energy source mix (e.g. coal, natural gas, nuclear and renewable sources) for electricity generation is quite different from one region to another. Moreover, they found that the impact of regional difference on the greenhouse gas emissions is larger than its impact on electricity demand. With the interest of studying how much the location may influence the environmental performance of the Green Room, we implemented a comparative study among selected locations.

### 2.1.1.1 Compared locations and system boundaries

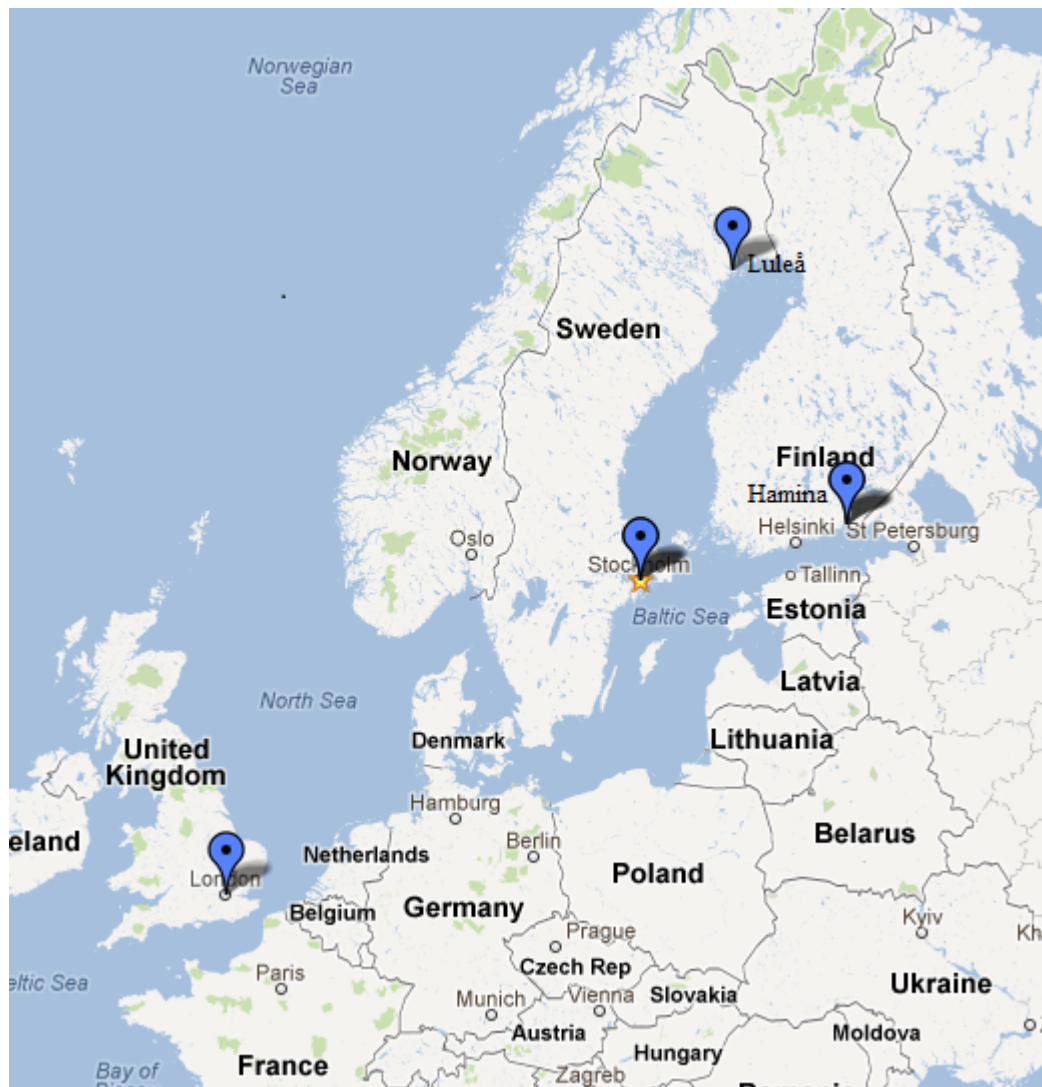


Figure 3 The four studied locations (Google, 2012)

Four cities in different European countries are selected for this study. Besides Stockholm where the built sample of “Green Room” is located in, Hamina in Finland and Luleå in Sweden are chosen for the comparison in the light of the location of Google and Facebook’s new data centers; London is also selected to represent a relatively different environment from Nordic countries. (See Figure 3)

### 2.2.1 Inventory analysis

#### 2.1.2.1 Energy use accounting

This comparative study will concentrate on the utilization phase of the Green Room not only because it is the predominant phase of the life cycle of the Green Room but also because the data set representing extraction/manufacture phase are similar as many of them are based on the European average level. The Green Room cooling solution is designed to take advantage of natural coolant, in our case, the nearby cold sea water, in order to minimize the use of traditional chiller based cooling. Since this technology is not available during the warmest season (defined as summer in this study) in a year, the Green Room will be completely air-conditioned by chillers

during this time. The time length of using sea water (defined as winter) cooling and the time length of chiller based cooling (defined as summer) according to the climate of each selected location can be found in Figure 4 and Table 1. The horizontal line in the diagram represents the approximate shifting temperature (13.5 °C)<sup>2</sup> between “summer” and “winter”. (Azzi & Izadi, 2012) When the temperature is above this temperature, the cooling system of the Green Room is shifted to chiller based cooling, otherwise it is assumed to be cooled by cold nearby sea water.

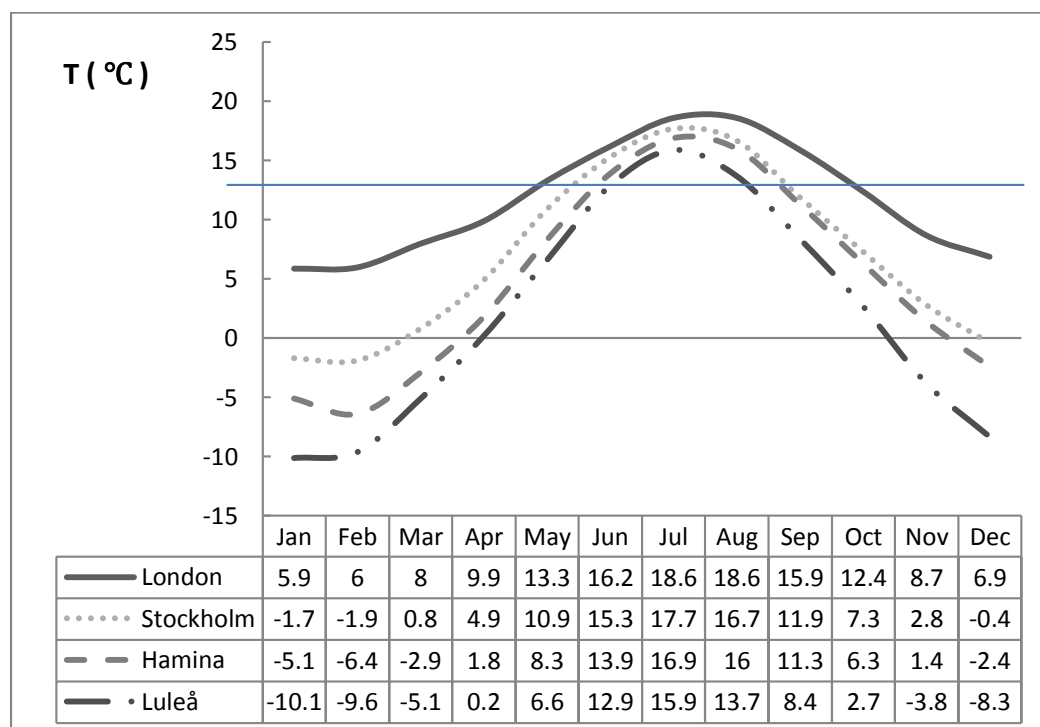


Figure 4 Monthly average temperature; London, Stockholm, Hamina, Luleå. (Norwegian Meteorological Institute and Norwegian Broadcasting Corporation, 2012 )

Table 1 Number of Summer weeks and winter weeks of four selected locations.

	Summer (Weeks)	Winter (Weeks)
London	19	33
Stockholm	12	40
Hamina	10	42
Luleå	8	44

<sup>2</sup> This temperature is estimated from the related test result of the Green Room reported by Azzi & Izadi (2012, p.33): during the week 37, 38, and 39 in the year of 2009 there was a sudden increase of electricity consumption in the test site, resulting from the chiller based cooling was taken place. According to the temperature statistic of 2009, it could be estimated that chiller based cooling starts being used at the temperature is about 13.5 °C.

It is known that cooling production power is 101.493kW for chiller based cooling (summer) and 31.612kW for sea water cooling (winter) (Azzi & Izadi, 2012. p.34). The power for the fans and other small components of the cooling system can be estimated as 4kW; therefore,

Total cooling system electricity power demand =

$$\frac{(101.493kW * summer\ weeks + 31.612kW * winter\ weeks)}{52\ weeks} + 4kW$$

For example, London has 19 weeks summer and 33 weeks winter, thus the electricity power demand for the Green Room in London is

$$\frac{(101.493kW * 19\ weeks + 31.612kW * 33\ weeks)}{52\ weeks} + 4kW \approx 61.1\ kW$$

The total electricity demand for one year is

$$61.1kW * 24h * 365 = 535236kWh \approx 535MWh$$

Therefore, the electricity demand for the Green Room's whole life span (defined as 20 years) is

$$535MWh * 20 = 10705MWh$$

Same calculation is done for other studied locations, the result is illustrated in the chart below:

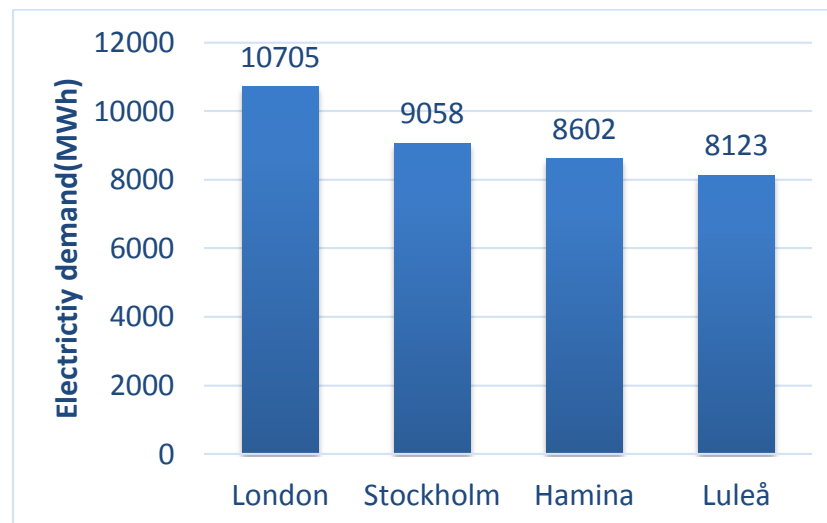


Figure 5 The electricity demand during the use phase of the Green Room in four selected locations.

In general the city with longer winter and shorter summer costs less amount of electricity. It can be predicted that Luleå demands the least amount of electricity (8123MWh) among these four locations. Hamina has the second lowest electricity

demand which is only 5.6% more than Luleå followed by Stockholm. London is 15.4% more than Stockholm and 19.6% more than Hamina and 24.1% more than Luleå

### **2.1.2.2 Electricity production sources in selected locations**

As described in previous section, the national electricity production source mix varies among different countries. In Sweden fossil fuel such as coal and oil only plays a minimal role in electricity generation since increasing amount of nuclear and hydropower have been introduced as main electricity fuels from 1990s, in 2010, their shares reach to 38% and 46% respectively. (Swedish energy agency and Statistic Sweden cited in Swedish energy agency, 2011, p.17) Whereas in UK the electricity generation heavily relies on fossil fuel combustion even though it has been slowly replaced by nuclear power and renewable sources. It is reported that by 2011 the use of coal and gas for electricity production still as high as 70% out of the total in the UK. (Department of Energy & Climate Change, 2012, p.121) The electricity sources mix in Finland also includes fairly large share of fossil fuels such as coal and natural gas; wood fuels including peat are mainly consumed in combined heat and power production; as well as nuclear power and hydropower. By 2010, slightly less than half of the electricity in Finland is generated from fossil fuels; the usage of peat (which is considered as non-renewable source) is accounted for 14%. (Statistics Finland, 2011, p.2)

The “certified electricity” is available to purchase in all of the selected countries - the UK, Sweden and Finland, however, there is no scientific reviewed dataset representing those processes in Simapro. In order to solve this problem, we decided to respectively create the “certified electricity” process for UK, Sweden and Finland by modifying the existing process for Swiss certified electricity “electricity, low voltage, certified electricity, at grid/kWh/CH” in Simapro. However, the user of these modified datasets need to be very aware about the uncertainty since the modification is fairly rough and there has not been any scientific review on these datasets.<sup>3</sup> Therefore an analysis based on each country’s national electricity mix is also implemented at the same time.

### **2.1.2 Inventory results**

#### **2.1.3.1 The comparison based on using conventional mix as electricity source**

As can be seen in Table 7 in [Appendix One](#), the carbon dioxide emission from both the Swedish locations (Stockholm and Luleå) is only one fifth of the Finnish location (Hamina) and one ninth of London, UK. This is because the electricity generation in Finland and UK is largely dependent on fossil fuel combustion; while a lower amount of fossil fuel is used for electricity production in Sweden, as mentioned in previous sections.

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<sup>3</sup> For example, in order to make the dataset representing Swiss situation suitable for Swedish situation, the dataset ‘electricity, hydropower, at power plant/CH’ is substituted by the dataset ‘electricity, hydropower, at power plant/SE; the dataset “Electricity, production mix photovoltaic, at plant/CH S” is substituted by “Electricity, production mix photovoltaic, at plant/SE S”. Same work is also applied for modeling the processes representing UK and Finland.

Manganese is also revealed as a significant pollutant emission in this study. Manganese naturally occurs in the coal deposits. The emission pollutes water bodies during coal mine drainage and thus cause impact on fossil fuel based electricity generation. In addition, Manganese is also released from the production of copper which is the major material for electricity distribution networks.

