KTH Industrial Engineering
and Management

LCC and LCA for Low Temperature Heating Integrated with Energy Active Envelope Systems

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Abstract

Windows has been always considered as heat sinks and they can account more than 25% of a building envelope. For this reason, its design and performance in dwellings play a major role in regulating the indoor environment. The construction sector has been investing in better insulation envelope systems for the last decades to reduce the heat transmissions losses and energy consumption in households.

LOWTE is a Swedish firm specialized in low energy building components and due to all these facts, it has recently developed a double slot energy active envelope window (EAW) for improving energy-saving in buildings. EAW is a window prototype that integrates low-temperature heating and energy active systems, and it is planned to be installed at Testbed KTH in Stockholm (Sweden). Waste heat from the current heating systems will be used during its whole operation.

Then, a life cycle assessment (LCA) will be accomplished for evaluating EAW feasibility and cost-effectiveness before its implementation. Furthermore, an LCA comparison with other two passive window systems will be made. A double-glazed and a triple-glazed window will represent the reference system and a competent alternative solution, respectively.

A sensitivity analysis for each model will be developed in order to consider multiples scenarios and obtain which variables affect the most EAW profitability. Thus, the feasibility of the EAW would be studied from an economic and environmental perspective.

The simulations of both models show the potential that EAW can represent for the current heating system in KTH Live-In-Lab apartments. Since EAW is quite subjected to the thermal conditions of the room, the ambience, and the internal flowing air; costs savings and avoided environmental impacts will depend mainly on the thermal performance of the whole system.

Keywords: EAW, U-value, energy savings, net present value, environmental impact, operating and maintenance costs.

Sammanfattning

Fönster har alltid betraktats som kylflänsar och de kan stå för mer än 25% av byggnadens kuvert. Av denna anledning spelar deras design och prestanda i bostäder en viktig roll för att reglera inomhusmiljön. Byggsektorn har investerat i bättre isoleringshölje system under de senaste decennierna för att minska värmeöverförings förlusterna och energiförbrukningen i hushållen.

LOWTE är ett svenskt företag som är specialiserat på byggnadskomponenter med låg energi och på grund av alla dessa fakta har det nyligen utvecklat ett fönster med dubbelspalt och energi aktivt kuvert (EAW) för att förbättra energibesparing i byggnader. EAW är en fönster prototyp som integrerar låg temperatur värme och energi aktiva system som kommer att installeras på Testbed KTH i Stockholm (Sverige). Avfallsvärme från de nuvarande värmesystemen kommer att användas under hela driften.

Sedan kommer en livscykelanalys (LCA) att genomföras för att utvärdera EAW med avseende på-genomförbarhet och kostnadseffektivitet innan denna implementering. Dessutom kommer en LCA-jämförelse med andra två passiva fönstersystem att göras. Ett dubbelglasat och ett tredubbelt fönster representerar referenssystemet respektive en kompetent alternativ lösning.

En känslighetsanalys för varje modell kommer att utvecklas för att ta hänsyn till flera scenarier och utvärdera vilka variabler som mest påverkar EAW-lönsamhet. Således skulle genomförbarheten för EAW studeras ur ett ekonomiskt och miljömässigt perspektiv.

Simuleringarna av båda modellerna visar potentialen som EAW kan representera för det nuvarande värmesystemet i KTHs Live-In-Lab-lägenheter. Eftersom EAW är helt utsatt för de termiska förhållandena i rummet, atmosfären och den inre flödande luften; beror kostnadsbesparingar och minskad miljöpåverkan främst på värmeprestandan för hela systemet.

Nyckelord: EAW, U-värde, energibesparingar, nuvärdet, miljöpåverkan, drifts- och underhållskostnader.

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Nomenclature and abbreviations

Abbreviations

BAU	Business as Usual
BBR	Buildings regulation documents
BEES	Building for Environmental and Economic Sustainability
BIPVT	Building integrated photovoltaic thermal
CAPEX	Capital Expenditures
CHP	Combined Heat and Power
COP	Coefficient of performance
EAW	Energy active window
EKS	Bovekert Series of Provision on the Application of European Construction Standards
ELCD	European reference Life Cycle Database
EPA	Environmental Protection Agency
EPBD	Energy Performance in Building Directives
Eurocodes	European Construction standards
EU	Europe Union
GHG emissions	Greenhouse gasses emissions
HX	Heat exchanger
IGU	Insulated glazed unit
ILCD	International Reference Life Cycle Data System
ISO	International Organization for Standardization
IPCC	Intergovernmental Panel on Climate Change
JEMAI	Japan Environmental Management Association for Industry
KTH	Kungliga Tekniska Högskolan
LCA	Life Cycle Assessment
LCC	Life Cycle Costs Assessment
LCCA	Life Cycle Costs Assessment
LCT	Life Cycle Thinking
LIL	Live-In-Lab
LowEx	Low exergy
LTH	Low temperature heating
MVHR or FTx	Mechanical ventilation with heat recovery
NPV	Net Present Value
NPV1	Net Present Value of the double-glazed unit (System 1)
NPV2	Net Present Value of the triple-glazed unit (System 2)
NPV3	Net Present Value of the Energy Active Window (System 3)
OPEX	Operating expenditures
OPEX1	Operating costs of the room with the double-glazed unit (System 1)
OPEX2	Operating costs of the room with the triple-glazed unit (System 2)
OPEX3	Operating costs of the room with the Energy Active Window (System 3)
SCNH	Swedish Centre for Zero-energy buildings
SDG	Sustainable Development Goals
SLS	Selective Laser Sintering
US	United States

Parameters in equations

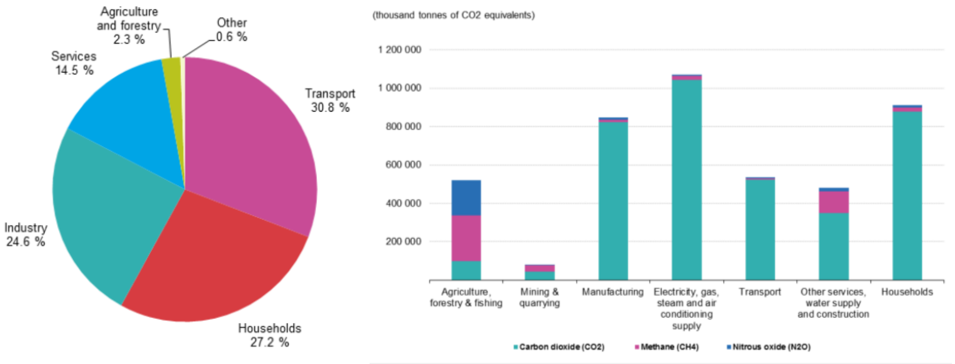
A_{window}	Window surface
ΔT	Temperature interval between ambient and indoors temperature
Cp_w	Heat capacity of the water
Cp_a	Heat capacity of the air
C_n	Future value cash flow in n period
C_o	Initial investment costs
DS	Double slot unit

L	Heat transmission losses
n	Time period
$\dot{m}_a$	Mass flow air
$\dot{m}_w$	Water flow rate
η_{HX}	Efficiency of the heat exchanger
PV	Present Value
Q	Heat
Q_{sun}	Solar heat gain
Q_{people}	Internal heat gain due to human heat
$Q_{facilities}$	Internal heat gain due to household and electrical appliances
$Q_{heating\ system}$	Heat supply from the heating systems
R	Discount rate
T	Temperature
$T_{w\ in}$	Temperature of the water at the entrance (inlet) of heat exchanger
$T_{w\ out}$	Temperature of the water at the outlet of heat exchanger
$T_{a\ out}$	Temperature of the supply air from the heat exchanger to double-slot unit
$T_{a\ in}$	Temperature of the return air from double-slot unit to the HX
U_m	Average heat transfer coefficient
v_w	Water flow rate speed
v_a	Internal air speed

1. Background

The increase of energy consumption of the last decades all over the world is a fact that cannot be ignored. All the countries are becoming more aware regarding the importance of reducing their energy demands and CO_2 emissions.

According to the statistics, the energy consumed by the buildings rises up to 40% of the total final energy consumption[1] in the European Union (EU) **[1]**. The building sector covers all the private houses, commerce, several public administrations, and services. In Figure 1 the final energy consumption by sector is shown in EU as well as the considerable contribution of the households in the total greenhouse gases emissions (GHG emissions)[2].



a. b.

Figure 1: a) 2017 final energy consumption by sector in the EU-28. b) Greenhouse gas emissions by economic activity, EU-28, 2017 **[2]**

Based on these figures, it is logical that investing in modern low-emissions houses and renovating old buildings will reduce final energy consumption and will save on costs in a long-term perspective. In fact, EU Member States governments are strictly subjected to different regulations regarding building energy performances. The existing Energy Performance in Building Directives (EPBD) are **[3]:**

- EPBD 2002/91/EC
- EPBD recast 2010/91/EC requiring certification of energy consumption levels (with a minimum energy performance) for owners and tenants. and also requiring the Member States to ensure that by 31 December 2020, all new buildings are nearly zero-energy buildings.

Moreover, the so-called Directive 20/20/20, signed in 2007 by the Governments of European Union, established a 20 % reduction of greenhouse gas emissions by 2020, 20% reduction of energy consumption through improved energy efficiency and 20% increase of the renewable energy use **[4].** There is also a 2050 goal that states the 80-95% reduction in greenhouse gases compared to 1990 levels.

Designing new systems in order to improve the energy efficiency and consumption of the buildings is becoming a good solution for reaching the desired energy goals. Some other advantages that can be achieved by improving energy control on buildings in EU are as follows **[5]:**

- Lower energy demand, that would help decrease dependence on energy imports.

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[1] Final energy consumption is the total energy consumed by end users. It excludes energy used by the energy sector, including for deliveries, and transformation.

[2] A greenhouse gas (GHG) is a gas that absorbs and emits radiant energy within the thermal infrared range. Greenhouse gases cause the greenhouse effect. The primary greenhouse gases in Earth's atmosphere are water vapor, carbon dioxide, methane, nitrous oxide and ozone.

- Lower energy bills that can especially benefit vulnerable customers and can help fight against fuel poverty.
- Imported natural gas reduction, because it is used mostly in buildings (more than 60%).
- Solving the problem of peak loads and insufficient energy production, thus increasing the overall resilience of the EU's energy system.

To be more specific, in 2019 Swedish households consumed 87 TWh of final energy, which represents 59,6% of the total final energy consumption of the country (Swedish Energy Agency and Statistics Sweden).

In fact, up to 50% of the energy used in buildings is for heating and cooling systems. Space heating and indoor climate systems are the main end-use on average and it is even more marked in Scandinavian countries. For instance, Sweden used about 13 MWh per dwelling in 2009 only for heating purpose while Spain used less than 6 MWh.

According to Eurostat statistics, in the following table is defined the final energy consumption in the residential sector by type of end-use for Sweden in 2017. **[1].**

Table 1: Share of 2017 final energy consumption in the Swedish residential sector by type of end-use.

Space heating (%)	Space cooling (%)	Water heating (%)	Cooking (%)	Lighting and appliances (%)	Other end uses (%)
54.5	0.0	13.6	1.5	19.1	11.3

1.1 Energy systems in buildings

1.1.1 Low-temperature heating system

Reducing these large quantities of energy used for heating is only possible if we understand how the heating of buildings works. In residential areas, the most common heating systems are gas boilers, piping systems based on hot water and radiators or convectors that work as heat emitters. **[6]**

However, these systems are usually accomplished by a heat distribution system operating at high temperatures (90-70 °C). For example, to realise a pleasant indoor air temperature of approximately 20 °C, often the system water is heated up to 90 °C by a gas flame in the boiler which is about 1200 °C **[6].**

Nonetheless, it could be reached if all the surrounding surfaces in a room are at 20 °C. By this way, the heating system supplies a good energy quality of 20°C **[7].** This not only enables using sustainable heat sources, like solar, geothermal and waste heat, but also reduces the size of the systems and the energy consumption of the building.

Hence, currently companies are developing new heating systems with the aim of dropping the mentioned high temperatures of heating systems, as well as improving the energy efficiency and the use of sustainable sources. Nowadays the principle energy resource used in households is gas (36%), followed by electricity (24,1%) and only the 17,5% of the energy used in households comes from renewable sources **[1]**. Then, lowering the temperatures for heat distribution systems permits the use of low valued energy as a resource. The concept of 'low valued energy' is related to the low exergy heating and cooling systems, and it we will be defined in next section

In Table 2 is shown a classification of heating systems by its design temperature.

Table 2 Definition of temperature ranges for heating designs **[8]**

System	Supply flow	Return flow
High temperatures (HT)	90°C	70°C
Medium temperatures (MT)	55°C	35-40°C
Low temperatures (LT)	45°C	25-35°C
Very low temperatures (VLT)	35°C	25°C

Therefore, low-temperature heating (LTH) system can be accurately defined as a heating system in which the hot water leaving the heat generator is always at a temperature not exceeding 45°C. This condition must be fulfilled even on the coldest day, or the called 'design day', in which the dwelling is subjected to the worst scenario and the maximum heat losses must be considered **[9].** Some well-known LTH emitters are radiators, convectors, air heaters as well as underfloor, walls or ceiling heating pipes that work under such temperature.

1.1.2 Low-exergy systems

Another energy system that this study will focus on are the low exergy (or LowEx) systems which are defined as heating or cooling systems that allow the use of low valued energy as the energy source.

Regarding the concept of "low valued energy" or "low quality energy", it can be defined as the energy delivered by sustainable energy sources (i.e., through heat pumps, solar collectors, either separate or linked to waste heat and energy storage) and in the end, it means low temperature heat **[10] [11].**

In contrast, one can define the "high valued energy" or "high quality energy" as electricity, mechanical energy or some forms of chemical stored energy, for example, the fossil fuels **[11].** Then, high valued energy sources are almost pure exergy whereas low valued energy contain low exergy[3] and higher entropy.

For this reason, high quality energy is more valuable and appreciated than low energy quality. According to the second law of thermodynamics, high quality energy can easily be used to produce low quality energy. For example, electricity can be easily used to produce low temperature heat. Nevertheless, the opposite is much more difficult and sometimes even impossible **[11].** The same occurs when we convert wind, waste heat or sun into electricity. The conversion efficiency is very low, and the final reason of it comes from the quantity of exergy that was contained in these low valued energy sources.

Exergy can be also understood as the kind of energy that is entirely convertible into other types of energy. For example, a car-battery and 1 kg water at a temperature of 43 °C in an ambient temperature of 20 °C both have 100kJ energy. But it is obvious that the energy stored into the battery is more useful, easier to transform than the water energy. Hence, the battery has more exergy than the water **[10].**

That is why high-quality energy is so appreciated, because in each step of energy conversion there are losses that one must consider. However, it is true that low valued exergy has notable advantages such its low operation costs, wide distribution and eco-friendly. Through its energy potential is limited, it fits well with the requirements of heating the air room whose temperature is low.

Nevertheless, in exergetic terms, one could say that LowEx systems save exergy rather than energy. In other words, LowEx systems save exergy because they let us use low quality energy resources to supply

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[3] In the theory of thermodynamics, the concept of exergy is stated as the maximum work that can be obtained from an energy flow or produced by a system. Entropy in contrast represents the unavailability of a system's thermal energy for conversion into useful work.

household energy demand instead of using high quality resources (e.g. electricity, which is pure exergy). It is the change of heating water by waste heating instead of using an electrical heater.

In practical, LowEx systems means that they will provide heating and cooling energy at a temperature close to room temperature and by producing energy from sustainable resources. Since they reduce the temperature interval, they represent a good option for the indoor comfort because many advantages such as the ones mentioned below. **[10] [12]**

- They solved problems related with the facilities and tubes. HT systems must be designed as heat-resistant and to endure high temperatures. Therefore, LT increased system lifespan.
- They are compatible with the existing natural gas or oil boilers with a conventional 80% of efficiency. **[11]**
- Homogeneous and comfortable indoor temperature because of a better thermal comfort and a better indoor air quality. In HT systems, the air does not lead homogenously in space. **[13]**
- The lower temperature that the heating system has to reach means lower energy consumption for heat production and lower heat losses. This is due to both of them are proportional to the temperature interval (ΔT).

  According to a KTH research hold in 2012, in which low temperature heating performance and thermal comfort were evaluated in five dwellings of Stockholm, shows that LTH systems can limit energy consumption in over 50% or even more. (Figure 2) **[13].**

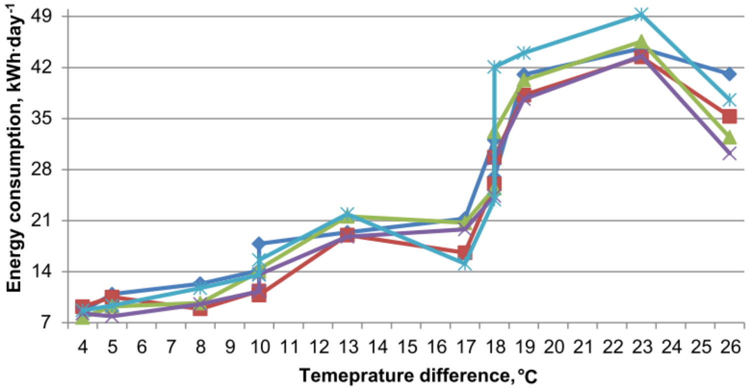

Figure 2 Heating load as a function of temperature difference between inside and outside for the five dwellings **[13]**

- Less emissions because all the system works at lower temperature. The lower energy consumption implies lower generated emissions.

- The system is much environmental friendlier due to its potential of using low temperature heating and sustainable sources. It also gives a huge flexibility in terms of fuel choice thanks for the diversified heat sources and its increased potential for CHP.
- Higher efficiency because of the lower temperature, which implies lower heat losses as mentioned before. As a rule of thumb, the coefficient of performance (COP)[4] of a heat pump improves between

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[4] COP is defined as the ratio between the useful heat supplied by the heat pump and the in-put work that it requires. It can be expressed by the ratio between the hot reservoir temperature and the temperature difference between hot and cold reservoirs. For this reason, one way of increasing COP of a heat pump is reducing the temperature interval.

1-2% for every degree reduction in supply water temperature. **[8]** **[13]**. From the definition of COP, Also, solar collectors increase its efficiency with lower temperatures.

Despite all the advantages, these systems have some drawbacks such as:

- Higher costs in investments than a conventional system.
- They require additional heat transfer surface.
- Sometimes they are not appropriate for the process needs.
- They are limited by domestic water heating.
- The heat transported for a given pipe diameter is lower.

1.1.3 Passive and active systems in envelope buildings

Environmental control systems such as lighting, heating, and cooling systems in a building can be categorized into two groups: “passive” and “active” systems.

“Passive” systems are defined as building envelope systems to make use of potentials that are found in the immediate environment such as the sun, wind, and others to illuminate, heat, ventilate, and cool the built environment **[10]**. Passive design does not convert those resources into useful energy. It uses the layout, fabric and form to reduce or remove the demand. Examples of passive design include optimising solar gains controls, maximise daylighting, manipulating the building form, facilitate natural ventilation, making effective use of thermal mass etc. **[14]**

In contrast, an “active system” uses or can produce electricity by itself. It uses technologies such as solar panels, heat recovery systems, or the use of renewable energy sources. As is expected, this technology fits well with the objectives that also low exergy systems looks forward. It takes benefits from the building environment to produce electricity from sustainable resources such as ground heat, wind, sun etc. implies that we are converting low temperature heating into high quality energy. According to the second thermodynamic law. the conversion efficiency is low.

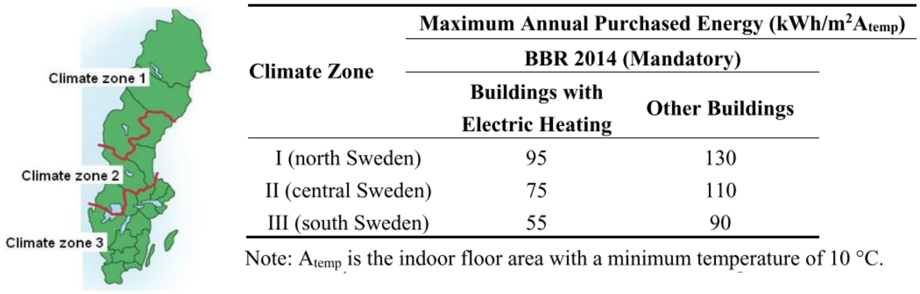
We could say that LTH and LowEx systems are in general active elements that are conditioned by the passive elements. That means they need well-thermal insulation, no ventilation losses, good quality of heat sources to be efficient enough for being installed in the building envelope.

1.1.4 Swedish building and construction regulations

In Sweden, the National Board of Housing, Building and Planning (Boverket) is the government organization responsible for regulating the energy performance of buildings. It established in January 2012 the new standard building regulations in Sweden **[15]**.

Boverket, in combination with the Swedish Centre for Zero-energy buildings (SCNH), defines the new building codes or building regulation documents (BBR). BBR contains several building performance criteria, applicable to new buildings and major renovations of existing buildings, with the purpose of fulfil the EDPB and the European Construction standards (Eurocodes).

For instance, to fulfil the EDPB 2010 (mentioned in Section 1), Sweden has introduced the ‘specific energy use’ concept in its building code. Specific energy use is the purchased energy use excluding electricity for household purposes. **[15]**



Climate Zone	Maximum Annual Purchased Energy (kWh/m^{2}A$_{temp}$)	
	BBR 2014 (Mandatory)	
	Buildings with Electric Heating	Other Buildings
I (north Sweden)	95	130
II (central Sweden)	75	110
III (south Sweden)	55	90

Note: A_{temp} is the indoor floor area with a minimum temperature of 10 °C.

Figure 3 Maximum annual purchased energy values in 2014 for new residential buildings with electric heating. **[13] [15]**

The Eurocodes together with Boverket Series of Provision on the Application of European Construction Standards (EKS) constitute the only system for the design of structures in Sweden. To be more specific, the current EKS 11 (2019), the official regulation of the application of the European construction standards. For instance, it establishes that the maximum installed electric input for heating is 4,5kW for single-family and multi-dwelling blocks in Stockholm. Other example is that the average heat transfer coefficient (U_m) expressed for a single-family dwelling smaller than 50 m^2 is 0.4 W/m$^2\cdot$K **[16][18]**

However, their energy targets have had little impact in practice because of the ease of reaching these regulations. For instance, the energy use per house and per square meter without including the household electricity in a single-family dwelling was 85.1 ±9.0 kWh/m2 (Swedish Energy Agency 2013)

However, there are also several economic and social drivers and barriers that affect the introduction of new systems in the new and retrofitted Swedish buildings. Some of them are summarized in the following table. **[17] [19]**

Table 3 Drivers and barriers for implementing new energy systems in buildings in Sweden.

Drivers	**Barriers**
• More efficient buildings world trend. • Attitude of the consumers and the companies are changing into a more responsible behaviour regarding energy consumption. • European Union as a regulatory driver. • A better insulation and new techniques for reducing ventilation losses (new piping materials etc.) reduce the heating demand of modern buildings. This ongoing trend enables smaller heating capacity needs. **[12]** • Their higher compatibility with solar, geothermal, heat pumps, condensing boilers or waste heat sources. • They offer lower life cycle costs, especially for the competition between district systems and independent building systems. This means long life, low losses and low maintenance. **[12]** • Educational initiatives and some construction firms have started to offer passive houses	• Lack of information on new technologies, hidden costs or distortion in fuel prices that inhibit investments from public and private organizations. Customers and construction companies need to know that these systems are feasibly and tangible. • Split agents' interests regarding a building project. For example, a construction firm cannot take benefits from the energy savings of passive houses. • Lack of LCC perspective. For instance, investments with long pay-back period are more ignored than the ones which shorter periods. • The slow response because the risk associated to the untested technologies. They can attain higher costs and complications in the construction, operation, or the maintenance than the conventional and proven systems. Constructions houses need

courses before they began to build. To the course the attendants were engineers, energy coordinators, project managers even sellers.	to have a long-term strategy regarding the implementation of new technologies. • It is favourable a broad knowledge of the system, including designers, engineers, managers, consultants, subcontractors… There are many knowledge gaps that difficult the credibility of these technologies. • Buildings regulations, codes developments and standards often lag energy innovations.

1.2 Windows in buildings

The building envelope (foundation, roof, walls, windows, doors and floors) primarily provides shelter and protects the occupants from the outdoor environment. Its design and performance play a major role in regulating the indoor environment to create a comfortable zone. Even in larger buildings, where the internal gains may exceed the transmission losses, the need of good insulation has been very important as it increases the thermal comfort **[20]**

Different parameters are used for measuring the thermal transmittance of the parts of a building. The one considered in this thesis is the universal U-value (or U-factor), expressed in $W/m^2 \cdot K$ and mentioned briefly in Section 1.1. Well-insulated parts of a building have a low thermal transmittance whereas poorly insulated parts of a building have a high thermal transmittance.

As walls, roof and floors today are rather good, with U-value around 0.1 and 0.2 $W/m^2 \cdot K$ **[21]**, more attention is being focused on windows which can account for 10 to 25% of a building's exposed surface **[22]**.

Windows perform multiple functions in a building envelope, acting as an interface to transmit light, circulate air, and provide outdoor view. While windows are available in different designs and sizes, their main components include the frame, sash, and insulated glazed unit (IGU). **[23]**

1.3 LOWTE project in KTH Live-In-Lab

KTH Live-In Lab offers a test environment ranging to housing, installation and management organizations. Research and testing can be carried out in real buildings, which means that not only the product or service itself is evaluated.

Among different projects, Testbed KTH, located in KTH Campus Valhallavägen, is developing in a 300 sqm building permit-free innovation environment with alterable student apartments. The size of standard apartments is almost 21 sqm and they enable to study technical innovations for a sustainable student housing. For instance, hot water and heat are generated via heat pumps connected to 12 boreholes with a total length of 360 m and the roof surfaces are covered by 1150 sqm of photovoltaic panels. There are many systems that monitoring hot water, electricity, CO_2 and light are measured in all apartments. **[24]**

Figure 4 KTH LIL **[24]**

One of the projects included in Testbed KTH is the implementation of a window prototype designed by LOWTE. LOWTE is a Swedish firm specialized in low energy building components due to their facilities usually work at low temperatures, from 4 to 30 ºC of temperature interval. Recently, they have developed the double slot energy active envelope window (EAW) for improving energy-saving in buildings.

Since this window consists of a low-temperature and low-exergy system, the possible energy savings and its economic and environmental impacts in comparison to the current system will be the purpose of this study. The installation of one EAW will be made in the apartment 0802-31004, whose plan is attached in Appendix A (Figure 57). The total surface of the apartment, counting with the bathroom, cover almost 21m^2. The surface of the room reaches almost the 17 sqm.

Figure 5 Plan and dimensions. **[24]**

Currently, KTH LIL provide the heat demand of the apartments by:

- A ventilation system with heat recovery (MVHR or FTx system) thar apart from the renovating the air of the whole apartment, it supplies warm air for indoor comfort temperature inside the room. The FTx is comprised only by one unit that supplies the required air for the four apartments.
- Underfloor heating that maintains a comfort indoor temperature in the bathroom.

- Ground heat pumps that supply domestic hot water.

This study is going to focus only on the room's heat demand. The sole variation in heat demand due to a better insulation could occur in the FTx flow rate supply.

It is interesting to notice that this project is quite related to Sustainable Development Goal (SDG) 7 and 9[5], due to the aim of obtaining clean energy and decreasing the energy household consumption. Furthermore, it can be related to SDG 11, 12 and 13 regarding the sustainability of the product by using waste heat and its purpose of being environmental-friendly.

In the end, this thesis will contain a comparison with two other window systems that would be hypothetically installed in KTH LIL. Then, a double-glazed and a triple glazed window will be compared with a prototype of an energy active window (EAW) as an energy active envelope system. The comparison will be done during their whole lifespan.

In the next section, the Life Cycle Thinking of a product is introduced for a better understanding of the methodology that is going to be followed.

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[5] SDG 7 is related with "Affordable and clean energy", SDG 9 with "Industry, innovation and infrastructure", SDG 11 with "Sustainable cities and communities", SDG 12 with "Responsible consumption and production" and SDG 13 with "Climate action".

2. Objectives of the study

The aim of this study is to analyse the feasibility and cost-effectiveness of the EAW during the next 20 years before its installation. Furthermore, the environmental impacts of the EAW performance will be studied. The estimations will be made by developing an economical and environmental model that will cover its lifespan. The scope of both studies is detailed in Section 6.1 and 7.1 respectively.

Besides the timeframe has been selected as a maximum for a suitable payback, this period should be representative enough for making a suitable estimation of the maintenance and the energy savings during its operation phase. Then, it is expected that the accumulative costs of the EAW would be lower in comparison to the ones of the double-glazed window in these 20 years.

The mentioned LCC and LCA study will be applied for three systems (Figure 6):

- Double-glazed window (reference system)
- Triple-glazed window
- Energy Active Window

In this study the insulation improvement is based on the different type of glazing. The frame as other common components are assumed to be identical for the three systems. The description of each system is attached in Section 4.

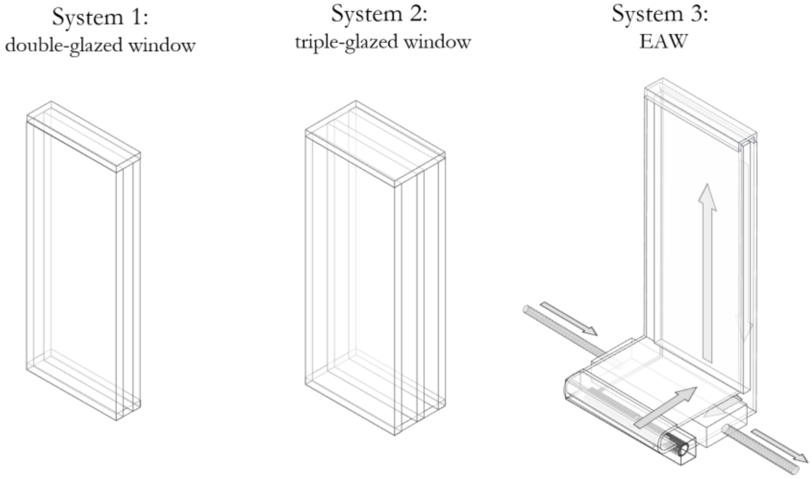

Figure 6 Sketch of the window systems.

The location of the three window systems would be in KTH Live-In-Lab, Stockholm (Sweden). The possible energy savings are studied for the current heat demand of the room of one apartment, without including the heat load of the bathroom.

Methodology and general assumptions

After a deep data collection procedure, LCT methodology (explained in Section 3) is followed by generating the LCC and LCA models. Several data inputs needed for the simulations are presented in Sections 5, 6.2, and 7.2.

After the validation of the two models, the 'business as usual' (BAU) [6] or base-case scenario was simulated by entering the parameters that are likely to occur. These results are shown in Section 6.3 and 7.3

Due to the great uncertain that the model is subjected to, a subsequent sensitivity analyses for each of the models are made. In this one, a range of values for the uncertain inputs used in BAU scenario will be studied. The sensitivity analyses represent a valuable source to understand better the system's behaviour and are presented in Section 6.4 and 7.4 respectively.

Some of the design assumptions of the EAW are mentioned in Section 4.3 such as the size of the window, the data sheet of the components that it includes etc. The system boundaries will be for both models the components of the window systems (Figure 6). Some specific details regarding the system boundaries will be made for each model in its correspondent section.

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[6] According to the Oxford Reference, BAU scenario is used for future patterns of activity which assumes that there will be no significant change in people's attitudes and priorities, or no major changes in technology, economics, or policies, so that normal circumstances can be expected to continue unchanged.

3. Life Cycle Thinking

Life Cycle Thinking (LCT) is about going beyond the traditional focus on production site and manufacturing processes to include environmental, social and economic impacts of a product over its entire life cycle. **[25].**

The term of life cycle from a productive perspective consists of five stages: product conception, design, product and process development, production and logistics. However, EAW is subjected to the customer perspective's phases too, which are: purchase, operating, support, maintenance and disposal. **[26]** In terms on product life cycle, a generic representation of a product life cycle is shown in Figure 7.

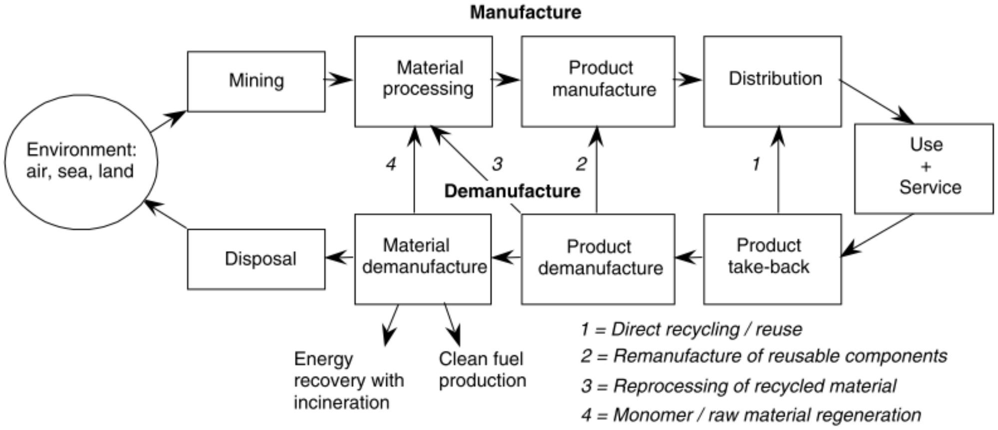

Figure 7 Generic representation of a product life cycle **[27]**

In each life cycle stage, there is the potential to reduce resource consumption and improve the performance of products. Some advantages or disadvantages are shown in the table below.

Table 4 Several advantages and disadvantages of LCT. **[25]**

Advantages	Disadvantages
It allows to integrate in a single value the complexity of production and consumption of a product's system.	Depending on the degree of precision required, the model can become very complex. It requires a complete database, material and human resources and computer tools.
Due to the integrated approach, each design phase can be analysed in parallel as a unitary process.	The identification, evaluation and weighting as well as the input of the variables has a high degree of subjectivity and requires the good judgment of the model developer.

In order to calculate the costs and the environmental impact of a product, Life Cycle Costs Analysis and Life Cycle Assessment will be fundamental pillars for LCT concept.

3.1 Life Cycle Costs Analysis

Life cycle thinking is increasing among constructors. Indeed, a survey by Sterner asking professional clients in the Swedish building sector about the consideration of life-cycle costs analysis (LCCA) in their decision-making process, came to the result that 66% of those who replied used the method. **[28]**

This methodology is quite extensive. Therefore, this document will explain only the models or methodologies in which we are interested in, as well as the specific economic factors that can affect the concerned window.

The purpose of LCC can be simplified as capturing all types of financial costs to a product or process along its whole lifespan, that means it the overall product cycle life. It has been original developed for being an effective engineering tool for providing decision support.

It is important to consider that the output of these methodology only looks at economic costs, and just in some cases, delivers approaches to quantify environmental or social costs. **[27]**

3.1.1 LCC model

There are many ways of performing LCC and the way of classifying them have been changing through the years. In the simplest way, there are three different main models: conceptual models, analytical models, and heuristic models **[26]**. Furthermore, "Life-Cycle Costing Using Activity-Based Costing and Monte Carlo Methods to Manage Future Costs and Risks" (2013) considers four different models (analogy, parametric, engineering cost methods, and cost accounting) and then the author subdivides each methodology into more techniques, including more specific methods in each subdivision.

Costs can be categorized in numerous ways depending on the certain type of LCC problem. There is a huge difficulty of quantifying costs as the project become broader and broader, with much more external factors. The Table 5 shows the category of the costs that we are going to use for the calculation tasks. Other way to categorize the costs are between capital expenditures (CAPEX) and operating expenditures (OPEX). However, they are usually used when a company is acquiring new equipment, in which the first investment and the operating costs attained to that equipment affect in the final decision of purchase.

For this thesis, these models are simplified into general life cycle cost models and specific life cycle cost models as it is shown in "Life Cycle Costing for Engineers" (2010) by Dhillon. As we mentioned, it will estimate the future costs in a component level, considering the cashes flows as a result of continuous changes of the acquisition, operational and disposal costs.

