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Faculty of Graduate Studies

Life Cycle Assessment of Water Heating Systems Used in Health Clubs

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Dedication

I dedicate this humble work to all the researchers who are striving the make the lives of humans more sustainable and safe; those who struggle to help the coming generations in having an Earth that is capable of fulfilling their needs.

Acknowledgments

After thanking God who has blessed me and helped me in going through this experience, I thank the following people for all the support they have provided throughout this journey:

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May God bless them with health, happiness, and the realization of their dreams.

إقرار

أنا الموقع أدناه مقدم الرسالة التي تحمل عنوان: **تقييم دورة حياة أنظمة تسخين المياه لاستعمالات نادي رياضي.**

أقر أن ما اشتملت عليه الرسالة هو نتاج جهدي الخاص، باستثناء ما تمت الإشارة إليه حيثما وردوأن هذه الرسالة أو أي جزء منها لم يقدم من قبل لنيل أي درجة أو لقب علمي أو بحثي لدى أي مؤسسة بحثية أو علمية أخرى.

اسم الطالب: **علي محمد علي عباس**

التوقيع :

التاريخ : **18.11.2015**

Declaration

The work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification.

Student's Name: **Ali M. Abbas**

Signature:

Date: **18.11.2015**

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List of Symbols

C_p	Specific Heat
g	Gradient Rate
i	Interest Rate
$\dot{m}$	Mass Flow Rate
n	Number of Years
q	Heat Capacity
T	Temperature

List of Abbreviations

AC	Air Conditioning
ADF	Abiotic Depletion Factor
AP	Acidification Potential
CML	Center of Environmental Science of Leiden University
COP	Coefficient of Performance
DV	Diminishing Value
EQA	Environment Quality Authority
GSHP	Ground Source Heat Pump
GWP100	Global Warming Potential for Time Horizon 100 years
HTP	Human Toxicity Potentials
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
kWh	Kilo Watt Hour
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
MEA	Ministry of Environmental Affairs
MWh	Mega Watt Hour
NP	Nutrification Potential
OC	Operating Cost
PA	Positional Analysis
PENRA	Palestinian Energy and Natural Resources Authority
POCP	Photochemical Ozone Creation Potential
PW	Present Worth
RF	Run Fraction
SV	Salvage Value
WMO	World Meteorological Organization

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Abstract

Commercial water heating systems are known for their high-energy consumption and high environmental effects.

This study compares between three heating systems suggested for an average health club in the city of Nablus, Palestine. The study took into consideration the daily hot water needs for the health club. Three water heating systems are considered which are electric boiler, heat pump, and gas fired boiler. The reason behind choosing the above mentioned systems is its availability and feasibility in local market.

A cradle to grave boundary limits has been adopted in this research, and the functional unit is 8 m^3/day at 43 °C. However, the Center of Environmental Science of Leiden University (CML) life cycle impact assessment (LCIA) method has been implemented due to its reliability and accuracy in such applications. It classifies the environmental effects into ten main clusters. Moreover, the study includes life cycle costing (LCC) analysis by using the

present worth value and assuming the minimum attractive rate of return to be 10% per year.

The study reveals that the heat pump system is the least energy consumptive during its life cycle, then the gas boiler, and the electric boiler is relatively the worst. However, from economic point of view, the cost of operating such systems consists mainly of its initial cost. Results show that heat pump system has the lowest LCC with 102,684 USD, then the gas fired boiler with 167,428 USD, and the worst system from LCC point of view is the electric boiler with 246,433 USD. In contrast, CML method results show that the gas boiler is considered the most environmental friendly; the heat pump comes second, followed by the electric boiler.

Finally, two scenarios of sensitivity analysis were performed. The first one consists of operating electric boiler and heat pump by electricity produced using natural gas instead of coal, however, results show that the gas boiler remained the most environmentally friendly. The second scenario assumed neglecting environmental impacts of transmission lines, transformers, and distribution lines, while retaining coal as a source of electricity production. Results show that the impacts of transmission lines and transformers are significant, but again, the gas-fired boiler remains the most environmental friendly.

Chapter One
Introduction

1.1 General Background

Sustainability is the ability to meet the needs of the present generations without compromising the ability of future generations to meet their own needs**.** It has become a global issue recently that there are limits to the availability of non-renewable resources and that there are limits to the nature's ability to absorb wastes. Heating and cooling systems consume the most energy and are the largest source of emissions in the entire life cycle of a house. [1]. Accordingly, studying such systems is of great importance before choosing and applying such systems in any residence/institute, so as to achieve greatest efficiency of the chosen system, with the least possible cost [2].

Several concepts and tools for achieving more sustainable products have been developed. The tools include but are not limited to environmental impact assessment (EIA), strategic environmental assessment (SEA), life cycle assessment (LCA), positional analysis (PA), cost–benefit analysis (CBA), material intensity per unit service analysis (MIPS), total material requirement analysis (TMR), ecological footprint (EF), energy analysis, energy analysis and risk assessment. Whereas the energy is used in operating a building, the energy-based tools are applied [3-7].

A product's life cycle starts with the extraction of raw material from the earth in order to create the product, till the return of all materials to the Earth. Life-cycle assessment (LCA), also known as life-cycle analysis, eco balance, and cradle-to-grave analysis) is a technique to assess environmental impacts associated with all the stages of a product's life from-cradle-to-grave (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling); hence providing a comprehensive picture of the environmental aspects of the product or process [8].

While LCA assesses the consumption of thermal systems, it also allows for the researcher to compare different systems’ environmental impact, cost efficiency, and effect on humans and their health [9].

1.2 Problem Statement

Despite the high dependence on electric boiler to heat the water for domestic use due to the low initial cost of this system. However, it does not seem the best possible option. Therefore it is important to re-evaluate water heating systems considering the environmental and economic effects of each system through a correct scientific methodology. In this study, three water heating systems, namely electric boiler, heat pump and gas boiler, are environmentally-compared using the life cycle assessment (LCA) tool.

1.3 Significance of The Study

The importance of the study comes from the fact that it researched different water heating systems, which has not been studied before. The amount of water to be heated on a daily basis, as well as appropriate temperatures were chosen. Three heating systems were then chosen to heat the water up, after which those three systems were evaluated in terms of their Life Cycle assessment.

1.4 Objectives of The Study

- Sizing of three water heating systems, to achieve the most effective operation conditions.
- Hold a comparison between the energy consumed by electric boiler, heat pump , and gas boiler over their life cycle.
- Compare between such systems from economic point of view.
- Study the environmental impact for each system during it’s life cycle.

1.5 Thesis Organization

The works done in this thesis are summarized in five chapters as follows:

Chapter 1: Introduction

This chapter discusses the objectives of this study, and then explains life cycle assessment (LCA), and water heating systems principles.

Chapter 2: Literature Review

This chapter discusses several studies were found to have been conducted to study different systems using LCA process.

Chapter 3: Methodology

This chapter presents mechanical, economical, and environmental analysis that adopted to get the results.

Chapter 4: Results and Discussion

This chapter comments the results obtained, and interprets what the results mean. Starting with the energy consumption results, than the financial results, and finally environmental results.

Chapter 5: Conclusions and Recommendations

This chapter includes a critical commentary covering the results of the study, and the most important recommendations .

1.6 Life Cycle Assessment

Life cycle assessment (LCA) was developed more than 30 years ago as a tool for analyzing environmental issues. It may be used as an instrument for information and planning, for uncovering the "weak points" in the life cycle of products and services as well as for comparison of possible alternatives. The LCA provides a single scale to evaluate the various environmental effects. Results of an LCA help decision-makers choose the best product or process in terms of impact on the environment [10]. LCAs provides a wide perspective on environmental effects through:

- “Compiling an inventory of relevant energy and material inputs and environmental releases;
- Evaluating the potential impacts associated with identified inputs and releases;
- Interpreting the results to help make a more informed decision.”

The LCA process is a systematic approach that consists of four stages: goal definition and scoping, inventory analysis, impact assessment and interpretation [10], which is the approach to be adopted by this research, as will be detailed in the Methodology Chapter.

1.6.1 Elements of Life Cycle Assessment

An internationally accepted framework for LCA methodology is defined in ISO standards 14040 and 14044. These standards define the generic steps which have to be taken when conducting an LCA[11].

Four different phases can be distinguished:

1.6.1.1 Goal and Scope Definition

Goal definition and scoping is the phase of the LCA process that defines the purpose and method of including life cycle environmental impacts into the decision-making process[11].In this phase, the following items must be determined: the type of information that is needed to add value to the decision-making process, how accurate the results must be to add value, and how the results should be interpreted and displayed in order to be meaningful and usable [12].

1.6.1.2 Inventory Analysis

A life cycle inventory (LCI) is a process of quantifying energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire life cycle of a product, process, or activity [11].

In the life cycle inventory phase of an LCA, all relevant data is collected and organized. Without an LCI, no basis exists to evaluate comparative environmental impacts or potential improvements. The level of accuracy and detail of the data collected is reflected throughout the remainder of the LCA process.

Life cycle inventory analyses can be used in various ways. They can assist an organization in comparing products or processes and considering environmental factors in material selection. In addition, inventory analyses can be used in policy-making, by helping the government develop regulations regarding resource use and environmental emissions [12].

1.6.1.3 Impact Assessment

The impact assessment translates the results of the inventory analysis into environmental impacts (e.g. global warming, ozone depletion, acidification, depletion of resources, eutrophication etc.). The aim of this phase is to evaluate the significance of potential environmental impacts [11,12].

1.6.1.4 Interpretation

Life cycle interpretation is a systematic technique to identify, quantify, check, and evaluate information from the results of the LCI and the LCIA, and communicate them effectively. Life cycle interpretation is the last phase of the LCA process[12].

ISO has defined the following two objectives of life cycle interpretation:

- Analyze results, reach conclusions, explain limitations, and provide recommendations based on the findings of the preceding phases of the LCA, and to report the results of the life cycle interpretation in a transparent manner.

• Provide a readily understandable, complete, and consistent presentation of the results of an LCA study, in accordance with the goal and scope of the study [12].

These four phases can be represented as shown in Fig.2.1

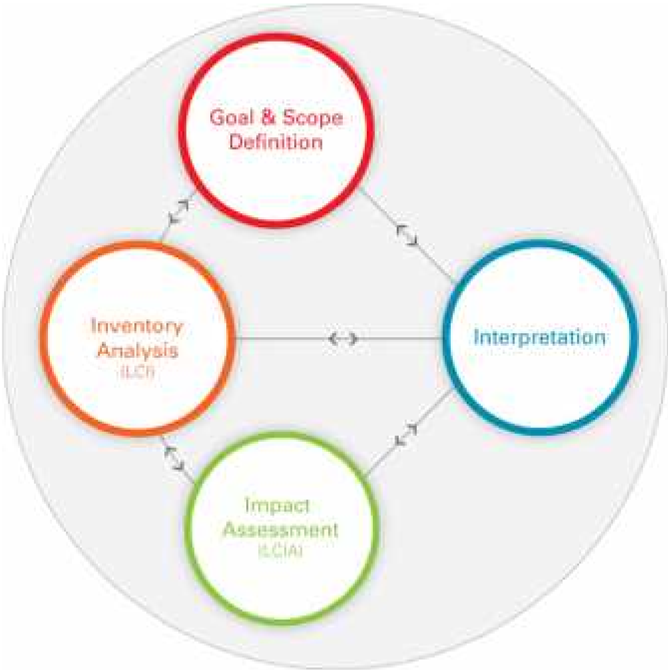

Fig.2.1 Life cycle assessment (LCA) phases (Source: Life Cycle Association of New Zealand)

1.6.2 Life Cycle Impact Assessment Methods

Life cycle impact assessment (LCIA) converts 'inventoried' flows into simpler indicators. In an LCIA, essentially two methods are followed: a problem-oriented method (mid-points) and a damage-oriented method (end points)[13]. In the problem-oriented approaches, flows are classified into environmental themes to which they contribute. Themes covered in most LCIA studies are greenhouse effect (or climate change), natural resource depletion, stratospheric ozone depletion, acidification, photochemical ozone creation, eutrophication, human toxicity and aquatic toxicity. These methods aim at simplifying the complexity of hundreds of flows into a few environmental areas of interest. The damage-oriented methods also start by classifying a system's flows into various environmental themes, but they model the damage of each environmental theme according to its effect on human health, ecosystem health or damage to resources [14].

CML 2001, Cumulative energy demand, Cumulative exergy demand, Eco-indicator 99, Ecological footprint, Ecological scarcity 1997 and 2006, Ecosystem damage potential (EDP), EPS 2000, IMP ACT 2002+, IPCC 2001, ReCiPe (Midpoint and Endpoint approach), TRACI, and USEtox are methods that have been developed by environmental research centers to calculate impact assessment results. CML baseline has been used in this study.

1.6.3 CML Method

CML (Center of Environmental Science of Leiden University)proposed a set of impact categories and characterization methods for the impact assessment step. The impact assessment method implemented as CML-IA methodology is defined for the midpoint approach. There are two version of CML method: a 'baseline' method with 10 impact categories; and an extended method with 'all impact categories' including other impact categories. In this study baseline method is used [14,15].

These baseline indicators are category indicators at "mid-point level" (problem oriented approach)" and are presented below:

1. Depletion of Abiotic Resources

This impact category is concerned with protection of human welfare, human health and ecosystem health. This impact category indicator is related to extraction of minerals and fossil fuels due to inputs in the system. The Abiotic Depletion Factor (ADF) is determined for each extraction of minerals and fossil fuels (kg antimony equivalents/kg extraction) based on concentration reserves and rate of de-accumulation. The geographic scope of this indicator is at global scale [14].

2. Climate Change

Climate change can result in adverse affects upon ecosystem health, human health and material welfare. Climate change is related to emissions of greenhouse gases to air. The characterization model as developed by the Intergovernmental Panel on Climate Change (IPCC) is selected for development of characterization factors. Factors are expressed as Global Warming Potential for time horizon 100 years (GWP100), in kg carbon dioxide/kg emission. The geographic scope of this indicator is at global scale [14,16].

3. Ozone Layer Depletion

Because of ozone layer depletion, a larger fraction of UV-B radiation reaches the earth surface. This can have harmful effects upon human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles and on materials. This category is output-related and at global scale. The characterization model is developed by the World Meteorological Organization (WMO) and defines ozone depletion potential of different gasses (kg CFC-11 equivalent/ kg emission). The geographic scope of this indicator is at global scale. The time span is infinity [14,16].

4. Human Toxicity

This category concerns effects of toxic substances on the human environment. Health risks of exposure in the working environment are not included. Characterization factors, Human Toxicity Potentials (HTP), are calculated with USES-LCA, describing fate, exposure and effects of toxic substances for an infinite time horizon. For each toxic substance HTP's are expressed as 1,4-dichlorobenzene equivalents/ kg emission . The geographic scope of this indicator determines on the fate of a substance and can vary between local and global scale [14,16].

5. Fresh Water Aquatic Eco-toxicity

This category indicator refers to the impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water and soil. Eco-toxicity Potential (FAETP) are calculated with USES-LCA, describing fate, exposure and effects of toxic substances. The time horizon is infinite Characterization factors are expressed as 1,4-dichlorobenzene equivalents/kg emissions. The indicator applies at global/continental/ regional and local scale [14].

6. Marine Eco-toxicity

Marine eco-toxicity refers to impacts of toxic substances on marine ecosystems.

7. Terrestrial Eco-toxicity

This category refers to impacts of toxic substances on terrestrial ecosystems.

8. Photo-oxidant Formation

Photo-oxidant formation is the formation of reactive substances (mainly ozone) which are injurious to human health and ecosystems and which also may damage crops. This problem is also indicated with “summer smog”. Winter smog is outside the scope of this category. Photochemical Ozone Creation Potential (POCP) for emission of substances to air is calculated with the UNECE Trajectory model (including fate), and expressed in kg ethylene equivalents/kg emission [14,16].

9. Acidification

Acidifying substances cause a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems and materials (buildings). Acidification Potential (AP) for emissions to air is calculated with the adapted RAINS 10 model, describing the fate and deposition of acidifying substances. AP is expressed as / kg emission. The time span is eternity and the geographical scale varies between local scale and continental scale [14,16].