Even though installing the Green Room in Sweden can avoid large amount of greenhouse gas emissions as well as fossil depletion, it is worth noting that Sweden uses nuclear power as one of the major source for electricity production. As we know no matter how well the safety of nuclear facility is assured by current technology and management, there is always a risk of nuclear leakage which makes this type of energy controversial in many countries. The Uranium usage in Stockholm is nearly twice the amount of the usage in London in our study. (See Table 7 in [Appendix One](#))

#### **2.1.3.2 The comparison based on using certified electricity**

Table 8 in [Appendix One](#) listed the most important environmental loads during the utilization of the Green Room in the four locations, using certified electricity source. Compared with the results when not using certified electricity, the overall environmental loads are remarkably lower. The emissions of greenhouse gases can be reduced by more than 90%, especially for London, where 6000 tons of CO<sub>2</sub> emission could be reduced by introducing certified electricity for the Green Room. In addition the amount of nuclear resource used from Swedish national electricity mix would also be significantly reduced if certified electricity is used for the Green Room.



## 2.1.3 Life Cycle Impact Assessment result

### 2.1.3.1 Cumulative Energy Demand analysis<sup>4</sup>:

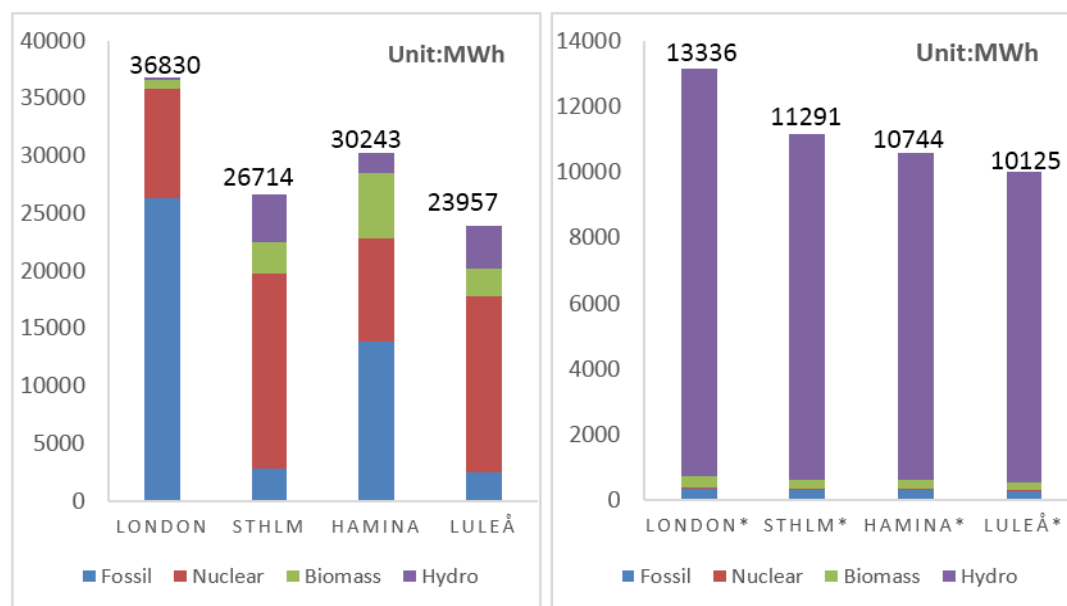


Figure 6 Cumulative Energy Demand comparison during the utilization phase of the Green Room among four locations, using national electricity mix and certified electricity respectively. \* represents the city using certified electricity

The left chart in Figure 6 illustrates the comparison among the selected locations for the Green Room when each site is using their local electricity mix. The sequence of the size of cumulative energy demand is London>Hamina>Stockholm>Luleå. There is an obvious difference (18%-35%) between London and the other three cities; the differences among the Swedish and Finnish cities are in a smaller range (10%-21%). In addition, if we compare this sequence with the electricity demand of this four locations : London>Stockholm>Hamina>Luleå (concluded in previous section) ; we can find there are more cumulative energy demand for Hamina than Stockholm, even though the electricity demand in Hamina is lower than in Stockholm due to the colder climate. This is because the national electricity production in Finland largely (50%) depends on fossil fuel power which is less efficient than hydro and nuclear power based electricity generation in Sweden.

The right chart in Figure 6 presents the sequence of the cumulative energy demand among these four cities when using local certified electricity mix: London>Stockholm>Hamina>Luleå, which is different from the previous result: the cumulative energy demand in Hamina become lower than in Stockholm when both of the cities utilize certified electricity sources. This can be explained as, when all of the selected locations are independent on fossil fuel, the total energy demand sequence of

<sup>4</sup> Cumulative Energy Demand is a life cycle impact assessment methodology quantifying the direct and indirect energy use during the life cycle of a product or a process. In our case, the study includes not only the electricity demand during the utilization phase but also the energy demand when producing this amount of electricity at the power plant.

these locations is mainly influenced by the local temperature: the colder the weather of the location is, the less cumulative energy will be consumed.

### 2.1.3.2 Life Cycle Impact Assessment by ReCiPe :

#### 2.1.3.2.1 Characterization results:

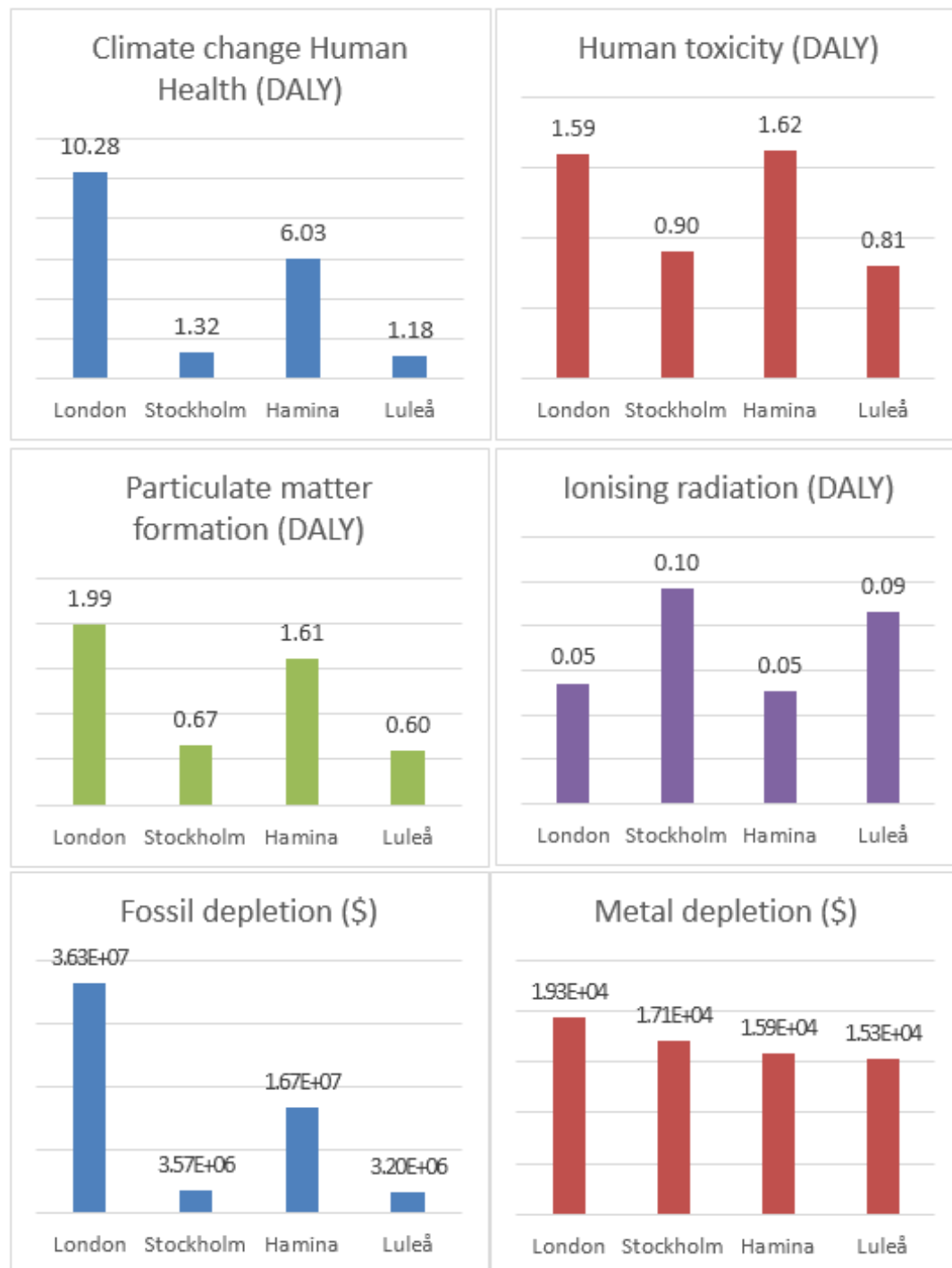


Figure 7 Environmental impact comparison of four locations, using national electricity mix. (Characterization results)

Figure 7 illustrates some of the most important impact assessment results from the characteristic by ReCiPe. As can be seen, London and Hamina have particularly higher impact in climate change human health, human toxicity, particulate matter formation category and fossil depletion, resulting from the emissions released by fossil fuel combustion. On the other hand, the ionizing radiation from Swedish cities is 40% higher than London and Hamina, due to the high level of nuclear power within their national electricity production source. The scale of metal depletion of each site seems rather less different among these four locations, which can be explain as each site needs a similar amount of metals for power generation facilities and distribution network construction.

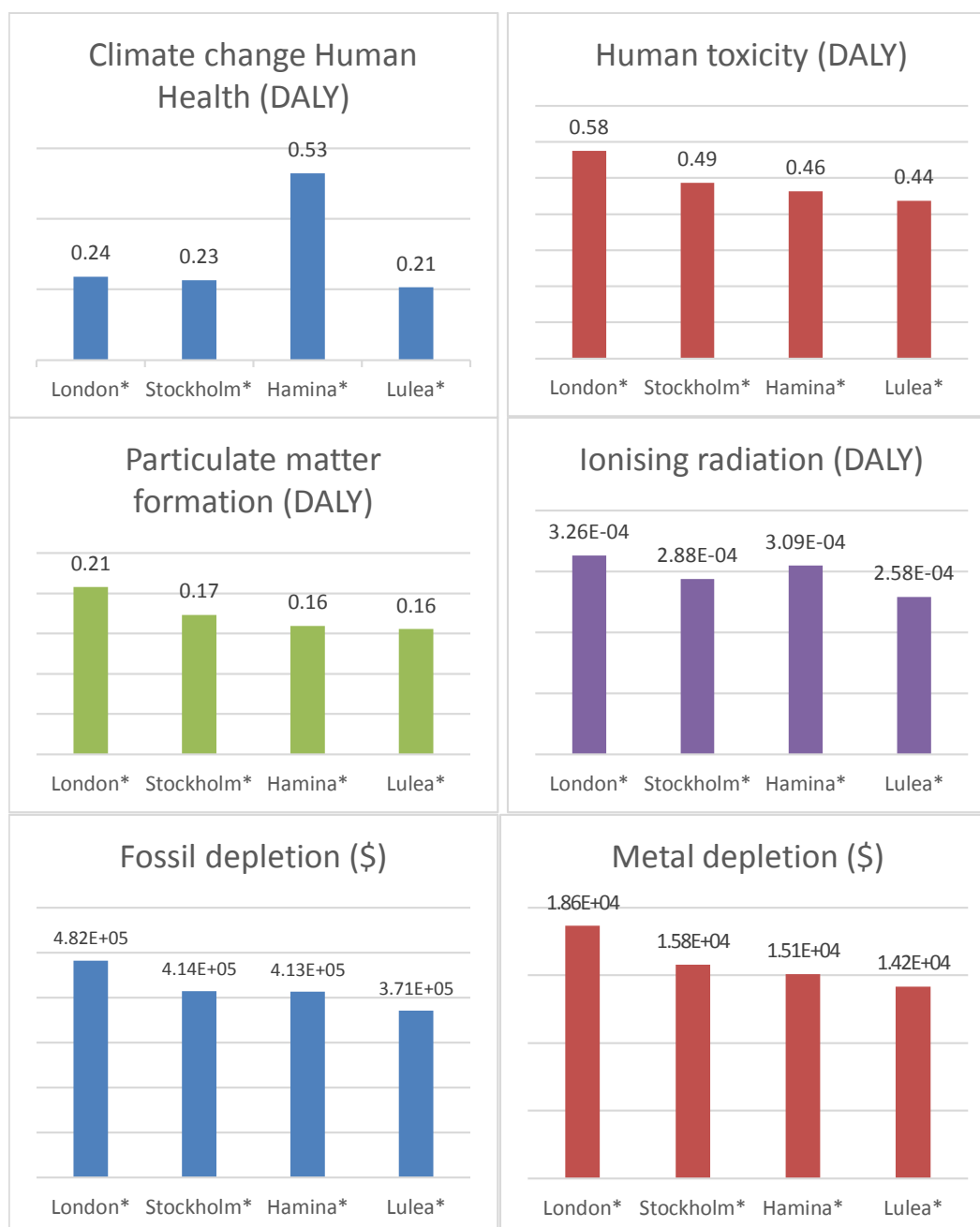


Figure 8 Environmental impact comparison of four locations, using certified electricity mix. (Characterization results.)

When introducing certified electricity in every location, the environmental impact dramatically reduces in climate change human health, human toxicity, particulate matter formation, ionising radiation and fossil depletion. Especially the fossil related impact categories such as climate change human health and fossil depletion can be reduced more than 90% in London. The ionising radiation is minimal among all of the four locations as the certified electricity is free from nuclear power. The impact on metal depletion does not change very much compared to the result of using traditional electricity since this impact is mainly caused by the construction of electricity distribution network.

Among these four cities from different countries, London and Luleå still have the biggest and smallest impact for most categories which probably due to they have the most and the least electricity demand respectively, resulting from the local temperatures. The most interesting finding is that in climate change human health category, the Finnish city Hamina has more than twice impact of the other locations. By seeking the related processes and environmental load in Simapro, we found that the hydroelectricity generation processes in Finland releases much more methane and carbon dioxide than the other three locations. (See [Appendix Two](#)) Research has shown that even though the hydropower is considered as carbon neutral electricity generation technology, sometimes when creating the dams, large amount of organic matter is composed in the flooded land, methane and carbon dioxide is then emitted from the decomposition of dead biomass and the soil. Because the greenhouse gases emission largely varies depending on the local ecology system, we believe it is the most possible reason to explain why Hamina has surprisingly higher impact than the other cities on climate change impact category. (Huttunen, 2002; Giles, 2006 and Farrø, 2008) (See the comparison of hydropower electricity life cycles in Figure 26 in [Appendix Two](#).)

