SUSTAINABLE URBAN AREAS
37

# Environmental impacts during the operational phase of residential buildings

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# 1 Introduction

In the present day debate about the environment, copious use is made of the terms ‘sustainable development’ and ‘sustainability’. Sustainable development generally focuses on three areas: social development, or reducing inequality; economic development, or securing prosperity now and in the future; and ecological development, or preserving and protecting the outdoor environment (Brundtland, 1987). In business strategy these three areas are also referred to as the Triple Bottom Line or the three P’s: people, profit (or prosperity), and planet (Elkington, 1997). In this thesis the term sustainability is applied to ecological sustainability.

This chapter first presents the scientific and practical context for the research in Section 1.1, followed by a definition of the problem the research will help solve in Section 1.2. The objective of the research and the research questions are set out in Section 1.3. Sections 1.4 and 1.5 deal with the research approach and Section 1.6 provides an overview of the thesis.

## 1.1 Background

### 1.1.1 Quantifying ecological sustainability

The primary challenge posed by ecological sustainability is to ease the pressure on the environment amid a constantly rising world population and ever-increasing prosperity. This challenge calls for methods to formulate quantified targets for sustainable development and to measure and monitor progress.

The ‘factor X’ concept is a way to formulate quantified ecological sustainability targets. ‘X’ is the factor by which the environmental performance of products, economic sectors or national economies has to improve in order to reach a desired situation (Reijnders, 1998; von Weizsäcker *et al.,* 1998; Jansen and Vergragt, 1992; Ehrlich and Ehrlich, 1990; Speth, 1989). When a factor X goal is stated, four parameters need to be identified: the factor X, which is the quantified environmental performance; the unit of measurement, e.g. the amount of primary energy resources used; the point of reference, e.g. a specified economic activity in a specific geographical area and time frame; and the time frame in for reaching the goal. The unit of measurement should take account of contextual developments, such as increasing population and prosperity, since a reduction in the environmental impact per capita or per production unit need not necessarily imply a reduction in the total environmental impact if the population or production increases. Factor X originally assumed that the required reduction in environmental impact could be achieved via technological measures to bring about more efficient use of resources (Chertow, 2001; Reijnders, 1998). However, especially in the long run, factor X has to be very large to accommodate upward trends in population and prosperity in western and upcoming economies. Existing technology has its limits when it comes to increasing resource efficiency. Robèrt *et al.* (2000) therefore suggest that factor X thinking be applied to determine a desired level of sustainability in the long-term future. Instead of trying to reach a goal from what is considered realistic and possible at this point in time in the present (forecasting), one should think back from that point in time in the future and determine what needs to happen now (backcasting) (Jansen and Vergragt, 1992). The factor X approach is often used in international coordination of policymaking.

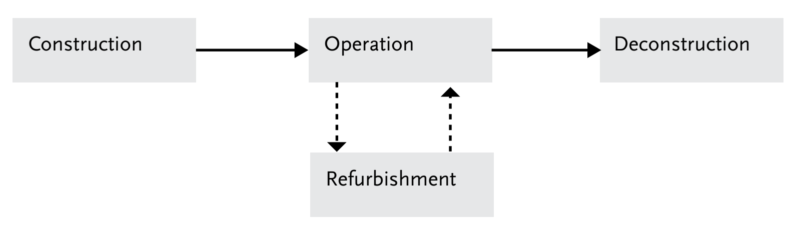
The challenge of ecological sustainability further calls for a quantified unit of measurement to monitor progress in ecological sustainability. Several approaches to measuring ecological sustainability have already been developed. The Ecological Footprint approach, inspired by the warning in the Brundtland Report (1987) concerning the limited availability of resources, compares the amount of ecologically productive land that is needed for the input and output flows of economic activity with the amount of available ecologically productive land (Wackernagel and Rees, 1996). The intention is to ensure that the use of environmental resources by economic systems does not exceed the carrying capacity of the environment. Another approach, Material Flow Analysis (MFA), analyses the energy and material input and output flows of economic activity and assesses the physical amount of material resources flowing into and out of a product system or economy (Brunner and Rechberger, 2004). In Material Flow and Stock Analysis (MFSA), which is intended for economies rather than product systems, the materials that remain in the system are also taken into account (Obernosterer *et al.*, 1998). Similarly, the energy resources needed to produce goods or services can be analysed by (Embodied) Energy Analysis (Brown and Herendeen, 1996). The Three Step Strategy approach to the use of energy and material resources states that in order to lower environmental damage it is necessary to first reduce the demand for energy and material resources, then to make greater use of more sustainable resources and, finally, using unsustainable resources more efficiently (Brouwers and Entrop, 2005; Lysen, 1996; Duijvestein, 1993). The Three Step Strategy has been updated by van den Dobbelsteen (2008) and Tillie *et al.* (2009) to the New Stepped Strategy, which includes the first step to reduce energy demand and material resources, then re-use material and energy waste flows and third to use sustainable resources. The New Stepped Strategy was inspired by the Cradle to Cradle theory by McDonough and Braungart (2002), which aims at closing material and energy cycles without producing waste. Straightforward analysis of material and energy flow follows the principle that the fewer resources are used the better, but it fails to provide any insight in the impact of individual materials and types of energy on the environment. The life cycle assessment (LCA) approach fills this void by analysing and quantifying the negative impact of material and energy flows on different environmental mechanisms called ‘environmental impact categories’ (Guinée, 2002). Currently, the UNEP/SETAC Life Cycle Initiative is working on guidelines for a Life Cycle Sustainability Assessment (LCSA) of products, in which LCA, Life Cycle Costing (LCC) and Social LCA (S-LCA) will be combined to form a Triple Bottom Line tool that includes all three aspects of sustainability (Life Cycle Initiative, 2010; Ugaya *et al.,* 2010). In this research LCA is used to quantify ecological sustainability. The results of an LCA show the contributions of products and processes to several environmental impact categories. The term ‘environmental impacts’ refers to the set of contributions to all impact categories that are assessed.

### 1.1.2 Current environmental policy

The United Nations (UN) deals with environmental problems at global level – global warming, depletion of the ozone layer and depletion of natural resources – which affect all people. The UN endeavours to initiate global action on sustainable development through international agreements. At the UN Conference on Environment and Development (Earth Summit) in Rio de Janeiro in 1992, an action agenda was set for international, national, regional and local actors in every area of the environment that is affected by human beings. This Agenda 21 was adopted by 178 governments (UN, 1993). Specific agreements have been reached on reducing global warming, protecting the ozone layer and preserving abiotic (non-living) natural resources. The Kyoto Protocol, the agreement on reducing greenhouse gas emissions, which cause global warming, had been signed by 84 signatories and ratified by 191 parties in June 2010 (UNFCCC, 1997, 2010). To protect the ozone layer, which is at risk mainly from CFCs, a UN agreement, the Montreal Protocol, on banning the use of CFCs has been signed and ratified by 191 nations (UNEP, 2000). Since the Montreal Protocol came into force, the depletion of the ozone layer appears to have come to a halt (McKenzie *et al.,* 2007; Weatherhead and Andersen, 2006). Lastly, the UN has developed activities in Africa to manage and protect reserves of natural resources.

The United Nations Environmental Programme (UNEP) and the European Commission (EC) have identified the building sector as a key factor in reaching the Kyoto Protocol targets (EC, 2006; UNEP, 2007). The building sector consumes an estimated 30-40% of energy worldwide and around 36% in the European Union (EU): the non-residential sector accounts for 8.7% and the residential sector for 27.5% of the total (UNEP, 2007). This thesis therefore focuses on residential buildings. EU governments have set minimum energy performance standards for new buildings, based on a common methodology to measure energy performance. The Energy Performance Building Directive (EPBD) applies from January 2006 to all new buildings and large old buildings undergoing major refurbishment. The Directive also requires sellers and

Figure 1.1 Schematic life cycle of a building



landlords to provide prospective buyers and tenants respectively with energy performance certificates. In 2008 the EC proposed a recast of the EPDB to include all buildings undergoing refurbishment and minimum performance requirements for building components. Furthermore, from 2020 all new buildings will have to comply with 'nearly zero' energy consumption standards. The definition of 'nearly zero' can be set by the individual Member States. The European Parliament approved the EPBD recast in May 2010 (Euractiv Network, 2009).

EU and national policies also contain regulations on building materials. The use of certain materials such as asbestos is prohibited for health and safety reasons and there are regulations for the collection and treatment of building waste. Between 1998 and 2001 the construction and demolition sector was responsible for about 31% of the total waste in western Europe (the 15 EU countries, plus Norway, Iceland and Switzerland) (EU, 2003). The EU has also developed an Integrated Product Policy (IPP) approach which seeks to improve the environmental performance in each phase of the life cycle of products (European Commission, 2001). Rather than one simple policy measure, the IPP consists of a whole arsenal of tools and measures – including Environmental Product Declarations (EPDs) – to cater for the many different products and actors who need different means to achieve the policy goal. An EPD contains environmental information about a product, according to the guidelines in the international ISO 14025 standard (ISO, 2010), which allows manufacturers to provide aggregated environmental information without releasing any confidential data. An additional international standard, ISO 12930 (ISO, 2007), is being developed for building products. The IPP concludes that LCA is the best available instrument for assessing the environmental impacts of products (European Commission, 2003). LCA has also been adopted in the ISO 14025 / ISO 12930 international standards.

## 1.2 Problem definition

LCA can also be applied to buildings. The life cycle of a building consists of three clearly distinguishable main phases: construction, operation and deconstruction (Figure 1.1). The construction phase includes all processes from the extraction of material resources to constructing the building on-site, while the deconstruction phase includes all processes from the deconstruction of building components to recycling and the final waste processing. The operational phase includes all processes between construction and deconstruction. In practice, a building might be refurbished or be given a new designation – e.g. an office building may become a residential building – which adds phases to the life cycle and starts a new operational phase after the changes have been made.

In the construction phase the environmental impacts of the building are directly related to the building and design decisions on, for example, the materials and building components or the energy needed for a specific type of construction. The environmental impacts in the deconstruction phase are similarly related to design decisions. The construction method and building components used in the construction phase, as well as any changes made during the operational phase, determine the parts of the building that can be re-used or recycled. The environmental impacts of the final waste processing depend on the materials used. Hence, design decisions made today will have environmental implications for decades or even centuries to come. Furthermore, the building design determines the possibilities and limitations for management and use in the operational phase.

In the operational phase the environmental impacts of the building are influenced by its characteristics and other – external – factors. For example, the thermal characteristics of a building determine how much energy is needed to establish and maintain a comfortable indoor climate, but it is the occupants who determine what a sufficiently comfortable climate is. The calculated energy consumption of a building is therefore valid only for the standardised comfort level and user behaviour which are assumed in the calculations. UNEP does recognise the influence of occupants on the energy consumption of buildings, as this may counteract efforts to improve energy efficiency (UNEP, 2007). Similarly, the building design and the local climate at the building site co-determine the speed at which a building deteriorates. This, in turn, influences levels of maintenance and the need to replace components. It is, however, the owner of the building who decides, on the basis of economic and functional rather than technical considerations, when actual maintenance and replacements are carried out. These decisions may then influence the total service life of the building.

The operational phase of a building spans multiple decades, which is why reducing the environmental impacts of buildings might be more effectively achieved by changing the way buildings are used and managed rather than by changing the building itself. This has been suggested by several authors (Fay *et al.*, 2000; Itard and Klunder, 2007; Klunder, 2002, 2005; Treloar *et al.*, 2000), but no comprehensive and detailed research has been published on this theme so far. International policy and research has focused up till now on energy consumption for climate control in buildings and the environmental impacts of specific building products, but little is known about the environmental impacts of processes and activities in the operational phase of a building, such as maintenance and renovation (Itard and Klunder, 2007). Klunder (2005) points out that little research has been conducted on the influence of occupant and management behaviour on the total environmental burden imposed by buildings. Borg (2001) and Paulsen (2001) do consider the operational phase of a number of separate building products and their influence on energy consumption, but not the use of a building as a whole.

Concluding, there is a lack of knowledge regarding the environmental impacts of regularly occurring activities in the operational phase of dwellings and the relationship between building-related and user-related impacts is unclear.

## 1.3 Objective and research questions

The objective of this research is to provide insight into the factors that cause the greatest environmental impacts in the operational phase of residential buildings and awareness of the long-term ecological consequences of decisions made in the design, construction and operational phases. The research further aims to contribute to the modelling of the operational phase of residential buildings in LCA by indicating if it is possible to assess the ecological sustainability of residential buildings with reasonable accuracy according to a limited number of contributing factors. The acquired knowledge may help policymakers to develop effective policies and can steer further developments in research and building practice towards areas that have the most potential for improving the environmental performance of residential buildings. The research includes a sensitivity analysis for variations in standard operational behaviour patterns, since those variations may have great influence on the results. The aim of this research is to establish how great the influence of operational behaviour and assumed variations thereof are compared to other factors. Further research may include behavioural science to determine how and why people behave like they do and how to effectively promote 'good' behaviour.

The main research questions are:

1. *What are the environmental impacts related to the operational phase of residential buildings?*
2. *Which factors significantly contribute to the various environmental impact categories?*
3. *To what extent do changes in the variable parameters of the assessment affect the environmental impacts?*
4. *How can the environmental impacts in the operational phase be most effectively reduced?*

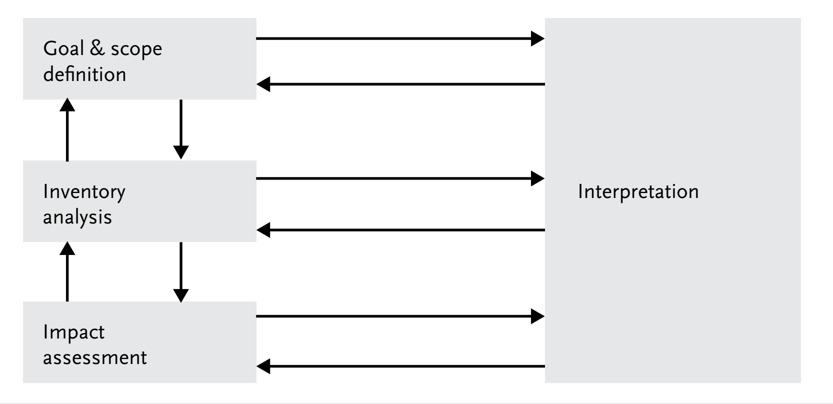
The factors that are taken into account are the use of material resources and production processes; waste processing; transportation of maintenance workers; and energy consumption. The variable parameters are for example the service life of building components and systems; maintenance frequency, transportation distance and energy consumption by users. The research questions are applied to three main aspects of the operational phase of dwellings and the operational phase as a whole:

- maintenance and replacement of façade components (Chapter 2);
- maintenance, replacement and use of heating and ventilation systems (Chapter 3);
- building-related and user-related gas and electricity consumption (Chapter 4);
- operational phase of dwellings, including the replacement of bathroom, toilet and kitchen (Chapters 5 and 6).

Since the research was completed in phases, the above research questions were sharpened over time and are therefore not literally repeated in all the chapters. However, all aspects of the main research questions are covered in the chapters. For example, question 3 is not mentioned specifically, but is addressed in the assessment of different use scenarios. Question 4 is part of the discussion and conclusion in the chapters. The research questions as formulated above will be reflected on in the final Chapter 6.

The main aspects of the operational phase have been selected on the basis of the probability of high environmental impacts, given the high frequency of activities and the amount of energy, materials and waste. The assessment of the operational phase is not exhaustive: it may exclude activities with low frequency and/or a relatively low flow of energy, materials or waste which have a high environmental impacts. Similarly, low volume elements of the façade components, climate systems and bathroom, toilet and kitchen that are omitted in the research may deliver high environmental impacts. Materials with known high environmental impacts have been included as far as possible. The research does not include extensive refurbishment of the dwelling, for example changing the floor plan, since that would change the functional performance of the building and produce a new product in terms of LCA. Maintenance and replacement of the roof has not been considered in this research, since roof maintenance has a low frequency and the roof of apartments in gallery flat buildings is shared by many dwellings, which reduces the material and waste flow per dwelling. Finishing of rooms has been limited to finishing provided by the building owner, therewith excluding all floor, wall and ceiling finishing except tiling in bathroom, toilet and kitchen.

Figure 1.2 Schematic overview of the four steps of life cycle assessment



# 1.4 Research approach: LCA methodology

## 1.4.1 General description

LCA is a method that can be used to quantify the negative impact of a product on the environment during production, use and disposal. As shown in Subsection 1.1.1, it is necessary to quantify environmental impacts in order to monitor and set specific goals for sustainable development. LCA methodology is widely accepted and applied in scientific research to assess the environmental impacts of products. An LCA consists of four steps, the requirements and guidelines for which are described in the ISO 14044 standard (2006) (Figure 1.2).

The first step is to define the goal and scope of the assessment. These serve as a description of the type of study – e.g. a comparative analysis of products or a study to improve a production process – and determine the questions that the assessment is required to answer. The scope of the study determines the processes to be included in the next step, the inventory phase, which involves the compilation of an inventory of the flow of all substances to and from the environment during the period of interest. In the third step, impact assessment, the potential contribution made by each substance to predefined environmental impact categories is calculated. This is done by comparing the impact of a particular substance flow with that of a reference substance for each category. Once the environmental impacts have been determined, the last step in the assessment is to interpret the results of the calculations by, for example, comparing the calculated environmental impacts with the results of similar research in the literature or with the overall environmental impacts in a region (normalisation), and by determining the sensitivity of the results to changes in the input variables. The process is iterative: the interpretation phase of the assessment may highlight unanswered questions or inconsistencies in the study which need to be addressed.

In LCA several methods can be used to assess the impact of the substance flows collected in the inventory phase. The SimaPro 7.2 software provides 20 different methods to choose from, each with its own calculation methods and (set of) indicators to quantify environmental performance. Two frequently used methods in scientific LCA research are the CML 2000 baseline method and the Eco-indicator 99 method. The CML method uses multiple indicators at midpoint level (Guinée, 2002), while the Eco-indicator includes multiple endpoint indicators that can be combined in a single endpoint indicator (Goedkoop and Spriensma, 2001). Endpoint indicators represent the ultimate consequences of the environmental impacts for humans and ecosystems. They reveal the 'endpoint' of a possible chain of causes and effects. As more environmental mechanisms are involved, one of the weaknesses of these indicators is a higher level of uncertainty in the results (Goedkoop *et al.,* 2009). Midpoint indicators, in contrast, show the potential direct negative impact on the environment, which can be situated anywhere along the chain of cause and effect. Both types of indicator are problem-oriented: the higher the score, the worse the environmental performance. The CML and Eco-indicator methods have recently been combined in a new method named ReCiPe, which allows the user to display results at different levels along the chain of effects (Goedkoop *et al.,* 2009). In this research the CML 2000 LCA midpoint method was used to determine the environmental impacts of building components and processes because the level of uncertainty is lower. Since CML is widely used and will probably go on being developed and used due to its inclusion in the new ReCiPe method, the results can be compared with other past and future scientific research.

The environmental impacts are quantified by LCA methodology. The LCA is performed with the SimaPro software package (Goedkoop *et al.,* 2007). The input data for the calculations of the environmental impacts come from the commercially available ecoinvent 2.0 database (ecoinvent, 2007). The data in the database were gathered from different literature sources and manufacturers and are kept up to date by the Swiss Centre for Life Cycle Inventories. More information about non-confidential data is available in extensive background reports by ecoinvent. All ecoinvent data entries have been reviewed by experts.

The environmental impact categories assessed in the CML 2000 method are selected from the most commonly used indicators in LCA studies. The impact categories used in this research are listed in Table 1.1 and further explained in Appendix 1. The full set of environmental impact categories is known as the 'environmental profile'. The impact category 'Marine aquatic ecotoxicity', one of the mandatory impact categories in the CML method, is not taken into account because significant problems are associated with the calculation of the contribution to that category using the CML method (Sim *et al.,* 2007). The problems in question are related to the time a substance is present in the marine ecosystem and to the absence of data for normalisation. The characterisation models for the influence of metals on ecotoxicity contain flaws in

**Table 1.1 Environmental impact categories considered in the CML 2000 method**

| Environmental impact category | Unit of measurement |
|---|---|
| Abiotic depletion | [kg Sb eq.] |
| Global warming | [kg $CO_2$ eq.] |
| Ozone layer depletion | [kg CFC-11 eq.] |
| Photochemical oxidation | [kg $C_2H_4$ eq.] |
| Human toxicity | [kg 1,4-DB eq.] |
| Fresh water aquatic ecotoxicity | [kg 1,4-DB eq.] |
| Terrestrial ecotoxicity | [kg 1,4-DB eq.] |
| Acidification | [kg $SO_2$ eq.] |
| Eutrophication | [kg $PO_4^{3-}$ eq.] |

Source: Guinée, 2002

terms of the length of time these metals are present in ecosystems and the form they take. As these factors whether they are harmful or beneficial, the results of the ecotoxicity impact categories have a higher level of uncertainty. Even so, it is still possible to compare product alternatives (Apeldoorn, 2004; Heijungs *et al.*, 2004).

### 1.4.2 Limitations of LCA

As an analysis method which is still in development, LCA will continue to be refined, improved and expanded for some time to come as a result of progressing insight. A distinction can be made in two areas of development: impact assessment, in which the environmental impacts are calculated; and inventory assessment, in which the processes that are taken into account are determined. LCA studies performed at different points in time cannot easily be compared. LCA methodology can be considered current best practice which is improving in time.

Reap *et al.* (2008a, 2008b) published an overview of 15 currently unresolved problems in life cycle assessment. These problems can be divided into technical problems in the methodology and problematic decisions that need to be made when performing an LCA according to ISO 14044 (ISO, 2006). LCA was originally developed to assess production processes and consumer goods. Some assumptions were made and simplifications were introduced, such as the elimination of time and geographical location factors: all extractions and emissions take place simultaneously at an unspecified location. The simplifications and assumptions in the LCA methodology may lead to an overestimation of the environmental burden imposed by the product, since some of the environmental impacts occur only after a certain concentration of substances has been reached. For buildings, the simplifications in the methodology are likely to create a large error margin, since many building materials and products are imported from other countries and continents, and the long service life of a building spreads the environmental impacts over a long period of time (Erlandsson and Borg, 2003). Below is a selection of problems identified by Reap *et al.* (2008a, 2008b), which are of particular interest when conducting an LCA of buildings, based on Blom (2006).

## 1. Functional unit definition

A functional unit is a description of the assessment object in measurable units, which allows for comparison between multiple objects or between different design options for a single object. For example, the functional unit of a coffee machine might be the production of six cups of coffee a day for five years. However, that description does not suffice if one coffee machine can make different types of coffee, while another only produces standard black coffee. In that case, the two coffee machines provide different services. Similarly, different buildings that provide different services complicate the performance of an environmental assessment. Some services can be defined in measurable units, such as the thermal insulation of the facades, floor and roof. These kinds of technical characteristics often have a minimum value to guarantee minimum building quality. In the Netherlands the minimum technical requirements for new buildings and refurbished existing buildings are recorded in the Building Decree (de Jong and Pothuis, 2009). Other services such as comfort level are more difficult to quantify since the experience of comfort is subjective. Furthermore, the functional requirements of the building may change over time. So, it is hard to describe the assessment object (Erlandsson and Borg, 2003). On the other hand, LCA can be used to assess different design options for a building without specifically taking account of all the services of the building. When different options are compared, there is no need to take account of the variables that stay the same. This will reduce the amount of required data and shorten the process of doing an LCA.

This research compares different scenarios for the operation of a single reference building. The functional unit, the basis of comparison, is therefore the reference building defined by its dimensions and some technical characteristics. The heat resistance of the roof and the closed façade parts is assumed to be 2.5 $m^2K/W$, as required by the Dutch Building Decree 2003 for new buildings (de Jong and Pothuis, 2009). The number of occupants is 2.8 persons, which is derived from the standardised occupancy characteristics in energy calculations according to NEN 5128 (2004). Other elements of the functional unit have not been set in advance in order to test the influence of the choice of system boundaries on the results. In Chapter 2, for example, scenarios for maintenance and replacement of façade components made of different materials are compared. When the glazing is replaced by glazing with better heat resistance the heat demand decreases, thus the system boundaries have to be altered to include gas consumption for space heating. The alteration of system boundaries then provides the opportunity to compare the order of magnitude of environmental impacts due to gas consumption with the impacts of maintenance and replacement activities. The temporal system boundaries will be discussed below.

## 2. Service life

Normally, an LCA of buildings deals with the entire life cycle of the building and is performed before the building is actually constructed. An assumption must then be made about the expected service life, usually 50-75 years is assumed in the Netherlands. Research by Van Nunen (2010) shows that 120 years is a more accurate estimate for the average service life of dwellings in the Netherlands, but it may even be much longer. The service life of a building is important when its value may influence the results or the interpretation thereof. When different variants of a building design which do not lead to changes in the expected service life are compared, the length of the service life is not particularly important. However, when the environmental impacts in different phases of the service life of a building are compared or when alternative building technologies leading to differences in service life are assessed, the value of the service life is crucial. Furthermore, the environmental impacts of the entire life cycle of a building are often expressed as the average environmental impacts per year. In this case the annual environmental impacts of the construction and deconstruction phases are lower for buildings with longer service lives, since they are spread out over a longer period of time. One may argue that this is justifiable, since a building that lasts 100 years could provide a similar service as two buildings lasting 50 years. However, this assumption may still obfuscate the results, since the origin of the environmental impacts is no longer visible.

In this thesis the environmental impacts in the operational phase of the dwelling are calculated as an accumulation over time. The temporal system boundaries have intentionally not been set beforehand in order to assess short and long term consequences of activities. Thus, the operational phase may be cut off at any given moment. In Chapters 2 (façade maintenance), 3 (climate systems) and 5 (complete operational phase), different cut off points are used of 70, 40 and 99 years respectively. However, all three cut-off points were calculated and compared in all chapters to pinpoint the influence of the duration of the scenario. The results for all three cut-off points are shown in the appendices.

## 3. Technical and scientific development

Technology and knowledge are almost certain to continue to develop during the service life of a building. Building components in the future may be completely different from building components now. An LCA cannot take account of recycling and waste processing technology of the future. What is more, the building may not lend itself to the incorporation of new technology as the application requirements are not known at the start of its life cycle. In this research it is assumed that all the building products are replaced by similar new products. The error margin introduced by this assumption is likely to be relatively small for façade components, such as window frames, which have not changed much in the past decades, and greater for climate systems, which are being developed continuously. Current waste processing technology is also assumed.

### 4. Temporal and geographical aspects of environmental impacts.

When a product is assessed, it is 'frozen' in space and time. This means that all the impacts during the life cycle of the product are assumed to take place at once at a single geographic location. This assumption is acceptable for environmental impact categories where the effect is accumulative and global, such as the depletion of abiotic non-renewable resources. However, some effects only occur when a substance reaches a certain concentration at a certain location (Boustead, 1999). As the emissions during the life cycle of a product need not all be produced at one location, the effect may not occur. Moreover, the emissions might not occur all at once or they may migrate to another of the environmental compartments air, water and soil, which may lead to a reduced local concentration of the emissions. If the temporal and geographical characteristics of impacts are not taken into account, local environmental impacts triggered by high concentrations of foreign substances might be seriously overestimated. This overestimation might be greater for buildings than for consumer goods, given that the life cycle of a building is longer and the environmental impacts are usually spread around the entire globe because of the import of material resources and ready-made components. These currently unsolved problems form part of the calculation methodology of LCA and will not be solved in this research. However, the results of the assessment are expressed as an accumulation over time, assuming that the total impact of the production and waste processing of building products occurs in the year that a replacement takes place. This will reveal the moment when environmental impacts occur during the operation of dwellings and provide insight into how it can be influenced.

### 5. Interpretation and comparison

An optional step in the interpretation phase of LCA is normalisation of the results, whereby the environmental impacts of a product or process are compared with the total annual environmental impacts in a certain region and year. The reference values are obtained by extrapolating the known environmental impacts of major processes to the scale of the region and are therefore approximate values for the total environmental impacts. In this study the results are normalised with 1997 as a reference year for the Netherlands (Guinée, 2002). The primary aims of normalisation are to provide a comparable scale between impact categories, a rough error check of the results and a reference value that is constant over time – which is why the 1997 values are still used (van Oers and Huppes, 2001). There are several issues associated with normalisation. The first relates to geography: the reference values are valid for a specific region, but the environmental impact scores are not location-specific. An environmental impact that has occurred in a different continent is therefore attributed to the product under assessment and compared with the local total environmental impact. Consequently, the normalised results may be too high, especially for local environmental impact categories such as eutrophication. The second issue is of a temporal nature: resources may have been extracted long before the products are produced and waste processing may take place long after the building waste has been disposed of. Since the products are frozen in time and place, all environmental impacts are counted at once and compared with the total environmental impacts in one year. The temporal issue may, however, be discounted because of the more or less continuous production of building components. Furthermore, the characterisation models for the influence of metals on ecotoxicity contain flaws with regard to the length of time these metals are present in ecosystems and the form the take. As these factors determine whether they are harmful or beneficial, the results of the ecotoxicity impact categories are subject to a higher level of uncertainty (Apeldoorn, 2004; Heijungs *et al.*, 2004). Finally, the current total environmental impacts in a region may be different and thus lead to either overestimations or underestimations depending on the relation between new and old reference values. Despite these drawbacks, normalisation is still a useful tool for interpreting results, since it provides a comparable scale between different impact categories and the point of reference is fixed, which allows for comparison of different studies. One may argue that not all dwellings in use are in the same stage of the operational phase and therefore the average environmental impacts per year can be compared with the total annual environmental impacts in the Netherlands, but the geographical issue is still unsolved and special care should be taken with local and regional environmental impact categories, such as ecotoxicity, photochemical oxidation, acidification and eutrophication.

It may be concluded that the complexity of the ‘product’ and the uncertainties in the life cycle assessment make it impossible to obtain an accurate and complete environmental profile of a building. Accordingly, the goal of an LCA for buildings should not be to obtain a complete environmental profile, but to compare alternative options for design, refurbishment and operation in order to gain insight into the different contributors to environmental problems. By pursuing this path it will be possible to effectively reduce the burden imposed by buildings on the environment.

## 1.5 Research approach: reference building

In order to assess the environmental impacts of activities in the use phase of dwellings, the amount of materials needed for building products and systems

**Figure 1.3 Gallery flat reference building**

Source: Novem, 2001

and the energy consumption of climate systems are calculated with the aid of a Dutch reference building. The Dutch reference buildings are a collection of typical Dutch dwellings of different construction types and sizes. They were developed with a view to assessing measures to improve the energy efficiency of existing dwellings, but are also frequently used for other environmental assessments (Novem, 2001; SenterNovem, 2007). The building selected for this research is the gallery flat constructed between 1966 and 1988 (Novem, 2001; SenterNovem, 2007). Figure 1.3 shows the floor plan and side elevation of the building. There are approximately 208,000 dwellings of this type in the Netherlands (3.2% of the dwelling stock), 67% of which are owned by housing associations and subject to regularly scheduled maintenance and replacement activities.

In order to show how environmental impacts accumulate in time as a result of decisions made in the operational phase of the dwellings, the environmental assessment is performed by applying scenarios to the reference building. A scenario describes when activities, such as maintenance and replacements, take place. The assembly of realistic scenario alternatives are validated by interviews with building management employees and by data from previous and ongoing research. This research assumes that each scenario commences with the production and installation of all building and system components. The environmental impacts of the annual gas and electricity consumption are assigned each year of the scenario. The gas and electricity consumption is calculated with Vabi EPA-W software, which was developed to assess the

Figure 1.4 Structure of the thesis

| | Group of activities | Contributing factors | | | |
|---|---|---|---|---|---|
| | | Material resources | Waste processing | Transportation of maintenance workers | Energy consumption |
| Chapter 5 | Chapter 2 Facade components maintenance and replacement | V | V | V | V |
| | Chapter 3 Climate systems maintenance, use and replacement | V | V | V | V |
| | Chapter 4 User-related energy consumption | – | – | – | V |
| | Kitchen, bathroom and toilet replacement | V | V | V | – |

V = relationship assumed between group of activities and contributing factors

energetic quality of dwellings and assign energy labels (Vabi Software, 2009). The software is attested according to the Dutch standard for energy performance calculation tools, BRL 9501 (ISSO, 2006), which measures calculation methods against current best available practice.

## 1.6 Structure of the thesis

With the exception of Chapter 5, the main chapters in this thesis were written as scientific papers that can be read independently. Some information is therefore repeated in various chapters. Figure 1.4 shows the structure of the thesis. The contributing factor ‘material resources’ includes extraction of natural resources, production processes of components including energy consumption, production waste; transportation of the materials or building components to the harbour of Rotterdam; and capital goods. ‘Waste processing’ includes transportation of waste products from the building site, incineration and landfill processing including energy consumption, and capital goods. ‘Transportation’ includes fuel resources and emissions to air related to the transportation of maintenance workers to the building site. Capital goods are included for the extraction and production of fuel, but the vehicles of the maintenance workers are not. The ‘energy consumption’ factor includes extraction of resources; generation of electricity or combustion of gas; transportation and distribution of energy to the dwelling; and capital goods.

Chapter 2 deals with the environmental impacts of the maintenance and replacement of façade components such as doors and windows. All the contributing factors mentioned in the header row of Figure 1.4 are taken into account. Similarly, the environmental impacts of the maintenance, use and replacement of climate systems are assessed in Chapter 3. In Chapter 2, only gas consumption for heating is taken into account, while the energy consumption in Chapter 3 is limited to gas for space heating and hot tap water and operational electricity for the heating and ventilation systems. In Chapter 4, the building-related energy consumption, as addressed in Chapter 3, is compared with user-related energy consumption. The material resources and waste processing of the systems and appliances that use energy are not taken into account. In Chapter 5 all aspects of the operational phase of dwellings are combined, including the replacement of bathroom, toilet and kitchen. Energy consumption for cooking is included in user-related energy consumption. The environmental impacts are analysed per group of activities and per contributory factor with a view to pinpointing the most relevant contributory factors in the operational phase of dwellings. Finally, Chapter 6 sets out the conclusions that can be drawn from the research, suggestions for policy goals and recommendations for practice and further research.

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# 2 Environmental impact of dwellings in use: maintenance of façade components

*Research completed: 2008*
*Blom, I.S., L.C.M. Itard and A. Meijer, 2010, Building and Environment, 45 (11), pp. 2526-2538, doi:10.1016/j.buildenv.2010.05.015*
*An overview of all results can be found in Appendix 2.*

**Abstract**

The use of dwellings contributes significantly to human-induced environmental burden in a number of ways, including energy consumption and the maintenance and replacement of building components. The present study deals with the maintenance and replacement of external doors and windows in a Dutch reference dwelling and describes how life cycle assessment (LCA) methodology can be applied to quantitatively assess the environmental impact of various maintenance scenarios for the façade components. First, the most effective way to reduce the negative environmental impact in this context is to replace existing single and double glazing with high efficiency double glazing, thereby reducing energy consumption for space heating. Second, the use of timber frames causes less environmental impact than PVC frames with a steel core. Third, extending the service life of building components decreases the input of material resources, production processes and the waste processing of building components during the service life of a dwelling, which is beneficial to the environment. Maintenance activities should only be performed when needed, keeping the building components in good condition while minimising the transportation movements of maintenance workers. Finally, protecting timber components with an alternative paint that contains less solvent does not lower the assessed environmental impact, but low-solvent paint may be preferred because of health aspects both for maintenance workers and occupants of the dwelling.

*Keywords: life cycle assessment (LCA), maintenance, replacement, façade, door, window*

## 2.1 Introduction

The construction, use and demolition of buildings are sources of a significant part of human-induced environmental burden (Levine *et al.*, 2007). In the EU-25 countries, 70% of the existing housing stock was built before 1980 and 23% before 1945. In 2004, an average of approximately 1% of the existing housing stock was newly built, while up to 0.75% of the existing stock was demolished (Federcasa, 2006; Itard *et al.*, 2008). On average, about 100 times more houses are in use than are built annually, meaning that the existing housing stock is both slowly growing and ageing. Moreover, the energy efficiency of the existing housing stock is, on average, lower than that of new housing (Beerepoot, 2007; Itard *et al.,* 2008). Thus, in order to lessen the annual negative impact of housing on the environment, it would be more efficient to improve the environmental quality of the existing housing stock than to focus only on new houses. The IPCC report on climate change (Levine *et al.,* 2007) and Treloar *et al.* (2000), for example, stress that when analysing a building's energy use over its lifespan it is important to take the building's operational phase and its inhabitants' activities into account.