Characterization factors including fate were used when available. When not available, the factors excluding fate were used (In the CML baseline version only factors including fate were used). The method was extended for Nitric Acid, soil, water and air; Sulphuric acid, water; Sulphur trioxide, air; Hydrogen chloride, water, soil; Hydrogen fluoride, water, soil; Phosphoric acid, water, soil; Hydrogen sulfide, soil, all not including fate. Nitric oxide, air (is nitrogen monoxide) was added including fate [14-16].

10. Eutrophication

Eutrophication (also known as nutrification) includes all impacts due to excessive levels of macro-nutrients in the environment caused by emissions of nutrients to air, water and soil. Nutrification potential (NP) is based on the stoichiometric procedure of Heijungs (4292), and expressed as equivalents per kg emission. Fate and exposure are not included, time span is eternity, and the geographical scale varies between local and continental scale [14,16].

1.7 Water Heating

Water heating can account for more than 20%of commercial building's energy use in US[17]. That means that there are significant environmental impacts resulting from this process.

1.7.1 Water Heating Methods

A hot water heating can be defined as an installation of one or more water systems, plus the associated cold and hot water plumbing, which can supply hot water to one or a number of outlets. This definition is general, and covers many types of water heating. Water heating methods is generally divided into [18]:

1.7.1.1 Instantaneous Water Method

The instantaneous unit is designed to heat water only at the time it is being used, rather than relying on any form of storage. Instantaneous water systems are normally connected directly to mains water supply. When a hot tap is opened, the flow of water activates a valve or switch causing gas or electricity to flow to heat the water as it passes through the system; this stops when the hot tap is closed. An integral water governor controls the flow rate of the water to the hot taps. These units can be single point heaters, as in a bath heater, or multipoint, supplying several outlets [17-20].

1.7.1.2 Storage Water Method

A storage unit is designed to hold a useful quantity of hot water in a thermally insulated container ready for immediate use. As hot water is used, cold water enters the storage tank to replace it. Reheating continues after the flow of hot water has ceased. These units can be designed either to store and supply hot water at mains pressure, or to store water at atmospheric pressure and distribute it by means of gravity. Again, this water system can be single point water system (e.g. sink water heaters) or multipoint water system. These are also known as "direct storage" units [18].

1.7.1.3 Heat Exchange - Coil Method

This type of unit consists of a heat exchanger, usually in the form of a coil of copper tubing immersed in a thermally insulated container of static heated water. Cold potable water, at mains pressure, passes through the heat exchanger and picks up heat from the stored water. The stored water is then reheated to bring it back to its original temperature. These are sometimes referred to as "indirect storage" units [17, 18, 20, 21].

1.7.1.4 Heat Exchange - Calorifiers Method

Similar to coil heaters, except the location of the heating water and potable water are reversed. Hot water, generated by some remote appliance, passes through a heat exchanger immersed in a container of stored potable water. The stored water, heated by the heat exchanger, is drawn off when a hot tap is opened. The remote supply of hot water (which is often circulated through the heat exchanger by a pump), can be provided by a water-heating appliance (i.e. a boiler), or can be waste heat recovered from some other process. This type of hot water production is usually confined to commercial or industrial uses [18, 21].

1.7.2Hot Water Systems

The systems are specified according the fuel type used to operate them or by technology used to produce them. The systems, which are used to be analyzed in this study, are:

1.7.2.1 Electric Boiler

Water in this boiler is heated as it passes through the water heater and then passes into an insulated storage tank. Circulation may be done by natural convection but is more frequently pumped. Commercial water heaters are used where large quantities of hot water are required[19]. A.O. Smith commercial electric Water boiler with heat capacity of 73 kW is used in this study[18].

1.7.2.2 Air to Water Heat Pump

Heat pump water heaters use electricity to move heat from one place to another instead of generating heat directly. Therefore, they can be three to four times more energy efficient than conventional electric resistance water heaters. To move the heat, heat pump works like a refrigerator in reverse [20]. AQUACIAT2 ILDH 300V air to water heat pump with heat capacity of 72 kW is used in this study[22,23].

1.7.2.3 Gas Boiler

Commercial gas water boiler is a range of instantaneous water heaters designed for commercial and industrial applications, offering high recovery with low storage. Their compact design makes them ideally suited for low ceiling height installations and other applications where space is a premium. Rheem Company produces the boiler use in this study with an impressive 80% thermal efficiency, and 73 kW capacity [19].

These systems have been used in this study since they are the most likely to be used in Palestinian market, in comparison to other systems such as diesel boiler or solar thermal system. This based on the survey conducted through out the research.

Chapter Two

Literature Review

2.1 Previous Studies

Several studies have been conducted to study different heating systems using LCA process.

A report by Lahjouji and Kharraz [24] discussed a comparative life cycle assessment for residential heating and cooling systems. This study used Ramallah/Palestine as a model case study, and aims to evaluate the environmental impact of air conditioning a house in Ramallah using conventional technologies (i.e. boiler and air conditioner) versus using Ground Source Heat Pump (GSHP) technology. The research used the Eco indicator 99 to compare between the systems from three different cultural perspectives (individualist, hierarchist, and egalitarian perspective). Further, the study looked at ecosystem quality, human health, and resources as environmental impact categories.

Lahjouji and Kharraz study indicated that the conventional air conditioning system is much higher than the geothermal one in terms of environmental impact. It was further revealed that from an environmental perspective, “the geothermal system for heating and cooling remains always the most favorable option as it has the least environmental impact”[24].

A study conducted by Shah, studied LCA of three residential heating and cooling systems in four regions in the United States of America over a period of 35 years. The systems include warm-air furnace and air-conditioner, hot water boiler and air conditioner, and air–air heat pump.

Simulation and life cycle assessment studies of the systems at four locations in the United States, namely Minnesota, Oregon, Pennsylvania and Texas determine the effect of regional variations in climate, energy mix, and the standard building characteristics on the systems' environmental impacts [1].

The comparison amongst the three systems in the four regions revealed that the boiler and AC system have the largest impacts in association with the appliance and distribution systems. It was also found that in regions where electricity is derived from fossil fuels (in heating and cooling climates), the heat pump displayed the maximum impacts. In such regions, the furnace as well as the AC system were found to perform the best. Moreover, in regions where a large amount of electricity is generated from hydropower (i.e., Oregon), the heat pump demonstrated the lowest impacts.

Another report cited several studies, which compared different energy systems using LCA is the Special Report of the World Energy Council titled as ”Comparison of Energy Systems Using Life Cycle Assessment”. One major study discussed in the report was the European Commission's Externalities of Energy Research Project. This study measured emission, dispersion of pollutants in the environment and the subsequent increase in ambient concentrations. This project studied selected case studies representing coal, lignite, oil, gas, nuclear, hydro and wind; generating more than 60 case studies for fifteen countries and twelve fuel chains. Renewable fuels and sources and nuclear compare favorably. Using new, advanced fossil technologies with higher efficiencies, the environmental performance of fossil fuel use can be improved significantly.

In heating applications, direct use of fuels compares favorably with electric heating based on the same fuels. In combined heat and power production, the efficiency of fuel use is similar to that of direct conversion to heat [8].

Another published paper by Pehnt [25] discussed dynamic life cycle assessment (LCA) of renewable energy technologies. This research paper studied dynamic approach towards the LCA of renewable energy technologies. The research found that the inputs of finite energy resources and emissions of greenhouse gases are notably lower than those of the conventional system for all renewable energy chains.

The research further revealed that the inputs of finite energy resources and emissions of greenhouse gases are much lower than the known conventional system. The relevant environmental impacts of the renewable energy systems amount to a maximum of 20% of an expected future German mix for electricity, a maximum of 15% of the reference mix for heat, and a maximum of 55% of the future diesel car in the case of fuels.[25]. Other findings of this study were that the use of the studied material resources (iron ore, bauxite) is equal or less than that resulting from conventional systems with few exceptions.

Another study by Norwood and Kammen [26], on the LCA for a distributed concentrating solar combined heat and power (DCS-CHP) systems, whilst focusing on effects on economics, global warming potential, and water (both for desalination and water use in operation). A detailed simulation of system performance was done on 1020 sites in the United Stated of America, together with a sensible cost allocation scheme, in order to complete this study[26].

The LCA done in this research confirmed that a solar Rankine CHP system, when compared with other fossil and renewable energy systems, is cost effective. However, there is room for improvement in this system in terms of trough and dish collector systems, as well as development of a low cost expander for use with steam as the working fluid. Further results of this research confirmed that the DCP-CHP rates amongst the best electric power generation systems as it minimizes water use in the maintenance and operation of the plant. Moreover, the LCA of the embodied water in the manufacture of a concentrating solar system, which uses primarily common metals and glass in simple manufacturing processes, promises to be insignificant, even in comparison to the water use in operation [26].

However, Norwood and Kammen stressed on the fact that using DCS-CHP in desalinating water is only economical and efficient in areas where water is very scarce or moderately expensive, primarily available through the informal sector, and where contaminated, or salt water is easily available as feed-water. Additionally, the cost of fossil fuels would have to be greater than DCS-CHP solar energy for the economics to favor solar desalination [26].

Another research conducted by García et al [27], resulted in the paper titled "Remodeling of the heating systems of a sports center based on life cycle assessment. Part II: Solar hybrid system." [27] The researchers used an LCA to study the inclusion of two sets of solar panels, those being a thermal panel, and a photovoltaic one, together with substituting old diesel boiler with natural gas equipment, so as to satisfy the power demands of the installation.

The study found that the supply directly from the grid has the greatest impact, and that the photovoltaic panel displays most efficiency from an environmental point of view. Nevertheless, a hybrid system proved to be the best option when the solar irradiation was insufficient for the needs of a health club. Similarly, the use of thermal panels along with natural gas boilers is a good choice to provide up to the heat demands of a sports center.

As affirmed by Shah et al. in order for a researcher to make an objective conclusion with regards to a heating system, it is important to pay specific attention to the methodology of used assessment as well as the assumptions made throughout the research. One needs to study cost, comfort, fuel availability, constructability as well as maintenance, together with the environmental impact, before reaching a decision with this regard [1].

It is also important to keep in mind that like all other assessments methodologies, Life Cycle Assessment too has their limitations. This is mainly due to the fact that subjectivity could play a big role in the nature of choices and assumptions made in the LCA [8]. Further, the comparison between different LCA studies conducted is possible only if we can prove similarity between them in terms of assumptions and the context the different studies have adopted. Accordingly, the world Energy council affirmed that the results of LCA studies should not be use isolation, but as part of a comprehensive process in order to fully understand the picture before making any relative decisions.

Further limitations of an LCA according to the world Energy Report is that it may not necessarily give conclusive answers as to whether one system is better or more efficient in comparison to another. Despite that, the LCA will however provide decision makers with a clearer picture describing the environmental and health impacts relative to each system, whether they occur locally, regionally, or globally, as well as the intensity of each type of impact for each alternative of the studied systems.

Other limitations of using LCA include the facts that performing an LCA can be resource and time intensive. Depending on how much detailed information the users wish to cover in an LCA, gathering the data can be problematic, and the availability of data can greatly impact the accuracy of the final results. Therefore it is important to weigh the availability of data, the time necessary to conduct the study and the financial resources required against the projected benefits of the LCA [8].

Chapter Three

Methodology

3.1 Goals and Scope

3.1.1 LCA Objective

The objective of the Life Cycle Assessment is to compare any two products or services achieving similar functions [28]. The current LCA considers three different water heating systems used in a health club. The first system is a heat pump. The second system is an electric water boiler. The third system is a gas boiler. The heated water is used in showers. Accordingly, the aforementioned systems achieve the same function which is heating service water. The main aim of this study is to determine which of the three systems is the best environmental friendly. It also aims to determine which phase of each system accounts for the highest impact on the environment. A health club in Nablus, Palestine is considered as a case study.

3.1.2 Expected Audience

The results of this LCA can be of great interest and provide valuable insights about conventional and heat pump systems from an environmental, energy consumption, and financial perspective to a large number of stakeholders. Researchers, government agencies like Environment Quality Authority (EQA). Private owners undertaking renovations can also be encouraged to adopt the most environment friendly alternatives. Companies operating in the heat pump sector can use the results of the LCA to gain visibility and attractiveness among potential customers in case the heat pump system is more environment-friendly and economically feasible. The heating systems companies can collaborate with universities and research institutes, which are also potential stakeholders of this LCA, to improve the component/material or the life cycle phase with the most impact on the environment. Although this LCA is country specific (i.e. Palestine), its results can be easily extended to neighboring countries having similar characteristics in terms of weather, geographical location, geological parameters and source of electricity generation. Anyway, this study has been prepared as master degree theses for the MS degree in Clean …. At An –Najah University.

3.2 System Boundaries

3.2.1 Conceptual Boundaries

Four different life cycle phases have been analyzed: construction, transport, operation, and disposal. In other words, it considers material inflow (i.e. land, energy, water) and outflow (i.e. solid waste, air and waterborne emissions) from raw material extraction (i.e. cradle), to use phase, and disposal phase (i.e. grave). The considered systems are essentially metallurgical components that require energy and heat intensive processing, which entails greenhouse gas emissions. To account for this fact, the embodied energy of metallurgical components, the energy required to manufacture the components, is explicitly considered on the LCA. The disposal includes waste treatment, recycling, and land filling. The environmental impact associated with transporting systems and the required components is considered. The environmental impact associated with electricity consumption during the operational phase was explicitly accounted for by multiplying the rated power of components consuming electricity times their total hours of operation. Three systems have a negligible environmental impact associated with their installation phase. Capital goods, storage tanks, and piping materials are considered outside the system boundary and are not accounted for. Fig.3.1, 3.2, and 3.3 show three systems boundaries.

3.2.2 Geographical Boundaries

Although Nablus, Palestine is considered as a case study for the three systems, the geographical boundaries were extended to include countries where some components and systems are manufactured and imported from. The heat pump is produced in France and is shipped directly to Ashdod port in Israel. The electric boiler and gas boiler are produced in USA and are shipped to Ashdod port too. Concerning the electricity used to operate the heating systems it is not generated locally and is imported from a neighboring region. This LCA considers that the electricity used to operate the heating systems is generated from coal.

3.2.3 Systems Boundaries

According to different literature, an average lifetime of the three systems was assumed to be 20 years [24, 28].

3.3 Functional Unit

The objective of this study is to assess and benchmark the environmental impact of heating service water that is used for showers in health clubs in Nablus city using conventional technologies (i.e. gas boiler and electric boiler) and air to water Heat Pump technology. In this LCA study, the functional unit is considered as the amount of hot water at 43 °C, which is used daily by the trainees in a health club.

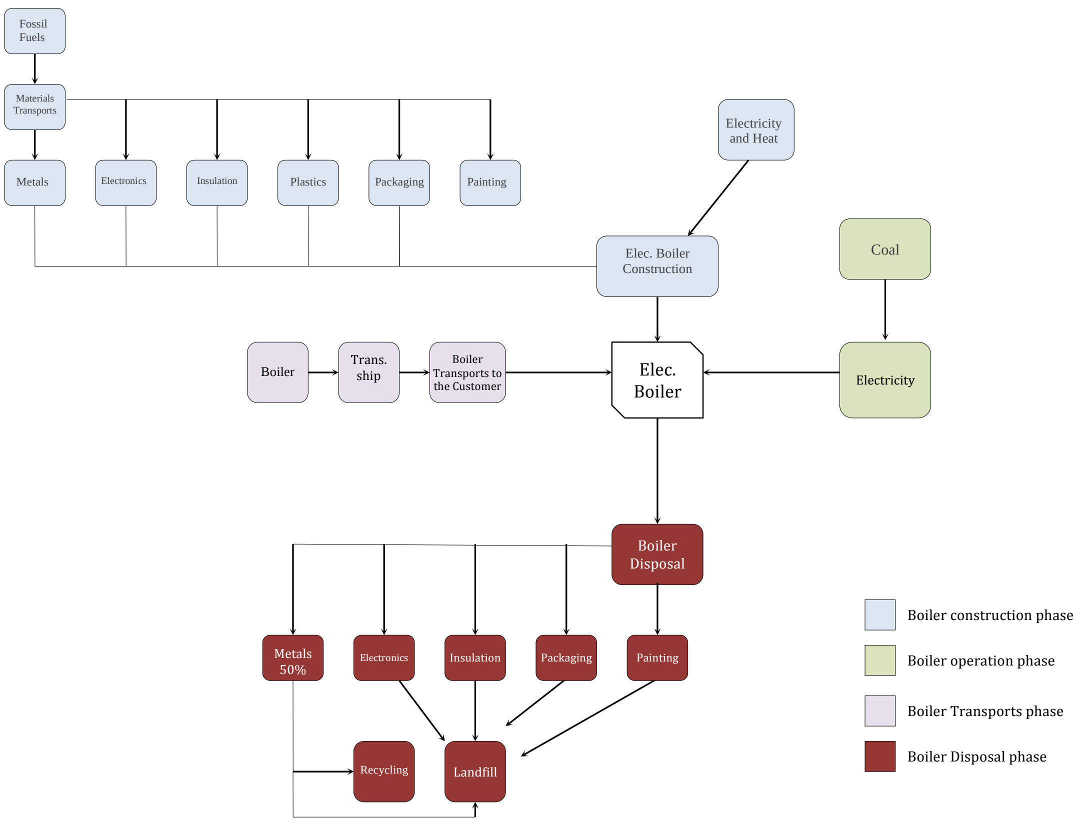

Fig.3.1 LCA system boundaries of the Electric Boiler system.