#### 2.1.4.2.2 Single score result by ReCiPe:

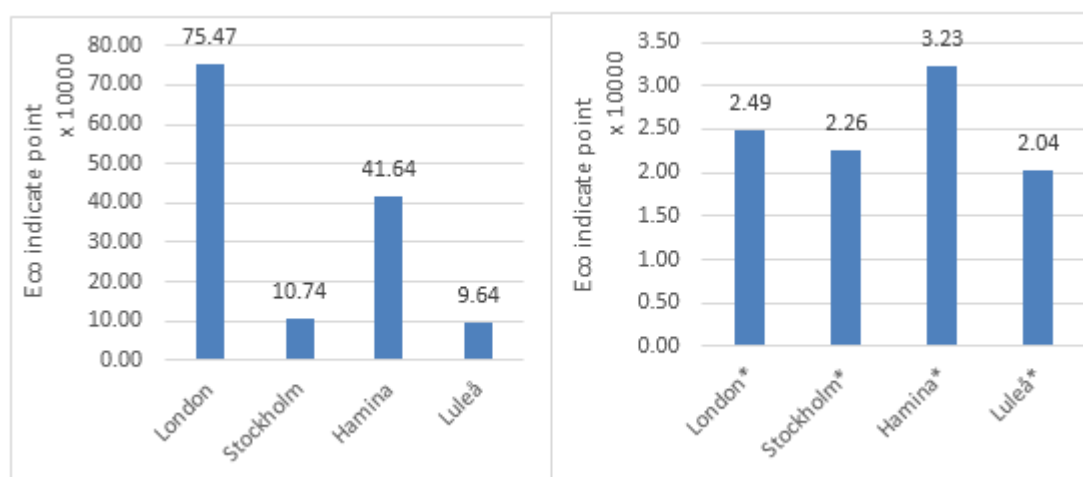
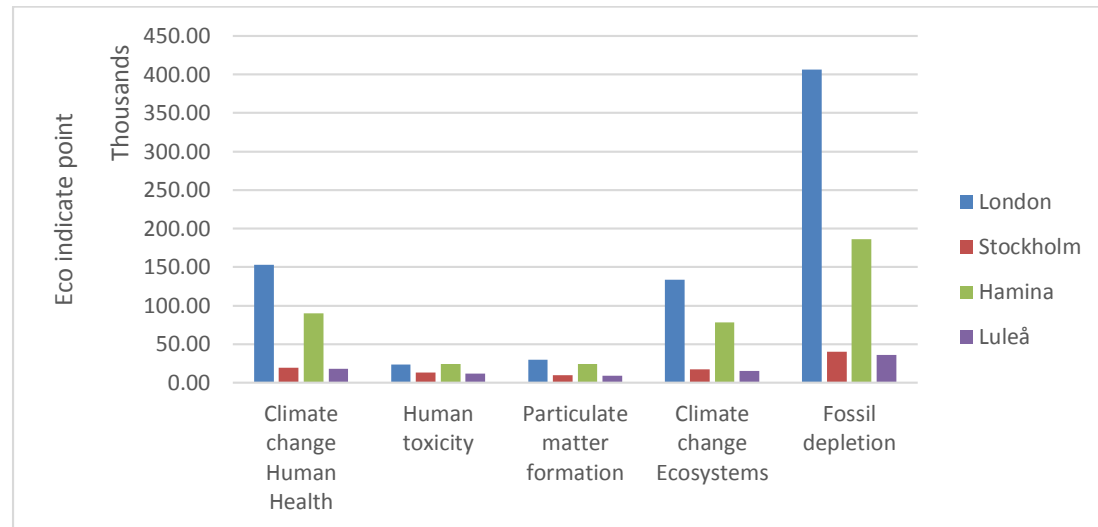


Figure 9 Total environmental impact comparison of four selected locations for the Green Room, using national electricity mix or certified electricity respectively. “\*” represents when the city uses certified electricity.

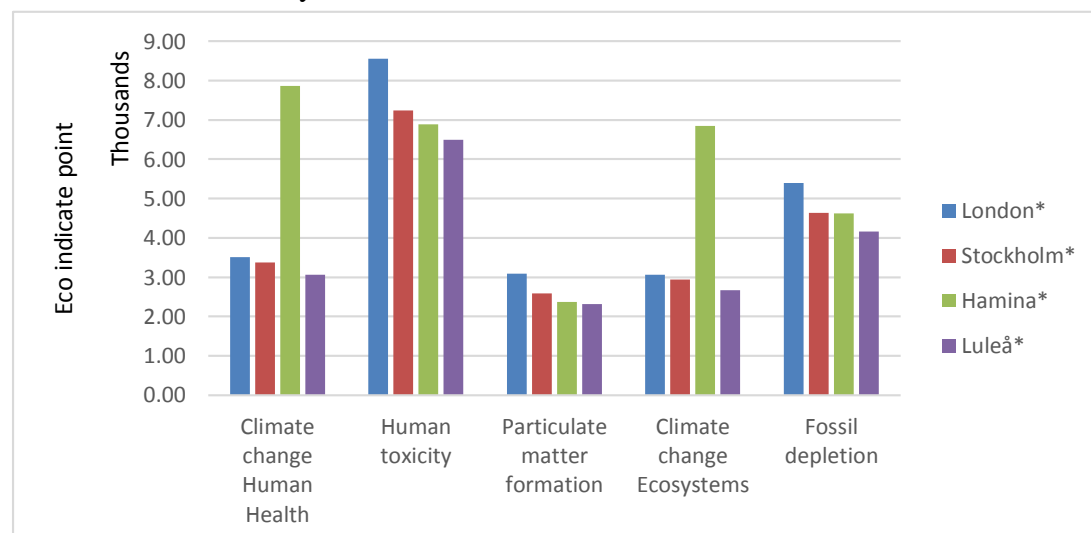
Figure 9 illustrates total environmental impact among the four locations, using different electricity sources. As shown in the left chart in Figure 9, when using traditional electricity mix, the most environmental preferable location is Luleå followed by Stockholm. In contrast, the environmental damage is significant larger

when the Green Room is settled in London. While introducing certified electricity, the environmental impact of the Green Room in each city decreases in various extent, from several times (Luleå) to 30 times (London). The Swedish cities Luleå and Stockholm still become the most environmentally preferable locations; the total impact in Hamina is higher than London when utilizing certified electricity in both cities, as discussed in characterization results, this is probably because more greenhouse gas is emitted from Finnish hydropower plants.



*Figure 10 Detailed environmental impact comparison of four selected locations for the Green Room when using traditional electricity.*

Figure 10 illustrates the environmental impact comparison within top five significant categories: fossil depletion, climate change human health, climate change ecosystems, particulate matter formation and human toxicity. As can be seen, the impact comparison among these four locations in each environmental impact category follow the same sequence: London>Hamina>Stockholm>Luleå. In climate change human health, climate change ecosystems and fossil depletion categories, the impact of both Swedish cities is much lower than Hamina and London, thanks to the nearly fossil free Swedish electricity source mix.



*Figure 11 Detailed environmental impact comparison of four selected locations for the Green Room when using certified electricity*

The Green Room will largely benefit from the renewable certified electricity source in all of the selected cities, as the corresponding environmental impact can be dramatically reduced. (E.g. The fossil depletion in London can be reduced more than 90 %). Similar with the conclusion of comparison of using traditional electricity, in human toxicity, particulate matter formation and fossil depletion, the sequence from the city costing biggest impact to the city costing smallest impact is London\* > Hamina\* > Stockholm\* > Luleå\*. However, in the categories of climate change human health and climate change ecosystem, Hamina is the city having much higher impact than the other cities.

## 2.2 Study Two: The relationship between the environmental performance of the Green Room and its life span

### 2.2.1 Introduction

It has been concluded that the utilization phase predominates the life cycle of the Green Room (Oliveira, 2012). It is therefore not difficult to understand that the overall environmental impact of the Green Room<sup>5</sup> increases with the increasing of its operation time length. (See Figure 12)

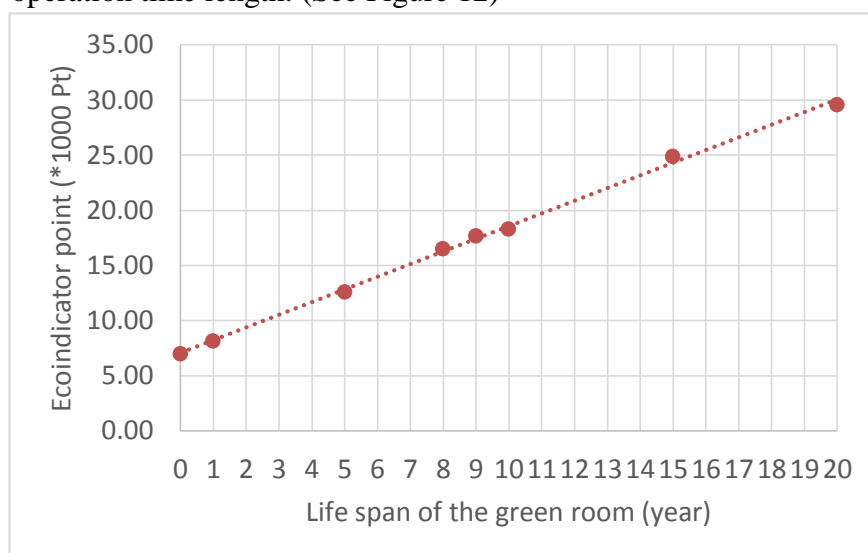


Figure 12 The environmental impact of the Green Room according to the life span.

However, the use phase is certainly not the most significant phase when the Green Room just starts working because the impacts from the extraction phase and transportation phase (from cradle to gate) have been existing before this time point. When will the utilization phase become the most dominate phase during the life time of the Green Room? If the life span of the Green Room is short enough, the most noticeable environmental impact would not be caused by the operation of the Green Room. Thus it would be interesting to study the relationship between the operation

<sup>5</sup> As mentioned in Section 1.3, the “Green Room” in this chapter refers to the site constructed in Stockholm, Sweden, powered by Swedish certified electricity.

time length/life span of the Green Room and the environmental impact of the corresponding life cycle.

### 2.2.2 The investigation procedure:

In order to study the longest time that the extraction and manufacture phase predominate the total environmental impact; and after how many years of running the Green Room, the utilization phase becomes the dominant phase of the total life cycle environmental impact; we selected 8 different lengths of the Green Room's life cycle, 0 year (the extreme situation that the Green Room is completely built up but not be used), 1 year, 5 years, 8 years, 9 years, 10 years, 15 years and 20 years, and accordingly change the amount of electricity consumption and refrigerant r134a emission.

We already know that the extraction and manufacture phase does not change when the construction of the Green Room is finished, and the maintenance of the Green Room and transportation are not taken into account since the corresponding impact is considered as negligible. (Oliveira, 2012) For the simplicity of our study, we assume that the waste treatment technology also does not change over time - the positive contribution of the end of life for total environmental impact is constant. In such case, the total environmental impact of the Green Room would only be affected by the utilization phase which consists of electricity consumption and leakage from the refrigerant r134a.

### 2.2.3 Results

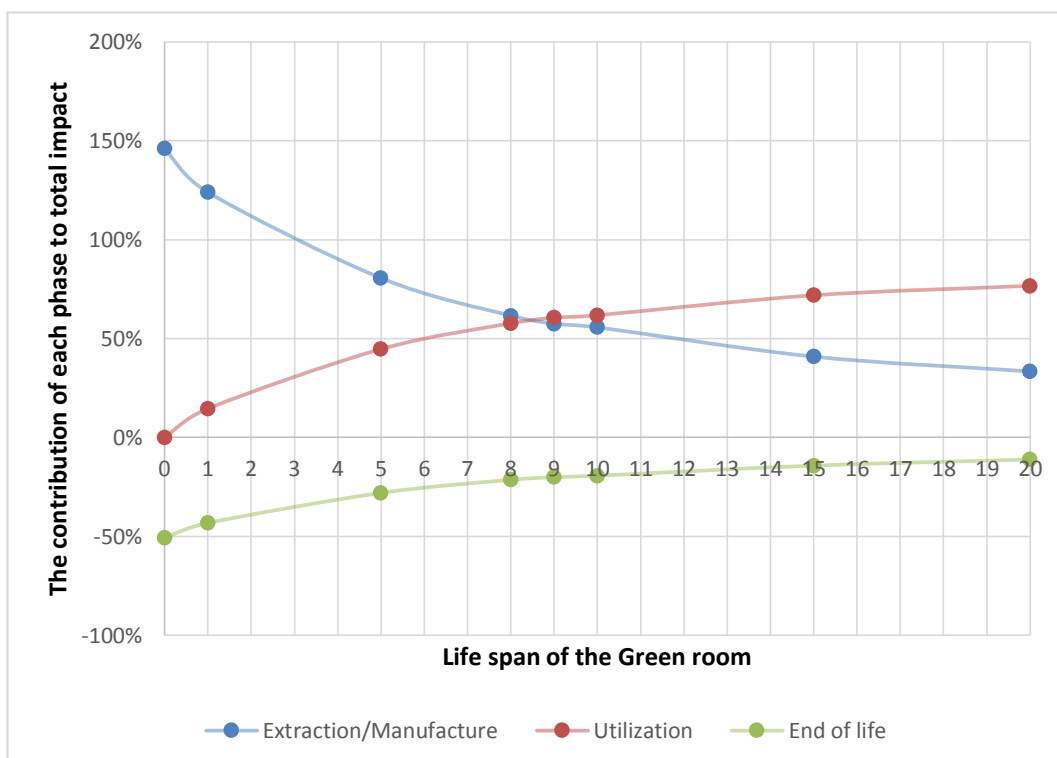


Figure 13 Relationship between the life span and the total environmental impact of the Green Room.

As illustrated in Figure 13, at the starting point - the manufacture phase occupies the biggest share of the total environmental impact since the Green Room has not yet been used. When the operation of the Green Room starts, the share of the environmental impact from extraction/manufacture declines and the share of utilization phase rises with prolonging the life span. When the life span of the Green Room is 8 years, the extraction/manufacture and utilization phase contributes to similar degree to the environmental impact. Then at some point between 8 years and 9 years, the utilization phase eventually becomes the largest in the whole life cycle. This result implies that the impact of the manufacture phase should not be overlooked since it could be the largest as long as the use phase is shorter than 8 years. Replacing some copper components into stainless steel products would reduce the environmental impact on manufacture phase, as discussed by Oliveira (2012). Certainly for long term use, minimizing the impact of the electricity production is still the key to achieve a sustainable cooling solution since the real life span could theoretically be prolonged by the maintenance of the components of the cooling system, according to Teliasonera.