During the operational phase of dwellings, negative environmental impact results from activities such as maintenance, the replacement of building components and energy used for both climate control and household appliances. The magnitude of the impact depends on physical building characteristics such as applied building services and materials, as well as other factors such as the rate of deterioration and maintenance activities. Activities that take place frequently but have a low environmental impact in themselves may still contribute significantly to the total environmental impact in the use phase of dwellings due to their high rate of occurrence. High-impact activities that occur only once during the service life of a building may also contribute significantly.

The present study is part of a research programme which intends to assess the environmental aspects of the operational phase of dwellings, including the maintenance of façade components, building services, operational energy use and major interior replacements. Those four aspects of the use phase have been selected because they represent high volume use of energy and material resources and high frequency activities which may accumulate to significant environmental impact. The present study focuses specifically on the maintenance and replacement of doors, windows and the surrounding frames in the façade. These are the parts of the façade that require regular maintenance since they are traditionally made of timber, which deteriorates because of the outdoor climate, and they wear because of frequent opening and closing. There are many tools available to assess the environmental performance of buildings, most of which are aimed at new buildings. Some of these tools include maintenance in the use phase of dwellings, usually limited to replacing building components (Erlandsson and Borg, 2003; von Forsberg and Malmborg, 2004). Other studies analyse the environmental impact of the refurbishment of buildings but do not specifically include the regular maintenance of buildings (Itard and Klunder, 2007; Klunder, 2005). Maintenance has been taken into account in more detailed studies of building components such as floor coverings (Paulsen and Borg, 2003). However, an assessment focused on regular maintenance of façade components in the use phase of dwellings is lacking. The results of the assessment could be used to select building components and maintenance strategies that will cause the least environmental impact during the use phase.

The goals of the study are to:

- Assess the environmental impact of maintenance of façade components, including the use of different materials in building components and the related need for maintenance and replacements, using a life cycle assessment (LCA) methodology.
- Assess the environmental impact of different maintenance strategies for façade components.
- Identify which factors contribute most to the environmental impact categories during maintenance activities of façade components.

## 2.2 Methodology

In this research, LCA is used to quantify the contribution of the maintenance and replacement of doors and windows in the façade to predefined environmental problems. In doing so, the following processes are taken into account: material resources used in the building components; production of the components; maintenance activities, including the replacement and maintenance of components and the transportation of maintenance workers; and waste processing.

Subsection 2.2.1 briefly explains LCA methodology. Different scenarios for maintenance of façade components are compared by applying maintenance and replacement activities to a Dutch reference apartment building. The reference building is described in Subsection 2.2.2. The frequency of maintenance activities and the times at which replacements are made are described in various scenarios in Subsection 2.2.3. Subsequently, in Subsection 2.2.4 the calculation of the energy use for each concept is set out. Finally, the assumptions and limitations of the calculation method and the data used will be discussed in Subsection 2.2.5.

### 2.2.1 Life cycle assessment

LCA is a method that can be used to quantify the negative environmental impact that a product has on the environment during its production, use and disposal. An LCA consists of four steps, the requirements and guidelines for which are described in the norm ISO 14044 (2006). The first step is to define the goal and scope of the assessment. These then serve as a description of the type of study to be conducted, such as comparing product alternatives or improving a production process, and determine the questions the assessment is supposed to answer. The scope of the study determines which processes should be included in the next step, the inventory phase of the assessment, in which an inventory is made of the flow of all substances to and from the environment during the period of interest. In the third step, impact assessment, each substance's potential contribution to predefined environmental impact categories is calculated. This is done by comparing the impact of a particular substance flow with that of a reference substance for each environmental impact category. Once the environmental impact has been determined, the last step of the assessment is to interpret the results of the calculations in the interpretation phase, for example by comparing the calculated environmental impact to the results of similar research found in the literature or to all annual environmental impact in a region (normalisation), and by determining the sensitivity of the results to changes in the input variables.

LCA uses several methods to quantify the environmental performance of a product or process. The methods use single or multiple indicators of environmental performance, either at the midpoint or endpoint level. For example, the CML method uses multiple indicators at midpoint level (Guinée, 2002), while the Eco-indicator method includes multiple endpoint indicators that can be combined in a single endpoint indicator (Goedkoop and Spriensma, 2001). The more indicators used, the more detailed becomes the information available on the origin and range of environmental impact. Single indicators, however, are easier to use and understand. All indicators are problem-oriented: the higher the score, the worse the environmental performance. Endpoint indicators are damage-oriented: they represent the ultimate consequences of the environmental impact for humans and ecosystems. These indicators reveal the 'endpoint' of a possible chain of causes and effects. A drawback of these indicators is a higher level of uncertainty in the results, , because more environmental mechanisms are involved (Goedkoop *et al.,* 2009). Midpoint indicators, in contrast, show potential direct negative impact on the environment, which can be situated anywhere along the chain of causes and effects. This research used the CML 2000 LCA method to determine the environmental profiles of building components and related processes because this method uses multiple indicators at midpoint level (Guinée, 2002). The environmental impact categories assessed in the CML 2000 method are selected from the most commonly used indicators in LCA studies. The impact categories taken into account in this research are listed in Table 2.1. The complete set of environmental impact categories is known as the 'environmental profile'. The impact category Marine aquatic ecotoxicity, one of the compulsory impact categories in the CML method, is not taken into account because of significant problems associated with the calculation of the contribution to that impact category using the CML method (Sim *et al.,* 2007). These problems are related to the time a substance is present in the marine ecosystem and missing data with respect to normalisation. The characterisation models regarding the influence of metals on ecotoxicity contain flaws regarding the time they are present in ecosystems and in what form, which determines if they are harmful or beneficial; therefore the results of the ecotoxicity impact cat-

**Table 2.1 Environmental impact categories considered in the CML 2000 method**

| Environmental impact category | Unit of measurement |
|---|---|
| Abiotic depletion | [kg Sb eq.] |
| Global warming | [kg $CO_2$ eq.] |
| Ozone layer depletion | [kg CFC-11 eq.] |
| Photochemical oxidation | [kg $C_2H_4$ eq.] |
| Human toxicity | [kg 1,4-DB eq.] |
| Fresh water aquatic ecotoxicity | [kg 1,4-DB eq.] |
| Terrestrial ecotoxicity | [kg 1,4-DB eq.] |
| Acidification | [kg $SO_2$ eq.] |
| Eutrophication | [kg $PO_4^{3-}$ eq.] |

Source: Guinée, 2002

egories have a higher level of uncertainty. However, it is still possible to compare product alternatives (Apeldoorn, 2004; Heijungs *et al.,* 2004).

The input data for the calculations of the environmental impact comes from the commercially available ecoinvent 2.0 database (ecoinvent, 2007). The data in the database is gathered from different sources in literature and from manufacturers. More information about the data that are not confidential is available in extensive background reports by ecoinvent. All ecoinvent data entries have been reviewed by experts.

### 2.2.2 Reference building

This research made an assessment of the maintenance activities specific to a Dutch reference building. The Dutch reference buildings are a collection of typical Dutch dwellings of different construction types and sizes. They have been developed to assess measures to improve energy efficiency of existing dwellings, but are also frequently used for other environmental assessments (Novem, 2001; SenterNovem, 2007). The selected building for this research is the gallery flat constructed between 1966 and 1988 (Novem, 2001; SenterNovem, 2007). Figure 2.1 shows the building's floor plan and side elevation. Approximately 208,000 dwellings of this type exist in the Netherlands, 67% of which are owned by housing associations and are thus subject to regularly scheduled maintenance activities.

The reference building consists of 70 dwellings in total, distributed across seven floors of ten dwellings each accessed from an open gallery. Each apartment has a floor area of 78 $m^2$. Owing to the fact that maintenance activities are often performed simultaneously on multiple dwellings, all apartments in the building are assessed together.

### 2.2.3 Scenarios

In this research, the environmental impact of the maintenance of doors, windows and surrounding frames in the façade is analysed by comparing different maintenance scenarios. The functional unit of the LCA is the maintenance and replacement of façade components in the reference building described in Subsection 2.2.2 during a fixed period of dwelling operation (70

**Figure 2.1 Gallery flat reference building**

Source: Novem, 2001

years), including transportation of maintenance workers. The variables in the scenarios are the materials used; maintenance frequency; service life of building components and subcomponents; transportation distance of maintenance workers; and gas consumption for heating in the case of glazing replacement. The sensitivity of the results is assessed by changing the variables, which are the boundary conditions of the LCA.

A building's maintenance scenario describes the maintenance and replacement activities that take place during its operational phase. In this research, it is assumed that the maintenance scenario commences with the replacement of all façade components. The activities taken into account are grouped into two categories: major replacements and maintenance activities. The former category concerns replacement of doors, window frames and glazing, while the latter concerns painting and replacement of sealant, hinges and locks. Table 2.2 provides an overview of the scenarios that will be assessed and compared. For all scenario comparisons, Scenario 1 serves as the reference scenario. The service life of building components and maintenance frequency for Scenario 1-6 indicated in the table are reference values as found in Huffmeijer *et al.* (1998), confirmed as being a good estimate by maintenance companies. The alternative service life and maintenance frequency values in Scenario 7-10 are variations used for sensitivity analysis. Maintenance activities take place every X years, in which X is the frequency indicated in Table 2.2. The starting point of a sequence of activities depends on the service life of the building product. For example, a new sequence of replacing sealant

**Table 2.2 Maintenance scenarios for façade components applied to the reference apartment building**

| Scenario | Materials | | | Service life (year)[b] | | | | Maintenance frequency (year)[b] | | | | Transport distance[d] [km] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Doors & frames | Paint | Glazing | Frame | Door | Window | Glacing | Paint | Replace paint | Replace sealant | Replace hinges & locks | |
| 1 | Spruce, preserved | Solvents | Regular[a] | 40 | 25 | 40 | 25 | 6 | 35 | 15 | 20 | 50 |
| 2 | Spruce | Solvents | Regular[a] | 25 | 15 | 20 | 25 | 6 | 35 | 15 | 20 | 50 |
| 3 | Azobe | Solvents | Regular[a] | 50 | 40 | 50 | 25 | 6 | 35 | 15 | 20 | 50 |
| 4 | PVC | Solvents | Regular[a] | 40 | 25 | 40 | 25 | - | - | - | 20 | 50 |
| 5 | Spruce, preserved | $H_2O$ | Regular[a] | 40 | 25 | 40 | 25 | 5 | 30 | 15 | 20 | 50 |
| 6 | Spruce, preserved | Solvents | High efficiency | 40 | 25 | 40 | 25 | 6 | 35 | 15 | 20 | 50 |
| 7 | Spruce, preserved | Solvents | Regular[a] | 60 | 38 | 60 | 38 | 6 | 35 | 15 | 20 | 50 |
| 8 | Spruce, preserved | Solvents | Regular[a] | 50[c] | 25 | 50[c] | 25 | 6 | 35 | 15 | 20 | 50 |
| 9 | Spruce, preserved | Solvents | Regular[a] | 40 | 25 | 40 | 25 | 8 | 40 | 17 | 30 | 50 |
| 10 | Spruce, preserved | Solvents | Regular[a] | 40 | 25 | 40 | 25 | 8 | 40 | 17 | 30 | 12.5 |

a) Single glazing in doors, double glazing in windows.
b) Source: Huffmeijer *et al.*, 1998.
c) Partial replacement: service life of sills is 30 years.
d) Average one-way transportation distance of maintenance workers, confirmed by maintenance companies.

activities starts when glazing is replaced. The transport distance is the average one-way transportation distance of maintenance workers. Maintenance companies confirmed that a 50 km average is a good estimate.

Two types of timber are considered: spruce, representing softwood in Scenarios 1 and 2, and azobe as a representative of tropical hardwood in Scenario 3 (Althaus *et al.*, 2007). In practice, azobe is not very suitable for the production of frames because it splits easily (Editors. Houtblad, 2005). However, the properties that make a difference in the scenarios assessed, such as $CO_2$ content and transportation distances, are sufficient to allow azobe to represent other tropical hardwood that can be used for frames, concerning which no sufficient data are available in the ecoinvent database and could not be found elsewhere at the detailed level needed to compare with other materials in the ecoinvent database.

European spruce is imported from Scandinavia to the Netherlands and is transported as raw sawn timber over 1500 km by freighter. The density of spruce is 500 kg/m$^3$. Azobe is imported from Cameroon, Africa. The transport distance by freighter is 7000 km and the wood is transported as debarked logs (Althaus *et al.*, 2007). Therefore, the transported weight is greater than that of spruce because the wood has not been processed as much before shipping. Additionally, the density of azobe is twice that of spruce: 1000 kg/m$^3$. Another difference between the two types of wood is the amount of $CO_2$ that the trees absorb from the atmosphere during growth: azobe absorbs 1970 kg/

m$^3$, while spruce absorbs 897 kg/m$^3$ (Althaus *et al.,* 2007). However, the $CO_2$ is released into the atmosphere when the timber is incinerated after disposal. Biogenic $CO_2$ uptake and release is accounted for in ecoinvent 2.0 and CML 2000. It is assumed that the electricity consumption for raw cutting and profiling both types of wood is equivalent, and that production waste is 25% in both cases (Kellenberger *et al.,* 2007). The waste percentage is similar to the complete wooden window frame in ecoinvent background documentation, in which data are used from German and Swiss window manufacturers. Production waste timber is burned in a furnace at the factory and the heat is used in the production process.

The service life of building components depends on the material from which they are made. Azobe is more durable than spruce and preserved spruce is more durable than unpreserved spruce. The difference between preserved spruce (Scenario 1) and unpreserved spruce (Scenario 2) lies in the preservative treatment process and the preservative used, both of which lead to a longer service life for preserved spruce. The preservative used in the assessment is chromium-free organic salt. Currently, most timber products can also be preserved by a heat-treatment process, of which no inventory data are available in the ecoinvent database or in literature. The advantage of new preservation technology is that harmful chemical substances are no longer used and that the treatment modifies the timber completely rather than locally or only at the surface. However, more energy is used during the heat-treatment process, which affects the environment in a different way.

In Scenario 4, the building components are made of PVC with a steel core. Resources for the production of PVC components are assumed to be primary (see also Subsection 2.2.5). The service life of PVC components is assumed to be the same as components made of preserved spruce (see also Section 2.4). Finally, the maintenance activity ‘painting’ is absent in Scenario 4, since PVC components do not need to be painted.

In Scenarios 1-4, the paint used is alkyd in solvent (white spirit). In Scenario 5, the paint is alkyd in $H_2O$. All paint in the ecoinvent database is white, the pigment of which is usually $TiO_2$, likely to be one of the more environmentally friendly pigments. In paints of different colours, metal pigments are mostly used (Kellenberger *et al.,* 2007). The properties of the two types of paint are thus:

▪ Alkyd in solvent (Sikkens, 2008a):
- Density 1.14 kg/dm$^3$ (wet)
- Layer thickness 60µm (wet), 40µm (dry)
- Area: 15 m$^2$/l

▪ Alkyd in $H_2O$ (Sikkens, 2008b):
- Density 1.25 kg/dm$^3$ (wet)
- Layer thickness 100µm (wet), 40µm (dry)
- Area: 10 m$^2$/l

**Table 2.3 Materials used per dwelling during 70 years of dwelling use for each scenario**

| Materials (kg) | Scenario | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 & 10 |
| Spruce | 826 | 1272 | - | - | 826 | 826 | 758 | 793 | 826 |
| - preservative | 5 | - | - | - | 5 | 5 | 5 | 4 | 5 |
| Azobe | - | - | 1520 | - | - | - | - | 212 | - |
| PVC | - | - | - | 615 | - | - | - | - | - |
| - steel in PVC | - | - | - | 471 | - | - | - | - | - |
| Glass | 1399 | 1144 | 1083 | 1442 | 1399 | 1471 | 1064 | 1064 | 1399 |
| Paint | | | | | | | | | |
| - alkyd in solvent | 27 | 30 | 27 | - | - | 27 | 26 | 26 | 23 |
| - alkyd in $H_2O$ | - | - | - | - | 50 | - | - | - | - |
| Sealant | | | | | | | | | |
| - polysulfide | 54 | 63 | 55 | - | 54 | 54 | 52 | 46 | 54 |
| - rubber | - | - | - | 26 | - | - | - | - | - |
| Hinges and locks | | | | | | | | | |
| - aluminium | 31 | 28 | 22 | 31 | 31 | 31 | 24 | 31 | 20 |
| - steel | 68 | 65 | 49 | 68 | 68 | 68 | 61 | 68 | 58 |

Both products comply with the 2010 Dutch guidelines on the maximum amount of volatile organic compounds (VOC) permissible in paint. The alkyd in solvent paint is a high solid: the share of solvents is relatively low. Alkyd in solvent is more durable than alkyd in $H_2O$. The documentation by the paint manufacturer Sikkens states that a new layer needs to be applied after 5 and 4 years respectively, but in this research it is assumed that a new layer is applied one year later, in accordance with Huffmeijer *et al.* (1998).

In Scenario 6, the thermal quality of the façade is improved by replacing all glazing with high efficiency double glazing. As a result, gas consumption for space heating will decrease. Therefore, gas consumption for space heating is taken into account when Scenario 6 is compared to Scenario 1. The calculation of gas consumption is found in Subsection 2.2.4.

In the remaining four scenarios, the influence of the timing of the maintenance and replacement activities on the environmental impact is assessed. In Scenario 7, the service life of the preserved spruce building components is extended by 50%. In Scenario 8, it is assumed that the service life of preserved spruce frames can equal the service life of azobe frames if the sills of the frames are replaced after 30 years. The sills, which are the horizontal bottom elements of the frames, and which are connected to the jambs, degrade faster because of their relatively prolonged contact with rain. In Scenario 9, maintenance frequency is reduced and in Scenario 10 a lower maintenance frequency is combined with a reduction in the distance travelled by maintenance workers to assess the combined influence of these factors on the environmental impact.

Table 2.3 lists the total amount of materials used in the scenarios during 70 years of dwelling use. Additionally, Table 2.4 shows the transportation distance of maintenance workers per replacement and maintenance activity for all 70 apartments in the gallery flat combined. For example, in order to apply one coat of paint to all timber components of the building, 10 people

**Table 2.4 Transportation distance of maintenance workers per activity for all 70 apartments**

| Activity | Transportation [km] |
|---|---|
| *Replacements* | |
| - frames | 4,200 |
| - frame sills | 2,100 |
| - windows | 4,200 |
| - window sills | 2,100 |
| - doors | 4,200 |
| - glazing | 4,200 |
| *Maintenance* | |
| - painting (apply 1 layer) | 10,000 |
| - painting (remove all paint, apply 3 layers) | 12,000 |
| - replacing sealant | 1,000 |
| - replacing hinges and locks | 7,000 |

must work for 20 days. It is assumed that on average two maintenance workers share a car and the return distance travelled is 100 km. The difference in transportation between the activities 'painting 1 coat' and 'removing all paint and applying 3 new coats of paint' is small. The numbers are derived from an estimate by maintenance companies of how long it would take to do the job for the entire building. In general, preparation for painting takes the most time, whether it is removing old paint or sanding. The application of paint takes relatively little time.

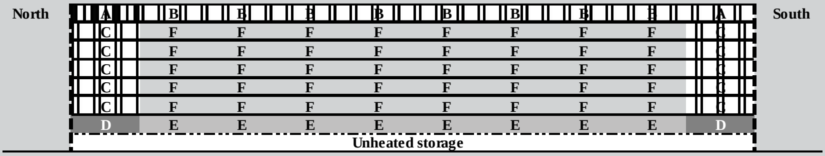
### 2.2.4 Energy

The comparison of Scenario 1 with Scenario 6 requires energy consumption for heating to be taken into account, since high efficiency glazing has higher thermal resistance than regular double glazing or single glazing. Most dwellings in the Netherlands are heated by gas. Gas consumption in both scenarios is calculated using Vabi EPA-W software, which has been developed to assess the energy efficiency of dwellings (Vabi Software, 2009).

The gas consumption of the apartments in the reference building depends on their location within it. Apartments which are located under the roof and have three façade walls (Type A) have a higher heating demand than apartments which are surrounded by other apartments (Type F). Figure 2.2 shows a simplified scheme of the reference building, in which the apartments are subdivided according to heating demand. The unheated elevator and stairwell shaft which is located in the middle of the building is not taken into account.

The dwellings in the reference building are heated by individual HR100 boilers and ventilated by collective mechanical exhaust ventilation. The heat resistance of the façades and the roof is assumed to be 2.5 $m^2K/W$, which is the required value for new buildings (de Jong and Pothuis, 2009). The percentage of glazing in the façades is 48.5%, or 21.2 $m^2$. Single glazing, regular double glazing and high efficiency double glazing have a U-value of 5.10, 2.90 and 0.64 $W/m^2K$ respectively. Single glazing is used in doors only and amounts to 1.8 $m^2$ of glazing. The average gas consumption for space heating is 709 $m^3$ per year for Scenario 1 with single and regular double glazing and 457 $m^3$ per

Figure 2.2 Different apartment types in the gallery flat reference building according to energy demand



year for Scenario 6 with high efficiency double glazing.

The results of the calculations relating to energy consumption for space heating strongly depend on the type of dwelling assessed. Apartments require less energy per square metre for space heating than detached houses, for example, because they are surrounded by other heated dwellings. Therefore, the calculated energy use and related environmental impact is representative for apartments only.

## 2.2.5 Assumptions and limitations

For the calculation of the environmental profiles of building components and maintenance activities the following processes are taken into account. Details can be found in the commercially available ecoinvent 2.0 database (ecoinvent, 2007).

- Production processes: input of substances from the environment, substance emissions into the environment during production and/or application, transportation and energy used from extraction of resources to available end product in wholesale business, production and assembly waste. Transportation of materials and products from foreign countries to the harbour of Rotterdam is taken into account.
- The frequency of maintenance is assumed to have no influence on gas consumption for space heating. Only when building components are replaced by components with higher thermal insulation is the change in gas consumption for space heating taken into account. Energy consumption for transportation of maintenance workers is influenced by maintenance frequency and is also taken into account.
- Waste fractions being land filled, incinerated and recycled are obtained from EcoQuantum (W/E adviseurs *et al.*, 2002) because they represent the way Dutch building waste is handled. The waste scenarios are listed in Table 2.5. Only the environmental impact of emissions related to landfill and incineration, which are given in the ecoinvent database (ecoinvent, 2007), are assigned to the reference building. Environmental impact related to recycling is assigned to the products that use recycled material as an input.
- The building products contain some recycled materials:
  - Aluminium consists of 10% old scrap (recycled aluminium), 22% new scrap (production waste) and 68% primary aluminium.
  - Steel consists of 37% scrap and 63% primary steel.
  - PVC is all primary material in this research. The technology to use recycled PVC in building products is available, but it is much more expensive

**Table 2.5 Waste scenarios for construction waste**[a]

| Materials | Waste type | Waste scenario | | |
|---|---|---|---|---|
| | | Landfill (%) | Incineration (%) | Recycling (%) |
| Aluminium | Aluminium | 3 | 3 | 94 |
| Glazing | Glass | 30 | 0 | 70 |
| Paint | Paint | 0 | 100 | 0 |
| PVC | PVC | 10 | 10 | 80 |
| Rubber | Plastics | 20 | 80 | 0 |
| Sealant | Not defined | 50 | 50 | 0 |
| Steel[b] | Steel, stainless steel | 5 | 0 | 95 |
| Timber | Wood | 5 | 95 | 0 |

a) The waste scenarios are equal to those included in NEN 8006, 2004: 'Environmental data of building materials, building products and building elements for application in environmental product declarations. Assessment according to the Life Cycle Assessment (LCA) methodology', except for the undefined waste types and those indicated

b) NEN 8006, 2004: steel is completely recycled or reused. 1% of light steel elements go to landfill.

Source: based on W/E adviseurs *et al.* (2002)

than using primary material. All manufacturers of PVC frames in the Netherlands are obliged to pay a fee per frame produced to support the recycling of used PVC frames (Ubbels, 2001). However, it is not clear if and how much PVC is used to produce new PVC building products.

- All glazing is made from primary resources.

The main limitations are as follows:

- The CML 2000 method does not currently cover the depletion of biotic resources such as wood (Guinée, 2002; Guinée and Heijungs, 1995; Stewart and Pedersen Weidema, 2005).
- The Human toxicity impact category reflects negative effects to the population in general rather than toxic effects to specific people. Emissions of substances during the use of building components and maintenance materials are not taken into account. Consequently, maintenance worker health is not part of the environmental assessment in this research. Furthermore, there are no characterisation factors available for the paint solvents used in the research which prohibits calculating the health effects of paint application.
- There are various options for waste treatment, including recycling, burning or dumping as landfill. As described above, only the latter two are taken into account. Dumping negatively affects the environment, as substances are emitted into the soil and into groundwater. During incineration, heat or other forms of energy can be produced, which in turn can be used in other processes. This is taken into account by subtracting the prevented environmental impact of producing an equal amount of energy from the total environmental impact.
- There are no specific data relating to the transportation of maintenance workers in vans. Data for passenger car transport using diesel fuel are adjusted for the use of fuel per kilometre for a Mercedes Vito van, which

in an urban environment is about 9 litres per 100 km (Daimler Chrysler AG, 2007). Only emissions into the air and the production of the fuel are taken into account; the environmental impact of road use, repairs to the car and wear to the tyres are not included.

- The transportation of building components from wholesale business to the building location is not taken into account.

## 2.3 Results and analysis

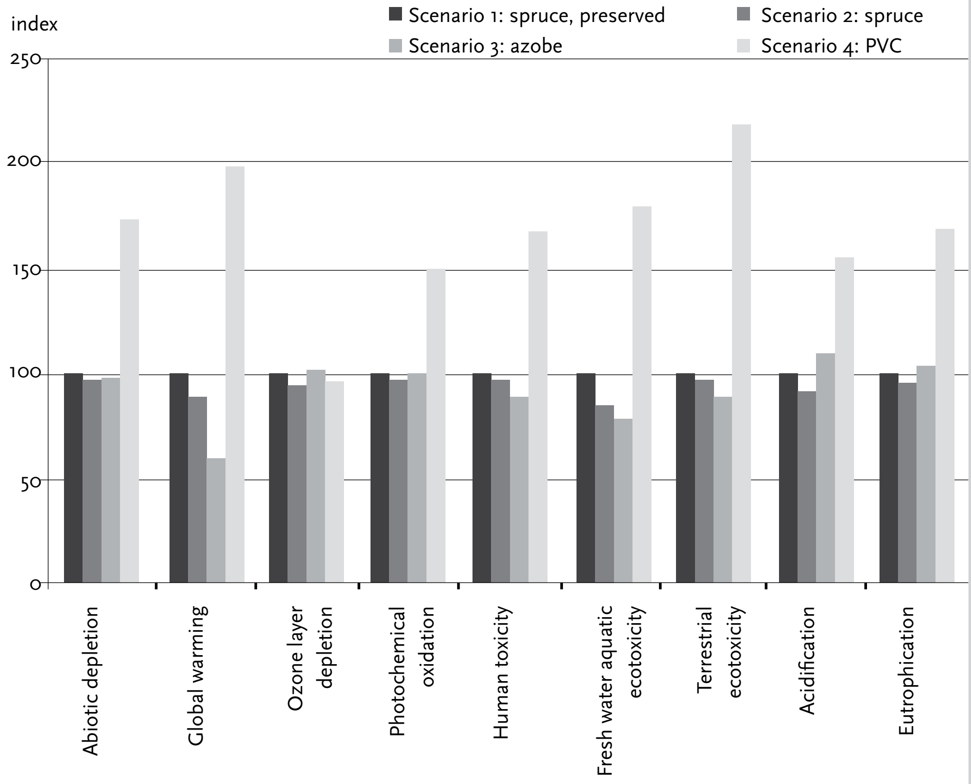
In this section, the results of the environmental assessment of the doors and windows in the façade and related scenarios for maintenance and replacement are discussed. The results of the assessment are shown as the accumulated contributions of all 70 apartments in the reference building to various environmental impact categories over 70 years of maintenance of façade components. The scenario starts with the replacement of all door and window components considered in the research, after which all environmental impacts are added as they occur in time. It is assumed that the building will continue to be used after this point in time; therefore the end of the scenario is a cut-off point. A 70 year time span is chosen because it is long enough to show the long-term consequences of material choices and the planning of maintenance and replacement activities, while also being a realistic operation period for dwellings. However, the differences between the environmental impact categories of the scenarios are of the same order of magnitude when the scenario calculations are extended to 100 or 150 years.

### 2.3.1 Comparison of different materials for building components

The first goal of this research is to assess whether it makes a difference to the total environmental impact of maintenance of façade components if different types of frame and door material, paint and glazing are used. Figure 2.3 shows the accumulated environmental impact of Scenarios 1-4, in which different types of timber and PVC are used in the frames and doors. The environmental impact score of Scenario 1 has been set to the index 100 in each impact category. The scores of the other scenarios are relative to Scenario 1.The maintenance and replacement scenarios are related to the material used. For example, PVC does not need to be painted and the service lives of the building components differ, as shown in Table 2.2.

The results show that the use of PVC frames and doors with a steel core contribute most to all of the environmental impact categories except Ozone layer depletion. For Abiotic depletion, the PVC content in the components is responsible for more than half of the contribution. For all other impact cat-

**Figure 2.3 Comparison of the indexed accumulated environmental impact after 70 years of façade components maintenance of four types of material for frames and doors**

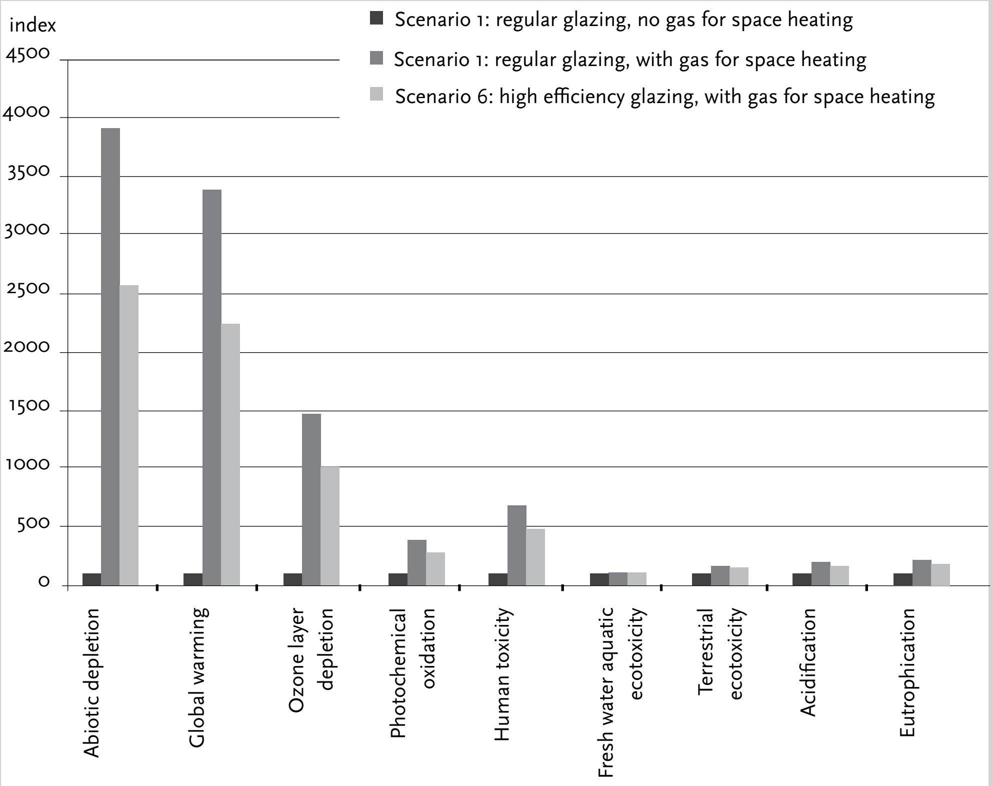


egories, the high contribution of PVC components is primarily caused by the steel core.

The differences between preserved and unpreserved spruce are small because the environmental benefits of extending the service life of the building components are equivalent to the additional environmental impact caused by the preservatives and the preservative treatment process. The differences between azobe and spruce can be explained by the difference in service life of the components, where azobe performs better, and the difference in oceanic transport distances, where spruce performs better. For Global warming, Figure 2.3 shows that azobe performs much better. This is because azobe trees absorb more $CO_2$ per $m^3$ while growing and the components that are still in the building at the end of the scenario are not disposed of, so the $CO_2$ is not released into the atmosphere through incineration.

Two types of paint are compared in Scenarios 1 and 5: high solid alkyd paint in solvent and alkyd paint in $H_2O$ respectively. At the scale of a maintenance and replacement scenario, the type of paint used only reveals up to 6% difference in the environmental impact categories in favour of alkyd in solvent paint. However, the difference between the scenarios is not significant, due to the low quality of the environmental data on the paint. Furthermore, direct health impacts of emissions from the paint drying on the painter or

**Figure 2.4 Comparison of the indexed accumulated environmental impact after 70 years of dwelling use and façade components maintenance for scenarios in which different types of glazing are used**



occupant of the dwelling are not taken into account in the methodology used. Therefore, for reasons of health, one type of paint may be preferred.

Finally, the influence of using different types of glazing in the façade is assessed by comparing Scenarios 1 and 6. Since the type of glazing used influences gas consumption for space heating, the latter is taken into account as well. Figure 2.4 shows the environmental impact of Scenario 1 without gas consumption, Scenario 1 with gas consumption and Scenario 6 with gas consumption, in which all single glazing (in doors) and regular double glazing is replaced by high efficiency double glazing. The environmental impact score of Scenario 1 without gas consumption has been set to the index 100 in each impact category. The scores of the other scenarios are relative to that scenario.

The results show that the environmental impact related to gas consumption is up to a factor of 40 higher than that related to material use and maintenance, especially for the environmental impact categories Abiotic depletion, Global warming, Ozone layer depletion and Human toxicity. Therefore, the replacement of façade components which leads to a reduction in gas consumption is a much more effective measure to reduce these four environmental impact categories than any other measure assessed in this research. The consumption of gas for space heating is reduced by 35%, which leads to a direct reduction in the contribution to the four environmental impact categories mentioned by 30-35%.

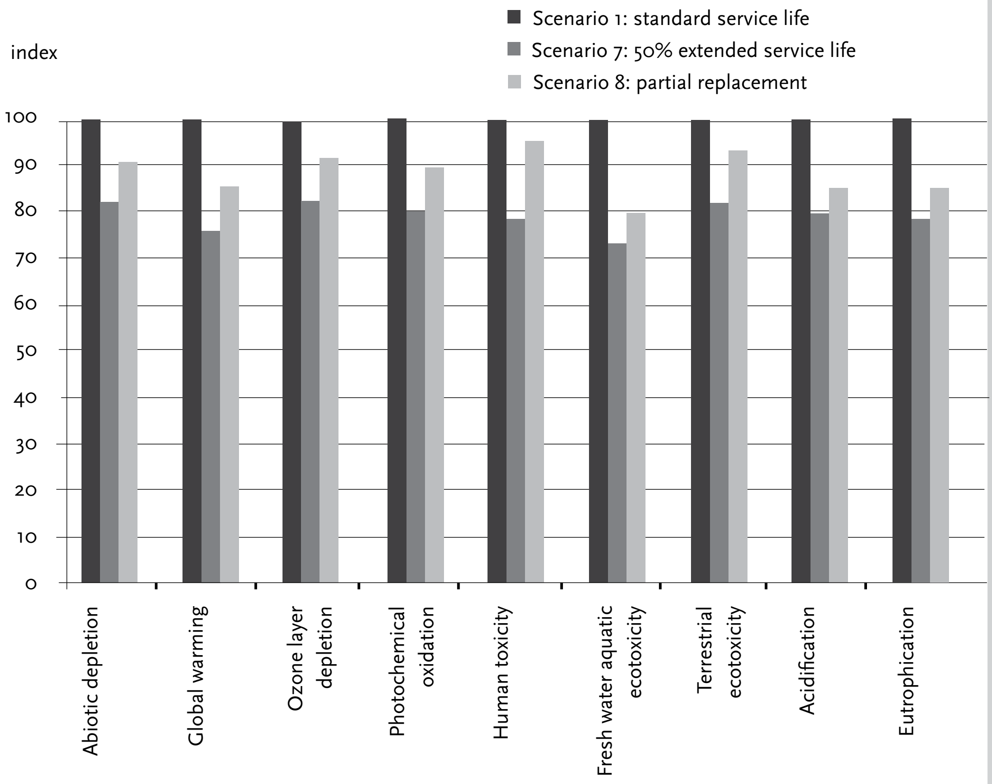
### 2.3.2 Comparison of different maintenance strategies for façade components

The second goal of the research is to assess the influence of maintenance strategies on the environmental impact of maintenance of façade components. In Figure 2.5, the environmental impact of Scenarios 1, 7 and 8, in which the building components have different service lives, are shown. The environmental impact score of Scenario 1 has been set to the index 100 in each impact category. The scores of the other scenarios are relative to Scenario 1. Extending the average service life of building components might be possible by performing maintenance activities when needed rather than when planned, or by replacing only those components that need to be replaced rather than replacing all of the components at once.