The data from several health clubs in Nablus was collected, the survey revealed that the average number of trainees who use services of clubs are 100 , and they use about 8 cubic meter of hot water in eight hours daily.

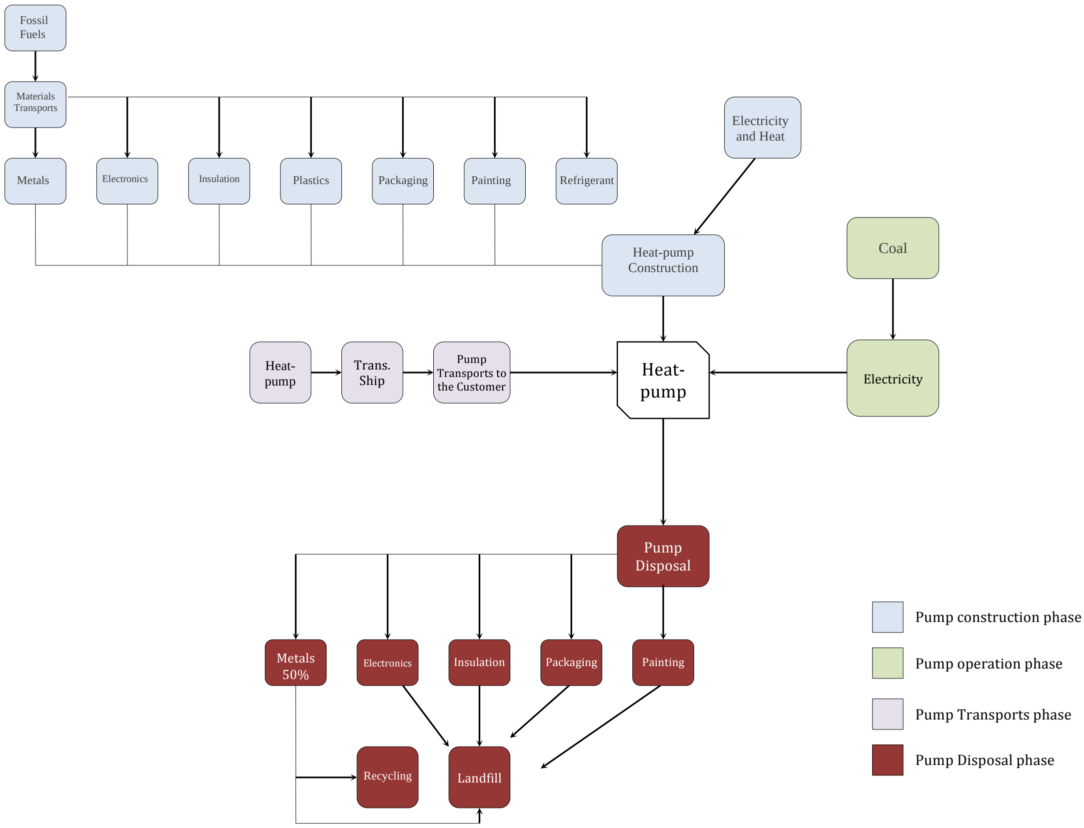

Fig.3.2 LCA system boundaries of the heat pump system

The limitations that have been taken into account when designing the systems: Water temperature and flow rate between boiler and storage tank are fixed for all systems, the losses in pipes and fitting between boiler and storage tank are neglected storage tank properties, tank size, and piping have been considered the same for three systems.

3.4 Heating Load Determination Procedure

The capacity of heating systems should fulfill the needs of hot water at worst conditions when the temperature of water is zero Celsius. The temperature in the hot water storage tank should not be less than 60 Celsius to prevent Legionella bacteria growth [21].

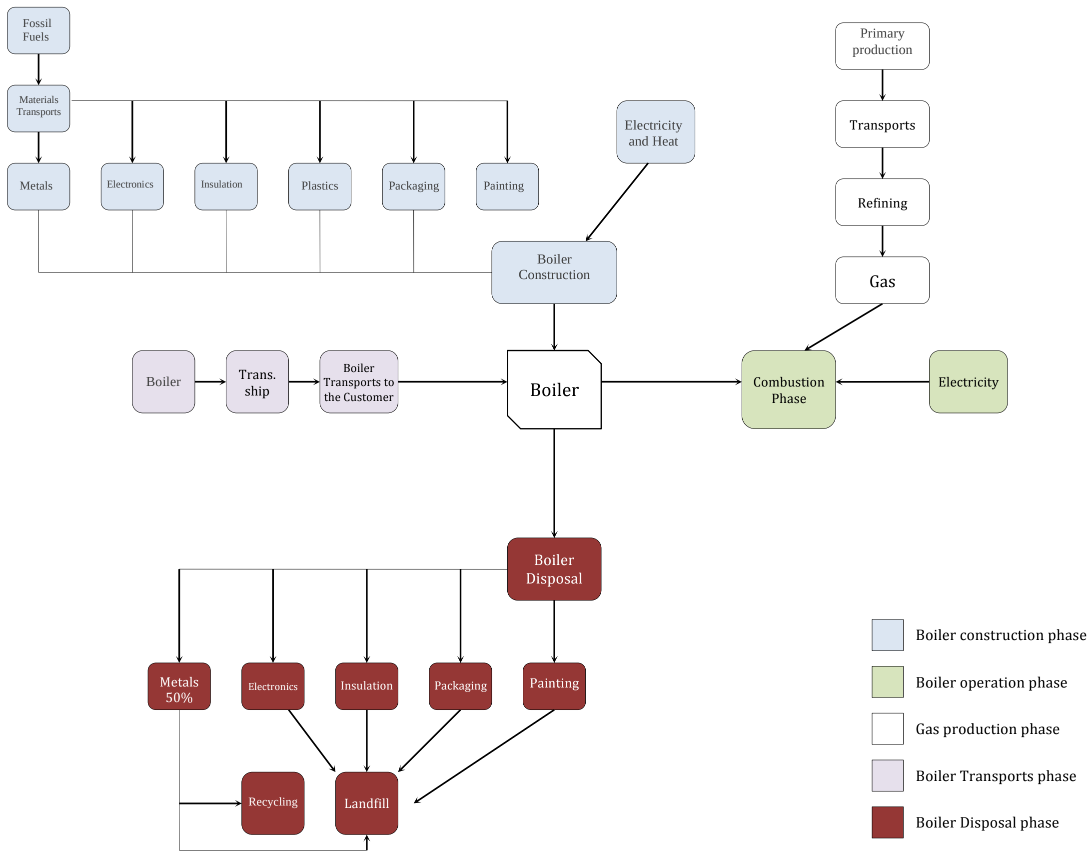

Fig.3.3 LCA system boundaries of gas boiler system.

3.4.1 Hot Water Flow Rate

Hot water flow rate between the boiler and the storage tank can be calculated using the following equation [29]:

$$\dot{m}_{ho} = \dot{m}_{m} \frac{T_{mixed} - T_{cold}}{T_{hot} - T_{cold}} \qquad 3.1$$

Where:

$\dot{m}_{ho}$: hot water flow rate kg/s

$\dot{m}_{m}$: mixed water flow rate kg/s

T_{mixed}: mixed temperature at fixture (°C)

T_{hot}: hot water temperature in storage tank (°C)

T_{cold}: cold water temperature (°C)

The mixed water flow rate is calculated by dividing the amount of water needed in hour by 3600 seconds. According to ASHRE mixed water temperature is 43 °C, and hot water temperature is 60°C in order to prevent the growth of Legionella [29]. Cold water temperature is considered as ambient temperature in winter, and as ambient temperature minus 2 degrees in summer [30]. Ambient temperature was taken from the Palestinian Meteorological Department [31]. After finding the hot water flow rate, optimal storage tank size can be calculated by multiplying hot water flow rate by 3600 seconds and dividing the total by factor 0.7 [29].

3.4.2 Steady State Heat Capacity

The steady state heat capacity of a boiler can be calculated using the following equation [32]:

$$q = \dot{m}_{ho}\ C_p(T_{hot} - T_0) \qquad 3.2$$

Where:

q: heat output capacity (kW)

$\dot{m}_{ho}$: hot water flow rate kg/s

C_p: specific heat (4.186kJ/kg.K)

T_{hot}: hot water temperature in storage tank (°C)

T_0: water temperature at the worst case (°C)

3.4.3 Energy Consumption

To find the actual monthly energy delivered to the water, Run fractions (RF) equations are used [21].

$$RF = \frac{h \quad r}{s \quad s \quad h \quad o \quad o \; b} \qquad 3.3$$

Further,

$$RF = \frac{b \quad r \quad ti}{t \quad m \quad e \quad ti} \qquad 3.4$$

Water heating requirements each month could be calculated using equation 3.5 [32]:

$$q = \dot{m}_{ho}\, C_p(T_{hot} - T_{cold}) \qquad 3.5$$

Where:

q: heat capacity (kW)

$\dot{m}_{ho}$: hot water flow rate

T_{hot}: hot water temperature in storage tank (°C)

T_{cold} : cold water temperature (°C)

To find total monthly run hour of boiler:

Monthly run hour = (daily operating hours) (monthly opening days) (RF) 3.6

Monthly energy delivered to water could be calculated through the following equation:

Energy delivered = (monthly heat required monthly) (running hours)   3.7

According to RF values and fig.3.4, the steady state efficiency for the three systems considered to be fixed [21].

Monthly energy consumption by boiler is calculated by the following equation:

$$\text{The enrgy consumption (input)} = \frac{e \qquad d}{e} \qquad 3.8$$

In the case of heat pump, coefficient of performance (COP) is used instead of efficiency.

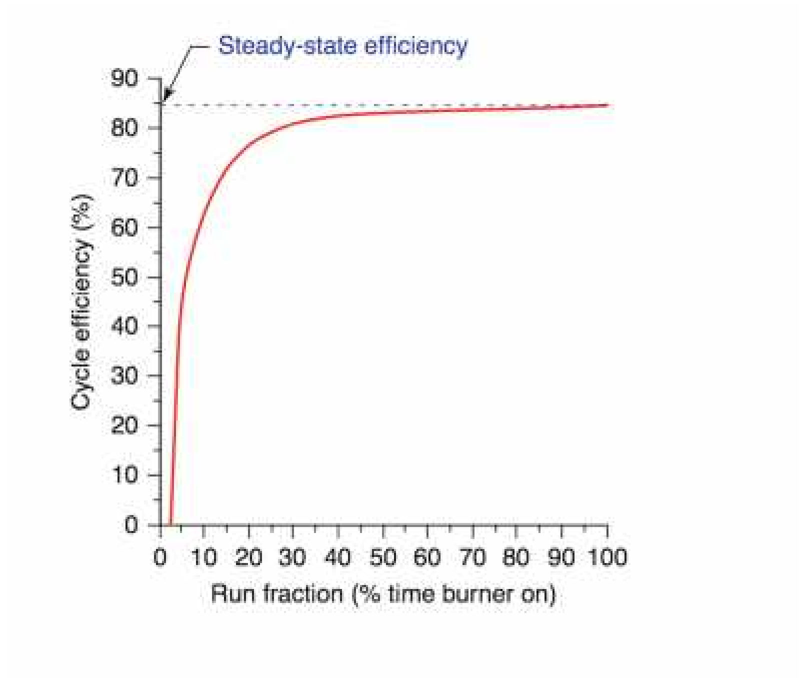

Fig.3.4 Cycle efficiency of a boiler versus run fraction (RF)

(Source: Modern Hydronic system)

The energy consumption at the first year equals the sum of energy consumed in the first 12 months. For coming years, the gradient rate 0.005 is used to present the drop in steady state efficiency each year [21].

3.5 Economic Analysis

To compare between the three systems, Present worth analysis is used by using gradient present worth equation [33]:

$$PW = IC + OC\frac{\left[\frac{(1+g)^n}{(1+i)^n} - 1\right]}{g - i} + SV\frac{1}{(1+i)^n} \qquad 2.9$$

Where:

PW: present worth.

IC : initial cost.

OC: operating cost.

SV : salvage value.

i: interest rate.

g: cost increase.

n: useful life.

The initial cost includes boiler, installation, mechanical, electrical, and civil works. The prices came from the dealers and included all VATs. Operating cost represents the electricity price for heat pump or electric boiler, or LPG price for gas boiler. Electricity and LPG tariff was taken from the

Palestinian Energy and Natural Resources Authority website (PENRA)[34].

To find salvage value for systems, the Diminishing value depreciation was determined as 0.15 [35], then the gradient drop in systems during system life cycle is calculated. Interest rate and cost increase is estimated at 0.1 and 0.02 respectively [33]. Increase rate here represents the increase in electricity and fuel prices, maintenance cost, and expected inflation during system's life cycle. The useful life cycle of the systems is estimated as 20 years [24, 28].

3.6 Impact Assessment

The open LCA software (version 1.4.2) has been used to perform life cycle impact analysis [36]. It also includes different impact assessment methods and the most updated Ecoinvent 3.1 , needs, elcd , and agribalys database libraries [37]. Global supply chains for products are also present in the database.

The CML (Institute of Environmental Sciences) method has been chosen as impact assessment methods [16].

According to the CML method, the environmental impact has been quantified on its 10 impact categories (Acidification potential, Climate change, Resources depletion, Eutrophication, Freshwater aquatic eco toxicity, Human toxicity, Marine aquatic eco-toxicity, Ozone layer depletion, Photochemical oxidation, Terrestrial eco-toxicity) [16].

The inventory process was the biggest challenge. All necessary data was collected from manufactures data sheets, manuals, and previous papers to specify the exact mass of materials, energy and other resources were used to build the systems. Fig.3.2,3.3,and 3.4 show three systems boundaries.

3.6.1Life Cycle Phases

Four different life cycle phases have been analyzed:

3.6.1.1 Construction

The amount of electricity, heat, insulation, metals, electronics, plastics, packaging materials and painting have been provided by manufacturers manuals, sheets, and scientific papers [18, 22, 23, 40, 41]. Ecoinvent 3.1 and needs databases have been used to form a complete image of the elements flow size, raw materials, natural sources inputs, and to calculate the environment impacts.

Fossil fuels are used to carry raw materials before construction. Metals recovery is not considered in the construction phase [37,38].

3.6.1.2 Transport

Only shipping by sea or ocean from country of origin port to Ashdod port is considered in this phase. Sea- distance organization website has been used to determine the distance between ports [39] Ecoinvent database has been used in to give impact results [37, 38].

3.6.1.3 Operation

This phase includes all upstream activities related to energy consumed in the three systems life cycles. For the heat pump and the electric boiler, electricity production, electricity in high voltage, transmission from high to medium voltage, electricity in medium voltage, transmission from medium to low voltage, and electricity in low voltage are considered. For the gas boiler; production, distribution, filling station, losses at loading and unloading, and refueling are considered. All data was taken from the Ecoinvent database [38].

3.6.1.4 Disposal

On average, metals are recovered up to 50% while the other 50% is sent to landfill as part of the electronic components, plastic, insulation and painting materials[18, 22, 23, 40, 41]**.** Input data and Ecoinvent 3.1 database are used to obtain the results in this phase [38].

Chapter Four

Results and Discussion

4.1 Energy Consumption Assessment

This section shows the consumption behavior for the systems, and disparity in the energy needs of each system.