## 2.3 Study Three: Environmental impact comparison of alternative cooling solutions

### 2.3.1 Introduction

*Traditional chiller based cooling* technology is widely used around the world, not only because of the mature and inexpensive technology but also the high cooling efficiency. However, apart from high energy consumption, a significant drawback of this technology is the usage of the refrigerant as many of them are ozone depleting and/or global warming substances. (US Environmental Agency, 2010a)

Since people find that there are natural coolants (cold water, cold air, etc.) that can be utilized for a sustainable cooling technology, the concept of free cooling is being studied. Cold water/air can be easily obtained from nature and used in heat conductors to remove heat from industrial equipment. This technology has been widely utilized for data center cooling. The *geothermal cooling* is also stimulating more and more researchers' interest: the underground of the earth constantly tends to be a certain temperature (around 13°C) at a certain depth (Avedon, 2008) connecting the building and underground in a closed loop can actively exchange the heat from the indoor environment to the earth, bringing coldness from the underground and condition the indoor air. (Enlund, personal communication, 2012a)

However, the application of free cooling is sometimes limited by the local climate conditions. For example, the cold water/cold air may not be available during warm seasons of the year, as we discussed above. Therefore a combination of free cooling and chiller based cooling is considered as reasonable. Take the example of the Green Room currently installed in Stockholm, as described above, the cooling system benefits from the cold sea water but during summer it has to be entirely air conditioned by traditional chillers. Moreover, the combination of seasonal cooling solutions can also be the free air cooling and geothermal cooling: during winter the cold air can be used as cooling resource whereas in warmer seasons, geothermal cooling is introduced as complementary technology.



The goal of this study is to compare the potential environmental impacts between the three cooling solutions – conventional chiller based cooling, combination of sea water cooling and chiller based cooling as well as the combination of indirect free air and geothermal cooling technology. The analysis especially focus on the energy consumption and refrigerant R134a emissions and corresponding damage.

### 2.3.2 Methodology

As mentioned in Section 1.3, the tested “Green Room” example in this chapter refers to the site constructed in Stockholm, Sweden, powered by Swedish certified electricity. Ideally the analysis of the entire life cycle of the Green Room project should be done since the different infrastructure of each cooling technology will surely affect the results especially in the extraction/manufacture phase, however, this study is only focusing on the utilization phase due to 1) Limited time and difficulties to collect raw data of the manufacture phase. 2) The predominance of the utilization phase in the Green Room life cycle.

#### 2.3.2.1 Data collection:

*Table 2 Data used for comparing three cooling solutions in Simapro*

	Energy demand (per year)	Energy demand in 20 years	Leakage of refrigerant R134a
<b>Chiller only</b>	1803MWh	36070MWh	65kg
<b>Sea water+Chiller</b>	418MWh	8357MWh	15kg
<b>Indirect free air +Geo cooling</b>	108MWh	2160MWh	0

All the data used for model modification for this study is listed in Table 2. There are two processes within the utilization phase, the electricity utilization and the R134a emission. The electricity demand of each cooling solution is directly collected from internal references (Enlund, personal communication, 2012b). The data of refrigerant emission from chiller based cooling is calculated based on the leakage of 15kg R134a during 20 years when the combination of sea water cooling and chiller based cooling solution is used. (Oliveira, 2012, p.102) Because the chiller based cooling solution is only used for 12 weeks within a year (52weeks), and there is no refrigerant consumption from sea water cooling; thus if the chiller based cooling is used all the time during the Green Room’s 20 years life span, the *amount of refrigerant R134a emission* can be calculated as:

$$\frac{\frac{15kg}{20years}}{12weeks} * 52weeks * 20years = \frac{15kg}{12} * 52 = 65kg$$

### 2.3.3 Inventory analysis result

In Table 9 in Appendix One some of the most important resource use and emissions during the utilization phase of each cooling solutions are listed. All the

environmental loads in Table 9 except “Ethane, 1, 1, 1, 2-tetrafluoro-, HFC-134a” of the three cooling solutions follows the same ratio (1803:418:108) as the energy demand of these cooling solutions. This is because all of the substances except “Ethane, 1, 1, 1, 2-tetrafluoro-, HFC-134a” (R134a) in this selected result is related to the electricity consumption. One may notice the unexpected existence (very little amount) of “Ethane, 1,1,1,2-tetrafluoro-, HFC-134a” in indirect free air +geo cooling since this option is supposed to be refrigerant free, this emission however from the electricity production processes.

An extra finding from the inventory analysis is the fairly low consumption of nonrenewable resources (crude oil, hard coal, and natural gas) among all of the three cooling solutions showing a promising result of using certified electricity in the overall project as it is almost completely independent on fossil fuel.

### **2.3.4 Environmental impact assessment and discussion**

#### **2.3.4.1 Characterization results by ReCiPe**

The characterization result shows the regularity of the comparison of these three solutions in all the categories. As can be seen in Figure 14, the trend of the environmental impact assessment results is similar to the trend revealed in the inventory results (See Table 9 in Appendix One), the impact of chiller based cooling is approximately 4.3 times higher than sea water+chiller based cooling, 16 times more than indirect free air+geo cooling in all of the selected impact categories - except climate change human health which is approximately 20 times higher instead. This is due to the effect from refrigerant emission as it is known that R134a (HFC-134a; formula:  $\text{CH}_2\text{FCF}_3$ ) has rather high Global Warming Potential (GWP), 1300 times higher than carbon dioxide. (US Environmental protect agency, 2012). On the other hand, the environmental impacts on ozone depletion from each cooling option are minimal since R134a does not contain chlorofluorocarbon (US Environmental protect agency, 2010b), which is its major advantage as a refrigerant.

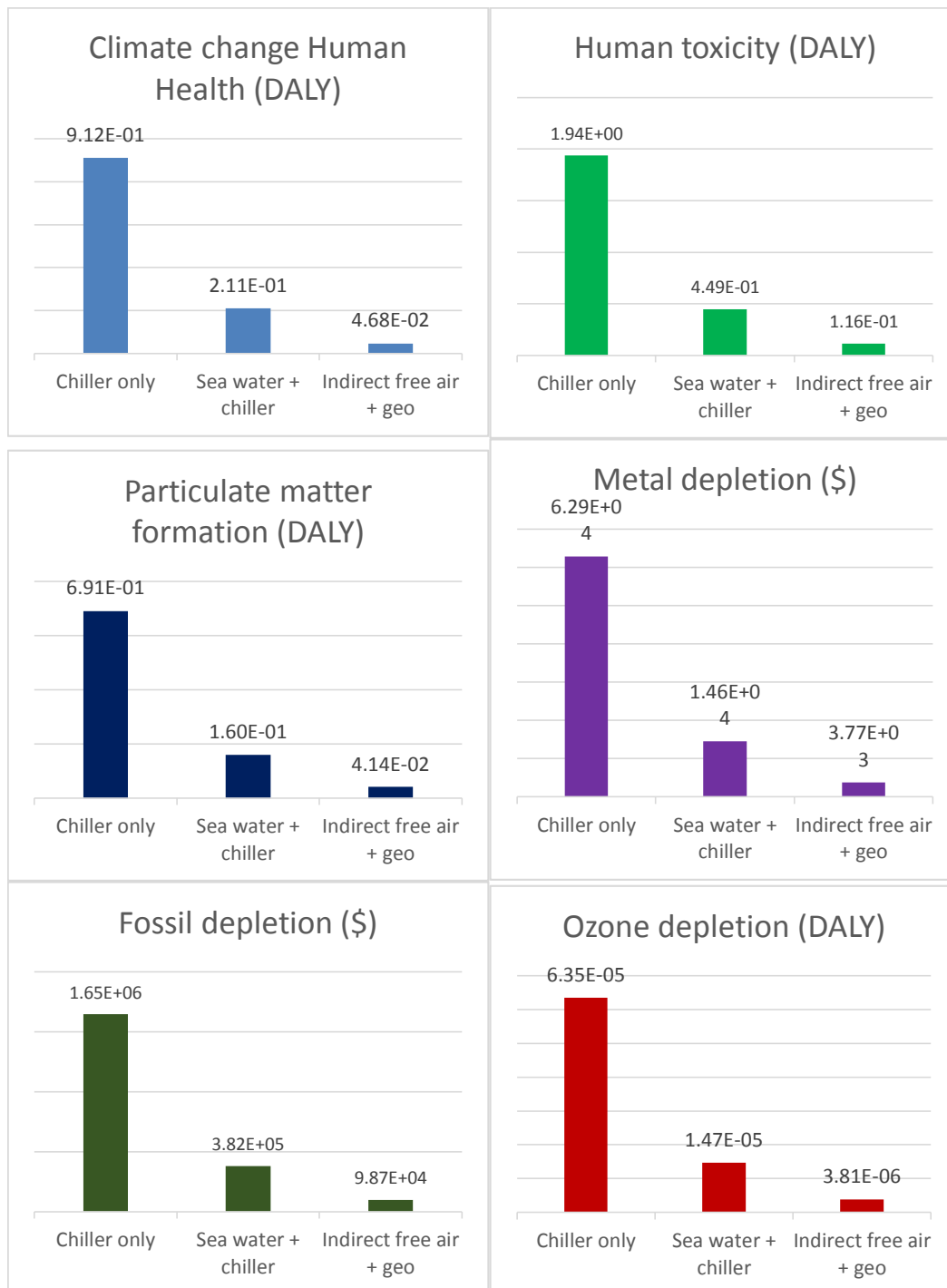


Figure 14 Characterization results comparison of three cooling solutions

### 2.3.4.2 Single score result by ReCiPe

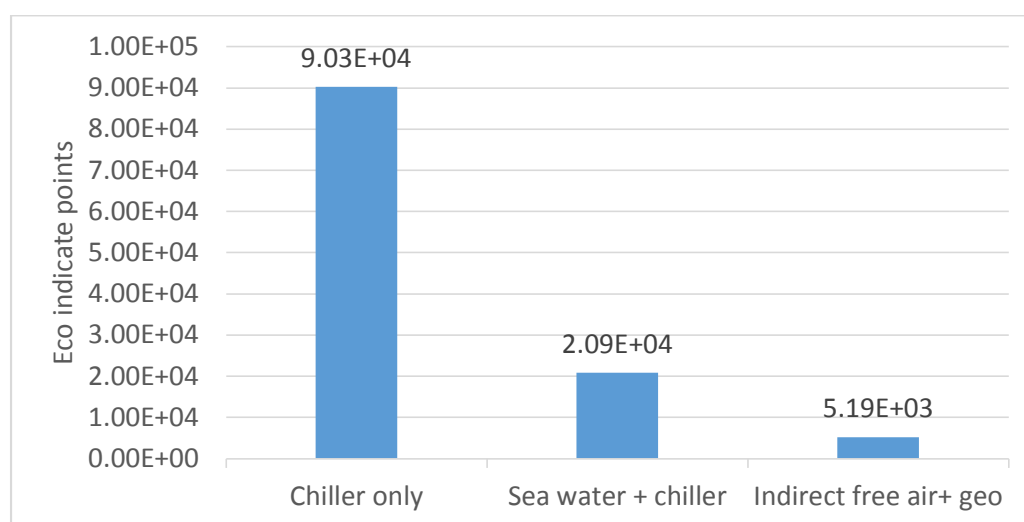


Figure 15 Total Environmental impact comparison of the utilization phase of three cooling solutions, chiller based cooling, combination of sea water and chiller, and combination of indirect free air and geo thermal cooling.

Figure 15 presents the overall environmental impact of each cooling solution during the utilization phase by ReCiPe single score. Similar with characterization results, the total environmental impacts of chiller based cooling solution is 4 times higher than the combination of sea water and chiller cooling, 18 times higher than the combination of indirect free air and geo thermal cooling solution.

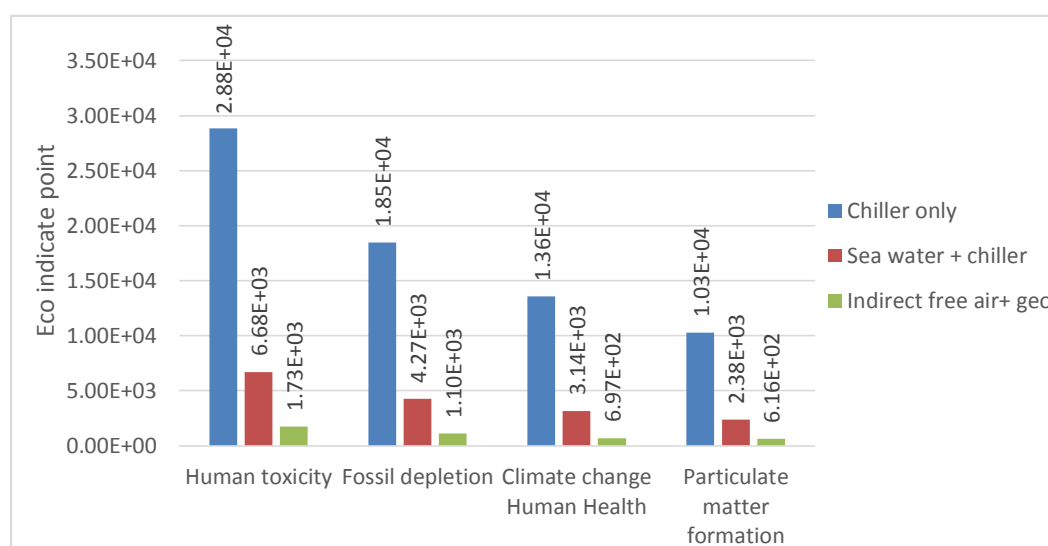


Figure 16 Environmental impact results of three cooling solutions during utilization phase, selected impact categories.

Detailed results in each impact category are presented in Figure 16. As can be seen, when adding weighting factors to the results, human toxicity is revealed as the most important environmental impact category among the three cooling options. As discussed above, the damage to human toxicity mainly comes from the construction of infrastructure power plant and the electricity distribution network, resulting from the emission from extraction/manufacture of metals (e.g. copper). However, we

believe that this result also reflects the advantage of using certified electricity source, as the fossil fuel related damages (e.g. climate change, fossil depletion and particulate matter formation) do not become the highest impacts, which achieves the original purpose of the design of the Green Room.