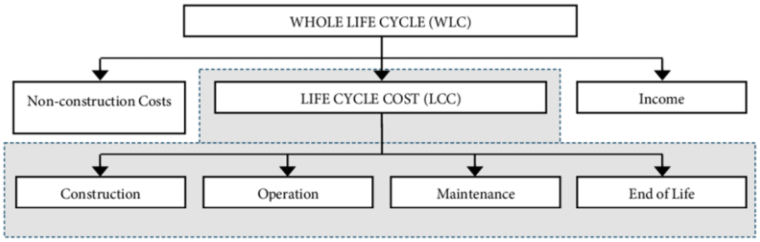

Figure 8 Whole life cycle. **[27]**

For calculating the life cycle cost for the EAW, we will simplify the model that was developed by the Material Command of the U.S. Army **[27]**:

$$LCC = C_{investments} + C_{operation} + C_{maintenance} + C_{disposal}$$

Table 5: Costs categories **[26]**

Investment cost	• cost of production • initial training cost • transportation cost • cost of data • cost of engineering changes • nonrecurring investment cost • cost of system test and evaluation • production phase system or project management cost • cost of initial spares and repair parts • operational or site activation cost • other investment costs
Operating costs	• cost of indirect support operations • consumption cost • electricity consumption
Maintenance cost	• cost of military personnel • cost of depot maintenance • cost of material modifications or replacements
Dismantling and disposal costs	• cost of other direct support operations such as recycle etc.

3.1.2 Economic factors

To analyse the profitability of a projected investment or project, some economic parameters have to been taken into account such as the Net Present Value (NPV), the discount rate, the payback, the interest, accumulative costs etc.

- **Lifespan:** It is important to make the distinction between the technical lifetime and the economic lifetime. In this analysis, regarding the prices considered, we are taking the economic lifetime of all assets.

- **Cashflow:** The cashflows can be defined as the total amount of liquid money being transferred into and out of the system during its lifespan. In contrast, to obtain a 'discounted cashflow' or 'actual cashflows' there is need to convert future costs into their equivalent in present ('present value'). The discount rate is needed for obtaining these discounted cashflows.

- The **discount rate (r)** defines the weight of costs occurring in the future to the present value because it considers the economic development in the sector. The discount rate is the interest rate that the Federal Reserve Bank charges to the depository institutions and to commercial banks on its overnight loans. **[29]**

  In the practice, the discount rate is used in the concept of the Time value of money- determining the present value of the future cash flows in the discounted cash flow analysis. It defines the weight of costs occurring in the future to the present value because it considers the economic development in the sector. It means that time influence on money value and for instance, 1000 SEK today will not have the same value as 1000 SEK in ten years.

This discount rate is decided by the Central Bank, not by the market, and it is not affected by the economical demand or supply needs. The central bank of Sweden (the Sveriges Riksbank or simply the Riksbank) abolished in 2002, the 'Discount rate' and replaced by a 'Reference rate' with no bearing on monetary policy **[30]**

- **Net Present Value (NPV)** is the difference between the present value of the expected cash inflows and the present value of cash outflows over a period of time. NPV is used in capital budgeting and investment planning to analyse the profitability of equipment and devices with a long-life span. It is assumed that an investment with a positive NPV will be profitable, and an investment with a negative NPV will result in a net loss.

  To convert future costs into their equivalent in present:

$$PV = \frac{C_n}{(1+r)^n}$$

PV: present value [SEK]
Cn: future value cash flow in n period [SEK]
r: discount rate [%]
n: time period [year]

And the net present value includes the initial investment costs:

$$NPV = -C_o + \sum \frac{C_n}{(1+r)^n}$$

Co: initial investment costs [SEK]

- The **discounted payback period** can be defined as the amount of time that takes to recover the initial investment. The comparison of costs should be given by a similar graph of the Figure 9, in which the **accumulative costs** are represented for both alternatives. After the intersection of the two cost functions, the difference between them represent the saving costs of the proposed system.

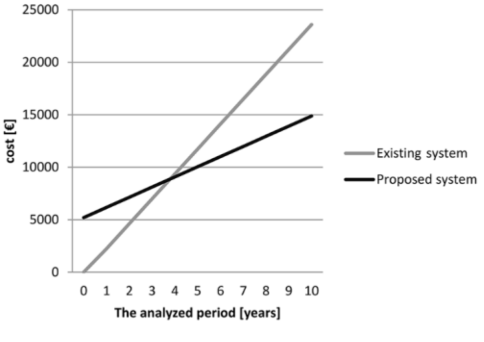

Figure 9 Generic representation of a product life cycle. **[27]**

- Variations in the **electricity price** will affect the operating costs of the devices that consume electricity during their operation phase. In 2011 Sweden was divided into 4 electricity areas (Figure 10), so there is not a unique electricity price for the country. Nordpool is the principle company that regulates the electricity in the country.

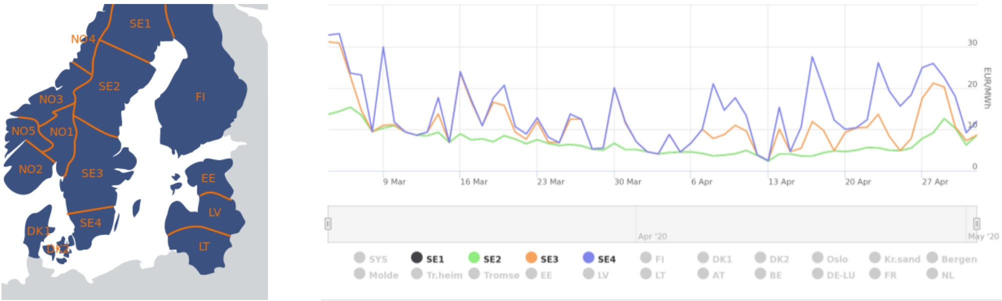

Figure 10 Electricity zones and example of electricity price variations. **[31]**

Also, we should consider for this analysis the range of currency change, from Swedish Krona to Euro. The currency is directly linked to the economy and the politics of a country. If the currency changes, consumption costs will change, as well as the final NPV.

Therefore, it is necessary to make a prediction of the future evolution of the electricity price in Sweden for the calculation of the operation costs year after year until 2040.

3.2 Life Cycle Analysis

The Life Cycle Assessment represents a fundamental pillar of Life Cycle Thinking. This concept contributes to the goal twelve of the well-known SDG, called Sustainable Consumption and Production.

One can define the Life Cycle Assessment (LCA) as an internationally standardised tool (ISO14040 and ISO14044) for the integrated environmental assessment of products, goods as well as services **[32]**. In other words, an LCA captures environmental impacting factors of a product that cannot be expressed fully in monetary terms and gives these aspects a weight in the process of deciding about its feasibility. Thus, it provides a standardised method to analyse upstream and downstream consequences derived from decisions in all the lifespan of a product.

There are for different phases of an LCA, defined by ISO 14044 **[33]**:

1. **Goal and Scope**, in which the central assumptions and system choices in the assessment are described. This phase includes a typical flow chart of the different inputs and outputs, the definition of the boundaries of the system etc.
2. **Life Cycle Inventory (LCI)** whose output is the quantity of the emissions and resources for the chosen products. It consists of a recompilation of environmental data: inputs of raw materials, energy, water, atmospheric emissions, solid wastes etc.
   During this phase, different calculations and assignment procedures are used as well as calculation tools and mathematic models.
3. **Life Cycle Impact Assessment (LCIA),** in which the previous data is translated into indicators that reflect the real environment impacts. This phase includes a classification, characterisation, and standardising process of the data.

4. **Interpretation** of the results and concluding into an overall vision of the environmental impact that the product represents.

It is important to take into account that the ISO guidelines on LCA provide a framework rather than technically detailed standardisation, that means that it provides a guide of recommended best practices of LCA and the basis to develop it. Many groups and international organizations have been working on a scientific consensus as JEMAI, US EPA and the European Commission.

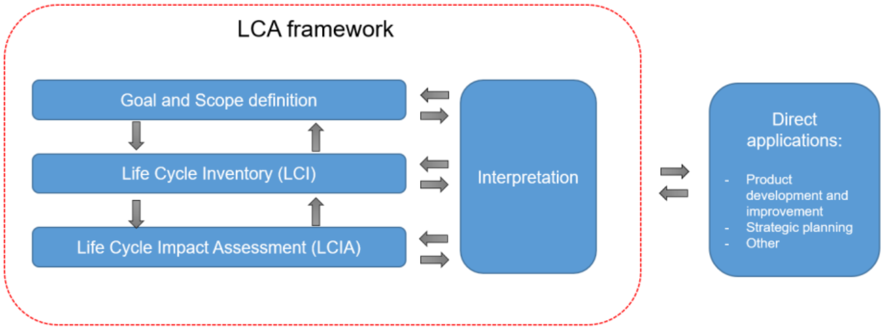

Figure 11 Life Cycle Assessment framework. **[33]**

As it is shown in Figure 11, LCA consists of an iterative technique. The integrity and coherence of the overall environmental study is essential to provide an accurate evaluation of the product impacts.

Apart from the framework, this methodology considers the elements of a system or subsystem exclusively as inputs or outputs. The inputs correspond to the energy resources and raw materials used, as well as transportation, electricity or energy. On the other hand, the outputs would be the products of the subsystem, likewise emissions to air, water and soil, solid wastes by products or co-products etc.

3.2.1 Goal and Scope definition

In this phase, the approach of the LCA and the product definition are going to be described, as well as the application of the assessment and the reasons for developing it. Some important elements that should be included are **[33]:**

- Target audience (confidential, private, public)
- Flow Chart: life cycle flow diagram of the product (inputs and outputs)
- Functional Unit [7]
- System Boundaries (Limits)
- Geographical and temporal delimitation of the study
- Computer Tools
- Allocation Procedures
- Impact assessment methodology used
- Type and format of report required for the study
- Whether or not there is a need for critical review and who will carry it out

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[7] The functional unit is used as a reference parameter for the data to be collected during an ACV. It must be an easily identifiable and quantifiable unit of measurement throughout all stages. It will be the reference from which the input and output data are normalized (in a mathematical sense).

For the case of EAW, the functional unit would be the installation and operation of a whole defined systems (described in Section 4) in a defined timeframe. For the three systems, we should study all the stages of the components (manufacturing, transportation, installation, operation, etc.), in essence, the perspective of the product life (Figure 7).

For this purpose, several computer tools have been developed such as: SimaPro, GaBi, Open LCA, BEES, Umberto LCA etc. SimaPro is the software tool selected for this research.

Short description of SimaPro

SimaPro is a well-recognised sustainability software package, with which the user can model and analyse complex life cycles in a systematic and transparent way, following ISO 14040 series recommendations **[53]**. This tool has a robust database and permits to collect, analyse, and monitor the sustainability performance data of products and services. Some remarkable advantages are the simplicity of usage, transparency and flexibility in results.

3.2.2 Life Cycle Inventory (LCI)

In this phase, identification, compilation and quantification of the environmentally relevant inputs and outputs to the system described in the life cycle flow diagram is carried out. The qualitative and quantitative data to be included in the inventory must be obtained for each unitary process within the borders of the system.

The inventory is fundamentally a balance of matter and energy of the system through the analysis of the inputs and outputs to the system that are relevant from the environmental point of view.

It is necessary to control the origin and quality of the data and it is recommended to carry out a sensitivity analysis in order to ensure the relevance, precision, reliability and representativeness of the data and the consistency of the methods used **[33].**

Therefore, this stage of LCA should include:

- Definition of unitary processes
- Inventory parameters: inputs (raw materials, energy, water…) and outputs (atmospheric emissions, liquid effluents, soil discharges, solid wastes…)
- Data collection and data quality
- Calculation procedures and sensitivity analysis
- Assignment procedures
- Evaluation of the model

SimaPro includes many LCI databases, including the renowned ecoinvent v3, the new industry-specific Agri-footprint database, and the ELCD database among others.

For this thesis, we are going to work with the ecoinvent database, since it is widely recognized as the largest and most consistent LCI database on the market until now. It consists of a compliant data source for studies and assessments based on ISO 14040 and 14044.

3.2.3 Life Cycle Impact Assessment (LCIA)

According to ISO standards, LCIA is usually divided into three stages **[33]** **[34]**:

- **Classification**, which is the assignment of LCI results to impact categories. For example, if CO_2 and CH4 are substances that participate in the input and output flows of LCI, they would be assigned to climate change.

- **Characterisation** of the impact, in which the substances that contribute to an impact category are multiplied by a characterization factor that expresses the relative contribution of the substance. Finally, the total result is expressed as an impact category indicator. The unit depend on the impact category, e.g. kg CO_2 equivalent, kg SO_2 equivalent etc.

- **Normalisation** and **weighting**, which are used to simplify the characterised results to understand better the relative magnitude for each indicator result. These steps are regarded as optional steps in ISO 14040/44 as they contain additional subjective steps. This stage can be not included depending on the depth of the study. The unit of the result for these phases is "year".

  For SimaPro Classroom version, the default normalisation values are used. These values are included in Appendix B, Table 41 and in references **[35]**.

Concerning the method of calculation for LCIA, a wide variety of calculation methodologies can be used: European methods (such as ILCD 2011Midpoint+, IMPACT 2002+ etc.), North American (BEES, TRACI 2.1 etc.), different versions of IPCC, CML, Eco-indicator… **[36]**

In this study, the global method called **ReCiPe 2016** is going to be used. ReCiPe is a follow up of Eco-indicator 99 and CML 2002 methods. It integrates and harmonises midpoint and endpoint approach in a consistent framework shown in Figure 12.

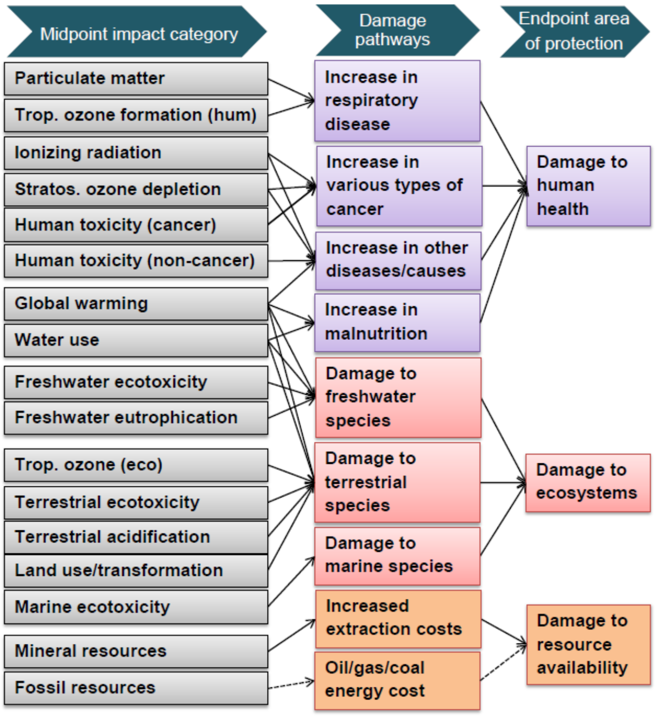

Figure 12 Framework of impact categories for characterisation modelling at midpoint and endpoint levels in accordance to ReCiPe 2016 methodology **[35]**

As seen, ReCiPe comprises two sets of impact categories with associated sets of characterization factors. At the midpoint level, 18 impact categories are addressed while at the endpoint level, most of these midpoint impact categories are multiplied by damage factors and aggregated into 3 endpoint categories. The factors conversion from midpoint to endpoint category are specified in **[35]** and **[37].**

In ReCiPe one can choose to use midpoint indicators or endpoint indicators. Each method has been created for three different perspectives: individualist, hierarchist, and egalitarian which differ mainly in timeframe considerations **[36].** The selected is the **hierarchist perspective**, which represents the consensus and as a default model, and it is often encountered in scientific models.

3.2.4 Interpretation

In this phase, conclusions and recommendations of the results of both the inventory and the impact assessment are carried out in line with the objective and scope of the study. An analysis of improvements can be carried out in which different qualitative or quantitative measures are identified and evaluated in order to reduce the environmental burdens and impacts associated with the system. Some significant outputs are:

- Evaluation that considers the verifications of the integrity, sensitivity, and consistency analyses.
- Conclusions, limitations, and recommendations
- Report
- Critical Review

3.3 Sensitivity analyses

The previous LCC and LCA models that we have generated are theoretical models and a prediction of what is expected to LOWTE's EAW. However, both of them depends on several factors that are out of our control (electricity prices, discount rate, contingencies of the equipment, maintenance and repair costs etc.). Thus, it is necessary to analyse the sensitivity of these models and their responsiveness when one specific value changes. This permits us to know the risk and the range of error of the calculations.

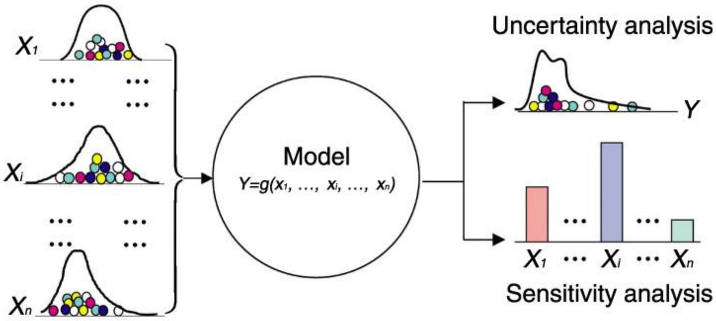

Figure 13 Concept of uncertainty and sensitivity analysis **[26]**

One can find two different analysis: uncertainty and the sensitivity as it is shown in Figure 13. The variable X, {X1, …, Xi, …, Xn}, represents the n uncertain inputs of the model. Variable Y is the output of the model or the result of uncertainty. While uncertainty analysis refers to the determination of the uncertainty in Y, sensitivity analysis refers to the determination of the contributions of the individual inputs to the uncertainty of Y. **[26]**

The uncertainty of a model input or a model output is characterized by a probability distribution. The Monte Carlo simulation is a numerical analysis and is considered as a good way to know the sensitivity of the models. It attributes a certain statistical distribution of values to the inputs instead of a fixed number. This permits to consider the uncertainty of the critical factors as well as it makes possible to define different ranges for the values and study the evolution of the model.

4. Systems to analyse

The mentioned LCC and LCA study will be applied to three systems (Figure 6)

- Double-glazed window (reference system)
- Triple-glazed window
- Energy Active Window

In this study, the insulation improvement consists of the different type of window glazing. It is assumed that the frame as other common components are identical for the three systems.

In this section, the specifications and components of each system are detailed. In Appendix B Table 38 the components, its materials and weight are specifically described.

4.1 System 1: Double-glazed window

This system represents the reference system for the whole study. It consists of a passive element with two panes of clear float glass of 2mm of thickness. This system is a common vacuum-insulated glazing unit (IGU), whose air gap works as an insulator layer, based on 18 mm thickness for this case. The air space contains spacers which help maintain the separation between the panes as other sealing components to keep the airtightness. The total thickness of the glazing would be 22 mm. Based on the apartment plans provided by KTH LIL, the size of current windows is 2.11x1 sqm.

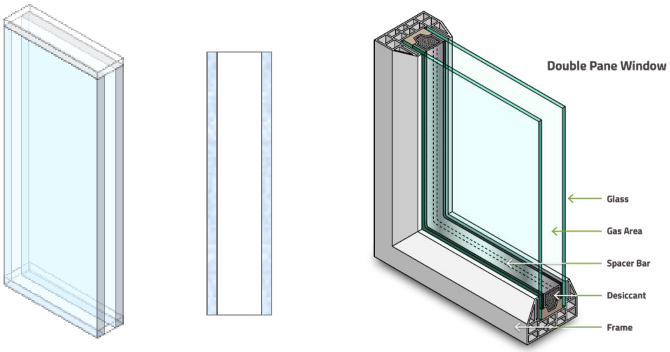

Figure 14 Sketch of the double-glazed window **[38]**

This type of windows has two options of opening, partial or full opening **[24]**. The frame is made by laminated oak that will cover the window door and the external part fixed to the walls of the building **[39].** In the end its thermal resistance, represented by U-value, is considered to be 1.2 $W/m^2\cdot K$. The heat flow direction could be only from indoors to outside. **[38]**

The materials considered for the handle, sealing or the whole internal hardware are included in the inventory in Appendix B Table 38. The aluminium spacers used in the insulator layer and the desiccant (silica pellets) surround the glazing unit edge. The lifespan considered for both glass panes and wooden frame is 21 years. After this lifetime, the whole window would need to be replaced.

4.2 System 2: Triple-glazed window

This window is considered as a competitive option in comparison to EAW. It consists of passive super-insulated window with two krypton-filled gaps. This type of window is considered a low-E[8] (low-emittance) product, and its composition layers are described in Table 6 **[40]**. Its size is identical to the reference system, 2.11x1 sqm, and the frame and internal hardware is made by the same materials **[39]**. The weight of this window can reach around 30 kg/m^2 with a total thickness of 48 mm.

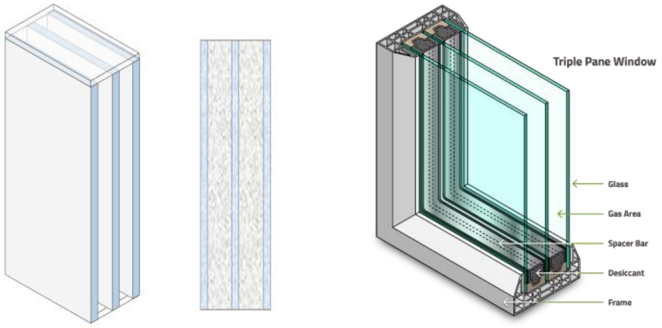

Figure 15 Sketch of the triple-glazed window **[38]**

Table 6 Triple-glazed layers

Triple-glazed window	Product	Thickness (mm)
Glass 1	Pilkington Optitherm™ S3	4
Gap 1	Krypton (90%)	18
Glass 2	Pilkington Optifloat™ Clear	4
Gap 2	Krypton (90%)	18
Glass 3	Pilkington Optitherm™ S3	4

According to Pilkington data, the overall U-value for this window would be 0.5W/m^2·K on average **[41]**. The lifespan considered for all glass panes and wooden frame is again 21 years. After this lifetime, the whole window would need to be replaced but until then, no replacement is needed. Also, small leakages of the krypton layer are disregarded.

4.3 System 3: EAW

EAW system, designed by LOWTE, can be defined as an active, LTH and lower-exergy system. The supply temperature of the working fluid is about 25-35 °C and the return temperature is below desired room temperature. **[42]**

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[8] Low-emittance (Low-E) is a coating that increases a window or door's ability to diminish heat transfer.

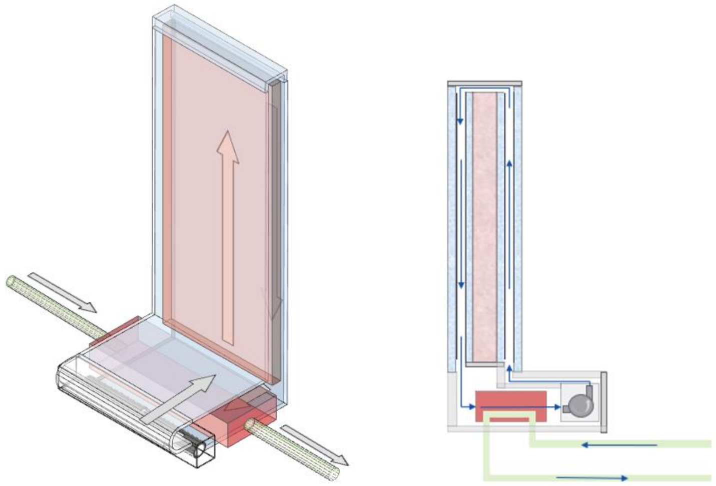


Figure 16 EAW design. **[42]**

As mentioned, EAW will be installed in Testbed KTH whose energy supply system was described in Section 1.3. EAW will take the waste heat (free heat) that comes from the bathroom's underfloor heating during winter, and the ground heat pumps during summer, and it will convert it into useful heat for space heating. Its mode of operation is better explained in the following sections. The overall thickness of the glazing part will be 48 mm.

4.3.1 Components

- **Double slot concept and the insulation layer (DS unit)**
  As shown in Figure 16, the EAW is comprised by an outer and inner double slot, that separate the gases contained within. The working fluids are the flowing air, whose temperature changes along the window surface, and argon (90%) as a 12mm thick insulator layer. The insulation is completely necessary to remove all possible heat transmission losses between the two air streams. The compartments of the flowing air are completely hermetic around glazing unit edge. Thus, any air filter would be needed. The thickness of the air channels will be fixed at 10 mm and the glass one at 4 mm.

  For this thesis, the size of the slots is considered to be 2x1.5 sqm each one. In principle, the dimensions of the EAW should be larger than the reference window due to larger glazing surface would imply higher energy savings for EAW nominal operation.

- **Electric fan**
  A fan is necessary to induced force convention along the air channels when it is required. A fan box of 1500 mm (the length of EAW width) will contain two cross flow fans that will supply the pre-heated or chilled air. The electric fan model is taken from Sofasco, and its data sheet is attached below.

Table 7 Electric fan specification sheet. **[43]** *

Fan Model	DFM60610-3P
Number of units	2
Rated Power supply voltage	24 V
Rated Power Input	17.52 W
Diameter	60 mm
Length	670 mm
Weight	1350 g
Max air flow	6.20 m^3/min
Max air pressure	2.3 mmH_2O
Nominal working hours	4000 h/year

* The data sheet provided by Sofasco is included in Appendix A (Figure 58). Several specifications in their webpage are non-updated according to the sales manager.

DC fans are assumed for this model since they are quieter and consume less energy. Furthermore, it is assumed that the supply flow rate is constant, but the supply air speed can change depending on the desired indoor temperature. The air flow rate is fixed at 0.03 kg/s and mass losses are disregarded. The energy consumption depends on the rpm of the fan and the working hours per year that will be working.

The original idea of the EAW design is that the fan electricity is covered partially or completely by an external solar collector system or a free energy source. However, neither the type of solar PV system nor its power capacity has been already defined for implementing in EAW system up until now. For this reason, it is assumed that both fans will work 4000 hours on average in per year and they will consume on average 70 kWh/year.

According to Sofasco, the fan will operate without any problem 60 000 hours, corresponding to at least 10 years operation because the clean environment and the appropriate temperature range. The replacement of the fan can be made without disassembling the whole EAW structure. **[43]**

- **Air drivers**
  Thermoplastics materials will be used in this thesis for driving the air from the slots to the heat exchanger and electric fans. It is assumed that polymeric materials will be used as well for the fan boxes in order to build a light and modular structure.

- **Heat exchanger (HX)**
  The purpose of the water-to-air heat exchanger in EAW will be to transfer the waste heat from the underfloor heating pipeline to the internal flowing air during winter. In contrast, during the summer season, the chilled water will come from the heat ground

  Several innovations will be implemented in the heat exchanger design. In order to improve its efficiency, its whole structure will be comprised of ABS (Acrylonitrile Butadiene Styrene), a common thermoplastic polymer. It is expected that the usage of plastic material will reduce heat transmission losses and corrosion issues. This HX would require less amount of material and would be lighter than a conventional unit. **[44]**

  Regarding the design, it will count a large amount of microchannels with a quite small hydraulic diameter. The objective is to create many parallel flow paths with short distance to ensure a laminar floor and get a higher heat transfer. **[45]**

  The HX will be produced by selective laser sintering (SLS) 3D printing. This 3D printing technique is used for both prototyping of functional polymer components and for small production runs. It offers a very high design freedom, high accuracy and produces parts with good and consistent mechanical properties **[46]**.

After the calculations of Section 4.3.2 regarding the heat transfer, the model HX-R-12 of Polycoil **[47]** has been selected for having a refence regarding power capacity and dimensions. The specifications data sheet is attached in Appendix A (Figure 59). **[47]**

- **Wooden frame**
  Even the wooden frame is made of the same laminated oak as System 1 and 2, EAW will not need handle or other accessories since it cannot be open; it is a fixed window. Since less internal hardware would be needed but it would need larger quantity of wood (due to a bigger size of the panes and the thickness), the budget is assumed to a little bit less expensive than the frame for the triple-glazed unit. **[39]**

- **New pipeline branch**
  It is assumed that the added pipeline branch would not affect the original pipeline system and propulsion devices. This branch is going to be installed in the return pipe of the underfloor heating of the bathroom. Currently, district heating during winter provides the heat load of the bathroom by supplying warm water though this underfloor piping system. Then, the pipe returns to district heating with cool water. Between this process, the EAW pipe is installed for taking profit from the waste heat. During summer, the pipes that provides chilled water is the one from the ground heat pumps that are connected to the boreholes.

  On the other hand, it is no needed to replace the original pumps with other with larger capacity since the added flow rate is quite small. Then, the increase of their energy consumption for pumping the new water flow rate can be neglected.

  KTH LIL has already the connections prepared for the addition of this new branch. Regarding its path, it is assumed the horizontal circuit shown in Figure 17. Also, it would be installed close to the ground level where vertical pathways are almost not considered.

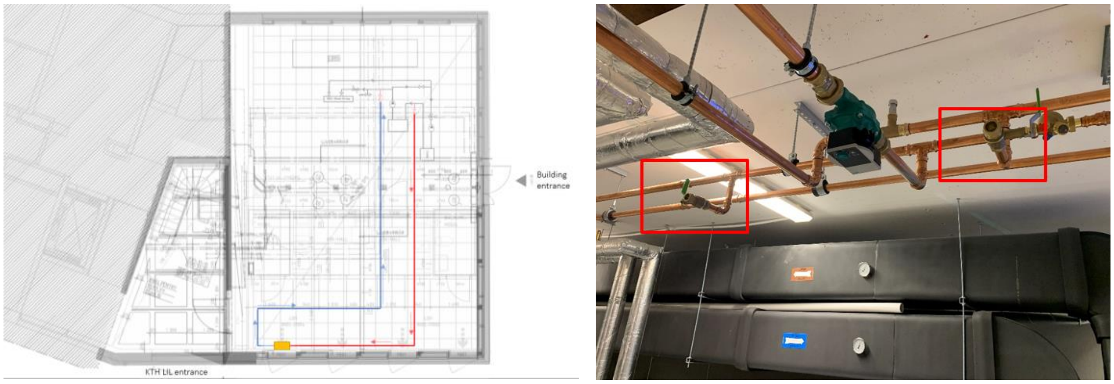


Figure 17 Circuit of the new pipeline branch

  In the end, this new branch would have a length of 28 meters. After the calculation of the HX (Section 4.3.2), the model selected is the Uponor PeXa pipe for 9.9x1.1. **[47]**

- As mentioned, a **possible solar collector** (any BIPVT) system could be installed in order to obtain low quality energy. Other possible systems are ground heat pumps connected to boreholes or other options of seasonable ground thermal storages.

Finally, the Table summarize the lifespan of all the components.

Table 8 Lifespan of the components

Component	Lifespan (years)
Electric fan	10
HX	15
Wooden casement. Glass sheets.	21
New pipeline	50
Air drivers	21

4.3.2 Operation

For a better understanding or the EAW design, it is necessary to distinguish between winter and summer operation since the ambient temperature will affect hugely in its mode of operation. The different components will work in different thermal conditions to provide a comfort indoor temperature which is around 21ºC.

- As mentioned, during winter, the water that enters the heat exchanger comes from the underfloor heating of the bathroom. The temperature is estimated in 27ºC. The heat is transferred in the HX and it preheats the internal air of the EAW to 25ºC. It is important to keep the inner slot at some degree above the desired indoor temperature.

  The temperature drop in the inner slot is very low in contrast to the outer slot. Due to the low outdoor temperature, heat losses in the outer surface are quite considerable. However, the outer slot is still at higher temperature than the outdoor temperature thanks for the internal flowing air. Hence, the inner slot is facing a higher temperature than the outdoor temperature, which would mean energy savings in the inner slot. **[42]**

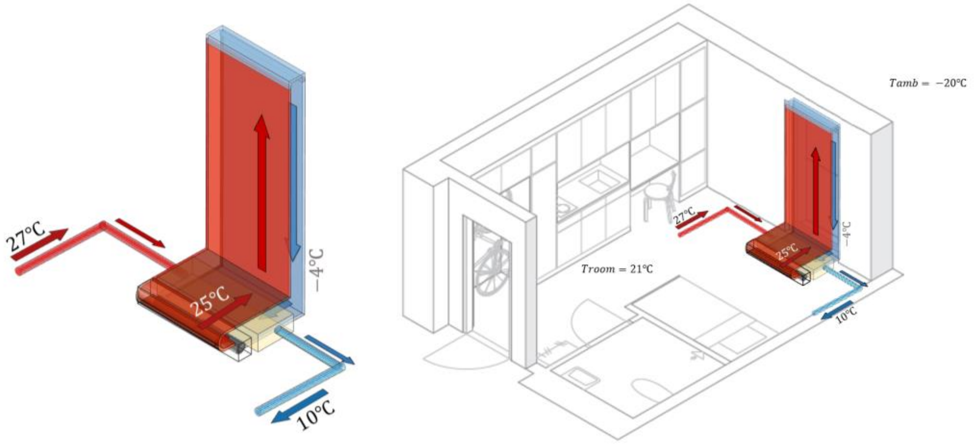


Figure 18 EAW during cold period acting as heating radiator under nominal parameters.

- During summertime, the chilled water comes from the boreholes and after passing though the ground heat pumps, it enters into the HX at 15ºC. Then, the inner slot supplies low grade cool (17ºC) below the desired room temperature. The flow in the inner slot absorbs heat from the room and would transfer the heat to the outer slot.

  As the temperature in the outer slot is below outdoor temperature, which is higher, again the inner slot is facing a lower temperature than outdoor temperature and hence saving cooling energy in the inner slot. The lower ΔT of the working fluids during hot seasons is related to the location of EAW (Stockholm) where the not so high temperatures are reached.

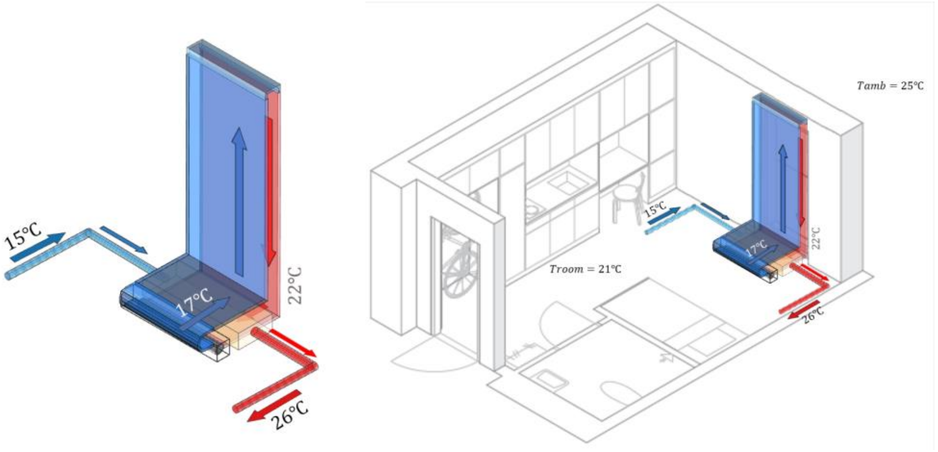


Figure 19 DS unit hot periods acting as cooling panel under nominal parameters.

Nevertheless, DS unit can supply heat or cool into the room by taking the heat or the cool from the outer slot to the inner slot. By removing the external supply of heating or cooling energy, we ensure that the continuous flow of the working fluid heats or cools the desired room. For example, high temperature indoors heats the fluid in the inner slot, and it is transferred to the outer slot. Therefore, the heat from the room is radiated to the ambient. Such operation can take place during the night, after a sunny day that have overheat the room.

The following table summarizes all the nominal parameters.

Table 9 Assumed nominal parameters

Winter operation		Summer operation	
T water inlet of HX ($T_{w\ in}$)	27ºC	T water inlet of HX	15ºC
T water outlet of HX ($T_{w\ out}$)	10ºC	T water outlet of HX	26ºC
T supply air to DS ($T_{a\ out}$)	25ºC	T supply air to DS	17ºC
T return air from DS ($T_{a\ in}$)	-4ºC	T return air from DS	23ºC
T ambient	-20ºC	T ambient	25ºC
T district heating	50ºC	T soil	10ºC
T after U-floor heating	30ºC	T after ground heat pumps	13ºC
General parameters			
Mass flow air ($\dot{m}_a$)		0.03 kg/s	
Internal air speed (v_a)		0.24 m/s	

The nominal parameters for winter will be used as design parameters for sizing the HX needed, as well as the pipeline specifications and the final U-value.