As shown in Fig.6.1,the monthly operating hours for the heat pump is the highest, while the run fraction values (RF) is the highest (Appendix C.3). The reason for this goes back to the boilers' capacity (Appendix A.1), the available heat pump has a capacity of 72 kW, which is smaller than the electric and gas boiler. Fig.4.1 also shows that the systems operate more hours when the weather is colder.

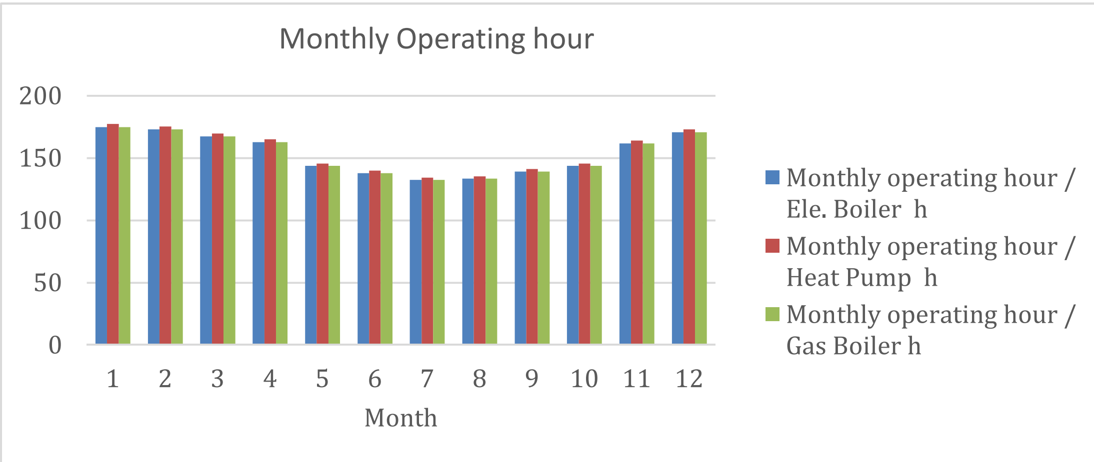

Fig. 4.1 Comparison between monthly operating hours for the electric boiler, the heat pump, and the gas boiler systems.

Monthly energy consumption for the heat pump is the lowest. It is about three times lower than the electric boiler as shown in Fig.4.2 This variation is caused by the heat pump's COP (Appendix A.1). The difference between the gas boiler and the electric boiler consumption is due to the difference in efficiency between the two systems (Appendix A.1,C.5). Fig.4.3 shows yearly energy consumption for the three systems.

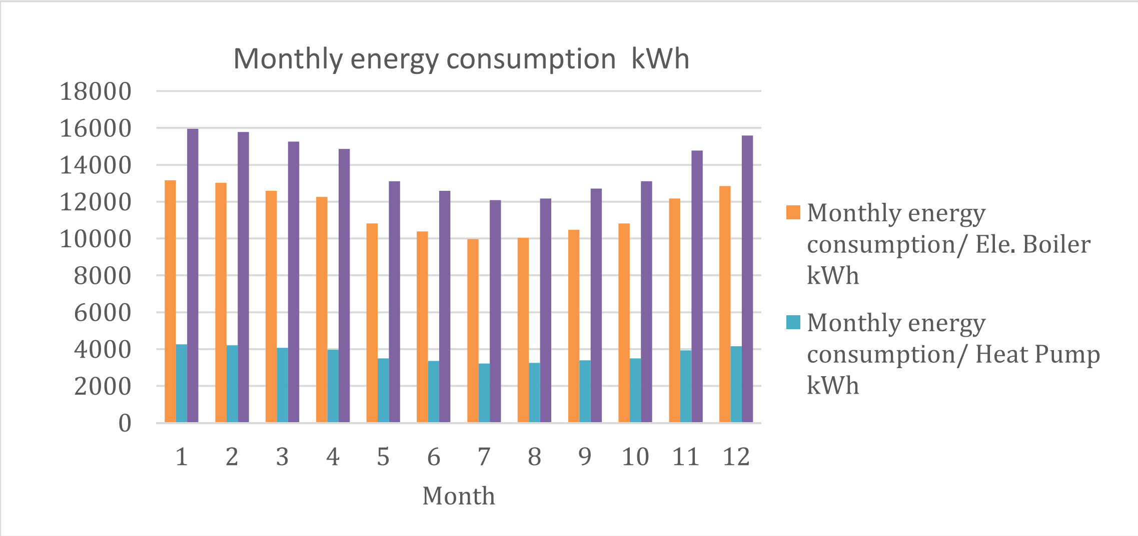

Fig.4.2 Comparison between monthly energy consumption for the electric boiler, the heat pump, and the gas boiler systems.

Fig.4.4 shows energy consumption for the three systems during their useful time cycles. The figure shows the vast range in the difference between the heat pump consumption (i.e. 939.8 MWh) and the other systems (i.e. 3524.3 MWh, and 2906.6 MWh for the gas boiler and the electric boiler respectively). Fig.6.4 gives the perception about the environmental impact and costs, while the comparison is between the electric boiler and the heat pump because they are being fed from the same source i.e. coal power station, and tariff (Appendix D.2). But this comparison will not be true when comparing between electricity and gas.

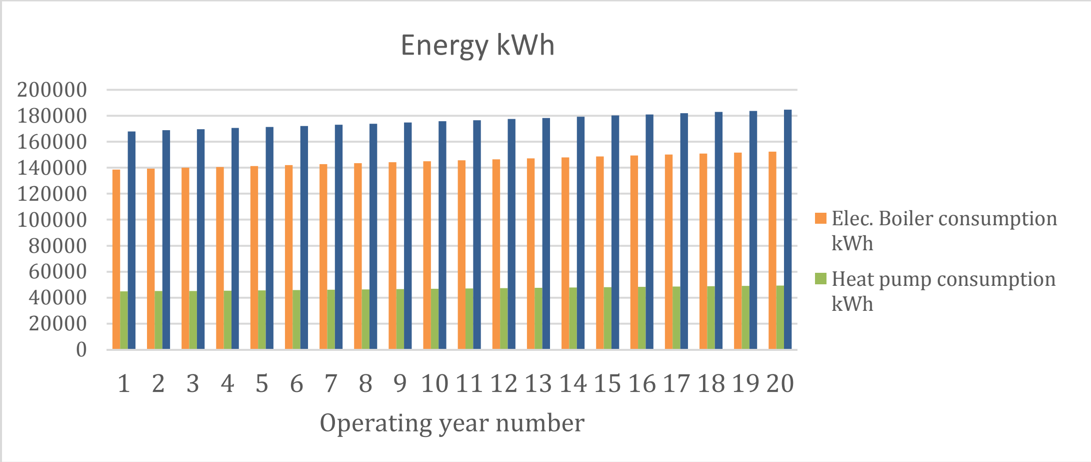

Fig.4.3 Comparison between yearly energy consumption for the electric boiler, the heat pump, and the gas boiler systems.

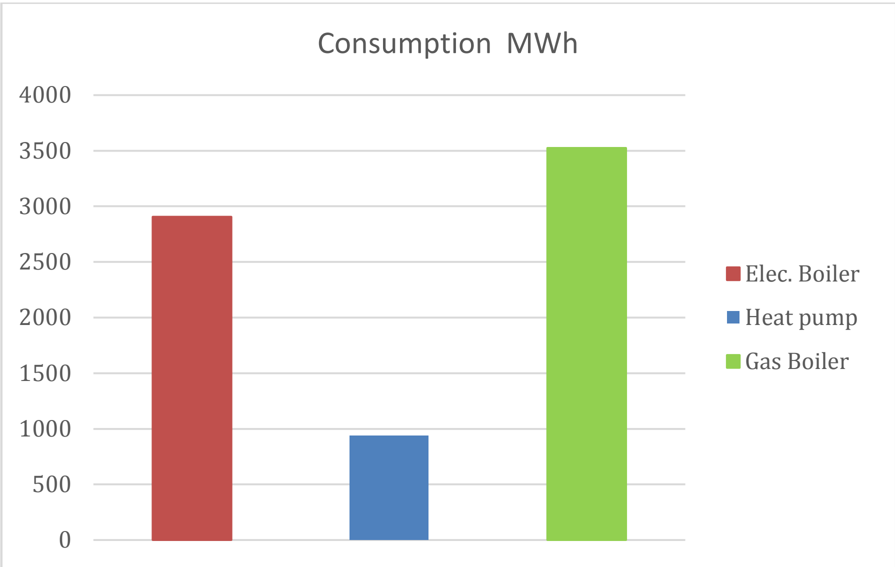

Fig.4.4 Comparison between the electric boiler, the heat pump, and the gas boiler energy consumption over 20 years.

4.2 Economic Assessment

This section discuses the initial and running costs of the three systems, and shows a comparison between these systems in terms of present worth analysis. Appendix D.2 shows electricity and gas unit prices.

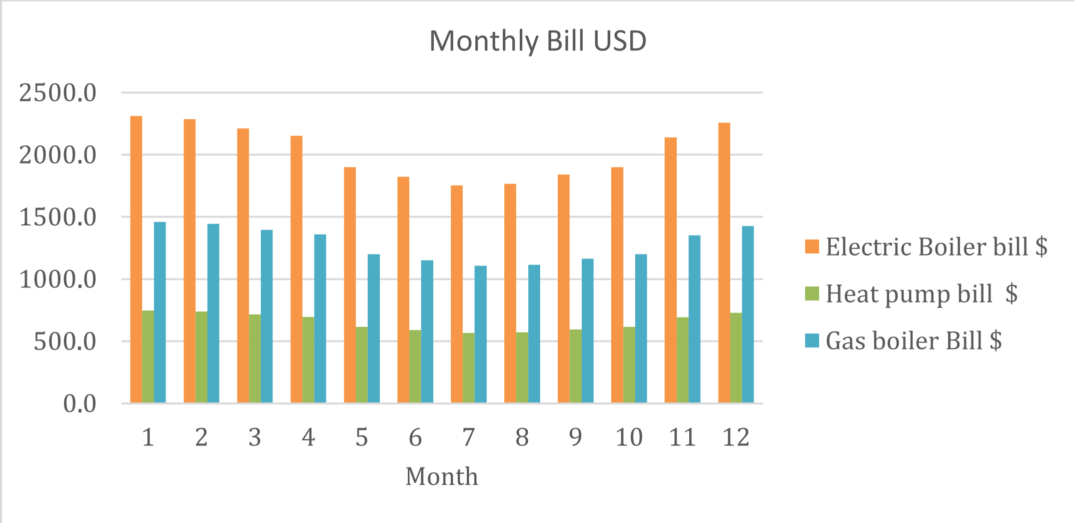

Fig.4.5 Comparison between electric boiler, heat pump, and gas boiler monthly energy bill.

The monthly energy bill (see Fig.4.5) shows that the cost of operating a gas boiler is less than the cost of operating an electric boiler. The reason for this goes back to the gross calorific value of liquid petroleum gas LPG (i.e. gross calorific value of LPG is7 kWh/L) [41]. Fig.4.5. Also shows that the heat pump has the lowest operating cost.

Fig.4.6 shows the initial cost and the annual depreciation values. The values in Fig.4.6is a guide to calculate the salvage value for the three systems i.e. 431, 1425, and 813 USD for the electric boiler, the heat pump, and the gas boiler respectively (Appendix D.3). Which used to evaluate present worth values.

Although the investment cost of heat pump is the highest, (see Fig.6.7) the present worth value of the heat pump is the least. (Fig.6.8) The gas boiler comes second with a large margin for the electric boiler value. This gives an indication of the need for attention to operational costs in the selection process.

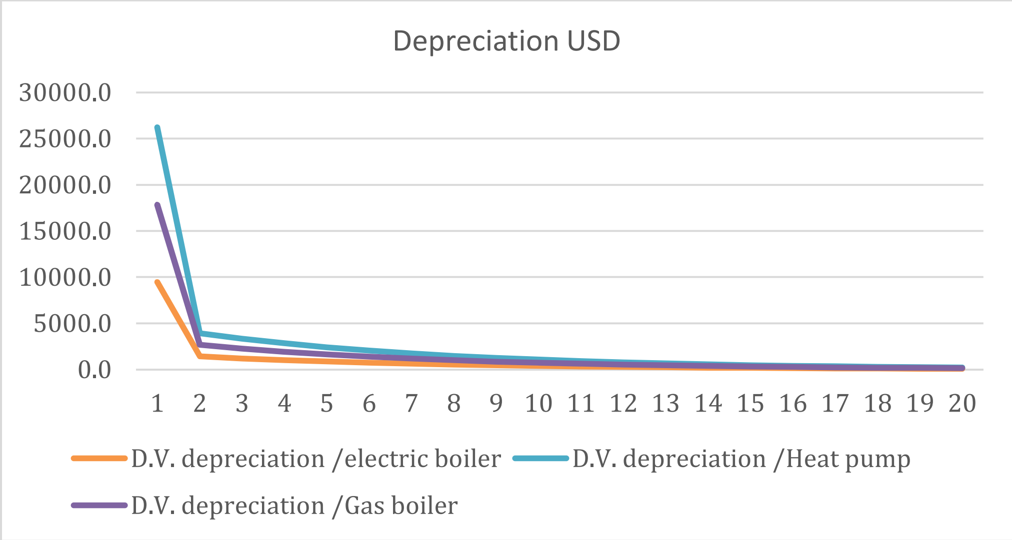

Fig.4.6 Depreciation values of electric boiler, heat pump, and gas boiler systems over 20 years.

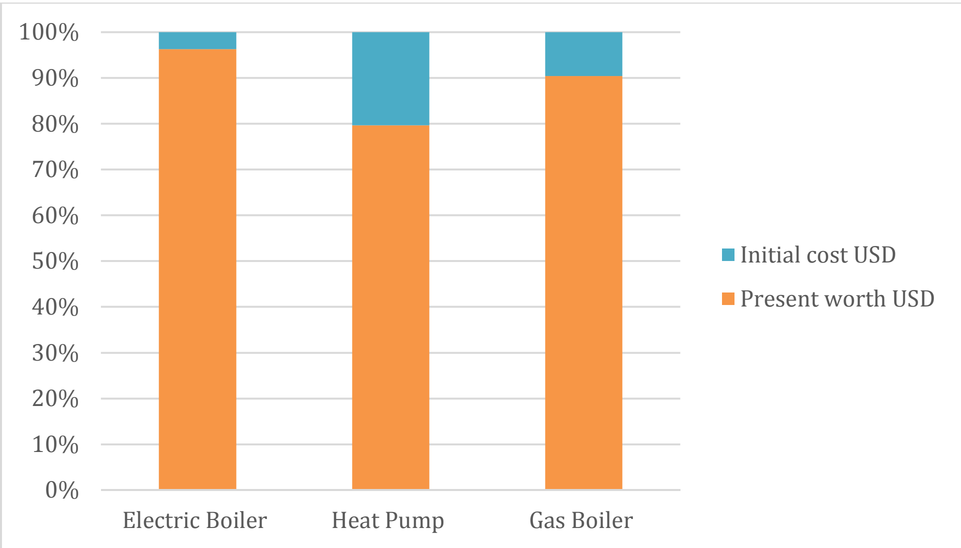

Fig.4.7 Percentage of initial cost to present worth value for the electric boiler, the heat pump, and the gas boiler over 20 years.

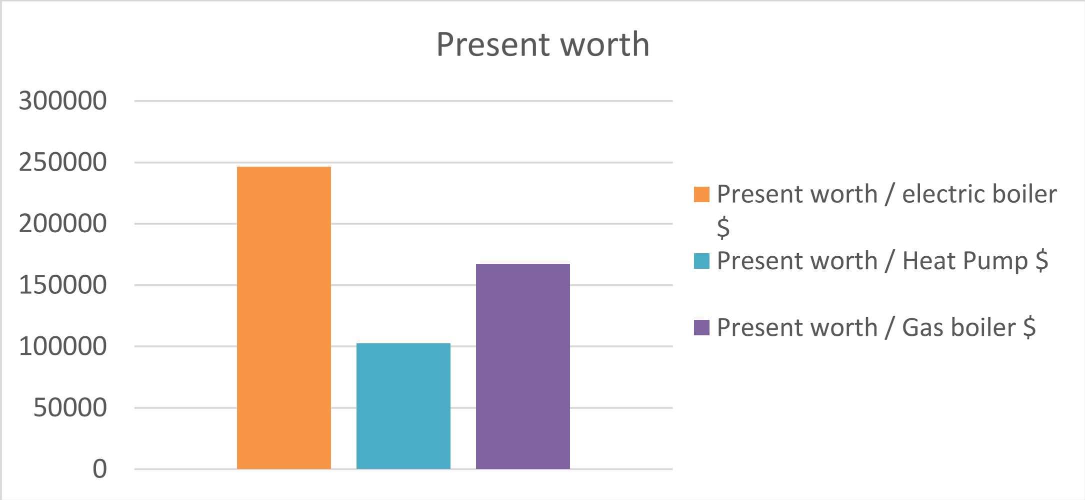

Fig.4.8 Comparison between the electric boiler, the heat pump, and the gas boiler present worth value for 20 years.