The results show that when the service life of the building components is extended by 50%, all of the environmental impact categories are reduced by 17–27%. This is because in this scenario fewer building components need to be produced and processed as waste and less transportation of workers is required. This measure leads to slightly increased benefits over time, since increasingly fewer products are needed as time progresses. However, it is quite likely that the service life of building products cannot be lengthened without changing the frequency or the quality of regular maintenance. The results show that early sill replacement to lengthen the service life of the entire spruce frame in Scenario 8 also leads to a reduction of environmental impact by 5-20%. The same result can be reached by producing spruce frames joined to hardwood sills which do not need to be replaced early, provided that both types of timber in the frame interact well (otherwise, using two types of timber in one frame would lead to faster degradation).

Figure 2.6 shows the environmental impact of maintenance Scenarios 1, 9 and 10, in which maintenance frequency and the strongly related factor of transportation distance of maintenance workers are varied. The environmental impact score of Scenario 1 has been set to the index 100 in each impact category. The scores of the other scenarios are relative to Scenario 1. The maintenance activities consist of painting, replacing seals and replacing hinges and locks. The results show that reducing maintenance frequency leads to an overall reduction of the environmental impact categories by 5-11%. For the toxicity impact categories, the reduction can be attributed to the hinges and locks, which are required to be replaced one time less during the length of the scenario. Since 75% of all transportation movements are related to maintenance activities, part of the reduction of the environmental impact is caused by the fact that less transportation takes place. When the transportation distance is reduced from 50 km one-way to 12.5 km one-way, even more reduc-

Figure 2.5 Comparison of the indexed accumulated environmental impact after 70 years of façade components maintenance for scenarios in which the service life of components is varied

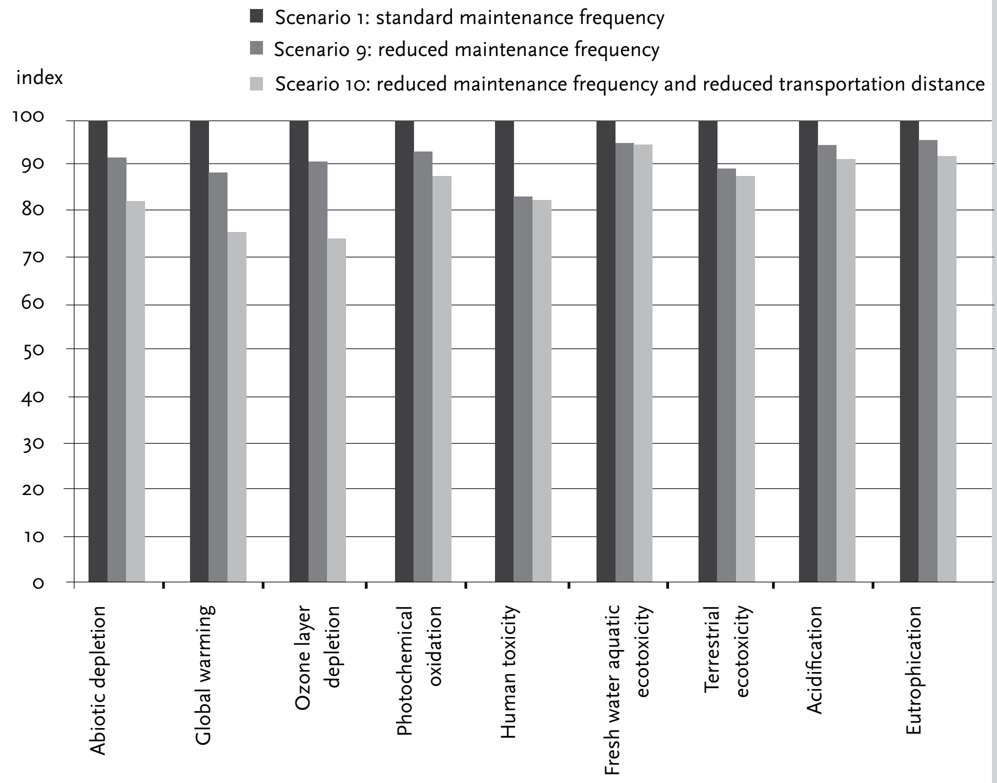


tion in environmental impact can be accomplished, especially for the Abiotic depletion, Global warming and Ozone layer depletion impact categories.

### 2.3.3 Normalised environmental impact

In LCA, normalisation of the impact score means that the environmental impact of a product or process is compared with the total annual environmental impact in a region. In this research, results are normalised to the Netherlands with reference year 1997. The total environmental impact in that year is given by CML in the spreadsheet belonging to the Handbook on LCA (Guinée, 2002). The main goals of normalisation are to provide a comparable scale between impact categories by referring to a rough error check of the order of magnitude of the results and a reference that is constant in time, which is why the reference values of 1997 are still used (van Oers and Huppes, 2001). Figure 2.7 shows the share of the total annual negative environmental impact in the Netherlands that is caused by maintaining and replacing façade components in the reference building with 70 apartments according to Scenarios 1-4. Fresh water aquatic ecotoxicity is the impact category most affected by façade components maintenance, mainly due to the steel components of the materials used (including hinges and locks, and steel sections clad in PVC). Other im-

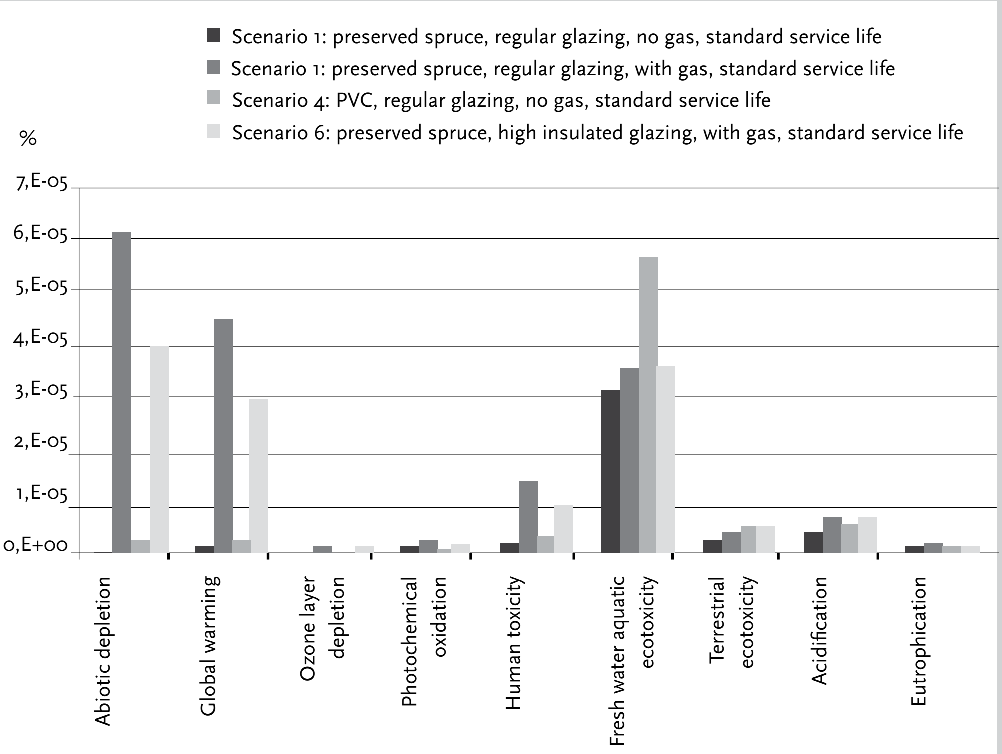
**Figure 2.6 Comparison of the indexed accumulated environmental impact after 70 years of façade components maintenance for scenarios in which frequency of maintenance activities and transportation distance are varied**



portant impact categories are Acidification, Terrestrial ecotoxicity and Human toxicity. When gas consumption for space heating is taken into account, Abiotic depletion and Global warming are the most important factors, followed by Terrestrial ecotoxicity and Human toxicity. This once again emphasises the effectiveness of reducing gas consumption.

The values shown in Figure 2.7 represent 70 apartments, while there are approximately 7 million dwellings in total in the Netherlands. If all 7 million dwellings in the Netherlands would be apartments, the share of the annual national contribution to Fresh water aquatic ecotoxicity caused by façade component maintenance would be 3%, which is only an indication of the order of magnitude of the environmental impact of the total dwelling stock. In reality, other dwelling types are larger and have more façade components to maintain and replace. User-owned dwellings will have different types of maintenance and replacement scenarios than apartment buildings, which are mostly maintained by the building owner or an organisation of apartment owners in the building. Similarly, gas for space heating only contributes about 6% of the total annual Abiotic depletion impact. Again it should be noted that apartments have the lowest gas consumption of all dwelling types.

Figure 2.7 Average annual environmental impact of 4 scenarios, normalised with respect to the total environmental impact in the Netherlands in 1997

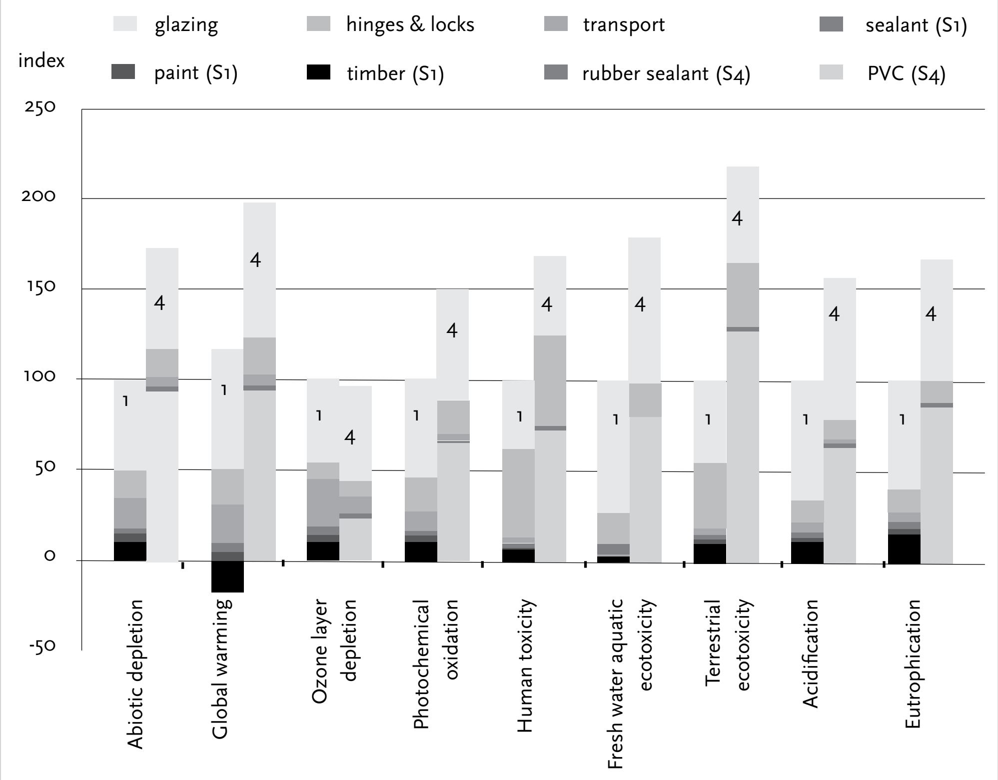


## 2.3.4 Contributing factors

The third goal of this research is to identify which factors in the maintenance and replacement of doors and windows in the façade contribute most to the environmental impact, keeping in mind the impact categories that are contributed to most on an annual basis in this case, compared to the Netherlands as a whole. For the scenarios in which gas consumption is taken into account, gas consumption is by far the most important contributing factor to Abiotic depletion (97%), Global warming (97%), Ozone layer depletion (93%), Photochemical oxidation (74%) and Human toxicity (85%). For Terrestrial ecotoxicity, Acidification and Eutrophication, gas consumption accounts for 40-55% of the contribution to the impact categories. The category that is most important on an annual basis, which is Fresh water aquatic ecotoxicity as shown in Figure 2.7, is contributed to most by glazing (65%), which is primarily the result of using zeolite in the space between the two glass planes to absorb moisture.

In Scenario 1 without gas consumption, glazing is the factor that contributes most to all environmental impact categories except Human toxicity, as is shown in Figure 2.8. In the figure, the total environmental impact score of all factors in Scenario 1 has been set to the index 100 in each impact category. The scores of the other scenarios are relative to Scenario 1. In relation

**Figure 2.8 Contribution to the environmental impact categories by different factors in Reference scenario 1 with timber components and Scenario 4 with PVC components**



to Abiotic depletion, Global warming and Ozone layer depletion, the large amount of fuel and electricity needed for the production of glazing is the reason for this high contribution. In relation to Human toxicity, the contribution is mainly due to the aluminium separator between the glass planes, while the contribution to Fresh water aquatic ecotoxicity is mainly due to the use of zeolite. The contribution to the other environmental impact categories is high because the material mass of glass is relatively high in comparison to the other materials used in doors and windows. Another important contributing factor to the toxicity categories is the hinges and locks in doors and windows, in particular the aluminium content of those components. The third important factor is transportation of maintenance workers, which contributes significantly to Abiotic depletion (17%), Global warming (22%) and Ozone layer depletion (28%). About 75% of the transportation is related to minor maintenance activities, while 25% is related to the replacement of major building components. Finally, Figure 2.8 shows that timber has a negative contribution to Global warming. This is because the last applied timber frames are not disposed of during the scenario and the $CO_2$ contained in the timber is deducted from the contribution to Global warming.

Figure 2.8 also shows the contributing factors in Scenario 4 with PVC doors and frames. The results show that glazing is still an important factor, but the PVC components are more important. For Abiotic depletion and Global warming, the PVC content of the frames and doors is responsible for most of the high contribution. For all of the other impact categories, 65-80% of the contribution of the PVC frames and doors is actually due to the steel content of the components. The third important factor for the toxicity categories is the hinges and locks, mainly because of the aluminium content. Finally, the transportation factor now only contributes a maximum of 10% to the environmental impact categories, due to the fact that PVC does not need to be painted and therefore requires less transportation of maintenance workers.

### 2.3.5 Reducing the environmental impact of maintenance of façade components

In this section, possible ways to reduce the environmental impact related to maintenance and replacement of doors and windows in the façade is assessed. First, the most effective way to reduce the environmental impact is to reduce gas consumption for space heating by replacing the glazing with high efficiency double glazing. This measure should be combined with the insulation of other parts of the façade if they have not yet been insulated; otherwise problems may arise regarding condensation on the inside of the façade. Second, it is best to lengthen the service life of building components, for example by closely monitoring the level of degradation and performing maintenance and replacement as needed, and definitely not undertaking more maintenance than needed, in order to keep the environmental impact of maintenance activities low. However, if increased maintenance is necessary to lengthen the service life of building components, the benefits of a longer service life might be greater than the negative environmental impact of maintenance. Partial replacements have a lower environmental impact than complete replacements. It might be possible to apply better protection and higher quality maintenance to fast degrading areas of the façade. Alternatively, the environmental impact related to the building components can be reduced by improving the production process or finding alternatives to the materials that contribute most to the environmental impact, such as replacing zeolite in double glazing by another material. Third, maintenance companies can reduce environmental impact related to the transportation of maintenance workers by reducing the distance travelled, which also reduces costs. Maintenance workers could share cars or could work on projects closer to home. Another way to reduce the transportation impact is to switch to more efficient cars or cars that use a different type of fuel.

## 2.4 Discussion

There are several uncertainties in the data used for the calculations which may influence the results, specifically in the values used for service life of building components, maintenance frequency and transportation distance of maintenance workers.

### 2.4.1 Service life

When the service life of building components is lengthened, the environmental impact related to the production process of the component, material resources and waste processing are reduced. Therefore, extending the service life of components such as hinges and locks and glazing that contribute greatly to environmental impact is most effective. Alternatively, the value of the service life of the high-impact components influences the results of the assessment. For example, the standard service life of hinges and locks is 20 years, which is shorter than the service life of doors and windows, and therefore the hinges and locks are always replaced at some time during the service life of the doors and windows. However, a better practice might be to replace hinges and locks only in the case of malfunction.

The service life of spruce can be extended by preservation treatment, of which there are several options. New preservation technology does not use chemicals to preserve the timber but instead uses heat treatment to change the chemical composition of the timber. These new preservation processes require more energy, which might result in a poorer environmental performance by preserved spruce.

In international literature as well as in practice, there is no consensus about the service life of PVC building components. The average service life of PVC building components is 50 years for doors and windows and 80 years for frames (Huffmeijer *et al.,* 1998). Research suggests that 50 years is a reasonable estimate for the 30-year-old components that were analysed (Hendriks, 1998, 2005). However, in practice several examples indicated that the service life is usually less than 50 years, especially for the first generations of PVC building components. Furthermore, Asif *et al.* (2005) found an average of 25-30 years, based on a survey of 25 local housing authorities, surveyors and architects in the United Kingdom. Therefore, the service life of PVC doors and windows is set at 25 years and their frames at 40 years, which is similar to preserved spruce building components. Additional calculations, the results of which are not shown in this paper, indicate that the conclusions of the research do not change when the service life is lengthened by 50%, although the differences between PVC and timber become smaller. These results comply with the results of Asif *et al.* (2005) and Werner and Richter (2007).

### 2.4.2 Transportation

For all scenarios, the impact of having workers travel 50 km (one-way) to maintenance locations is taken into account. According to maintenance companies, this is a realistic estimate for the Netherlands. If the transport distance were to be altered, the conclusions of the research would remain the same. However, the differences between the various scenarios might be less significant if the transport distance were shorter.

This research does not currently take the transportation of building components to building sites into account. If this had been taken into account, the environmental impact of replacing components would increase for all scenarios. The positive impact on the environment due to increasing the service life of building components would thus also be increased. However, the overall conclusions of the research would not change radically as a result. The energy used to power machines used for maintenance activities, such as sanding machines or gas burners for removing paint, was also not taken into account. This might also affect the results.

### 2.4.3 Further research

The type of assessment performed in this research could be applied to other dwelling, building and construction types to determine whether the same factors make a significant contribution to the environmental impact in those cases. Furthermore, more activities could be added to maintenance scenarios, such as repair activities, which might further extend the service life of building components. Finally, when comparing maintenance scenarios for a particular building, a more detailed analysis which takes into account the performance level of the building components, the rate of degradation caused by the local climate and the specific wishes of the owner should be performed.

## 2.5 Conclusions

The most effective way to reduce the environmental impact related to the maintenance of façade components is to replace existing single and regular double glazing with high efficiency double glazing because the annual environmental impact of gas consumption is bigger than the environmental impact of maintenance and replacement activities by a factor of up to 40. In the reference apartment building used in this research, replacing all glazing by low-emissivity double glazing would lead to 35% less gas consumption for space heating. This would lead to a 35% reduction in the contribution to Abiotic depletion and Global warming, as well as a 30% lower contribution to Ozone layer depletion and Human toxicity. There is no increase in any environmental impact category as a result of switching to high efficiency double glazing.[1]

When compared with timber façade components, the environmental impact of using PVC façade components is 1.5 to 2 times bigger, except for Ozone layer depletion, the contribution to which is equal for both materials. The main reason for the relatively high contribution of PVC components is that they contain a steel core frame which is responsible for most of the material's contribution to all of the environmental impact categories except Abiotic depletion. The oil-based PVC part of the components contributes most to the latter category. The difference between African tropical hardwood and Scandinavian softwood door and window frames was small, keeping in mind that limited differences in wood processing were taken into account due to lack of data. The final choice between different types of timber should therefore be made on the basis of a more detailed assessment.

Extending the service life of façade components by 50% leads to a reduction in all environmental impact categories by 17-27% after 70 years of façade components maintenance and replacements. The reduced environmental impact is due to the fact that less façade components need to be produced and processed as waste during the use phase of the dwelling. Additionally, transportation of maintenance workers for replacement activities is reduced. The effect of extending the service life of façade components slowly increases over time: after 150 years of dwelling use, the environmental impact of façade components maintenance decreases by 24-35%.

The effect of decreasing maintenance frequency in itself is marginal: a reduction in environmental impact is mainly caused by reduced transportation movements of maintenance workers as a result of a lower activity frequency. The environmental impact can further be reduced by shortening the distance travelled by maintenance workers, carpooling or switching to more sustainable modes of transport. Finally, maintenance activities should be performed when needed rather than according to set schedules in order to save on needless transportation and minor replacements.

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[1] Due to the production of the glazing. The differences between the production of regular double glazing and high efficiency double glazing are so small that they disappear by rounding off to three significant digits.

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# 3 LCA-based environmental assessment of the use and maintenance of heating and ventilation systems in Dutch dwellings

*Research completed: 2009*
*Blom, I.S., L.C.M. Itard and A. Meijer, 2010, Building and Environment, 45 (11), pp. 2362-2372, doi:10.1016/j.buildenv.2010.04.012*
*An overview of all results can be found in Appendix 3.*

**Abstract**

Buildings contribute significantly to the human-induced environmental burden. This comes not only from construction and demolition but also from activities throughout the operational phase – building maintenance and energy use for climate control. This paper describes how life cycle assessment (LCA) methodology can be applied to quantitatively assess the environmental performance of the use and maintenance of heating and ventilation systems. The studied climate systems include individual non-condensing boilers, condensing boilers and heat pumps on exhaust air for heating and hot tap water combined with either collective mechanical exhaust ventilation or individual balanced ventilation with heat recovery. This study shows that a heat pump causes the highest environmental burden of all the assessed climate systems due to the electricity needed for operation, high material content of the system and the refrigerant used. If the electricity used by the heat pump is generated fully by local photovoltaic cells, environmental performance will improve, but not for all environmental impact categories. Climate systems that reduce energy demand for heating, such as ventilation with heat recovery, will reduce the environmental impact related to energy use for space heating. However, if the electricity used to operate the system increases, along with the material content of the systems and distribution networks, other environmental impact categories than those related to space heating will also increase. Finally, maintenance frequency and related transportation of maintenance workers have a marginal effect on total environmental impact.

*Keywords: life cycle assessment (LCA); heating; ventilation; dwelling; energy*

## 3.1 Introduction

Buildings make a significant contribution to the human-induced environmental burden. This is due not only to material used in construction and waste processing after demolition; activities undertaken during the operational phase, such as the use and maintenance of building services, also cause negative environmental impact. During the operational phase, for example, household energy use constitutes approximately 25% of total annual energy use in the EU-25 countries (Eurostat, 2007). In the EU-15 countries, space heating accounts for 68% of the final energy use, while hot tap water accounts for 14% (ADEME and IEEA, 2007; Balaras *et al.,* 2007). Meanwhile, during building construction and demolition, the building sector makes a significant contribution to total waste production. In the EU-15 and EFTA countries (Iceland, Liechtenstein, Norway, and Switzerland), for example, the construction and demolition sector produced almost 50% of all waste in 2004 (EEA, 2007).

In the EU-25 countries, 70% of the existing housing stock was built before 1980, and 23% was built before 1945. In 2004, on average approximately 1% of the EU-25 countries' existing housing stock was newly-built, while up to 0.75% of the existing stock was demolished (Federcasa, 2006; Itard *et al.,* 2008). On average, about 100 times more houses are in use than are built annually, meaning that the existing housing stock is both slowly growing and ageing. An estimated more than 10 million boilers in Europe are over 20 years old and therefore have a lower energy efficiency than those currently available on the market (Balaras *et al.,* 2007). Thus, in order to lessen the annual negative impact of housing on the environment, it would be more efficient to improve the existing housing stock than to focus only on new houses. Treloar *et al.* (2000), for instance, stress the importance of the operational phase when assessing the energy consumption in a buildings' life cycle, while Yang *et al.* (2008) and Itard (2006) show the importance of the environmental impact of heating systems.

During the operational phase of dwellings, environmental impact results from activities such as maintenance, the replacement of building components, and energy used for both climate control and household appliances. The magnitude of the impact depends on a building's characteristics, such as its functionality and deterioration rate, and on decisions made by its owners and occupants, such as maintenance planning and the choice of building services and materials.

This study is part of a research programme that is assessing the environmental aspects of the maintenance of façades, building services, operational energy consumption and major interior replacements. Eventually all of these aspects will be compared to obtain an overview of the entire operational phase of dwellings. The present study focuses on the use and maintenance of heating and ventilation systems. The aims of the study are to:

1. Compare the environmental impact of the use of different heating and ventilation systems in a reference dwelling, using life cycle assessment methodology.

2. Identify the environmental impact categories to which the heating and ventilation systems contribute most compared with the total annual environmental impact in the Netherlands (reference year 1997).
3. Identify the factors which have the biggest environmental impact during the use of heating and ventilation systems.
4. Assess the sensitivity of the results.
5. Assess how the environmental impact related to heating and ventilation systems usage can be reduced.

## 3.2 Methodology

In this research, LCA is used to calculate the environmental impact of the use, maintenance and replacement of heating and ventilation systems. In doing so, the following processes are taken into account: material resources used in the systems; production of the systems; maintenance activities: replacement and maintenance of the systems including transportation of maintenance workers; and waste processing.

This section briefly explains the LCA methodology. To be able to compare different heating and ventilation concepts, the systems are fitted to a Dutch reference apartment building. The reference building and the heating and ventilation system concepts to be compared are described in greater detail below. Subsequently, the calculation of the energy use for each concept is set out. The results of the assessment are expressed as the accumulation of environmental impact over time; therefore the frequency of maintenance activities and the times at which replacements are made are described in scenarios. Finally, the assumptions and limitations of the calculation method and the data used are discussed.

### 3.2.1 Life cycle assessment[1]

LCA can be used to quantify the impact that a product has on the environment during its production, use and disposal. An LCA consists of four steps, the requirements and guidelines for which are described in the norm ISO 14044 (2006). The first step is to define the goal and scope for the assessment, which serve as a description of the type of study conducted, such as comparing product alternatives or improving a production process, and the questions the assessment is supposed to answer. The goal and scope of the assessment for this study were defined at the end of Section 3.1.The scope of the study

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[1] Subsections 3.2.1 and 3.2.2 closely resemble Subsections 2.2.1 and 2.2.2 and can therefore be skipped by front-to-back cover readers.

determines which processes should be included in the next step, the inventory phase of the assessment, in which an inventory is made of the flow of all substances to and from the environment related to the product or process of interest. In the third step, impact assessment, each substance's potential contribution to predefined environmental impact categories is calculated. This is done by comparing the impact of a particular substance flow with that of a reference substance, e.g. comparing the human toxicity of a certain substance with that of 1,4-dichlorobenzene. A detailed description of the calculations in the impact assessment phase is available in the Handbook on LCA (Guinée, 2002). Once the environmental impact has been calculated, the last step of the assessment is to interpret the results of the calculations in the interpretation phase, for example by comparing the calculated environmental impact to the results of similar research found in the literature or to all annual environmental impact in a region (normalisation), and by determining the sensitivity of the results to changes in the input variables. Normalisation of the results means that the environmental impact of a product or process is compared with the total annual environmental impact in a certain region and year. In this research, results are normalised to the Netherlands with reference year 1997 (Guinée, 2002). The main goals of normalisation are to provide a comparable scale between impact categories, a rough error check of the results and a reference value that is constant in time, which is why the values of 1997 are still used (van Oers and Huppes, 2001).

LCA includes several methods to quantify the environmental performance of a product or process. The methods use single or multiple indicators for environmental performance, either at the midpoint or endpoint level. For example, the CML method uses multiple indicators at midpoint level (Guinée, 2002), while the Eco-indicator method includes multiple endpoint indicators that can be combined in a single endpoint indicator (Goedkoop and Spriensma, 2001).The more indicators are used, the more detailed information is available on the origin and range of environmental impact. Single indicators, however, are easier to use and understand. All indicators are problem-oriented: the higher the score, the worse the environmental performance. Endpoint indicators are damage-oriented: they represent the ultimate consequences of negative environmental impact to humans and ecosystems. These indicators are the 'endpoint' of a possible chain of causes and effects. A drawback of these indicators is a higher level of uncertainty in the results, because more environmental mechanisms are involved (Goedkoop *et al.,* 2009). Midpoint indicators, in contrast, show direct impact on the environment, which are situated anywhere along the chain of causes and effects. This research used the CML 2000 LCA method to determine the environmental profiles of building services and related processes, because it uses multiple indicators at midpoint level (Guinée, 2002). This method will therefore provide detailed information about several environmental impact

**Table 3.1 Environmental impact categories considered in the CML 2000 method**

| Environmental impact category | Unit of measurement |
|---|---|
| Abiotic depletion | [kg Sb eq.] |
| Global warming | [kg $CO_2$ eq.] |
| Ozone layer depletion | [kg CFC-11 eq.] |
| Photochemical oxidation | [kg $C_2H_4$ eq.] |
| Human toxicity | [kg 1,4-DB eq.] |
| Fresh water aquatic ecotoxicity | [kg 1,4-DB eq.] |
| Terrestrial ecotoxicity | [kg 1,4-DB eq.] |
| Acidification | [kg $SO_2$ eq.] |
| Eutrophication | [kg $PO_4^{3-}$ eq.] |

Source: Guinée, 2002

categories related to climate systems with a relatively low level of uncertainty in the quantification method. The environmental impact categories assessed in the CML 2000 method are a selection of the most commonly used indicators in LCA studies. The impact categories taken into account in this research are listed in Table 3.1. The complete set of environmental impact categories is known as the 'environmental profile'. Marine aquatic ecotoxicity, part of the compulsory impact categories in the CML method, is not taken into account because of significant problems associated with the calculation of the impact in the CML method (Sim *et al.,* 2007). These problems are related to the time a substance is present in the marine ecosystem and missing data for normalisation. The characterisation models regarding the influence of metals on ecotoxicity contain flaws regarding the time they are present in ecosystems and in what form, which determines if they are harmful or beneficial; therefore the results of the ecotoxicity impact categories have a higher level of uncertainty. However, it is still possible to compare product alternatives (Apeldoorn, 2004; Heijungs *et al.,* 2004).

### 3.2.2 Reference building

This research assesses the heating and ventilation systems in a Dutch reference apartment building, a gallery flat built between 1966 and 1988 (Novem, 2001; SenterNovem, 2007). Figure 3.1 shows the building's side views and floor plan. Approximately 208,000 dwellings of this type exist in the Netherlands, 67% of which are owned by housing associations and are thus subject to organised maintenance and replacement of building services. The apartments in the reference building are equipped with individual non-condensing boilers for space heating and a collective mechanical exhaust ventilation system.

The reference building consists of 70 dwellings in total, distributed across seven floors of ten dwellings each along an open gallery. Owing to the fact that maintenance activities are often performed simultaneously on multi-family houses, all apartments in the building are assessed together.

**Figure 3.1 Gallery flat reference building**

Source: Novem, 2001

### 3.2.3 Heating and ventilation system concepts

The functional unit in this study consists of the heating and ventilation equipment[2] in a multi-family building of 70 dwellings, including heat and air distribution, which is operated and maintained during 40 years. The equipment aims at providing an average indoor temperature of 18°C and a ventilation rate as required by the Dutch Building Decree, i.e. 0.7 $dm^3/s$ per $m^2$ floor area (de Jong and Pothuis, 2009). For the material content of the systems, an average of several manufacturers' systems with the best fitting capacity available on the market is used. The distinguishing characteristics of the heating and ventilation concepts are outlined in Table 3.2.

The first heating and ventilation concept, which serves as the reference concept throughout the study, is based on the heating and ventilation systems found in most existing apartment buildings built between 1966 and 1988 in the Netherlands. Heat is generated by a non-condensing boiler. Nowadays, this type of boiler is no longer installed in new buildings and many existing non-condensing boilers are being replaced by high efficiency condensing boilers. However, it is not always possible to install condensing boilers in existing buildings because they lack the space for the extra ducts needed. This is why concept I is based on a non-condensing boiler. The efficiency of a condensing boiler is related to the lower heating value (LHV) of gas, in accordance

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[2] The heating system provides space heating and hot tapwater.

**Table 3.2 Heating and ventilation concepts**

| Concept | Heating system | Efficiency | Temperature (supply/return (°C)) | Ventilation system |
|---|---|---|---|---|
| I | Non-condensing boiler | 93% | 90/70 | Collective mechanical exhaust |
| II | Condensing boiler | 107%[a] | 90/70 | Collective mechanical exhaust |
| III | Condensing boiler | 107%[a] | 55/45 | Collective mechanical exhaust |
| IV | Condensing boiler | 107%[a] | 90/70 | Individual balanced with heat recovery |
| V | Heat pump (heating) | CoP[b] 3.2 | 55/45 | Collective mechanical exhaust |
|  | Heat pump (hot tap water) | CoP[b] 2.3 |  |  |

a) The efficiency of a condensing boiler is related to the lower heating value (LHV) of gas. Since a high efficiency condensing boiler recovers heat from combustion gases, an efficiency of more than 100% is gained.
b) Coefficient of Performance (CoP): ratio between the heating/cooling provided by the system and the energy it consumes.

with European guidelines. Since a high efficiency condensing boiler recovers heat from combustion gases, an efficiency of more than 100% is gained. If the higher heating value of gas is used, the efficiency would be below 100%.

Concepts I, II and IV are based on high temperature heating with supply/return temperatures of 90°Cand 70°Crespectively. Since condensing boilers are about 2.5% more efficient when they work at lower temperatures and heat pumps can only be combined with low temperature heating, low temperature heating with a supply temperature of 55°C and a return temperature of 45°C is used in concepts III and V. High temperature heating is always combined with steel piping since plastic cannot withstand prolonged high temperatures of 90°C. For low temperature heating, either a steel or plastic piping system can be used. In practice, low temperature heating systems in new buildings are normally combined with plastic piping. Existing steel piping systems will seldom be replaced, only in extensive renovations. Therefore, steel piping is used in concept III and plastic piping in concept V.

In all concepts, including low temperature heating concept III, heat is issued to the room by radiators. In new buildings, low temperature heating is typically combined with floor heating. However, in existing buildings it is often not possible to install floor heating because it requires raising the floor level by about 5 cm and the ceiling height is not always sufficient to do so in accordance with the Dutch Building Decree. Radiators for low temperature heating, used in concept III, require a larger radiating surface and are therefore much bigger than high temperature radiators.

The heat pump in concept V uses exhaust air as its source of heat for providing hot tap water and heating. It can only be used in combination with exhaust air ventilation.

Mechanical exhaust ventilation (concepts I, II, III and V) is a system with ducts and duct ventilators in each dwelling to extract air, collective ducts leading up to the roof and ten roof ventilators that each extract the air from one column of seven apartments. The balanced ventilation system with heat recovery (concept IV) consists of individual units with local ducts in each apartment linked to a collective supply and exhaust duct system and 20 roof ventilators.

### 3.2.4 Energy consumption

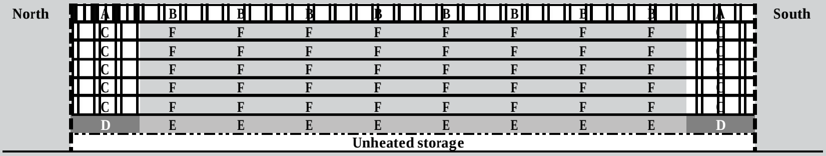
Energy consumption for climate control depends on the location of apartments in the gallery flat. Figure 3.2 shows a simplified scheme of the gallery flat reference building with apartments subdivided according to heating demand. The unheated elevator and stairwell shaft, located in the middle of the building, is not taken into account. Apartments located under the roof and with three façade walls (type A) have a higher energy demand for heating than apartments located in the middle of the building (type F). Gas and electricity consumption are calculated with Vabi EPA-W software, which is used to assess the energetic quality of dwellings (Vabi Software, 2009). The calculated gas and electricity consumption for each apartment type is set out in Table 3.3 and 3.4 respectively.

The EPA-W software incorporates standard characteristics related to occupancy to calculate heating demand and use of hot tap water. The indoor heat production is 6 W/m$^2$. The dwelling is modelled as one heated zone with a constant temperature of 18°C. In practice, not all rooms are heated and there are temperature variations during the day. The highest temperature setting may be higher than 18°C and the night settings may be lower. The number of occupants depends on useable floor area, in this case 2.8 occupants per apartment.

Electricity operates system components, such as ventilators, circulation pumps and the heat pump. The auxiliary electricity consumption for all apartment types is equal because of simplifications in the calculation method. Electricity used for the circulation pump and ventilators in boilers as well as electricity used for the ventilation system is standardised, which means it does not depend on the heat demand. In practice, a greater heat demand or a less efficient boiler leads to differences in operating time and therefore differences in auxiliary electricity consumption.