It appears that the sea water + chiller cooling solution could reduce 75% of the damage to the environment, comparing to the traditional chiller based cooling solution. The indirect free air+ geo cooling solution could even avoid up to 90% of environmental impact among all of the impact categories, thanks to the fairly low electricity demand and no use of any refrigerant. However, it is also important to study the infrastructure/manufacture phase of geo cooling technology in the future. For example, since such technology causes low impact on the environment during the utilization phase, how many years would the manufacture phase be the dominant phase during the life span of the Green Room? Would the manufacture phase turn to be the dominant phase (instead of the utilization phase) during the whole life span of the Green Room? Would the environmental study of geo cooling technology therefore need to be more concentrated on the infrastructure/manufacture phase? How much the expenditure of the infrastructure of the geo cooling technology and would it be covered by the saving on the energy bill?

## **2.4 Study Four: Examining the environmental mitigation when recycling and reusing the waste heat**

### **2.4.1 Introduction**

As there is a huge amount of heat generated from the servers in a data center, there has recently been growing interest in recycling and reusing the waste heat to provide a low carbon footprint yet money saving heat resource for dwellings and offices. The heat can be utilized for helping heating residential buildings, supplying hot water or just sold to local energy market. A research from Intel shows that about USD 250,000 can be saved annually from fuel consumption even if they invested USD168, 000 on constructing the heat recovery system between their data center and the office building. (Intel, 2007) Meanwhile, Microsoft recently initiated the “Data Furnace” concept which suggests to send the servers to end users as a primary heat source besides cloud computing service in order to reduce the total cost of ownership per server. (Jie et al., 2011, p.2) However, those studies tend to focus on the concrete technique and economic benefits rather than the environmental mitigation of such a combined system. There is little research about how much this type of heating solution could reduce the total environmental impact, especially on fossil depletion as well as pollutions - the quantitative study is missing as supportive evidence in current research. Therefore, this study is going to take the Green Room as an example and study the environmental performance of combining the Green Room with a heat recovery system, and compare the result to the traditional technology.

This study is designed as shown in Figure 17 based on information from Teliasonera. (Enlund, personal communication, 2012b) There are two studied systems, each system consists of a data center and a single building. In System1, the data center is using traditional cooling system; the single building uses traditional district heating.

While within the System 2, the Green Room<sup>6</sup> high efficient cooling solution is introduced for data center; and the single building is connected to the Green Room by a heat exchanger which helps recycle and reuse the waste heat generated from the Green Room. In addition, a small amount of district heating is added to the single building as a complement since the waste heat from the Green Room itself is not enough for fulfilling the heating demand of the building.

This study aims to perform a comparative LCA study between System 1 and System 2. Again due to lack of related data and information of the manufacture phase of both systems, the study will only focus on the utilization phase, meaning that the infrastructure and the end of life phase are excluded.

## 2.4.2 Inventory analysis

### 2.4.2.1 Energy use accounting

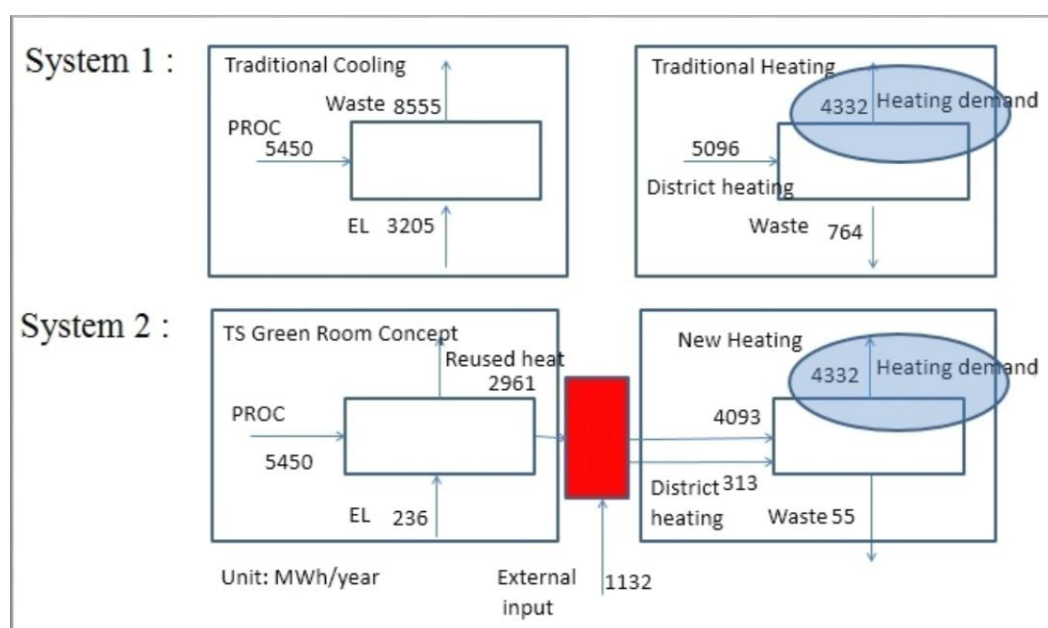


Figure 17 Flow chart of the two studied systems. (Enlund, personal communication, 2012b)

Figure 17 presents the flow chart of the two systems, the data were obtained from internal references. (Enlund, personal communication, 2012b) The initial process load for cooling production is 5450MWh/year. In system 1, the traditional cooling solution needs 3205MWh/year of electricity for operation. 8555 MWh waste heat is generated from this data center every year. At the same time, 5096 MWh/ year of heat is provided to the single building in order to fulfill its 4332MWh/year of heat demand. The heat loss through the single building is 764MWh/year. In system 2, the Green Room only costs 236MWh/year of electricity. The emitted heat is recycled by a heat exchanger (the red box in Figure 17) and then piped to the single building for heating and/or supplying hot water. This process costs 1132MWh/year of extra electricity. In addition, since the total available heat still cannot fulfill the energy demand including

<sup>6</sup> The term “Green Room” here and after in this chapter refers to the site constructed in Stockholm, Sweden.

the heat loss through the single building (4093MWh/year); 313MWh/year of district heating is introduced to fill in the energy gap between the heat supply and demand.

In system 1, the total electricity consumption is

$$5450\text{MWh/year} + 3205\text{MWh/year} = 8655\text{MWh/year}$$

The total district heating consumption is 5096MWh/year

In system 2, the total electricity consumption is

$$5450\text{MWh/year} + 236\text{MWh/year} + 1132\text{MWh/year} = 6818\text{MWh/year}$$

The total district heating consumption is 313MWh/year

Therefore, compared to system 1, the percentage of *electricity* which can be saved by using system 2 is

$$\frac{8655\text{MWh/year} - 6818\text{MWh/year}}{8655\text{MWh/year}} \times 100\% = 21.2\%$$

Therefore, compared to system 1, the percentage of *district heating* which can be saved by using system 2 is

$$\frac{5096\text{MWh/year} - 313\text{MWh/year}}{5096\text{MWh/year}} \times 100\% = 93.9\%$$

Data set for modeling electricity use:

In addition, according to Enlund (personal communication, 2012b) the electricity supporting this combined system is from the common grid in Stockholm, therefore data for Swedish national electricity mix (instead of the certified electricity) is chosen for modeling this project.

Data set for modeling district heating use:

There was no specific data set of Swedish district heating in the databases in Simapro. Thus a process is created especially for this study based on the data for the year of 2010 from the table of energy supplied to district heating by Swedish Energy Agency and Statistics Sweden. (2011 cited in Swedish energy Agency, 2011, p.17)

*Table 3 Energy supply for district heating in Sweden for the year of 2010.*

<b>Energy source</b>	<b>TWh</b>
<b>Oil</b>	4.9
<b>Natural gas including LPG</b>	4.2
<b>Energy coal including coke oven and blast furnace</b>	3.3
<b>Electric boilers</b>	0.1
<b>Heat pumps</b>	5.3
<b>Industrial waste heat</b>	3.8

<b>Waste</b>	11.7
<b>Wood fuels</b>	31.7
<b>Tall oil pitch</b>	0.9
<b>Peat</b>	2.9
<b>Total</b>	68.8

Data source: Swedish Energy Agency and Statistics Sweden, 2011<sup>7</sup>

### 2.4.2.2 Inventory analysis result

The inventory result can be found in Table 10 Appendix One. In general more than half of the total environmental load could be avoided in System 2. For example, as can be seen in Table 10, the Nitrogen oxide<sup>8</sup> would be reduced by as much as 60%. This reduction is mainly due to lower use of district heating where fossil fuels are partly (around 20% of total according to Table 3) used as an energy source.

### 2.4.3 Impact assessment

#### 2.4.3.1 Cumulative energy demand

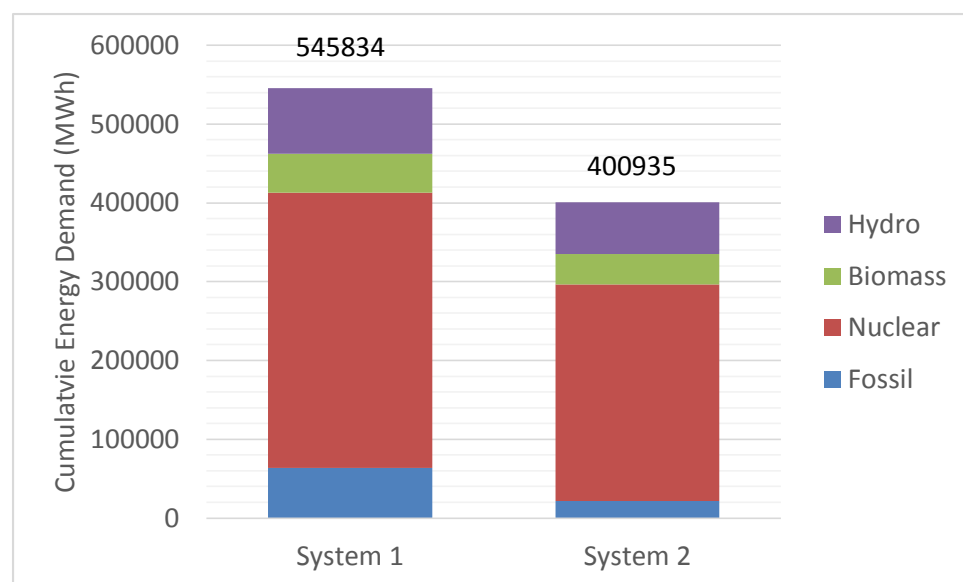


Figure 18 Comparison of cumulative energy demand of the two studied systems

In Figure 18 we can see that when the combination of the Green Room and a single building is in operation, nearly 30% of the cumulative energy demand could be saved compared to when the Green Room cooling system and the heating system of single building are working independently.

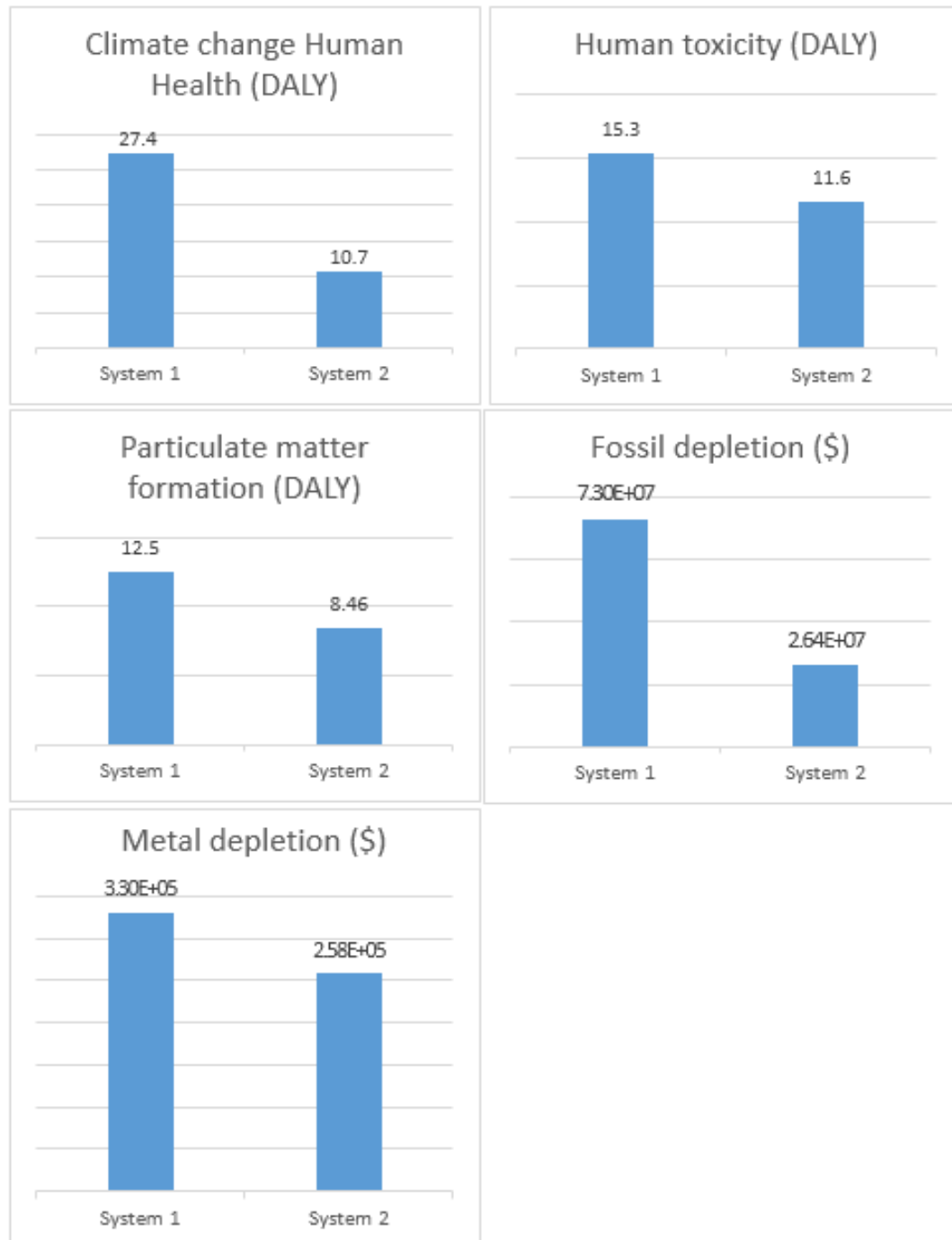
<sup>7</sup> Swedish Energy Agency and Statistics Sweden 2011 cited in Swedish energy Agency, 2011, Table for figure 29: Energy supplied to district heating, 1970–2010, in TWh

<sup>8</sup> Nitrogen oxide is a significant contributor to acid rain, eutrophication and human health damage.