4.3 Environment Impact Assessment

This section discusses the environmental impacts of the three systems using the CML base line (Institute of Environmental Sciences) method.

Appendix E includes LCA input data for the three systems, which is used as a base to assess the impact of each system.

Fig.4.9, 4.10, and 4.11show the environmental impacts during the four phases of the life of each system separately. It seems that the operation phase contributes to the bulk of the damages. Construction phase also contributes significantly in the systems' life cycle impact. Therefore, the mass of the system plays an important role in its life cycle. Transportation and disposal phases do not contribute significantly as the case in construction and operation phases with the exception of their impact on the Marine aquatic eco-toxicity, which somewhat looks big.

Fig.4.12, 4.13, 4.14, and 4.15. show the impacts of each phase alone for three systems. Appendix F contains the impact on each CML damage subcategory of all phases as digits. In construction phase, the heat pump has the largest value for all impacts. This is due to the large mass and high amount of energy used in manufacturing it.

The striking in Fig.15.is the high values of Ozone layer depletion, Photochemical oxidation, and Depletion of a biotic resources – elements for gas boiler compared to the heat pump and the electric boiler values.

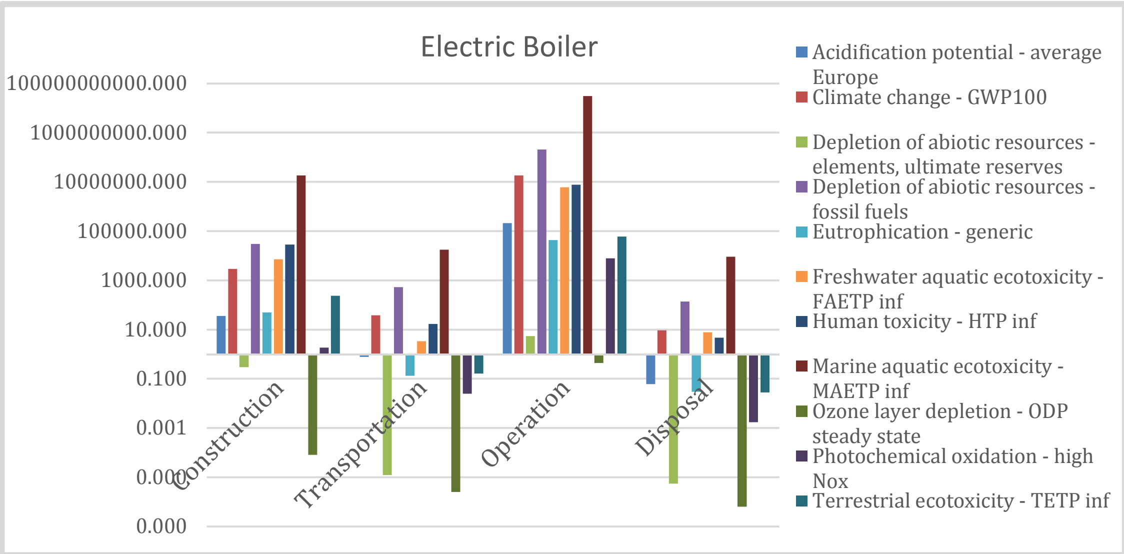

Fig.4.9 Comparison between the impacts of each phase in electric boiler life. Single histograms show the impact on each CML damage subcategory.

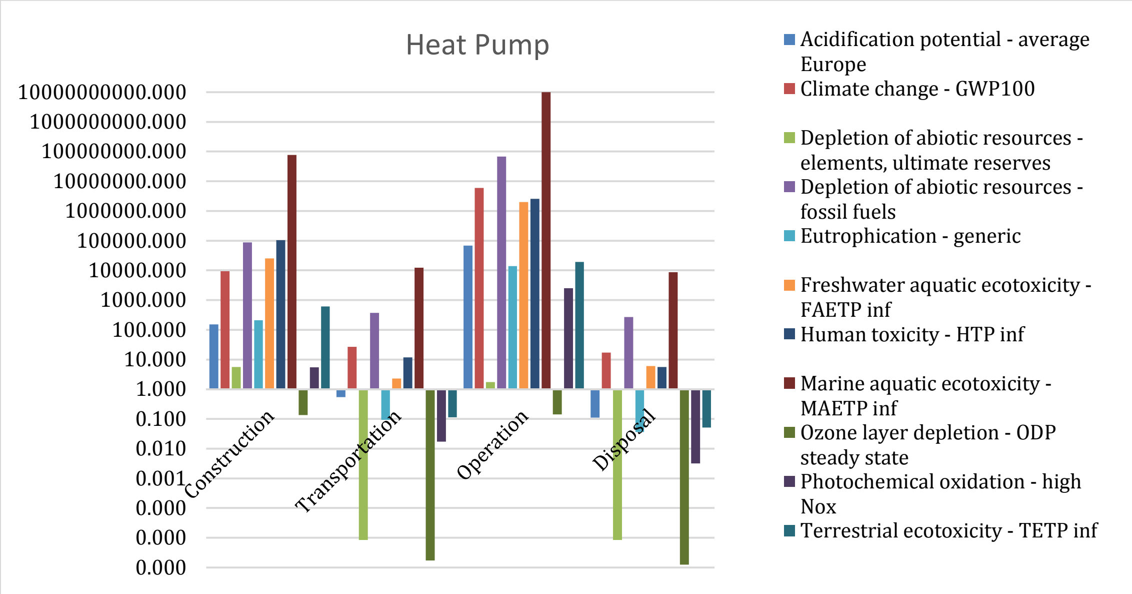

Fig.4.10 Comparison between the impacts of each phase in heat pump life.

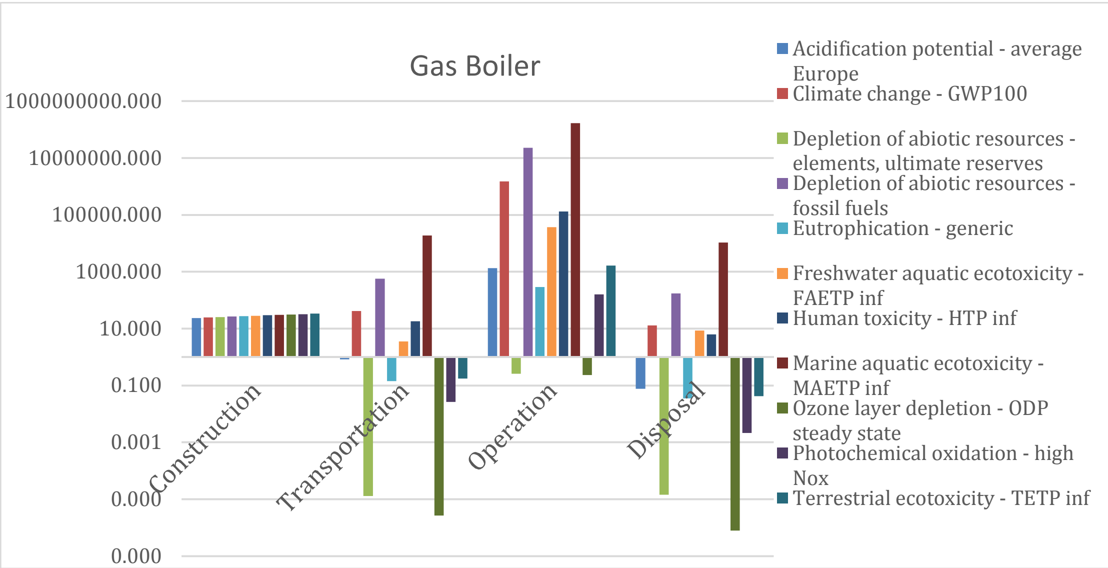

Fig.4.11 Comparison between the impacts of each phase in gas boiler life.

Fig.4.14 shows the operation phase for the three systems. The majority of categories in the electric boiler reveal the biggest impact values. This is due to the large amount of energy consumption and the used source of the energy (i.e. coal power station).

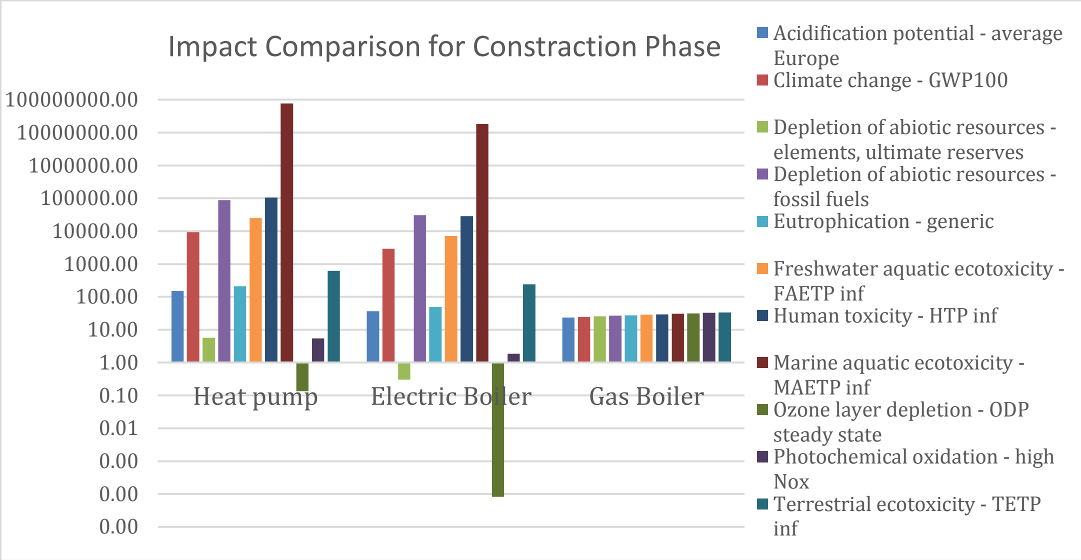

Fig.4.12 Comparison between the impacts of each system in construction phase.

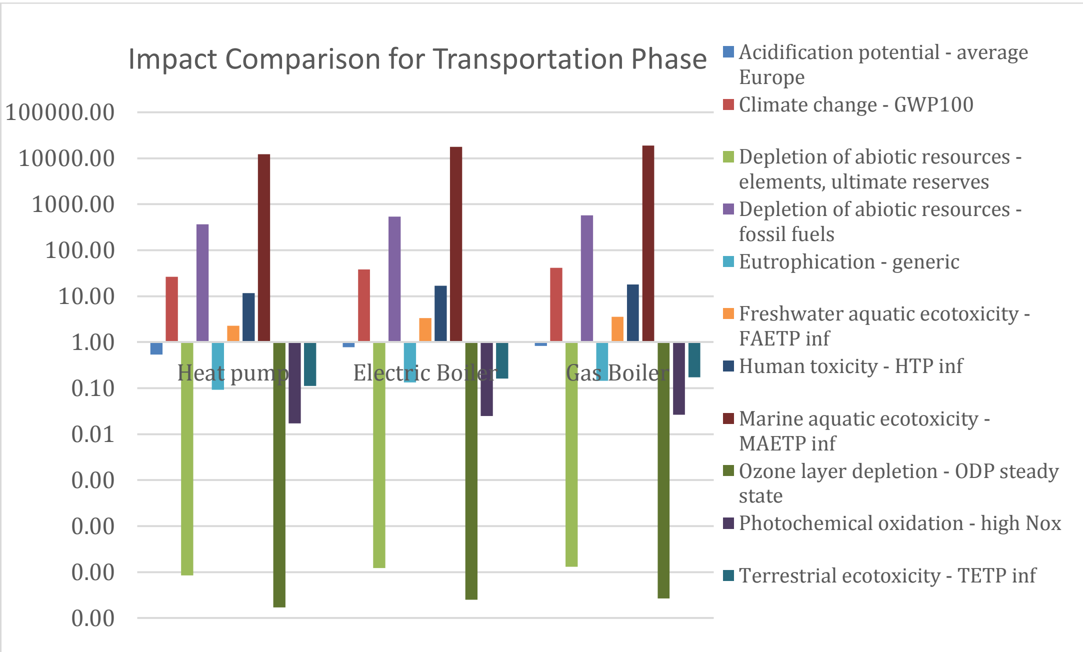

Fig.4.13 Comparison between the impacts of each system in transportation phase.

The high values of the heat pump impacts in comparison to the gas boiler gives us a clear indication about the extensive damage caused by the burning coal compared to gas, despite the fact that the heat pump consumes less energy than the boiler.

Fig.4.16, 4.17, 4.18, and 4.19.together give a clear idea about the contribution of each phase as a percentage. Fig.4.16 shows that 76.2% of Depletion of abiotic resources – elements impact comes from the construction phase for the heat pump.

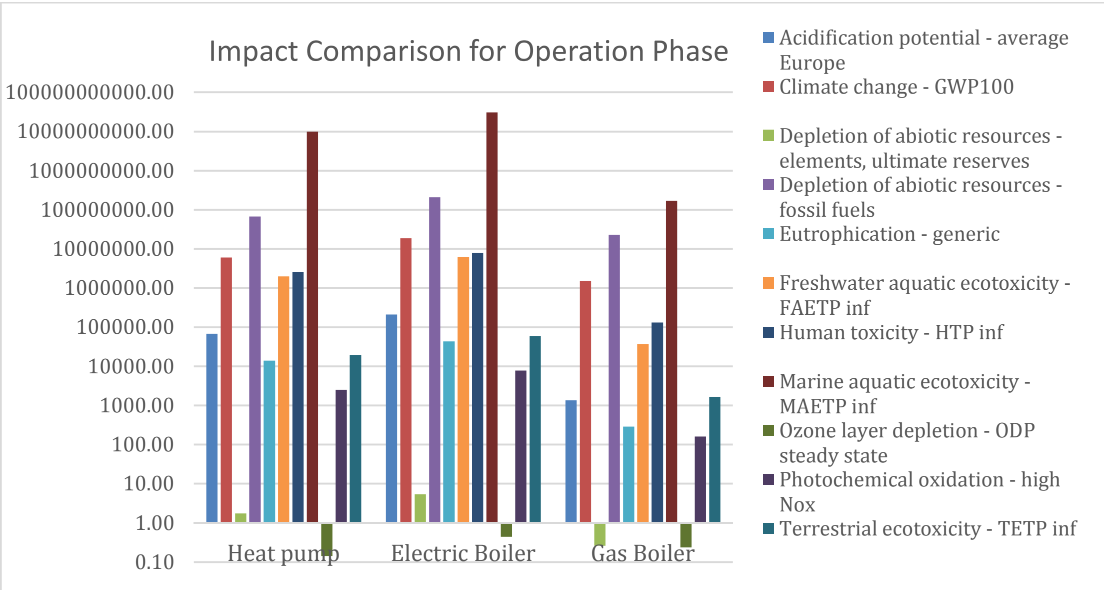

Fig.4.14 Comparison between the impacts of each system in operation phase.

The transportation and the disposal phases don't actually contribute in the three systems life cycle impact (see Fig.4.17 and 4.19). In the transportation phase, the reason goes back to the relatively small mass of the systems. As for the disposal phase, the reason is that metals constitute the largest percentage of the weight of these systems, and the majority of these metals are recycled and treated (Appendix E).