- **Heat balance in HX**

By applying the following equations, one can estimate the water flow rate ($\dot{m}_w$) needed for preheating the air to 25°C ($T_{a\ in}$) during winter conditions. The values used are in Table 9. The thermal efficiency of the HX (η_{HX}) is assumed in 85%, and the heat capacity of the water ($C_{p\ w}$) and air ($C_{p\ a}$) are 4.18 and 1kJ/kg·°C respectively.

$$Q_{demanded\ by\ air} = \eta_{HX} \cdot Q_{delivered\ by\ water} \qquad (1)$$

$$\dot{m}_a C_{p\ a} \cdot (T_{a\ out} - T_{a\ in})] = \eta_{HX}\,[\dot{m}_w C_{p\ w} \cdot (T_{w\ in} - T_{w\ out})] \qquad (2)$$

$$\dot{m}_w = v_w \cdot \pi \frac{D^2}{4} \qquad (3)$$

Finally, the resulting water flow rate is 0.0144L/s, which is a small flow rate due to the tiny air flow rate. The heat (Q) delivered by the water would be approximately 1050W (3500 BTU/h). According Uponor standards **[45],** by assuming a flow speed of 0.4 m/s (v_w), the minimum diameter required would be 6.4 mm. For this reason, a 9.9mm of diameter is selected from Uponor catalogue.

- **U-value of EAW**

The U-value of the window concentrates its whole thermal performance and is quite complex to determine accurately since the uncertainty of many values. Up until now some facts are sure concerning the U-value **[48]**

1. The thickness of DS unit components would imply different U-values. For instance, if air channels decrease their width, slight reductions in U-value are expected.
2. U-value varies along the height of the window. After supplying the preheated or chilled air to DS unit, its temperature will decrease or increase respectively along the slot.
   For winter nominal parameter, higher air supply temperature would imply lower U-value and higher air return temperature as well.
3. Air thermal parameters as the flow rate or the speed will change the U-value too. The air temperature impacts were mentioned in the previous point. Higher speed values imply lower U-value.
4. The ambient temperature and solar radiation change the temperature of the slots and the indoor thermal requirements. This imply variations as well in the air thermal parameters.

It is important to take into account that U-value can reach negative values. When U-value is greater than zero, EAW is working as a passive window system, where heat is flowing from indoors to outside. Lower heat transmissions losses would come with lower U-values. However, if U-value become negative, that means that it is supplying heat to indoors. In this case, all heat losses are compensated with bigger heat gains, and EAW would become a heat supply system that works with free heat.

In this thesis, for being able to establish a base case scenario, the U-value will be calculated by using the nominal parameters shown in Table 9 as constants.

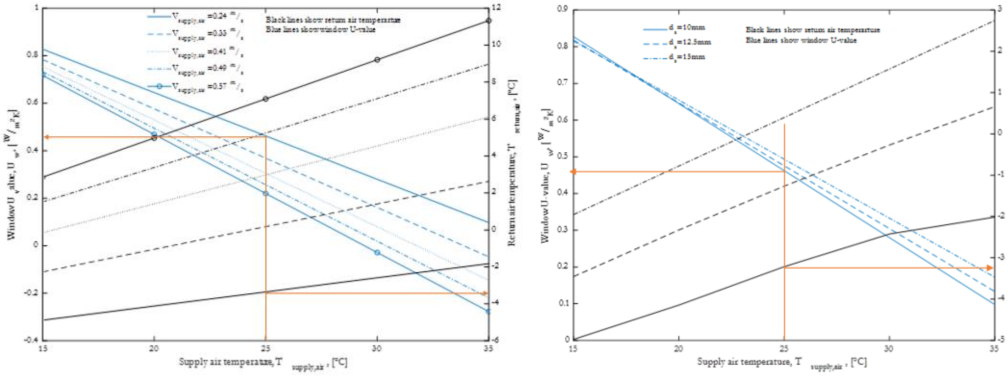


Figure 20 Application of the assumed nominal parameters **[48]**

As seen in Figure 20, for these specific conditions, the U-value would be approximately 0.4 W/m²·K. As a simplification, this value would be the one used in the energy savings calculation for the BAU scenario. Nonetheless, since U-value can reach quite lower values, they will be considered in the sensitivity analysis for both models.

5. Energy savings for BAU scenario

The energy savings that the triple glazed and EAW systems can achieve are critical for the LCC and LCA studies. Both systems represent a better insulation than the reference system, which means lower heat losses through the glazing. Thus, the energy required to be provided by the heat supply systems would be lower.

For a better understanding of this idea, the energy balance in one apartment can be expressed as following:

$$Q_{sun} + Q_{people} + Q_{facilities} + Q_{\substack{heating\\system}} = L_{\substack{transmission\\through\ windows}} + L_{\substack{transmission\\through\ walls}} + L_{ventilation} + L_{infiltration}$$

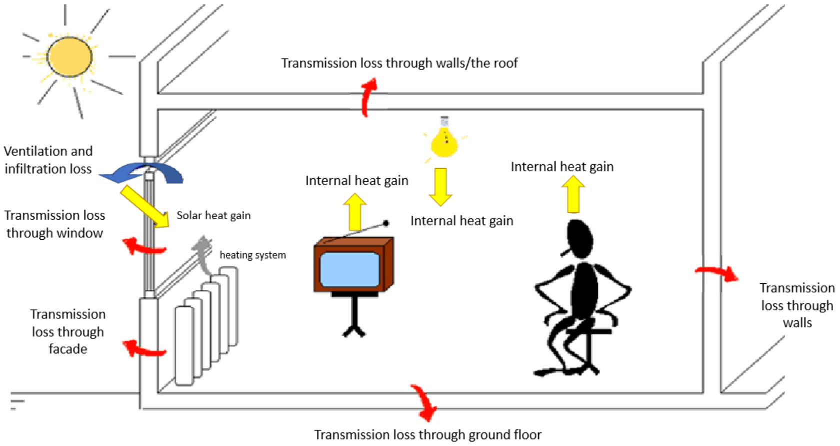


Figure 21 Heat balance in a building **[49]**

Then, the main heat losses in one room are the ones through heat transmission, ventilation, and air leakage. By changing the glazing of the window, the transmission losses through windows is the term that will be reduced. Furthermore, by assuming that the rest of the heat flows maintain the same values, the energy savings (due to better insulation) can be translated directly to energy savings in the energy supply required by the heating systems.

$$\downarrow L_{\substack{transmission\\through\ windows}} \Rightarrow \downarrow Q_{\substack{heating\\system}} \qquad (4)$$

As mentioned, currently the heat demand of the room is provided by the ventilation system. It is assumed that the new window systems can affect only the temperature of the room. For this reason, the bathroom is not included in the calculation of the heat load.

The mechanical ventilation system with heat recovery (MVHR) is located inside the lab and it provides warm air to the four apartments. It is expected that, when a better insulation is implemented, the ventilation system will have to introduce lower flow rate to maintain the desired temperature inside the room.

Nevertheless, it is true that replacing only one window in one of the four apartment represents a slight change in the current heat supply system. It is expected that the reduction of the total flow rate supplied by the MVHR unit will not vary more than 5-10%.

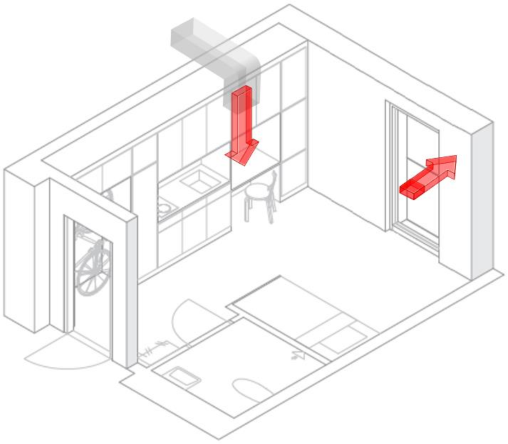


Figure 22 Sketch of the heat flows that will be calculated in the KTH LIL apartment's room.

Finally, energy savings are defined as the difference between the reference heat losses (heat losses of the System 1) and the new heat losses. Figure 23 might clarify this equation.

$$Energy\ savings\ =\ Reference\ \ heat\ losses\ -\ New\ heat\ losses \quad (5)$$

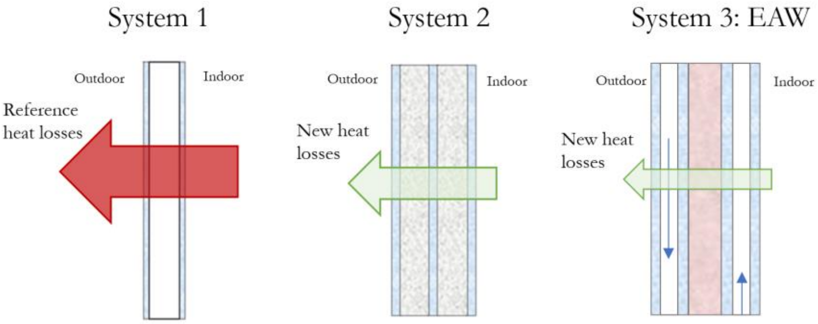


Figure 23 Sketch of the heat losses of the systems and concept of energy savings

An approximation of the current heat demand of the room and the heat losses of the three window systems will be calculated for using it as data input in LCA and LCC models.

As a reference, a Swedish single-family house in 2017 has an average heat demand for space heating and domestic hot water of 106 kWh/m2·year. From the statistics shown in Section 1, around 80% of this energy would be used for space heating, which means a heat demand of 85 kWh/m^2 per year. **[50]**. Furthermore, according the Swedish Energy Agency an average house with a floor area of 144 square metres uses around 15 000 kWh annually for space and water heating **[33]**. For both references, the room would have a heat demand of approximately 1450 kWh per year.

To be more accurate, KTH LIL provided us the energy consumed per hour in the room from March 2018 as well as the indoor temperature. The table below show the thermal data per month.

Table 10 Calculation of the reference heat demand

Month	Room temperature (°C)	Energy consumption (kWh/month)
January	21.29	139.22
February	21.06	132.03
March	20.84	127.98
April	21.66	121.32
May	21.16	107.92
June	22.25	84.49
July	22.35	70.43
August	22.45	86.01
September	22.11	133.73
October	21.90	136.37
November	21.76	138.74
December	21.64	139.86
	Total:	**1418.09 kWh/year**

Then, for the models 1419 kWh/year will be considered as the reference heat demand. This would mean that the ventilation unit consumes around 5700 kWh for heating the four rooms.

On the other hand, according to the Swedish Energy Agency an average house in Sweden losses from 25% to 33% of the heat through ordinary double-glazed windows **[51].** Besides, in Sweden a common building has around 16% of window to floor surface ratio **[52].**

Since the reference room has a window to floor ratio of up to 13%, the heat losses for the reference system can be estimated around 300 kWh/year. In order to validate this approximation, the following equation will be used for estimating the heat losses.

$$U - value = \frac{Heat\ Tranmission\ losses}{A_{window} \cdot \Delta T \cdot Time} \qquad (6)$$

In which A_{window} represents the window surface, ΔT the temperature interval between outdoor and indoor. The factor *Time* is only added for converting the heat transmissions losses from power units to energy units.

It is clear that the heat flow by heat transfer though the windows depends mainly on its U-value that varies as well with the temperature indoor and outdoor. Then, for this study the average temperatures in Stockholm will be considered as well as a nominal U-value.

As mentioned, the heat losses flow for the three systems will be usually from indoors to outside since the temperature of the room will be higher than the ambient temperature. For this heat flow direction, we assume positive values for U-value. System 1 and 2 will have always positive values since they are passive elements. In contrast, the range of U-value for EAW can be positive and negative. That means that for EAW system, the final heat flow can be from indoors to outside or from outdoor to inside. As mentioned in Section 3, the following U-values are the one used for the calculations.

	System 1	System 2	System 3
U-value ($W/m^2 \cdot K$)	1.2	0.5	0.35

In the following table the calculations using the formula (6) is shown. ΔT is the difference between the outdoors and indoors average temperature.

Table 11 Calculation of the heat losses for System 1, 2 and 3.

						Heat losses (kWh/month)		
Month	T room (ºC)	T min (ºC)	T max (ºC)	T outdoors average (ºC)	ΔT	System 1	System 2	System 3
January	21.29	-4	0	-2	23.29	43.87	18.28	18.19
February	21.06	-4	1	-1.5	22.56	38.38	15.99	15.91
March	20.84	-2	4	1	19.84	37.38	15.58	15.50
April	21.66	2	10	6	15.66	28.55	11.89	11.84
May	21.16	7	16	11.5	9.66	18.19	7.58	7.54
September	22.11	10	16	13	9.11	16.61	6.92	6.89
October	21.90	6	10	8	13.90	26.18	10.91	10.86
November	21.76	1	5	3	18.76	34.19	14.25	14.18
December	21.64	-2	2	0	21.64	40.77	16.99	16.91
					Total (kWh/year)	**284.12**	**118.38**	**117.82**

As seen, the hot season heat losses were not included in the calculation due to, during summer, in Stockholm the outdoor temperature is quite similar on average to the desired indoor temperature. This responds to the concept of thermal balance between outdoors and the room. The slight cooling demand needed for the apartment is provided by the district heating and the ground heat pumps. That means:

1. The heat losses through transmission would be almost negligible due to a small ΔT, in comparison to other seasons.
2. Climatization would be the only requirement for the ventilation system. In other words, renewing the room air would be enough for maintaining a comfort indoors. Nevertheless, this energy demand has been considered in Table 10 because it contributes in getting a comfort temperature indoors even though the ventilation unit does not supply chilled air.

Another important fact is that the energy savings in the case of EAW (System 3) could be called as 'gross' energy savings. It is because only the energy exchanged in the window glaze are considered.

The energy savings of EAW depend (as mentioned in section 3.3.2) of the final U-value. Higher flow rate introduced by the fan implies lower U-value of the glazing, but also more power consumed by the fan. In other words, for getting a lower U-value, higher flow rate is needed, and it implies that the fun will consume more electricity. For this reason, the concept of 'net energy savings' only for EAW system is introduced. It can be defined as:

$$Net\ EAW\ energy\ savings\ =\ Gross\ EAW\ energy\ savings\ -\ Electricity\ fan\ consumption \qquad (7)$$

By applying our estimations and the rated power consumption of the fans selected, for the BAU scenario the net EAW energy savings would be 97 kWh/year.

If these net energy savings are positive or negative implies if the gross energy savings are higher or lower than the fan consumption. If the average is higher than zero it means that, after all, EAW system saves energy in comparison to the reference system. But this net energy could be also negative, which means that the gross energy saved by a better glazing insulation is not enough for compensating the electricity that the fan consumes. The net energy savings can vary to negative if:

1. the fans consume more than expected
2. the fans work more hours than expected
3. the U-value takes higher values than expected due to temperature variations etc.

Then the net EAW energy savings depends hugely on the balance between fan consumption and the U-value. Even though EAW uses waste heat from the district heating, it needs a non-negligible energy input what decreases the feasibility of the window.

In section 6.3 and 6.4 one can see that the fan consumption will affect the operating costs of EAW. It will make the difference when the feasibility of EAW is compared with the triple glazed. However, even if all the electricity input of the fans could be supplied by a free energy source, the NPV results would not change considerably. Bigger changes in EAW energy performance would be needed.

Apart from these facts, from the Table 12 now we would be able to estimate the energy savings for the base-case scenario with nominal parameters and average temperatures. The numbers are closed to the given as reference, so they are considered as valid for introducing them as data input into LCA and LCC models.

Table 12 Calculation of energy savings for BAU scenario

	System 1: double-glazed	System 2: Triple-glazed	System 3: EAW system
Heat losses (kWh/year)	285	119	118
Gross energy savings	-	166	167
Net energy savings* (kWh/year)	-	-	97
Heat demand (kWh/year)	**1419**	**1253**	**1322**
Total electricity purchased by ventilation system (kWh/year)	5673	5507	5577

* Taking into account the electric fan consumption

Some important facts of this base case scenario regarding only the energy saving calculation could be:

1. The triple-glazed and EAW system have a similar gross energy savings because the U-values and the sizes of the window. Triple-glazed has higher U-value than EAW, but the window surface of EAW is larger[9] which means higher heat losses too. Then, for this base case, a lower U-value of EAW does not compensate the increase of higher heat losses with the window surface.
2. When the U-value decrease from 1.2 to 0.35 $W/m^2 \cdot K$, the heat losses of the room would be reduced up to 40% from the reference value.
3. A better insulation in the window glazing (in the case of EAW system) means an energy saving of 7% in the room. For this base case, the triple-glazed unit represent a better option due to the EAW fan's electricity consumption.
4. Since only one window is being replaced, the total consumption of the ventilation system for the four rooms would be reduced 1,7% from the reference.

For validating these conclusions, a similar research developed by the Umeå University for Swedish buildings, is used as a reference. It studied the reduction of energy purchased when the U-value of an overall building envelope changes: when it changes from 0.31 to 0,2 W/m2·K (35% of reduction), the specific energy purchased reduced around 22% **[52]**. Through a simple calculation, this ratio can be applied for the four rooms in KTH LIL. From the plans of the building, it is known that each room has two windows and only one window in one room is being replaced.

---

[9] EAW was planned to have larger window surface than the other because larger EAW surface with very low or negative U-values, implies higher energy savings (See section 3.3.1)

Table 13 Data for calculating energy purchased reduction

Area (m²)	Envelope of 1 room	88.6
	Total envelope of 4 room	354.1
	1 window surface	2.11
U-value (W/m²·K)	External walls	0.13
	Roof	0.08
	Foundation	0.24
	Reference window	1.2
	EAW	0.35

Table 14 Estimations for one and four rooms

	With double-glazed	With EAW system
Overall U-value for 1 room (W/m2·K)	0.199	0.180
Reduction of overall U-value for 1 room (%)		9.55
Reduction in electricity purchased for 1 room (%)		6.10

	With double-glazed	With EAW system
Overall U-value for 4 rooms (W/m2·K)	0.199	0.194
Reduction of overall U-value for 4 rooms (%)		2.31
Reduction in electricity purchased for 4 rooms (%)		1.46

By applying the ratios of this study, we can validate our estimations for energy savings by using them as a reference.

6. LCC model

6.1 Goal and scope

The aim of this economic model is calculating the feasibility and the cost-effectiveness of installing EAW system in one room. Then, an economic comparison of the energy performance of the three systems will be carried out. The scope of the LCC study is the following:

1. To determine the **net present value** of the three systems after 20 years.
2. To calculate the **operation and maintenance costs** for the three systems during this timeframe and the **costs savings** caused by improving the energy performance of the room.
3. To calculate the accumulative costs for the next 20 years for the three systems and to know the **payback period** for the EAW.
4. Apart from the validation of the model, a **sensitivity analysis** is going to be developed for knowing which economic changes would be make EAW more profitable.

6.2 LCC assumptions

For the BAU scenario, we will consider current and real Swedish economic factors. Furthermore, the energy consumption and savings calculated in Section 5 will be used for the base-case results.

In Section 4 the components of the windows were described. For this LCC section, the following assumptions are going to take into account as well.

- The heat exchanger uses waste heat (free heat). Then no energy consumption costs will be considered for this component.
- The frame, internal hardware and small accessories are the same material and suppliers for the three systems. However, the price differs due to thickness and quantity of material needed. Table 38 in Appendix B contains the information regarding the size and the material needed for each window. Nevertheless, small components prices have been disregarded for LCC model, e.g. desiccant, spacers, construction materials etc.
- It is assumed that neither argon nor krypton have to been renewed because of small leakages during the timeframe.

6.2.2 Assumptions in electricity price

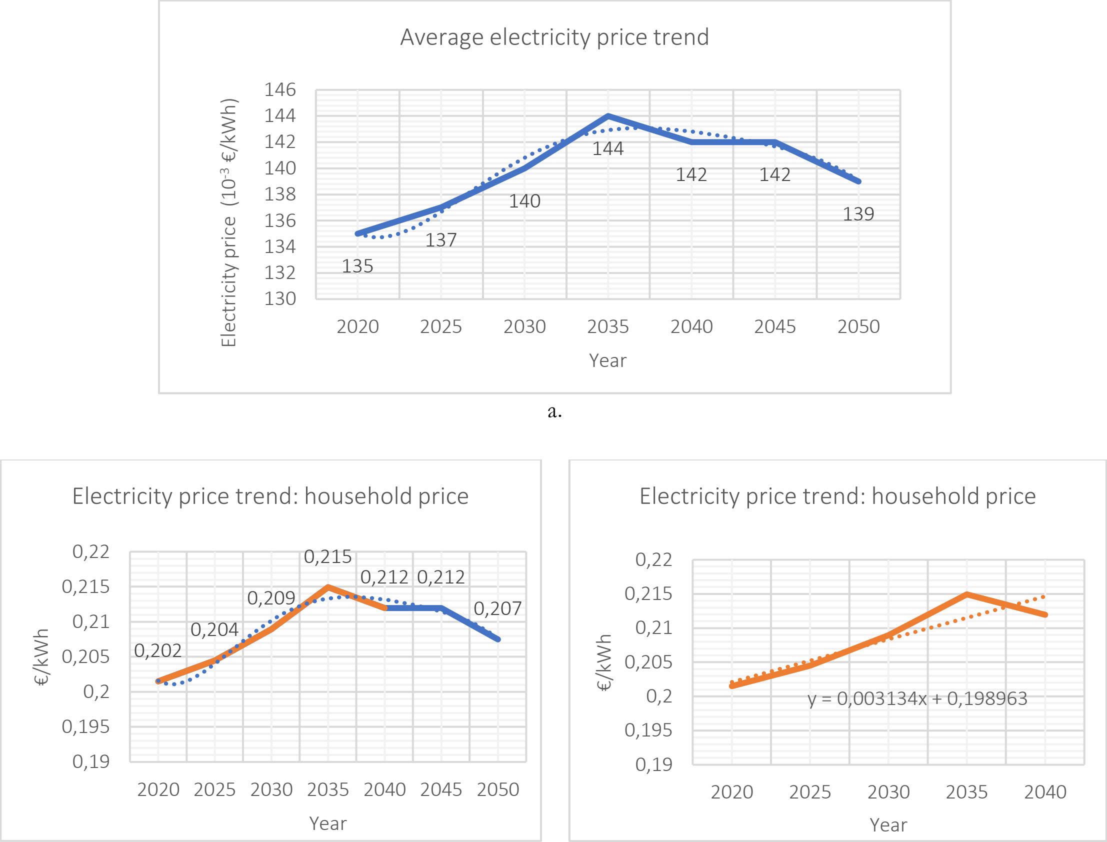
As mentioned, the electricity price is going to be used only to know the variable energy costs (operation costs) per year of the devices that need electricity input (electric fan, ventilation system…). Our model considers a pattern of linear and continuous growing of the electricity price. The electricity is purchased as a household customer from the Swedish grid.

It is quite difficult to predict electric prices even in short term due to the huge uncertainty that the electricity price is subjected to. In this study, the evolution of the electricity price has been obtained from a Statista's study of the average electricity price in Sweden **[53].**

The electricity price of households is different in relation with the applied to non-households. If it is one type or another depends on the annual consumption of the building: higher price (household price) is applied when the consumption is between 2500 kWh and 5000 kWh. For example, the household's electricity price in Sweden during 2019 first semester was 0.21 €/kWh and the non-household electricity price was 0.08 €/kWh. Then the average is 0.14 €/kWh **[54].**

To be able to use this forecast, it is assumed that

1. The household electricity price would follow the same trend.
2. Only the forecast for the following 20 years is interesting for our study. Moreover, probably, it has more accuracy the closer data to the present. Extracting its linear trend, we can get an approximation of the next 20-years forecast of the electricity price.



a.

b.

c.

Figure 24 a. average electricity price of household and non-household. b. c. estimation for electricity household price **[53]**

Finally, by calculating the average of increase rate (%), the specific values of the electricity price would be obtained for the LCC model. In the end, we obtain that year after year the electricity price become 1.013% more expensive. Also, an average of the currency change of the last 10 years has been applied **[55]**.

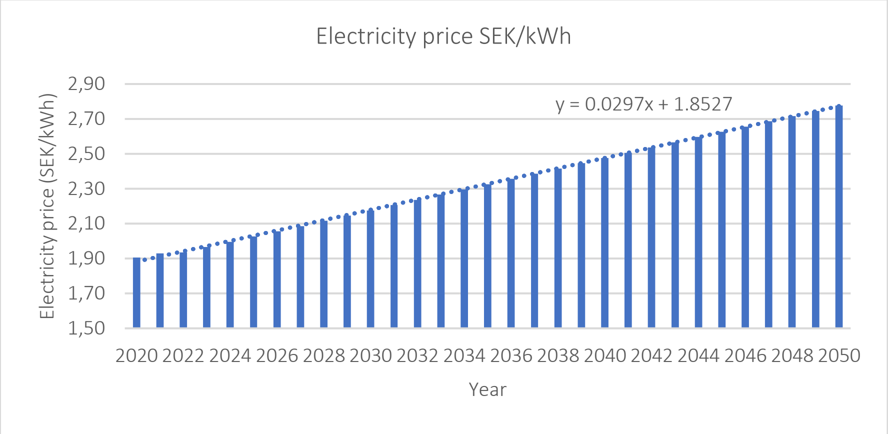


Figure 25 Electricity price trend assumed for BAU scenario

Average electricity price increase rate (%)	Average currency conversion (€ to SEK)
1.013	9.46

Table 28 in Appendix A is attached with the specific values used in this calculation.

6.2.3 Assumptions in discount rate

As mentioned, the discount rate is needed for obtaining the discounted cashflows.

In contrast to other countries, after the financial crisis of 2008, the Sveriges Riksbank moved to a negative interest rate as an economical strategy. This produced a reduction in the discount rate to 0.5%. Nowadays, discount rate (known as the 'reference rate') figures maintain in low values.

As mentioned, the discount rate (%) is needed in the calculation of the discounted cashflows. We will apply the average discount rate during the next 20 years from 2020. For obtaining this average, the last 10 years values have been considered **[56].** These values are included in Table 29 into Appendix A.

Average discount rate (%)
0.43

6.2.4 Structure of the LCC model

The **system boundaries** are the window systems and the heat demand of the room. For the investments, maintenance, and disposal costs only the components for the window are considered. Nevertheless, for being able to compare the NPV of the three systems, the operation costs cover the electricity consumption for space heating.

- **Investment cost:** it would represent the purchase cost of the system. So, it is included the manufacturing cost on it and the installation process as well as the transportation expense. It is assumed that the capital investment is made only at the beginning of the timeframe and intermediate investments do not exist. Then the cashflows will fluctuate mainly because of the operation and maintenance expenses (O&M).

Regarding the model of the components, their own installation costs or data such as the hours of work of the technician, his labour payment (175 SEK/h) or the cost allowance are taken from the Sektionsfakta® - VVS 17/18 (Elanders 2017). All this data is included in Appendix A (Table 30). This table also contains the prices unstructured components by component.

- **Operation cost:** we just consider the electricity bills due to space heating by the ventilation unit. Also, the operation costs savings would be the savings of the electricity purchased when each window system is installed in the room.

  It is important to remark that System 1 and 2 are passive systems and they do not have the so-called 'operation costs' by themselves. In contrast, EAW could have them because it is an active system. Its energy costs or savings would be the ones related to the net EAW energy savings. Anyway, it would be needed to relativize its energy flows to the reference.

- **Maintenance cost:** it includes both predictive and corrective maintenance (revisions, repairing…). It would include the costs of the software or any electronic and control devices.

  There are models that define different functions to estimate the predictive and corrective maintenance costs. Besides maintenance costs are age-dependent, and they can be expressed by parameters as linear functions based on the failure rate. Very specific data from each element is needed to consider its failure rate and nowadays EAW is a prototype whose some components are not still 100% designed. For this reason, and also because it is a common assumption in LCC studies, the maintenance costs are studied as constant expense per year.

  The common annual maintenance cost is between 2-3% of the capital costs. In the case of windows, the usual rate is around 1% of the initial investment. Since EAW has more mechanical components that are in movement (e.g. electric fan) the annual maintenance costs will be considered a little bit higher than other systems (1.5%).

  When a device has to be renewed, the purchase of the new element is included in maintenance costs. It is assumed that the old component is replaced by one identical to it. As mentioned, in the purchase cost is included the logistic issues for the installation. This replacement expense is included in the specific year of replacement, defined in Table 8 (Section 4.3.1)

- o **Dismantling and disposal cost:** it considers the uninstalling costs plus the costs of carrying them into to the landfill or recycling process. One can assume that when one component is replaced, the company that dismantles and installs the new component also manages the waste treatment and transport. We assume it is a 10% of the total capital investment.

Then, this table summarize the main economic parameters used for BAU scenario as data input. The rest of the component budgets are included in Table 30 in Appendix A.

Table 15 BAU scenario data input for LCC model

Parameter	**Data input**
Discount rate r (%)	0.43
Electricity price trend (%)	1.013
Currency conversion	9.46

Transport costs for disposal (%)		0.1
Maintenance rate (%)	System 1 and 2	1
	System 3	1.5
Heat demand (kWh/year)	System 1	1419
	System 2	1253
	System 3	1322

6.3 Results for BAU scenario

The Table 31, attached in Appendix A, shows all the cashflows calculated per year as well as the capital investment operation, maintenance, and accumulated PV for the next 20 years. In this section the main conclusions are present. For instance, the Net Present Values for the base case scenario is the following.

Table 16 NPV of the three systems for a timeframe of 20 years (BAU scenario)

System	NPV (10^3 SEK)
Double-glazed (System 1)	76
Triple-glazed (System 2)	73
EAW (System 3)	98

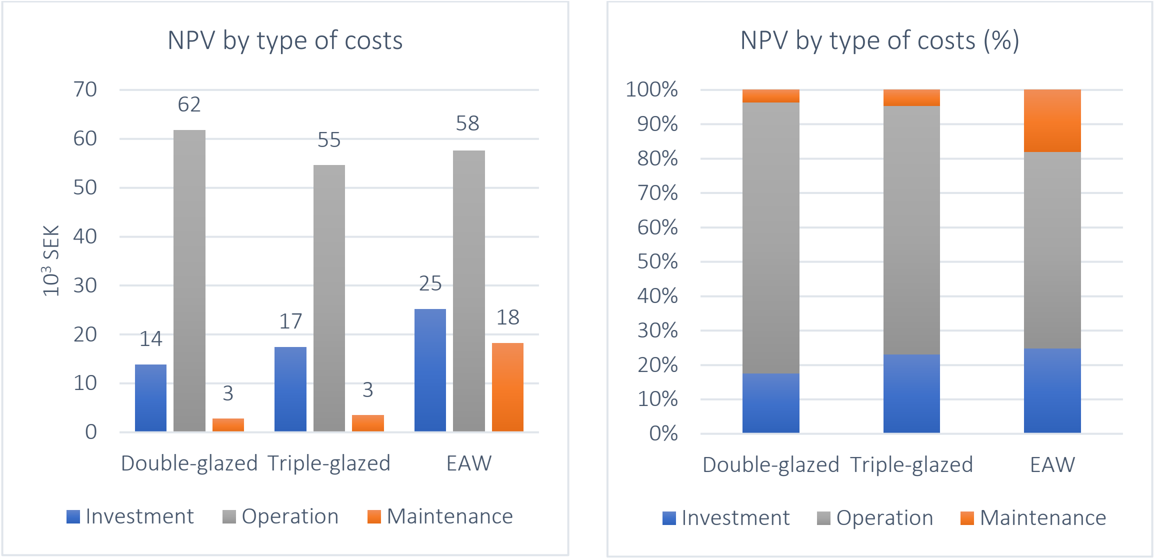
As seen above, the lowest NPV corresponds to the triple-glazed system. That would mean that System 2 would be most cost-effective system for this base-case. Moreover, the NPV for the EAW system (NPV3) is higher than the one for the reference system (NPV1).

Particularly it is about 23 000 SEK higher which means an increase of 30% in the costs of the system after 20 years. For a better understanding of the costs, the following table shows the different expenses for each type of window.

Table 17 Unstructured costs of the three systems for a timeframe of 20 years (BAU scenario)

By type of cost	Double-glazed	Triple-glazed	EAW
Investment (10^3 SEK)	14	17	25
Maintenance (10^3 SEK)	3	3	18
Operation (10^3 SEK)	62	55	58

Lower operation costs for System 2 and 3 are directly related with the electricity consumption and the energy savings. The fan electricity consumption in EAW system is the main responsible for making the operation expenses higher than triple-glazed unit. Figure 26 enables see better the proportions



a. b.

Figure 26 a. NPV by type of cost b. Composition of NPV by type of cost (%) (BAU scenario)

From both figures we can draw several insights from an economic perspective.

1. System 1 and 2 would have similar NPV since the higher investment of the triple glazed window is returned with lower operation costs. The tripe-glazed would require an investment about 20% higher than the double-glazed window but after 20 years its operation costs would be 12% lower.

2. System 1 is would be more profitable than EAW for the base-case since the lower operation costs of EAW cannot compensate the higher capital investment and maintenance costs. After 20 years, due to the major complexity of the EAW system, its maintenance costs are over six times higher than the reference and a capital investment are up to seven times higher.

Regarding the years of payback of each system, both System 2 and 3 would need a lot of years for recovering the initial investment. The main reason is that, since only one window is replaced, the energy savings represent a slight quantity of the total energy.

While the triple-glazed unit would need 12 years of payback, EAW's accumulated costs trend would grow in parallel with the reference trend (Figure 27b). After 20 years, that would mean that the EAW system would have bigger expenses than the reference. It is easy to notice that the continuous component replacements (like the electric fans or the heat exchanger) affects considerably the slope of EAW curve. That means that the saving costs in purchasing electricity are lower than the increasing maintenance costs year after year. This conclusion is better explained in Figure 28.

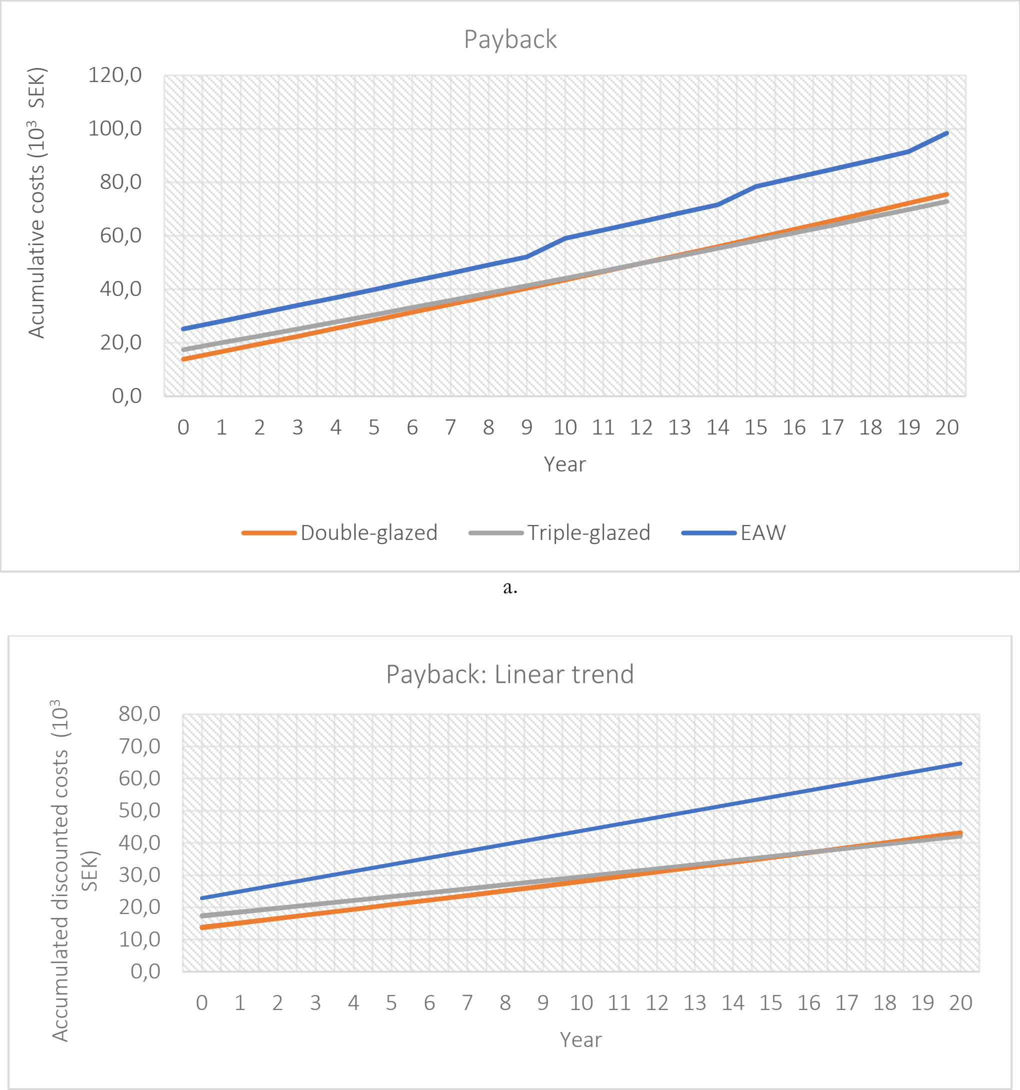


Figure 27 Year of payback for BAU scenario. a. Accumulated discounted costs
b. Linear trend of the accumulated discounted costs

If the operation and maintenance costs per year are analysed deeply, one can see in Figure 28 that the maintenance expenses are bigger than the operating savings. The replacement of the two fans every 10 years and the heat exchanger are huge expenses in comparison to the electricity saved.