Table 3.3 shows that when a more efficient boiler is used (concept II), gas consumption for hot tap water decreases by 7% and gas for heating by 15% for all apartment types compared with a less efficient boiler in concept I. The software does not distinguish between high temperature heating (concept II) and low temperature heating (concept III). However, the condensing boiler operates more efficiently at lower supply and return temperatures: 97.5% instead of 95% according to NEN 5128 (2004), Table 18. Therefore, the gas use of concept IV has been reduced by 95/97.5 to the value shown in Table 3.3. Using low temperature heating instead of high temperature heating reduces gas consumption for heating by 2.5%, but does not reduce gas consumption for hot tap water. When a balanced ventilation system is installed (concept IV), gas for heating is reduced more in apartment type F than in type A. In the model used, heat loss occurs through ventilation and through façades, roof and floor that border on the outdoor climate. In apartment type F, the share of

## Figure 3.2 Different apartment types in the gallery flat reference building according to energy demand



## Table 3.3 Annual gas consumption per apartment for each heating and ventilation concept

| | Number of apartments | Climate system concept | | | | |
|---|---|---|---|---|---|---|
| | | I[a] (m³/y) | II[b] (m³/y) | III[b] (m³/y) | IV[b] (m³/y) | V (m³/y) |
| Apartment A | 2 | 1,021 | 888 | 873 | 686 | - |
| Apartment B | 8 | 928 | 809 | 796 | 610 | - |
| Apartment C | 10 | 794 | 697 | 686 | 505 | - |
| Apartment D | 2 | 999 | 869 | 854 | 668 | - |
| Apartment E | 8 | 906 | 791 | 778 | 593 | - |
| Apartment F | 40 | 704 | 620 | 612 | 438 | - |
| Total gas use of flat building | 70 | 54,791 | 48,099 | 47,388 | 34,906 | 0 |
| Average gas use per apartment | | 783 | 687 | 677 | 499 | 0 |

a) For each apartment, 312.5 m³ of gas is used for hot tap water.
b) For each apartment, 291.1 m³ of gas is used for hot tap water.

## Table 3.4 Annual auxiliary electricity consumption per apartment for each heating and ventilation concept

| | Number of apartments | Climate system concept | | | | |
|---|---|---|---|---|---|---|
| | | I (kWh/y) | II (kWh/y) | III (kWh/y) | IV (kWh/y) | V[a] (kWh/y) |
| Apartment A | 2 | 456 | 497 | 497 | 723 | 3,814 |
| Apartment B | 8 | | | | | 3,585 |
| Apartment C | 10 | | | | | 3,255 |
| Apartment D | 2 | | | | | 3,760 |
| Apartment E | 8 | | | | | 3,531 |
| Apartment F | 40 | | | | | 3,029 |
| Total electricity use of flat building | 70 | 31,892 | 34,755 | 34,755 | 50,596 | 225,771 |
| Average electricity use per apartment | | 456 | 497 | 497 | 723 | 3,225 |

a) For each apartment, 1,336 kWh of electricity is used for hot tap water.

ventilation heat loss is the largest, because it only has two façades that separate indoor from outdoor climate. Gas consumption for heating in concept IV is reduced by 34% in apartment type A and 55% in type F compared with concept II. Tables 3.3 and 3.4 further show that when a heat pump is used for heat generation, the energy type used switches from gas to electricity.

**Table 3.5 Service life of components, maintenance frequency and transportation distance of maintenance workers per activity for all 70 apartments**

| Activity | Service life (years) | Transportation (km) |
|---|---|---|
| **Replacements** | | |
| - boiler or heat pump | 15 | 2,800 |
| - radiators | 30 | 7,000 |
| - mechanical exhaust ventilation system | 20 | 1,500 |
| - balance ventilation unit (Scenario 4) | 15 | 2,800 |
| - roof ventilators and air ducts (Scenario 4) | 20 | 1,550 |
| - mechanical exhaust ventilation system (Scenario 5) | 20 | 900 |
| | **Frequency (years)** | **Transportation (km)** |
| **Maintenance** | | |
| - boiler or heat pump | 1 | 1,800 |
| - replace 3-way valve in boiler | a | 2,800 |
| - replace hot tap water heat exchanger in boiler | a | 2,800 |
| - clean air ducts | 5 | 600 |
| - clean air ducts[b] (Scenario 4) | 5 | 1,200 |
| - balance ventilation unit (Scenario 4) | 2 | 1,800 |

a) During 15 years, 40% of all 3-way valves and hot tap water heat exchangers are replaced, which takes 2,800 km in total transportation.

b) There are twice as many ducts in balanced ventilation systems, therefore there is twice as much transportation.

### 3.2.5 Maintenance scenarios

A maintenance and replacement scenario for heating and ventilation systems in the reference apartment building describes when activities take place. This research assumes that the scenario commences with the production and installation of all system components. Table 3.5 provides an overview of the variables in the scenarios. The service life of system components and maintenance frequencies indicated in Table 3.5 are a combination of reference values as found in Huffmeijer *et al.* (1998), values found in maintenance manuals of heating and ventilation equipment and information acquired from installation companies. Additionally, Table 3.5 shows the transportation distance of maintenance workers per replacement and maintenance activity for all 70 apartments in the apartment building combined. For example: maintaining the boilers in all the apartments takes two people 18 working days. It is assumed that on average, two maintenance workers share a car and the return distance travelled is 100 km.

The calculations are cut off after 40 years, a time span long enough to have some system replacements take place and short enough to still be a realistic maintenance planning time frame. The differences between the scenarios remain in the same order of magnitude when the scenario calculations are cut off after 100 or 150 years. Material quantities are gathered from product manufacturers, freely available manuals, and the commercially available ecoinvent and EcoQuantum databases (ecoinvent, 2007; W/E adviseurs *et al.*, 2002). Data from system manufacturers concerning material quantities per climate system component are confidential. Table 3.6 shows the total amount of materials used during 40 years of maintenance and replacements of the

**Table 3.6 Materials used during 40 years of dwelling use (in kg) for maintenance scenarios 1 to 5**[a]

| Materials | | Scenario | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| Metal | Aluminium, production mix | 270 | 270 | 270 | 305 | 188 |
| | Aluminium, cast alloy | 767 | 2,688 | 2,688 | 2,688 | - |
| | Brass | 1,129 | 833 | 833 | 833 | - |
| | Cast iron | 2,100 | - | - | - | - |
| | Copper | 505 | 346 | 346 | 391 | 7,392 |
| | Stainless steel 16/10 grade[b] | 463 | 463 | 463 | 463 | 0 |
| | Stainless steel 18/8 grade | 655 | 672 | 672 | 1,089 | 13,815 |
| | Steel | 32,968 | 30,624 | 62,185 | 39,812 | 74,746 |
| Plastics | ABS | 261 | 261 | 261 | 254 | - |
| | Elastomere | - | - | - | - | 3,360 |
| | EPDM | 158 | 158 | 158 | 158 | 158 |
| | HDPE | 88 | 88 | 88 | 148 | 60 |
| | Nylon | 9 | 9 | 9 | 1 | - |
| | PA | 50 | 50 | 50 | - | - |
| | PC | 9 | 9 | 9 | 1 | - |
| | PE-Xc[c] | - | - | - | - | 198 |
| | PP | 1 | 1 | 1 | - | - |
| | PS | - | - | - | 2,125 | - |
| | PUR | 4 | 4 | 4 | 6 | 3 |
| | PVC | 1 | 1 | 1 | - | 336 |
| | PVDF | - | - | - | - | 102 |
| | Rubber, synthetic | 23 | 23 | 23 | 26 | 3 |
| Other | Ceramics | 4 | 4 | 4 | 4 | - |
| | Electronics | 407 | 407 | 407 | 555 | 75 |
| | Kraft paper | 98 | 98 | 98 | 98 | - |
| | Refrigerant R134a | - | - | - | - | 823 |

a) Includes materials used for production of the climate systems, which are described as heating and ventilation concepts in Table 3.2, and all replacements during the 40-year maintenance scenario.

b) Stainless steel 16/10 grade: EN 1.4408; Stainless steel grade 18/8: EN 1.4310.

c) Electron beam cross-linked polyethylene, used in plastic piping.

heating and ventilation systems.

### 3.2.6 Assumptions and limitations

The calculations of the environmental profiles of building components and activities take the following processes into account. Details are available in the ecoinvent database and the ecoinvent background reports (ecoinvent, 2007; Frischknecht *et al.*, 2007a).

- Production processes: input of material and energy resources from the environment, substance emissions to the environment during production and/or application, transportation and energy used from extraction of resources to available end product in wholesale business, production and assembly waste. Transportation of building components from wholesale business to the building location is not taken into account. Capital goods are taken into account as far as there are data available in the ecoinvent database, except for the 'average metal working' processes, in which the capital goods would be counted twice if they were to be taken into account.

- The calculation of electricity used by the heat pump is based on a dual system: one heat pump working on exhaust air to heat the apartment and another heat pump working on outdoor air to provide hot tap water. The environmental impact of the production, maintenance and waste processing of the heat pump used in this research is based on a single exhaust air heat pump system that can provide both space heating and hot tap water, since this is the only heat pump system of which material data were available. It is assumed that the material content of the single heat pump system is representative for the dual heat pump system.
- The efficiency of the heating and ventilation systems is a yearly average and is assumed to be constant during the service life of the system. Therefore, system aging, repairs and maintenance activities do not influence their performance.
- Waste processing: the waste scenarios available in EcoQuantum (W/E adviseurs *et al.*, 2002) are used because they represent the way Dutch building waste is handled. Table 3.7 shows what percentage of each waste type goes to landfill, incineration and recycling. In this research, only the environmental impact related to landfill and incineration is taken into account. It is assumed that environmental impact related to recycling is assigned to the product that uses the recycled material as an input.

The main limitations in this study are as follows:

- The process of electroplating zinc, used for steel piping, is not available in the ecoinvent database, but it is available in the Idemat database. The Idemat data is combined with data from the ecoinvent database to create a profile for electroplating zinc.
- Some plastics are not available in the ecoinvent database and are therefore replaced by similar plastics. PE-Xc, used in plastic piping, is replaced by regular PE. The process of treating PE with electron beams to acquire PE-Xc is not available in the database and is not taken into account. PVDF, used in coupling elements of plastic piping, is not available either. The alternative to PVDF is emulsion polymerized PVC. Finally, PA is replaced by nylon 66.
- There are no specific data relating to the transportation of maintenance workers in vans. Data for the operation of a passenger car using EURO 4 diesel fuel are adjusted for the use of fuel per kilometre for a Mercedes Vito van, which in an urban environment is about 9 l/100 km (Mercedes-Benz, 2009). Capital goods (the car, roads) are not taken into account since the data in the database are derived from the Swiss situation; only fuel resources and emissions during use are included in the assessment.

**Table 3.7 Waste scenarios for construction waste, based on W/E adviseurs (2002)[a]**

| Waste type | Materials | Waste scenario | | |
|---|---|---|---|---|
| | | Landfill (%) | Incineration (%) | Recycling (%) |
| Aluminium | Aluminium | 3 | 3 | 94 |
| Non-ferro | Brass | 5 | 5 | 90 |
| Ferro metals[b] | Cast iron | 5 | 0 | 95 |
| Coppers | Copper | 10 | 5 | 85 |
| Steel[c] | Steel, stainless steel | 5 | 0 | 95 |
| Plastics | ABS, EPDM, nylon, PA, PC, PUR, rubber | 20 | 80 | 0 |
| PE | HDPE, PE-Xc | 10 | 85 | 5 |
| PP | PP | 10 | 85 | 5 |
| PS | PS | 5 | 90 | 5 |
| PVC | PVC, PVDF | 10 | 10 | 80 |
| Ceramics[b] | Ceramics | 0 | 100 | 0 |
| Not defined | Refrigerant R134a | 0 | 0 | 100 |
| Not defined | Electronics | 50 | 50 | 0 |

a) The waste scenarios are equal to those included in NEN 8006, 2004: ‘Environmental data of building materials, building products and building elements for application in environmental product declarations. Assessment according to the Life Cycle Assessment (LCA) methodology’, except for the undefined waste types and those indicated.

b) Not included in NEN 8006, 2004.

c) NEN 8006, 2004: steel is completely recycled or reused. 1% of light steel elements go to landfill.

Source: based on W/E adviseurs, 2002

## 3.3 Results, analysis and discussion

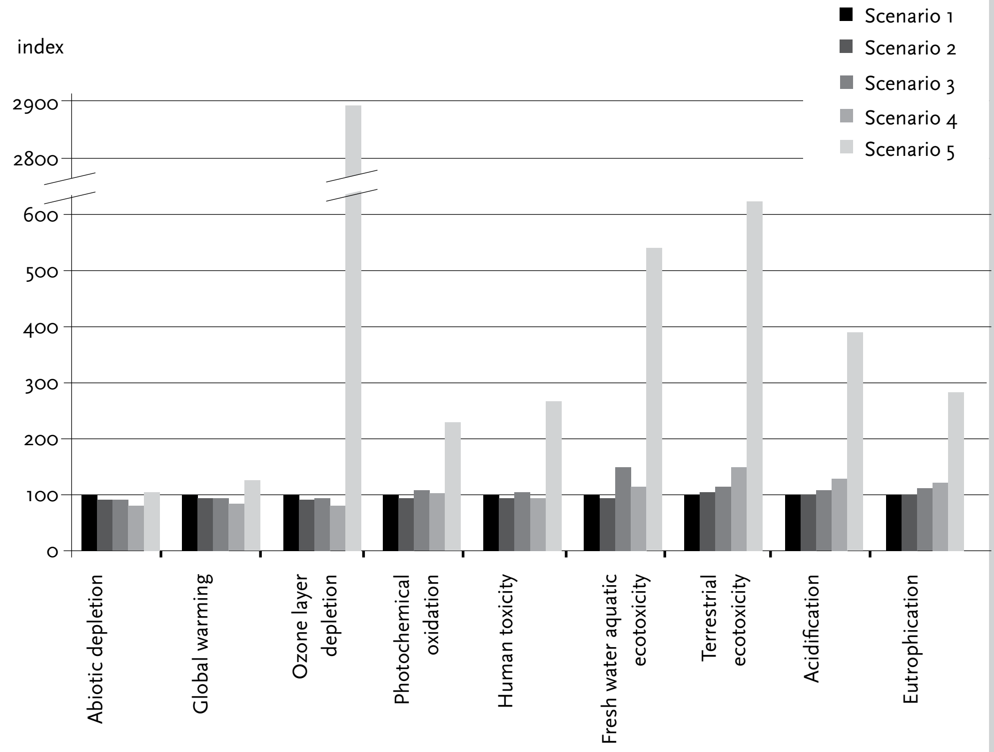
This section discusses the results of the environmental assessment of the heating and ventilation concepts and related maintenance scenarios. The environmental assessments results are shown as the accumulated contributions to various environmental impact categories over time. The scenarios have a 40 year time span.

### 3.3.1 Comparison of heating and ventilation systems

The first aim of this research is to compare the environmental impact of the defined heating and ventilation system concepts and related maintenance scenarios. Figure 3.3 shows the accumulated environmental impact of each scenario after 40 years of use and maintenance. The environmental impact score of Scenario 1 has been set to the index 100 in each impact category. The scores of the other scenarios are relative to Scenario 1.

The results show that the heat pump in Scenario 5 performs worst on all environmental impact categories. Heat pumps are often considered to be a sustainable alternative for condensing boilers, because they extract heat from continuously available sources instead of burning non-renewable fossil fuels, thereby reducing $CO_2$ emissions. Other research suggests this to be true, as is shown by Cockroft & Kelly (2006) and Ossebaard *et al.* (1997). However, when

**Figure 3.3 Comparison of the indexed accumulated environmental impact after 40 years of dwelling use of five heating and ventilation concepts and related scenarios**



other aspects of the heat pump are taken into account, such as the electricity needed from the grid to operate it and the material resources needed to produce the system, and environmental impacts other than $CO_2$ emissions are assessed as well, the heat pump actually performs far worse than regular condensing boilers. In Subsection 3.3.4, a sensitivity analysis for the type of electricity used is carried out. The production of the heat pump refrigerant R134a, with an ozone depletion potential (ODP) of 0.009 kg CFC-11 equivalent per kg, causes a relatively high contribution to Ozone layer depletion. Research by Bovea *et al.* (2007) shows that other commercially available refrigerants have an impact in the same order of magnitude. However, how the refrigerant improves the efficiency of the system might be more important than how much it contributes to Ozone layer depletion, since the contribution to that environmental impact category is small compared to the total annual contribution in the Netherlands (see Subsection 3.3.2).

Installing a condensing boiler (Scenario 2) instead of a non-condensing boiler (Scenario 1) for high temperature heating will reduce the contribution to Abiotic depletion, Global warming and Ozone layer depletion by 8-9% because of a reduction in gas consumption. All other environmental impact categories are reduced by 1-5% except for Terrestrial ecotoxicity, which increases by 5%. The increase is caused by the additional operational electricity needed for the condensing boiler, in particular by the copper parts in the electricity distribution network. Using condensing boilers for low temperature heating (Scenario 3) will not further reduce the contribution to Abiotic depletion, Global warming and Ozone layer depletion, since gas consumption does not decrease much because of that measure. It does, however, show an increase of 8-55% in all other impact categories due to the increased material use in the heat radiators. Low temperature radiators require a larger radiating area to provide an equal amount of heat as high temperature radiators.

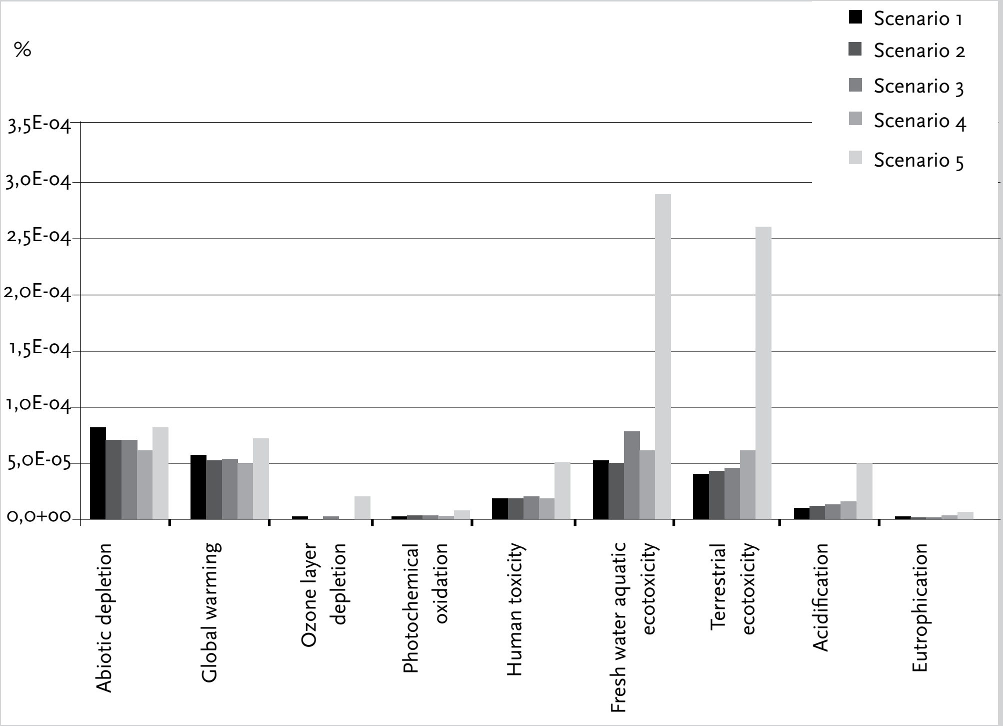
The combination of individual balanced ventilation with heat recovery and a condensing boiler at high temperature (Scenario 4) will reduce the contribution to Abiotic depletion, Global warming and Ozone layer depletion by 11-13% compared to collective mechanical exhaust ventilation combined with a condensing boiler at high temperature heating (Scenario 2). Human toxicity will decrease slightly by 3%. However, all other environmental impact categories will increase by 7-41% due to the material content of the ventilation units, the air ducts and the increased operating electricity needed for the ventilation system.

### 3.3.2 Normalised environmental impact

The second aim of this research is to see which environmental impact categories are most severely affected in the Netherlands by using and maintaining the defined climate systems. This is done by comparing the average annual environmental impacts of the scenarios per impact category to the total annual environmental impact in all of the Netherlands. This step is called normalisation in LCA methodology (Guinée, 2002; van Oers and Huppes, 2001). Figure 3.4 shows the share of the total environmental impact in the Netherlands that is caused by using and maintaining climate systems in the reference apartment building. Abiotic depletion, Global warming, Fresh water aquatic ecotoxicity and Terrestrial ecotoxicity are contributed to more than the other impact categories. In the Netherlands, heating and ventilation systems contribute most to Abiotic depletion and Global warming through energy use, to Terrestrial ecotoxicity through electricity use and to Fresh water aquatic ecotoxicity through material use in the system.

The values shown in Figure 3.4 represent 70 apartment dwellings, while there are approximately 7 million dwellings in the Netherlands. A rough estimate of the impact of the total dwelling stock can be made by multiplying the results in Figure 3.4 by 100,000. For example, 70 apartments cause about $6.10^{-5}$% of the total Global warming in the Netherlands. If all 7 million dwellings in the Netherlands were apartments, around 6% of total Global warming would be caused by using and maintaining climate systems in the total Dutch dwelling stock. As mentioned in the introduction, energy demand for space heating and hot tap water in residential buildings in Europe is on average 20% of the total energy use. Global warming is strongly related to energy use. The value of 6% is

**Figure 3.4 Average annual environmental impact normalised to the total annual environmental impact in the Netherlands**

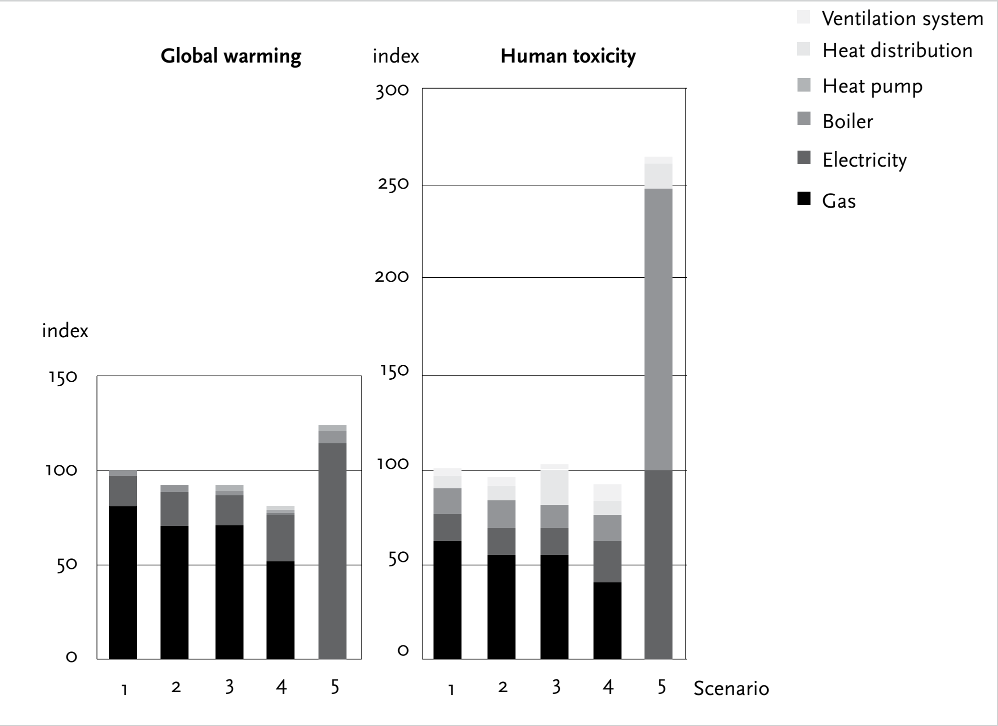


low, but an apartment dwelling has the lowest energy demand of all dwelling types. Energy for cooking, hot tap water, major household appliances and other consumer goods is not taken into account.

### 3.3.3 Contributing factors

The third aim of this research is to identify the factors which contribute most to the environmental impact categories during the use of heating and ventilation systems. To do this, the environmental impact categories are grouped by impact related to gas consumption, electricity consumption, and materials and production. Several factors are responsible for high contributions. Figure 3.5 shows the distribution of environmental impact among the contributing factors for Global warming and Human toxicity impact categories, respectively. The environmental impact score of Scenario 1 has been set to the index 100 in both impact categories. The scores of the other scenarios are relative to Scenario 1. The Global warming figure is similar to those for Abiotic depletion and Ozone layer depletion. Gas and electricity use contribute most to these impact categories. In Scenario 5, the impact of electricity consumption is in the same order of magnitude as the total impact in the other scenarios because up to 7 times more electricity is used by the heat pump than by the alternative climate systems. Additionally, electricity use is the single high contributing factor to Terrestrial ecotoxicity because of the copper used in the

Figure 3.5 Comparison of the contribution to global warming and human toxicity by different factors in each scenario



distribution network of electricity.

The Human toxicity figure is similar for Photochemical oxidation, Acidification and Eutrophication. It shows that the contribution of different factors is more evenly divided between energy use and material use. Again, the impact of electricity in Scenario 5 is in the same order of magnitude as the total impact of the other scenarios because of the high electricity consumption by the heat pump. For Fresh water aquatic ecotoxicity, material use in the climate systems is the dominant contributing factor.

### 3.3.4 Sensitivity analysis

*Electricity* – Electricity makes a major contribution to Abiotic depletion, Global warming and Terrestrial ecotoxicity impact categories. The amount of electricity used is a key defining characteristic of the heating and ventilation concepts. Therefore, the type of electricity used in the analysis influences the results of the calculations; this is also shown in research by Shah *et al.* (2008). The electricity mix used for calculations in this research is the 2004 electricity supply mix from the Dutch grid (Frischknecht *et al.*, 2007b). Sensitivity analysis was performed by defining two alternative electricity mixes: an alternative supply mix with more electricity from renewable sources, based on policy goals for 2020 (Ministerie van VROM, 2009); and electricity generated locally with photovoltaic cells. It is assumed that it is possible to generate enough

**Table 3.8 Composition of the Dutch electricity supply mix in 2004 and 2020 and the German export mix in 2020**

| Source of electricity | The Netherlands | | Germany |
|---|---|---|---|
| | 2004, supply (%) | 2020, supply (%) | 2020, export (%) |
| *Fossil fuels* | *73.27* | *57.66* | *49.64* |
| - Hard coal | 19.11 | 15.04 | 19.00 |
| - Lignite | - | - | 17.00 |
| - Oil | 2.30 | 1.81 | 2.64 |
| - Natural gas | 49.63 | 39.06 | 11.00 |
| - Industrial gas | 2.23 | 1.75 | - |
| *Hydropower* | *0.08* | *0.09* | *5.00* |
| *Pumped storage hydropower*[a] | - | - | *1.06* |
| *Nuclear power* | *3.06* | *2.41* | *1.00* |
| *Renewable sources* | *3.34* | *32.90* | *42.00* |
| - Wind power on shore | 1.58 | 3.67 | 19.00 |
| - Wind power off shore | 0.03 | 11.75 | 6.00 |
| - Biomass | 1.49 | 16.26 | 9.00 |
| - Biogas | 0.24 | - | - |
| - Photovoltaic | - | 1.22 | 7.00 |
| - Geothermal | - | - | 1.00 |
| *Waste incineration* | *2.08* | *0.94* | *1.30* |
| *Import from Germany* | *14.73* | *6.00* | - |
| *Import from Belgium* | *3.44* | - | - |
| **Total** | **100** | **100** | **100** |

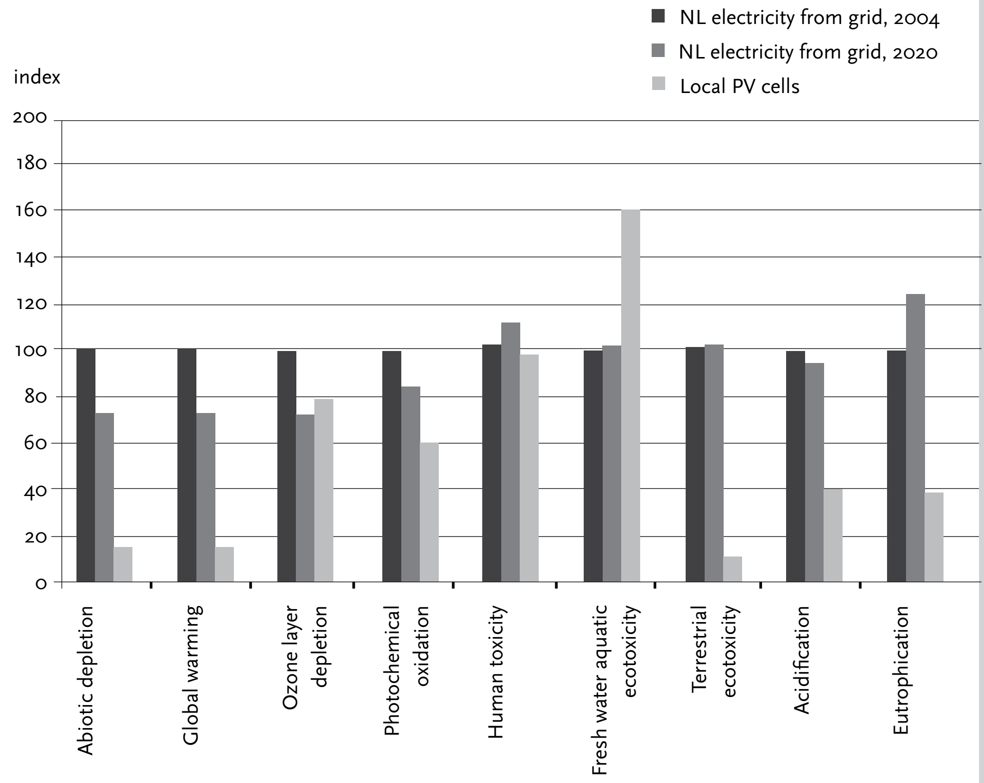
a) During low electricity demand, water is pumped in elevated water reservoirs. During peak demand, the water is released through turbines to create electricity.

Sources: BEE and AEE, 2009; Frischknecht *et al.*, 2007b; Ministerie van VROM, 2009; van Dril and Elzenga, 2005; van Tilburg *et al.*, 2006)

electricity to operate the climate systems. Table 3.8 shows the composition of the regular 2004 electricity mix and the electricity mix aspired for 2020. It also shows the estimated German production mix in 2020, which is included in the Dutch supply mix as imported electricity. The environmental impact of a kWh of electricity produced by photovoltaic cells is calculated by determining the environmental impact of a façade-mounted multi-Si solar PV panel and dividing the results by the amount of kWh that can be generated during the 30-year life span of the panel (Jungbluth and Tuchschmid, 2007). The photovoltaic electricity is merely included in the sensitivity analysis as an alternative to electricity from the grid.

Figure 3.6 shows a comparison of 1 kWh of each type of electricity. The environmental impact score of the 2004 Dutch electricity mix supplied by the grid has been set to the index 100 in each impact category. The scores of the other electricity types are relative to the 2004 mix. The high contribution to Fresh water aquatic ecotoxicity by photovoltaic electricity is due to the aluminium used in the mounting construction, the electricity and steel used for the production of multi-silicon wafers and the production of the inverter. The contribution of photovoltaic electricity to Ozone layer depletion is due to the use of the chemical tetrafluoroethylene in the production of photovoltaic cells. The 2020 electricity mix contributes more to Human toxicity,

**Figure 3.6 Comparison of three electricity profiles per1 kWh of electricity**



Fresh water aquatic ecotoxicity and Eutrophication than the 2004 electricity mix. For all of these three impact categories, the higher contribution is mainly due to the production of electricity from biomass. In that process, no single factor is dominant over the other factors. The relatively high contribution to Fresh water aquatic ecotoxicity by the 2020 electricity mix is also caused by the use of stainless steel in the offshore plant for the production of electricity from wind power. Finally, when compared with photovoltaic electricity the high contribution to Terrestrial ecotoxicity of the 2004 and 2020 electricity mixes is due to the copper used in the distribution network.

Table 3.9 shows the results of the sensitivity analysis for three scenarios: Scenario 2 with the condensing boiler and mechanical exhaust ventilation, Scenario 4 with the condensing boiler and balanced heat ventilation, and Scenario 5 with the heat pump. The heat pump system benefits most from using alternative electricity, becoming the best performing system on Abiotic depletion, Global warming and Terrestrial ecotoxicity when electricity is provided by local solar PV panels. However, electricity from renewable resources requires new systems to be built which causes increased contributions to the Human toxicity, Fresh water aquatic ecotoxicity and Eutrophication.

*Service life* – When the service life of a climate system is extended, fewer climate systems have to be produced and disposed of during the use phase of a dwelling and therefore the total environmental impact of the dwelling is re-

Table 3.9 Comparison of three scenarios with three electricity types, indexed values.

| | Scenario | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2 (HE 107 boiler) | | | 4 (balanced ventilation) | | | 5 (heat pump) | | |
| **Environmental impact category** | **2004** | **2020** | **PV cells** | **2004** | **2020** | **PV cells** | **2004** | **2020** | **PV cells** |
| Abiotic depletion | 100 | 96 | 85 | 86 | 80 | 65 | 114 | 85 | 20 |
| Global warming | 100 | 95 | 83 | 89 | 81 | 64 | 135 | 101 | 26 |
| Ozone layer depletion | 100 | 96 | 97 | 87 | 81 | 83 | 3177 | 3152 | 3158 |
| Photochemical oxidation | 100 | 96 | 90 | 107 | 101 | 92 | 240 | 213 | 172 |
| Human toxicity | 100 | 102 | 99 | 97 | 100 | 96 | 279 | 292 | 275 |
| Fresh water aquatic ecotoxicity | 100 | 100 | 106 | 121 | 122 | 130 | 569 | 570 | 610 |
| Terrestrial ecotoxicity | 100 | 100 | 24 | 141 | 142 | 30 | 591 | 594 | 95 |
| Acidification | 100 | 98 | 73 | 130 | 126 | 90 | 391 | 375 | 213 |
| Eutrophication | 100 | 108 | 79 | 124 | 136 | 93 | 290 | 345 | 153 |

duced. This is most evident for the impact categories that are affected by the production and disposal of systems. Systems with high material content will benefit most from extending the service life of the system. However, the results of this research do not change significantly unless the service life of the heat pump is more than three times higher than that of a boiler, which is not a realistic assumption.

*Transport* – The return travel distance is estimated to be 100 kilometres per car for replacement and scheduled maintenance activities, which may be done by a specialised company not located near the building. The estimated number of cars and return trips is based on information from maintenance companies. For unplanned maintenance activities, such as repairing a broken system, a one-way trip of 50 kilometres is taken into account, since the maintenance worker will go to another building next. Fifty kilometres for repair activities is a high estimate, since repairs are often done by local personnel. On the other hand, data on the number of repairs may be underestimated. In Scenario 2, the contribution of transportation of maintenance workers to the environmental impact categories ranges from 0.2 to 2.1%. When the transport distance is doubled, the contribution of transport still does not exceed 5%. Therefore, it may be concluded that environmental impact categories related to transportation of maintenance workers are not a major contributing factor on the scale of the use and maintenance of building services. However, reducing transport can reduce negative environmental impact on a smaller scale. Additionally, transport is directly related to costs, another reason for reducing transportation of maintenance workers as much as possible.

*Piping system* – The difference in the environmental impact of using steel piping and plastic piping for low temperature heating is negligible on the scale of the scenarios, even though steel piping has a higher environmental impact than plastic piping when the two are compared. Plastic piping is made from PE-Xc, which is polyethylene treated by electron beams. There is no environmental information about the production process of PE-Xc, which is why regular PE was used as a substitute.

### 3.3.5 Uncertainty

The environmental profiles of the climate systems are based on simplified systems with estimated material types and quantities based on total weight and product descriptions. Production process estimates were based on available processes in the ecoinvent database and the estimated materials used in the systems. The differences in the systems were modelled with as much detail as possible to provide a good basis of comparison for the scenarios. Nevertheless, the environmental impact categories influenced most by the system products are uncertain. These categories are Fresh water aquatic ecotoxicity, and to a lesser extent Photochemical oxidation, Human toxicity, Acidification and Eutrophication. Of these impact categories, only Fresh water aquatic ecotoxicity is a relatively important factor when the results are normalised, as is shown in Figure 3.4.