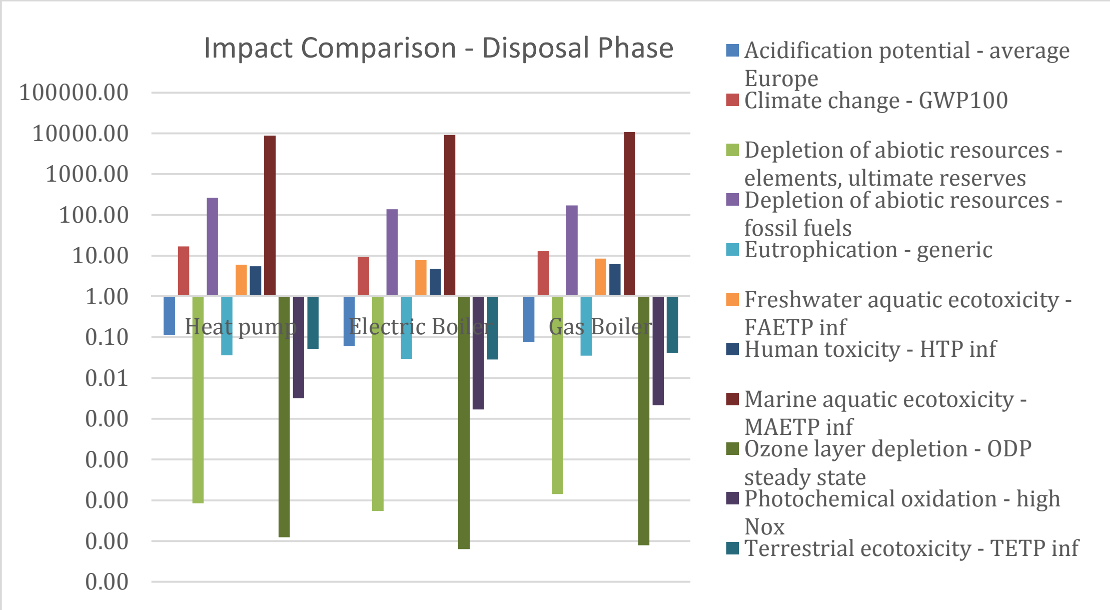

Fig.4.15 Comparison between the impacts of each system in disposal phase.

Fig.4.18 shows the huge effect of the operation phase for the three systems. 99.8%, 99.9%, and 99.9% of climate change impact for the heat pump, the electric boiler, and the gas boiler respectively comes from the operation phase. 98.7%, 99.8%, and 99.8% of freshwater aquatic eco-toxicity impact of the heat pump, the electric boiler, and the gas boiler also comes from the operation phase.

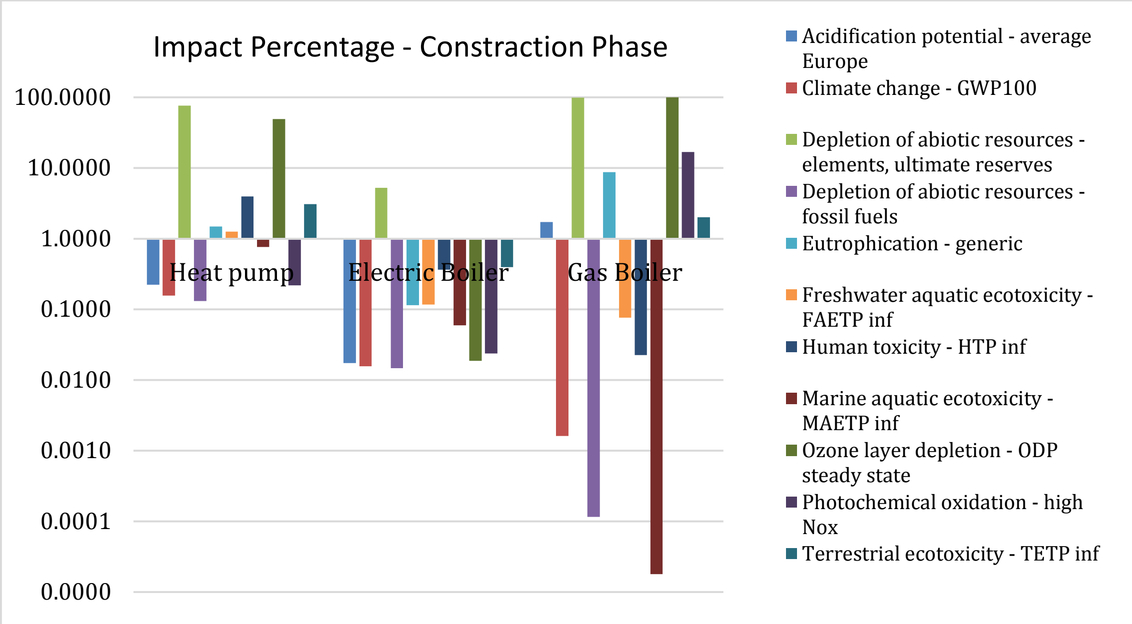

Fig.4.16 Construction Phase- percentage of contribution in the three systems' life cycle's impact.

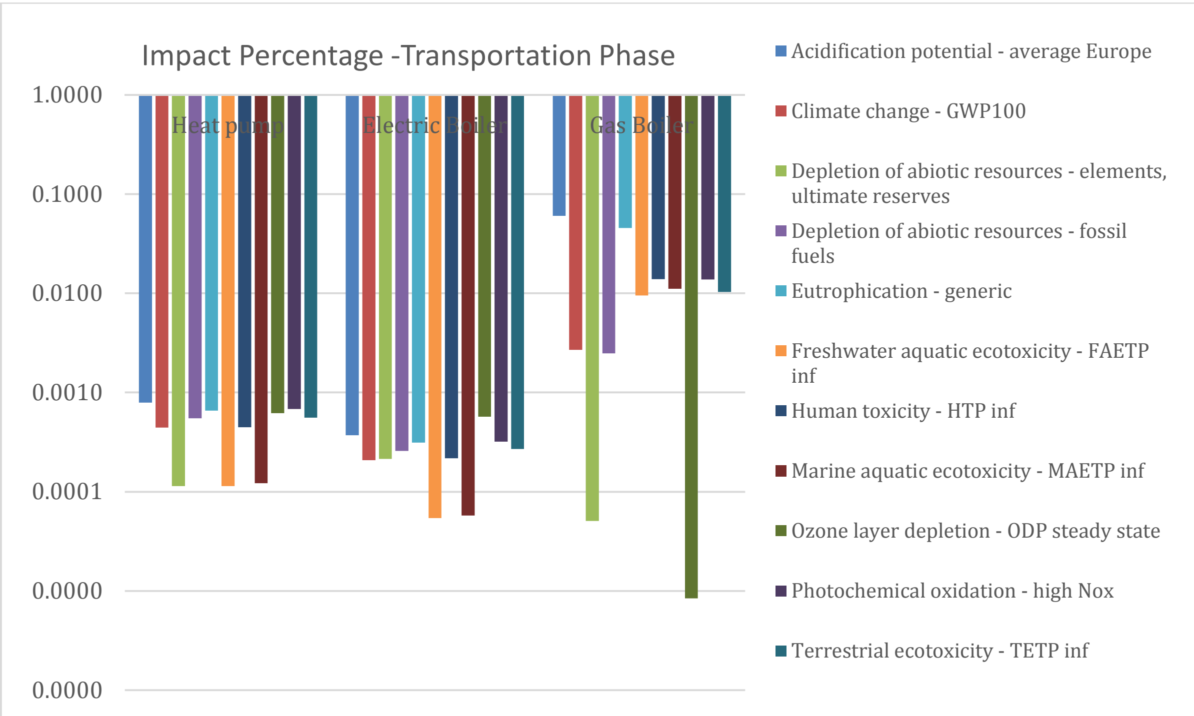

Fig.4.17 Transportation phase- percentage of contribution in the three systems life cycle's impact.

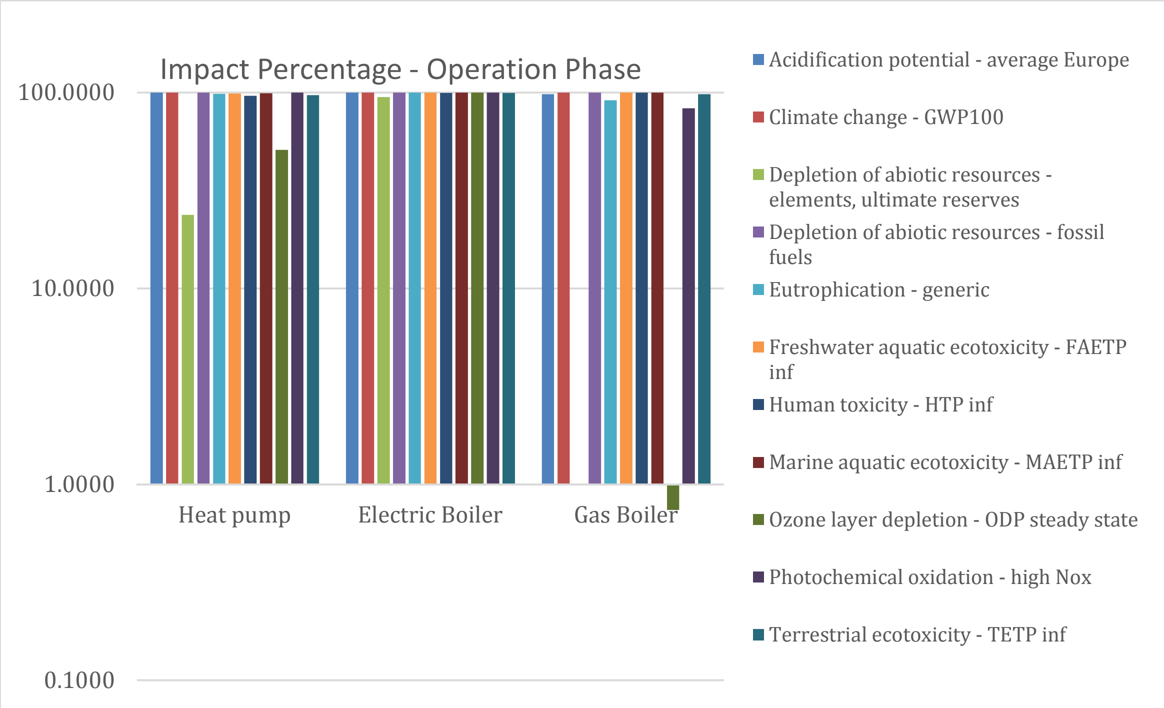

Fig.4.18 Operation phase- percentage of contribution in the three systems' life cycle's impact.

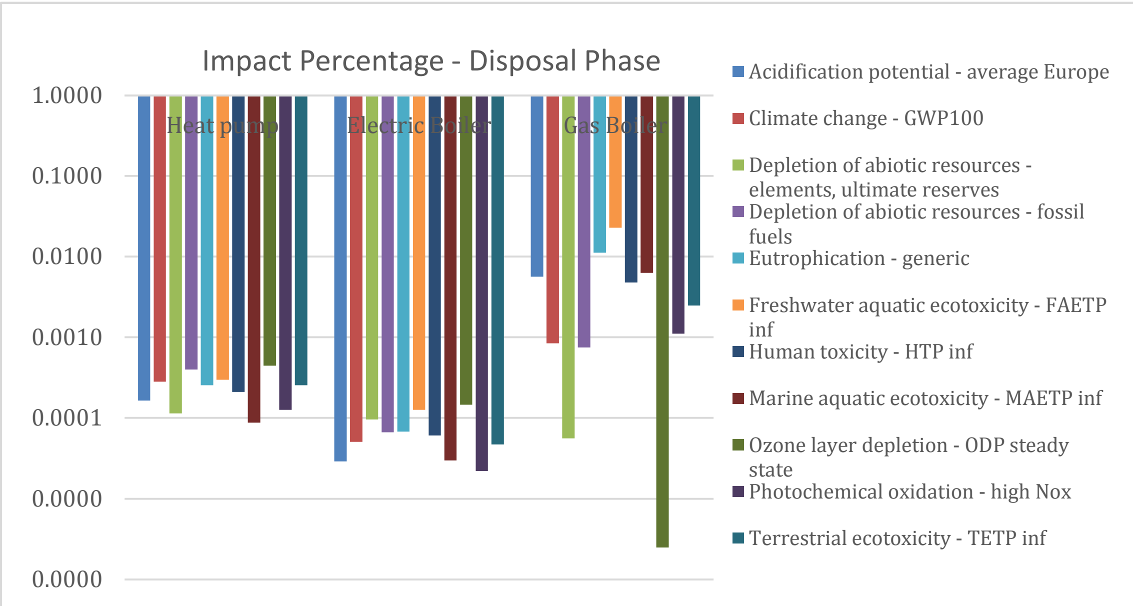

Fig.4.19. Disposal phase-percentage of contribution in the three systems' life cycle's impact.

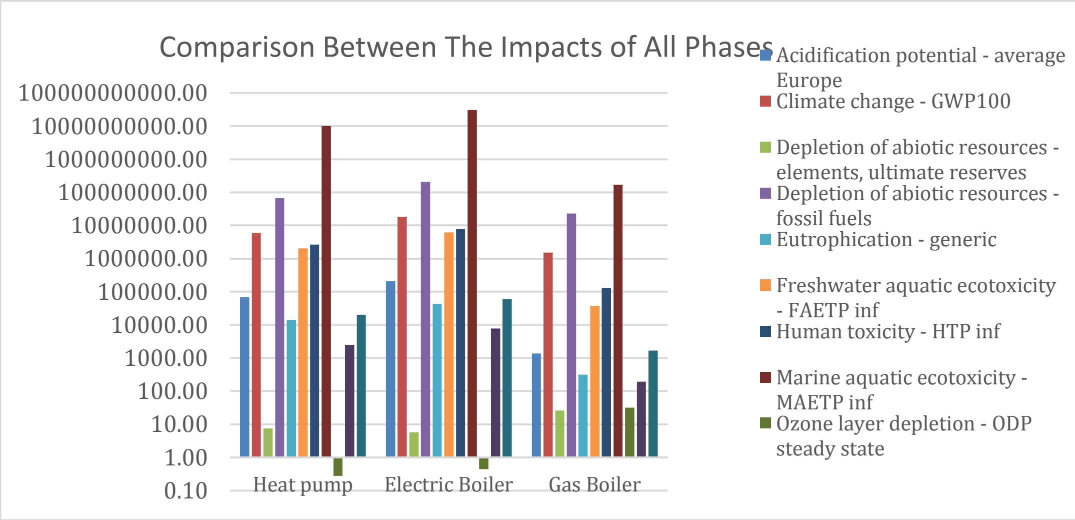

Fig.4.20 Comparison between the impacts of all phases together for three systems.

99% of these impacts come from the construction phase. Other than that, the electric boiler captures the highest values or rather the worst results.

4.4 Sensitivity Analysis

4.4.1 Scenario I: Natural Gas

The first scenario consists of operating electric boiler and heat pump by electricity produced using natural gas at conventional power plant from Israel instead coal. As seen in Fig.4.21 the environmental impacts result in operation phase for electric boiler and heat pump are decreased dramatically, but the gas boiler remained the most environmentally friendly.

4.4.2 Scenario II: Neglecting Transmission and distribution Lines

The second scenario consists of neglecting environmental impacts of transmission lines , transformers, and distribution lines .

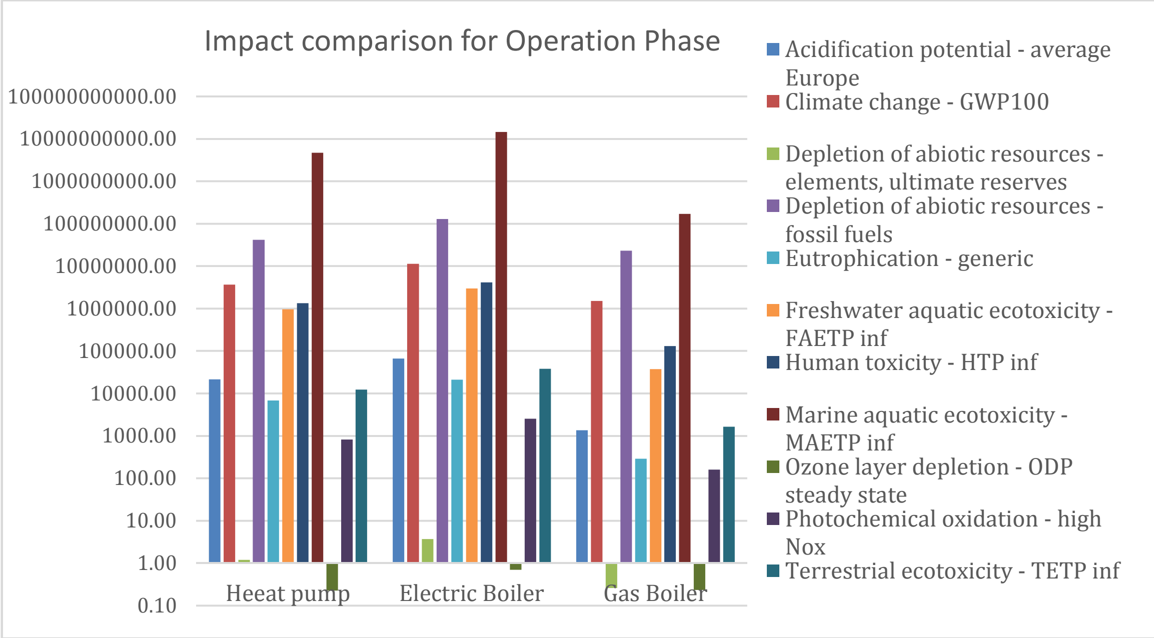

Fig.4.21 Comparison between the impacts of each system in operation phase using natural gas at conventional power station as fuel to produce electricity.