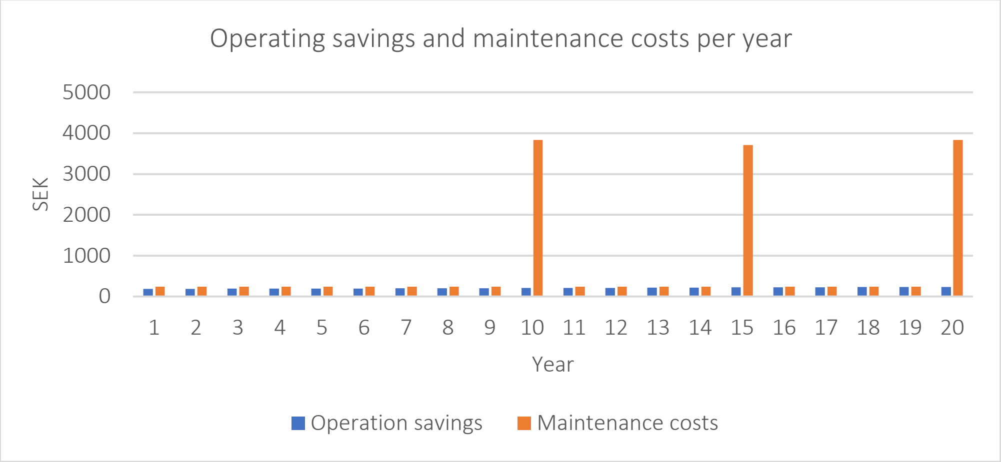


Figure 28 Operating savings and maintenance costs per year.

Finally, in Table 18 the savings costs are described. As mentioned, they are small in comparison to the overall costs due to only one window is being replaced.

Table 18 Saving costs for BAU scenario in absolute and relative terms

Saving costs	Room with triple-glazed	Room with EAW system
SEK/year	270	136
SEK/ (m^2 ·year)	128	46
Accumulated SEK after 20 years	5400	2750
Accumulated SEK/m^2 after 20 years	2600	950

Even though the base-case study is an estimation of what is expected to occur, and the system is subjected to many uncertainties, some useful insights can be drawn from this scenario:

1. The higher complexity of EAW would affect notably in the capital investment in comparison to a passive window system.
2. The maintenance costs and the replacement of the components represent a big part of the total EAW expenses. If the operating savings are not enough high to compensate them, in the end the profitability of the system would reduce hugely.
3. The energy consumption of the electric fans can affect considerably in the operating savings. Even though EAW uses waste heat from the district heating, it needs a non-negligible electricity input as well when they are translated in monetary terms.
4. Since only one window is replaced in the room, the energy savings are in general small in comparison to the overall energy consumption. In the main, it would imply long payback period.

6.4 LCC sensitivity analysis

As explained in Section 3.3, it is needed to measure how sensitive is the model when data input changes. Until now, only the parameters for BAU scenario have been simulated. The following sensitivity analysis will help us to understand how BAU results could change if the EAW can provide higher energy savings or if its maintenance is lower than expected for example. Furthermore, more variations will be studied to know which are the limits of the feasibility of the window.

The LCC model have several uncertain variables that we can vary. The main are the following:

- Electricity trend
- Discount rate
- Currency conversion
- Maintenance of EAW
- Total investment of EAW
- Net EAW energy savings

We assume that the NPV of the three systems can change because of the three first ones. However, for EAW case, more variables are subjected to uncertainties during its operation phase. The effect of the last three variables of the list are the ones which are going to be analysed. It is assumed that the rest of the variables remain constant (e.g. lifespan, reference electricity consumption, ambient temperature etc.). The maintenance rates for the double and triple-glazed window are considered as constant as well.

Then, this sensitivity analysis consists of two parts: in the first one only one uncertain variable will be varied, one by one, the variation in NPV and costs changes (maintaining the 20 years of timeframe) is analysed. The second one studies how the model changes when two important parameters vary at the same time.

The methodology followed is a simplification of Monte Carlo method. One thousand random values for the uncertain variables will be run to get its normal distribution. Then, the most probable value range will be selected. By 'probable' it means there is 95% of certain of being between the interval [a, b] where a represents the minimum value of the range and b the maximum.

After that, the model is simulated introducing the values from 'a' to 'b' of that variable. The following average and standard deviation of the parameters are considered.

Table 19 Normal distribution of the parameters

Parameter	Average	Standard deviation
Discount rate r (%)	0.43	0.0075
Electricity price trend (%)	1.013	0.025
Currency conversion	9.46	0.875
Total EAW investment (SEK)	25 200	3750
EAW Maintenance (%)	1.5	0.65
Net EAW energy savings (kWh)	97	150

The nomenclature that is going to be followed will be:

- NPV1, NPV2 and NPV3 are the Net Present Value for the System 1 (double-glazed or reference system), System 2 (triple-glazed) and System 3 (EAW) respectively.
- OPEX1, OPEX2 and OPEX3 are the operating costs for the System 1, 2 and 3 respectively.
- The average of the parameters in Table 19 are the ones used in BAU scenario. Sometimes the variations of the variables will be expressed as an increase or decrease percentage. This percentage is relativized to this average or the base case's NPV (Table 16).

5.4.1 Individual variations in BAU scenario

Apart from the graphs shown in this section, all the values used for them are attached in Appendix A, from Table 32 to Table 37.

1. Discount rate

After plotting the Figure 29a, the discount rate value would be between the range -1.2 and 1.8% with a 95.2% of possibility.

It is easy to distinguish a decrease of NPV of the three systems when the discount rate rises. When discount rate rises 0.1% its value, NPV decrease in a ratio of 0.88% for NPV1; 0.82% for NPV2 and 0.85% for NPV3 in relation to BAU scenario.

It means that each 1% increase in the discount rate rise, the NPV becomes on average 8.5% lower than the base case. Since NPV behaves almost in the same ratio, even if the discount rate rose hugely, the curves would never cross each other under possible discount rate ratios.

In other words, even though the final NPV changes considerable with the discount rate, its variations do not change the cost-effectiveness of the systems. The expenses of the EAW after 20 years would be still higher than the reference even if discount rate varied a lot from BAU scenario.

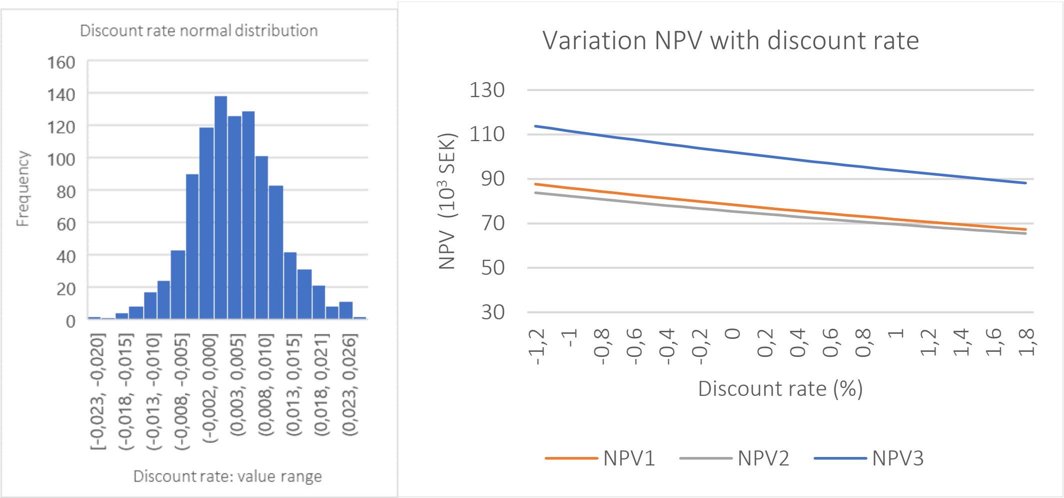


Figure 29 a. Normal distribution of discount rate.
b. Variation of NPV when discount rate changes

2. Electricity price

In the case of electricity price increase rate, we can ensure with a 95.22% of certainty that the price can increase between -3% to 8% each year. A -3% of decrease would mean that the electricity price becomes 3% cheaper each after year.

NPV increases exponentially for the three systems when the trend of the electricity price rises. Since this increase is directly related with the operational costs, System1 is more sensitive to these changes. In particularly, per 1% increase of the electricity price every year, on average NPV1 would rise 9%; NPV2 8.2% and NPV3 would grow 6.5% in relation to the BAU scenario. Then, the room with EAW is the least sensitive system in relation to the electricity price.

The reason for this is related to the NPV cost composition. While OPEX3 represents the 57% of the total NPV3, the OPEX1 is the 79% of the total costs of NPV1, as it was shown in Figure 30b. The one whose operation costs represent the lowest percentage of the total expenses, its NPV would be less sensitive to electricity price changes.

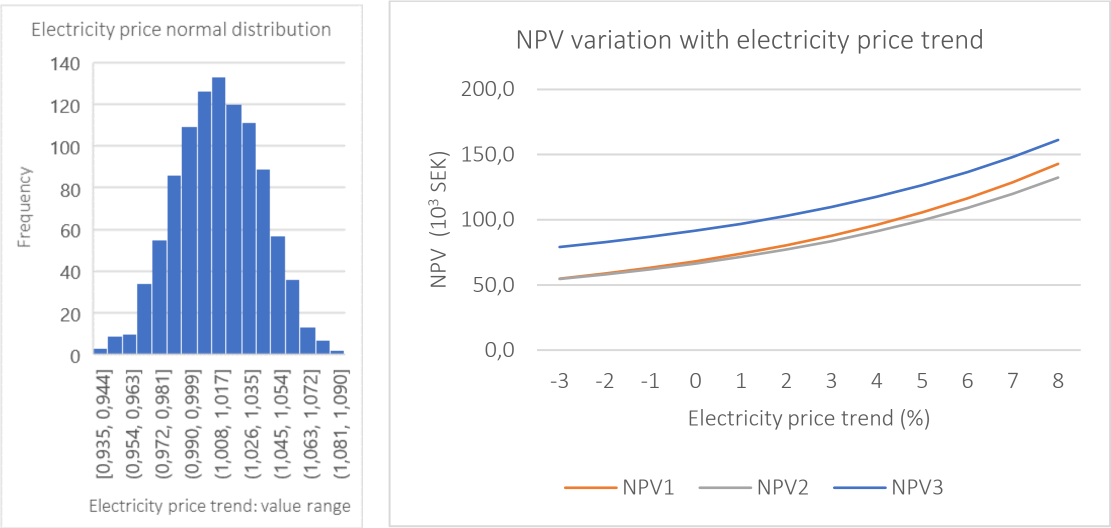


Figure 30 a. Normal distribution of electricity price trend.
b. Variation of NPV when electricity price trend changes

Then the reference system is the most sensitive to electricity prices changes. As seen, for feasible ranges the results of BAU scenario would not change neither. However, by extending the input values out of the selected range (Figure 31) we could see two intersections in the NPV curves.

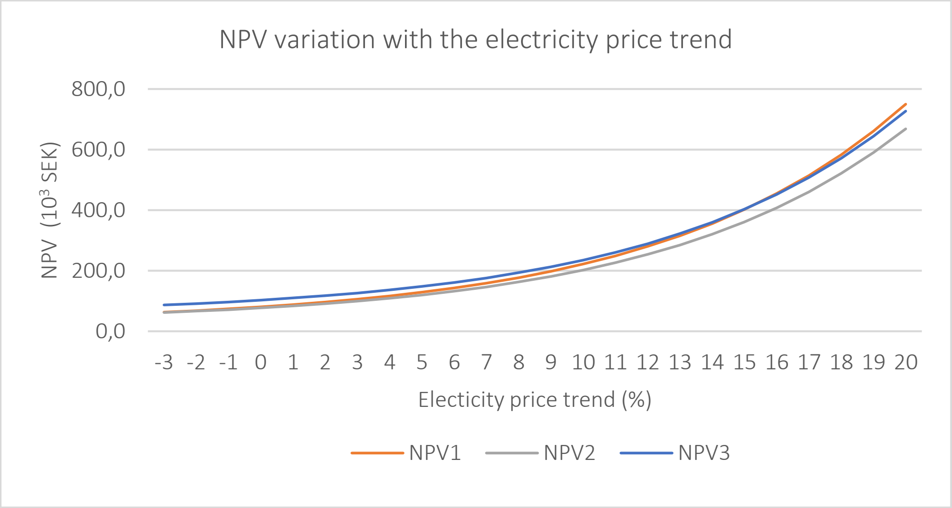


Figure 31 Variation of NPV when electricity price trend changes out of range

The NPV1 and NPV2 curves intersect each other in -0.1%, what means that, from this point, NPV2 will become lower in 20 years than NPV1. In other words, when the electricity price becomes more expensive than -0.1% every year, the triple-glazed is more suitable than the double-glazed unit. That would happen with the EAW if the electricity became on average 17% more expensive every year. In this case, the payback of EAW would be lower than 20 years.

Finally, if the operating costs variation are studied for electricity price changes (Figure 32) each 1% increase of the price every year, operation cost would increase 10.2% for the three systems. The ratio is identical although it implies higher expenses for System 1 in absolute terms.

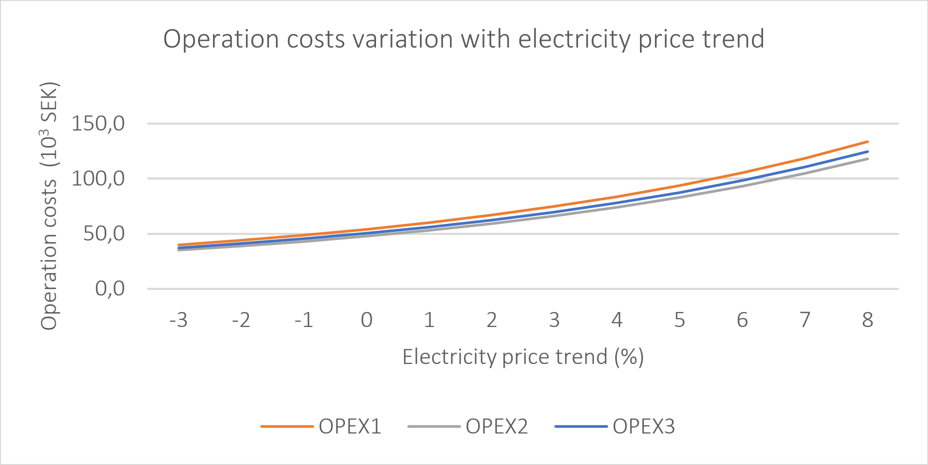


Figure 32 Variation of OPEX when electricity price trend changes

3. Currency conversion

The currency conversion is directly related to the electricity price then, with the operation costs as well. The currency change of 1 Euro to Swedish Krona can be considered between 8 and 15 SEK with a probability of 95.24% of being under this range.

It is logical that if EUR becomes more valuable and the currency change rises, the electricity would be more expensive and NPV would rise.

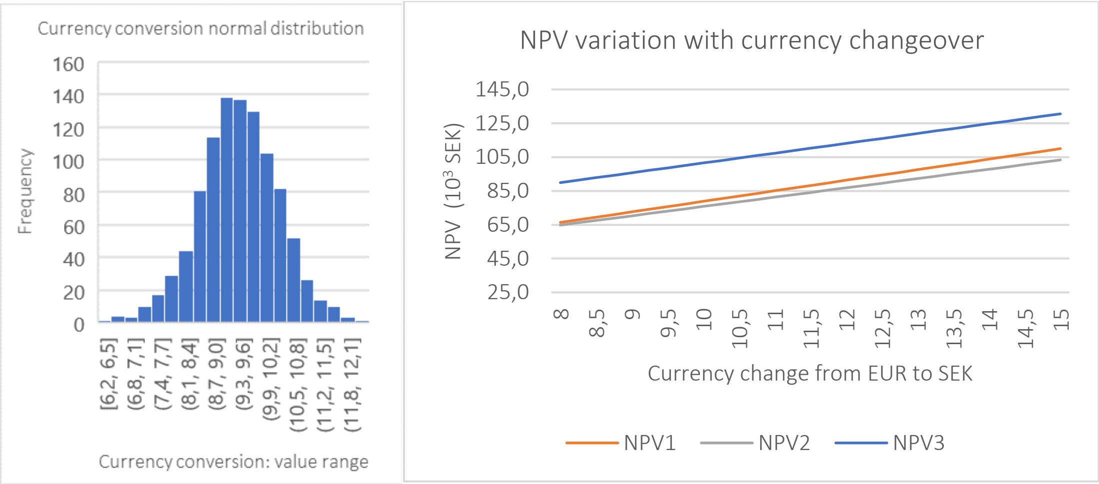


Figure 33 a. Normal distribution of currency conversion.
b. Variation of NPV when currency conversion changes

Again, System 1 is the most sensitive to currency changes. However, the rate of increase is lower than the previous parameters. Each 1 SEK that the currency changeover increases, NPV1 rises on average 4.1%; 3.4% for NPV2 and 2.7% for NPV3. By the moment, it is the variable that affects the least the NPV.

4. Total investment

Since the window is not already manufactured, its purchase cost is another uncertain variable. It can differ from the one expected due to logistic issues, materials more expensive, shipping, extra fees etc. If we consider that the investment is between 19 000 and 45 000 SEK, there is 95.1% of certain of being in this range.

Each 5000 SEK that EAW investment increases, NPV3 would increase 650 SEK that would be 6.10% in relation to the BAU scenario. This ratio would be interesting during the decisions about the manufacturing processes and the related costs. Nevertheless, in the end 5000 SEK represents around a 20% of variation in relation to the BAU scenario initial budget. That means that each 10% that the investment decrease, NPV3 would decrease only 3%.

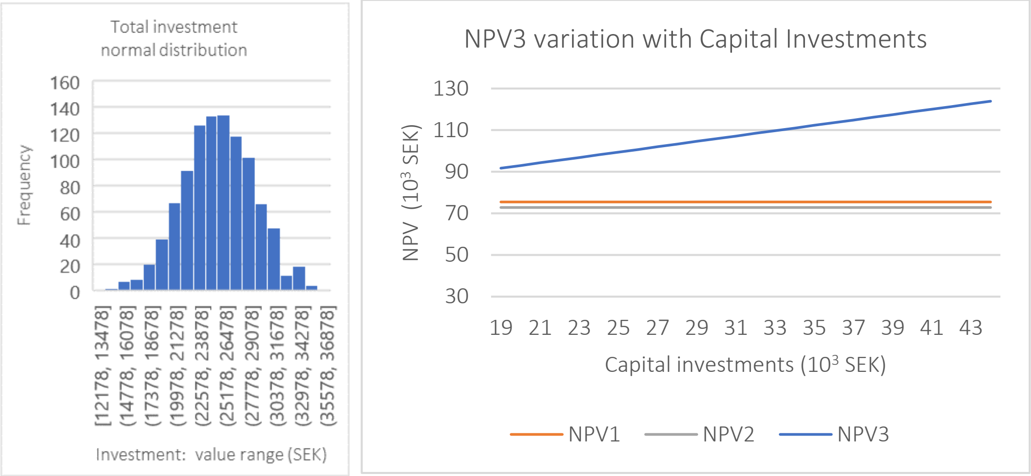


Figure 34 a. Normal distribution of EAW investment.
b. Variation of NPV when EAW investment changes

5. Maintenance

For the BAU scenario, the maintenance rate for EAW was defined as 1.5% of the capital investment. The rate can be in the interval from 0.3 to 3% with a 95.71% of certain.

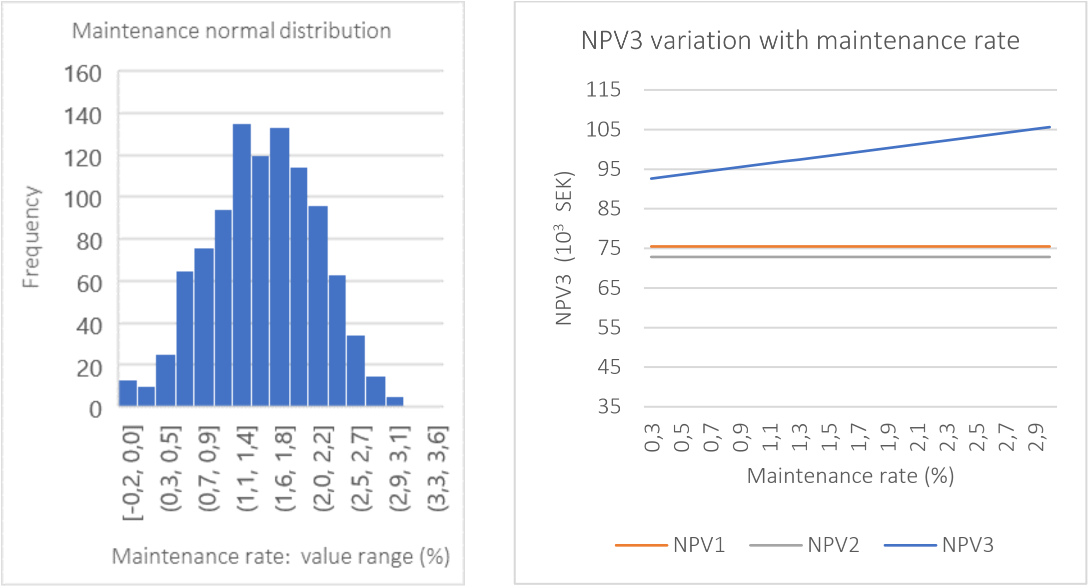


Figure 35 a. Normal distribution of the maintenance rate.
b. Variation of NPV when maintenance rate changes

Each 0.1% increase in the maintenance rate, NPV3 rises on average 500 SEK (0.5% in relation to the BAU scenario). Furthermore, if the maintenance costs are analysed for the same value range, each 0.1% of increase implies 3% of higher maintenance expenses.

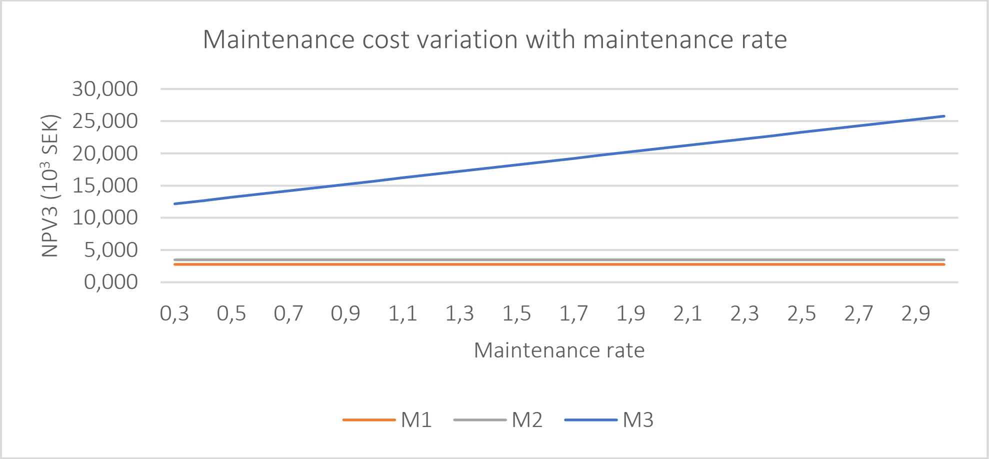


Figure 36 Variation of maintenance costs when maintenance rate changes

6. Net EAW energy savings

The net energy savings that EAW can achieve are quite uncertain and it would affect hugely in the heat demand and the energy performance of the room.

For the sensitivity analysis we consider the possibility that net energy savings can be lower or much higher than 97 kWh. The range is established between -150 and 700 kWh/year of net savings. Negative net EAW energy savings would imply that the fans consume more than the gross energy saved, so in the end the system would be consuming more energy than the reference.

The upper limit of 700 net kWh/year can be translated to 4.7 net W/m² of floor room, counting with the consumption of the electric fans. An estimation can be made for the U-value that would be needed for reaching this energy savings (Table 20). The data used for this estimation is the one used in Section 5.

Table 20 Estimation of the correspondence between U-value and net EAW energy savings

U-value (W/m^2·K)	Estimated Net Energy savings (kWh/y)
-1.5	700
-1	550
-0.5	400
0	220
0.5	50
1	-130

From the graph, each 50 net kWh/year saved would imply 2100 SEK in NPV reduction, which is 2.2% of decrease.

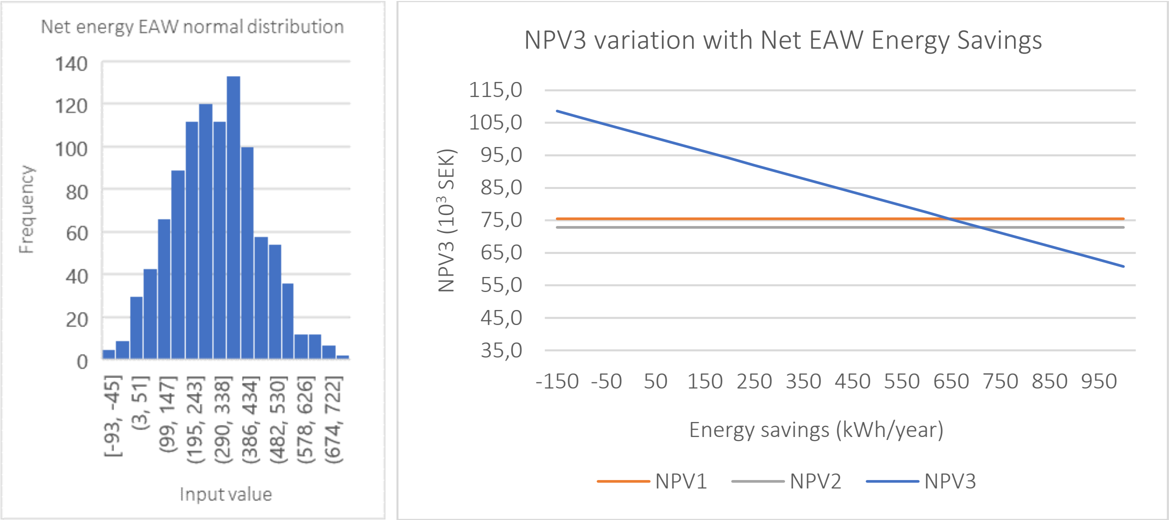


Figure 37 a. Normal distribution of the net energy savings.
b. Variation of NPV3 when net energy saving changes (some values out of selected range)

System 1 would be more profitable than EAW before reaching the 650 net kWh/year as energy savings. It is due to lower operation costs can not compensate the higher capital investment and maintenance costs. That would mean that the window is supplying heat to indoors (no heat losses) and the U-value should have negative values, on average -1.5 W/m2·K. If this would be the case, lower operation costs could compensate the maintenance and investment costs of the EAW, and the payback would be lower than 20 years.

If we were saving such quantity of energy, the operation costs savings would be on average 1500 SEK/year. In other words, if we were saving in electricity purchased more than 1500 SEK/year, the payback would be less than 20 years and the EAW would be more feasible than the other window systems. With 650 kWh/year of net savings, the EAW would be providing practically the 50% of the room's heat demand and the ventilation unit would reduce around 13% its total electricity input.

Actually, from 200 net kWh/y saved, the EAW would have less operation costs than the triple-glazed window. It means that we were saving more energy. However, even though the operation cost would be lower than other systems, the NPV3 would not be smaller than NPV1. Again, low operation costs can not compensate the higher maintenance and investment cost and triple-glazed unit would be continuing being more cost-effective.

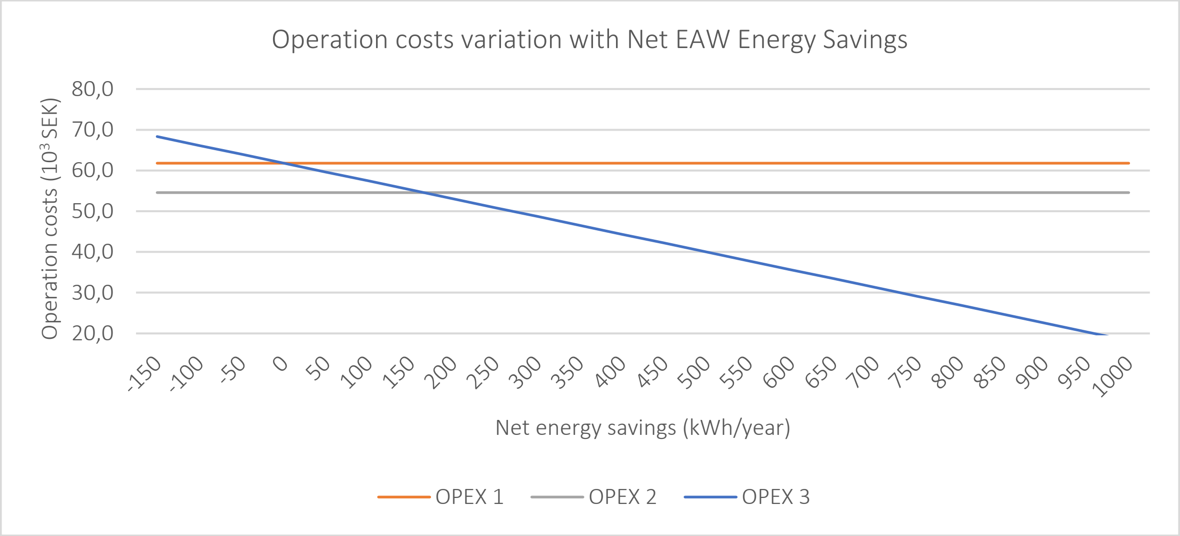


Figure 38 Variation of OPEX when net EAW savings changes

As a conclusion of this sensitivity analysis, one can see that by varying the uncertain parameters between their likely ranges none of them achieve that EAW become more feasible than the reference. Only if the net energy savings are high enough (around 700 net kWh/year) the total EAW expenses after 20 years could be lower than the reference.

The LCC model responds largely when electricity price and discount rate vary. Currency changeover and EAW capital investment affect in less quantity in the final NPV. Small changes in net energy savings, after all, would not imply a considerable variation in NPV3. However, since its range of values is bigger than other parameters, it represents an essential variable and the decisive parameter that determines EAW profitability.

5.4.2 Double variations in BAU scenario

In the previous chapter we have seen that varying variables one by one between probable ranges, neither of them makes the EAW more profitable than the reference system.
For this section only the parameters that have more possibilities to vary regarding EAW are going to be combined. Electricity price, maintenance, and energy savings are the uncertain parameters that are more likely to change more from the BAU scenario. The aim is to know if varying two variables at the same time between probable ranges, NPV3 could be lower than NPV1.

All the values expressed in the Table 21,22 and 23 are the different values that NPV3 can take. They are going to be compared with the NPV1, presented in the last column. The combinations of value ranges in which EAW is more profitable than the reference, are highlighted in green. The cells with grey NPV3 values mean that they are out of the probable ranges.
The blue cell is the position of the BAU scenario. Then, it is more visible how far is the base-case scenario for reaching the 'green area' in which EAW is more feasible than the reference.

1. NPV3 (electricity price, net energy savings)

As seen in Table 21, by combining incremental variations in the electricity price trend and higher net energy savings, for both parameters the NPV3 becomes lower than NPV1. The profitability area starts when the net energy savings grow and, at the same time, electricity price increases.

For instance, the combination of 700 net kWh/year in energy savings with a 1% electricity price increase every year has been studied in the previous section. Now, one could see that if the electricity price increase 2% every year, the net energy savings needed would be 600 kWh/year instead. The extreme case would be that if the price trend became 8% more expensive every year during the next 20 year, the net energy savings needed would decrease to 400 kWh/year for making EAW more profitable than the reference.

Table 21 NPV3 variation when electricity price trend and net EAW energy savings change

Savings (kWh/y) / E. price (%)	100	200	300	400	500	600	700	NPV1
-3	79.0	76.3	73.6	70.9	68.20	65.5	62.8	54.8
-2	82.6	79.7	76.7	73.7	70.74	67.8	64.8	58.7
-1	86.8	83.5	80.2	76.9	73.62	70.3	67.0	63.2
0	91.5	87.8	84.2	80.5	76.87	73.2	69.6	68.2
1	96.8	92.7	88.7	84.6	80.57	76.5	72.5	73.9
2	102.8	98.3	93.8	89.3	84.76	80.3	75.8	80.4
3	109.6	104.6	99.6	94.6	89.53	84.5	79.5	87.7
4	117.4	111.8	106.2	100.6	94.94	89.3	83.7	96.1
5	126.3	120.0	113.7	107.4	101.11	94.8	88.5	105.6
6	136.3	129.3	122.2	115.2	108.13	101.1	94.0	116.5
7	147.8	139.9	132.0	124.0	116.13	108.2	100.3	128.8
8	160.9	152.0	143.1	134.2	125.24	116.3	107.4	142.9

2. NPV3 (electricity price, maintenance)

In contrast to the previous combination, when electricity price trend and maintenance rate are varied simultaneously, the profitability area is still out of probable ranges. The profitability area begins when the maintenance rate is very low, and the electricity price trend continues rising.

The electricity price trend needed to increase until 16% with a very low maintenance rate for EAW would become more profitable than the reference.

Table 22 NPV3 variation when electricity price trend and net EAW energy savings change

Maintenance rate (%) / E. price (%)	0	0.3	0.6	0.9	1.2	1.5	1.8	NPV1
-2	75.5	77.0	78.4	79.9	81.3	82.8	84.2	58.7
0	84.4	85.8	87.3	88.7	90.1	91.6	93.0	68.2
2	95.7	97.2	98.6	100.1	101.5	103.0	104.4	80.4
4	110.4	111.8	113.3	114.7	116.2	117.6	119.1	96.1
6	129.4	130.8	132.3	133.7	135.1	136.6	138.0	116.5
8	154.0	155.5	156.9	158.3	159.8	161.2	162.7	142.9

10	186.0	187.5	188.9	190.4	191.8	193.3	194.7	177.3
12	227.7	229.2	230.6	232.1	233.5	235.0	236.4	222.0
14	282.0	283.5	284.9	286.3	287.8	289.2	290.7	280.2
16	352.7	354.1	355.6	357.0	358.5	359.9	361.4	356.0
18	444.7	446.1	447.6	449.0	450.5	451.9	453.4	454.7

3. NPV3 (maintenance, net energy savings)

The profitability zone of EAW in this case starts when its maintenance costs are low and the net energy savings increase. As seen in the Table 23, if the energy savings achieve around 550 net kWh/year practically with probable maintenance costs ranges NPV3 would be lower than NPV1.

Table 23 NPV3 variation when EAW maintenance and net EAW energy savings change

Savings (kWh/y) / Maintenance Rate (%)	100	200	300	400	500	600	700
0.2	91.97	87.81	83.65	79.49	75.33	71.17	67.01
0.4	92.45	88.29	84.13	79.97	75.81	71.65	67.49
0.6	92.93	88.77	84.61	80.45	76.29	72.13	67.98
0.8	93.41	89.25	85.09	80.93	76.78	72.62	68.46
1	93.89	89.74	85.58	81.42	77.26	73.10	68.94
1.2	94.38	90.22	86.06	81.90	77.74	73.58	69.42
1.4	94.86	90.70	86.54	82.38	78.22	74.06	69.90
1.6	95.34	91.18	87.02	82.86	78.70	74.54	70.38
1.8	95.82	91.66	87.50	83.34	79.18	75.02	70.87
2.00	96.30	92.14	87.98	83.82	79.67	75.51	71.35

NPV1
75.5

This last table confirms that the model and NPV are more sensitive to the net energy savings changes as well as the electricity price. The maintenance rate affects in less quantity than the electricity price.