### 2.4.3.2 Life Cycle Impact Assessment by ReCiPe

#### 2.4.3.2.1 Characterization results



*Figure 19 Selected Characterization result of environmental impact comparison of the two studied systems*

Some of the characterization results are shown in Figure 19. The climate change human health and fossil depletion are reduced by more than 60% when the waste heat from the Green Room is reused by the single building (System 2), because less district heating is needed in system 2, and correspondingly less fossil fuel is consumed for heating. The reduction of the combustion of fossil fuel can also avoid the emission of

greenhouse gases. Besides, the impact of human toxicity, particulate matter formation (PM2.5) and metal depletion of system 2 can also be mitigated more than 25%.

2.4.3.2.2 The single score results by ReCiPe

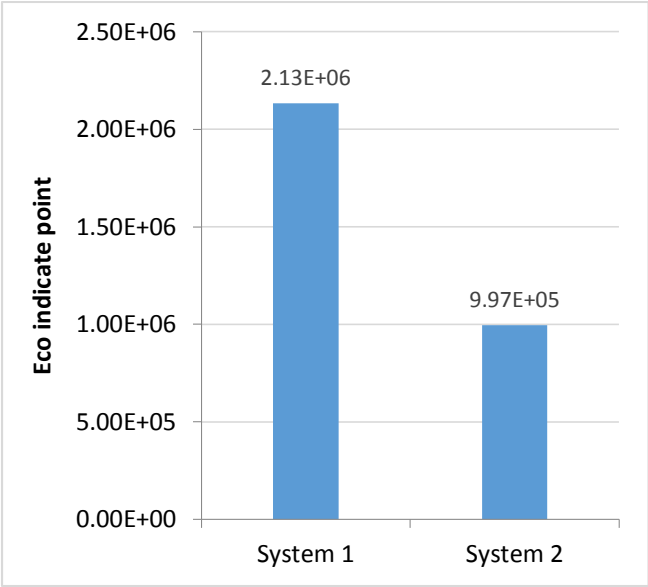


Figure 20 Comparison of total environmental impact of the two studied systems

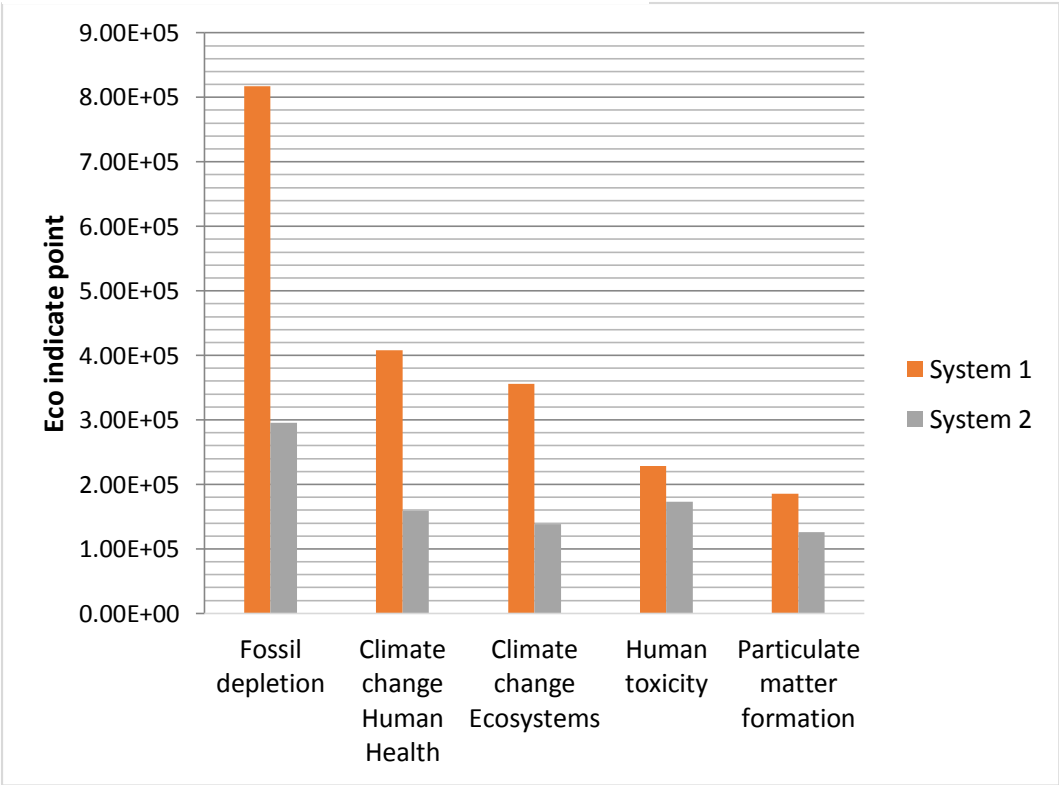


Figure 21 Comparison of environmental impact in selected categories of the two studied systems

Figure 20 and 21 provide overall and detailed environmental impact comparison of these two systems respectively. In general more than half of environmental impact could be mitigated when introducing the heat recovery system between the Green Room and the single building (=System2) instead of a traditional cooling system. Similar with the characterization results, the single score results also show the impact mitigation (more than 60%) on fossil depletion and climate change are the most significant effect when the waste heat from the Green Room is reused for heating a building instead of a traditional cooling system without heat recovery; at the same time, 25% to 30% of mitigations could be attained in human toxicity and particulate formation categories.

## **2.5 Study Five: Impact on the results from the choice of different Life Cycle Impact Assessment (LCIA) methods**

### **2.5.1 Introduction**

There are many LCIA methods available for an LCA study, some methods provide comprehensive environmental assessment of studied object such as CML (Guinée et al., 2002), EDIP (Hauschild & Potting, 2005), EPS (Steen, 1999a, b); some methods just focus on one to several environmental perspectives such as USEtox (Hauschild et al., 2008; Rosenbaum et al., 2008), Cumulative Energy demand (VDI, 1997 & Frischknecht et al., 2004) and Cumulative Exergy Demand. (Bösch et al., 2007) as mentioned in Section 1.1.3, ISO standard requires each LCIA methodology should follow the same framework.

Even if the standard is followed, every LCIA methodology still needs to choose their own way to implement each step and consequently leading to results variation. A typical example is that during the development of the characterization step, the calculations within different LCIA methodologies naturally vary as they reflect developers' knowledge and thoughts on the extremely complex environmental system. Besides, there can be categories missing or incomplete sets of equivalent factors in an LCIA methodology; for instance the characterization factors for resource use, land use and toxic substances are less developed than the emission caused impacts such as global warming and eutrophication. (Baumann & Tillmann, 2004, pp.144-145)

Current research has been focusing on investigating the effect of the choice of LCIA method to LCA results and recommend best LCIA method to LCA practitioner. For example, (Pizzol, 2011) investigated the differences and uncertainties when determining the impact of metals' emission on human health through nine different LCIA methods. They included that the LCA result greatly changes according to the used LCIA method, due to the different calculation methods for the characterization stage of each method. Similar comparison has been done by Zhou et al.(2011) based on a case study of analyzing the environmental impact of Reverse Osmosis (RO) desalination by different LCIA methodologies. Their paper reported that there are minimal variations in the result of "large issues" such as global warming and ozone depletion potential yet significant differences in acidification, eutrophication, human toxicity and other impact categories. Hauschild et al., (2012. pp.6-7) evaluated characterization models on each impact category in most of the existing LCIA methodologies and recommended some best available characterization models both at

midpoint and endpoint. They concluded that most of the recommendations given for midpoint methods can be classified as sufficient, only one recommendation needs to be “applied with caution”. On the other hand, recommendations of best LCIA method at endpoint can only be given for three impact categories, for the rest impact categories the quality of the best available LCIA method is still weak and therefore can only be marked as “interim”, which means it is not recommended by the authors but can be used as an initial basis for further development. (Hauschild et al, 2012, p.2)

In the LCA study of the Green Room, ReCiPe is chosen as the LCIA methodology which is a newly developed LCIA method combining both midpoint and endpoint approach for the midpoint result from ReCiPe has relatively low uncertainty whereas the endpoint interprets the result in a way which is easy to understand although subjective evaluation is involved during the calculation. (Oliveria, 2012, pp.6-7). As a further research of the LCA study of the Green Room, we did an experimental study in order to provide a preliminary picture of how the choice of LCIA methodology would influence its final results<sup>9</sup>. As there is a large number of LCIA methodologies including different impact categories, in order to simplify and specialize our work, the analysis will select resource use impact category and human toxicity impact category from eight LCIA methodologies to compare the assessed results for the impact of the most important processes during the Green Room life cycle on these two impact categories.

## 2.5.2 Methodology

*Table 4 The selected processes and LCIA methodologies.*

	Processes	LCIA methods
<b>Resource Use</b>	Electricity, hydropower	ReCiPe, EPS, CML, EDIP, Cumulative Energy Demand (CED), Cumulative Exergy Demand (CExD)
	Distribution network, electricity, low voltage	
	Copper, at regional storage	
	Chromium steel 18/8, at plant	
<b>Human Toxicity</b>	Copper, at regional storage	ReCiPe, USEtox, USEtox+interim
	Copper product manufacturing, average metal working	

As shown in Table 4, the processes of “Electricity, hydropower”, “Distribution network, electricity”, “Copper, at regional storage”, “Copper product manufacturing, average metal working” and “Chromium steel 18/8, at plant” are selected as the study examples, representing the electricity demand from hydropower plant, the infrastructure of electricity distribution network, copper extraction process at regional storage, copper product manufacturing as well as stainless steel production respectively. The selection of these processes is based on the investigation of process

<sup>9</sup> The corresponding results are based on the tested site of “Green Room” located in Stockholm, Sweden and powered by Swedish certified electricity.

contribution analysis results reported from all the selected LCIA methods - these processes are always shown in the top ten influential processes in resource use and human toxicity impact category.

At the same time, ReCiPe, EPS, CML 2001, EDIP, Cumulative Energy Demand(CED) and Cumulative Exergy Demand(CExD) has been chosen as LCIA methods for resource use analysis; while ReCiPe, USEtox and USEtox+interim are selected for human toxicity analysis.

Results from “Process Contribution Analysis” provided by each LCIA method in Simapro are used in our study. Moreover, they are collected from characterization results in order to avoid unnecessary complexities and uncertainties from the optional elements of LCIA method. In addition, the obtained data originally appeared to be difficult to compare since these LCIA methodologies use different units to describe the environmental impacts. Therefore we managed to get the proportion of each process’ contribution in order to make our results comparable: the impact of each selected process is divided by the total impact under each impact category (resource use or human toxicity). The new results were then collected and eventually used for the comparative study.

When comparing resource use categories among considered LCIA methodologies, one problem is that in different LCIA method the resource category is either generalized as one single category such as the “Depletion of Abiotic Resources” category in CML, or divided into different categories by resource types, such as the “Fossil depletion” impact category and “Metal depletion” impact category in ReCiPe. Table 5 provides a guideline showing which of resources categories are comparable in selected LCIA methods. Our comparative study is correspondingly separated into three parts: the comparison of results for fossil depletion among ReCiPe, CExD and CED; the comparison of results for metal depletion between ReCiPe and CExD; and the comparison of results for abiotic resource depletion among CML, EPS and EDIP. For comparison of results for human toxicity, there is only one single category for human toxicity in ReCiPe while in both of the two versions of USEtox human toxicity is divided into two categories - Cancer and Non-cancer (See Table 6). In order to make the two versions of USEtox methods comparable to ReCiPe, the impacts of Cancer and Non-cancer are added together within each version of USEtox method, the new result is then used to represent the impact for entire “Human toxicity” which is corresponding to the result of human toxicity category in ReCiPe.

*Table 5 Resource categories in ReCiPe, CML, EPS, EDIP, CExD and CED*

	ReCiPe	CML	EPS	EDIP	CExD	CED
<b>Fossil depletion</b>	Yes				Yes	Yes
<b>Metal depletion</b>	Yes				Yes	
<b>Only one single category for abiotic resource depletion</b>		Yes	Yes	Yes		

Table 6 Human toxicity categories in ReCiPe, USEtox and USEtox+interim

	ReCiPe	USEtox	USEtox+interim
<b>Cancer</b>		Yes	Yes
<b>Non-cancer</b>		Yes	Yes
<b>Only one single category for human toxicity</b>	Yes		

## 2.5.3 Results

### 2.5.3.1 Comparison of resource use impact categories

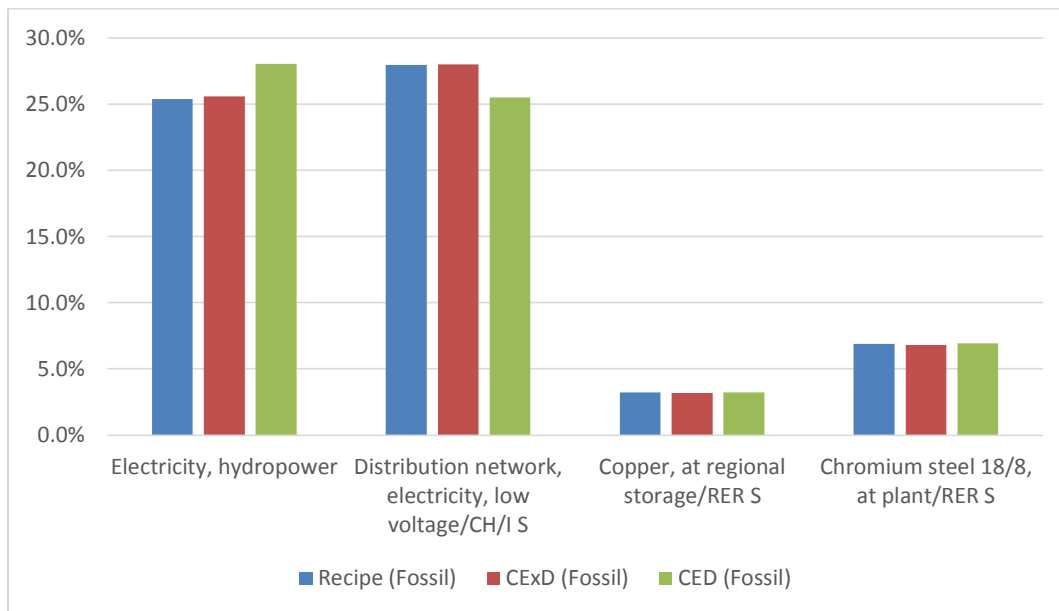


Figure 22 Comparison of the impact on fossil depletion from four selected processes, calculated by three different LCIA methodologies (ReCiPe, CExD and CED).