While retaining coal as a source for the production of electricity. As seen in Fig. 4.22 the impacts of lines and transformers is extremely large . For example the value of Depletion of abiotic recourse-fossil fuel category including transmission lines, distribution lines, and transformers is: 66873953MJ in comparison with 35585706 MJ without considering lines and transformers. These results show significant impact of the transmission lines, distribution lines, and transformers.

But striking that the environmental impact of the gas boiler indicators remained the least.

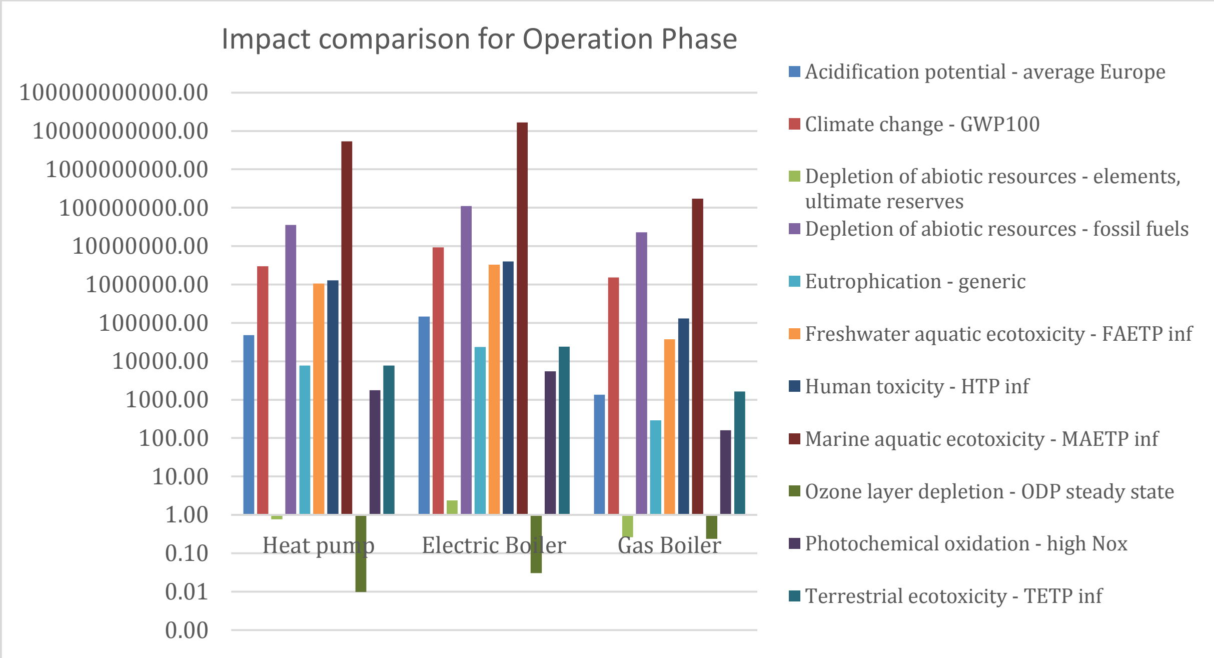

Fig.4.22 Comparison between the impacts of each system in operation phase with neglecting transmission lines, distribution lines, and transformers.

Chapter Five

Conclusions and Recommendations

5. 1 Conclusions

In this study a life cycle analysis was performed on three commercial scale water heating systems. The openLCA software (v. 1.4.2), Ecoinvent 3.1 and Needs databases were used, and the CML baseline LCIA method was chosen for the evaluation of all systems' impact on its 10 categories.

For all systems, it was found that the operation phase contributes most to the overall environmental impact followed by the construction phase. The disposal phase and the transportation phase always represented a negligible contribution. Although the energy consumption of the heat pump during the operating phase is the least, but most environmental indicators of the gas boiler are the least. The reason for that is related to the source of electricity generation (i.e. coal) and the multiple stages the current passes through before reaching the end user.

The three systems recorded high results in marine aquatic eco-toxicity indicator. The heat pump seems the most friendly to the ozone layer, and the electric boiler is the most friendly to abiotic resource – elements. The highest impacts of human toxicity come from the electric boiler because of the large amounts of energy consumption in the operation phase and the source of this energy.

A low initial cost doesn’t mean that the system has the least cost. The heat pump's initial cost is three times higher than the electric boiler 's initial cost with a variance of 16,757 USD, but the present worth value of the electric boiler is 2 times higher than that of the heat pump, with a variance of 143,759 USD.

5.2 Recommendations

Considering the results of this study, the following are recommended:

- Despite its relatively high initial costs, using heat pumps as a source of producing hot water in health clubs has the highest feasibility from economic point of view taking into consideration the system life time.
- Gas fired boilers are the most environmental friendly when its compared with electric boilers and heat pumps in heating an average local gym daily demand of hot water.
- Changes in the electrical power source conditions such as distribution network and fuel source can significantly affect the environmental footprint of the systems working on electricity.
- It is advisable that the Palestinian Environment Quality Authority EQA develops policies and motivating laws to enhance business owners toward using gas-fired boilers instead of other systems due to its low environmental effects.

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Appendices

APPENDIX A

A.1 Heat Capacity and Efficiency

System	Capacity kW	Efficiency
Electric Boiler	73	0.97
Heat Pump	72	3
Gas Boiler	73	0.8

APPENDIX B

B.1 Monthly Average Temperature

Month	Average ambient temp. °C	Average water temp. °C
1	10.1	10.1
2	10.7	10.7
3	12.5	12.5
4	15.9	13.9
5	21.9	19.9
6	23.7	21.7
7	25.4	23.4
8	25.1	23.1
9	23.3	21.3
10	21.9	19.9
11	16.2	14.2
12	11.4	11.4

APPENDIX C

C.1 Water's Flow and Temperature

Month	T_{mixed}°C	T_{hot} °C	T_{cold} °C	Mixed water flow rate kg/s	Hot water flow rate kg/s	Flow rate between boiler & tank kg/s
1	43	60	10.1	0.27	0.178	0.278
2	43	60	10.7	0.27	0.177	0.278
3	43	60	12.5	0.27	0.173	0.278
4	43	60	13.9	0.27	0.170	0.278
5	43	60	19.9	0.27	0.156	0.278
6	43	60	21.7	0.27	0.150	0.278
7	43	60	23.4	0.27	0.145	0.278
8	43	60	23.1	0.27	0.146	0.278
9	43	60	21.3	0.27	0.151	0.278
10	43	60	19.9	0.27	0.156	0.278
11	43	60	14.2	0.27	0.170	0.278
12	43	60	11.4	0.27	0.176	0.278

C.2 Run Fraction

Month	Required Heating kW	RF Electric boiler	RF Heat pump	RF Gas boiler
1	63.84	0.87	0.89	0.87
2	63.14	0.86	0.88	0.86
3	61.05	0.84	0.85	0.84
4	59.42	0.81	0.83	0.81
5	52.44	0.72	0.73	0.72
6	50.35	0.69	0.70	0.69
7	48.37	0.66	0.67	0.66
8	48.72	0.67	0.68	0.67
9	50.81	0.70	0.71	0.70
10	52.44	0.72	0.73	0.72
11	59.07	0.81	0.82	0.81
12	62.32	0.85	0.87	0.85

C.3 Monthly Operating Hour

Month	Electric Boiler h	Heat Pump h	Gas Boiler h
1	175	177	175
2	173	175	173
3	167	170	167
4	163	165	163
5	144	146	144
6	138	140	138
7	133	134	133
8	133	135	133
9	139	141	139
10	144	146	144
11	162	164	162
12	171	173	171
Total h	1841	1867	1841

C.4 Monthly Energy Delivered to Water

Month	Electric Boiler kWh	Heat Pump kWh	Gas Boiler kWh
1	12767	12767	12767
2	12628	12628	12628
3	12209	12209	12209
4	11884	11884	11884
5	10488	10488	10488
6	10070	10070	10070
7	9674	9674	9674
8	9744	9744	9744
9	10163	10163	10163
10	10488	10488	10488
11	11814	11814	11814
12	12465	12465	12465
Total kWh	134394	134394	134394

C.5 Monthly Energy Consumption by The Systems

Month	Electric Boiler kWh	Heat Pump kWh	Gas Boiler kWh	LPG cosumption L
1	13162	4256	15959	15959
2	13018	4209	15785	15785
3	12587	4070	15261	15261
4	12251	3961	14854	14854
5	10813	3496	13110	13110
6	10381	3357	12587	12587
7	9974	3225	12093	12093
8	10045	3248	12180	12180
9	10477	3388	12703	12703
10	10813	3496	13110	13110
11	12179	3938	14767	14767
12	12850	4155	15581	15581
Total kWh	138550	44798	167992	167992 Litter

C.6 Life Cycle Energy Consumption

Year	Electric Boiler kWh	Heat Pump kWh	Gas Boiler kWh
1	138550	44798	167992
2	139243	45022	168832
3	139939	45247	169676
4	140639	45473	170525
5	141342	45701	171377
6	142049	45929	172234
7	142759	46159	173096
8	143473	46390	173961
9	144190	46622	174831
10	144911	46855	175705
11	145636	47089	176583
12	146364	47324	177466
13	147096	47561	178354
14	147831	47799	179245
15	148570	48038	180142
16	149313	48278	181042
17	150060	48519	181948
18	150810	48762	182857
19	151564	49006	183772
20	152322	49251	184691
Total kWh	138550	44798	167992

APPENDIX D

D.1 Initial Costs

System	Cost $
Electric boiler	9459
Heat pump	26216
Gas boiler	17838

D.2 Energy Price

LPG price Nis/L	2.37
elec. Price Nis / kWh	0.65
exchange rate Nis/$	3.7
Electricity Price $/kWh	0.176
LPG Price $/L	0.641

D.3 Diminishing Value Depreciation and Salvage Value

Year	Electric Boiler $	Heat Pump $	Gas Boiler $
1	0	0	0
2	1418.9	3932.4	2675.7
3	1206.1	3342.6	2274.3
4	1025.2	2841.2	1933.2
5	871.4	2415.0	1643.2
6	740.7	2052.8	1396.7
7	629.6	1744.8	1187.2
8	535.1	1483.1	1009.1
9	454.9	1260.6	857.8
10	386.6	1071.6	729.1
11	328.6	910.8	619.7
12	279.3	774.2	526.8
13	237.4	658.1	447.8
14	201.8	559.4	380.6
15	171.6	475.5	323.5
16	145.8	404.1	275.0
17	123.9	343.5	233.7
18	105.4	292.0	198.7
19	89.6	248.2	168.9
20	76.1	211.0	143.5
Salvage Value	431	1195	813

APPENDIX E

Systems inventories

E.1 Construction Phase
E.1.1 Electric Boiler

	Material	Database process	Quantity	Unit
Energy in production	Electricity in production		547.2	kWh
	Heat in production		256.32	kWh
Insulation	Glass fibre	Glass fibre production US	2.3	kg
	Rock wool	Rock wool production, US	1.4	kg
	Ceramics	Sanitary ceramics	3.5	kg
	Vermiculite	Expanded vermiculite, US	8.5	kg
Metals	Brass	Brass production Rest of the world	11.6	kg
	Cast iron	Cast iron production US	39.4	kg
	Galvanized steel	Galvanized steel sheet at plant RNA	75.6	kg
	Stainless steel	Steel, Chromium steel 18/8, converter steel productionUS	45.5	kg
	Low alloyed steel	Steel, low alloyed, steel production converter US	64	kg
	Mild unalloyed steel	Steel, unalloyed (US) steel production, converter, unalloyed	45.7	kg
Electronics	Cables	Cable, unspecified, production GLO	32.5	kg
	Clamps	Electric connector, wire clamp production GLO	3.1	kg
	Thermostat and user interface	Electronics for control units	2.4	kg
	Electronic board	Printed wiring board production, for surface mounting, Pb free surface GLO	4.6	kg
	Resistor	Resistor, wirewound	7.4	kg
Plastics	Handles	Nylon 6-6 RER production	0.67	kg
	Gaskets	Polyvynilchloride production, bulk polymerization	0.24	kg
	Gaskets	Polyethilene low density granulate production mix at plant US	0.48	kg
	Sealing	Silicone product, production rest of the world	0.36	kg
Packaging	Packaging film	Packaging film low density LDPE production	0.87	kg
	Installation manuals	Printed paper offset US	0.77	kg
	Cardboard box	Corrugated board production	0.33	kg

	Warning stickers	Polyester resin, unsaturated	0.03	kg
Painting	White coating	Alkyd paint whitout solvent white 60% H2O	2.5	kg
	Coating	Coating powder	0.65	kg
Boiler weight			354	kg

E.1.2 Heat Pump

	Material	Database process	Quantity	Unit
Energy in production	Electricity in production		1140	kWh
	Heat in production		534	kWh
Insulation	Polyurethane foam		6.8	kg
Metals	Brass	Brass production Rest of the world	167.1	kg
	Cast iron	Cast iron production RER	142.2	kg
	Galvanized steel	Galvanized steel sheet at plant RNA	127.6	kg
	Stainless steel	Steel, Chromium steel 18/8, converter steel production RER	87.3	kg
	Low alloyed steel	Steel, low alloyed, steel production converter RER	134.1	kg
	Mild unalloyed steel	Steel, unalloyed (RER) steel production, converter, unalloyed	62.6	kg
	Silver	Silver production RER	3.2	kg
Electronics	Cables	Cable, unspecified, production GLO	24.6	kg
	Clamps	Electric connector, wire clamp production GLO	2.4	kg
	Thermostat and user interface	Electronics for control units	0.86	kg
	Electronic board	Printed wiring board production, for surface mounting, Pb free surface GLO	2.7	kg
	Resistor	Resistor, wirewound	3.9	kg
Plastics	Handles	Nylon 6-6 RER production	0.86	kg
	Gaskets	Polyvynilchloride production, bulk polymerization	0.44	kg
	Gaskets	Polyethilene low density granulate production mix at plant RER	0.75	kg
	Sealing	Silicone product, production rest of the world	0.46	kg
Packaging	Packaging film	Packaging film low density LDPE production	0.87	kg
	Installation manuals	Printed paper offset RER	0.48	kg
	Cardboard box	Corrugated board production	0.33	kg

	Warning stickers	Polyester resin, unsaturated	0.01	kg
	White coating	Alkyd paint whitout solvent white 60% H2O	1.8	kg
Painting	Coating	Coating powder	0.4	kg
Liquid	oil	Copeland 3MAF(32 cST) Polyol ester (POE) oil	4.17	kg
Refrigerant	R410A	R410A (GWP=1720)	13.1	kg
Heat-Pump weight			789	kg