Thus, the most probable scenario close to BAU scenario parameters would be gaining up to 600 net kWh/year (that would imply an U-value around -1W/m²·K) and an electricity price increase of 3% every year during the next 20 years. For this scenario, the year payback would be 18 years and the operation costs savings would be 1400 SEK/year.

7. LCA model

The methodology explained in Section 3.2 will be applied phase by phase.

7.1 Goal and Scope

- **Main goal:** to calculate the environmental impact of EAW assembly and life cycle from cradle-to-grave. Besides comparing the impacts of the double-glazed and triple-glazed assemblies and life cycle, the energy savings effectiveness will be evaluated from an environment-friendly perspective.

- **Scope:** the calculation of the environmental impacts will cover all the product stages i.e. extraction of raw materials, manufacturing processes, use phase and the recycling and disposal stage. A simplified process tree that represent the life cycle that is going to be implemented in the LCA model is shown in Figure 39.

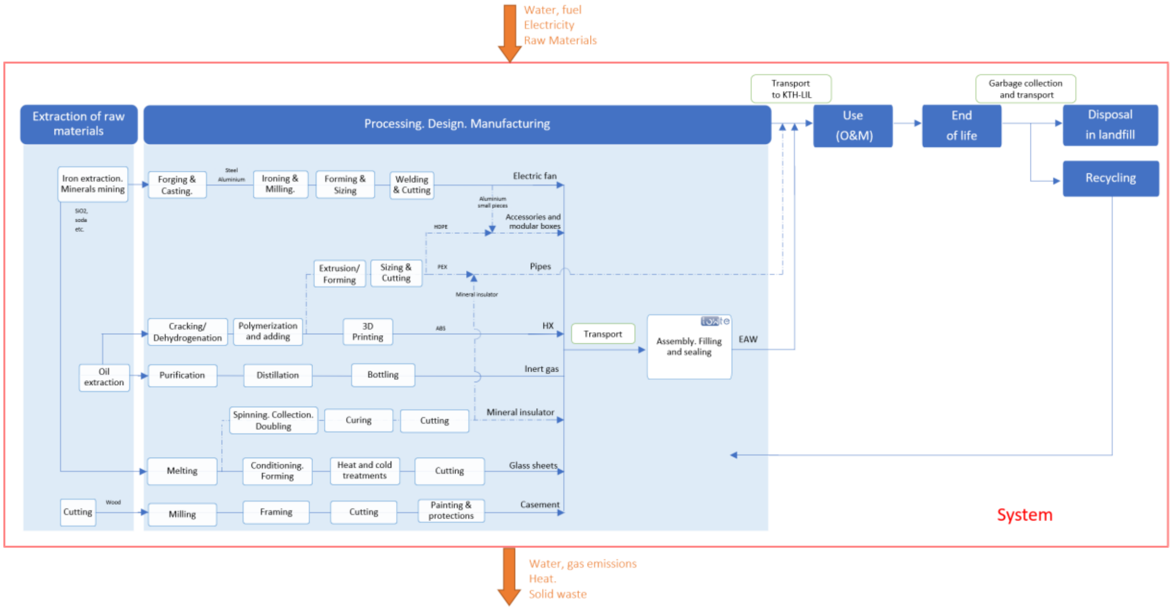


Figure 39 Simplified process tree used as reference for building LCA model in SimaPro.

- **Functional Unit:** 1 double-glazed unit, 1-triple-glazed unit and 1 EAW usage for 20 years.

- **System Boundaries:** the system boundaries are again the window systems and the components mentioned in Section 3. For this reason, the energy savings of triple-glazed window and EAW system will be negative and they will be deducted from their base emissions. In other words, the electricity savings will be translated as avoided emissions. In section 7.3.1 and 7.3.2 this observation can be understood better.

- **Geographical and temporal delimitation**: The implementation will be in Stockholm (Sweden) and the life cycle covers the next 20 years.

- **Computer Tools:** SimaPro (version 9.0.0.4.9)
- **Allocation Procedures:** Attributional modelling. EcoInvent 3 (cut-off by classification)

- **Impact assessment methodology used:** SimaPro simulations run under the statements of ISO 14043:2006 and the ReCiPe method 2016 (version 1.1) has been selected.

  For the midpoint and endpoint method, the hierarchist version was used and the calculation set was '*Midpoint (2010) H'* and '*World (2010) H/A'* [10]respectively.

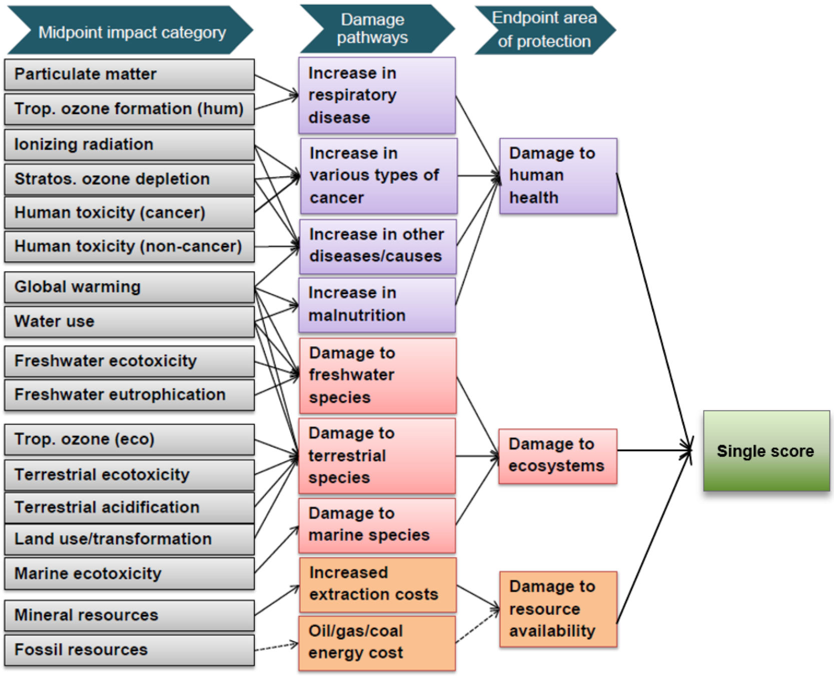


Figure 40 Overview of the impact categories that are covered in the ReCiPe2016 methodology and their relation to the areas of protection. **[35]**

7.2 Life Cycle Inventory (LCI)

This phase consists of identification, compilation and quantification of the environmentally relevant inputs and outputs: raw materials, energy, water, atmospheric emissions, solid wastes etc. All the data input can be check in the Table 38 included in Appendix B.

7.2.1 Structure of the LCA model in SimaPro

This section explains from a qualitative perspective some of the assumptions and simplifications that have been made. Table 39 attached in Appendix B clarifies the structure followed for building the LCA model. Moreover, it includes the numerical data used as data input in the assemblies, life cycle and customized processes.

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[10] The calculation set World H/A refers to the normalisation values of the world with the average weighting set in the ReCiPe hierarchist version.

- **SimaPro libraries usage: Ecoinvent**

  Ecoinvent 3, with cut-off by classification as its allocation method and specialised in system processes, is one of the libraries included in SimaPro software. This library includes manufacturing processes data regarding the impacts, emissions, inputs and outputs until cradle-to-gate **[57]**. Figure 41 can help to understand the production chain.

  For this LCA model, its environmental data of the upstream and production activities (such as mining and extraction and the usage of the infrastructure required) has been used. Since the main imports in Sweden are from Europe **[58]**, all the manufacturing processes selected are related to the European standards.

  Then, the gate-to-gate activities (downstream activities in Figure 41) are processes that have been customized for System 1,2 and 3. Most of them are unitary processes[11] of the last stages of the production chain. As mentioned, the specific materials, weights and input and outputs flows are included in Table 39 in Appendix B.

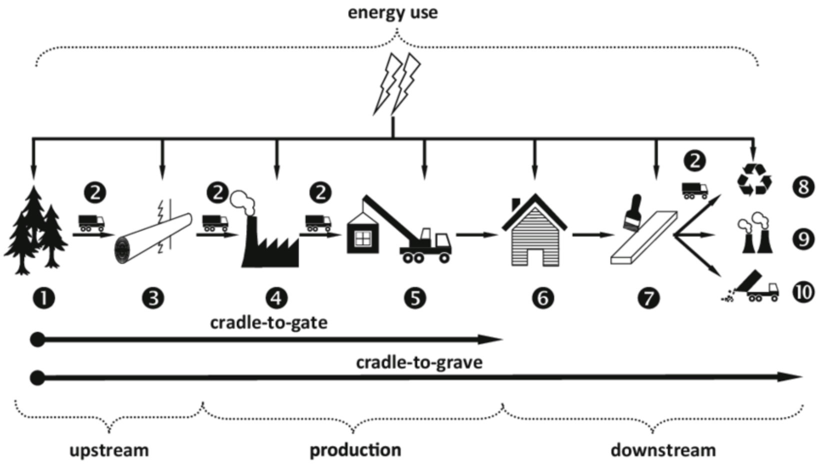

Figure 41 Concept of cradle-to-gate and gate-to-gate activities. **[57]**

- **Assumptions in the manufacturing processes**

  a. For obtaining the aluminium spacers, it is assumed that after a standard European metal rolling process, they are milled and cut again for the specific perimeter of the window. No intermediate transport is considered.
  b. Similar processes are carried out for the aluminium internal hardware, made by extrusion, and sawed to implement them in the structure of the wooden frame.
  c. Construction material such as stone wood, sealing components or coated flat glass are modelled with the global production processes.
  d. For the thermoplastic accessories it is assumed that they are made by injection moulding.
  e. Same simplification is made for the air drivers and the pipelines. Both of them are made by plastic extrusion.
  f. For the HX manufacturing we created the ABS 3D printing procedure. ABS is made by melting acrylonite, styrene and butadiene in an industrial furnace **[58]**. Then the ABS power is sintered by a SLS 3D-printer. By assuming the data sheet of EOS Formiga P 110 (industrial SLS 3D

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[11] The unit process are the steps of transformation until the last product. A combination of 'unit processes' is a so-called "system process".

printer) with a printing speed of 1.2 L/h and a laser 'Type 30W CO_2', in around 2 h the HX could be ready for shipping. **[59]**

g. Krypton and argon gases are produced industrially by the fractional distillation of liquid air in a cryogenic air separation unit **[60]**. The global process is considered until the fractional distillation. After this, these both chemicals are stored in the plant and carried by tanker trucks until the supplier.
h. For the wooden frame, standard process is considered for manufacturing 1kg of glued laminated timber from wood chips. Then, it is included the sawing and coated processes until get the finished frame. Assuming a medium industrial wood saw of 100L/min, the cutting speed can reach 74.5 kg of wood/min **[61]**.

- **Assumptions in life cycle components and energy consumption**

  a. The three window systems are modelled first as assemblies[12]. Then, when the energy demand calculated in Section 5 is included for BAU scenario, they are being modelled as life cycles[13].
  b. Concerning EAW composition, HX and electric fan are commercial products as themselves even they are integrated in the system. Since HX uses waste heat, it is considered only as an assembly and no as a life cycle. In contrast, electric fan has its defined life cycle and it is included in EAW life cycle as an additional life cycle.
  c. EAW life cycle contains the total sum of components that uses during the 20 years i.e. 2 HX units, 4 electric fans etc. In other words, the replacement during the timeframe is included. It is assumed that neither argon nor krypton layers need to be renewed because of small leakages during the timeframe. The lifespan considered is the one defined in Section 4.3.1.
  d. In the assembly of the three systems, electricity consumption is included taking as reference the process double glazing" and "triple glazing" of Ecoinvent3.
  e. For representing the energy savings, the model has an entry called "Energy demand" where the values of the heat demand are entered. System 1 is again the reference. The energy savings of System 2 and 3 will be translated into negative environmental impacts by comparing its 'Energy demand' with the reference.
  f. The frame, internal hardware and some insulator layer components are common for the three systems, but they contain different quantity of them. In this LCA model, small parts, and components (such as desiccant, spacer etc.) have been included.

- **Assumptions regarding the transport**
  It is important to take into consideration that EAW is a prototype that is not already manufactured. Some data regarding the traceability of its components is right now unknown. For this reason, the data regarding the transport of cradle-to-gate activities, was taken from the library Ecoinvent 3 "market".

  Then customized transport was added for the activities gate-to-gate, that is basically the assembly of all the components and subcomponents. It is expected that most of the components will be purchased in prefabricated conditions from Swedish suppliers.

  a. As a simplification, glass, wood, aluminium, and sealing materials are provided by the same suppliers for all systems.

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[12] Assemblies and subassemblies in SimaPro connect materials and processes but do not contain environmental data. It is a way for nesting or defining the product component by component.

[13] Life cycle in SimaPro refers to the utilization of the product. It includes at least one assembly, the possible energy consumption, transport, or the waste disposal scenario. Additional life cycles of other products can be added as well.

Table 24 Assumptions in transport

Material	Supplier and origin	
Glass	Pilkington Sverige AB	Stålvägen 3, 574 38 Vetlanda
Laminated timber	SCA Timber AB Bollsta Sågverk	Bruksvägen 7B, 873 30 Bollstabruk
Construction material	XL-BYGG	Saluvägen 4, 703 75 Örebro
EAW components	Supplier and origin	
PE and HDPE	Erteco Rubber & Plastics AB	Wennerbergsgatan 10, 112 58 Stockholm
Heat exchanger	Wematter, SLS 3D printing service	Södra Oskarsgatan 4, 582 73 Linköping
Construction material	Bygg-Ole	Odensala Ista 175, 195 92 Märsta
Electric fan	Sofasco	182 Garber Lane Winchester, Virginia 22602-4308
Pipes	Uponor Distribution center	Hackstavägen 1, 721 32 Västerås

b. The assembly of Systems 1 and 2 is made by the same manufacturing centre located in Örebro. Then, the windows are carried to KTH LIL. The method of transport is by road, in a large lorry, and the distance is 207 km.
c. In contrast, the assembly of the EAW is made in the technical centre of LOWTE, in Sigtuna. After the assembly of the EAW, it will be carried 50km by road until KTH LIL for its installation. It is assumed that a light vehicle (like a company van) will carry it.
d. The transport of the other components and materials across Sweden to LOWTE's centre is assumed to be by road, by lorry of different dimensions in dependence on the size of the component. The fan is carried from Canada by boat and the HX is brought by a light vehicle. The distances for shipping vary from 10-500km by road for the construction material and it achieves almost 6700 km in the case of the electric fan. The new pipeline branch will be carried directly to KTH for its installation.

- **Assumptions in waste scenario**

  Sweden is aiming towards a zero-waste future by 2020. Its targets were 90% of recycling of glass, 47% for plastic and 82% for paper. In 2017 69% of all packing was recycle and the figures were quite close to the targets **[62]**.

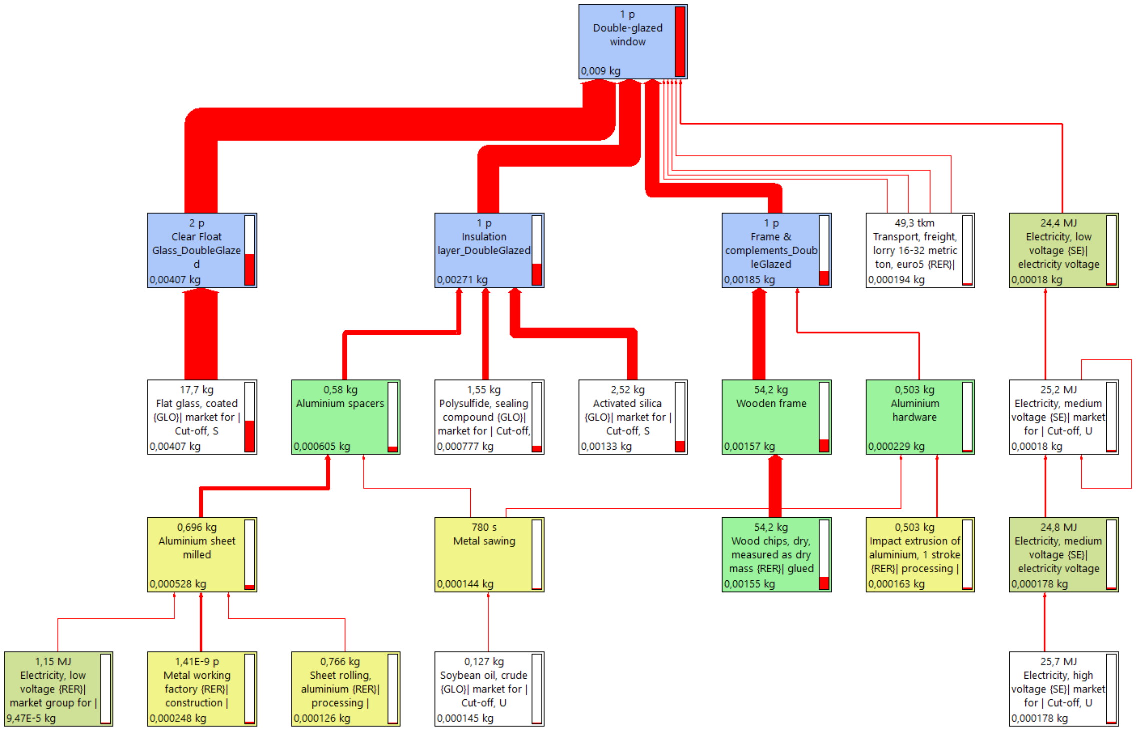
  Then it is assumed that the materials of the windows are likely to be recycled. The waste scenario selected in SimaPro is the Netherlands' waste treatment, due to the similarity of the percentages of materials recycled to Swedish goals. The transport to the infrastructure of waste treatment is disregarded.

7.2.1 Network of the systems for BAU scenario

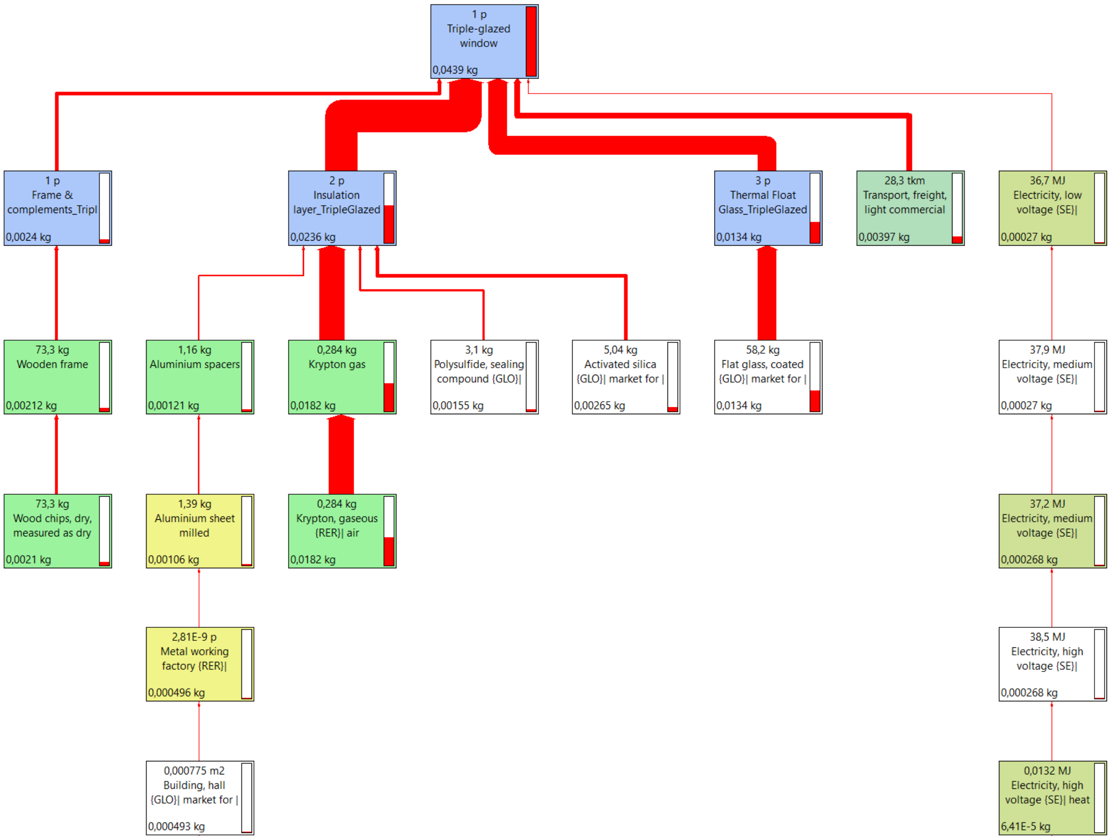
SimaPro generates simplified process trees represented in the Figure 42. The thickness of lines on the graphs illustrates the level of environmental impact of the particular processes of the life cycle of the window. Negative values in the boxes result from the fact that some emissions are avoided (case of System 1 and 2) and are the ones painted in green.

In Appendix B, a larger version of the networks is included in Figures 60, 61 and 62. There, the contribution of each component can be seen in more level of detail. The inventory of elements for the three systems is about 1500 elements. These networks are simulated with the data input of the BAU scenario.

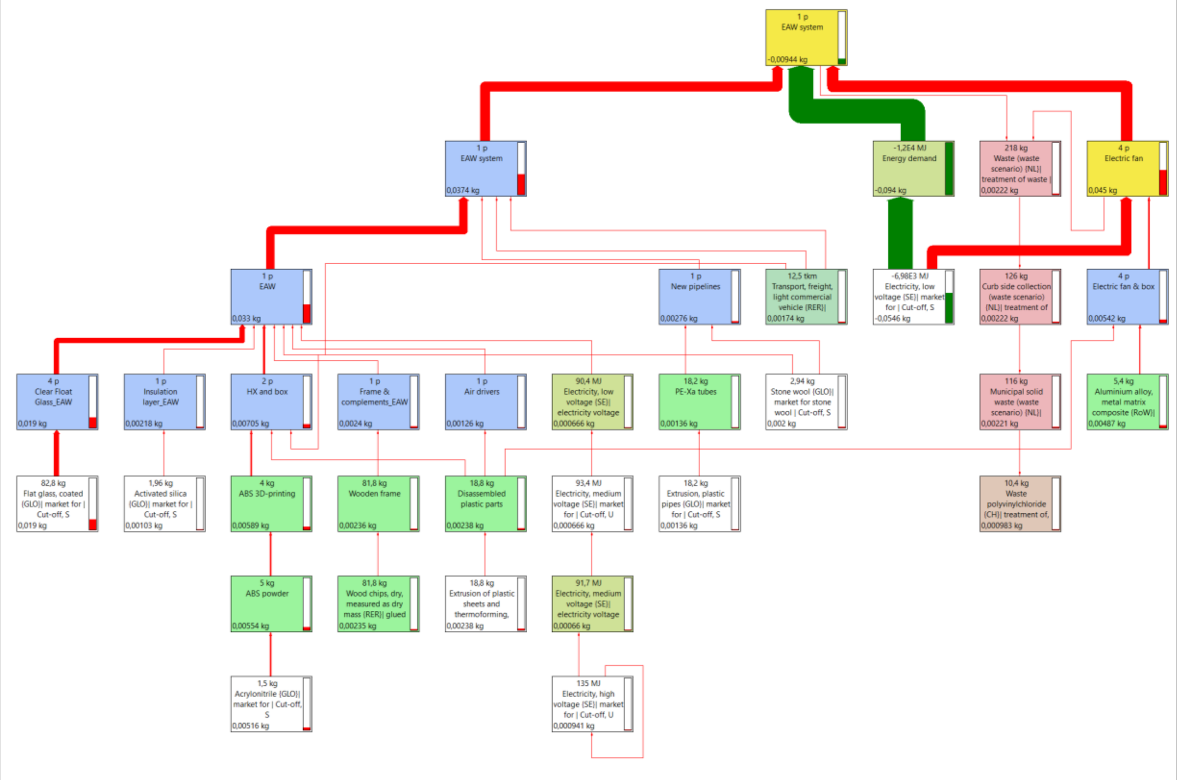
The simplification of the visible network and boxes depends on the index as (threshold expressed as %) for the impact categories.


1 p
Double-glazed window
0,009 kg
2 p
Clear Float Glass_DoubleGlazed
0,00407 kg
1 p
Insulation layer_DoubleGlazed
0,00271 kg
1 p
Frame & complements_DoubleGlazed
0,00185 kg
49,3 tkm
Transport, freight, lorry 16-32 metric ton, euro5 {RER}|
0,000194 kg
24,4 MJ
Electricity, low voltage {SE}| electricity voltage
0,00018 kg
17,7 kg
Flat glass, coated {GLO}| market for | Cut-off, S
0,00407 kg
0,58 kg
Aluminium spacers
0,000605 kg
1,55 kg
Polysulfide, sealing compound {GLO}| market for | Cut-off,
0,000777 kg
2,52 kg
Activated silica {GLO}| market for | Cut-off, S
0,00133 kg
54,2 kg
Wooden frame
0,00157 kg
0,503 kg
Aluminium hardware
0,000229 kg
25,2 MJ
Electricity, medium voltage {SE}| market for | Cut-off, U
0,00018 kg
0,696 kg
Aluminium sheet milled
0,000528 kg
780 s
Metal sawing
0,000144 kg
54,2 kg
Wood chips, dry, measured as dry mass {RER}| glued
0,00155 kg
0,503 kg
Impact extrusion of aluminium, 1 stroke {RER}| processing |
0,000163 kg
24,8 MJ
Electricity, medium voltage {SE}| electricity voltage
0,000178 kg
1,15 MJ
Electricity, low voltage {RER}| market group for |
9,47E-5 kg
1,41E-9 p
Metal working factory {RER}| construction |
0,000248 kg
0,766 kg
Sheet rolling, aluminium {RER}| processing |
0,000126 kg
0,127 kg
Soybean oil, crude {GLO}| market for | Cut-off, U
0,000145 kg
25,7 MJ
Electricity, high voltage {SE}| market for | Cut-off, U
0,000178 kg

a.


1 p
Triple-glazed window
0,0439 kg
1 p
Frame & complements_Tripl
0,0024 kg
2 p
Insulation layer_TripleGlazed
0,0236 kg
3 p
Thermal Float Glass_TripleGlazed
0,0134 kg
28,3 tkm
Transport, freight, light commercial
0,00397 kg
36,7 MJ
Electricity, low voltage {SE}|
0,00027 kg
73,3 kg
Wooden frame
0,00212 kg
1,16 kg
Aluminium spacers
0,00121 kg
0,284 kg
Krypton gas
0,0182 kg
3,1 kg
Polysulfide, sealing compound {GLO}|
0,00155 kg
5,04 kg
Activated silica {GLO}| market for |
0,00265 kg
58,2 kg
Flat glass, coated {GLO}| market for |
0,0134 kg
37,9 MJ
Electricity, medium voltage {SE}|
0,00027 kg
73,3 kg
Wood chips, dry, measured as dry
0,0021 kg
1,39 kg
Aluminium sheet milled
0,00106 kg
0,284 kg
Krypton, gaseous {RER}| air
0,0182 kg
37,2 MJ
Electricity, medium voltage {SE}|
0,000268 kg
2,81E-9 p
Metal working factory {RER}|
0,000496 kg
38,5 MJ
Electricity, high voltage {SE}|
0,000268 kg
0,000775 m2
Building, hall {GLO}| market for |
0,000493 kg
0,0132 MJ
Electricity, high voltage {SE}| heat
6,41E-5 kg

b.



c.

Figure 42 a. Simplified process tree for the double-glazed window whose elements have an environmental index larger than 1% are included. b. Simplified process tree for triple-glazed window whose elements have an index larger than 0.5% c. Simplified process tree for EAW whose elements have an index larger than 1%.

In Figure 43, the EAW's simplified process tree where the elements shown have an environmental index larger than 3%. One can see, from a qualitative perspective, that the electricity savings and consumption by the fans are the bigger impacts. They affect largely the final environmental impact of the EAW, even more than some heavy components like the glass sheets required in the assembly. In the end, EAW would have a negative impact, what means avoided emissions.

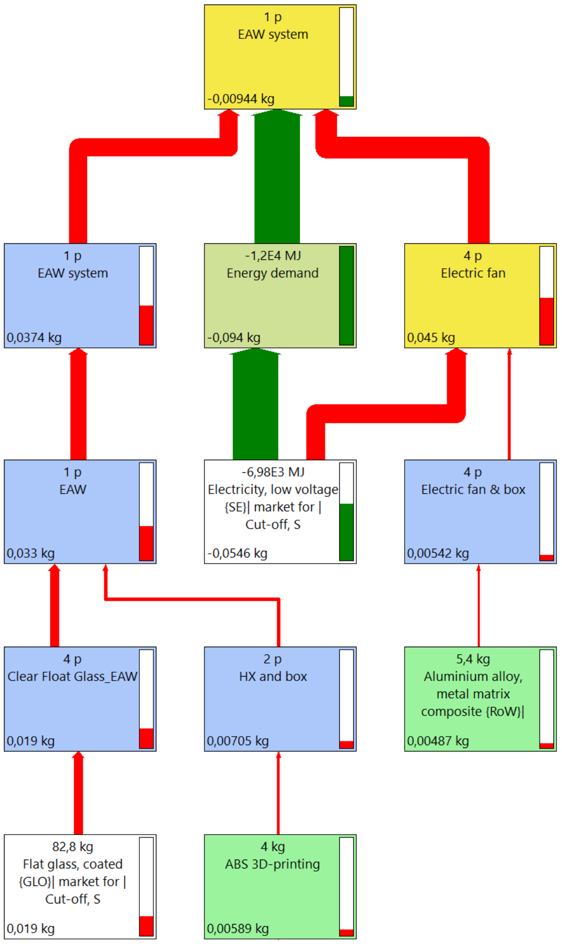


Figure 43 Simplified tree process for EAW whose elements have an index larger than 3%

In the following section these impacts will be studied quantitively through ReCiPe method. Nevertheless, even from a qualitive perspective, one can notice that the electricity savings implies directly large quantity of avoided emissions.

7.3 Life Cycle Impact Assessment (LCIA) for BAU scenario

In this chapter the Life Cycle Assessments and a comparison of the three systems (comparative LCA) will be made. First, only the assemblies (the structure of the windows) will be analysed and compared. Then, the energy savings and the direct environmental impacts savings will be considered in LCIA of the life cycles.

Since SimaPro provides the emissions for the 18 midpoint environmental impacts. For a better managing of the data output, the methodology followed will be the same for Sections 7.3.1 and 7.3.2. First the EAW midpoint impacts will be extracted, both for the assembly and its life cycle. After the normalisation[14], the main categories will be selected, and its emissions will be plotted in absolute terms (kg equivalent of the correspondent indicator). Then, the comparison with the other systems will be made.

The selection of the impact categories is done after simulating the model for all system. But for a better understanding, the Figure 44 is attached, where the most relevant impacts (that will be mentioned numerous times) are remarked in green.

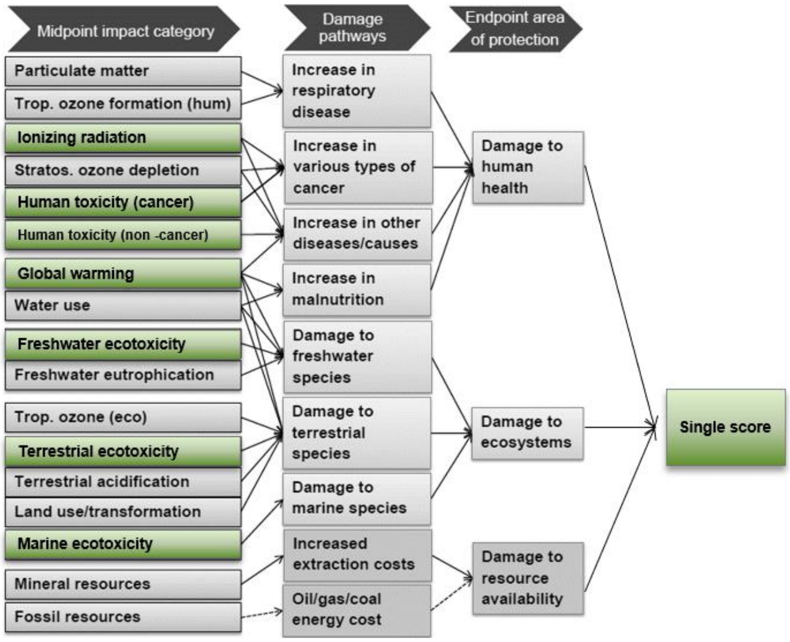


Figure 44 Impacts categories that will be relevant in LCIA **[35]**

The definition of all of these impacts is included in Appendix B, Table 40. Moreover, the whole LCIA data, with all the environmental impact categories are included in Appendix B (Table from 42 to 45).

As a quick description of these impacts, the characterization factor of human toxicity and ecotoxicity accounts for the environmental persistence and accumulation in the human food chain and toxicity of a substance. **[35]**

7.3.1 LCIA for systems assemblies

By only considering the assembly of EAW (the components and subcomponents without energy consumption), the main relevant contributions by category are made by marine and freshwater ecotoxicity followed by human carcinogenic and non-carcinogenic toxicity as seen in Figure 45a. These 5 midpoint impact categories sum the 99.6% of the total emissions after their normalisation. For this reason, henceforward the LCIA will analysed this midpoint categories. The global warming indicator would be included too due to the scope of the project.

The normalisation phase has a great importance because it solves the incompatibility of units. For this reason, it is the sole phase in which one can compare emissions per category. It is interesting to into account that the ecotoxicity indicators of a European are on average quite small and, for this reason,

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[14] Normalisation shows if an impact category indicator result has a relatively high or a relatively low value compared to a reference. ReCiPe takes the average annual impact of a European citizen in the year 2000 as a reference.

construction components generate high emissions of these indicators when they are normalised. The normalisation values that ReCiPe takes are on the Table 41 in Appendix B.

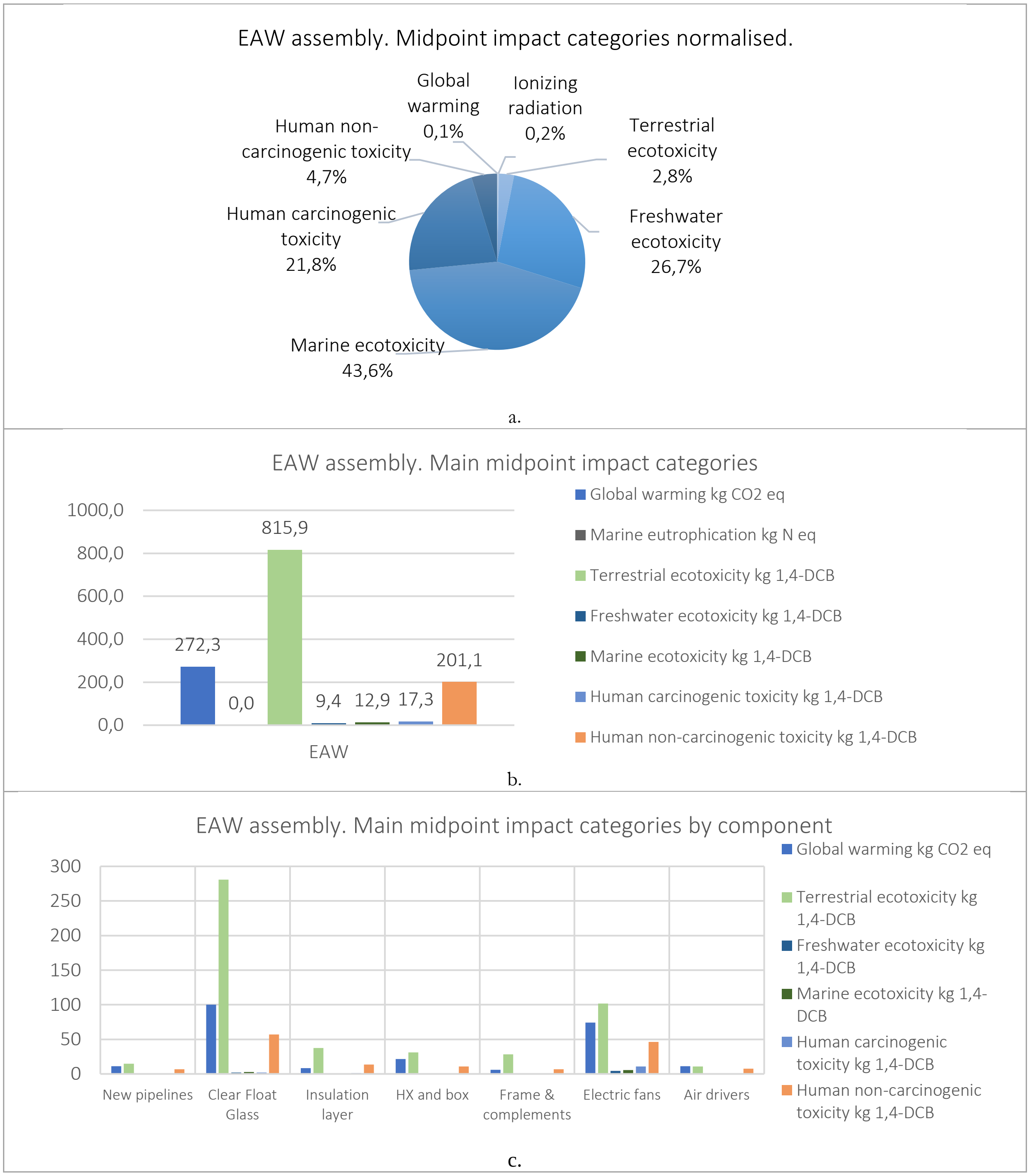


Figure 45 Main midpoint impact categories for EAW assembly.
a. Normalised. b. Characterised c. Characterised by component

One can see that the main contribution of the marine (44%) and freshwater ecotoxicity (27%) comes from the float glass. The quantity of material used for the four glass sheets is, with difference, the largest and heaviest one and it implies directly higher emissions. The transport of this component is the one that generates more emissions since it is measured in mass units multiplied by the distance.