Other variables that may influence the environmental performance related to climate systems during the use of the dwelling are:

- the quality of the climate system (production errors, installation errors);
- occupant behaviour, using more or less energy than the standard occupants in the calculation;
- thermal quality of outer construction of the dwelling, which affects energy use (assumed equal for all scenarios in this research).

These variables were not taken into account in this research.

### 3.3.6 Reducing the environmental impact of climate systems

The last aim of the research is to determine how the environmental impact related to climate systems can be reduced. The most effective way to reduce environmental impact is to reduce energy use, first by reducing the energy demand for space heating and hot tap water – which is related to building characteristics and occupant behaviour – and second by improving the energy efficiency of the climate system. However, improving system efficiency can have adverse effects when operating energy and material content increase. For example, research by Prek (2004) and Nyman & Simonson (2005) show how these factors interact.

Other ways to reduce environmental impact include improving the efficiency of the production process of the systems, using less material or substituting materials with less environmental impact, and reusing and recycling discarded systems. There are many possible variations in boilers from different manufacturers. The total weight of suitable boilers for the reference dwellings ranges from 25 to 40 kg. The biggest difference between boilers is the type of heat exchanger and the material it is made of. A quick comparative study of three boilers with different heat exchangers and different total weights showed that the boilers' environmental profiles are quite similar, since none of the boilers combined the best material with the lowest total weight. The environmental performance of boilers could therefore be improved by reducing total weight and choosing materials that have less impact on the environment.

The environmental impact related to the climate systems can also be reduced by extending their service lives, although when more efficient technology becomes available, the environmental impact of producing and using a new, more efficient system may be less than continuing the use of the existing, less efficient system.

## 3.4 Conclusions

Even though heat pumps are generally considered to be sustainable heating systems because they extract heat from renewable sources rather than by burning non-renewable fossil fuels, this research shows that a heat pump is actually not more environmentally friendly than a gas-fired boiler. This conclusion is based on several characteristics of the heat pump. First, it requires electricity from the grid in order to work and often extra electricity is needed to provide backup heating in case the heat source does not provide enough. Second, in comparison with a boiler up to ten times as many material resources are needed to produce a heat pump. Third, the heat pump contains a refrigerant which affects the ozone layer. Nevertheless, the heat pump is a relatively new development with much room for improvement, whereas by now the gas-fired boiler can most likely be only marginally improved.

Decreasing energy consumption by decreasing heat demand in dwellings is the most effective way to reduce environmental impact related to climate systems for heating and ventilation. Second, improving energy efficiency of the climate systems will reduce environmental impacts, but when more systems are added increasing operating energy and material content might cause shifts in the impact categories that are affected most. When mechanical exhaust ventilation is replaced by balanced ventilation with heat recovery contributions to Abiotic depletion, Global warming and Ozone layer depletion are effectively reduced. However, a balanced ventilation system requires more material input and electricity for operation than mechanical exhaust ventilation, which leads to increased contributions to Fresh water aquatic ecotoxicity and Terrestrial ecotoxicity. When a non-condensing boiler is replaced by a condensing boiler, gas consumption is reduced because it is used more efficiently, while there is less material input for a condensing boiler and more need of auxiliary electricity. Therefore, the contribution to all environmental impact categories will decrease, except Terrestrial ecotoxicity which is mostly affected by electricity use. However, the savings on gas consumption are lower than when a balanced ventilation system is installed.

The use aspect of the scenarios is hardly visible in the results: the materials used for replaced components and the transportation of maintenance workers do not contribute much to the environmental impact categories compared to the energy and material use in the entire scenario. However, it is still possible to make small improvements to the environmental performance of climate systems by using systems that require little maintenance (less malfunctioning). For the environmental impact categories affected most by material use, it is best to try to extend the service life of the systems, thus reducing environmental impact related to producing a replacement system. However, sometimes systems can be replaced by others with much higher efficiency or a replacement can be necessary because of major renovations, in which case it might be better to replace a system before its technical service life is over.

Further research should focus on developing climate systems which reduce gas consumption without increasing operational electricity consumption or material consumption. Alternative courses of action are to reduce the environmental impact of electricity on the supply side, to improve the service life, durability and adjustability of climate systems so that less maintenance and replacement is needed, and to use materials that create less negative environmental impact. The latter measure could be reached by using recycled materials and improving the processing of both primary and recycled materials.

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# 4 Environmental impact of building-related and user-related energy consumption in dwellings

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An overview of all results can be found in Appendix 4.

**Abstract**

Energy consumption in dwellings contributes significantly to their total negative environmental impact. This paper quantitatively assesses the environmental impact of building-related and user-related gas and electricity consumption in a Dutch apartment dwelling using life cycle assessment (LCA) methodology. Several scenarios for gas and electricity consumption are compared to assess what effect changes in building characteristics and user behaviour have on the environmental impacts of energy consumption. This study shows that gas consumption significantly contributes to four environmental impact categories, which can be most effectively countered by reducing the heat demand of the dwelling. A 23% reduction in gas consumption leads to up to 13% less overall environmental impacts. Particularly in buildings with low heat demand, electricity consumption dominates all environmental impact categories. These can most effectively be reduced by changing the electricity demand of the user: 47% less electricity consumption leads to a 9-45% reduction in the total environmental impact. However, since electricity consumption continues to rise, the environmental effects of electricity use may be better reduced by changing the environmental impact of the electricity supply. Theoretically, when electricity consumption remains the same, over 90% less environmental impact could be reached by using 100% wind power to generate electricity.

## 4.1 Introduction

The largest part of energy consumption during the total service life of buildings takes place in the operational phase. In a review article that analysed 60 life cycle energy case studies of buildings, Sartori and Hestnes (2007) found that in low energy (Thormark, 2002) and conventional dwellings (Treloar *et al.*, 2000) a minimum of 54% and 62% of energy consumption respectively occurs during the operational phase. Adalberth (1997) showed that as much as 85% of the total energy consumption during construction, use and demolition of a single unit dwelling with a service life of 50 years occurs in the operational phase. Additionally, a European study of the energy use of all households combined found that it constituted approximately 25% of the total annual energy use of the EU-25 countries (Eurostat, 2007).

The studies mentioned above focus on the amount of embodied and operational energy in buildings as an indicator of environmental performance. However, different types of energy will affect the environment differently. For example, gas combustion for heat will lead to the depletion of fossil fuels and the emission of $CO_2$, while nuclear electrical power will result in depletion of uranium and creation of radioactive waste. Therefore, this research uses LCA methodology to assess and compare different types of environmental impact related to energy consumption in dwellings. In prior research, the authors have shown that the negative environmental impact related to energy consumption for heating, ventilation and hot tap water are larger than those related to the maintenance and replacement of façade components and climate systems in the operational phase of dwellings (Blom *et al.,* 2010a, 2010b). The present study assesses the total energy consumption of households, which includes energy for cooking, lighting, household appliances such as washing machines and kitchen appliances, and other appliances such as televisions and computers.

The Trias Energetica theory developed by Duijvestein states that in order to decrease environmental damage as a result of energy consumption the latter should first be reduced, followed by making more use of sustainable energy resources and, finally, using less sustainable energy resources more efficiently (Brouwers and Entrop, 2005; Duijvestein, 1993). However, when measures are taken to make the building more energy efficient (such as reducing consumption), more energy for other purposes may be consumed by the building user. This is called the rebound-effect (Herring and Sorrell, 2009). Furthermore, energy demand cannot be reduced indefinitely. Therefore, to reduce the environmental impact of energy consumption it might be more effective to reduce the environmental impact of energy on the supply side.

Several studies have compared the negative environmental impact of electricity generated from different sources. However, these studies mainly focus on Global warming or $CO_2$ emissions (Dones *et al.,* 1999; Dones *et al.,* 2003; Varun *et al.,* 2009), sometimes supplemented with the categories of Radioactivity (Dones *et al.,* 1999) or Acidification (Pehnt, 2006). When different resources and technologies are used to generate electricity, it is possible that negative environmental impacts will shift; for example, reducing greenhouse gas emissions might lead to higher radiation levels when shifting from fossil fuel sources to nuclear power (Dresselhaus and Thomas, 2001). Therefore, it is important to take into account the full spectrum of environmental impact categories when comparing alternative electricity production processes.

The goal of this study is to assess the negative environmental impact of building-related and user-related energy consumption for each type of energy. The processes which cause an environmental impact will be analysed to determine which measures most effectively reduce the environmental impact. This study is limited to gas and electricity delivered to dwellings, with all production processes and capital goods included, and aims to gain an understanding of how to reduce the negative environmental impact of energy consumption in dwellings. The research questions are:

1. What is the negative environmental impact of gas consumption compared with that of electricity consumption in a reference dwelling and how does it change when energy-saving measures are introduced?
2. What is the environmental impact of building-related energy consumption compared with user-related energy consumption?
3. How much does the environmental impact change as a result of variations in user behaviour?
4. What is the origin of the environmental impact of gas and electricity consumption?

## 4.2 Methodology

In this study LCA is used to calculate the environmental impact of gas and electricity consumption in dwellings. The following processes are taken into account: resources for gas and electricity production, transportation and distribution, including capital goods, and gas combustion in the dwelling.

This section briefly explains the LCA methodology. To compare different energy consumption scenarios, the study assesses the gas and electricity consumption of a household in a Dutch reference apartment. The reference building and the energy consumption concepts that are compared will be described below. Subsequently, the calculation of energy use for space heating, hot tap water, lighting and the operation of climate systems will be described, along with the electricity consumption of appliances. Finally, the assumptions and limitations of the calculation method and the data used will be discussed.

### 4.2.1 Life Cycle Assessment (LCA)[1]

LCA can be used to quantify the negative impact of a product or process on the environment during its production, use and disposal. An LCA consists of four steps, the requirements and guidelines for which are described in the standard ISO 14044 (2006). The first step is to define the goal and scope of the assessment, which serves as a description of the type of study conducted – such as comparing product alternatives or improving a production process –

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[1] Subsections 4.2.1 and 4.2.2 closely resemble Subsections 2.2.1, 2.2.2, 3.2.1 and 3.2.2 and can therefore be skipped by front-to-back cover readers.

and the questions the assessment is supposed to answer. The goal and scope of this study were defined in Section 4.1. The scope of the study determines which processes should be included in the next step, the inventory phase of the assessment, in which an inventory is made of the flow of all substances to and from the environment related to the product or process of interest. In the third step, impact assessment, the potential contribution of each substance to predefined environmental impact categories is calculated. This is done by comparing the impact of a particular substance flow with that of a reference substance for each environmental impact category, for example, comparing the human toxicity of a certain substance with that of 1.4-dichlorobenzene. A detailed description of the calculations in the impact assessment phase is available in the Handbook on LCA (Guinée, 2002). The complete set of environmental impact categories is known as the 'environmental profile'. Once the environmental impact has been calculated, the last step of the assessment is to interpret the results of the calculations in the interpretation phase, for example by comparing the environmental impact calculated to the results of similar research or to the overall annual environmental impact in a region (normalisation), and by determining the sensitivity of the results to changes in the input variables.

LCA can choose from several methods to quantify the environmental performance of a product or process, using single or multiple indicators of environmental performance, either at a midpoint or endpoint level. For example, the CML method uses multiple indicators at midpoint level (Guinée, 2002), while the Eco-indicator method includes multiple endpoint indicators which can be combined to form a single endpoint indicator (Goedkoop and Spriensma, 2001). The more indicators used, the more detailed the information available on the origin and range of the negative environmental impact. Single indicators, however, are easier to use and understand. All indicators are problem-oriented: the higher the score, the worse the environmental performance. Endpoint indicators are damage-oriented: they represent the ultimate consequences of the environmental impact for humans and ecosystems. These indicators are the 'endpoint' of a possible chain of causes and effects. A drawback of these indicators is a higher level of uncertainty in the results, because more environmental mechanisms are involved (Goedkoop *et al.,* 2009). Midpoint indicators, in contrast, show the direct potential impact on the environment, and are situated halfway along the chain of causes and effects. In this study, the CML 2000 LCA method was used to determine the environmental profiles of building services and related processes. This method uses multiple indicators at midpoint level (Guinée, 2002). The environmental impact categories assessed by the CML 2000 method are a selection of the most commonly used indicators in LCA studies. The impact categories that are taken into account in this study are listed in Table 4.1; the environmental impact category Marine aquatic ecotoxicity, one of the compulsory impact categories in the CML

**Table 4.1 The environmental impact categories considered in the CML 2000 method**

| Environmental impact category | Unit of measurement |
|---|---|
| Abiotic depletion | [kg Sb eq.] |
| Global warming | [kg $CO_2$ eq.] |
| Ozone layer depletion | [kg CFC-11 eq.] |
| Photochemical oxidation | [kg $C_2H_4$ eq.] |
| Human toxicity | [kg 1,4-DB eq.] |
| Fresh water aquatic ecotoxicity | [kg 1,4-DB eq.] |
| Terrestrial ecotoxicity | [kg 1,4-DB eq.] |
| Acidification | [kg $SO_2$ eq.] |
| Eutrophication | [kg $PO_4^{3-}$ eq.] |

Source: Guinée, 2002

method, is not taken into account because of significant problems associated with the calculation of the contribution to that category in the CML 2000 method (Doka, 2007; Sim *et al.*, 2007). These problems are related to the time a substance is present in the marine ecosystem and missing data for normalisation. The characterisation models with respect to the influence of metals on ecotoxicity contain flaws regarding the time they are present in ecosystems and in what form, which determines if they are harmful or beneficial; therefore, the results of the ecotoxicity scores have a higher level of uncertainty. Nonetheless, it is still possible to compare product alternatives (Apeldoorn, 2004; Heijungs *et al.*, 2004).

### 4.2.2 Reference building

This study assesses annual energy consumption in a Dutch reference apartment building, a gallery flat constructed between 1966 and 1988 (Novem, 2001; SenterNovem, 2007b). The reference building consists of 70 dwellings in total, distributed across seven floors of ten dwellings each, along an open gallery. The apartments in the reference building are equipped with individual non-condensing boilers for space heating and a collective mechanical exhaust ventilation system.

### 4.2.3 Energy consumption scenarios

This study assesses the environmental impact of six different scenarios for annual gas and electricity consumption in the reference apartment. The first scenario serves as the reference scenario, to which all other scenarios are compared. Scenarios II, III and IV deal with building characteristics and Scenarios V and VI concern consumer behaviour. Table 4.2 contains an overview of the distinguishing characteristics of the scenarios.

Scenario I is the average gas and electricity consumption in the reference apartment. The apartment is equipped with collective mechanical exhaust ventilation and a non-condensing boiler. The glazing is regular double glazing and the two doors leading to the balcony contain single glazing. The alternative scenarios are chosen to compare the effects that different measures have on gas and electricity consumption and on environmental impacts as a

**Table 4.2 Distinguishing characteristics of the six energy consumption scenarios**

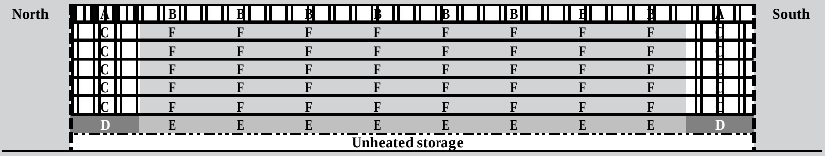
| | Scenarios | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Characteristics** | **I** | **II** | **III** | **IV** | **Va** | **Vb** | **VIa** | **VIb** |
| Heating | Boiler HE100 | Boiler HE100 | Boiler HE107 | Heat pump | Boiler HE100 | Boiler HE100 | Boiler HE100 | Boiler HE100 |
| Ventilation | Mechanical exhaust | Mechanical exhaust | Individual balanced | Mechanical exhaust | Mechanical exhaust | Mechanical exhaust | Mechanical exhaust | Mechanical exhaust |
| Glazing | Regular double | High efficiency | High efficiency | High efficiency | Regular double | Regular double | Regular double | Regular double |
| Appliances | Average | Average | Average | Average | Fewer apps, more efficient | More apps, less efficient | Average | Average |
| Gas | o | - | - - | n/a | o | - | o | o |
| Electricity | o | o | + | + + + | - - - | + + | o | o |

o : energy consumption of reference Scenario I
\+ : higher energy consumption than Scenario I
\- : lower energy consumption than Scenario I

consequence. Scenario II adopts a building measure, which is to replace glazing by high-efficiency double glazing (U-value: 0.64 W/m$^2$·K), which reduces heat loss and therefore gas consumption for heating. In addition to the measure of Scenario II, Scenario III adopts another building measure, which is to replace the climate systems by a high-efficiency condensing boiler and individual balanced ventilation with heat recovery. The climate systems in Scenario III further reduce gas consumption for heating and hot tap water by additional reductions to heat loss and by generating heat using gas more efficiently, but auxiliary electricity use increases. Scenario IV is an alternative electricity-only building measure to Scenario III, in which heating and hot tap water are provided by a heat pump using exhaust air and the ventilation system is a collective mechanical exhaust system. The heat pump needs to extract enough heat from the indoor air to heat the dwelling, which leads to an increased need for ventilation and an associated heat loss. The additional ventilation required depends on the useable floor area: in the reference building 17.7 dm$^3$/s extra ventilation is needed. High-efficiency glazing is also used in Scenario IV.

Scenario V assesses the influence of the occupant on electricity consumption. There are two variants of this scenario: low electricity consumption and high electricity consumption. In Scenario Va, energy efficient lighting and appliances are used and some appliances such as the dishwasher and clothes drier are not present. In Scenario Vb, more appliances which are also less efficient are used, including cooking with electricity. Finally, Scenario VI assesses the influence of the occupant on gas consumption. Gas consumption for space heating is influenced, for example, by temperature settings and the period that the heating is on, while hot tap water consumption depends on the number and length of showers taken. Similar to Scenario V, a low gas consumption and a high gas consumption variant have been defined. In Scenario VIa, it is assumed that 7% less gas is used for space heating by lowering the

**Figure 4.1 Different apartment types in the gallery flat reference building according to energy demand**



temperature setting by 1°C (Milieu Centraal, 2010) and it is assumed that by taking shorter or fewer showers, 10% less gas is used for hot tap water. In Scenario VIb, the reverse is true: 7% more gas for space heating and 10% more gas for hot tap water.

These scenarios use the Dutch electricity supply mix of 2004, as available in the ecoinvent 2.0 database and the background reports (ecoinvent, 2007; Frischknecht *et al.*, 2007b). The sensitivity analysis will consider alternative electricity mixes, as described in Subsection 4.3.6 below.

### 4.2.4 Calculation of gas and electricity consumption

Gas consumption for heating and hot tap water, and electricity consumption for lighting and the operation of the heating and ventilation systems were calculated using Vabi EPA-W software, which was developed to assess the energy efficiency of dwellings (Vabi Software, 2009). The heating demand of the apartments in the reference building depends on their location within the building. Figure 4.1 shows a simplified scheme of the reference building, in which the apartments are subdivided according to heating demand. Apartments that are located under the roof and have three façade walls (Type A) have a higher heating demand than apartments that are surrounded by others (Type F). The unheated lift and stairwell shaft located in the middle of the building is not taken into account.

It is assumed that the thermal resistance (R-value) of the closed façade parts and the roof have been upgraded to 2.5 m$^2$K/W, which is the required value for new buildings (de Jong and Pothuis, 2009). Each apartment contains 21.2 m$^2$ of regular double glazing with a U-value of 2.90 W/m$^2$K and 1.8 m$^2$ of single glazing with a U-value of 5.10 W/m$^2$K. Scenarios II, III and IV use 23 m$^2$ of high-efficiency glazing with a U-value of 0.64 W/m$^2$K.

The condensing boiler has an efficiency of 107%. This efficiency is related to the lower heating value (LHV) of gas. Since a high-efficiency condensing boiler recovers heat from combustion gases, it has an efficiency of more than 100%. The heat pump system consists of a heat pump using exhaust air for space heating and a heat pump using outside air for hot tap water. The efficiency of a heat pump is expressed in the Coefficient of Performance (CoP), which is the ratio between the heating/cooling provided by the system and the energy it consumes. The CoPs of the heat pumps are 3.2 and 2.3 respectively.

The EPA-W software further incorporates standard characteristics related to occupancy to calculate heating demand and the use of hot tap water. The 24-hour average indoor temperature is set at 18°C and indoor heat production is 6 W/m$^2$. The average gas consumption for space heating is 709 m$^3$ per apartment per year. Gas consumption for hot tap water depends on the household size. In the software, the number of occupants depends on useable floor area: in this case 73 m$^2$ equals 2.8 occupants per apartment. The average gas consumption for hot tap water is 313 m$^3$ per apartment per year.

Table 4.3 shows the average energy consumption per apartment in all scenarios, divided into energy consumption categories. The building-related energy consumption categories are heating, hot tap water, electricity for the operation of climate systems and lighting. The user-related energy consumption categories are cooking, household appliances and other electrical appliances. It is not possible to completely separate building and user-related energy use because there is an interaction between the building and its users. For example, building characteristics will determine the heat demand, but the user will set indoor temperatures and control ventilation, which also influence heat demand.

The energy consumption of a single reference apartment is calculated as the average consumption of all 70 apartments in the gallery flat building. The electricity consumption for lighting (438 kWh per year) and the operation of the climate systems (456 kWh per year) is equal for all apartment types because of simplifications in the calculation method. Operational electricity used for the circulation pump and ventilators in boilers, as well as electricity used for the ventilation system, are standardised, which means they only depend on the type of climate system used and not on the heat demand. Table 4.4 gives a detailed overview of the electrical appliances in each scenario.

Most dwellings in the Netherlands are heated by a gas-fired boiler. An average Dutch household consumes approximately 1530 m$^3$ of gas per year for heating, hot tap water and cooking (EnergieNed, 2008). Apartments are smaller and have a lower heating demand, with an average Dutch apartment consuming about 825 m$^3$ of gas per year (Nibud, 2009). This number corresponds with the calculated gas consumption in Scenario II.

Electricity is needed for the operation of climate systems, lighting and appliances. An average Dutch household consumes about 3500 kWh per year (EnergieNed, 2008). Electricity consumption strongly depends on the number of people per household. A Dutch apartment occupied by 2 people uses an average of 3325 kWh per year (Nibud, 2009).

### 4.2.5 Assumptions and limitations

The calculation of the environmental profiles of gas and electricity takes the following processes into account. Details are available in the ecoinvent database and the ecoinvent background reports (ecoinvent, 2007; Faist-Emmenegger *et al.,* 2007; Frischknecht *et al.,* 2007a; Frischknecht *et al.,* 2007b).

- The extraction of natural resources, including capital goods.

**Table 4.3 Energy consumption scenarios for an average apartment in the gallery flat reference building**

| Category | I | II | III | IV | Va | Vb | VIa | VIb |
|---|---|---|---|---|---|---|---|---|
| **Gas (m$^3$/year)** | | | | | | | | |
| Heating | 709 | 470 | 208 | - | 709 | 709 | 659 | 759 |
| Hot tap water | 313 | 313 | 291 | - | 313 | 313 | 281 | 344 |
| Cooking | 40 | 40 | 40 | - | 40 | - | 40 | 40 |
| **Total** | **1062** | **823** | **539** | **0** | **1062** | **1022** | **981** | **1142** |
| **Electricity (kWh/year)** | | | | | | | | |
| Heating | - | - | - | 1498 | - | - | - | - |
| Hot tap water | - | - | - | 1336 | - | - | - | - |
| Cooking | - | - | - | 500 | - | 500 | - | - |
| Operational energy climate systems | 456 | 456 | 723 | 391 | 456 | 456 | 456 | 456 |
| Lighting | 438 | 438 | 438 | 438 | 146 | 540 | 438 | 438 |
| Household appliances | 1810 | 1810 | 1810 | 1810 | 650 | 1810 | 1810 | 1810 |
| Other appliances | 645 | 645 | 645 | 645 | 545 | 945 | 645 | 645 |
| **Total** | **3349** | **3349** | **3616** | **6618** | **1797** | **4251** | **3349** | **3349** |

- Transportation and distribution of natural gas to the dwelling, including capital goods.
- Burning gas in a boiler to produce heat and hot tap water, excluding the boiler and the burning of gas for cooking.
- Transportation of natural resources to the power plant and the generation of electricity, including capital goods.
- Distribution of electricity to the dwelling, including capital goods.

The main limitations are as follows:

- The ecoinvent database contains no data on the Dutch low-pressure gas distribution network and its connections to dwellings. The only information provided concerns the Swiss low-pressure distribution network, which is less dense than in the Netherlands, and the soil type and piping materials also differ (Faist-Emmenegger *et al.*, 2007). Therefore, the Swiss piping network was adjusted to the Dutch situation. Data about the Dutch low-pressure network were obtained from publicly available inventories of regional gas suppliers in the Netherlands. One supplier did not provide the information, but in any case mainly services greenhouse agriculture companies. Data were available for about 61,000 km of the low-pressure distribution network with 5.97 million connections to households (Delta Netwerkbedrijf BV, 2009; Enexis, 2009; Essent Netwerk B.V., 2007; Intergas Energie BV, 2007; Liander NV, 2009; Netbeheer Centraal Overijssel BV, 2007; Rendo NV, 2009; Stedin, 2009; Westland Infra, 2009). The documentation does not provide information on the length of the connecting pipes. It is assumed that, on average, 15 metres of pipeline lies between the low-pressure pipe and the house and that 5 metres of piping is laid within the house. The total length of connecting pipes is thus 119,000 km. It is assumed that the unspecified piping is made of the same materials and that the materials are divided according to the same ratio as the specified piping. The service life of the piping system is assumed to be 40 years and the average annual household gas consumption of 1,530 m$^3$ gas / 55,080 MJ gas is assumed to be delivered

**Table 4.4 Annual electricity (kWh) used per appliance in an apartment for each energy consumption scenario**

| Appliances | Scenarios | | | |
|---|---|---|---|---|
| | I, II, III, VIa,V Ib | IV | Va | Vb |
| Electrical cooking | - | 500 | - | 500 |
| Lighting | 438 | 438 | 146 | 540 |
| Household appliances | | | | |
| - Refrigerator | 200 | 200 | 85 | 200 |
| - Freezer | 500 | 500 | 150 | 500 |
| - Microwave / oven combination | 100 | 100 | 100 | 100 |
| - Dishwasher | 300 | 300 | - | 300 |
| - Coffee-maker | 80 | 80 | 80 | 80 |
| - Electric kettle | 35 | 35 | 35 | 35 |
| - Washing-machine | 170 | 170 | 125 | 170 |
| - Clothes drier | 350 | 350 | - | 350 |
| - Iron | 25 | 25 | 25 | 25 |
| - Vacuum cleaner | 50 | 50 | 50 | 50 |
| **Total household appliances** | **1810** | **1810** | **650** | **1810** |
| Other appliances | | | | |
| - Desktop computer | 135 | 135 | 135 | 135 |
| - Television: CRT / 26 inch | 200 | 200 | - | - |
| - Television: plasma | - | - | - | 500 |
| - Television: LCD / 26 inch | - | - | 100 | - |
| - DVD player | 100 | 100 | 100 | 100 |
| - Audio equipment | 85 | 85 | 85 | 85 |
| - Landline telephone | 25 | 25 | 25 | 25 |
| - Loading portable devices | 100 | 100 | 100 | 100 |
| - Total other appliances | 645 | 645 | 545 | 945 |
| **Total** | **2893** | **3393** | **1341** | **3795** |

Sources: Ecofys and Stichting Natuur en Milieu, 2010; Milieu Centraal, 2010; SenterNovem, 2007a

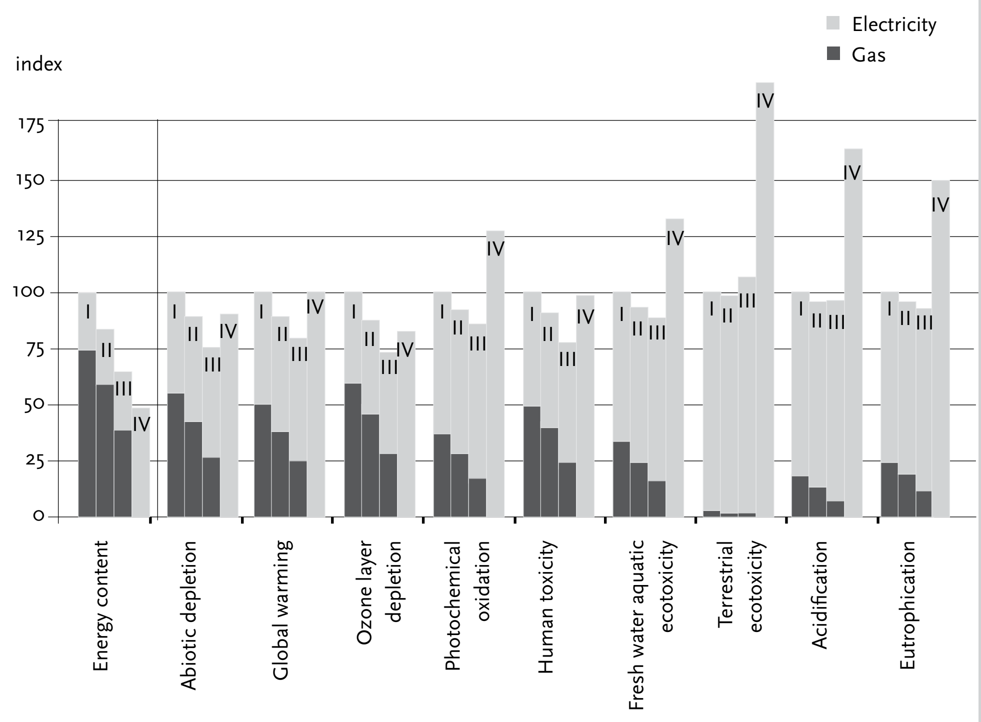
through each connection. The environmental effects of the low-pressure network and connection piping per cubic metre of gas delivered are calculated by dividing the total environmental effects of the network by the total amount of gas delivered during the network's service life.

- Material resources and production processes related to the climate systems and appliances in the dwelling are not within the scope of the research and are therefore not taken into account.
- There is no data on gas-fired cooking devices available in the ecoinvent database. Thus, it is assumed that burning gas in a non-condensing modulating boiler leads to the same emissions as burning gas on gas hobs.

## 4.3 Results

This section discusses the results of the environmental assessment of the energy consumption scenarios. The environmental assessment results are shown as the annual contributions of a single apartment to various environmental impact categories.

**Figure 4.2 Comparison of the environmental impact of annual gas and electricity consumption per apartment according to Scenarios I (reference), II, III and IV**

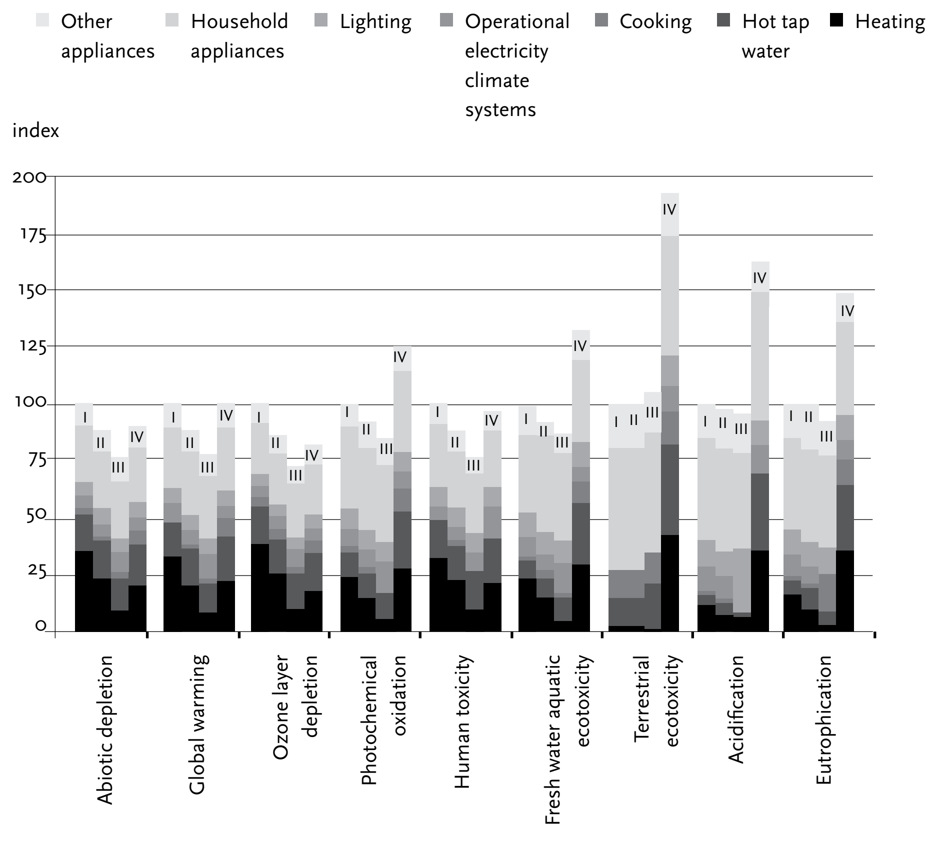


## 4.3.1 Comparison of energy consumption scenarios

The first aim of the study is to compare the annual environmental impact of four different energy consumption scenarios in the reference apartment. Figure 4.2 shows the relative energy content of gas and electricity consumed in each scenario and the environmental impact of the energy consumption in Scenarios I, II, III and IV. The total energy content and the environmental impact scores of Scenario I were set to an index of 100. The scores of the other scenarios are relative to Scenario I.

Figure 4.2 shows that the fraction of the environmental impact due to electricity consumption is higher than the proportion of electricity in the total energy content. The main reason for this is that electricity, which is produced from other energy sources such as gas and coal, is less efficient for heating dwellings than heating by gas combustion, since energy is partly lost in the conversion process. Gas consumption in Scenario I makes a high contribution to Abiotic depletion (55%), Global warming (50%), Ozone layer depletion (59%) and Human toxicity (51%). However, limiting heat loss by replacing glazing (Scenario II) reduces gas consumption by 22.5%, resulting in an 11-13% reduction in its contribution to the four environmental impact categories mentioned above. When both glazing and the climate system are replaced (Scenario III), gas consumption decreases by 49% but electricity consumption rises by 8%. These measures lead to a 22-27% reduction in the contribution to

Figure 4.3 Comparison of indexed environmental impact of energy consumption in Scenarios I (reference), II, III and IV, divided into categories

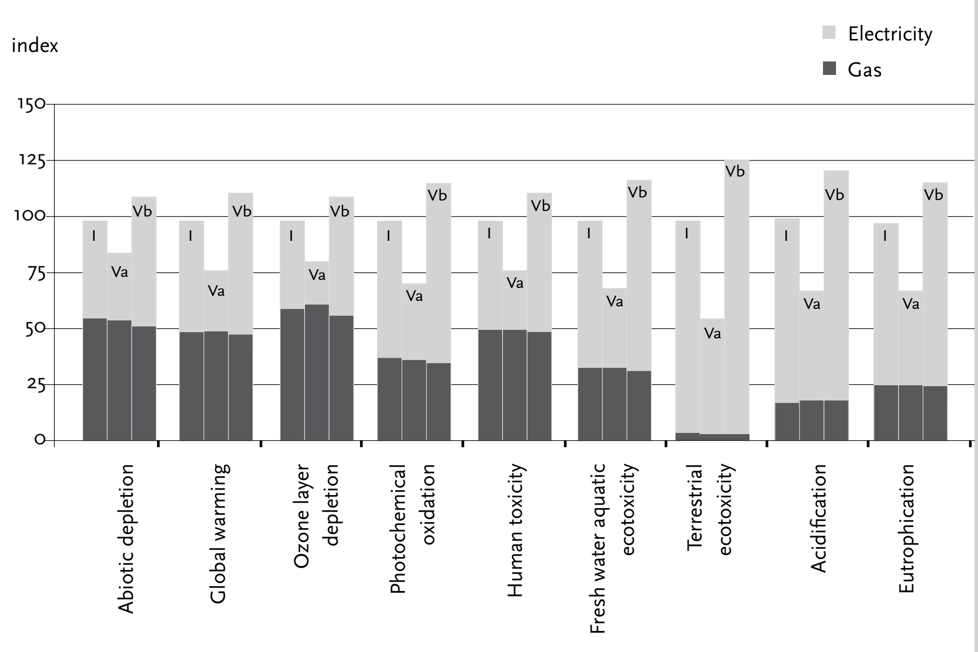


the four environmental impact categories mentioned above, but a 6% increase in the contribution to Terrestrial ecotoxicity, due to increased electricity consumption. Thus, the additional electricity used for a balanced ventilation system and more efficient boiler counteracts some of the positive effects of using less gas. This means that the benefits of saving gas are very small or non-existent in relation to the environmental impact categories that are dominated by electricity: Photochemical oxidation, Fresh water aquatic ecotoxicity, Terrestrial ecotoxicity, Acidification and Eutrophication.