E.1.3 Gas Boiler

	Material	Database process	Quantity	Unit
	Electricity in production		492.48	kWh
Energy in production	Heat in production		230.688	kWh
	Glass fiber	Glass fiber production US	1.2	kg
	Rock wool	Rock wool production, US	1.6	kg
	Ceramics	Sanitary ceramics	1.4	kg
Insulation	Vermiculite	Expanded vermiculite, US	6.6	kg
	Brass	Brass production Rest of the world	18.4	kg
	Cast iron	Cast iron production US	48.3	kg
	Galvanized steel	Galvanized steel sheet at plant us	75.6	kg
	Stainless steel	Steel, Chromium steel 18/8, converter steel productionUS	89.3	kg
	Low alloyed steel	Steel, low alloyed, steel production converter US	68.3	kg
Metals	Mild unalloyed steel	Steel, unalloyed (US) steel production, converter, unalloyed	45.7	kg
	Cables	Cable, unspecified, production GLO	7.4	kg
	Clamps	Electric connector, wire clamp production GLO	1.7	kg
	Thermostat and user interface	Electronics for control units	0.56	kg
	Electronic board	Printed wiring board production, for surface mounting, Pb free surface GLO	2.6	kg
Electronics	Resistor	Resistor, wirewound	2.9	kg
	Handles	Nylon 6-6 RER production	0.89	kg
	Gaskets	Polyvynilchloride production, bulk polymerization	0.24	kg
	Gaskets	Polyethilene low density granulate production mix at plant US	0.58	kg
Plastics	Sealing	Silicone product, production rest of the world	0.36	kg
Packaging	Packaging film	Packaging film low density LDPE production	0.87	kg

	Installation manuals	Printed paper offset US	0.77	kg
	Cardboard box	Corrugated board production	0.33	kg
	Warning stickers	Polyester resin, unsaturated	0.01	kg
Painting	White coating	Alkyd paint without solvent white 60% H2O	1.5	kg
	Coating	Coating powder	0.65	kg
Boiler Weight			378	kg

E.2 Disposal Phase

E.2.1 Electric Boiler

	Material	Database process	Per. %	Desc.	Quantity	Unit
Insulation	Rock wool	Inert waste, for final disposal {GLO} treatment of inert waste, inert material landfill	12	Assembly weight	0.168	kg
	Glass fibre, vermiculite, ceramics	Inert waste, for final disposal {ROW} treatment of inert waste, inert material landfill	100	Remaining material	14.3	kg
Metals	Ferro metals	Steel and iron (waste treatment) {GLO} recycling of steel and iron	50	Assembly weight	135.1	kg
	Remaining metals	Scrap steel {CH} treatment of, inert material landfill	50	Remaining material	135.1	kg
		Inert waste, for final disposal {CH} treatment of inert waste, inert material landfill	50	Remaining material	5.8	kg
Electronics	Thermostat	Electronics scrap from control units {GLO} market for	23	Assembly weight	0.552	kg
	Cables	Used cable {GLO} treatment of	68	Assembly weight	22.1	kg
	Wiring, clamps	Waste electric wiring {CH} treatment of, collection for final disposal	8	Assembly weight	0.248	kg
	Remaining materials	Inert waste, for final disposal {GLO} treatment of inert waste, inert material landfill	100	Remaining material	12	kg
Plastics	Gaskets	Waste polyethylene {GLO} market for	0.2	Assembly weight	0.00096	kg
	Gaskets	Waste polyvinylchloride {GLO} market for	76	Assembly weight	0.1824	kg
	Handles, sealing	Waste plastic, mixture {GLO} market for	100	Remaining material	1.03	kg
Packaging	Instruction manuals, cardboard box	Paper (waste treatment) {GLO} recycling of paper	85	Assembly weight	0.935	kg
	Packaging film	Waste polyethylene {GLO} market for	100	Assembly weight	0.87	kg

	Warning stickers	Waste plastic, mixture {GLO} market for	100	Remaining material	0.01	kg
Painting	Paint	Waste paint on metal {IL} treatment of, collection for final disposal	100	Assembly weight	3.15	kg

E.2.2 Heat Pump

	Material	Database process	Per. %	Desc.	Quantity	Unit
Insulation	Polyurethane foam	Inert waste, for final disposal {GLO} treatment of inert waste, inert material landfill	100	Remaining material	6.8	kg
Metals	Ferro metals	Steel and iron (waste treatment) {RER} recycling of steel and iron	50	Assembly weight	245.6	kg
	Remaining metals	Scrap steel {CH} treatment of, inert material landfill	50	Remaining material	245.6	kg
		Inert waste, for final disposal {CH} treatment of inert waste, inert material landfill	50	Remaining material	85.3	kg
Electronics	Thermostat	Electronics scrap from control units {GLO}	23	Assembly weight	0.1978	kg
	Cables	Used cable {GLO} treatment of	68	Assembly weight	16.728	kg
	Wiring, clamps	Waste electric wiring {GLO} treatment of, collection for final disposal	8	Assembly weight	0.192	kg
	Remaining materials	Inert waste, for final disposal {CH} treatment of inert waste, inert material landfill	100	Remaining material	6.6	kg
Plastics	Gaskets	Waste polyethylene {GLO} market for	0.2	Assembly weight	0.0015	kg
	Gaskets	Waste polyvinylchloride {GLO} market for	67	Assembly weight	0.2948	kg
	Handles, sealing	Waste plastic, mixture {GLO} market for	100	Remaining material	1.32	kg
Packaging	Instruction manuals, cardboard box	Paper (waste treatment) {GLO} recycling of paper	85	Assembly weight	0.6885	kg
	Packaging film	Waste polyethylene {GLO} market for	100	Assembly weight	0.87	kg
	Warning stickers	Waste plastic, mixture {GLO} market for	100	Remaining material	0.01	kg
Painting	Paint	Waste paint on metal {ROW} treatment of, collection for final disposal	100	Assembly weight	2.2	kg

E.2.3 Gas Boiler

	Material	Database process	Per. %	Desc.	Quantity	Unit
Insulation	Rock wool	Inert waste, for final disposal {CH} treatment of inert waste, inert material landfill	12	Assembly weight	0.192	kg
	Glass fibre, vermiculite, ceramics	Inert waste, for final disposal {GLO} treatment of inert waste, inert material landfill	100	Remaining material	9.2	kg
Metals	Ferro metals	Steel and iron (waste treatment) {GLO} recycling of steel and iron	50	Assembly weight	163.6	kg
	Remaining metals	Scrap steel {ROW} treatment of, inert material landfill	50	Remaining material	163.6	kg
		Inert waste, for final disposal {ROW} treatment of inert waste, inert material landfill	50	Remaining material	9.2	kg
Electronics	Thermostat	Electronics scrap from control units {GLO} market for	23	Assembly weight	0.1288	kg
	Cables	Used cable {GLO} treatment of	68	Assembly weight	5.032	kg
	Wiring, clamps	Waste electric wiring {CH} treatment of, collection for final disposal	8	Assembly weight	0.136	kg
	Remaining materials	Inert waste, for final disposal {CH} treatment of inert waste, inert material landfill	100	Remaining material	5.5	kg
Plastics	Gaskets	Waste polyethylene {GLO} market for	0.2	Assembly weight	0.00116	kg
	Gaskets	Waste polyvinylchloride {GLO} market for	76	Assembly weight	0.1824	kg
	Handles, sealings	Waste plastic, mixture {GLO} market for	100	Remaining material	1.25	kg
Packaging	Instruction manuals, cardboard box	Paper (waste treatment) {GLO} recycling of paper	85	Assembly weight	0.935	kg
	Packaging film	Waste polyethylene {GLO} market for	100	Assembly weight	0.87	kg
	Warning stickers	Waste plastic, mixture {GLO} market for	100	Remaining material	0.01	kg
Painting	Paint	Waste paint on metal {ROW} treatment of, collection for final disposal	100	Assembly weight	2.15	kg

E.3 Transportation Phase

E.3.1 Electric Boiler

From country of origin to local port

Shipping	Distance km
New Jeresy-US, to Ashdod port - Israel	9,651

E.3.2 Heat Pump

From country of origin to local port

Shipping	Distance km
La Mede port- France, to Ashdod port - Israel	9,651

E.3.3 Gas Boiler

From country of origin to local port

Shipping	Distance km
New Jeresy-US, to Ashdod port - Israel	9,651

APPENDIX F

Life Cycle Impact Assessment (LCIA)

F.1 Electric Boiler

Impact category	Reference unit	Const.	Trans.	Operation	Disposal
Acidification potential - average Europe	kg SO2 eq.	36.2	0.779	209831	0.061
Climate change - GWP100	kg CO2 eq.	2902.228	38	18538616	9.371
Depletion of abiotic resources - elements, ultimate reserves	kg antimony eq.	0.298	0.000	5.434	0.000005
Depletion of abiotic resources - fossil fuels	MJ	30361.6	535	206826655	137.383
Eutrophication - generic	kg PO4--- eq.	49.2	0.135	43154	0.029
Freshwater aquatic ecotoxicity - FAETP inf	kg 1,4-dichlorobenzene eq.	7177	3.3	6142362	7.742
Human toxicity - HTP inf	kg 1,4-dichlorobenzene eq.	28384	16.988	7812824	4.751
Marine aquatic ecotoxicity - MAETP inf	kg 1,4-dichlorobenzene eq.	18256025	17726	30847498003	9159.935
Ozone layer depletion - ODP steady state	kg CFC-11 eq.	0.000	0.000002	0.436	0.000001
Photochemical oxidation - high Nox	kg ethylene eq.	1.83	0.025	7760	0.002
Terrestrial ecotoxicity - TETP inf	kg 1,4-dichlorobenzene eq.	238.654	0.163	60081	0.028

F.2 Heat Pump

Impact category	Reference unit	Const.	Trans.	Operation	Disposal
Acidification potential - average Europe	kg SO2 eq.	151	0.536	67845]	0.112
Climate change - GWP100	kg CO2 eq.	9351	26.54	5994152	16
Depletion of abiotic resources - elements, ultimate reserves	kg antimony eq.	5.654	0.0	1.757	0.000008
Depletion of abiotic resources - fossil fuels	MJ	87652	368	66873952	266
Eutrophication - generic	kg PO4--- eq.	209	0.093	13953	0.036
Freshwater aquatic ecotoxicity - FAETP inf	kg 1,4-dichlorobenzene eq.	25190	2.29	1986030	5.967
Human toxicity - HTP inf	kg 1,4-dichlorobenzene eq.	104121	11.70	2526146	5.526
Marine aquatic ecotoxicity - MAETP inf	kg 1,4-dichlorobenzene eq.	76329103	12212	9974024354	8755
Ozone layer depletion - ODP steady state	kg CFC-11 eq.	0.136	0.0000017	0.141	0.000001
Photochemical oxidation - high Nox	kg ethylene eq.	5.458	0.017	2509	0.003
Terrestrial ecotoxicity - TETP inf	kg 1,4-dichlorobenzene eq.	613	0.112	19426	0.051

F.3 Gas Boiler

Impact category	Reference unit	Const.	Trans.	Operation	Disposal
Acidification potential - average Europe	kg SO2 eq.	23.5	0.831	1349	0.077
Climate change - GWP100	kg CO2 eq.	24.5	41.1	1525500	12.8
Depletion of abiotic resources - elements, ultimate reserves	kg antimony eq.	25.5	0.000	0.259	0.000014
Depletion of abiotic resources - fossil fuels	MJ	26.5	571	22973231	171
Eutrophication - generic	kg PO4--- eq.	27.5	0.144	289	0.035
Freshwater aquatic ecotoxicity - FAETP inf	kg 1,4-dichlorobenzene eq.	28.5	3.5	37351	8.5
Human toxicity - HTP inf	kg 1,4-dichlorobenzene eq.	29.5	18.1	131062	6.234
Marine aquatic ecotoxicity - MAETP inf	kg 1,4-dichlorobenzene eq.	30.5	18928	170748848	10736
Ozone layer depletion - ODP steady state	kg CFC-11 eq.	31.5	0.0000027	0.235	0.0000008
Photochemical oxidation - high Nox	kg ethylene eq.	32.5	0.027	160.907	0.002
Terrestrial ecotoxicity - TETP inf	kg 1,4-dichlorobenzene eq.	33.5	0.174	1646.842	0.042

F.4 Total Impact Assessment for Each System

Impact category	Reference unit	Electric Boiler	Heat pump	Gas boiler
Acidification potential - average Europe	kg SO2 eq.	209868	0.831	1349
Climate change - GWP100	kg CO2 eq.	18541566	41.1	1525500
Depletion of abiotic resources - elements, ultimate reserves	kg antimony eq.	5.7	0.000	0.259
Depletion of abiotic resources - fossil fuels	MJ	206857690	571	22973231
Eutrophication - generic	kg PO4--- eq.	43203	0.144	289
Freshwater aquatic ecotoxicity - FAETP inf	kg 1,4-dichlorobenzene eq.	6149550	3.5	37351
Human toxicity - HTP inf	kg 1,4-dichlorobenzene eq.	7841230	18.1	131062
Marine aquatic ecotoxicity - MAETP inf	kg 1,4-dichlorobenzene eq.	30865780916	18928	170748848
Ozone layer depletion - ODP steady state	kg CFC-11 eq.	0.44	0.000002	0.23
Photochemical oxidation - high Nox	kg ethylene eq.	7762	0.027	160
Terrestrial ecotoxicity - TETP inf	kg 1,4-dichlorobenzene eq.	60320	0.174	1646

جامعة النجاح الوطنية
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تقييم دورة حياة أنظمة تسخين المياه لاستعمالات نادي رياضي

إعداد
علي محمد علي عباس

إشراف
د. عبد الرحيم أبو الصفا
د. محمد السيد

قدمت هذه الأطروحة استكمالا لمتطلبات الحصول على درجة الماجستير في هندسة الطاقة النظيفة واستراتيجيات توفير الاستهلاك بكلية الدراسات العليا في جامعة النجاح الوطنية في نابلس، فلسطين.

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الملخص

تقارن هذه الدراسة بين ثلاثة أنظمة تسخين مياه مقترحة لنادي صحي متوسط الحجم في مدينة نابلس في فلسطين . ولكونها الأكثر استخداما في الأسواق المحلية فقد تم اعتماد مرجل الكهرباء ومرجل الغاز والمضخة الحرارية لدراستها. وكنقطة مرجعية في اختيار الحجم المناسب من كل نظام فقد تم الاعتماد على الاستهلاك اليومي من المياه الساخن على درجة الحرارة المناسبة والذي قدر بمعدل ٨ متر مكعب من الماء على درجة حرارة ٤٣ مئوية.

ولتقييم الأثار البيئة المترتبة على دورة حياة هذه الأنظمة فقد استخدم اسلوب مركز العلوم البيئية في جامعة ليدن، حيث يتم تقسيم الأثار البيئية المترتبة إلى ١٠ أثار رئيسية. تطرقت الدراسة كذلك إلى التكلفة الإجمالية لكل نظام على اعتبار أن نسبة العائد هي ١٠٪ .

الدراسة بينت أن المضخة الحرارية هي الاقل استهلاكا للطاقة بينما يحل مرجل الغاز، بينما كان مرجل الكهرباء الأكثر استهلاكا. ومن جهة التكاليف وبالنظر إلي التكاليف الانشائية والتشغيلية للانظمة الثلاث، فقد اشارت النتائج إلى أن المضخة الحرارية هي الأقل تكلفة خلال فترة حياتها بواقع ١٠٤،٦٨٣ دولر امريكي ، بينما حل مرجل الغاز ثانيا بواقع ١٦٧،٤٢٨ دولر امريكي ، أما مرجل الكهرباء فقد كان الأعلى تكلفة بواقع ٢٤٦،٤٣٣ دولر أمريكي.

أما من ناحية الأثار البيئية المترتبة فقد كان هناك نوع من الإختلاف ، حيث أظهرت النتائج أن مرجل الغاز هو الأقل أثر على البيئة ، بينما تحل المضخة الحرارية ثانيا ، ومرجل الغاز ثالثا.

في نهاية الدراسة تم تطبيق اثنين من السيناريوهات لاختبار حساسية الأنظمة تجاه الظروف التشغيلية المختلفة. ففي أول حال تم افتراض أن الكهرباء المستعملة لتشغيل مرجل الكهرباء والمضخة الحرارية تم انتاجها بواسطة محطة توليد تعمل بالغاز الطبيعي عوضا عن الفحم ، كان هناك تحسن في المؤشرات البيئية ، لكن بقي مرجل الغاز هو الافضل من ناحية الأثر البيئي. وفي الحالة الثانية تم استبعاد الأثر البيئي المترتب على خطوط النقل والتوزيع والمحولات. نتائج المؤشرات البيئة للمضخة الحرارية ومرجل الكهرباء تحسنت بشكل كبير وملحوظ ، لكن هذا لم يغير في حقيقة أن مرجل الغاز بقي الأكثر صداقة للبيئة حتى تحت هذه الظروف.