The human carcinogenic toxicity represents the 22% of the total damage and it is caused by some materials included in the float glass and fans composition. Since the model is considering the four electric fans required during the next 20 years of EAW lifespan, their contribution is much higher than other components that are only comprised by one unit.

Moreover, even though in absolute terms the emissions of kilograms of CO_2 equivalent are much higher than marine or freshwater ecotoxicity indicators, when they are normalised these last ones have more significance.

The footprint does not represent an important role (in relative terms) regarding the environmental impact for EAW. Nevertheless, since it is in the scope of the project, the global warming indicator will be commented individually.

EAW assembly in total it sums 272 kg CO_2-eq and again, the float glass (37% of the total CO_2 emissions) and the fans (27%) are the components that contributes the most. The total transport in this chart concerns the transportation of the components from the suppliers to LOWTE's centre and the transportation for installing the window in KTH LIL.

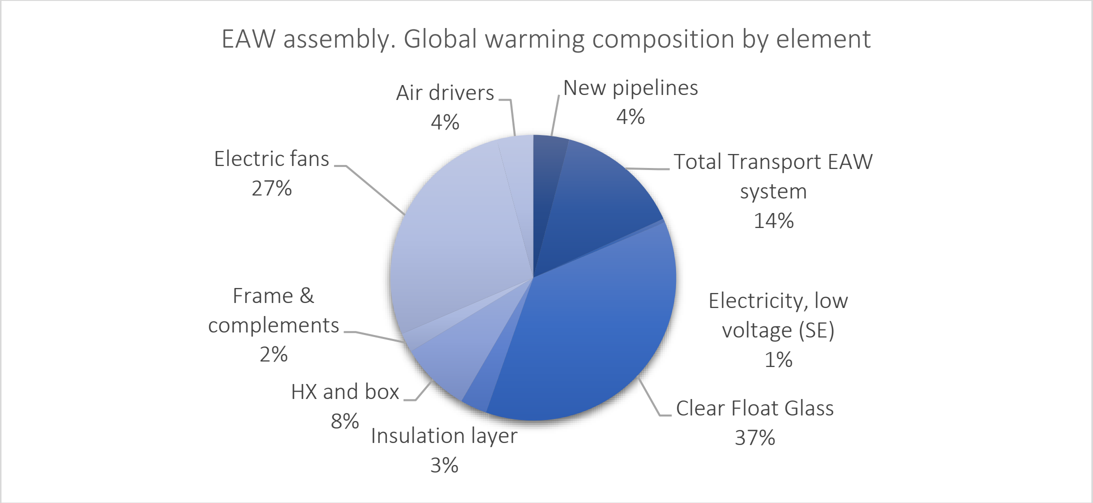


Figure 46 Global warming composition for EAW assembly.

If EAW assembly is compared with double-glazed and triple-glazed windows, it would generate more emissions since it is a more complex product. In Figure 47 one can see that, naturally, it has higher indicators than System 1. However, although the system of EAW is much more complex than the triple-glazed unit, its emissions are not quite distant.

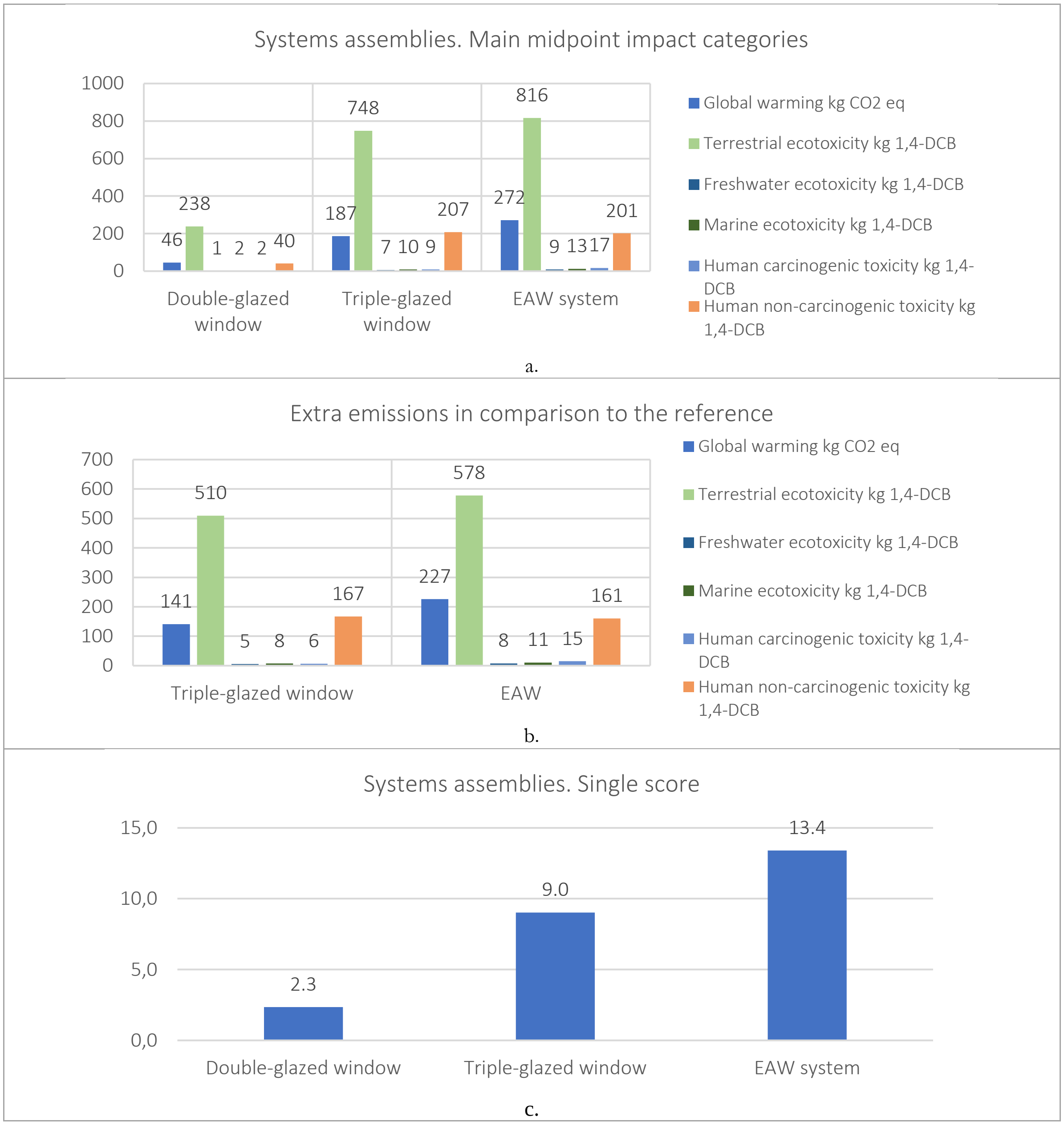
This fact is due to the triple-glazed insultation layer, which generates larger emissions than EAW. Besides the individual layer is thicker than EAW, System 2 is comprised by two krypton filling gaps. Thus, it requires more mass of krypton than argon. In fact, the krypton is denser than argon. As only the glazing unit is heavier, it affects the transport impact too.

The global warming of common components is compared in Table 25. The four panes of glass affect largely in the total footprint of EAW. The insulation layer and the frame have smaller CO_2 emissions than the reference due to less quantity of desiccant and aluminium caused by a thinner layer. Moreover, EAW has been designed for not being opened. Since it is a fixed window, some accessories in the frame are saved.

Table 25 Global warming comparison for common components

	Total (kg CO_2-eq)	Frame & complements	Insulation layer	Float glass
Double-glazed window	46	5	10.4	21.4
Triple-glazed window	187	7	48	70
EAW system	272	6	8	100

For a better understating, it is plotted the added emissions due to a more complex assembly in Figure 47b. In the end, by concentrating all the environmental impacts in a sole single score (end-point method), one can see that EAW is the one with a greater number of eco-points. This is directly related to its complexity and a greater number of components.



a.

b.

c.

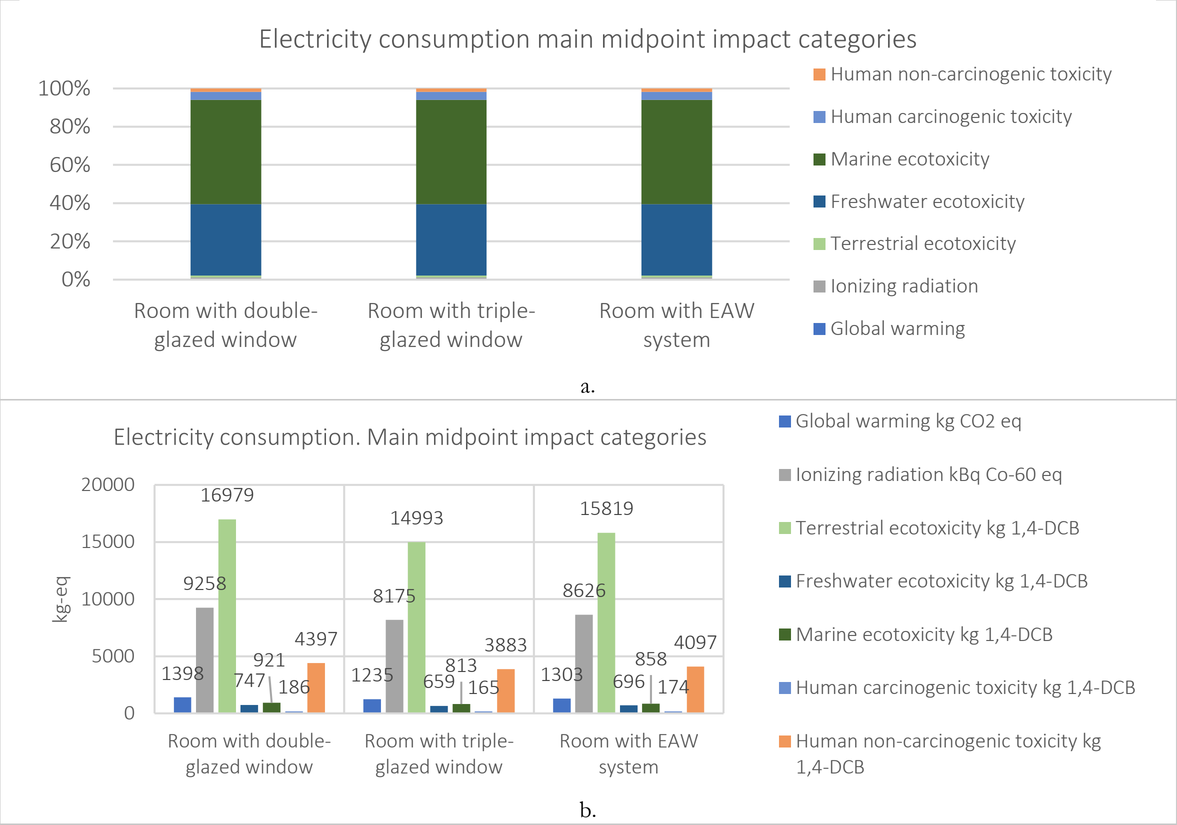
Figure 47 Systems assemblies comparison. a. Main midpoint impact categories for the three systems
b. Extra midpoint emissions of System 2 and 3 due to a more complex system in relation to the reference.
c. Single-score for the three systems

7.3.2 LCIA for systems life cycles

In this chapter the same LCIA structure is followed. However, this time the energy savings during the lifespan for the EAW are added.

It is important to remark that double and triple-glazed unit are passive systems. They do not consume or produce electricity by themselves. After 20 years, the room would consume on average 28.8 MWh with the current double-glazed window. By installing the triple-glazed unit, it would become 25 MWh. And for our BAU scenario, with EAW the consumption would rise to 25.4 MWh for heating the spaces counting with the electric fans.

This energy consumption would imply the environmental impacts in Figure 48. By analysing the indicators normalised, one can see that its midpoints impacts are practically the same as before: marine and freshwater ecotoxicity, human carcinogenic and non-carcinogenic toxicity. Actually, the ionizing radiation and the non-carcinogenic toxicity in absolute terms grows largely when the electricity is included in the model.



a.

b.

Figure 48 Main midpoint impact categories due to the electricity consumption.
a. Normalised. b. Characterised

The large emissions in comparison to the previous numbers are caused by the big quantity of electricity consumed during the timeframe. Actually, in relative terms depending on the impact category, 1 kilogram of material can cause more environmental damage than 1kWh. For instance, in relative terms of CO_2 emissions, 1 kg of float glass generates 0.9 kg CO_2-eq while 1kWh consumed in a Swedish household produces 0.68 kg CO_2-eq. Nevertheless, regarding the marine ecotoxicity, 0.024 kg 1,4-DCB are generated per kilogram of glass but 0.034 kilograms are produced per kWh consumed.

However, since the kWh consumed in a household are much higher than the quantity of glass used in the window, the avoided emissions that can be achieved by saving energy are quite high. Then, for EAW life cycle the energy savings represent a high quantity of avoided emissions in comparison to the ones emitted due to the assembly (In Figure 49 a. and b.).

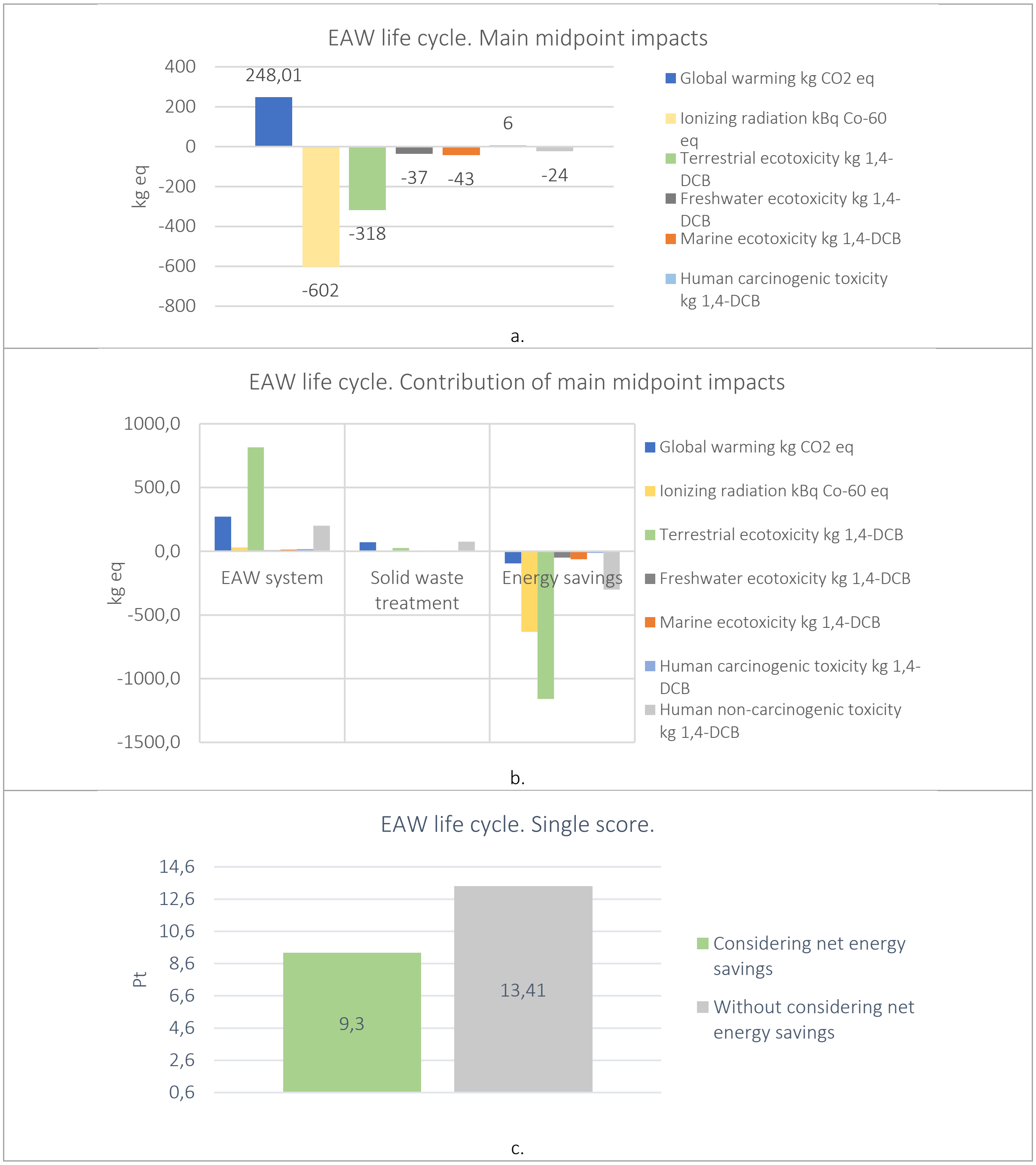


Figure 49 Main midpoint impact categories for EAW life cycle.
a. Characterised b. Characterised by component c. Single score reduction

From the graph one can see that the emissions due to the waste scenario are quite disregardful in comparison to the others. In Figure 48c the reduction of the single score when the net energy savings are considered is shown.

One can think that the decrease is not much remarkable after seen how much the electricity can avoid emissions in absolute terms. The reason of this, is quite related to the weighting phase of the end-point method. ReCiPe (and SimaPro classroom version) weight by default the human carcinogenic toxicity indicators much higher than other categories. Since the electricity savings do not reduce in great quantity this indicator, the damage in "human health category" changes only from 12.3 to 8.5 pt. It continues being 91% the total of the single score.

Regarding the CO_2 emissions, in Figure 50 one can see that the energy savings do not affect considerably the global warming. As mentioned, their main impacts are related to the ecotoxicity. For this reason, the reduction in CO_2 kilograms equivalent are still positive for EAW life cycle even discounting the savings.

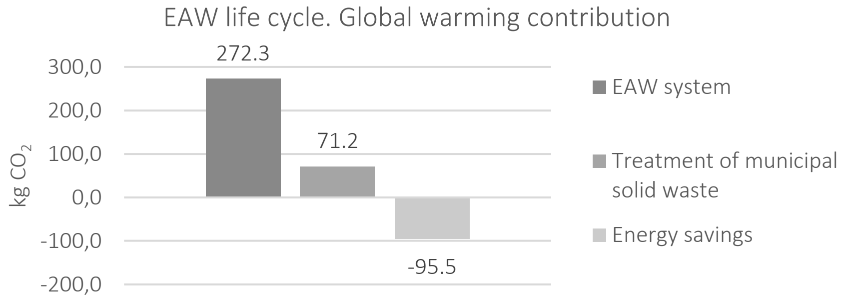
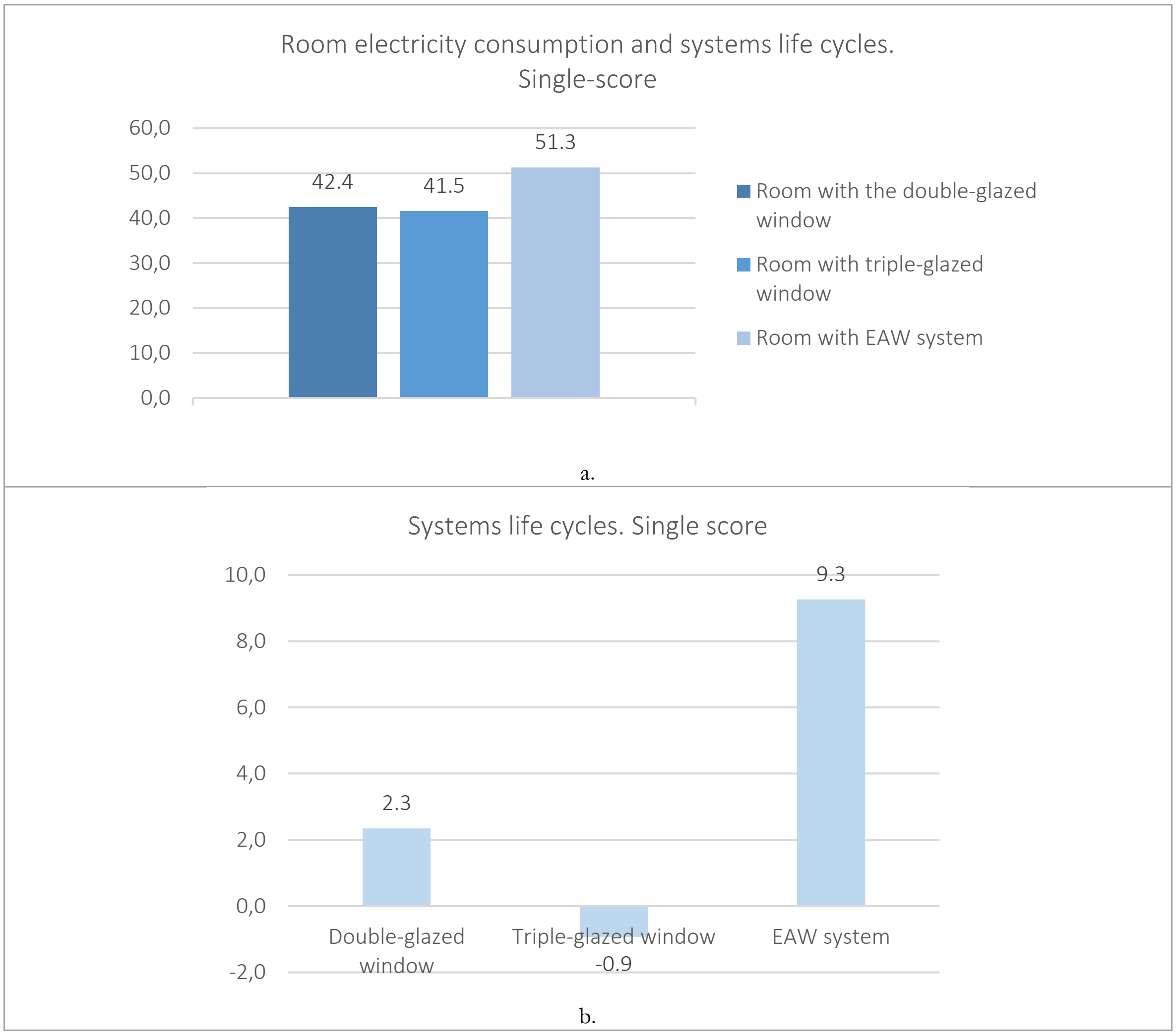


Figure 50 EAW life cycle. Reductions in global warming indicator

Finally, in Figure 51 the final score is compared for the three systems after 20 years of performance, considering for all of them their respective energy savings or consumption. One can see that the energy savings of EAW do not compensate the higher emissions that the assembly implies in comparison the refence.

Nevertheless, the ratio of difference has reduced hugely. While by only comparing the assemblies, the environmental impact of EAW was almost 6 times the reference, when the electricity savings are considered in the model, the ratio decrease to 1.2. That means directly that the LCIA is quite sensitive to energy savings variations. This fact will be studied in the sensitivity analyses.
On the other hand, the energy savings of the triple-glazed window are enough for compensating the higher emissions produced by the assembly. Then, its final score is lower than the reference.

When one studies the final score in relative terms of the energy consumption of the reference, it is more obvious that for BAU scenario triple-glazed would avoid emissions and EAW would need to increase its energy savings for compensating the damage due to a more complex system.



a.

b.

Figure 51 LCA comparison (single score) of the three systems considering the energy savings
a. In absolute terms regarding room consumption b. In relative terms

As a conclusion and an interpretation of BAU scenario, one could say that:

1. Since EAW system assembly has more components than the reference window, naturally the environmental impact would be higher. However, there is not much difference with the assembly of the triple-glazed window emissions.

2. The main impacts of the EAW assembly when they are normalised are marine and freshwater ecotoxicity and human carcinogenic toxicity. The components that generates more emissions are the heaviest ones and the ones that require more quantity of materials, which are the panes of glass and the electric fans. The global warming would not represent a significant indicator when construction components are the case of the study.

3. In relative terms depending on the impact category, 1 kilogram of material can cause more environmental damage than 1kWh. However, since the electricity consumed in a household is much higher than the quantity of construction materials, the avoided emissions that can be achieved by saving energy are quite high.

4. When the electricity savings are considered for the next 20 years, the environmental damage of the EAW reduces largely in absolute terms. They should be enough high for compensating the higher emissions of the assembly in comparison the reference.

7.4 LCIA Sensitivity analysis

In Section 3.3 the importance of measuring the sensitivity of the model was explained. Until now, only the parameters for BAU scenario have been simulated. The following sensitivity analysis will help us to understand how the environmental impact indicators can change if the EAW can provide higher energy savings or if the maintenance become lower.

Then, the main uncertain variables that are going to be changed in LCIA are
- Net energy savings
- Maintenance and number of replacements in 20 years

The results that are going to be studied are the main midpoints mentioned and the single score.

1. Net EAW energy savings

The range of values in which they can vary will be taken from the LCC sensitivity analysis (Section 5.4.1). A variation between -150 and 700 kWh/year will be considered again for the net energy savings.

In Figure 52 one can see how the main midpoint indicators would vary when EAW saved more energy. The variation of all emissions would decrease linearly when the energy savings grow. The most sensitive to these variations are the freshwater and terrestrial ecotoxicity. However, the less sensitive are the marine ecotoxicity and the human toxicity indicators.

This fact can explain why the changes in the EAW final score are slight in comparison to the great quantity of avoided emissions in absolute terms. As mentioned, the indicators that behaves slower with an energy saving variation are the ones that have higher weight factors after the normalisation.

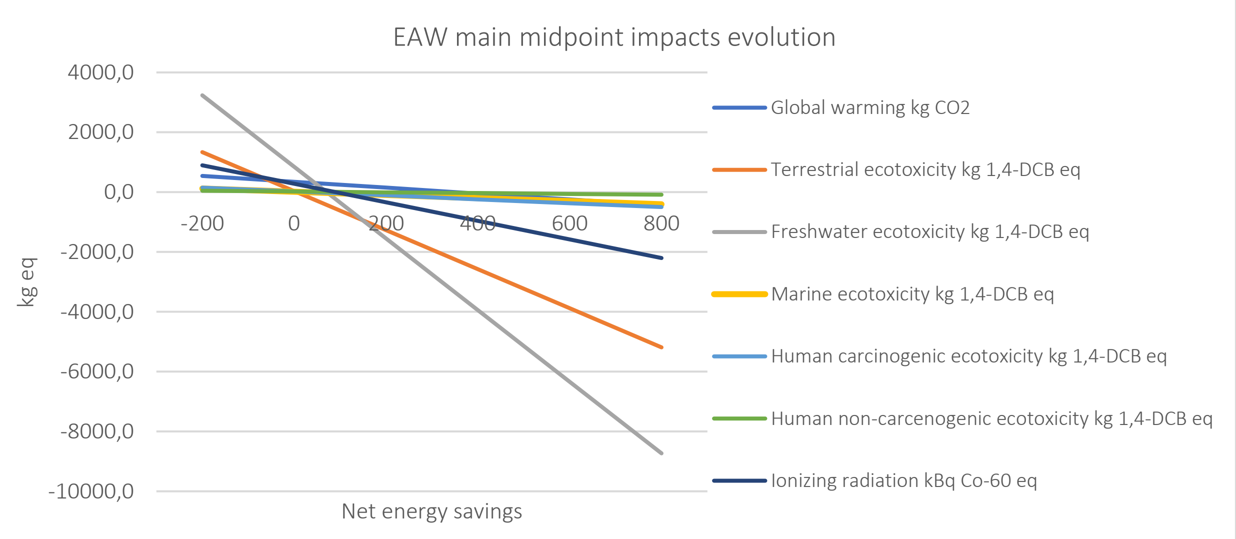


Figure 52 EAW midpoint impacts evolution when net energy savings change.

Every 100 kWh/year that EAW saves, would mean a decrease of the following emissions in absolute terms.

Table 26 Avoided emissions per 100 net kWh/year saved

Midpoint indicator	Global warming	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity	Human carcinogenic ecotoxicity	Human non-carcinogenic ecotoxicity	Ionizing radiation
Avoided emissions	98.6 kg CO_2 eq	652.5 kg 1,4-DCB eq	1196.5 kg 1,4-DCB eq	52.6 kg 1,4-DCB eq	64.9 kg 1.4-DCB eq	13.1 kg 1,4-DCB eq	309.9 kBq Co-60 eq

By applying the end-point method, the Figure 53 summarize again how the final score would behave when the energy savings increase. One can see that EAW single score would achieve a lower score than the reference system when around 250 net kWh/year are reached.

That would mean that if EAW could supply this quantity of energy, from an environment-friendly point of view, EAW would be more feasible than the reference system. This is because this energy savings would compensate its higher damage caused by a more complex product, in comparison to the double-glazed window.

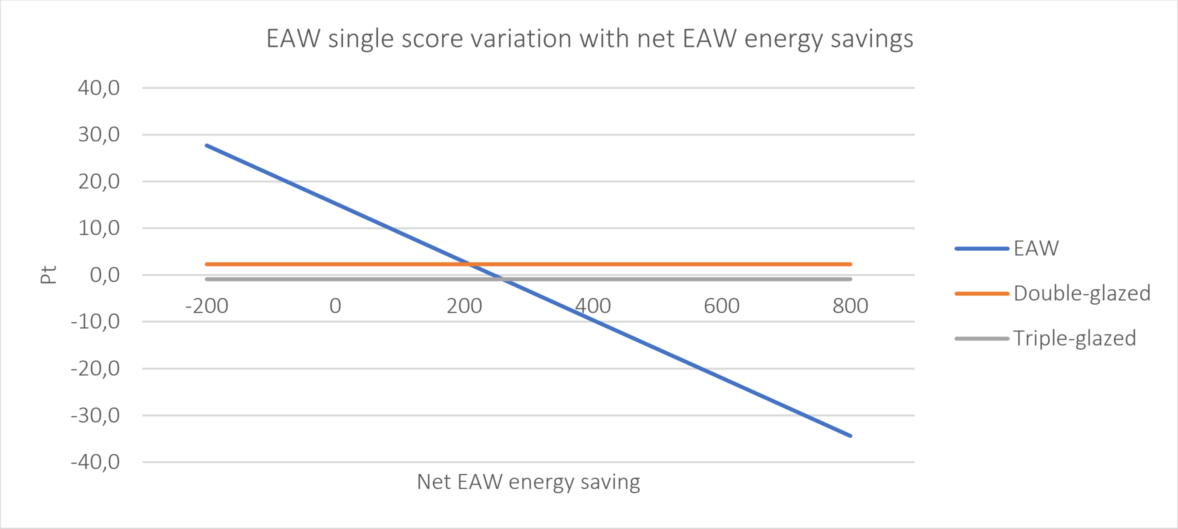


Figure 53 EAW single score variation when net energy savings change.

2. Number of components replacements

In this section, variations in the heat exchanger and electric fan replacements are analysed. Among all the EAW components, these would be probabilities to be replaced. The rest of the parameters remain constant as well as EAW energy performance.

Firstly, the emissions produced by only one unit are studied. Table 27 shows the main midpoint indicators for them. In the base-case scenario we considered that during the 20 years of timeframe, EAW would use 2 HX and 4 electric fans.

Table 27 Individual midpoint impact contribution for 1 heat exchanger and 1 electric fan

	Global warming (kg CO_2)	Terrestrial ecotoxicity (kg 1,4-DCB eq)	Freshwater ecotoxicity (kg 1,4-DCB eq)	Marine ecotoxicity (kg 1,4-DCB eq)	Human carcinogenic toxicity (kg 1,4-DCB eq)	Human Non-carcinogenic toxicity (kg 1,4-DCB eq)	Single score
1 HX	22.59	35.73	0.45	0.64	0.69	12.46	0.93
1 fan	21.62	26.37	1.50	1.96	2.75	18.74	1.08

However, in relative terms regarding the total EAW life cycle emissions, this individual contribution may have different relevance. For both components, the category that would increase in a higher rate is the human toxicity. This is one of the reasons why the single score grows rapidly with each replacement.

In Figure 54 and 55 EAW life cycle emissions variation is represented when the number of units increase. As one can see, the replacements of fans affect more than the renewal of HX. The ecotoxicity indicators have a relatively small emissions, specially the related to freshwater and marine categories. Despite this, the normalisation makes them a non-negligible increase in EAW total.