The electricity-only Scenario IV performs worst on these latter categories. The contribution to Photochemical oxidation, Fresh water aquatic ecotoxicity, Terrestrial ecotoxicity, Acidification and Eutrophication is 25-92% higher than reference Scenario I, and 33-93% higher than Scenario II, which has comparable glazing. Scenario IV is comparable to Scenario I for Global warming and Human toxicity, but performs 8-11% worse than Scenario II. Scenario II and IV are comparable for Abiotic depletion and Ozone layer depletion. In Scenario IV, half of all of the electricity is used for heating, hot tap water and cooking, not including auxiliary electricity use.

Figure 4.3 presents the same results as Figure 4.2, but the energy consump-

**Figure 4.4 Comparison of the indexed environmental impact of the annual energy consumption per apartment according to Scenarios I (reference), Va and Vb**



tion is categorised into gas consumption for heating, hot tap water and cooking, and electricity used for the climate system operation, lighting, household appliances and other appliances. In Scenario IV, all of the categories are powered by electricity.

Figure 4.3 shows that in Scenario I, the category of gas consumption for heating contributes most to Abiotic depletion, Global warming, Ozone layer depletion and Human toxicity. For all other scenarios and environmental impact categories the electrical household appliances have the greatest negative impact, even when electricity is used for heating, cooking and hot tap water as is the case in Scenario IV. In Scenarios I and II, heating provided by gas also has a greater environmental impact than hot tap water provided by gas. In Scenario III, the reverse is true. In Scenario IV, the environmental impact of both heating and hot tap water being provided by electricity is of the same order of magnitude, but is much higher in comparison with Scenarios I, II and III. Cooking with electricity produces a negative impact that is higher by a factor of 3 to 15 than cooking with gas. The environmental impact related to operational electricity use for climate systems is greatest in Scenario III, which can mostly be attributed to the balanced ventilation system.

### 4.3.2 Comparing variations in electricity and gas consumption due to user behaviour

In Scenarios Va and Vb, variations in user-related electricity consumption are compared with reference Scenario I. Figure 4.4 shows the results of the comparison. The environmental impact score of Scenario I was set to an index of 100 for each impact category. The scores of the other scenarios are relative to Scenario I.

The electricity consumption in Scenario Va is 47% lower and in Scenario Vb 27% higher than in Scenario I. Additionally, gas consumption in Scenario Vb is 4% lower due to cooking with gas being replaced by cooking with electricity. Figure 4.4 shows that the negative environmental impact in Scenario Va is 9-45% lower than in Scenario I, while Scenario Vb shows an increase in the environmental impact of 9-26%. The differences in the environmental impact between Scenario Va and Vb range from 30-70%.

Scenarios VIa and VIb apply variations in user-related gas consumption and are compared with reference Scenario I. Gas consumption is 8% higher in Scenario VIa and 8% lower in Scenario VIb, in comparison with Scenario I. The results of this comparison are not shown because the differences between the scenarios are small and similar for all environmental impact categories. The results reveal a 0-4% decrease in the environmental impact in Scenario VIa and a 0-4% increase in Scenario VIb compared with Scenario I.

### 4.3.3 Environmental impact of gas consumption

The contribution of gas consumption to the environmental impact categories occurs in different phases, from gas extraction to the combustion of gas in the dwelling. Figure 4.5 shows the main contribution of each phase to the environmental impact categories. Only fractions equivalent to more than 5% are shown.

The extraction of natural gas only contributes significantly to Abiotic depletion (97%) and Human toxicity (34%). The depletion of natural gas reserves is the reason for the high score in the former impact category, while exploration and production wells contribute to the latter by means of substance emissions into water, which might be reduced by process improvements. After extraction, gas is transported through long-distance pipelines. In this phase, the emissions from diesel and gas-fired pumps and compressors dominate the Ozone layer depletion impact category, which might be solved by exploring alternative technology. The high-pressure distribution network does not contribute more than 5% to any of the environmental impact categories, but the low-pressure distribution network does. The source of most of the environmental impact of the low-pressure distribution network is the reinforcing steel and copper used in the capital goods. The copper low-pressure pipelines are responsible for the total contribution of the low-pressure distribution system to Human toxicity and for 25% of the contribution to Acidification, which equals 7% of the total contribution of gas consumption to Acidification. The source of the contribution to Fresh water aquatic ecotoxicity is the disposal of plastics related to the low-pressure pipelines (18%), and the dis-

**Figure 4.5 Environmental impact of gas burned in HE100 boiler**

| | Abiotic depletion | Global warming | Ozone layer depletion | Photo-chemical oxidation | Human toxicity | Fresh water aquatic ecotoxicity | Acidification | Terrestrial ecotoxicity | Eutrophication |
|---|---|---|---|---|---|---|---|---|---|
| Gas extraction | 97% | | | | 34% | | | | |
| Long-distance transport | | | 93% | | | | | | |
| High-pressure distribution | | | | | | | | | |
| Low-pressure distribution | | | | 20% | 11% | 81% | 75% | 31% | 17% |
| Gas combustion | | 93% | | 56% | 46% | | | 39% | 49% |
| | 97% | 93% | 93% | 75% | 91% | 81% | 75% | 70% | 66% |

posal of slag from steel production, nickel smelter slag, sludge from steel rolling and bauxite red mud (aluminium production), which are all related to the capital goods. Finally, the only phase that can be influenced in the dwelling is gas combustion in the HE100 boiler, which dominates the Global warming impact category and is a significant contributor to the impact categories of Photochemical oxidation, Human toxicity, Acidification and Eutrophication. The remaining contributions to the different impact categories cannot be assigned to any specific phase, from extraction to burning, but are the accumulation of the many processes and capital goods required to produce natural gas for the consumer.

### 4.3.4 Environmental impact of Dutch electricity consumption

The environmental impact of Dutch electricity consumption is due to power plants fuelled by different resources, such as hard coal and natural gas, and renewable resources such as wind and solar energy. Additionally, electricity generated in Germany and Belgium is imported to the Netherlands. The distribution network also has an environmental impact through production, maintenance and waste processing. Figure 4.6 shows the origins of the environmental impact of electricity consumption.

Hard coal power plants provide only 19% of Dutch electricity, but are responsible for 23-51% of the environmental impact in six out of the nine impact categories. Their contribution to Abiotic depletion is mostly due to the depletion of hard coal reserves. Substances emitted during the burning

**Figure 4.6 Environmental impact of the Dutch electricity mix in 2004[a]**

| | Abiotic depletion | Global warming | Ozone layer depletion | Photo-chemical oxidation | Human toxicity | Fresh water aquatic ecotoxicity | Acidifica-tion | Terrestrial ecotoxicity | Eutrophi-cation |
|---|---|---|---|---|---|---|---|---|---|
| Electricity from hard coal (19%) | 30% | 31% | 7% | 39% | 10% | 23% | | 51% | 42% |
| Electricity from natural gas (19%) | 52% | 43% | 53% | 26% | 31% | 6% | | 15% | 29% |
| Electricity from industrial gas | | 7% | | | | | | | |
| Import from Germany | 14% | 15% | 9% | 14% | 6% | 32% | | 13% | 11% |
| Distribution network | | | | 9% | 39% | 24% | 94% | 8% | |
| | 96% | 96% | 69% | 88% | 86% | 85% | 94% | 87% | 82% |

a) The remaining contributions to the different impact categories cannot be assigned to any specific process.

of hard coal are the reason for most of the Global warming contribution of electricity generated from hard coal and they also account for 26-42% of the contribution to Photochemical oxidation, Human toxicity, Acidification and Eutrophication. The operation of oceanic freight ships in which the coal is transported account for 32-40% of the contribution to the same four environmental impact categories. The blasting of hard coal contributes 8% and 19% respectively to Acidification and Eutrophication. Finally, the power plants contribute to Fresh water aquatic ecotoxicity through the disposal of cooling tower residue, hard coal ash, nickel smelter slag and steel.

Natural gas power plants provide 50% of Dutch electricity, but account for less than 50% of the environmental impact of this electricity source in seven out of the nine impact categories. The depletion of natural gas reserves is the reason for most of the contribution of electricity generated from natural gas to Abiotic depletion. The combustion of natural gas emits substances that contribute to the impact categories of Global warming, Photochemical oxidation, Acidification and Eutrophication. The contribution to Human toxicity is partly due to gas combustion in the power plant, but half of the contribution is due to the emission of substances into water in the exploration well. The contribution to Ozone layer depletion is due to diesel and gas-fired engines used in the long-distance transportation network.

Finally, the electricity distribution network contributes significantly to three environmental impact categories. A combination of all emissions into soil and air accounts for the environmental impact in the category of Terrestrial ecotoxicity. Copper blasting is responsible for 45% of the contribution to Human toxicity, while 15% is due to the disposal of steel. The source of Fresh water aquatic ecotoxicity is the disposal of nickel smelter slag (48%), the disposal of chrome preserved wood poles (8%) and the use of copper (6%).

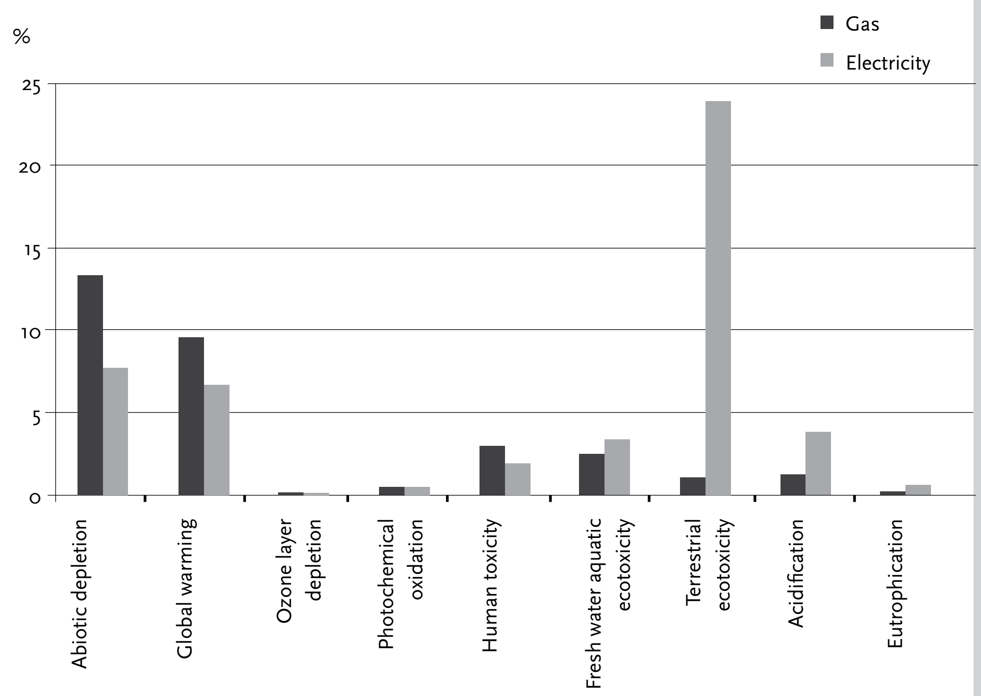
None of the processes and capital goods involved in the supply of electricity can be influenced by building design or decisions of the owner. Occupants may, however, request electricity from sustainable resources from the electricity supplying companies, which are subsequently obligated to generate or buy more sustainable electricity. Another alternative is to produce electricity at the building site, for example by applying photovoltaic solar panels.

### 4.3.5 Normalisation

The normalisation of the results involves the comparison of the environmental impact of a product or process with the total annual environmental impact in a certain region and year. In this study, the results are normalised to the Netherlands using 1997 as a reference year (Guinée, 2002). The main aims of normalisation are the provision of a comparable scale between impact categories, a rough error check of the results and a reference value that is constant over time, which is why the 1997 values are still used (van Oers and Huppes, 2001). In this section, the average annual gas and electricity consumption of all households are compared with the total environmental impact in the Netherlands in the reference year. The total gas consumption is the average gas consumption of all dwelling types, which is 1530 $m^3$ gas per household per year multiplied by 7 million households. Similarly, the average annual electricity consumption of 3350 kWh per household per year is multiplied by 7 million. Figure 4.7 shows the environmental impact of gas and energy consumption of households as a percentage of the annual environmental impact in the Netherlands.

Figure 4.7 shows that residential gas consumption is the source of approximately 13% of the total Abiotic depletion and 9% of total Global warming caused in the Netherlands, which are equivalent to factors of 6 and 4 respectively more than other kinds of environmental impact caused by gas consumption. The electricity consumption of households accounts for almost 24% of the total national contribution to Terrestrial ecotoxicity. This result suggests that almost all of the contribution to Terrestrial ecotoxicity in the Netherlands is caused by electricity consumption, since households consume about 25% of all electricity consumption in the European Union (Section 4.1). However, as indicated in Subsection 4.2.1, the ecotoxicity scores have a higher level of uncertainty due to flaws in the modelling of metal substances in ecosystems. The contributions to Abiotic depletion and Global warming are

Figure 4.7 Normalised environmental impact of total annual residential gas and electricity consumption in the Netherlands



8% and 7% respectively. The ratio of the impact of gas and electricity is different to the results shown in Subsection 4.3.1. This is because the average gas consumption of all households is much higher than the average gas consumption of households living in apartments, while electricity consumption is more closely related to household size and income. Electricity consumption in the reference apartment is equal to the average electricity consumption of all households.

### 4.3.6 Sensitivity analysis: electricity supply

Figure 4.2 showed that electricity makes a major contribution to most environmental impact categories. Therefore, the electricity mix used in the analysis influences the results of the calculations; this was also shown in a study by Shah *et al.* (2008). Furthermore, electricity consumption is highly variable due to user behaviour in the dwelling, while average electricity consumption in the European Union has been rising by 2% per year despite the increased energy efficiency of appliances (ECN, 2008). This section assesses the effect of different electricity mixes on the environmental impact of energy consumption in the reference building. The electricity mix used for calculations in this research is the 2004 electricity supply mix from the Dutch grid (Frischknecht *et al.*, 2007b). An alternative electricity mix that uses more electricity from renewable sources was also defined, based on policy goals for 2020 (Ministerie van VROM, 2009), which state that 35% of the electricity supply should be gen-

**Table 4.5 Composition of the Dutch electricity supply mix (%) in 2004 and 2020**

| Source of electricity | 2004 | 2020 |
|---|---|---|
| *Conventional sources* | *73.3* | *57.7* |
| - Coal | 19.1 | 15.0 |
| - Lignite | - | - |
| - Oil | 2.3 | 1.8 |
| - Natural gas | 49.6 | 39.1 |
| - Coke-oven | 2.2 | 1.8 |
| *Hydropower* | *0.1* | *0.1* |
| *Heat storage* | - | - |
| *Nuclear power* | *3.1* | *2.4* |
| *Renewable sources* | *3.3* | *32.9* |
| - Wind power onshore | 1.6 | 3.7 |
| - Wind power offshore | 0.0 | 11.8 |
| - Biomass | 1.5 | 16.3 |
| - Bio gas | 0.2 | - |
| - Photovoltaic | - | 1.2 |
| - Geothermal | - | - |
| *Waste incineration* | *2.1* | *0.9* |
| *Import from Germany* | *14.7* | *6.0* |
| *Import from Belgium* | *3.4* | - |
| **Total** | **100** | **100** |

Sources: Frischknecht *et al.*, 2007b; Ministerie van VROM, 2009; Van Dril and Elzenga, 2005; Van Tilburg *et al.*, 2006

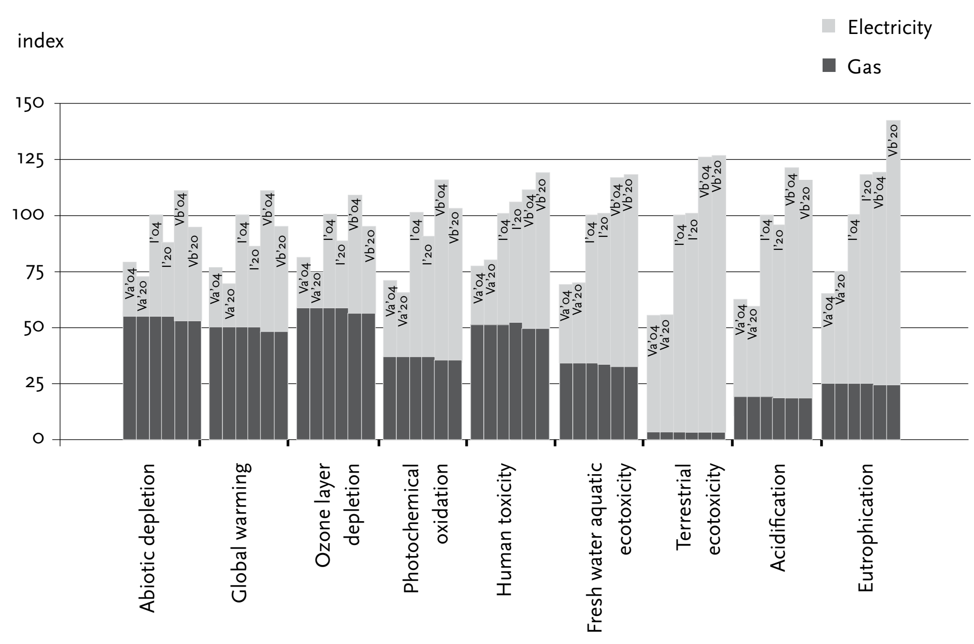
erated from renewable sources by 2020. Table 4.5 shows the composition of the regular 2004 electricity mix and the electricity mix aspired for 2020. It is assumed that 35% of the electricity production mix will be generated from renewable sources. Since 6% of the electricity mix is imported from Germany, 35% sustainable energy production equals 32.9% of the electricity supply mix. The fractions of individual renewable sources are in the same proportions as the prospective German electricity production mix as described in BEE and AEE (2009). The remaining sources of electricity are in the same proportions as the 2004 Dutch electricity supply mix.

Figure 4.8 compares reference Scenario I with Scenarios Va and Vb, all three having the 2004 and 2020 electricity mixes. The environmental impact score of Scenario I with the 2004 electricity mix has been set to an index of 100 in each impact category. The scores of the other scenarios are relative to Scenario I.

Figure 4.8 shows that the 2020 electricity mix contributes slightly more to Human toxicity, Fresh water aquatic ecotoxicity and Eutrophication than the 2004 electricity mix. The higher contribution to these three impact categories is mainly due to the production of electricity from biomass (cogeneration). The relatively high contribution to Fresh water aquatic ecotoxicity of the 2020 electricity mix is also due to the use of stainless steel in the offshore plant for the production of electricity from wind power.

When the 2020 electricity mix is used, a 20-45% reduction in environmental impact is observed for Scenario Va and between a 6% reduction to a 43% increase for Scenario Vb compared with Scenario I (2004 mix). The 2020 elec-

**Figure 4.8 Comparison of the Reference scenario I with Scenario Va and Scenario Vb, all with the 2004 and 2020 electricity mixes**

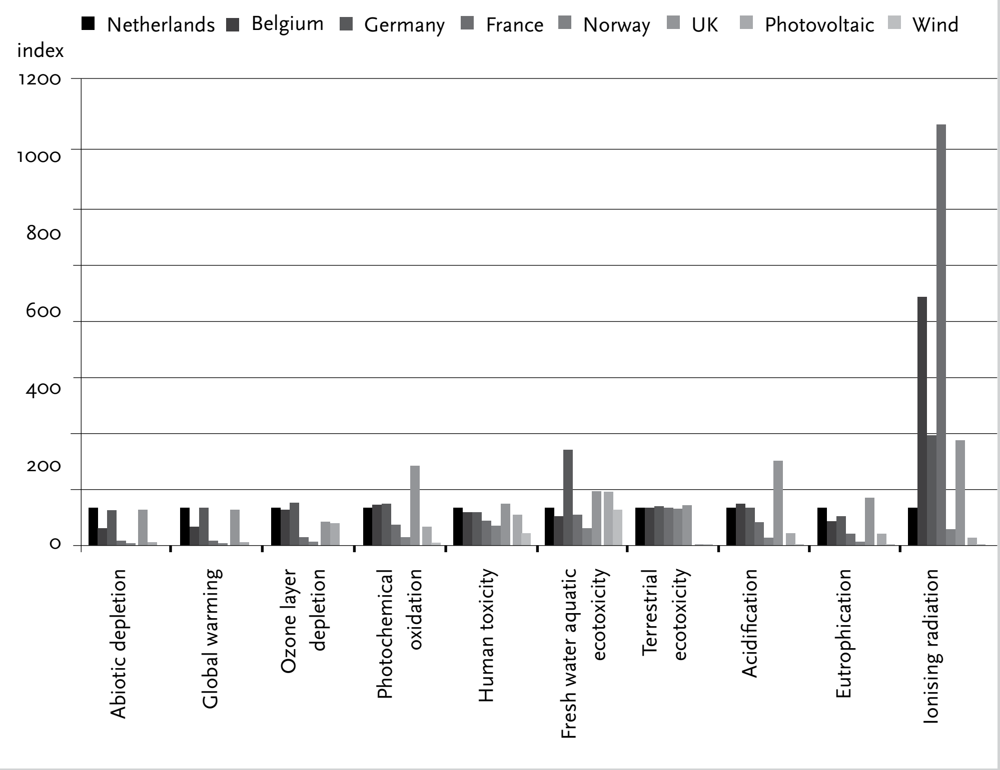


tricity mix performs better for Abiotic depletion, Global warming, Ozone layer depletion, Photochemical oxidation and Acidification than the 2004 mix. For the other environmental impact categories, the 2004 electricity mix performs better. The difference between Scenarios Va and Vb for the 2020 electricity mix is between 20-70%. The range is smaller than that of the 2004 electricity mix for the environmental impact categories that benefit from using more sustainable resources, while the range is equal or greater for the environmental impact categories that are negatively affected by the more sustainable resources.

In other countries, electricity is generated from different sources. Figure 4.9 shows a comparison between the 2004 electricity mixes of the Netherlands and five other countries. The composition of the electricity mixes is shown in Table 4.6. Belgium, Germany and the United Kingdom (UK) are included because the Dutch electricity grid is connected to their grids. France is included because it has a large share of nuclear power plants, and Norway because it has a high share of hydropower plants. Furthermore, the electricity mixes of all six countries are compared with a 100% photovoltaic electricity supply from the grid and a 100% wind power supply to show the possible theoretical environmental impact reductions when 100% sustainably generated electricity is used. The wind power electricity data and the production data for the photovoltaic cells are general for Europe, while the efficiency of the photovoltaic electricity generation is specific to the Netherlands.

The original set of environmental impact categories does not include nucle-

Figure 4.9 Comparison of the 2004 electricity mixes of 6 countries and electricity from wind power and photovoltaic cells



Source: Frischknecht *et al.*, 2007b

ar radiation. Therefore, the CML impact category of Ionising radiation is added to cover the impact arising from the release of radioactive substances and direct exposure to radiation. There are different types of radiation which act differently on living tissue, therefore the contribution to this impact category is expressed in DALY: disability-adjusted life years (Goedkoop and Spriensma, 2001).

The results in Figure 4.9 show that the Norwegian electricity mix, which is mostly hydropower, has the smallest environmental impact of the six country mixes. Second is the electricity mix of France, mostly using nuclear power, except for the Ionising radiation impact category. Belgium, Germany and the UK all use some nuclear energy, which explains the high contribution to Ionising radiation. The electricity mixes of Belgium, Germany and the Netherlands have a similar environmental impact, with small variations due to changes in the composition of the electricity mix. Even though the Dutch electricity mix contains a high share of electricity from fossil fuels (73%) it does not have the highest environmental impacts, since the type of fossil fuel used (gas) offers a more sustainable electricity generation than other fossil fuels. Finally, the UK electricity mix has the highest environmental impact in relation to most impact categories due to the high share of electricity from hard coal power plants.

Electricity generated from wind power has the smallest environmental

**Table 4.6 Composition of the 2004 electricity supply mix (%) in Belgium Germany, France, the Netherlands, Norway and the United Kingdom**

| Source of electricity | Belgium | France | Germany | Netherlands | Norway | UK |
|---|---|---|---|---|---|---|
| *Fossil fuels* | *34.5* | *8.9* | *8.9* | *73.3* | *0.4* | *74.6* |
| - Hard coal | 9.1 | 4.4 | 4.4 | 19.1 | 0.0 | 32.6 |
| - Lignite | - | - | - | - | - | - |
| - Oil | 1.7 | 1.0 | 1.0 | 2.3 | 0.0 | 1.1 |
| - Natural gas | 21.4 | 3.1 | 3.1 | 49.6 | 0.3 | 39.9 |
| - Industrial gas | 2.3 | 0.5 | 0.5 | 2.2 | 0.0 | 1.0 |
| *Hydropower* | *0.3* | *10.6* | *10.6* | *0.1* | *86.4* | *1.3* |
| *Pumped storage hydropower*[a] | *1.3* | *0.9* | *0.9* | - | *0.4* | - |
| *Groundwater circulation*[b] | - | - | - | - | - | *0.7* |
| *Nuclear power* | *46.6* | *76.8* | *76.8* | *3.1* | - | *19.1* |
| *Renewable sources* | *0.9* | *0.6* | *0.6* | *3.3* | *0.5* | *1.5* |
| - Wind power | 0.2 | 0.2 | 0.2 | 1.6 | 0.2 | 0.5 |
| - Wind power on shore | - | - | - | - | - | - |
| - Wind power offshore | - | - | - | - | - | - |
| - Biomass | 0.5 | 0.2 | 0.2 | 1.5 | 0.2 | 1.0 |
| - Biogas | 0.2 | 0.1 | 0.1 | 0.2 | - | - |
| - Photovoltaic | - | - | - | - | - | - |
| - Tidal power[b] | - | 0.1 | 0.1 | - | - | - |
| *Waste incineration* | *1.2* | *0.6* | *0.6* | *2.1* | *0.1* | *0.4* |
| *Import* | *15.1* | *1.6* | *1.6* | *18.2* | *12.2* | *2.5* |
| **Total [%]** | **100** | **100** | **100** | **100** | **100** | **100** |

a) During low electricity demand, water is pumped in elevated water reservoirs. During peak demand, the water is released through turbines to create electricity.

b) These sources of electricity are not included in the ecoinvent database and are therefore omitted from the calculations.

impact of all electricity mixes, except for the Fresh water aquatic ecotoxicity impact category. The contribution to this category is due to the wind turbines needed to generate the electricity and the distribution network. Electricity generated from photovoltaic cells generally has a lower environmental impact than the French electricity mix – which is mostly nuclear power generated – on all impact categories, and a higher environmental impact than the Norwegian electricity mix – mostly hydropower generated – on all impact categories except Terrestrial ecotoxicity and Ionising radiation.

In order to reduce the environmental impact of energy consumption by changing the electricity supply mix it is necessary to replace electricity generated from fossil fuels by electricity coming from other sources. Electricity generated by wind power has 92-98% less environmental impact than the current Dutch electricity mix, except for the Fresh water aquatic ecotoxicity impact category, to which wind power contributes only 6% less than the current Dutch electricity mix. Electricity from photovoltaic cells, hydropower and nuclear power are all generally less damaging to the environment than the current Dutch electricity mix, but all have drawbacks. Nuclear power will generate radioactive waste, hydropower has to be imported and requires the building of dams and the flooding of land, and photovoltaic cells require the use of damaging materials. However, photovoltaic technology is relatively new, and efficiency and material use are likely to be optimised in the future.

## 4.4 Conclusion and discussion

The first aim of the study was to compare the negative environmental impact of gas consumption with that of electricity consumption in the reference apartment dwelling and to assess how this changes when energy saving measures are taken. The results show that electricity consumption has a higher negative impact on the environment than gas per MJ of energy. Electricity consumption dominates all environmental impact categories except Abiotic depletion, Global warming, Ozone layer depletion and Human toxicity. In these impact categories, the contribution of gas consumption is in the same order of magnitude as the contribution of electricity consumption. However, the reference dwelling is an apartment with relatively low heat demand compared with other dwelling types. When the average gas and electricity consumption of all households in all dwelling types are compared, gas consumption contributes most to the environmental impact categories of Abiotic depletion, Global warming and Human toxicity. In the reference dwelling, gas consumption and its related environmental impact can be reduced by up to 25% by introducing high-efficiency glazing and more efficient climate systems; although an increase in some environmental impact categories can occur due to additional electricity use for the operation of the climate system. Finally, the results show that although a heat pump does not directly use fossil fuels as a heat source it still needs electricity to operate and thereby makes an equal or higher contribution to the environmental impact categories than a gas-fired boiler when its CoP is in the range 2.3- 3.2. However, this research does not take into account the materials used in the climate systems. Prior research has shown that because the mass of a heat pump is about twice the mass of a boiler and refrigerants are also used in heat pump systems, the difference in the environmental impact of the two systems will be even larger (Blom *et al.,* 2010b). On the other hand the CoP of heat pumps is continuously increasing, which will reduce their environmental impact related to electricity use.

The second aim of the research was to assess the environmental impact of building-related energy consumption and user-related energy consumption. In the reference apartment dwelling, electrical household appliances caused most of the negative environmental impact (20-45%), except for Scenario I, in which gas used for heating made a higher contribution to Abiotic depletion, Global warming, Ozone layer depletion and Human toxicity. All electrical appliances combined caused 30-70% of the total environmental impact. As gas consumption for space heating decreases, gas consumption for hot tap water becomes a more important factor regarding environmental impacts of the heating system. Therefore, new technology for reducing energy use for hot tap water, recovering heat from washed away hot tap water and locally generating heat from sustainable resources may help to further decrease gas consumption in households. Occupants of dwellings may endeavour to reduce the use of hot tap water for bathing and showering.

The third research question concerned how much the environmental impact of household energy consumption changes due to variations in user behaviour. When gas consumption is varied by -8% to +8% of the reference gas consumption, the environmental impact for all categories respectively decrease or increase by 0-4%. Since changes in user behaviour do not lead to great changes in gas consumption, this is an ineffective way to reduce the overall environmental impact of household energy consumption. In contrast, electricity consumption is highly related to user behaviour. Changes in behaviour, which in the context of this research means changes in the number of appliances present in the dwelling and their energy efficiency can lead to reductions in the negative environmental impact of up to 60%.

The fourth aim of the research was to assess the origin of the environmental impact of gas and electricity consumption. The environmental impact of electricity and gas consumption is due to resource depletion, fuel combustion, fuel transportation (gas, coal) and the distribution network. This study shows that different phases of the energy supply chain contribute to different environmental impact categories. The only way to proportionally decrease the environmental impact for all categories is to reduce final energy consumption. However, total annual energy consumption in Dutch households is rising. Gas consumption is rising because of the increasing number of households, even though gas use per household is decreasing, while electricity consumption is rising due to a combination of rising numbers of households and increasing numbers of appliances in each household, even though most household appliances are increasingly efficient (EnergieNed, 2008). Since energy consumption continues to rise, reducing the negative environmental impact of energy consumption might be more efficient when done on the supply side, by changing to different resources for electricity production or developing new sustainable technology. However, changing to the 35% sustainable electricity mix in 2020 as described in this study will not significantly reduce the environmental impact in all categories, and if electricity consumption remains equivalent it will lead to a maximum 14% impact reduction for Abiotic depletion, Global warming, Ozone layer depletion and Photochemical oxidation. However, the results of the 2020 mix in this study are influenced by the use of electricity generated from biomass (cogeneration), which makes a high contribution to Human toxicity, Fresh water aquatic ecotoxicity and Eutrophication. Therefore, the type of sustainable resource used should be chosen carefully.

This study has shown that residential gas consumption significantly contributes to the environmental impact categories of Abiotic depletion, Global warming, Ozone layer depletion and Human toxicity. These impacts can be effectively reduced using building measures that reduce heat demand. However, when heat demand is lowered by embedding more electric climate systems or when gas consumption for heating and hot tap water is replaced by electricity consumption, special attention should be paid to the shift in environmental impacts from the aforementioned four impact categories to the lesser known impact categories of Photochemical oxidation, Fresh water aquatic ecotoxicity, Terrestrial ecotoxicity, Acidification and Eutrophication. The amount of electricity consumed is mainly user-related, therefore changes in user behaviour may be effective in reducing the environmental impact of electricity consumption. Because electricity consumption in households continues to rise, the environmental impact could best be addressed by a combination of reducing the environmental impact of the electricity supplied, generating power locally and encouraging households to use less electricity.

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# 5 Total environmental impact of maintenance, replacement and energy consumption in Dutch dwellings

*Research completed: 2010*
*An overview of all results can be found in Appendix* 5.

## 5.1 Introduction

In the previous chapters the environmental impacts of groups of activities in the operational phase of dwellings were assessed: the maintenance and replacement of façade components in Chapter 2; the maintenance, replacement and use of climate systems in Chapter 3; and building-related and user-related energy consumption in Chapter 4 (Figure 5.1). In this chapter the operational phase of the reference apartment building is assessed as a whole, including the replacement of kitchen, bathroom and toilet.

Specific factors that contribute to environmental impact are assessed in all groups of activities, namely: the material resources used, waste processing and transportation for maintenance workers. Finally, energy consumption is addressed in relation to façade components (gas for heating) and climate systems (gas for heating and hot tap water, electricity for operation). In Chapter 4 the total gas and energy consumption of households was assessed, including user-related energy consumption in the form of gas for cooking and electricity for lighting and electrical appliances. The V in Figure 5.1 indicates a relationship between the group of activities and the contributing factors, while the – indicates that there is no relationship assumed in this research (see: Section 1.6).

The primary aim of this chapter is to identify the factors that contribute significantly to environmental problems with a view to eventually reducing the environmental impacts caused in the operational phase of dwellings. The research questions are:

1. What are the environmental impacts in the operational phase of the reference building?
2a. Which of the following factors contribute significantly to the environmental impact categories: material resources; waste processing; transportation; gas consumption; electricity consumption?
2b. Which of the following groups of activities contribute significantly to the environmental impact categories: façade maintenance and replacement; climate systems maintenance and replacement; kitchen and bathroom replacement?
3. To what extent do changes in the groups of activities affect the environmental impacts?

**Figure 5.1 Groups of activities and contributing factors to environmental impacts in the use phase of dwellings**

| | Group of activities | Contributing factors | | | |
|---|---|---|---|---|---|
| | | Material resources | Waste processing | Transportation of maintenance workers | Energy consumption |
| Chapter 5 | Chapter 2 Facade components maintenance and replacement | V | V | V | V |
| | Chapter 3 Climate systems maintenance, use and replacement | V | V | V | V |
| | Chapter 4 User-related energy consumption | – | – | – | V |
| | Kitchen, bathroom and toilet replacement | V | V | V | – |

V = relationship assumed between group of activities and contributing factors

4. How does the environmental impact in the operational phase of the reference building accumulate in time?

The fourth main research question as formulated in Section 1.3: ‘How can the environmental impact be reduced most effectively?’ will be answered in Chapter 6.

## 5.2 Methodology

The methodology used in this chapter is the same as the methodology in Chapters 2, 3 and 4: several scenarios for the operational phase of the reference dwelling are assessed and compared. This section presents data on the kitchen, bathroom and toilet (Subsection 5.2.1) and a description of the assessment scenarios (Subsection 5.2.2).

Figure 5.2: Kitchen lay-out in the reference apartment dwelling.

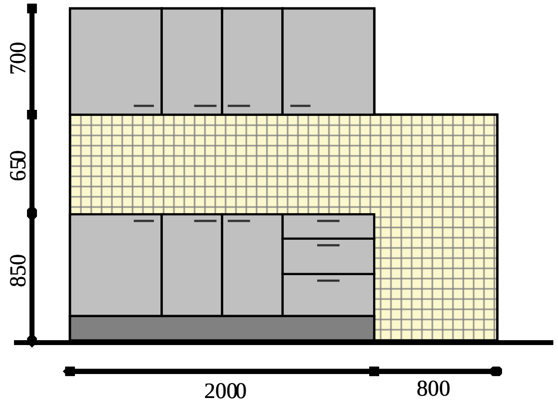


Table 5.1 Materials used (in kg) in the kitchen, bathroom and toilet of one reference dwelling[a]

| Materials | | Bathroom | Tool | Kitchen |
|---|---|---|---|---|
| Metal | Brass | 5.4 | 1.4 | 1.0 |
| | Stainless steel 16/10 grade | - | - | 4.0 |
| | Stainless steel 18/8 grade | - | - | 2.1 |
| | Steel | - | - | 9.0 |
| Plastic | LDPE - low-density polyethylene | 0.0 | 0.0 | - |
| | Melamine | - | - | 8.4 |
| | PA (polyamide (nylon 66)) | - | - | 1.6 |
| | PP (polypropylene) | 0.5 | 0.5 | 0.6 |
| | PS (polystyrene) | - | 2.9 | - |
| | PVC (polyvinylchloride) | - | 1.8 | - |
| | Synthetic rubber | - | - | 0.1 |
| Stone | Ceramic tiles, wall | 248.9 | 62.5 | 30.6 |
| | Tile adhesive (dry weight) | 58.7 | 14.5 | 7.5 |
| | Tile grout (dry weight) | 3.9 | 1.0 | 0.5 |
| | Sanitary ceramics | 15.2 | 37.7 | - |
| Wood | Fibreboard, hard | - | - | 48.3 |
| | Particle board, indoor | - | - | 131.3 |
| | Particle board, outdoor | - | - | 31.1 |

a) Stainless steel 16/10 grade: EN 1.4408; Stainless steel grade 18/8: EN 1.4310.