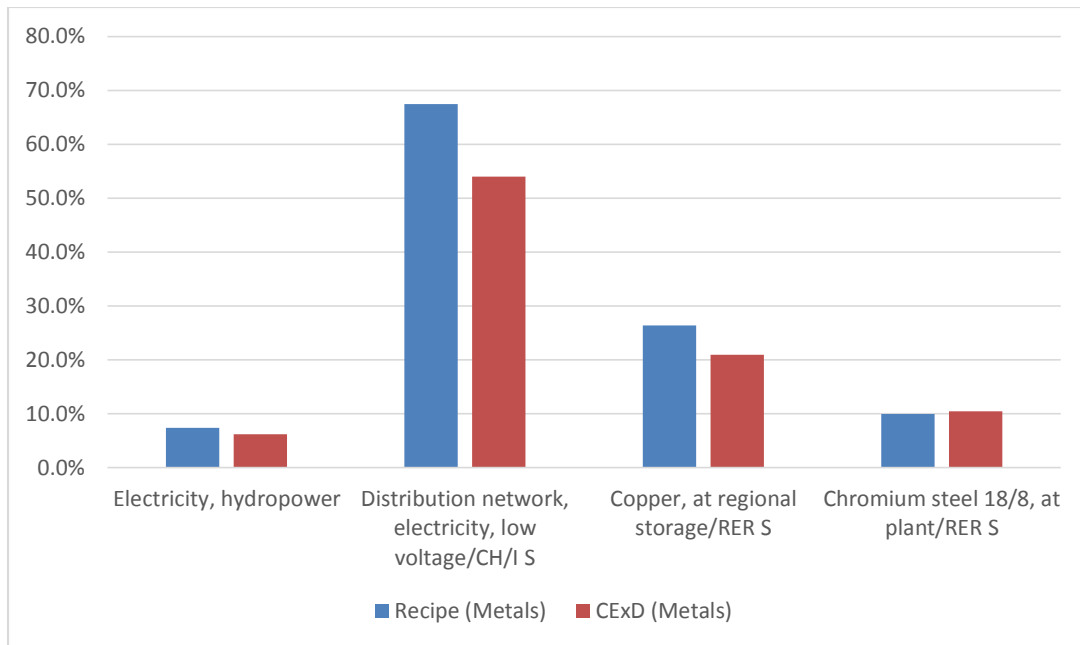


Figure 23 Comparison of the impact on metal depletion from four selected processes, calculated by two different LCIA methodologies (ReCiPe and CExD).

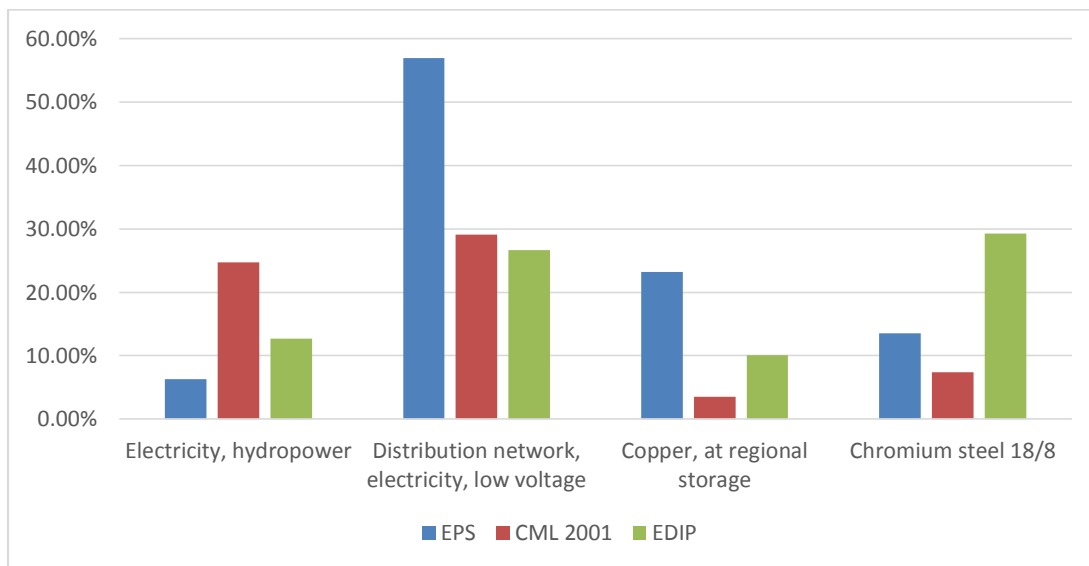


Figure 24 Comparison of the impact on resource use from four selected processes, calculated by four different LCIA methodologies (EPS, CML and EDIP).

The comparison of impact on the fossil depletion among the results reported by ReCiPe, CExD and CED is presented in Figure 22. With the exception of the small differences in “Electricity, hydropower” and “Distribution network, electricity” between CED and the other two methods, the results of fossil depletion impact category from these three methods are almost the same. Besides fossil depletion, a comparison of the impacts on metal depletion under ReCiPe and Cumulative Exergy demand methodologies is also made as shown in Figure 23. For the evaluation of the impact on metal depletion, ReCiPe tends to “give” more scores to the processes “Distribution network, electricity” and “Copper, at regional storage” than CExD, while presents similar results as CExD to “Electricity, hydropower” and chromium

steel production processes. The results comparison of impact on resource use calculated by EPS, CML and EDIP is illustrated in Figure 24. It can be seen from the chart that the results of the impact of same processes on resource use calculated by different LCIA methodologies may not be similar. For example, EPS values “Distribution network, electricity” as a significant dominant (57%) process in the life cycle of the Green Room on resource depletion, which is almost two times the results of the other LCIA methods. The same trend can also be found in the process “copper, at regional storage”, which has a much higher contribution to the total impact according to EPS than the results from the other methodologies. On the other hand, the EPS method gives the process “Electricity, hydropower” a much lower result - only half as much as the result from EDIP and one fourth as much as the results given by CML. In addition, according to EDIP, chromium steel production contributes the most of the impact on resource use; while the process causing the most significant impact on resource use is “Distribution network, electricity” according to EPS and CML.

### 2.5.3.2 Comparison of human toxicity impact categories

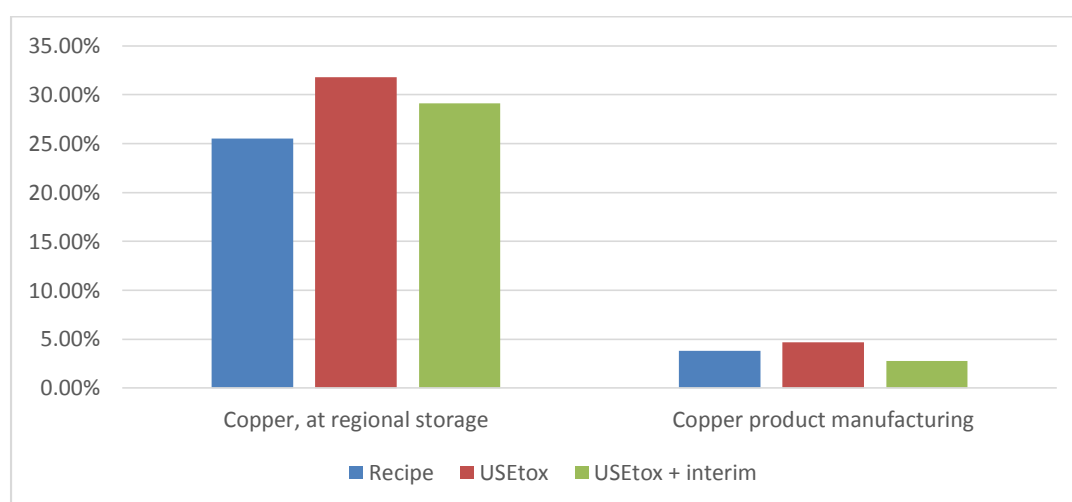


Figure 25 Comparison of the impact on human toxicity from two selected processes, calculated by three different LCIA methodologies (Recipe, USEtox and USEtox interim).

The results of the impact on human toxicity varies only in a small range among these three methods (See Figure 25). The impact of the two copper production processes suggested by ReCiPe is approximately 20% lower than the results from USEtox. While the results from USEtox+interim are a bit more “uncertain”, as the impact of “copper, at regional storage” is just slightly lower (8%) than the result given by USEtox but the result of “copper product manufacturing” is 40% lower than USEtox.

### 2.5.4 Discussion

In this study, the selected life cycle assessment methodologies provide similar results in most of the cases except the comparison of resource use result provided among CML, EPD and EDIP.

Although a Life Cycle Impact Assessment methodology contains impact category definition, classification, and characterization, normalization, grouping and weighting steps, this study only includes the mandatory steps as the results used are collected



from characterization step in order to avoid the uncertainty caused by subjectivity during grouping and weighting has been initially excluded in order to simplify our comparative analysis.

When assigning the inventory results into impact categories in the classification step, a factor causing result variety is that different LCIA methodologies tend to include different number of substances in the same impact category/criteria which leads to different aggregate impact under the impact category results (Pizzol et al., 2011). For example, many types of metals are not included in USEtox due to the lack of confirmed description and quantification of the impact of those metals on human toxicities but are counted in USEtox+ interim model with high uncertainties caused by the limited/not fully proved information about their toxicity on human health. (Rosenbaum et al., 2008, pp.532-546) Since the impact of each process in our study is divided by the total impact in a certain impact category in order to get their corresponding proportion to the total impact in each impact category, this factor would inevitably affect the final results. Another important factor causing the result difference is, as mentioned in previous text, when defining characterization factors during the characterization step, different mathematic models are chosen by difference LCIA methods. This could be one of the major reason for the relatively large result difference in the comparative study among EPS, CML and EDIP.

Although this experimental study shows how the choice of LCIA methods effects the final results of the LCA study, from those data we are still not able to determine which LCIA method is most suitable for the Green Room project. We suggest assess the LCA model by different LCIA methodologies for a more comprehensive and objective understanding of the project. In addition, Hauschild et al (2012, pp.6-7) recently evaluated the most common LCIA methods used in current LCA research and recommended best available characterization models for different impact categories. (See Appendix Five) Even though there are still some limitations on their results, their conclusion may be seen as a basis for the choice of LCIA methodology in the future.

### **3 Conclusion and Limitations**

This exploratory study offers some insight into several aspects of the “Green Room Concept” - a cooling system design for data centers and its possible extensions from environmental point of view. The conclusions in Study 2, Study 3 and Study 5 are drawn from the study based on the existing site of the Green Room which is located in Stockholm and powered by Swedish certified electricity; while the conclusions in Study 1 and Study 4 are based on the simulation of the Green Room installed in other locations and/or powered by other type of electricity sources.

First of all, the location comparison in Study 1 indicates that the local climate as well as local electricity sources could fundamentally influence the environmental performance of the Green Room. Study 2 shows that the green innovation on manufacture phase of the Green Room should not be ignored. In the case of the Green Room site installed in Stockholm and powered by Swedish certified electricity, the utilization phase only becomes the environmentally most important phase between the eighth and the ninth year after start using the Green Room. In Study 3 the “natural

coolant” is confirmed as a key for sustainable cooling innovation since it could substantially reduce both energy consumption and environmental impact (including the damage from refrigerants), especially the geo cooling technology. Further studies regarding the manufacture phase of geo cooling technology from both environmental and economic aspects are suggested. Study 4 shows that recycling and reusing the waste heat from the ICT equipment in the Green Room can be transformed into a new carbon neutral heating resource to the municipality. In addition, the uncertainty caused by choice of the LCIA methodologies for the Green Room LCA study itself was discussed in Study 5.

The major restriction of this study is the lack of data, which led to most of our analysis only focus on the utilization phase instead of the overall life cycle. Therefore, there are a few points worthy to explore more in the further. For instance during the cooling solutions comparison in Study 3, different infrastructures of the chiller based cooling, free water/air cooling and geo cooling could make the impact of their corresponding manufacture phases substantially different from each other. This is also the case for the heat recovery system discussed in Study 4. If the manufacture phase of the “linking part” (i.e. the heat exchanger and pipes and tubes) between the Green Room and the building can be also included into our model, the final interpretation of its environmental performance will be more complete.