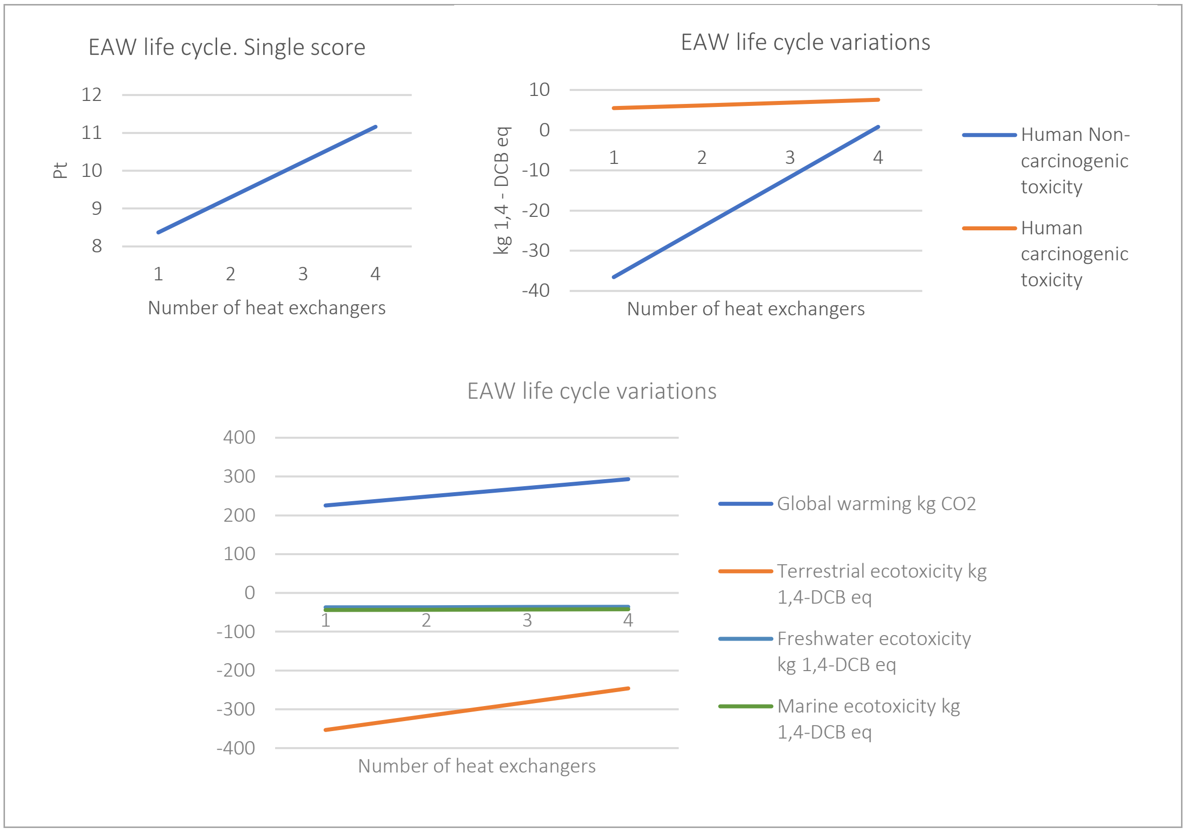


Figure 54 EAW environmental impact variations when the number of heat exchanger replacement changes

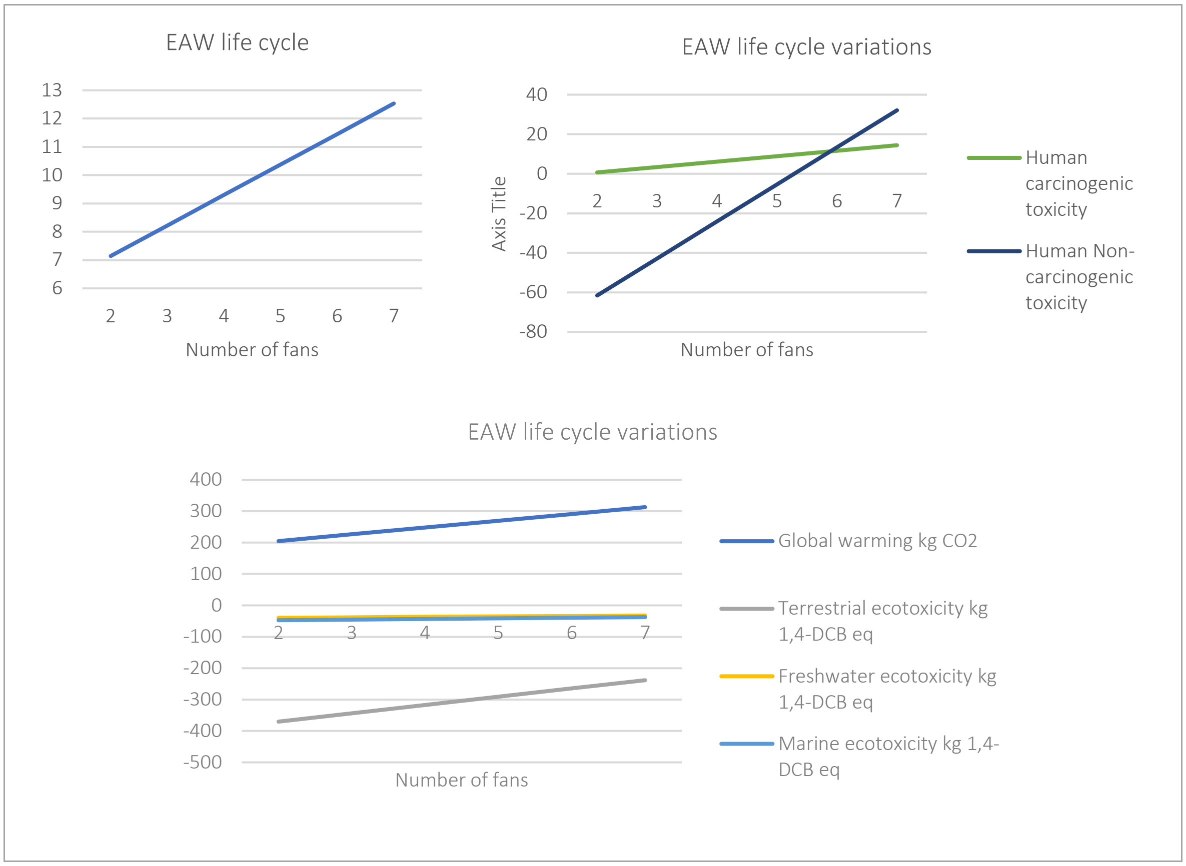


Figure 55 EAW environmental impact variations when the number of electric fans replacement changes

As a conclusion of the sensitivity analyses one can draw:

1. LCA is quite sensitive to energy savings and replacements variations. This is quite related to the factors of normalisation and weighting used in ReCiPe method. Depending on the impact category, relatively small emissions can become a significant source of damage to the environment.
2. The environment indicators related to the human toxicity are the ones that affect the most the final single score of EAW life cycle. At the same time, their decrease is the slowest ones when energy savings changes since they come mainly from the component materials. Then, choosing durable components that have lower emissions in terms of human toxicity and ecotoxicity categories would affect positively in the final EAW environmental impact.
3. In comparison to the LCC requirements for making EAW profitable, from an environment perspective it is much achievable that EAW become more feasible than the reference. The energy savings can compensate relatively easily the higher emissions due to the assembly.

8. Conclusions

After the life cycle assessment some interesting conclusions can be extracted regarding the energy performance of the EAW. Even though the great uncertain that the models are subjected to, several insights and some useful insights regarding costs and environmental impacts can be draw.

1. Since only one window is replaced in the room, the energy savings are small in relative terms in comparison to the overall energy consumption. In the main, it would imply long payback periods.

2. The net EAW energy savings depends hugely on the balance between fan consumption and the U-value. Even though EAW uses waste heat from the district heating, it needs a non-negligible electricity input due to the fans when it is translated into monetary and environmental terms.

3. The higher complexity of EAW affects notably in the capital investment and the maintenance costs in comparison to a conventional window system. Furthermore, the large number of components implies as well greater emissions, especially the ones related to ecotoxicity and human toxicity.

4. The energy savings should be enough high to compensate the larger maintenance costs, as well as the higher emissions of the product by itself. Nevertheless, the energy required for making EAW profitable is much higher from an economic perspective than from an environmental point of view.

   In other words, EAW can reach relatively easily being more environmental-friendly than the reference by small improvements in energy savings. In contrast, in costs terms, operating savings need to be quite high for compensating the other expenses that its complexity implies.

   This last fact can be checked in LCC and LCA sensitivity analysis. Slight changes in net energy savings, after all, would not imply a considerable variation in EAW net present value. Moreover, regarding the environmental impacts, 1 kilogram of material can cause more environmental damage than 1kWh depending on the impact category.

   However, the value range of energy savings that EAW can achieve is bigger than other parameters. For this reason, the avoided emissions and the operating savings that can be reached can be quite high and this fact makes the net energy savings an essential variable and the decisive parameter that would determine EAW profitability.

5. Despite this, in the BAU scenario considered, a triple-glazed unit would be a more cost-effective solution than EAW system, from both LCC and LCA model. The main reasons are higher maintenance costs and lower energy savings due to the fan's consumption.

   If the electricity required by the fans could be entirely provided from a free energy source, the feasibility of the EAW in comparison to the triple-glazed unit would change positively, if the boundaries of the study are maintained.

   In contrast, the feasibility of the EAW compared to the reference system would not change considerable in costs terms. Greater changes in the EAW energy performance would be needed for making it economically suitable. But, from an environmental perspective, a free energy supply in relation to the fans would implies large avoided emissions.

9. Possible improvements in EAW design and manufacturing

Finally, in reference to EAW design, it is true that its energy efficiency depends largely on thermal parameters that are difficult to be predicted accurately.

From an economic perspective, a standardised plastic heat exchanger could be an interesting option instead of the customized 3D printed version. A deep study could be carried out for determining if an innovative design (short microchannels etc.) can compensate the higher costs in comparison to a conventional plastic HX.

On the other hand, due to the small flow rate flowing inside the EAW, probably only one electric fan would be enough for forcing the internal air circulation. The air drivers could be designed as a divergent duct, to direct the flow along the whole width of the EAW. In this case, the reduction in components and power input would be quite profitable for EAW.

A solar PV system is an interesting option to ensure that the electric fans have a free source energy, powerful enough to supply all the electricity required. Nevertheless, it is important to maintain a balance between system complexity and feasibility.

Furthermore, humidity or noise issues due to the flowing air and the electric fan operation should be studied deeply to ensure the minimum maintenance costs and replacements.

10. Future research areas

It is important to consider that the developed LCC and LCA models are used for obtaining an estimation of how the EAW energy performance can behave and its implications. Nonetheless, a more complex models could give more accurate numbers and insights.

For instance, in LCC model can be interesting adding a solar PV system and studying its performance too. The system boundaries could be extended for the whole energy system of the apartments e.g. heat ground pumps, underfloor heating etc. The analysis and simulation of the shared heat supply would reflect a scenario closer to the reality.

On the other hand, the LCA model could be corrected with more certain information about the ended EAW product. Concerning the calculation method of the environmental impacts, the classroom version used in SimaPro does not permit changing the normalisation and weighing values. If it was the case, customized values could be given for weighing better the environmental categories.

Regarding again the system boundaries, the EAW energy performance has been only studied for its installation in Stockholm. Since its operation depends hugely on the ambient temperature, a parallel study could be simulated for an identical implementation in other country with warm weather, such as Spain.

Indeed, a model of the overall EAW energy performance in which all the components were integrated (such as heat exchanger efficiency, temperature of the flowing air along its whole circuit, real thermal losses in both slots etc.) would be much useful to improve its design. Furthermore, this would permit to optimize the design in terms of size or power requirements to enhance the net energy savings.

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Time schedule

	Action	Note
	Phase 1: Literature	
1	Literature presentation and checkpoints	Nov 2019
	Phase 2: Development of the models	
2	Defining system boundaries and EAW components	Information from: Behrouz Nourozi (Ph.D.). Peter Platell (CEO Lowte AB). Safira Figueiredo (KTH LIL Project Manager)
3	Defining economic parameters and LCC data input	
4	Developing the LCC model of EAW	February 2020 check point
5	Introduction to SimaPro	
6	Developing the EAW inventory and LCA data input	
7	Developing the LCA model in SimaPro	April 2020 check point
	Phase 3: Validation and writing	
8	Improving the LCC and LCA models	
9	Sensitivity analysis of LCC and LCA	
10	Final report	Submitted in June 2020
11	Submission of Master Thesis and defense	11 June 2020

Figure 56 Time Schedule

Appendix A

Figure 57 Testbed KTH plan

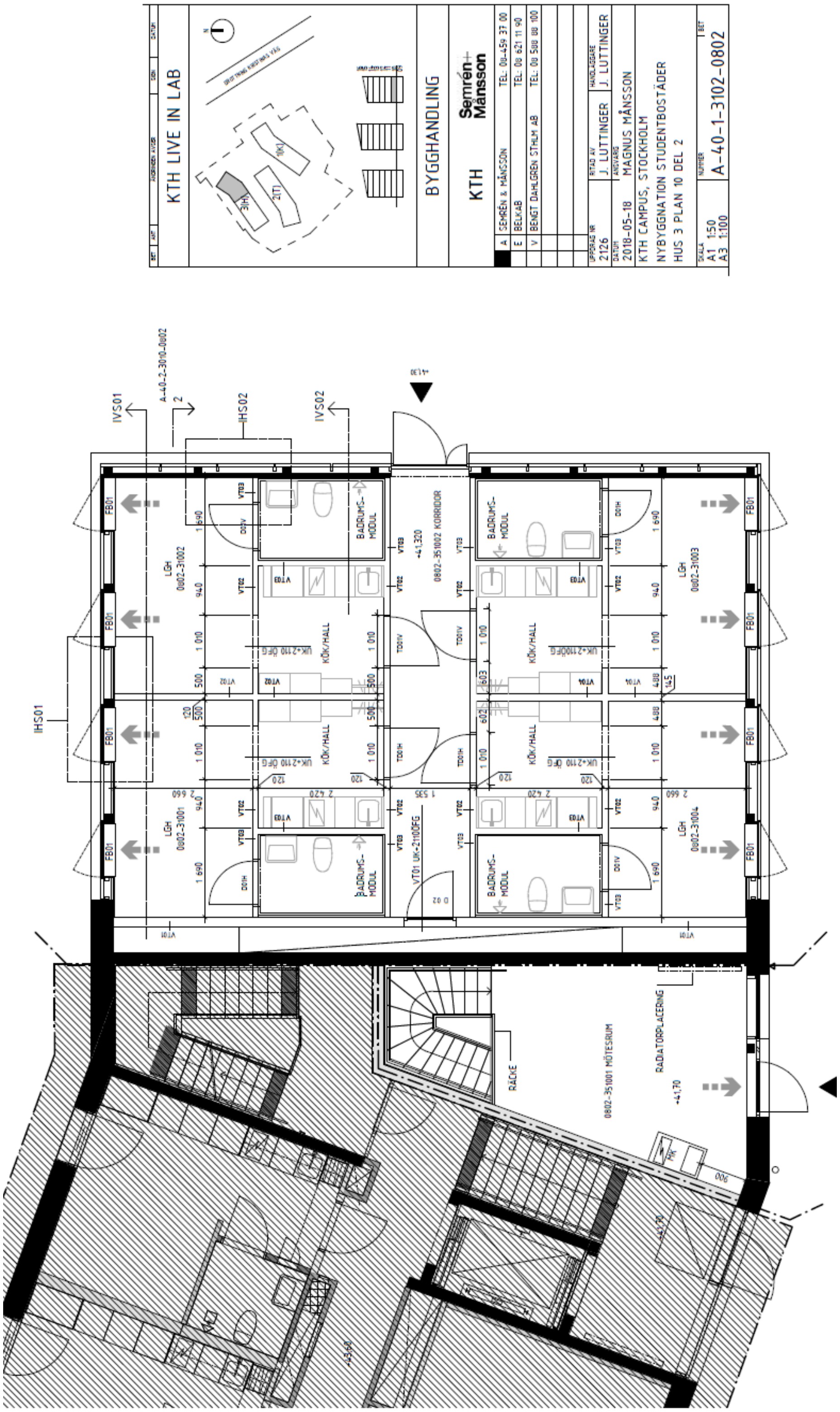
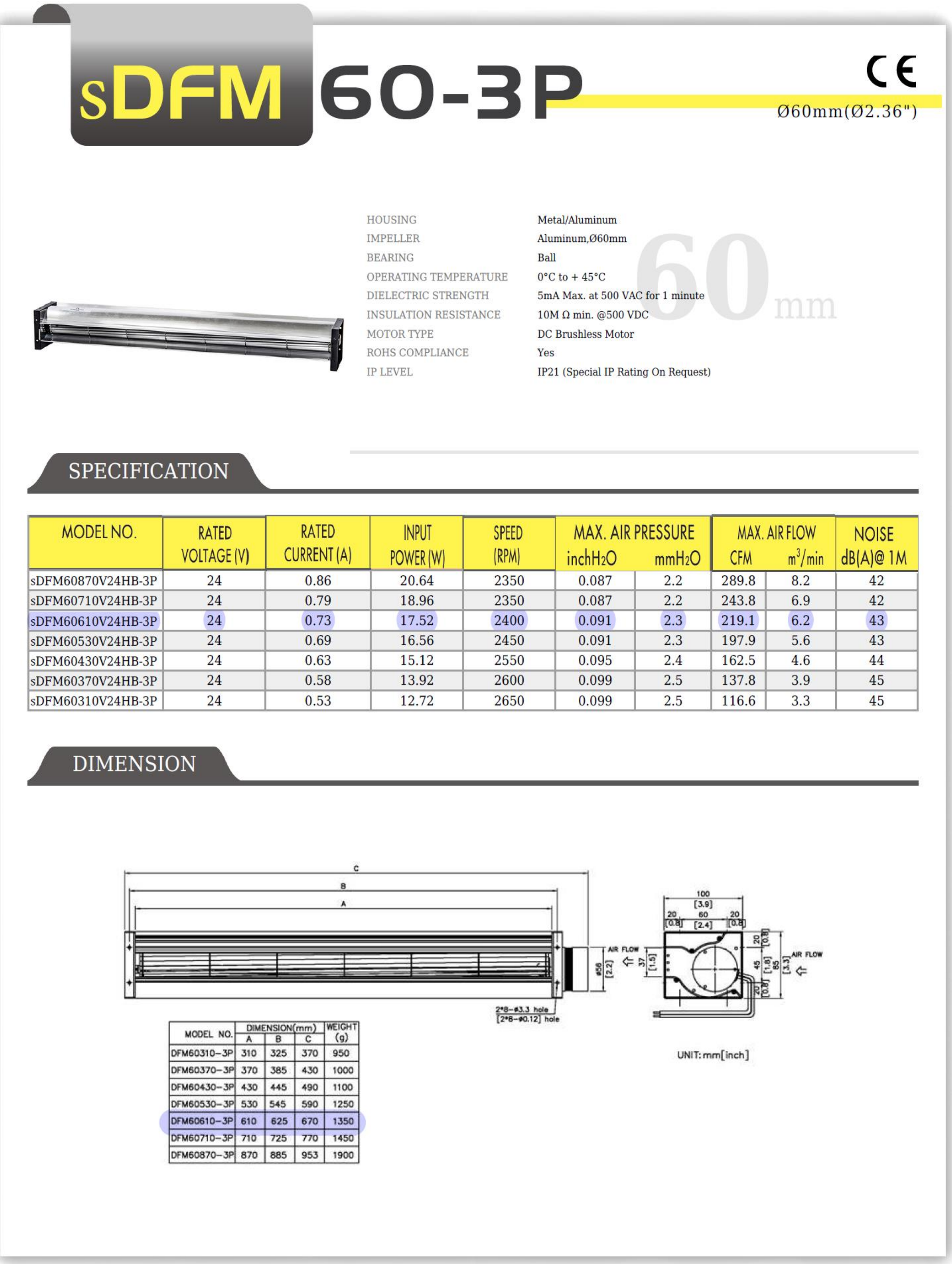


Figure 58 Sofasco fan. Specification data sheet.



sDFM 60-3P

Ø60mm(Ø2.36")

HOUSING	Metal/Aluminum
IMPELLER	Aluminum,Ø60mm
BEARING	Ball
OPERATING TEMPERATURE	0°C to + 45°C
DIELECTRIC STRENGTH	5mA Max. at 500 VAC for 1 minute
INSULATION RESISTANCE	10M Ω min. @500 VDC
MOTOR TYPE	DC Brushless Motor
ROHS COMPLIANCE	Yes
IP LEVEL	IP21 (Special IP Rating On Request)

60mm

SPECIFICATION

MODEL NO.	RATED VOLTAGE (V)	RATED CURRENT (A)	INPUT POWER (W)	SPEED (RPM)	MAX. AIR PRESSURE inchH2O	MAX. AIR PRESSURE mmH2O	MAX. AIR FLOW CFM	MAX. AIR FLOW m³/min	NOISE dB(A)@ 1M
sDFM60870V24HB-3P	24	0.86	20.64	2350	0.087	2.2	289.8	8.2	42
sDFM60710V24HB-3P	24	0.79	18.96	2350	0.087	2.2	243.8	6.9	42
sDFM60610V24HB-3P	24	0.73	17.52	2400	0.091	2.3	219.1	6.2	43
sDFM60530V24HB-3P	24	0.69	16.56	2450	0.091	2.3	197.9	5.6	43
sDFM60430V24HB-3P	24	0.63	15.12	2550	0.095	2.4	162.5	4.6	44
sDFM60370V24HB-3P	24	0.58	13.92	2600	0.099	2.5	137.8	3.9	45
sDFM60310V24HB-3P	24	0.53	12.72	2650	0.099	2.5	116.6	3.3	45

DIMENSION

MODEL NO.	DIMENSION(mm) A	B	C	WEIGHT (g)
DFM60310-3P	310	325	370	950
DFM60370-3P	370	385	430	1000
DFM60430-3P	430	445	490	1100
DFM60530-3P	530	545	590	1250
DFM60610-3P	610	625	670	1350
DFM60710-3P	710	725	770	1450
DFM60870-3P	870	885	953	1900

UNIT: mm[inch]

Figure 59 Heat exchanger reference. Specification data sheet.

PolyCoil

Specification Sheet

Model: HX-R-12

Features

Polycoil heat exchangers are an all plastic heat exchangers with superior corrosion resistance. They provide high heat transfer performance though 440 ultra-thin walled tubes (0.008in). Superior durability is achieved by a plastic-to-plastic weld of each individual tube to their manifold allowing for high operating pressures. Polycoil exchangers are extremely light weight making installation easy and provide a very low internal pressure drop. They are suitable for use with air-to-liquid and liquid-to-liquid applications. Multiple banks/arrays of exchangers can be connected together easily utilizing a built in compression snap clip (supplied) allowing the side frame on each unit to be firmly linked. All exchanger undergo two pressure tests before shipping and inspected for leaks.

Applications

- Cooling Towers
- HVAC (non-refrigerates)
- Geothermal
- Marine, Swimming Pools
- Automotive
- Radiant Heating/Cooling

Materials

Exchanger	Nylon or HPDE
Baffles:	ABS, Nylon, HDPE
Side Frame:	PVC, Nylon, HDPE

Physical Details

Dimension (LxWxH)	18.39in x 11in x 3in
Tube Length	12.63in
Dry Weight	3.3 lb
Internal Fluid Volume	0.32 gal
Number of Tubes	440
Tube Diameter	0.118in

Connections

Available : (1in)	Hose Barb, PEX, NPT
Clamp Torque Spec	35 in-lb

Fluid Compatibility

Water
Glycols
Salt/Brine Solutions
Hydro Carbon & Oils
Acids & Alcohols (HDPE only)
Chloride Solutions (Nylon 612 only)

**For a additional fluids or a comprehensive list please contact us*

Warranty

3 year limited warranty on all materials

Durability

250,000 Pressure Cycle @ 120psi

Operating Conditions

Nylon		***Polyethylene***	
Operating Pressure	80 psi (max)	Operating Pressure	40 psi (max)
Burst Pressure	400 psi	Burst Pressure	130 psi
Temperature Range	-40°F to 250°F	Temperature Range	-40°F to 140°F
Flow Rate	60 GPM (max)	Flow Rate	60 GPM (max)

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Table 28 Electricity price for the next 20 years used in LCC model. **[53]**

Year		Model trend (€/kWh)	Model Trend (SEK/kWh)
2020	0	0.2015	1.9062
2021	1	0.2040	1.9301
2022	2	0.2046	1.9544
2023	3	0.2078	1.9789
2024	4	0.2110	2.0038
2025	5	0.2142	2.0289
2026	6	0.2173	2.0544
2027	7	0.2205	2.0802
2028	8	0.2237	2.1063
2029	9	0.2268	2.1328
2030	10	0.2300	2.1596
2031	11	0.2332	2.1867
2032	12	0.2364	2.2141
2033	13	0.2395	2.2420
2034	14	0.2427	2.2701
2035	15	0.2459	2.2986
2036	16	0.2491	2.3275
2037	17	0.2522	2.3567
2038	18	0.2554	2.3863
2039	19	0.2586	2.4163
2040	20	0.2618	2.4466

Table 29 Discount rate. Values of the last 10 years. **[55]**

Date	Discount rate value (%)
01/01/2020	0.0
01/07/2019	0.0
01/01/2019	-0.5
01/07/2018	-0.5
01/01/2018	-0.5
01/07/2017	-0.5
01/01/2017	-0.5
01/07/2016	-0.5
01/01/2016	0.0
01/07/2015	0.0
01/01/2015	0.0
01/07/2014	1.0
01/01/2014	1.0
01/07/2013	1.0
01/01/2013	1.0
01/07/2012	1.5
01/01/2012	2.0
01/07/2011	2.0
01/01/2011	1.5
01/07/2010	0.5
01/01/2010	0.5

Table 30 Components of each system: data of the models and installation costs

SYSTEM 1: Double-glazed window

Component	Quantity			Units	Materials		Installation time	
	Per element	Number	Sum		Per Unit	Sum (SEK)	Per Unit	In total (h)
Clear Float Glass	2.11	3	6.33	m2	108.69	688.1	2.4	2.4
Wooden EI60 frame. Accessories. Internal hardware. Handle	1	1	1	st	11511.46	11511.5		
					TOTAL (SEK)	12199.47		
					Labour payment (SEK)	420		
					Cost allowance per working salary (SEK)	1226.4		
						13845.8677	**SEK**	

SYSTEM 2: Triple-glazed window

Component	Quantity			Units	Materials		Installation time	
	Per element	Number	Sum		Per Unit	Sum (SEK)	Per Unit	In total (h)
Pilkington Insulight™ Therm Triple. Krypton filling. Product Code: 4S(3)-18Ar-4-18Ar-S(3)4. (U-value=0.5 W/m2·K)	2.11	1	2.11	m2	1440.3	3039.1	3	3
Wooden EI60 frame. Accesories. Internal hardware. Handle	1	1	1	st	12315.62	12315.6		
					TOTAL (SEK)	15354.7		
					Labour payment (SEK)	525		
					Cost allowance per working salary (SEK)	1533		
						17412.653	**SEK**	

SYSTEM 3: EAW system

Components: frame. glazing and air drivers	Quantity			Units	Materials		Installation time	
	Per element	Number	Sum		Per Unit	Sum (SEK)	Per Unit	In total (h)
Pilkington Optifloat™ Clear. float glass. Argon filling	3.00	4	12	m2	338.37	4060.4	3	3
Wooden EI60 frame.	1	1	1	st	8620.934	8620.9		
Customized HDPM air drivers	-	-	10	kg	10.38	103.8	0.6	0.6
					TOTAL (SEK)	12785.2		
					Labour payment (SEK)	630		
					Cost allowance per working salary (SEK)	1839.6		
						15254.774	**SEK**	

Component: electric fan	Quantity			Units	Materials		Installation time	
	Per element	Number	Sum		Per Unit	Sum (SEK)	Per Unit	In total (h)
Sofasco. DC electric fan. SDFM60-610-3P	1	2	2	st	418.462	836.92	0.7	1.4
					TOTAL (SEK)	836.92		1.4
					Labour payment (SEK)	245		
					Cost allowance per working salary (SEK)	715.4		
						1797.3	**SEK**	

Component: Heat exchanger	Quantity			Units	Materials		Installation time	
	Per element	Number	Sum		Per Unit	Sum (SEK)	Per Unit	In total (h)
Water-to-air ABS heat exchanger. Reference: HX-R-12 by PolyCoil	1	1	1	st	2854.8	2854.8	0.9	0.9
					TOTAL (SEK)	2854.8		0
					Labour payment (SEK)	157.5		
					Cost allowance per working salary (SEK)	459.9		
						3472.2	SEK	

Component: new pipelines	Quantity			Units	Materials		Installation time	
	Per element	Number	Sum		Per Unit	Sum (SEK)	Per Unit	In total (h)
Uponor Comfort Pipe nr 1063287. PE-Xa 9.9 x1.1mm oxygen-tight. class 4/8 bar.	1	28	28	m	21.3	596.4	0.15	4.2
Insulation. Stone wood 100mm	1	2.1	2.1	m2	50.7	106.47		
Detail plastic. clips and clamps	2		56	st	9.80	548.8	0.2	0.2
					TOTAL (SEK)	1251.67		4.4
					Labour payment (SEK)	770		
					Cost allowance per working salary (SEK)	2248.4		
						4270.07	**SEK**	
					TOTAL INVESTMENT	**25182.8**	**SEK**	

Table 31 NPV and cash-flows calculation (SEK)

SYSTEM 1: Double-glazed window							
Year	Investment	Operation	Maintenance	Dismantling & Disposal	Cashflow	PV (actual cashflow)	Accumulated PV
0	-13845.9				-13845.9	-13845.9	-13845.9
1		2737.1	138.5		-2875.6	-2863.3	-16709.2
2		2771.5	138.5		-2909.9	-2885.1	-19594.3
3		2806.3	138.5		-2944.7	-2907.2	-22501.5
4		2841.5	138.5		-2980.0	-2929.4	-25430.9
5		2877.2	138.5		-3015.7	-2951.9	-28382.8
6		2913.3	138.5		-3051.8	-2974.5	-31357.3
7		2949.9	138.5		-3088.4	-2997.3	-34354.6
8		2987.0	138.5		-3125.4	-3020.3	-37374.9
9		3024.5	138.5		-3162.9	-3043.5	-40418.4
10		3062.5	138.5		-3200.9	-3066.9	-43485.3
11		3100.9	138.5		-3239.4	-3090.5	-46575.8
12		3139.9	138.5		-3278.3	-3114.3	-49690.1
13		3179.3	138.5		-3317.7	-3138.3	-52828.5
14		3219.2	138.5		-3357.7	-3162.5	-55991.0
15		3259.6	138.5		-3398.1	-3187.0	-59178.0
16		3300.6	138.5		-3439.0	-3211.6	-62389.6
17		3342.0	138.5		-3480.5	-3236.4	-65626.0
18		3384.0	138.5		-3522.5	-3261.5	-68887.5
19		3426.5	138.5		-3565.0	-3286.7	-72174.2
20		3469.5	138.5		-3608.0	-3312.2	**-75486.4**

SYSTEM 2: Triple-glazed window							
Year	Investment	Operation	Maintenance	Dismantling & Disposal	Cashflow	PV (actual cashflow)	Accumulated PV
0	-17412.7				-17412.7	-17412.7	-17412.7
1		2417.2	174.1		-2591.3	-2580.3	-19992.9
2		2447.6	174.1		-2621.7	-2599.4	-22592.3
3		2478.3	174.1		-2652.4	-2618.6	-25210.9
4		2509.4	174.1		-2683.5	-2638.0	-27848.9
5		2540.9	174.1		-2715.1	-2657.6	-30506.5
6		2572.8	174.1		-2747.0	-2677.4	-33183.9
7		2605.2	174.1		-2779.3	-2697.3	-35881.2
8		2637.9	174.1		-2812.0	-2717.4	-38598.6
9		2671.0	174.1		-2845.1	-2737.7	-41336.3
10		2704.5	174.1		-2878.7	-2758.1	-44094.5
11		2738.5	174.1		-2912.6	-2778.8	-46873.3
12		2772.9	174.1		-2947.0	-2799.6	-49672.9

13		2807.7	174.1		-2981.8	-2820.6	-52493.4
14		2843.0	174.1		-3017.1	-2841.8	-55335.2
15		2878.7	174.1		-3052.8	-2863.1	-58198.3
16		2914.8	174.1		-3089.0	-2884.7	-61083.0
17		2951.4	174.1		-3125.6	-2906.4	-63989.4
18		2988.5	174.1		-3162.6	-2928.3	-66917.7
19		3026.0	174.1		-3200.2	-2950.4	-69868.1
20		3064.0	174.1		-3238.2	-2972.7	**-72840.8**

SYSTEM 3: EAW system							
Year	Investment	Operation	Maintenance	Dismantling & Disposal	Cashflow	PV (actual cashflow)	Accumulated PV
0	-25182.8				-25182.8	-25182.8	-25182.8
1		2551.4	377.7		-2929.1	-2916.6	-28099.4
2		2583.4	377.7		-2961.2	-2935.9	-31035.4
3		2615.9	377.7		-2993.6	-2955.4	-33990.8
4		2648.7	377.7		-3026.5	-2975.1	-36965.9
5		2682.0	377.7		-3059.7	-2995.0	-39960.9
6		2715.7	377.7		-3093.4	-3015.0	-42976.0
7		2749.8	377.7		-3127.5	-3035.3	-46011.2
8		2784.3	377.7		-3162.0	-3055.7	-49066.9
9		2819.3	377.7		-3197.0	-3076.3	-52143.2
10		2854.7	3972.4	359.5	-7186.5	-6885.7	-59028.9
11		2890.5	377.7		-3268.3	-3118.1	-62146.9
12		2926.8	377.7		-3304.6	-3139.2	-65286.2
13		2963.6	377.7		-3341.3	-3160.6	-68446.8
14		3000.8	377.7		-3378.5	-3182.2	-71629.0
15		3038.5	3849.9	347.2	-7235.6	-6786.1	-78415.0
16		3076.6	377.7		-3454.4	-3225.9	-81641.0
17		3115.3	377.7		-3493.0	-3248.1	-84889.0
18		3154.4	377.7		-3532.1	-3270.4	-88159.5
19		3194.0	377.7		-3571.7	-3293.0	-91452.5
20		3234.1	3972.4	359.5	-7566.0	-6945.7	**-98398.2**

Table 32 Variation of NPV (10^3 SEK) with the discount rate

Discount rate	NPV1	NPV2	NPV3
0.0043	75.5	72.8	98.4
-0.012	87.7	83.8	113.7
-0.011	86.8	83.0	112.7
-0.01	86.0	82.3	111.6
-0.009	85.2	81.6	110.6
-0.008	84.4	80.8	109.6
-0.007	83.6	80.1	108.6
-0.006	82.8	79.4	107.6
-0.005	82.1	78.7	106.7
-0.004	81.3	78.1	105.7
-0.003	80.6	77.4	104.8
-0.002	79.8	76.7	103.9
-0.001	79.1	76.1	103.0
0	78.4	75.5	102.1
0.001	77.7	74.8	101.2
0.002	77.0	74.2	100.3
0.003	76.3	73.6	99.5

0.004	75.7	73.0	98.6
0.005	75.0	72.4	97.8
0.006	74.4	71.8	97.0
0.007	73.7	71.3	96.2
0.008	73.1	70.7	95.4
0.009	72.5	70.1	94.6
0.01	71.9	69.6	93.9
0.011	71.3	69.0	93.1
0.012	70.7	68.5	92.4
0.013	70.1	68.0	91.6
0.014	69.5	67.5	90.9
0.015	68.9	67.0	90.2
0.016	68.4	66.5	89.5
0.017	67.8	66.0	88.8
0.018	67.3	65.5	88.1
0.019	66.7	65.0	87.5
0.02	66.2	64.5	86.8

Table 33 Variation of NPV (10^3 SEK) and OPEX (10^3 SEK) with the electricity price

Electricity	NPV1	NPV2	NPV3	OPEX1	OPEX2	OPEX3
1.013	75.5	72.8	98.4	61.8	54.6	57.6
0.97	54.8	54.6	79.1	39.9	35.2	37.2
0.98	58.7	58.0	82.8	44.0	38.9	41.0
0.99	63.2	62.0	86.9	48.7	43.0	45.4
1	68.2	66.4	91.6	54.1	47.7	50.4
1.01	73.9	71.4	96.9	60.1	53.1	56.0
1.02	80.4	77.2	103.0	67.0	59.2	62.4
1.03	87.7	83.7	109.8	74.8	66.1	69.7
1.04	96.1	91.0	117.6	83.7	73.9	78.0
1.05	105.6	99.5	126.5	93.9	82.9	87.5
1.06	116.5	109.0	136.6	105.4	93.1	98.3
1.07	128.8	119.9	148.1	118.6	104.7	110.5
1.08	142.9	132.4	161.2	133.6	118.0	124.5
1.09	159.0	146.6	176.2	150.7	133.1	140.5
1.1	177.3	162.7	193.3	170.3	150.4	158.7
1.11	198.1	181.2	212.7	192.6	170.1	179.6
1.12	222.0	202.2	235.0	218.1	192.6	203.3
1.13	249.2	226.2	260.3	247.3	218.4	230.5
1.14	280.2	253.6	289.2	280.5	247.7	261.5
1.15	315.6	284.9	322.2	318.5	281.2	296.9
1.16	356.0	320.6	359.9	361.8	319.5	337.2
1.17	402.2	361.3	402.9	411.3	363.2	383.3
1.18	454.7	407.8	451.9	467.7	413.0	436.0
1.19	514.7	460.7	507.8	532.1	469.9	496.0
1.2	583.1	521.1	571.6	605.6	534.8	564.5

Table 34 Variation of NPV (10^3 SEK) with the currency change

Currency conversion	NPV1	NPV2	NPV3
9.46	75.5	72.8	98.4
8	66.4	64.8	89.9
8.25	67.9	66.2	91.4
8.5	69.5	67.5	92.8
8.75	71.1	68.9	94.3
9	72.6	70.3	95.7
9.25	74.2	71.7	97.2
9.5	75.7	73.1	98.6
9.75	77.3	74.4	100.1
10	78.8	75.8	101.5
10.25	80.4	77.2	103.0
10.5	82.0	78.6	104.4
10.75	83.5	79.9	105.9
11	85.1	81.3	107.3
11.25	86.6	82.7	108.8
11.5	88.2	84.1	110.2
11.75	89.8	85.4	111.7
12	91.3	86.8	113.1
12.25	92.9	88.2	114.6
12.5	94.4	89.6	116.1
12.75	96.0	90.9	117.5
13	97.5	92.3	119.0
13.25	99.1	93.7	120.4
13.5	100.7	95.1	121.9
13.75	102.2	96.5	123.3
14	103.8	97.8	124.8
14.25	105.3	99.2	126.2
14.5	106.9	100.6	127.7
14.75	108.5	102.0	129.1
15	110.0	103.3	130.6