### 5.2.1 Kitchen, bathroom and toilet

The reference apartment contains a kitchen of 6.5 m$^2$, a bathroom of 3 m$^2$ and a separate toilet of 1 m$^2$. The components in the assessment are the same as those provided in social housing, namely: kitchen cabinets, including shelves, drawers, doors and handles; counter top; sinks and taps, including drainpipe under sink; toilet; shower tap; wall tiling; floor tiling (bathroom and toilet on-

**Table 5.2 Waste scenarios for materials used in kitchen, bathroom and toilet in the reference dwelling (in %)[a]**

| Waste type | Materials | Landfill | Incineration | Recycling |
|---|---|---|---|---|
| Non-ferro | Brass | 5 | 5 | 90 |
| Steel[d] | Steel, stainless steel | 5 | 0 | 95 |
| Plastics | PA, synthetic rubber | 20 | 80 | 0 |
| PE | LDPE | 10 | 85 | 5 |
| PP | PP | 10 | 85 | 5 |
| PS | PS | 5 | 90 | 5 |
| PVC[c] | PVC | 10 | 10 | 80 |
| Wood | Melamine[b] | 5 | 95 | 0 |
| Ceramics 1[e] | Ceramic tiles | 100 | 0 | 0 |
| Ceramics 2 | Sanitary ceramics | 15 | 0 | 85 |
| Cement[e] | Tile adhesive, tile grout | 100 | 0 | 0 |
| Wood | Fibreboard, particle board | 5 | 95 | 0 |

a) The waste scenarios are equal to those included in NEN , 2004, except for the undefined waste types and those indicated.
b) The coating of fibreboard and particle board is made of melamine.
c) The actual percentage of recycled PVC is likely to be much lower. The value used in this research is part of a set of representative Dutch building waste scenarios found in EcoQuantum.
d) NEN 8006, 2004: steel is completely recycled or reused. 1% of light steel elements go to landfill.
e) Not available in NEN 8006, 2004.

Source: Van der Sman, 2002

ly). Not included are the wall and floor finishing in the kitchen, ceiling paint, appliances, shower curtain and rod. The shower in the bathroom consists of a floor threshold and a tap. A shower cabin or shower tray is not provided. This is common in Dutch housing association dwellings. Figure 5.2 shows the lay-out of the kitchen. Table 5.1 shows the amount of material used for the kitchen, bathroom and toilet of one apartment; and Table 5.2 shows the waste scenarios for the materials used. The type and total weight of materials used in the kitchen were derived from the Faktum/Rationell kitchen series of IKEA (2010), which is representative of standard kitchens in dwellings owned by housing associations. Data on sanitary equipment was derived from the Sphinx 300 product series (2010a). Information on tiles, tile adhesive and grout was obtained from Sphinx tiles (2010b) and Beamix (2010) respectively.

### 5.2.2 Scenarios for the operational phase

In this chapter four scenarios are assessed for the operational phase of the reference dwelling. Reference scenario 1 is based on the characteristics of the reference dwelling, while Sustainable scenario 2 is compiled on the basis of the most effective measures found in Chapters 2-4. Heat pump scenario 3 and User electricity scenario 4 represent the most distinctive options that have emerged in Chapters 3 and 4 respectively. The distinguishing characteristics of the scenarios assessed in this chapter are shown in Table 5.3. The numbers in brackets refer to scenarios in previous chapters, e.g. (3.1) refers to Scenario 1 in Chapter 3.

**Table 5.3 Distinguishing characteristics of the four used scenarios for the reference building**

| Distinguishing characteristics | Scenarios | | | |
|---|---|---|---|---|
| | 1 Reference scenario | 2 Sustainable scenario | 3 Heat pump scenario | 4 User electricity scenario |
| Façade component | (2.1)[a] | | | |
| - glazing | regular double | high-efficiency double (3.6) | high-efficiency double (3.6) | high efficiency double (3.6) |
| - service life | standard | lengthened by 50% (3.7) | lengthened by 50% (3.7) | lengthened by 50% (3.7) |
| - maintenance frequency | standard | reduced (2.10) | reduced (2.10) | reduced (2.10) |
| Kitchen and bathroom | | | | |
| - service life | standard | lengthened | lengthened | lengthened |
| Climate system | (3.1) | (3.4) | (3.5) | (3.4) |
| - heating system | individual HE100 boiler | individual HE107 boiler | individual air-water heat pump | individual HE107 boiler |
| - ventilation system | collective mechanical exhaust | individual balanced | collective mechanical exhaust | individual balanced |
| - service life | standard | standard | standard | standard |
| Transportation | 50 km one-way | 12.5 km one-way | 12.5 km one-way | 12.5 km one-way |
| Gas consumption[b] | 1062 m$^3$ (4.1) | 539 m$^3$ (4.3) | - | 539 m$^3$ (4.3) |
| Electricity consumption[b] | 3349 kWh (4.1) | 3349 kWh (4.1) | 6618 kWh (4.4) | 1797 kWh (4.5a) |
| - electricity mix | Dutch 2004 mix | Dutch 2004 mix | Dutch 2004 mix | Dutch 2004 mix |

a) Reference to previous chapter, e.g. (2.1), refers to Chapter 2, Scenario 1.

b) Consumption per apartment per year.

It is assumed in all scenarios that the heat resistance (R-value) of the closed parts of the façade and the roof has been upgraded to 2.5 m$^2$K/W, which is the required value for new buildings in the Dutch Building Decree (de Jong and Pothuis, 2009). The material used for the doors and windows in the façade is preserved spruce painted with alkyd in solvents.

In Reference scenario 1 each apartment has 21.2 m$^2$ of regular double glazing with a U-value of 2.90 W/m$^2$K and 1.8 m$^2$ of single glazing with a U-value of 5.10 W/m$^2$K. The service life of the façade components and the maintenance frequencies of Reference scenario 1, as shown in Table 5.4, are reference values found in Huffmeijer *et al.* (1998) and were confirmed as a reliable estimate by maintenance companies. Maintenance activities are carried out every X years, in which X is the frequency indicated in Table 5.4. In all other scenarios 23 m$^2$ of high-efficiency glazing with a U-value of 0.64 W/m$^2$K was used. The service life of all façade components was extended by 50% and maintenance frequencies were reduced (Table 5.4).

The kitchen, bathroom and toilet were replaced according to the standard service life in Reference scenario 1 and the lengthened service life in the other scenarios (Table 5.4). The standard service life of the kitchen was set at ten years, which is the minimum time that Dutch housing associations take to depreciate kitchens. Similarly, the service life of the bathroom and the toilet was 15 years. The service life is lengthened by ten years, working out at 20 years for the kitchen and 25 years for the bathroom and toilet. These values

Table 5.4 Service life of building components, maintenance frequency and transportation distance of maintenance workers per activity

| Activity | Scenario 1 | | Scenario 2,3,4 | |
|---|---|---|---|---|
| | year | km[a] | year | km[a] |
| **Replacement** | | | | |
| Kitchen | 10 | 8,250 | 20 | 2,063 |
| Bathroom and toilet | 15 | 11,700 | 25 | 2,925 |
| Façade | | | | |
| - frames | 40 | 6,300 | 60 | 1,575 |
| - window frames | 40 | 6,300 | 60 | 1,575 |
| - doors | 25 | 4,200 | 38 | 1,050 |
| - glazing | 25 | 4,200 | 38 | 1,050 |
| Climate system | | | | |
| - heat pump or boiler | 15 | 2,800 | 15 | 700 |
| - radiator | 30 | 7,000 | 30 | 1,750 |
| - mechanical exhaust ventilation | 20 | 1,500 | 20 | 225 |
| - balanced ventilation unit | - | - | 15 | 700 |
| - roof ventilator and air ducts | - | - | 20 | 388 |
| **Maintenance** | | | | |
| Façade | | | | |
| - painting (1 layer) | 6 | 10,000 | 8 | 2,500 |
| - painting (new basis, 3 layers) | 35 | 12,000 | 40 | 3,000 |
| - replacement of sealant | 15 | 1,000 | 17 | 250 |
| - replacement of hinges and locks | 20 | 7,000 | 30 | 1,750 |
| Climate system | | | | |
| - boiler or heat pump | 1 | 1,800 | 1 | 450 |
| - ventilation unit | - | - | 2 | 450 |
| - clean air ducts | 5 | 600 | 5 | 150[b] |
| - replacement of 3-way valve | [c] | 2,800[d] | [c] | 700[d] |
| - replacement of hot tapwater heat exchanger | [c] | 2,800[d] | [c] | 700[d] |

a) Average transportation distance is 50 km one-way in Scenario 1 and 12.5 km in Scenarios 2-4.

b) Scenario 4: 300 km.

c) The 3-way valve and hot tapwater heat exchangers of 40% of the boilers will be replaced during the service life of the boiler.

d) Total during 15 years, the parts will be replaced in 40% of the boilers.

are the maximum depreciation periods found in documents of Dutch housing associations. Maintenance of these facilities was not taken into account.

In Reference scenario 1 the climate system consists of individual non-condensing boilers (HE100) for heating and hot tap water and a collective mechanical exhaust ventilation system. The boiler has an efficiency of 93%. In Sustainable scenario 2 and User electricity scenario 4 the boiler is replaced by a condensing boiler (HE107) with an efficiency of 107%. The efficiency of a condensing boiler is connected with the lower heating value (LHV) of gas. It can achieve over 100% because it recovers heat from combustion gases. The ventilation system is replaced by individual balanced ventilation units with heat recovery. In Heat pump scenario 3 heating is provided by a heat pump on exhaust air with a Coefficient of Performance (CoP) of 3.2, while hot tap water is provided by a heat pump on outside air with a CoP of 2.3. A collective mechanical exhaust ventilation system is also used. In all scenarios the service life of the climate systems is the standard reference value shown in Table 5.4. Even though the technical service life of climate systems may be lengthened, they are often replaced early to cash in on more energy efficient-technology.

In this research air-water heat pumps were selected for Scenario 3 because this is the type of heat pump that is most widely used in existing buildings (Breslauer, 2008; SenterNovem, 2008). However, the air-water heat pump is the least efficient type of heat pump, largely because the highest heat demand occurs when the air temperature is lowest. In this study the external air heat pumps has a CoP of 2.3 and the exhaust air heat pump has a CoP of 3.2. Other types of heat pump used in (new) dwellings, such as the ground water-water heat pump, can have a CoP of 5 or more (SenterNovem, 2008), which means that the heat pump will deliver 5 kWh of heat for every kWh hour of electricity that it consumes. Since heat pumps are relatively new technology, the CoP can be expected to rise in the future. The heat pump is discussed further in Chapter 6.

Gas consumption for heating and hot tap water depends on the heat demand and the efficiency of the heating system. The heat demand in Sustainable scenario 2 is lower than in Reference scenario 1 due to the high-efficiency glazing, a more efficient heating system and the use of heat recovery in the ventilation system. In Heat pump scenario 3 electricity is used for heating, hot tap water and cooking. The consumption of electricity is usually determined by the appliances in the household (see Chapter 4) and the type of climate system. Reference scenario 1 and Sustainable scenario 2 represent the average residential electricity consumption per household in the Netherlands. In Heat pump scenario 3 electricity consumption is higher because of the heat pump climate system. In User electricity scenario 4 electricity consumption for lighting and appliances in the household is reduced by assuming the use of more efficient lighting and appliances and by lowering the number of appliances. The 2004 Dutch electricity mix is used in all scenarios. In Subsection 5.3.1 Scenarios 2 and 4 are calculated with the alternative electricity mix which the Netherlands hopes to achieve by 2020. These scenarios are referred to as Scenario 2a and 4a respectively.

The one-way transportation distance of maintenance workers is 50 km in Reference scenario 1 and 12.5 km in the other scenarios. Table 5.4 shows the total distance travelled by maintenance workers per replacement or maintenance activity, servicing all 70 apartments in the reference building.

**Table 5.5 Total materials used (in kg) for 70 apartments during 99 years of building use**[a]

| | | Scenario | | |
|---|---|---|---|---|
| | | 1 | 2,4 | 3 |
| **Façade components** | | | | |
| Chemicals | Alkyd in solvent | 2,769 | 1,899 | 1,899 |
| | Timber preservative | 503 | 347 | 347 |
| Metals | Aluminium | 2,873 | 1,928 | 1,928 |
| | Steel | 6,076 | 4,523 | 4,523 |
| Plastics | Polysulfide | 5,570 | 5,570 | 5,570 |
| Wood | Spruce | 88,965 | 57,848 | 57,848 |
| Other | Glass | 122,762 | 102,968 | 102,968 |
| **Kitchen and bathroom** | | | | |
| Metal | Brass | 4,012 | 2,243 | 2,243 |
| | Stainless steel 16/10 grade | 2,800 | 1,400 | 1,400 |
| | Stainless steel 18/8 grade | 1,435 | 718 | 718 |
| | Steel | 6,300 | 3,150 | 3,150 |
| Plastic | LDPE - low-density polyethylene | 39 | 22 | 22 |
| | Melamine | 5,880 | 2,940 | 2,940 |
| | PA (polyamide) | 1,085 | 543 | 543 |
| | PP (polypropylene) | 855 | 461 | 461 |
| | PS (polystyrene) | 1,441 | 823 | 823 |
| | PVC (polyvinylchloride) | 882 | 504 | 504 |
| | Synthetic rubber | 35 | 18 | 18 |
| Stone | Ceramic tiles, wall | 174,009 | 97,902 | 97,902 |
| | Tile adhesive (dry weight) | 41,133 | 23,129 | 23,129 |
| | Tile grout (dry weight) | 2,742 | 1,542 | 1,542 |
| | Sanitary ceramics | 25,897 | 14,798 | 14,798 |
| Wood | Fibreboard, hard | 33,810 | 16,905 | 16,905 |
| | Particle board, indoor | 91,882 | 45,941 | 45,941 |
| | Particle board, outdoor | 21,770 | 10,885 | 10,885 |

a) Stainless steel 16/10 grade: EN 1.4408; Stainless steel grade 18/8: EN 1.4310.

▶

## 5.3 Results

This section discusses the results of the environmental assessment of the scenarios for the operational phase of the reference building. The results are shown as the accumulated contributions of all 70 apartments in the reference building to various environmental impact categories during 99 years of dwelling operation. A 99-year time span was chosen to show the long-term consequences of the use scenarios. The cut-off point was set at 100 years because as many activities take place in the 100th year, to include it would have obfuscated the results (see Subsection 5.3.4). The scenario starts with the replacement of all door and window components, climate systems, kitchens and bathrooms considered in the research, after which all the environmental impacts are added as they occur in time. It is assumed that the building will continue to be used after this point in time, so the end of the scenario is a cut-off point.

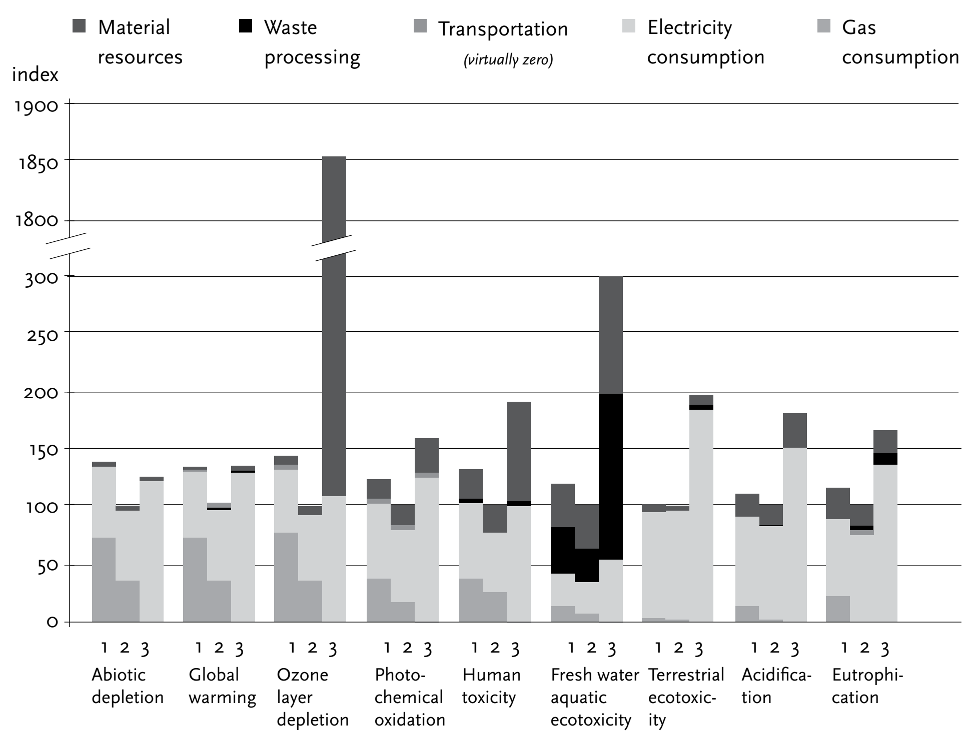
| | | Scenario | | |
|---|---|---|---|---|
| | | 1 | 2,4 | 3 |
| **Climate systems** | | | | |
| Metals | Aluminium, production mix | 450 | 631 | 228 |
| | Aluminium, cast alloy | 1,789 | 6,272 | 0 |
| | Brass | 2,168 | 1,478 | 0 |
| | Cast iron | 4,900 | 0 | 0 |
| | Copper | 1,108 | 911 | 17,248 |
| | Stainless steel 16/10 grade | 1,058 | 1,058 | 0 |
| | Stainless steel 18/8 grade | 1,266 | 2,027 | 31,985 |
| | Steel | 62,930 | 76,081 | 154,411 |
| Plastics | ABS (acrylonitrile butadiene styrene) | 604 | 592 | 0 |
| | Elastomere | 0 | 0 | 7,840 |
| | EPDM (ethylene propylene diene monomer) | 368 | 368 | 368 |
| | HDPE (high-density polyethylene) | 165 | 265 | 100 |
| | Nylon | 15 | 2 | 0 |
| | PA (polyamide) | 83 | 0 | 0 |
| | PC (polycarbonate) | 15 | 3 | 0 |
| | PE-Xc (polyethylene) | 0 | 0 | 198 |
| | PP (polypropylene) | 2 | 0 | 0 |
| | PS (polystyrene) | 0 | 4,959 | 0 |
| | PUR (polyurethane) | 7 | 11 | 5 |
| | PVC (polyvinylchloride) | 2 | 0 | 784 |
| | PVDF (polyvinylidene fluoride( | 0 | 0 | 102 |
| | Synthetic rubber | 51 | 57 | 5 |
| Other | Ceramics | 10 | 10 | 0 |
| | Electronics | 897 | 1,193 | 125 |
| | Kraft paper | 229 | 229 | 0 |
| | Refrigerant R134a | 0 | 0 | 1,921 |

### 5.3.1 Comparison of scenarios

The aim in research questions 1 and 2a is to assess the environmental impact from the operational phase of the reference building and to assign it to different factors. Research question 3 requires a comparison between the different use scenarios in order to assess the effect of changes to the scenario parameters on the total environmental impacts in the operational phase. The results of the scenario assessments have been divided across two figures to avoid an information overload. Figure 5.3 shows Scenarios 1-3 in which the characteristics of the reference dwelling are varied, while Figure 5.3 shows Scenarios 2, 2a, 4 and 4a in which the energy consumption of the dwelling is varied. In both figures the environmental impact score of Scenario 2 is set to the index 100 in each impact category. The scores of the other scenarios are relative to Scenario 2.

Figure 5.3 shows the accumulated environmental impact during 99 years of use in Reference scenario 1, Sustainable scenario 2 and Heat pump scenario 3, divided into gas consumption, electricity consumption, transportation of

**Figure 5.3 Relative accumulated environmental impact of Reference scenario 1, Sustainable scenario 2 and Heat pump scenario 3 during 99 years of dwelling operation**

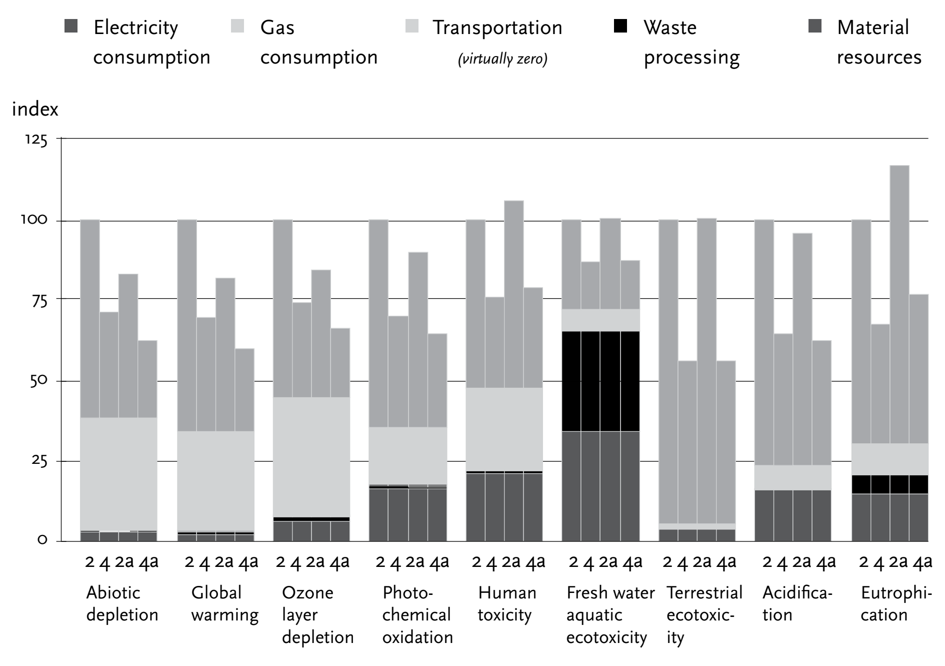


maintenance workers, waste processing and material resources.

Figure 5.3 shows that Sustainable scenario 2 has the lowest impact score for all environmental impact categories. This is explained mainly by the reduced heat demand resulting from improvements to the thermal performance of the glazing and to the efficiency of the climate systems compared with Reference scenario 1. The impact scores of Reference scenario 1 are 2-44% higher than those of Sustainable scenario 2.

Heat pump scenario 3 has the highest environmental impact in all the categories apart from Abiotic depletion, 26-1753% more than Sustainable scenario 2. The use of a heat pump instead of an HE100 boiler reduces the impact score for Abiotic depletion by 9% because fossil fuels are not used directly as a heat source. Fossil fuels are, however, indirectly used to operate the heat pump, since, at the moment, most of the electricity is still generated from fossil fuels. The Global warming impact score of Heat pump scenario 3 is in the same order of magnitude as Reference scenario 1, but the contribution to the remaining impact categories is 30-1188% higher. The large difference in the score for Ozone layer depletion impact score is caused by the refrigerant used in heat pump systems. However, as will be shown in Subsection 5.3.5, the Ozone layer depletion score is relatively low compared with the total annual Dutch contribution to Ozone layer depletion. The high impact scores for Photochemical oxidation, Fresh water aquatic ecotoxicity, Terrestrial ecotoxici-

**Figure 5.4 Relative accumulated environmental impact of Sustainable scenario 2 and User electricity scenario 4 with the 2004 electricity mix and the 2020 electricity mix (Scenario 2a and 4a respectively) during 99 years of dwelling operation**



ty, Acidification and Eutrophication are caused by energy consumption (combined gas and electricity) resulting from the replacement of gas with electricity for heating, hot tap water and cooking. Finally, the high amount of material resources and waste processing for heat pumps increases the impact on Photochemical oxidation, Human toxicity, Fresh water aquatic ecotoxicity, Acidification and Eutrophication.

Figure 5.4 compares Sustainable scenario 2 and User electricity scenario 4. The difference between these two scenarios is the user-related energy consumption: in User electricity scenario 4, electricity consumption is 47% lower than in Sustainable scenario 2. This was achieved by fewer and more efficient electrical appliances in the household. The 2004 Dutch electricity mix is used in both scenarios. For comparison purposes, both scenarios were also calculated with the 2020 Dutch electricity mix, 35% of which is generated from sustainable resources as explained in Chapters 4 and 5. Scenario 2a corresponds with Scenario 2, while Scenario 4a corresponds with Scenario 4.

Figure 5.4 shows that the environmental impact of User electricity scenario 4 is 13-44% lower than that of Sustainable scenario 2. The use of a more sustainable electricity mix in Scenario 2a shows a significant reduction of 4-17% for five environmental impact categories, but an increase of 6% and 17% for two. Another two are in the same order of magnitude. The combination of lower electricity consumption on the part of the user and a future electricity mix also reduces environmental impact by 13-44%, but some impact scores are reduced more than in User electricity scenario 4. The scores for Eutrophication and Human toxicity are best for User electricity scenario 4 with the current – most unsustainable – electricity mix.

### 5.3.2 Factors causing environmental impact

Research question 2a asks which of the following factors causes the greatest environmental impact in the use phase of the reference building: material resources; waste processing; transportation; gas consumption; or electricity consumption. Figures 5.3 and 5.4 show that, in general, energy consumption (combined electricity and gas) is the strongest contributor to all environmental impact categories except Fresh water aquatic ecotoxicity. The magnitude of the environmental impact caused by gas or electricity depends on the gas:electricity ratio in MJ. In Reference scenario 1, this ratio is about 3:1 and gas consumption is responsible for up to half of the impact scores for Abiotic depletion, Global warming, Ozone layer depletion and Human toxicity. In Sustainable scenario 2 (49% less gas consumption), the gas:electricity ratio in MJ is 1.5:1 and the share of gas in the environmental impact decreases to a maximum of 37%. Electricity consumption dominates Photochemical oxidation, Terrestrial ecotoxicity, Acidification and Eutrophication, with contributions of 49 to 93% to the total score per scenario.

In Heat pump scenario 3 material resources dominate the impact score fir Ozone layer depletion (94%). This is due to the use of refrigerants in the heat pump. Material resources contributes 19-45% to Human toxicity while material resources and waste processing contribute 31-34% and 31-47% to Fresh water aquatic ecotoxicity respectively. These high percentages are caused by the large metal content in the climate systems.

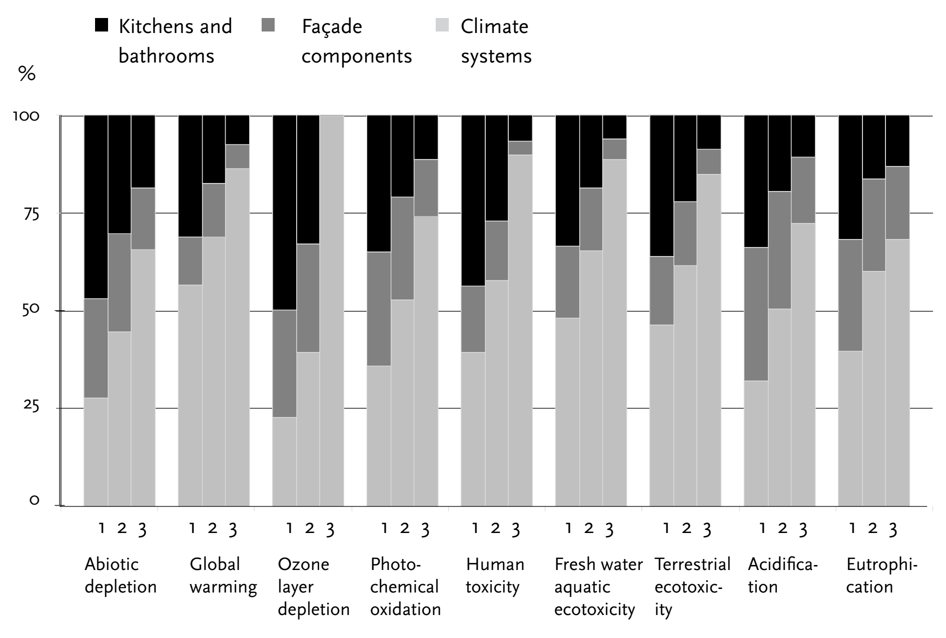
Except in the case of Fresh water aquatic ecotoxicity (31-47%) and Eutrophication (5-8%), the environmental impact of waste processing is marginal. The influence of transportation of maintenance workers is negligible for all impact categories.

### 5.3.3 Environmental impact per group of activities

Research question 2b asks which of the following groups of activities cause significant environmental impacts in the use phase of the reference building: maintenance and replacement of façade components; maintenance and replacement of climate systems; or replacement of kitchen, bathroom and toilet. Figure 5.5 shows the relative spread of the environmental impact caused by material resources in the three groups of activities. The results of User electricity scenario 4 are equal to those of Sustainable scenario 2.

The environmental impact of material resources is dominated by the maintenance and replacements of climate systems: 45-100% is caused by materi-

**Figure 5.5 Relative spread of the environmental impact of material resources per group of activities in Reference scenario 1, Sustainable scenario 2 and Heat pump scenario 3 during 99 years of dwelling operation**



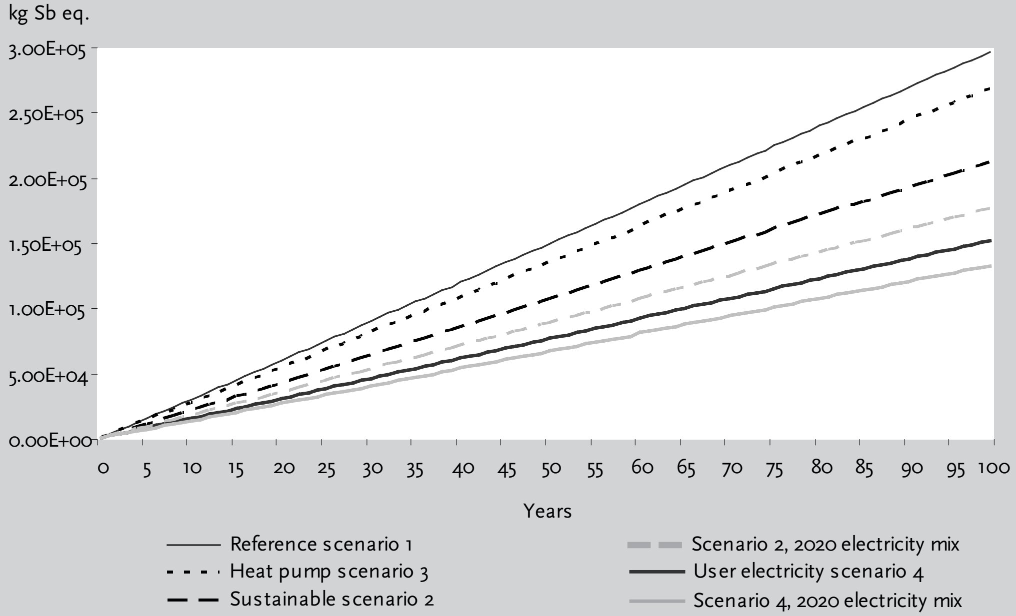
als used in climate systems, except for Reference scenario 1, where the distribution is more evenly divided with 12-34% caused by façade components, 17-45% by climate systems and 31-50% by kitchens, bathrooms and toilets. The difference between Reference scenario 1 and the other scenarios is attributable to the longer service life of kitchens, bathrooms and toilets and façade components in Scenarios 2, 3 and 4. As energy efficiency improvements occur relatively fast, the functional service life of climate systems cannot be lengthened as much as the service life of façade components, kitchens, bathrooms and toilets.

The contribution of waste processing to Global warming is dominated by façade components and kitchens because a larger proportion of the waste is wood-based, and the incineration of wood waste causes greenhouse gas emissions. The contribution of waste processing to Fresh water aquatic ecotoxicity and Eutrophication is more evenly divided among the groups of activities, except in the case of Heat pump scenario 3, where waste processing is dominated by climate systems.

### 5.3.4 Accumulation of environmental impact over time

The fourth aim of the research is to assess how the environmental impact in the use phase of the reference building accumulates over time. Figures 5.6 and 5.7 show the Abiotic depletion and Fresh water aquatic ecotoxicity impact categories during the 99 years of the use scenarios. The units of measurement on the y-axes for the impact categories are kg antimony (Sb) equiv-

**Figure 5.6 Accumulated contribution to abiotic depletion during 99 years of dwelling operation**



alents and 1,4 dichlorobenzene (1,4-DB) equivalents respectively (see: Appendix 1).

Figure 5.6 shows a gradual increase in Abiotic depletion over time. This is because the contribution to Abiotic depletion, as shown in Subsection 5.3.1, is dominated by the annual gas and electricity consumption of households. Since these factors are dominant, replacement and maintenance activities, shown as step-wise increases in environmental impact, are not observable in Figure 5.6. The timelines for Global warming, Terrestrial ecotoxicity, Photochemical oxidation, Acidification and Eutrophication are similar to the timeline for Abiotic depletion in Figure 5.6. The same is true for the Ozone layer depletion timelines in all scenarios except Heat pump scenario 3.

In Figure 5.7 the contribution to Fresh water aquatic ecotoxicity increases in steps at the times when maintenance and replacement activities are carried out. This is because the score for this environmental impact category is dominated by material resources and waste processing. For example, the step-wise increase in environmental impact every 15 years is caused by the replacement of climate systems, which have a service life of 15 years. The larger increase every 30 years reflects the replacement of radiators at the same time as climate systems. The timelines for Ozone layer depletion (Heat pump scenario 3 only) and Human toxicity are similar to the timeline for Fresh water aquatic ecotoxicity in Figure 5.7. The two scenarios with the 2020 electricity mix are missing because electricity makes only a marginal contribution to Fresh water aquatic ecotoxicity and the results are the same as for Scenario 2 and 4. The timelines for Photochemical oxidation, Acidification and Eutrophication show small increases, for example in year 60, when many replacements coincide, but these timelines more closely resemble the timeline in

**Figure 5.7 Accumulated contribution to fresh water aquatic ecotoxicity during 99 years of dwelling operation**

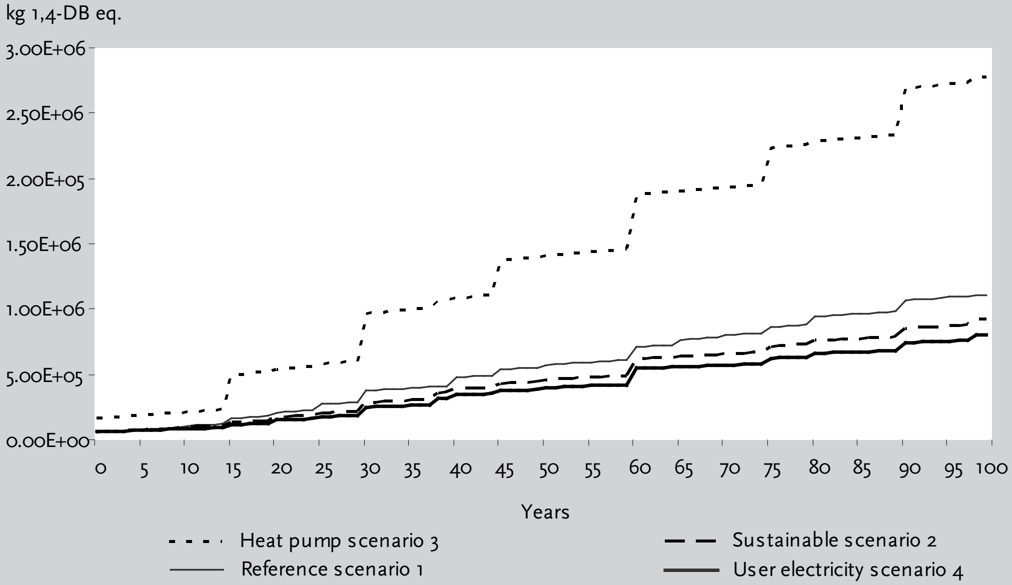


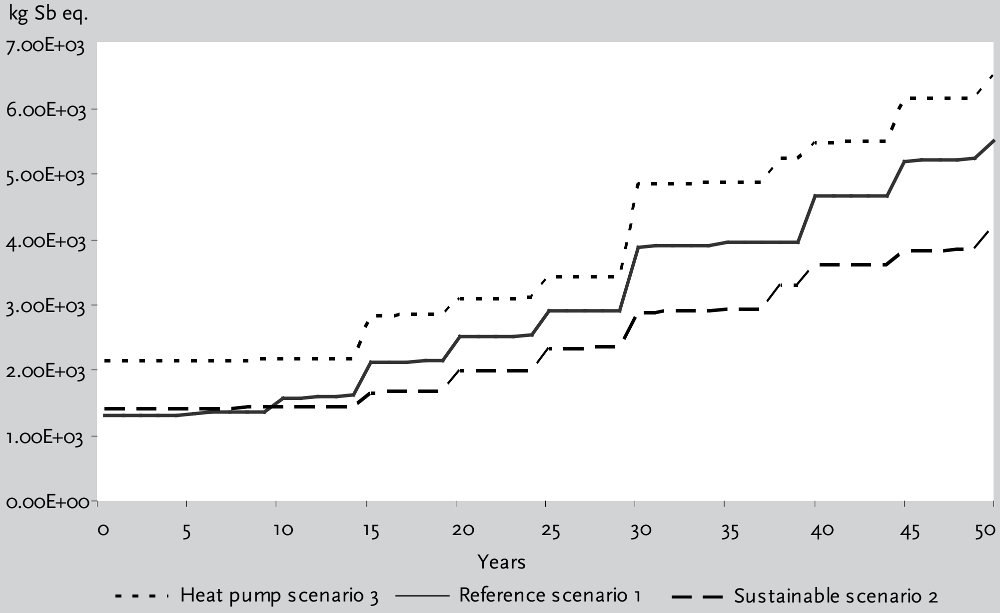
Figure 5.6.