## Appendixes

### Appendix One: Inventory results

*Table 7 Selected inventory results of the Green Room location comparison, when using each country's conventional electricity mix.*

Compounds	Unit	London	Sthlm	Hamina	Luleå
<b>Emissions to air</b>					
CO2	ton	6.84E+03	8.22E+02	3.91E+03	7.38E+02
SO2	Kg	1.59E+04	2.47E+03	8.35E+03	2.22E+03
NOx	Kg	1.26E+04	2.39E+03	7.25E+03	2.15E+03
PM2.5	Kg	1.27E+03	1.25E+03	2.64E+03	1.12E+03
CH4	Kg	1.44E+04	1.93E+03	1.08E+04	1.73E+03
<b>Emissions to water</b>					
Manganese	kg	2.08E+03	8.60E+02	1.86E+03	7.71E+02
<b>Resource use</b>					
Coal	ton	2.45E+03	2.21E+02	1.16E+03	1.98E+02
Natural Gas	m3	1.10E+06	5.40E+04	3.60E+05	4.80E+04
Oil	ton	1.07E+02	4.04E+01	4.23E+01	3.62E+01
Uranium	Kg	6.09E+01	1.09E+02	5.71E+01	9.81E+01

*The choice of the results consist of most common environmental loads, largest environmental loads and particularly problematic environmental loads.*

*Table 8 Selected inventory results of the Green Room location comparisons, when using each country's certified electricity mix.*

Compounds	Unit	London*	Sthlm*	Hamina*	Luleå *
<b>Emissions to air</b>					
CO2	ton	1.00E+02	8.79E+01	1.34E+02	7.88E+01
SO2	Kg	8.94E+02	7.59E+02	7.31E+02	6.81E+02
NOx	Kg	5.24E+02	4.48E+02	4.38E+02	4.02E+02
PM2.5	Kg	2.47E+02	2.08E+02	1.95E+02	1.87E+02
CH4	Kg	1.89E+02	1.63E+02	1.62E+02	145.7
<b>Emissions to water</b>					
Manganese	kg	6.30E+02	5.33E+02	5.07E+02	4.78E+02
<b>Resource use</b>					
Coal	ton	2.07E+01	1.76E+01	1.72E+01	1.58E +01
Natural Gas	m3	7.80E+03	6.60E+03	6.60E+03	5.90E+03
Oil	ton	1.07E+01	9.20E+00	9.32E+00	8.30E+00
Uranium	Kg	4.00E-01	4.00E-01	4.00E-01	3.00E-01

*Cities with \* represents certified electricity is utilised for the Green Room. The choice of the results consist of most common environmental loads, largest environmental loads and particularly problematic environmental loads.*

*Table 9 selected inventory results for three cooling solutions, based on eco invent databases and collected data for Green Room project.*

<b>Compound</b>	<b>Unit</b>	<b>Chiller only</b>	<b>Sea water+chiller</b>	<b>Indirect free air+ geo</b>
<b>Emissions to air</b>				
Carbon dioxide, fossil	ton	350	81.1	21
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	kg	65	15	0.00179
Particulates, < 2.5 um	kg	828	192	49.6
<b>Emissions to water</b>				
Manganese	kg	2.12E+03	492	127
Arsenic, ion	kg	27.9	6.47	1.67
<b>Resource use</b>				
Oil, crude, in ground	ton	36.8	8.52	2.2
Coal, hard, unspecified, in ground	ton	70.3	16.3	4.21
Gas, natural, in ground	m3	2.64E+04	6.12E+03	1.58E+03

*Table 10 selected inventory results of the comparison between the separated system and combined system in Study Four.*

		<b>System 1 (Separated system)</b>	<b>System 2 (Combined System)</b>
<b>Emissions to air</b>			
Carbon dioxide, fossil	ton	1.49E+04	6.48E+03
Nitrogen dioxide	ton	81.4	30.2
Sulphur dioxide	ton	46.3	22.2
PM2.5	ton	41.3	18.7
<b>Resource use</b>			
Coal	ton	2.69E+03	1.12E+03
Natrual gas	m3	1.03E+06	3.99E+05

## Appendix Two: Hydropower in Finland, UK and Sweden

Table 11 Carbon dioxide and methane emissions comparison in hydropower electricity generation among Finland, UK and Sweden. Functional Unit: 1MJ of electricity. Data source: ecoinvent database

	Unit	Finland	UK	Sweden
Carbon dioxide, biogenic	mg	20.4	13	15
Methane, biogenic	mg	298	0.00831	15.9

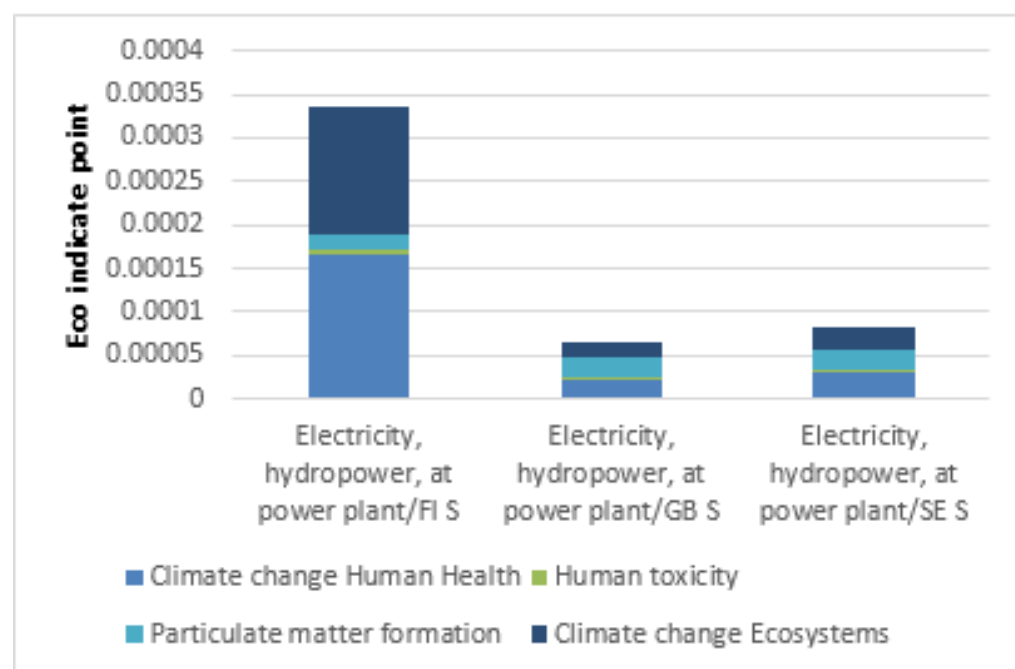


Figure 26 Comparison of environmental impact of hydroelectric power generation. Functional Unit: production of 1 MJ of electricity.

## Appendix Three: The used data in Study Five

*Table 12 Comparison of results of resource depletion in ReCiPe, EPS, CML and EDIP; the raw data from Simapro*

	<b>ReCiPe</b>	<b>EPS</b>	<b>CML</b>	<b>EDIP</b>
<b>Unit</b>	\$	ELU	kg Sb eq	kg
<b>Electricity, hydropower</b>	1.50E+05	9.72E+04	212	51.9
<b>Distribution network, electricity, low voltage/CH/I S</b>	1.76E+05	8.92E+05	2.49	109
<b>Copper, at regional storage/RER S</b>	2.37E+04	3.60E+05	0.298	41.4
<b>Chromium steel 18/8, at plant/RER S</b>	4.22E+04	2.09E+05	0.631	120
<b>Total</b>	<b>6.05E+05</b>	<b>1.55E+06</b>	<b>857</b>	<b>409</b>

*Table 13 Comparison of results of resource depletion in ReCiPe, EPS, CML and EDIP; in percentage*

	<b>ReCiPe</b>	<b>EPS</b>	<b>CML</b>	<b>EDIP</b>
<b>Electricity, hydropower</b>	24.8%	6.3%	24.7%	12.7%
<b>Distribution network, electricity, low voltage/CH/I S</b>	29.1%	57%	29.1%	26.7%
<b>Copper, at regional storage/RER S</b>	3.9%	23.2%	3.5%	10.1%
<b>Chromium steel 18/8, at plant/RER S</b>	7.0%	13.5%	7.4%	29.3%

*Table 14 Comparison of results of resource depletion in ReCiPe, CExD and CED; the raw data from Simapro*

	<b>ReCiPe</b>		<b>CExD</b>		<b>CED</b>	
	Fossils	Metals	Fossils	Metals	Fossils	Metals
<b>Unit</b>	\$	\$	MJ	MJ	MJ	(N/A.)
<b>Electricity, hydropower</b>	1.49E5	1.36E3	3.94E5	4.06E4	4.29E5	(N/A.)
<b>Distribution network, electricity, low voltage/CH/I S</b>	1.64E5	1.24E4	4.31E5	3.54E5	3.9E5	(N/A.)
<b>Copper, at regional storage/RER S</b>	1.88E4	4.86E3	4.91E4	1.37E5	4.91E4	(N/A.)
<b>Chromium steel 18/8, at plant/RER S</b>	4.04E4	1.83E3	1.05E5	6.87E4	1.06E5	(N/A.)
<b>Total</b>	<b>5.87E5</b>	<b>1.84E4</b>	<b>1.54E6</b>	<b>6.56E5</b>	<b>1.53E6</b>	<b>(N/A.)</b>

*Table 15 Comparison of results of resource depletion in ReCiPe, CExD and CED, in percentage*

	<b>ReCiPe</b>		<b>CExD</b>		<b>CED</b>	
	Fossils	Metals	Fossils	Metals	Fossils	Metals
<b>Electricity, hydropower</b>	25.4%	7.4%	25.6%	6.2%	28.0%	(N/A.)
<b>Distribution network, electricity, low voltage/CH/I S</b>	27.9%	67.4%	28.0%	54.0%	25.5%	(N/A.)
<b>Copper, at regional storage/RER S</b>	3.2%	26.4%	3.2%	20.9%	3.2%	(N/A.)
<b>Chromium steel 18/8, at plant/RER S</b>	6.9%	9.9%	6.8%	10.5%	6.9%	(N/A.)

*Table 16 Comparison of results of Human toxicity in ReCiPe, USEtox and USEtox interim, the raw data from Simapro*

	<b>ReCiPe</b>	<b>USEtox</b>		<b>USEtox interim</b>	
		Cancer	Non Cancer	Cancer	Non Cancer
<b>Unit</b>	DALY	CTUh	CTUh	CTUh	CTUh
<b>Copper, at regional storage</b>	1.64E-1	2.15E-7	3.94E-4	6.79E-3	9.94E-2
<b>Copper product manufacturing</b>	2.43E-2	2.13E-7	5.74E-5	1.13E-3	1.47E-2
<b>Total</b>	<b>6.42E-1</b>	<b>2.78E-5</b>	<b>1.21E-3</b>	<b>1.49E-1</b>	<b>4.25E-1</b>

*Table 17 Comparison of results Human toxicity in ReCiPe, USEtox and USEtox interim, in percentage.*

<b>LCIA method</b>	<b>ReCiPe</b>	<b>USEtox</b>	<b>USEtox + interim</b>
<b>Copper, at regional storage</b>	25.5%	31.8%	29.1%
<b>Copper product manufacturing</b>	3.8%	4.7%	2.8%

## **Appendix Four: The LCIA methodologies discussed in Study Five**

EPS (Environmental Priority Strategies in product design) (Steen B, 1999a,b) is a methodology aiming being a tool for a company's internal product development. In other words, the model and data in EPS could be used to help improve the environmental performance of a product rather than for environmental protection strategies for a substance. Its abiotic depletion result contains both the impact of mineral and fossil depletion.

CML (Guinée et al, 2002) is a midpoint method developed by the Institute of Environmental Sciences (CML), Leiden University. It is a classic midpoint LCIA method which limit the quantitate modeling at early stages in cause effect chain and thus reduce uncertainties. The impact category “depletion of abiotic resources” has been chosen for our study, containing the extraction of minerals and fossil fuels. (kg antimony equivalents/kg extraction)(Pre product ecology consultants 2008, p.29)

EDIP (Environmental Design of Industrial Products, in Danish UMIP) (Hauschild et al, 2005) is a Danish LCIA method aiming at providing a better characterization model for non-global impact categories. Like CML, EDIP is also a midpoint LCIA methodology.(Pre product ecology consultants 2008, p.33)

ReCiPe (Goedkoop et al., 2009) is a Life Cycle Impact Assessment method recently being developed by Institute of environmental sciences (CML) and PR éconsultant from the Netherlands. It aims for providing a combination of midpoint and end point approach, which make users free to choose and make the results from both approach under consistent model and principles. This is an important reason for the choice of LCIA methodology for the original the Green Room LCA study.

Cumulative Energy Demand (CED) (VDI, 1997 & Frischknecht et al, 2004) is often considered as a complement indicator to an LCA study as it only concerns the demand of energy source. (Karim, 2011, p.57) However, since it quantifies the direct and indirect energy use from all type of energy source (both nonrenewable and renewable) during the life cycle, it is especially suitable for our study of which the energy consumption is a crucial part of the whole life cycle.

Cumulative Exergy Demand (CExD) (Bösch et al, 2007) is a parameter depicting “total exergy removal from nature to provide a product, summing up the exergy of all resources required.” (Bösch et al. 2007, p.1) The exergy includes the minimal work that needs to be done when forming a resource or the maximal energy that can be obtained when bring a resource component to its most common statues in nature. Apart from the energy intensive material such as fossil fuels, nuclear, biomass, water, even wind and solar; the biggest advantage of CExD comparing to CED is the inclusion of minerals and metals since they also contain some amount of obtainable energy- the exergy. This feature of CExD makes itself comparable to resource indicators in ReCiPe and other comprehensive LCIA methodologies.

USEtox (Hauschild et al., 2008; Rosenbaum et al., 2008) is an LCIA methodology developed by UNEP/SETAC Life Cycle Initiative, aiming to provide “globally preferred” characterization model for human and eco toxicity. There are thus two



versions of USEtox available in Simapro: the USEtox recommended and the USEtox recommended + interim.<sup>10</sup>

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<sup>10</sup> According to the level of reliability of the calculations in a qualitative way, substances included in USEtox are divided into two groups: a) recommended characterization factors, which only includes highly reliable characterization factors, and therefore exclude some important substances such as metals. b) Interim characterization factors, which still have relatively high uncertainty; metals, dissociating substances are all defined in this group.

## Appendix Five: Best available characterisation models of LCIA methodologies suggested by Hauschild et al (2012, pp6-7)

*Table 18 Best available characterization models at midpoint*

<b>Impact category</b>	<b>Best among existing characterization models</b>	<b>Indicator</b>	<b>Classification</b>
<b>Climate change</b>	Baseline model of 100 years of the IPCC	Radiative forcing as global warming potential (GWP100)	I
<b>Human toxicity, cancer effects</b>	USEtox model	Comparative toxic unit for humans (CTUh)	II/III
<b>Human toxicity, non-cancer effects</b>	USEtox model	Comparative toxic unit for humans (CTUh)	II/III
<b>Particulate matter/respiratory inorganics</b>	Compilation in Humbert (2009) based on Rabl and Spadaro (2004) and Greco et al. (2007)	Intake fraction for fine particles (kg PM2.5-eq/kg)	I/II
<b>Resource depletion, mineral and fossil</b>	CML 2002	Scarcity	II

Models that are classified as level I, II, or III are recommended under the ILCD. A mixed classification is related to the application of the classified method to different types of substances.

*Table 19 Best available characterization models from midpoint to endpoint*

<b>Impact category</b>	<b>Best among existing characterization models</b>	<b>Indicator</b>	<b>Classification</b>
<b>Climate change</b>	Model developed for ReCiPe	Disability Adjusted Life Years (DALY) for human health Potentially disappeared fraction of species (PDF m3 year) for ecosystem health	Interim
<b>Human toxicity, cancer effects</b>	DALY calculation applied to USEtox midpoint	DALY	II/interim
<b>Human toxicity, non-cancer effects</b>	DALY calculation applied to USEtox midpoint	DALY	Interim
<b>Particulate matter/Respiratory inorganics</b>	Adapted DALY calculation applied to midpoint	DALY	I/II
<b>Ionizing radiation, human health</b>	Frischknecht et al. (2000)	DALY	Interim
<b>Resource depletion, mineral and fossil</b>	Method developed for ReCiPe	Surplus costs	Interim

Only the models classified above interim are recommended under the International Reference Life Cycle Data System (ILCD).

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