Table 35 Variation of NPV3 (10^3 SEK) with the EAW investment

Total investment	NPV3
25200	98.4
19000	90.4
20000	91.7
21000	93.0
22000	94.3
23000	95.6
24000	96.9
25000	98.2
26000	99.4
27000	100.7
28000	102.0
29000	103.3
30000	104.6
31000	105.9
32000	107.2
33000	108.4
34000	109.7
35000	111.0
36000	112.3
37000	113.6

38000	114.9
39000	116.2
40000	117.5
41000	118.7
42000	120.0
43000	121.3
44000	122.6
45000	123.9

Table 36 Variation of NPV3 (10^3 SEK) and maintenance costs (10^3 SEK) with the EAW maintenance rate

Maintenance	NPV3	Maintenance 3
1.5	98.4	18.2
0.3	92.6	12.2
0.4	93.1	12.7
0.5	93.6	13.2
0.6	94.1	13.7
0.7	94.5	14.2
0.8	95.0	14.7
0.9	95.5	15.2
1	96.0	15.7
1.1	96.5	16.2
1.2	96.9	16.7
1.3	97.4	17.2
1.4	97.9	17.7
1.5	98.4	18.2
1.6	98.9	18.7
1.7	99.3	19.2
1.8	99.8	19.7
1.9	100.3	20.2
2	100.8	20.7
2.1	101.3	21.2
2.2	101.8	21.7
2.3	102.2	22.2
2.4	102.7	22.7
2.5	103.2	23.3
2.6	103.7	23.8
2.7	104.2	24.3
2.8	104.6	24.8
2.9	105.1	25.3
3	105.6	25.8

Table 37 Variation of NPV3 (10^3 SEK) and OPEX3 (10^3 SEK) with the net EAW energy savings

Energy savings	NPV3	OPEX 3
96.22	98.4	57.6
-150	108.6	68.3
-100	106.5	66.1
-50	104.5	64.0

0	102.4	61.8
50	100.3	59.6
100	98.2	57.4
150	96.1	55.3
200	94.1	53.1
250	92.0	50.9
300	89.9	48.7
350	87.8	46.5
400	85.8	44.4
450	83.7	42.2
500	81.6	40.0
550	79.5	37.8
600	77.4	35.6
650	75.4	33.5
700	73.3	31.3
750	71.2	29.1
800	69.1	26.9
850	67.0	24.8
900	65.0	22.6
950	62.9	20.4
1000	60.8	18.2

Appendix B

Table 38 SimaPro Data input. System 1. 2 and 3

SYSTEM 1: Double-glazed window

Element	Components	Nº units	Material	Size LxHxW or L.Di.e [mm]	Volume [m3]	Density [kg/m3]	Weight [kg]
Double-glazed	-	2	Pilkington Insulight™ Protect	2110x1000x2	0.008440	2100	**35.6**
Insulation gap	Desiccant	-	Silica pellets	6220x10x18	0.001120	2330	**2.6**
	Sealing	-	Polysulfide	6000x10x18	0.00108	1435	**1.5**
	Spacer	-	Aluminum sheet	6220x1x18 (x2)	0.000224	2690	**0.6**
Frame	Wooden frame and leaf	-	Laminated oak EI60	6220x78x68 + 7500x78x68	0.072771	745	**54.2**
Sealing & joints	Rubber. Silicone	-	Expanded EPDM Sponge rubber	6220x20x8 (x1.5)	0.001493	80	**0.1**
Internal hardware	Gaskets. weather stripping. clips	-	Aluminum	-	0.000187	2690	**0.5**
Handle & accessories	-	-	PE	-	0.000124	940	**0.1**

SYSTEM 2: Triple-glazed window

Element	Components	Nº units	Material	Size LxHxW or L.Di.e [mm]	Volume [m3]	Density [kg/m3]	Weight [kg]
Triple-glazed unit	-	3	Pilkington Optitherm™ S3. and Optifloat Clear™	2110x1000x4	0.025320	2300	**58.2**
Insulation gap (x1)	Inert gas filling (x1)	1	Krypton	2110x1000x18	0.037800	3.75	**0.1**
	Desiccant (x1)	-	Silica pellets	6220x10x18	0.001120	2330	**2.6**
	Sealing	-	Polysulfide	6000x10x18	0.00108	1435	**1.5**
	Spacer (x1)	-	Aluminium sheet	6220x1x18 (x2)	0.000224	2690	**0.6**
Frame	Wooden frame and leaf	-	Laminated oak EI60	6220x78x92 + 7500x78x92	0.098455	745	**73.3**
Sealing & joints	Rubber. Silicone	-	Expanded EPDM Sponge rubber	6220x20x8 (x1.5)	0.001493	80	**0.1**
Internal hardware	Gaskets. weather stripping. clips	-	Aluminium	-	0.000187	2690	**0.5**
Handle & accessories	-	-	PE	-	0.000124	940	**0.1**

SYSTEM 3: EAW system

Element	Components	Nº units	Material	Size LxHxW or L.Di.e [mm]	Volume [m3]	Density [kg/m3]	Weight [kg]
DS	Glass sheet (x4)	4	Pilkington Optifloat Clear™	2000x1500x4	0.04800	2300	**110.4**
HX	Pipes. Baffles. Side frame. Tank/Header	1	ABS	470x280x80	0.01053	1070	**2.0**
	Insulation jacket		Stone wood	500x300x10 (x2) + 500x85x10 (x2) + 300x85x10 (x2)	0.00436	100	**0.4**
	HX box		HDPE	1500x400x1.5 (x2) + 1500x100x1.5 (x2) + 400x100x1.5 (x2)	0.00237	940	**2.2**
Insulation gap	Inert gas	1	Argon (90%)	2000x1500x12	0.03600	1.73	**0.1**
	Desiccant	-	Silica pellets	7000x10x12	0.00084	2330	**2.0**

	Sealing	-	Polysulfide	7000x10x12	0.00084	1435	**1.2**
	Spacer	-	Aluminium sheet	7000x1x12 (x2)	0.00017	2690	**0.5**
Electric fan (x1)	Housing. Impeller. Bearing. Motor	1	Metal/Aluminium	670 (x2) x 100x85 or 670 (x2). 60	-	-	**1.4**
	Fan box (for 2 electric fans)	-	HDPE	1500x150x1.5 (x2) + 1500x100x1.5 (x2) + 150x100x1.5 (x2)	0.00117	940	**1.1**
Box drivers	Air drivers. Panel boxes	-	HDPE	1500x100x3 (x2) + 1500x600x3 (x2) + 1500x50x3 (x2) + …	0.01058	940	**9.9**
Frame	Wooden frame and leaf	-	Laminated oak EI60	7000x78x92 + 8300x78x92	0.10979	745	**81.8**
Sealing & joints	Rubber. Silicone	-	Expanded EPDM/Sponge rubber	7000x20x8 (x1.5)	0.00168	80	**0.1**
New Pipeline	Pipe. bends	-	PEX (PE-Xa)	28000. 9.9. 1.1	0.01933	940	**18.2**
	Insulation jacket	-	Stone wood	25000. 13. 10	0.02060	100	**2.1**

Table 39 LCA Model structure

SYSTEM 1: Double-glazed data set				
		Input	Quantity	Unit
Assemblies	Double-glazed window	Frame & complements_DoubleGlazed	1	p
		Insulation layer_DoubleGlazed	1	p
		Clear Float Glass_DoubleGlazed	2	p
		(glass) Transport, freight, lorry 16-32 metric ton, euro5 {RER} | market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	4.08	tkm
		(timber) Transport, freight, lorry 16-32 metric ton, euro5 {RER} | market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	29.76	tkm
		(construction material) Transport, freight, lorry 16-32 metric ton, euro5 {RER} | market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	0.01	tkm
		(installation) Transport, freight, lorry 16-32 metric ton, euro5 {RER} | market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	15.04	tkm
		Electricity, low voltage {SE} | electricity voltage transformation from medium to low voltage | Cut-off, U	6.77	kWh
	Insulation layer _DoubleGlazed	Aluminium spacers	0.602	kg
		Polysulfide, sealing compound {GLO} | market for | Cut-off, S	1.550	kg
		Activated silica {GLO} | market for | Cut-off, S	2.609	kg
	Clear Float Glass _DoubleGlazed	Flat glass, coated {GLO} | market for | Cut-off, S	8.862	kg
	Frame & complements _DoubleGlazed	Wooden frame	54.214	kg
		Seal, natural rubber based {GLO} | market for | Cut-off, S	0.119	kg
		Aluminium hardware	0.503	kg
		Handle & accessories.	0.117	kg
Life cycles	Double-glazed window	Assembly: Double-glazed window	1	p
		Energy demand	28380	kWh
		Waste (waste scenario) {NL} | treatment of waste | Cut-off, S		

SYSTEM 2: Triple-glazed data set

		Input	Quantity	Unit
Assemblies	Triple-glazed window	Frame & complements_TripleGlazed	1	p
		Insulation layer_TripleGlazed	2	p
		Thermal Float Glass_TripleGlazed	3	p
		(installation) Transport, freight, light commercial vehicle {RER} | market group for transport, freight, light commercial vehicle | Cut-off, S	28.41	tkm
		(glass) Transport, freight, lorry 16-32 metric ton, euro5 {RER} | market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	13.39	tkm
		(construction material) Transport, freight, lorry 16-32 metric ton, euro5 {RER} | market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	0.17	tkm
		(timber) Transport, freight, lorry 16-32 metric ton, euro5 {RER} | market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	40.27	tkm
		Electricity, low voltage {SE} | electricity voltage transformation from medium to low voltage | Cut-off, U	10.16	kWh
	Insulation layer _TripleGlazed	Krypton gas	0.142	kg
		Aluminium spacers	0.602	kg
		Polysulfide, sealing compound {GLO} | market for | Cut-off, S	1.550	kg
		Activated silica {GLO} | market for | Cut-off, S	2.609	kg
	Thermal Float Glass _TripleGlazed	Flat glass, coated {GLO} | market for | Cut-off, S	19.412	kg
	Frame & complements _TripleGlazed	Wooden frame	68.656	kg
		Seal, natural rubber based {GLO} | market for | Cut-off, S	0.119	kg
		Aluminium hardware	0.503	kg
		Handle & accessories.	0.117	kg
Life cycles	Triple-glazed window	Assembly: triple-glazed window	1	p
		Energy demand	25060	kWh
		Waste (waste scenario) {NL} | treatment of waste | Cut-off, S		

SYSTEM 3: EAW

		Input	Quantity	Unit
Assemblies	EAW system	EAW	1	p
		New pipelines	1	p
		(installation Uponor) Transport, freight, light commercial vehicle {RER} | market group for transport, freight, light commercial vehicle | Cut-off, S	9.67	tkm
		(installation) Transport, freight, light commercial vehicle {RER} | market group for transport, freight, light commercial vehicle | Cut-off, S	2.31	tkm
	EAW	Clear Float Glass_EAW	4	p
		Insulator layer_EAW	1	p
		HX	2	p
		Frame & accessories_EAW	1	p
		Air drivers	1	p
		(fan) Transport, freight, inland waterways, barge {GLO} | market group for transport, freight, inland waterways, barge | Cut-off, S	8.95	tkm
		(HX)Transport, freight, light commercial vehicle {RER} | market group for transport, freight, light commercial vehicle | Cut-off, S	0.48	tkm
		(PE)Transport, freight, lorry 7.5-16 metric ton, euro5 {RER} | market for transport, freight, lorry 7.5-16 metric ton, EURO5 | Cut-off, S	1.99	tkm
		(glass)Transport, freight, lorry 16-32 metric ton, euro5 {RER} | market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	42.84	tkm
		(timber)Transport, freight, lorry 16-32 metric ton, euro5 {RER} | market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S	36.89	tkm
		(construction material) Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER} | market for transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cut-off, S	0.13	tkm
		Electricity, low voltage {SE} | electricity voltage transformation from medium to low voltage | Cut-off, U	25.04	kWh

	Air boxes	Disassembled plastic parts	9.95	kg
	Electric fan & box	Disassembled plastic parts	1.10	kg
		Aluminium alloy, metal matrix composite {RoW} | aluminium alloy production, Metallic Matrix Composite | Cut-off, S	1.35	kg
	Clear Floated Glass_EAW	Flat glass, coated {GLO} | market for | Cut-off, S	27.60	kg
	New pipelines	PE-Xa tubes	18.17	kg
		Stone wool {GLO} | market for stone wool | Cut-off, S	2.06	kg
	HX & box	Disassembled plastic parts	2.23	kg
		Stone wool {GLO} | market for stone wool | Cut-off, S	0.44	kg
		ABS 3D-printing	2.00	kg
	Insulator layer_EAW	Argon, gas	0.062	kg
		Aluminium spacers	0.45	kg
		Polysulfide, sealing compound {GLO} | market for | Cut-off, S	1.21	kg
		Activated silica {GLO} | market for | Cut-off, S	1.96	kg
	Frame & accessories_ EAW	Wooden frame	81.80	kg
		Seal, natural rubber based {GLO} | market for | Cut-off, S	0.13	kg
Life cycles	Electric fan	Electricity, low voltage {SE} | market for | Cut-off, S	350.4	kWh
		Waste (waste scenario) {NL} | treatment of waste | Cut-off, S		
		Transport, freight, inland waterways, barge {GLO} | market group for transport, freight, inland waterways, barge | Cut-off, S	8.9505	tkm
		Assembly: Electric fan & box	1	p
	EAW system	Energy demand	25040	kWh
		Assembly: EAW system	1	p
		Additional LC: Electric fan	4	p
		Waste (waste scenario) {NL} | treatment of waste | Cut-off, S		

NEW ENTRIES						
	Input	Quantity	Unit	Output	Quantity	Unit
1. Energy demand	Electricity, low voltage {SE} | market for | Cut-off, S	1	kWh	Energy demand	1	kWh
2. Disassembled plastic parts	Extrusion of plastic sheets and thermoforming, inline {GLO} | market for | Cut-off, S	1	kg	Disassembled plastic parts	1	kg
3. PE-Xa tubes	Extrusion, plastic pipes {GLO} | market for | Cut-off, S	1	kg	Pe-Xa tubes	1	kg
5. ABS powder	Acrylonitrile {GLO} | market for | Cut-off, S	0.3	kg	ABS powder	1	kg
	Styrene {GLO} | market for | Cut-off, S	0.5	kg			
	Butadiene {RER} | market for butadiene | Cut-off, S	0.2	kg			
	Electricity, high voltage {SE} | market for | Cut-off, S	0.44	kWh			
	Heat, district or industrial, natural gas {Europe without Switzerland} | heat production, natural gas, at industrial furnace >100kW | Cut-off, S	1.674	MW			
	Carbon dioxide, biogenic	0.55	kg			
5.1 ABS-3D printing	ABS powder	2.5	kg	ABS 3D-printing	2	kg
	SLS 3D-printing	1.56	h	plastic waste	0.5	
5.2 SLS 3D-printing	Electricity, high voltage {SE} | market for | Cut-off, U	3.500	kWh	SLS 3D-printing	1	h
	Thermoforming of plastic sheets {RoW} | processing | Cut-off, U	1.2	kg			
6. Argon gas	Argon, crude, liquid {RER} | air separation, cryogenic | Cut-off, S	1	ton	Argon	1	ton
	Chemical tanker truck, 16 metric ton	500	tkm			
6.1 Chemical tanker truck, 16 metric ton	Reference: Transport, freight, lorry 16-32 metric ton, EURO5 {RER} | transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, U					

	Added: Lorry with refrigeration machine, carbon dioxide, liquid as refrigerant, 16 metric ton {GLO} | lorry production, with refrigeration machine, carbon dioxide, liquid as refrigerant, 16 metric ton | Cut-off, U					
6.2 Krypton gas	Krypton, gaseous {RER} | air separation, xenon krypton purification | Cut-off, S	1	ton	Krypyon gas	1	ton
	Chemical tanker truck, 16 metric ton	500	tkm			
7. Aluminium spacers	Aluminium sheet milled	1.2	kg	Aluminium spacers	1	kg
	Metal sawing	0.2	h	Aluminium waste	0.2	kg
7.2 Aluminium sheet milled	Compressed air, 700 kPa gauge {GLO} | market for | Cut-off, U	1.28	m3	Aluminium sheet milled	1	kg
	Electricity, low voltage {RER} | market group for | Cut-off, U	0.356	kWh	Aluminium waste	0.1	kg
	Electricity, low voltage {RER} | market group for | Cut-off, U	4.41	kg			
	Lubricating oil {RER} | market for lubricating oil | Cut-off, U	0.00382	kg			
	Metal working factory {RER} | construction | Cut-off, U	2.02E-09	p			
	Metal working machine, unspecified {RER} | production | Cut-off, U	0.000174	kg			
	Sheet rolling, aluminium {GLO} | market for | Cut-off, S	1.1	kg			
7.3 Aluminium hardware	Impact extrusion of aluminium, 1 stroke {RER} | processing | Cut-off, S	1	kg	Aluminium hardware	1	kg
	Metal sawing	0.2	h			
7.3 Metal sawing	Reference: Power sawing					
8. Handle, accessories	Injection moulding {GLO} | market for | Cut-off, S	1	kg	Handle, accessories	1	kg
9. Wooden frame	Wood chips, dry, measured as dry mass {RER} | glued laminated timber production, for indoor use | Cut-off, S	1	kg	Wooden frame	1	kg
	Power sawing, with catalytic converter {RER} | processing | Cut-off, U	1.25	s			

Figure 60 Double-glazed window whose components have an environmental index larger than 1%.

Figure 61 Triple-glazed window whose components have an environmental index larger than 0.8%.

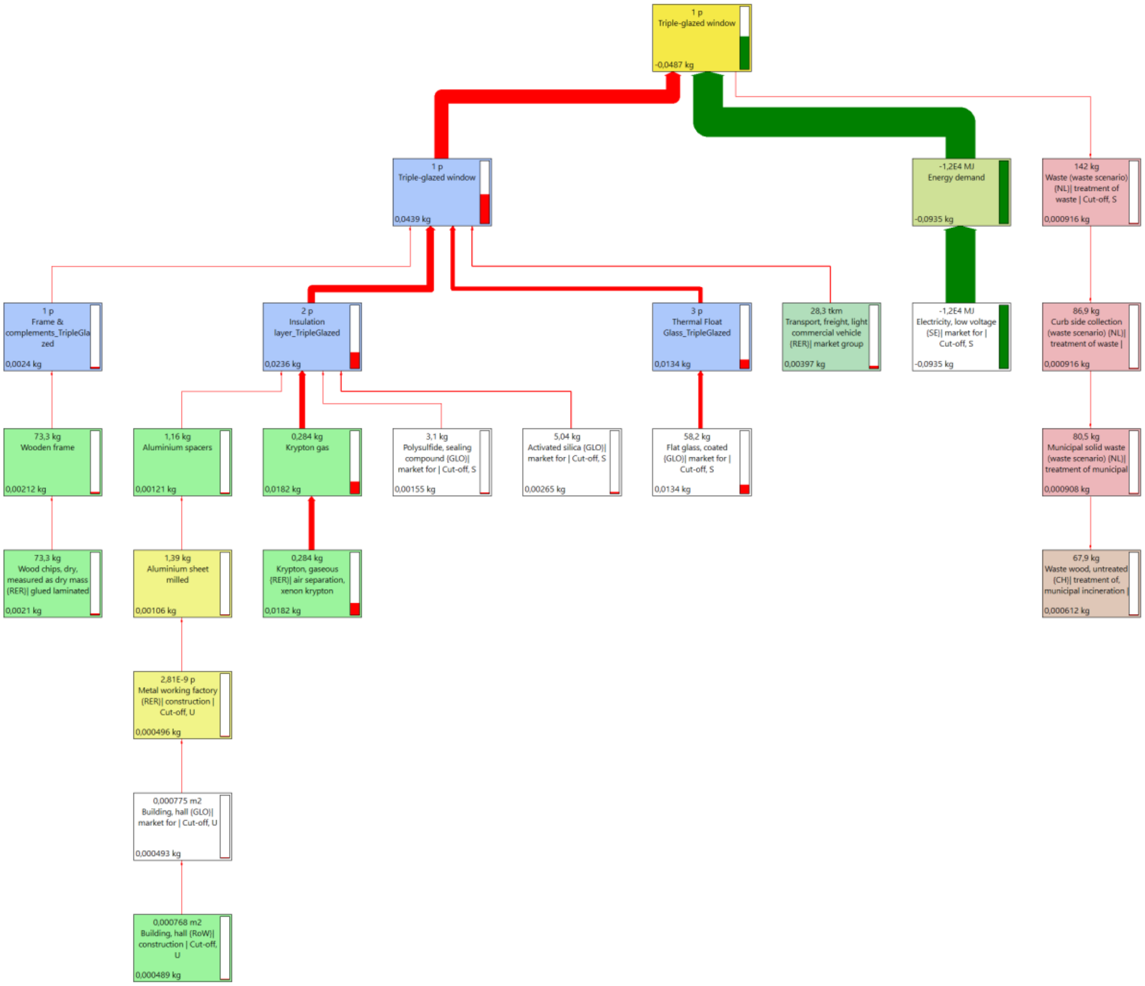

Figure 62 Double-glazed window whose components have an environmental index larger than 0.1%.

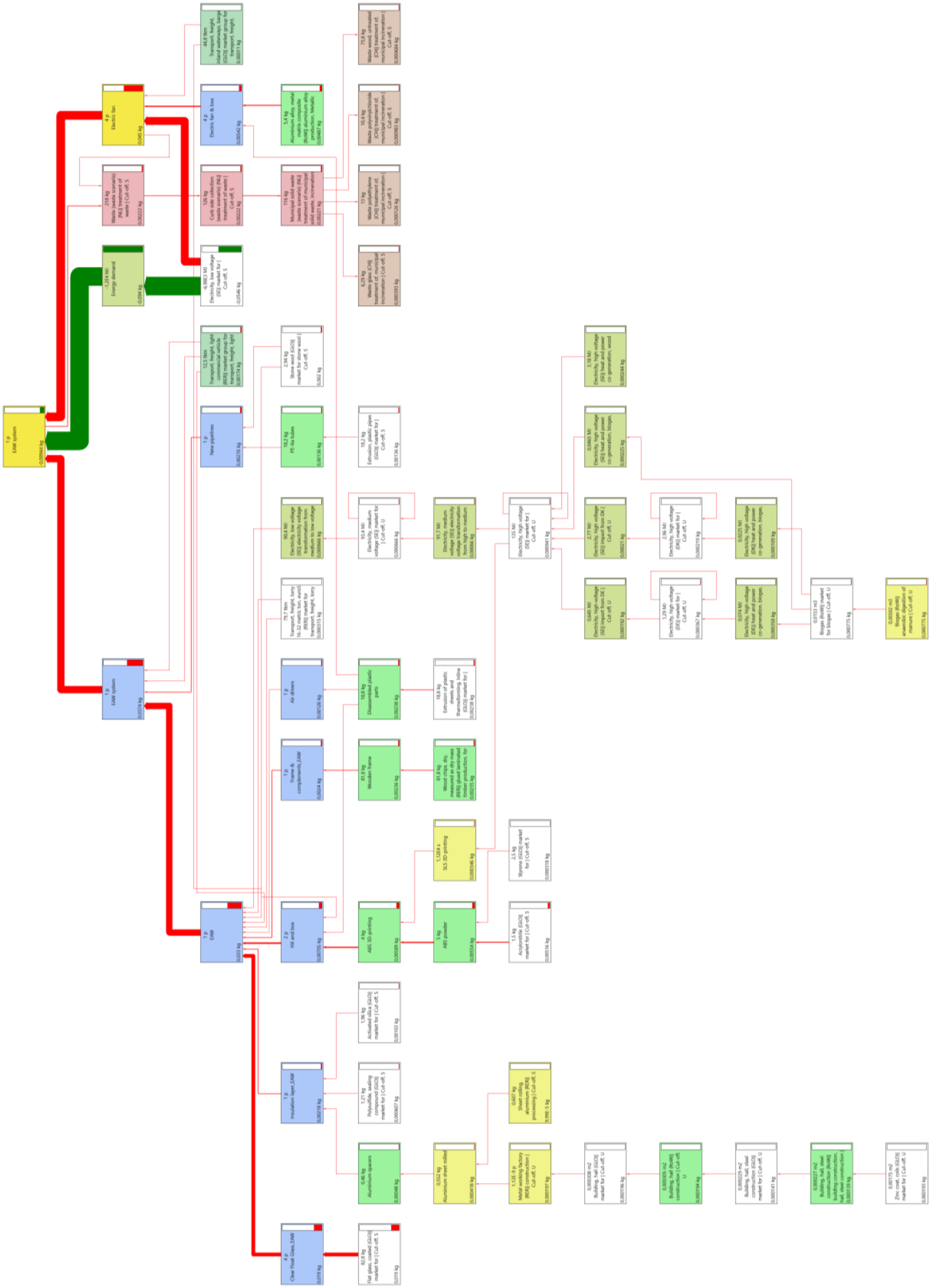

Table 40 ReCiPe 2016, midpoint impact categories definition. **[35]**

MIDPOINT IMPACT CATEGORIES		
	Unit	Description
Climate change	kg CO_2 equivalents.	The characterization factor of climate change is the global warming potential, based on IPCC 2013 report. For the Hierarchist perspective 100-year time horizon was used. Climate-carbon feedbacks are included for non-CO_2 GHGs in the Hierarchist perspective.
Ozone depletion	kg CFC-11 equivalent	The characterization factor for ozone layer depletion accounts for the destruction of the stratospheric ozone layer by anthropogenic emissions of ozone depleting substances (ODS).
Ionizing radiation	kBq Cobalt-60 equivalents to air	The characterization factor of ionizing radiation accounts for the level of exposure for the global population.
Fine particulate matter formation	kg PM2.5 equivalents	The characterization factor of particulate matter formation is the intake fraction of PM2.5.
Photochemical ozone formation, terrestrial ecosystems	kg NOx equivalents	The characterization factor is determined from the change in intake rate of ozone due to change in emission of precursors (NOx and NMVOC).
Photochemical ozone formation, human health	kg NOx equivalents.	The characterization factor is determined from the change in intake rate of ozone due to change in emission of precursors (NOx and NMVOC).
Terrestrial acidification	kg SO2 equivalents.	The characterization factor for terrestrial acidification is Acidification Potential (AP) derived using the emission weighted world average fate factor of SO2.
Freshwater eutrophication	kg P to freshwater equivalents.	The characterization factor of freshwater eutrophication accounts for the environmental persistence (fate) of the emission of P containing nutrients.
Marine eutrophication	kg N to marine equivalents.	The characterization factor of marine eutrophication accounts for the environmental persistence (fate) of the emission of N containing nutrients.
Human toxicity and ecotoxicity	kg 1,4-dichlorobenzeen (1,4-DCB)	The characterization factor of human toxicity and ecotoxicity accounts for the environmental persistence (fate) and accumulation in the human food chain (exposure), and toxicity (effect) of a chemical.
Land use	m2*yr.	The amount of land transformed or occupied for a certain time. The unit is
Water use	m3 water consumed	The factor for the water use is the amount of freshwater consumption.
Mineral resource scarcity	kg Copper (Cu) equivalents	The characterization factor for mineral resource scarcity is the surplus ore potential.
Fossil resource scarcity	kg oil equivalents	The characterization factor of fossil resource scarcity is the fossil fuel potential, based on the higher heating value

Table 41 Normalisation values – European citizen 2000 **[35]**

Impact category	Unit	Domestic	**Normalisation Factor per Person (domestic)**
Climate change	kg CO_2 eq./year	4.60E+12	9.22E+03
Ozone depletion	kg CFC-11 eq. /year	1.08E+07	2.16E-02
Human toxicity - cancer effect	CTUh /year	1.84E+04	3.69E-05
Human toxicity - non-cancer effect	CTUh /year	2.66E+05	5.33E-04

Acidification	mol H+ eq.	2.36E+10	4.73E+01
Particulate matter/Respiratory Inorganics	kg PM2.5 eq.	1.90E+09	3.80E+00
Ecotoxicity for aquatic fresh water	CTUe	4.36E+12	8.74E+03
Ionising radiations – human health effects	kBq U235 eq. (to air)	5.64E+11	1.13E+03
Photochemical ozone formation	kg NMVOC eq.	1.58E+10	3.17E+01
Eutrophication - terrestrial	mol N eq.	8.76E+10	1.76E+02
Eutrophication - freshwater	kg P eq.	7.41E+08	1.48E+00
Eutrophication - marine	kg N eq.	8.44E+09	1.69E+01
Land use	kg C deficit	3.74E+13	7.48E+04
Resource depletion - water	m3 water eq.	4.06E+10	8.14E+01
Resource depletion - mineral, fossil & renewable	kg Sb eq.	5.03E+07	1.01E-01

Table 42 LCIA of EAW assembly. Midpoint and endpoint results for BAU

		Characterisation				Normalisation			
Midpoint impact category	Unit	EAW system	EAW	New pipelines	Total Transport	EAW system	EAW	New pipelines	Total transport
Global warming	kg CO_2 eq	272.300	239.330	11.056	38.587	0.0341	0.0300	0.0014	0.0048
Stratospheric ozone depletion	kg CFC11 eq	0.000	0.000	0.000	0.000	0.0019	0.0016	0.0001	0.0004
Ionizing radiation	kBq Co-60 eq	29.627	27.370	1.223	1.412	0.0616	0.0569	0.0025	0.0029
Ozone formation. Human health	kg NOx eq	0.920	0.797	0.025	0.169	0.0447	0.0387	0.0012	0.0082
Fine particulate matter formation	kg PM2.5 eq	0.587	0.528	0.025	0.054	0.0229	0.0207	0.0010	0.0021
Ozone formation. Terrestrial ecosystems	kg NOx eq	0.949	0.822	0.026	0.174	0.0534	0.0463	0.0015	0.0098
Terrestrial acidification	kg SO2 eq	1.401	1.274	0.051	0.125	0.0342	0.0311	0.0012	0.0030
Freshwater eutrophication	kg P eq	0.085	0.075	0.005	0.006	0.1315	0.1159	0.0083	0.0097
Marine eutrophication	kg N eq	0.012	0.012	0.000	0.000	0.0027	0.0025	0.0001	0.0001
Terrestrial ecotoxicity	kg 1.4-DCB	815.892	682.213	14.968	304.822	0.7873	0.6583	0.0144	0.2942
Freshwater ecotoxicity	kg 1.4-DCB	9.373	7.908	0.266	1.475	7.639150964	6.4449	1.202041353	1.2020
Marine ecotoxicity	kg 1.4-DCB	12.867	10.781	0.368	2.188	12.46859511	10.44635501	2.1201642	2.1202
Human carcinogenic toxicity	kg 1.4-DCB	17.259	15.791	0.468	1.387	6.230430371	5.700623671	0.500657632	0.5007
Human non-carcinogenic toxicity	kg 1.4-DCB	201.117	153.897	6.825	50.488	1.349496322	1.032647592	0.338775456	0.3388
Land use	m2a crop eq	44.302	42.712	0.971	1.303	0.007176888	0.006919392	0.000211065	0.0002

Mineral resource scarcity	kg Cu eq	1.295	1.188	0.027	0.116	1.07862E-05	9.89871E-06	9.66735E-07	0.0000
Fossil resource scarcity	kg oil eq	76.769	66.589	2.777	13.101	0.078304137	0.067920401	0.013363239	0.0134
Water consumption	m3	2.932	2.634	0.215	0.133	0.010993377	0.009876399	0.000497221	0.0005

Endpoint damage category	Unit	EAW system	EAW	New pipelines	Total transport
Total	Pt	13.41	11.88	0.53	1.60
Human health	Pt	12.30	10.89	0.49	1.46
Ecosystems	Pt	0.93	0.84	0.03	0.10
Resources	Pt	0.18	0.15	0.00	0.04

Table 43 LCIA comparison of system assemblies.

Midpoint Impact category	Unit	Double-glazed window	Triple-glazed window	EAW system
Global warming	kg CO_2 eq	46	187	272
Stratospheric ozone depletion	kg CFC11 eq	0	0	0
Ionizing radiation	kBq Co-60 eq	4	25	30
Ozone formation, Human health	kg NOx eq	0	1	1
Fine particulate matter formation	kg PM2.5 eq	0	0	1
Ozone formation, Terrestrial ecosystems	kg NOx eq	0	1	1
Terrestrial acidification	kg SO2 eq	0	1	1
Freshwater eutrophication	kg P eq	0	0	0
Marine eutrophication	kg N eq	0	0	0
Terrestrial ecotoxicity	kg 1,4-DCB	238	748	816
Freshwater ecotoxicity	kg 1,4-DCB	1	7	9
Marine ecotoxicity	kg 1,4-DCB	2	10	13
Human carcinogenic toxicity	kg 1,4-DCB	2	9	17
Human non-carcinogenic toxicity	kg 1,4-DCB	40	207	201
Land use	m2a crop eq	27	40	44
Mineral resource scarcity	kg Cu eq	0	1	1
Fossil resource scarcity	kg oil eq	13	54	77
Water consumption	m3	0	2	3

Endpoint Damage category	Unit	Double-glazed window	Triple-glazed window	EAW system
Total	Pt	2.35	9.03	13.41
Human health	Pt	2.06	8.20	12.30
Ecosystems	Pt	0.26	0.70	0.93
Resources	Pt	0.03	0.13	0.18

Table 44 LCIA EAW life cycle. Midpoint and endpoint results for BAU

		Characterisation					Normalisation
		TOTAL ENERGY DEMAND					
Midpoint impact category	Unit	Room with double-glazed window	Room with triple-glazed window	Room with EAW system	EAW energy savings	EAW system	EAW system
Global warming	kg CO_2 eq	1398	1235	1303	95.516	248.009	0.031
Stratospheric ozone depletion	kg CFC11 eq	0	0	0	0.000	0.000	-0.001
Ionizing radiation	kBq Co-60 eq	9258	8175	8626	632.362	-601.648	-1.251

Ozone formation. Human health	kg NOx eq	3	3	3	0.217	0.765	0.037
Fine particulate matter formation	kg PM2.5 eq	2	2	2	0.157	0.452	0.018
Ozone formation. Terrestrial ecosystems	kg NOx eq	3	3	3	0.221	0.791	0.045
Terrestrial acidification	kg SO2 eq	6	5	6	0.414	1.035	0.025
Freshwater eutrophication	kg P eq	1	1	1	0.071	0.020	0.030
Marine eutrophication	kg N eq	0	0	0	0.014	0.000	0.000
Terrestrial ecotoxicity	kg 1,4-DCB	16979	14993	15819	1159.688	-317.546	-0.306
Freshwater ecotoxicity	kg 1,4-DCB	747	659	696	51.001	-36.668	-29.885
Marine ecotoxicity	kg 1,4-DCB	921	813	858	62.874	-43.407	-42.061
Human carcinogenic toxicity	kg 1,4-DCB	186	165	174	12.732	6.177	2.230
Human non-carcinogenic toxicity	kg 1,4-DCB	4397	3883	4097	300.338	-24.106	-0.162
Land use	m2a crop eq	559	494	521	38.191	6.326	0.001
Mineral resource scarcity	kg Cu eq	20	17	18	1.345	-0.015	0.000
Fossil resource scarcity	kg oil eq	240	212	224	16.411	62.536	0.064
Water consumption	m3	183	162	171	12.502	-9.327	-0.035

	TOTAL ENERGY DEMAND				
Endpoint damage category	Room with the double-glazed window	Room with triple-glazed window	Room with EAW system	Energy savings EAW	EAW system
Total	88.197	77.879	82.173	6.02	9.3
Human health	80.577	71.151	75.074	5.50	8.5
Ecosystems	7.236	6.389	6.741	0.49	0.6
Resources	0.384	0.339	0.358	0.03	0.2

Table 45 LCIA comparison of system life cycles

Endpoint Damage category	Unit	Double-glazed window	Triple-glazed window	EAW system
Total	Pt	42.4	41.5	51.3