Figure 5.8 shows the accumulated contribution to Abiotic depletion, without the impact of gas and electricity consumption. Contrary to Figure 5.6 the timeline now shows a step-wise accumulation of environmental impact.

Figures 5.7 and 5.8 illustrate why it is so important to select the time period of the operational phase assessment carefully. For example, when the Scenario is cut off at 30 years, the impact score for Heat pump scenario 3 is 23% higher than the impact score for Reference scenario 1, even though the difference at year 29 is 16%. The same is true when calculating the average environmental impact per year: the 30-year average impact in Reference scenario 1 is 111 kg Sb eq., while the 29-year average is 98 kg Sb eq. The scenarios in this research are cut off at 99 years instead of 100 because many replacement activities take place in year 100 and inclusion of that extra year could produce skewed results.

The electricity mix – either the 2004 electricity mix or the 2020 electricity mix – in the scenario calculations is constant over time. In reality the electricity mix will change. Figure 5.9 shows several scenarios with different electricity mixes. Sustainable scenario 2 is shown with a continuous 2004 mix and a continuous 2020 mix. Additionally, Sustainable scenario 2 and User electricity scenario 4 have been calculated with the 2004 mix for year 1-10, the 2020 mix for year 11-30 and an all wind power mix for year 31-50. Thereby, it is assumed that the aims for the electricity mix in 2020 are achieved in 2020, 10 years from now, and 20 years later all electricity comes from sustainable resources, in this case represented by 100% wind power. Heat pump scenario 3 is shown with a continuous 2004 electricity mix. Since the efficiency of heat pumps is expected to increase in the future, an alternative scenario with an increasing CoP has also been calculated. The original CoP of 3.2 for heating

Figure 5.8 Accumulated contribution to abiotic depletion during 99 years of dwelling operation, excluding gas and energy consumption



and 2.3 for hot tap water is used in year 1-10. The CoP for both heating and hot tap water is 5.0 in year 11-30 and 12.0 in year 31-50. The material resources used in the production of the heat pump are assumed to remain the same. Finally, the increasing CoPs are combined with the different electricity mixes as with Scenarios 2 and 4.

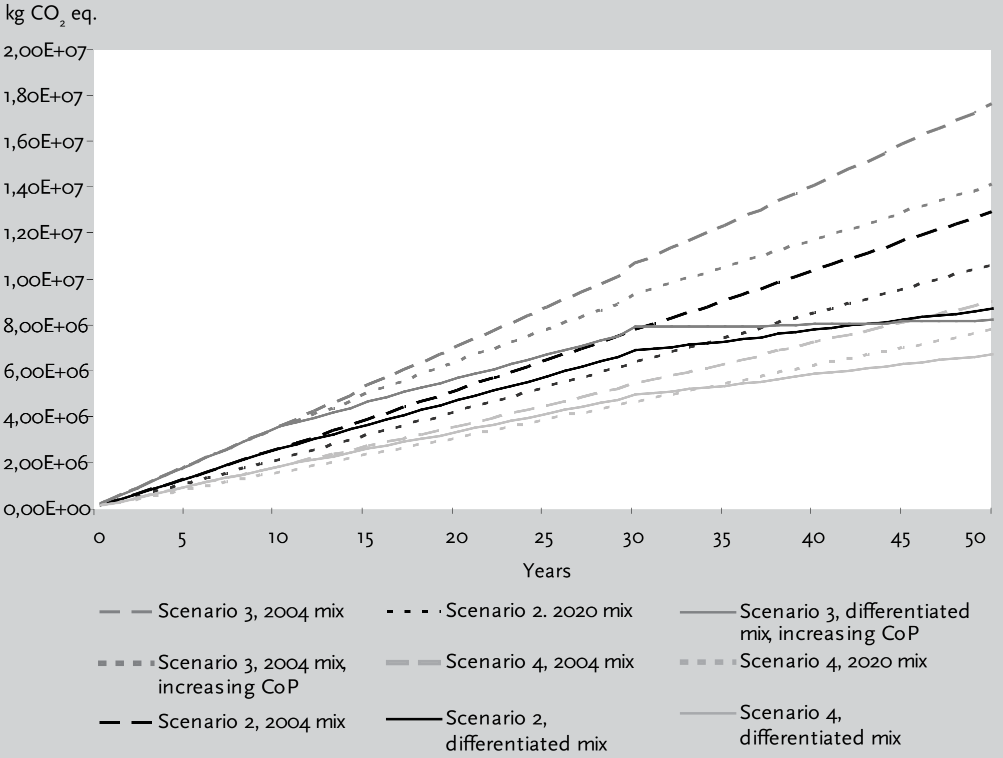
The unit of measurement for the Global warming impact category shown in Figure 5.9 is kg carbon dioxide ($CO_2$) equivalents (y-axis). The legend alongside the graph shows the scenarios for the accumulated environmental impact in year 50 in descending order.

Figure 5.9 shows that an increasing CoP of the heat pump, with the current electricity mix, still delivers a higher score for Global warming than Sustainable scenario 2. However, when the electricity mix improves, the Heat pump scenario is better than the Sustainable scenario 2. Figure 5.9 also shows that the most efficient scenario is one in which the electricity consumed by the users is reduced. Since the electricity consumption is lower in User electricity scenario 4, the benefits of improving the electricity mix are smaller.

## 5.4 Overall conclusion

The results of the environmental assessment of the scenarios show that it is not a specific group of activities that has the greatest influence on the environment, but rather factors that are involved in all kinds of activities, such as energy consumption and the use of high-impact material resources. Therefore, the environmental impacts in the operational phase of residential buildings is not a matter of eliminating specific events, but reducing material and

**Figure 5.9 Accumulated contribution to global warming over 50 years of dwelling operation for Sustainable scenario 2, Heat pump scenario 3 and User electricity scenario 4 with different electricity mixes and increasing CoP for the heat pump**



energy flows and improving the environmental quality of the flows that are indispensable.

Reducing the demand for gas and electricity, whether by improving the building or by reducing the occupants' consumption, would prove an effective means of lowering the environmental impacts in the operational phase of dwellings. Alternatively, the environmental impacts of the electricity supplied to the households could be improved.

Furthermore, while certain environmental impact categories are most contributed to by one factor, another factor may have the largest influence on other impact categories. The use of material resources and the production of building components contribute considerably to some specific environmental impact categories. Manufacturers of building components and semi-finished products could help to reduce the environmental impacts of dwellings by decreasing the input of high-impact material resources and eliminating high-impact processing, thus improving the environmental performance of their products. Particular attention should be paid to the consequences of employed measures across the full spectrum of environmental impact categories to assure that shifting the environmental impact is not merely being displaced to other categories.

Chapter 6 will continue with an extensive discussion on the research, more detailed conclusions and recommendations for policy, practice and further research.

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# 6 Discussion, conclusions and recommendations

## 6.1 Introduction

The objective of the research described in this thesis was to provide insight into the factors that cause the greatest environmental impact in the operational phase of residential buildings and awareness of the long-term ecological consequences of decisions made in the design, construction and operational phases. The research further aims to contribute to the modelling of the operational phase of residential buildings in life cycle assessment (LCA) by indicating if it is possible to assess the sustainability of residential buildings with reasonable accuracy according to a limited number of contributing factors. The acquired knowledge may help policymakers to develop effective policies and can steer further developments in research and building practice towards areas that have the most potential for improving the environmental performance of residential buildings. The modelling and the results of the environmental assessments have been validated in a number of ways:

- the assumptions made in the operational scenarios for the reference buildings have been verified by experts in building practice;
- modelling and calculation errors have been traced and corrected by tracking any high impact score - or scores that were higher or lower than expected based on experience and literature - back to the input data from the database and the scenarios;
- the average annual impact scores have been compared with the annual environmental impact in the Netherlands in a reference year to obtain a sense of the order of magnitude of the environmental impacts and to judge the scores of the different environmental impact categories to a comparable scale.

In Section 6.2 the main research questions of this thesis are answered, the validity of the results and implications for other types of new and existing dwellings, different types of ownership and other countries are discussed, and the main conclusions are set out. Section 6.3 presents recommendations for policy, practice and further research.

## 6.2 Discussion and conclusions

In this section the answers to the research questions posed in Section 1.3 will be discussed, one at a time in a separate subsection. The research questions are:

1. What are the environmental impacts related to the operational phase of residential buildings? (Subsection 6.2.1).
2. Which factors significantly contribute to the various environmental impact categories? (Subsection 6.2.2).
3. To what extent do changes in the variable parameters of the assessment

affect the environmental impacts? (Subsection 6.2.3).
4.How can the environmental impacts in the operational phase be most effectively reduced? (Subsection 6.2.4).

In Subsection 6.2.5 the validity of the results is discussed and an overall conclusion is drawn in Subsection 6.2.6.

### 6.2.1 Environmental impacts in the operational phase

The literal answer to the research question 'What are the environmental impacts related to the operational phase of residential dwellings?' does not make sense when it is not put into context. Therefore, different alternatives for the operational phase were compared to a reference operational scenario in Chapter 5 and the environmental impact scores were related to the total annual impacts in the Netherlands to acquire insight into the relative order of magnitude of the impact category scores.

The results show that when the technical measures for reducing environmental impacts that were proven effective in Chapters 2 and 3 are implemented – namely, applying high-efficiency glazing and climate systems and reducing maintenance and replacement activities – the environmental impact scores will fall by 2-30% depending on the impact category. The main reason for the lower scores is the reduced heating demand in the dwelling. When, in addition to the technical measures mentioned above, the user-related electricity consumption for appliances is reduced by 47% by decreasing the number of appliances in the dwelling and using appliances that are more energy efficient, the environmental impact scores will fall by 27-49% compared with the reference scenario.

The average annual environmental impacts of the operational phase of dwellings have been compared to the total environmental impacts in the Netherlands in order to show the relative order of magnitude of the impact categories. The results show that the contributions to the impact categories Abiotic depletion, Global warming, Fresh water aquatic ecotoxicity and Terrestrial ecotoxicity are relatively high, followed by Human toxicity and Acidification, whereas the impact scores of Ozone layer depletion, Photochemical oxidation and Eutrophication are relatively low. The most important categories are mainly contributed to by gas and electricity consumption, with the exception of Fresh water aquatic ecotoxicity which is mainly contributed to by material resources and waste processing. The contribution to Human toxicity is a combination of both.

As electricity consumption causes a large part of the environmental impacts of residential dwellings, the reduction of environmental impacts of the entire residential building stock can also be established by reducing the impacts of the electricity supply. Both of the above mentioned scenarios make use of the electricity mix supplied to Dutch households in 2004. Both have also been calculated with a 2020 electricity mix in which 35% of the electricity is generated from sustainable renewable resources. The results show that the contribution to some environmental impact categories would then be further reduced by 15-18% (Abiotic depletion, Global warming, Ozone layer depletion and Photochemical oxidation), while others would increase compared with the 2004 electricity mix (slight increase for Human toxicity and notable increase for Eutrophication – 17%). The other impact scores have the same order of magnitude.

This research does not take account of energy rebound effects, whereby the financial spin-off from lower energy consumption may be diverted to other activities that require energy consumption. The results of the 2020 mix in this study are influenced by the use of electricity generated from biomass (cogeneration), which makes a sizeable contribution to Human toxicity, Fresh water aquatic ecotoxicity and Eutrophication. The validity of the results for other types of dwellings is discussed in Subsection 6.2.5.

### 6.2.2 Significant contributing factors

In order to answer research question 2 'Which factors significantly contribute to the various environmental impact categories?', the main factors material resources, waste processing, transportation of maintenance workers, gas consumption and electricity consumption are assessed. Further analysis has been done on the factors that contribute most to the environmental impact scores.

In the operational phase of the reference apartment dwelling gas and electricity consumption causes 80-95% of the environmental impact in all categories except Fresh water aquatic ecotoxicity, which is dominated by material resources and processing of waste metals (65-80% of the total). Since electricity was generated from primary resources with a relatively high negative environmental impact in 2004, it has a higher impact on the environment than gas per MJ of energy. The results show that in Reference scenario 1 and User electricity scenario 4a with the 2020 electricity mix, gas consumption is responsible for around 50% of the score for Abiotic depletion, Global warming, Ozone layer depletion and Human toxicity (Table A5.3). In the other scenarios the ratio between MJ gas and MJ electricity is different, which leads to a dominant role for electricity consumption in all the categories. Gas consumption can partly be reduced by technical measures, such as better insulation, and partly by user behaviour, for example by limiting the duration and number of showers taken. As gas consumption for space heating decreases, reduction of gas consumption for hot tap water becomes a more important factor for improving the environmental performance of dwellings in use. To a far lesser extent, electricity consumption can be reduced by technical measures, for example regarding operation of climate systems and lighting, and for a large part by user behaviour, such as conscious use of lighting and limiting the amount of appliances.

Material resources account for about 5-20% of the contribution to the environmental impact categories. Some material resources and related production processes contribute significantly to specific impact categories. For example, metals used in climate systems, PVC frames, and hinges and locks have a significant impact on Human toxicity and Fresh water aquatic ecotoxicity, while refrigerants used in heat pumps dominate Ozone layer depletion. Other research has shown that other types of refrigerants have the same effect (Bovea *et al.,* 2007). Even small amounts of metals from, say, metal hinges and locks on a door can contribute significantly. It is therefore necessary to identify known and suspected high-impact materials in building products and to include them in environmental assessment studies.

It has been shown in this study that waste processing of replaced building components contributes only marginally to the total environmental impact in the operational phase, except for the impact of waste-metal processing on Fresh water aquatic ecotoxicity. However, the calculation of the environmental impact of waste processes has a high level of uncertainty. In this study general emission data about waste incineration and landfill processes were used. Hence, when for example, 10 kg of preserved timber frames are incinerated, the emissions of 10 kg of general waste incineration are taken into account. The same applies to emissions from landfill. General incineration and landfill data were used because there is a dearth of specific incineration and landfill characterisation data for many materials. In the case of metal material resources, the waste that causes high environmental impact occurs in the early processing stages when metals are extracted from ore. It is therefore vital to collect and recycle metals as much as possible and reduce the need to extract virgin materials, keeping in mind that recycling may shift environmental impact to other categories.

In Section 1.3, it is mentioned that the results of this research may indicate if it is possible to assess the sustainability of residential buildings with reasonable accuracy according to a limited number of contributing factors. According to the results, most of the environmental impacts in the operational phase of dwellings are related to a few factors, namely energy consumption and high-impact materials used in building products. It is therefore possible to assess the general ecological sustainability of residential buildings by a few factors, provided that a checklist of high-impact materials is available and it is known how much material is used in building components and systems. Additionally, more detailed analysis of building waste processing should determine if waste processing is a factor that should be included as well. Another possibility for less time consuming ecological assessment of buildings is the use of Environmental Product Declarations (EPDs) of building components, which are detailed studies the results of which enable simply adding the environmental impacts of products.

### 6.2.3 Parameter variations

Electricity consumption is a factor that contributes significantly to most environmental impact categories. Therefore, the type of resources and techniques used to generate electricity will influence the results of the assessment. In Chapter 3, the Dutch electricity mix as supplied in 2004 is compared with the electricity mix aspired in 2020, with 35% electricity generated from sustainable resources. In Figure 3.6 it is shown that the 2020 electricity mix has an up to 25% lower impact score in the categories Abiotic depletion, Global warming, Ozone layer depletion and Photochemical oxidation. The other impact categories are in the same order of magnitude or 10-20% higher, which is the case for Human toxicity and Eutrophication. This means that the environmental impact shifts to different environmental problems. Alternative building services may have other benefits than energy efficiency that make owners and occupants opt for them, such as flexibility and higher comfort levels of the dwelling. While those services may currently cause shifting and even growing rather than diminishing environmental problems, future sustainable energy sources may prove them to be the best option after all. For example, electricity generated by wind power has considerably lower environmental impacts than other types of electricity, except for Fresh water aquatic ecotoxicity due to the material content in the wind turbines and distribution network. Electricity from centralised photovoltaic cells has lower impact than electricity from nuclear power, but higher than hydropower.

The results in Chapter 5 show that for individual dwellings, reducing energy consumption is more effective than improving the supply mix over time. When the efficiency of the heat pump increases (to 5.0 in 10 years and 12.0 in 30 years) and the electricity supply is improved as described above, the heat pump causes less environmental impact than an efficient boiler and ventilation with heat recovery, assuming equal user-related energy consumption (Figure 5.9).

Subsection 6.2.2 shows that material resources contribute 5-20% to the impact in all environmental categories except Fresh water aquatic ecotoxicity. Chapter 2 shows that extending the service life of façade components by 50% reduces the environmental impacts from the maintenance and replacement of façade components by 17–27% after 70 years. The reduced environmental impact stems from the fact that fewer façade components need to be produced and processed as waste during the operational phase of the dwelling. Additionally, transportation of maintenance workers to perform replacement activities is reduced. The effect of extending the service life of façade components increases slowly over time: after 150 years of dwelling operation, the environmental impact of the maintenance of façade components decreases by 24–35%.

The theoretical variations of occupant behaviour in this research have relatively little influence on the gas used for heating and hot tap water, therefore they have little influence on the environmental impacts of gas consumption (Guerra Santin et al., 2009). However, in practice the gas consumption of occupants living in identical dwellings may vary widely due to different temperature settings and ventilation habits. Electricity consumption is strongly related to user behaviour. Changes in behaviour, which in the context of this research mean changes in the number of appliances in the dwelling and their energy efficiency can reduce the environmental impacts by up to 60%.

### 6.2.4 Effective reduction of environmental impacts

The results show that reducing energy consumption is a very effective means of reducing the environmental impact in the operational phase of dwellings. Gas consumption can be lowered most effectively by improving the properties of the thermal shell of the building; for example, regular single and double glazing could be replaced by high-efficiency glazing and the energy efficiency of the climate systems could be improved, for example by using ventilation with heat recovery. These measures are most effective for non-insulated existing dwellings that have not yet been refurbished, since the energy efficiency of such dwellings is relatively low. Changes in occupant behaviour towards the use of gas for heating are not as effective as changing the heat demand in the dwelling, but they can reduce the gas consumption for hot tap water.

Electricity consumption is mostly user-related, except in cases where the heating system does not operate on gas. The electricity needed to operate systems which extract heat from freely available resources in the environment can be reduced by improving the energy efficiency of the systems. User-related electricity consumption can only be slightly influenced by making changes to the building (e.g. the lighting). Most of the electricity consumption depends on the number of electrical appliances in the dwelling, the energy efficiency of these appliances and how they are used.

Even though energy consumption plays a dominant role in the environmental impact from the operation of dwellings, the amount and type of material resources used also offer opportunities for reducing this environmental impact. The most effective measure to reduce the environmental impact related to material resources, waste processing and worker transportation for the maintenance and replacement of façade components, kitchens, bathrooms and toilets is to extend the service life of the building components, provided the required additional maintenance does not outweigh the impact that is avoided by extending the service life. Measures that may be worth considering include the use of more durable (protection of) building components (e.g. paint or higher quality kitchen cabinets), partial instead of complete replacement of building components (e.g. replacing only the sills of façade components), or using more durable building products in the façades facing the main direction of wind and rain. Maintenance activities should be performed when needed rather than according to set schedules in order to avoid needless transportation and to save minor replacements. However, the service life to some extent also depends on non-technical factors such as fashion, perceived quality and changing ways of living.

Measures could be taken in the design stage to slow down degradation by better protecting building components from climatic and user influences. It is important for product manufacturers to design building components in a way that optimally protects them from degradation. Virgin materials might be replaced by recycled materials and without the addition of ingredients that would require the entire component to be treated as chemical waste.

Extending the service life of climate systems is not an effective measure, since climate systems can often be replaced by new, more energy-efficient systems before their technical service life has reached an end. The environmental performance of current climate systems could be improved by the deployment of systems that have fewer malfunctions and need less parts replaced. Second, manufacturers might be able to use alternative materials in their systems that perform equally or better and have less impact on the environment, or materials that can be more easily recovered and recycled or reused. Third, climate systems may allow for essential elements to be replaced by future technology without replacing the casing and other parts that do not wear out after only 15 years. The risk of system components that have been taken out of production and thus render an entire system useless would then be much smaller. However, all these measures are aimed at improving existing systems, while new technology may bring about much greater reductions of environmental impacts. New systems will likely require more fine-tuning and maintenance activities for the system to work well and maintenance workers to gain experience, but this should not deter from developing and applying new technological solutions.

### 6.2.5 Validity of results for other situations

This research focused on a specific type of dwelling in the Netherlands, the gallery flat apartment which, due to its compactness and lower exposure to the outdoor air, has the lowest energy consumption per square metre of living area. Gas consumption for heating is therefore higher in most other dwelling types. The relationship between dwelling type and electricity consumption is less clear. Electricity consumption seems to be more closely related to the occupants' lifestyle, which is co-determined by the household income. Both lifestyle and income are related to dwelling type (Weber and Perrels, 2000; Wier *et al.,* 2001).

The environmental impacts related to the production and waste processing of replaced façade components are likely to be higher in other dwelling types as they have larger façades than apartments. The size of the ventilation systems and air distribution is closely related to the volume of the dwelling, thus increasing the environmental impact of ventilation systems in larger dwellings. The capacity of heating systems is more closely related to the demand for hot tap water than space heating. For example, more people taking showers or the availability of a bath requires higher volumes of hot tap water and necessitates a larger boiler with greater capacity. The heat distribution system will increase with the size of the dwelling (length of piping) and the dimensions and number of rooms will influence the size and number of radiators. The environmental impact of the material resources used for and waste processing of the heating system will therefore increase for larger dwellings and larger households. Kitchens, bathrooms and toilets are likely to be larger in other dwelling types than in apartments. In larger and more expensive dwellings, the possibly superior quality of the kitchens, bathrooms and toilets may extend the service life of the services. On the other hand, the service life of kitchens and bathrooms is subject to fashion trends and is often replaced when people move house, which may shorten the service life, especially in owner-occupied dwellings. So, it is impossible to say whether the environmental impact from the replacement of kitchens, bathrooms and toilets will be greater or smaller than for apartments.

The maintenance and replacement of building components, climate systems and kitchens, bathrooms and toilets is most likely to be pre-scheduled for housing association dwellings. Housing associations have maintenance strategies for their real estate; they can apply strategies that are both financially and environmentally sound. In the Netherlands, owner-occupiers of multi-family residential buildings are required by law to organise themselves in home-owner associations and to jointly maintain the structural elements of the building and the shared space. The larger the home-owner association, the greater the opportunity to apply economically and environmentally sustainable maintenance strategies. Housing associations in the larger Dutch cities can assist home-owner associations with their maintenance strategy. Private landlords are also required to maintain their building. Landlords with a large real-estate portfolio may adopt maintenance strategies similar to those of housing associations or private home-owner associations. Private landlords with only a small real-estate portfolio may act more like private owner-occupants of single-family dwellings. The latter group is least likely to adopt home-maintenance strategies. They may set aside money to finance maintenance, but they may not plan actual activities until they are necessary. This strategy may be sustainable as long as the quality of the building is maintained. Then maintenance and replacements are performed just in time, but it may be very unsustainable if activities are postponed and the service life of building components is shortened. Finally, some owner-occupiers neither plan nor reserve money for home-maintenance and thus cause a shorter service life of the building components and the building itself.

It may be concluded that the results of the research can partly be generalised to include the operational phase of other dwelling types. Gas and electricity consumption are likely to remain the greatest contributors to all environmental impact categories apart from Fresh water aquatic ecotoxicity, which is affected most by material resources and waste processing. The ratio between the impact of gas consumption and electricity consumption may vary, as well as the ratio between the impact of energy consumption on the one hand and material resources, waste processing and transportation of maintenance workers on the other hand. Further research is needed to determine the differences between different dwelling types.

The environmental impacts of the operational phase of dwellings in other countries than the Netherlands will be different for several reasons. First, local building traditions related to dwelling typology, construction methods, production processes, materials and technical standards will influence the resources used for building components and services. Second, the local climate will further influence the need for the maintenance and replacement of building components exposed to the elements and the type of climate systems in the dwellings will depend on the local climate, technical standards and tradition. Third, building codes, standards, policies and institutions may be different. Policies of the European Union that are aimed at the built environment often leave room for national governments to take local circumstances into account. Fourth, the environmental quality of the energy resources will have a strong influence on the environmental impact of dwellings. As shown in Chapter 4, the environmental impacts of the electricity supplied in different countries can vary widely. Further research will therefore have to ascertain what the environmental impacts of the operational phase of dwellings in other countries are and the factors that significantly contribute to the environmental impact categories.

### 6.2.6 Main conclusions

The results of this research show that the consumption of gas and electricity combined contributes up to 95% to impact scores, while material resources contribute up to 20% of the impact scores. Technical building measures which reduce heat demand, such as applying high efficiency glazing and more efficient climate systems, and measures which lengthen the service life of building components can reduce the environmental impact by up to 30%. However, the energy efficiency of relatively new space heating technology should be improved before applying it at a large scale, particularly regarding auxiliary electricity consumption. The design of new buildings should focus on reducing the heat demand as much as possible, but the heat demand should not be replaced by the auxiliary electricity demand in such a way that the operation of the climate system significantly increases the environmental impact. A 47% reduction of user-related energy consumption by using fewer appliances that are more energy efficient leads to up to 49% lower impact scores.

The environmental impacts of material resources can be reduced by extending the service life of building components, either by improving the design of the building or the component, or the maintenance. Furthermore, buildings should be designed with enough flexibility and adaptability to accommodate implementation of yet unknown future technology and changing functional preferences, thus building components and climate systems should be easily removed and replaced.

In Chapter 1, the Three Step Strategy was mentioned. The results of this research support this theory at the level of individual buildings, as it is more effective to reduce electricity consumption than to improve the environmental quality of the electricity supplied to the dwellings, especially given the rate at which the capacity of sustainable electricity production is currently growing, or to increase the energy efficiency of the building and its systems. Yet, the total annual energy consumption of Dutch households is expected to continue to rise for several reasons. Gas consumption is growing because of the increasing number of households, even though consumption per household is declining. Electricity consumption is rising due to the increasing number of households combined with increasing numbers of appliances in each household, even though most household appliances are becoming more energy-efficient all the time (EnergieNed, 2008). Hence, it may be more effective in terms of the overall building stock to improve the environmental quality of the electricity supply by changing to different sources of generation or by developing new sustainable technology, as better-quality electricity would affect the environmental impacts of all households, while behavioural change is an individual decision and would only affect some of the dwellings. The share of sustainable electricity should, however, be substantial and the type of sustainable resource should be chosen carefully to ensure that a reduction in the environmental impact in one category does not take place at the expense of another.

The shift of environmental impact from one category to another can also be observed in other aspects of the research. It occurs, for example, when gas consumption is replaced by electricity, when energy efficiency is reached by applying more material resources in the dwelling, or when alternative building products made of different materials are chosen. Accordingly, this research stresses the importance of full-range environmental assessments that show the environmental impact embodied in building products as well as material and energy resources consumption and the full range of environmental impact categories. It has been apparent throughout the research that specific parts of the production processes and energy supply affect specific environmental impact categories. For example, zeolite, which is used to absorb moisture in the space between the panes in double glazing, is a dominant factor in Fresh water aquatic toxicity. By the same token, the pumps and compressors used to distribute gas dominate the contribution to Ozone layer depletion. The score of specific impact categories could therefore be reduced by targeting specific areas of production and supply processes.

Finally, the environmental impacts from the operation of dwellings can only be reduced by concerted effort by the manufacturers of building products and services, the owners of residential buildings, maintenance companies, energy supply companies and, last but not least, the occupants (Browne and Frame, 1999).

## 6.3 Recommendations for policy, practice and further research

This section contains recommendations for government and housing association policy (Subsection 6.3.1), and for the practices of different actors during the operational phase of dwellings (Subsection 6.3.2) as well as suggestions for further research (Subsection 6.3.3).

### 6.3.1 Recommendations for policy goals

Policies are made by different actors and serve different goals. This subsection focuses on policies made by governments and housing associations, which have a strong influence on the operational phase of dwellings. The policies of housing associations on their dwelling stock should include environmental sustainability goals alongside strategic and financial goals.

National government policy should aim to improve the energy efficiency of the older housing stock by supporting and stimulating building owners who are willing to enhance the thermal quality of the outer shell of the building and the energy efficiency of the climate systems. Furthermore, the general development of electricity generated from sustainable resources should be stimulated and the share of sustainable electricity should grow much faster than in the current target, which is 35% electricity from sustainable resources in the Netherlands in 2020 (Ministerie van VROM, 2009a). However, as sustainable energy technology is being developed, all the environmental aspects of it should be assessed in order to avoid shifts in environmental problems. Frontrunners in the development of new techniques should be supported. Occupants of dwellings should be persuaded to consume less electricity and encouraged to switch to electricity from renewable resources by, for example, changing the price of electricity from unsustainable resources. However, influencing energy use behaviour has been the aim of many programmes to date and proves to be a difficult topic (Mourik and Heiskanen, 2009; Smits, 2007). Consumers who want to generate their own sustainable energy should be optimally supported through reliable measures. A guaranteed long-term feed-in tariff for electricity delivered to the grid could stimulate local generation of sustainable energy (Europe's Energy Portal, 2010; Klein *et al.,* 2008). Finally, manufacturers of building products and services should be encouraged to improve the environmental impacts embodied in their products by using sustainable energy resources and more efficient production processes and by demanding the same of manufacturers whose products they use. For example, the Dutch government has initiated the Sustainable Purchasing program, which is a guideline for large purchasing organisations – such as the government itself – to put up environmental criteria for the products they purchase (Ministerie van VROM, 2009b).

At the level of European policy, similar goals for improving the energy efficiency of housing can be adopted. However, there are large differences in climate among the EU countries, which makes it impossible to impose specific measures. Therefore, European policies are enforced in all EU countries, but leave room for local interpretation. It may be possible to define a minimum energy performance level that leaves room for local differences, such as maximum building-related energy consumption per square or cubic meter. Second, the development of more sustainable energy systems should be part of European policy, since the gas and electricity networks are all connected and major energy supplying companies are multinationals. The development of new sustainable energy technology should be supported, either financially or by simplifying regulations in EU countries. Finally, the development and use of Environmental Product Declarations for manufacturers of semi-manufactured products and end products should be stimulated, to provide insight in the environmental impacts in the supply chain of products. As a result, competition based on the environmental quality of products will become possible.

### 6.3.2 Recommendations for practice

The owners of residential real-estate with low energetic quality can improve energy efficiency by using alternative façade components and more efficient climate systems. It is, however, more desirable to regulate the climate by passive building measures than to install more elaborate systems, as the latter often leads to more materials in the systems and an increase in auxiliary electricity consumption. New dwellings should be designed with the operational phase in mind. The design of a building should shield the components from degradation. As in the case of existing dwellings, it is best to strive for passive climate control and buildings with zero or near zero energy consumption. Designers of new buildings and refurbishment plans alike should look into techniques from manufacturers abroad, since there are plenty of successful techniques abroad that are barely known in the Netherlands.

Building product manufacturers should work on the environmental quality of their products by, for example, using recycled material in their products, by using sustainable energy resources to produce products and by making the products easy to recycle or process as waste at the end of their service life. Furthermore, they should assess the environmental performance of their products and persuade their suppliers to do likewise. Low-impact products may provide competitive vantage, especially if Sustainable Purchasing becomes common practice among large purchasers.

Occupants – particularly owner-occupiers – have a strong hand in the environmental impact of dwellings. However, as Klunder (2005) also mentions in the conclusions of her PhD thesis, occupants cannot be held solely responsible for their actions. Other actors in the construction and real estate sector should provide practical and easily maintainable dwellings with a quality that is high enough to prevent rapid deterioration. Furthermore, occupants should have access to information on how to lower their energy consumption. In the end, occupants are responsible for the amount of energy they waste through ignorance and the amount of energy that is used by appliances in the home.

### 6.3.3 Recommendations for further research

The research described in this thesis points to various avenues of further research. First, it could be extended by including the maintenance and replacement of other building components, such as the roof (Majcen, 2009) or interior finishing, and other activities such as the introduction of new technology and building products in the dwelling. Second, the level of detail could be increased by, say, including specific waste-treatment processes or the transportation of building components from the harbour to the building site. Third, the current work could be applied to different types of dwellings as a basis for comparison and for the validation of the conclusions of this research for the total dwelling stock in the Netherlands. Similarly, comparisons can be made between the use of dwellings that are constructed differently, such as timber frame, steel frame, and concrete constructions (Blom, 2006), or traditional building methods and flexible, (de)mountable construction (van Nunen, 2010). Another comparison can be drawn between the use of traditionally built dwellings and passive or near-zero energy dwellings to determine whether the latter are used differently. Fourth, the use of Dutch dwellings could be compared with the use of dwellings in other countries. Differences in building traditions and climate mean that dwellings in other countries have different characteristics, which make the dwellings themselves hard to compare (see: functional unit issues in Subsection 1.4.1); but it may still be interesting to ascertain the contributing factors that dominate the environmental impact in the operational phase of dwellings in other countries. Furthermore, since energy consumption during the operation of dwellings has a strong influence on the results, differences in the type and quality of energy resources used in other countries may provide useful insight for policymakers.

This thesis also provides leads for other types of research. First, life-cycle assessments of building components and climate systems can be used to make research like this more detailed and accurate. Environmental Product Declarations (EPD) by manufacturers in the building industry, when defined according to international standards, are a valuable source of input data for LCAs in the operational phase as well. Second, this research also raises questions about the decision-making processes of various actors in the operational phase of dwellings. It is useful to know which actors influence the environmental impacts that occur in the operational phase of dwellings and how and why they make decisions in order to set up effective policy measures. Third, this research has highlighted the need to improve certain aspects of LCA methodology, particularly the temporal and geographical issues in the impact assessment (Hellweg *et al.*, 2005; Potting and Hauschild, 2006; Ross and Evans, 2002), so that it is better suited to assess products and processes with a long service life and components from all over the world. Another aspect of LCA methodology is the inventory assessment, or how LCA is applied to buildings. Future LCA research on buildings should focus on obtaining deeper and more detailed insight into the environmental effects related to the entire service life of buildings, focusing first on identifying the major contributors to environmental problems and systematically assessing the influence of different parameters on the environmental impact. Environmental impact cannot be assigned only to the physical components of the building, but also to the different actors. As shown by Brunklaus *et al.* (2010), all actors in the production, use and demolition of buildings are responsible for part of the environmental impact. If the focus is only on the end product, many opportunities to improve the environmental quality will be missed. Further research could address how to define a sustainable benchmark for testing new buildings and comparing building assessments over time, or develop guidelines for scenario assessments and find ways of reporting the assessment results allocated to regions, actors or time frames. Fourth, further research could shed more light on user behaviour regarding energy consumption, e.g. the difference between short-term and long-term stated and revealed user preferences and how they are influenced by, for example: demographic, social and psychological factors; available information and the price of energy. Feed-back mechanisms that show real-time and accumulated energy consumption could be tested for effectiveness (Fischer, 2008; Jensen, 2008). A fifth research topic that may help to make the operation of dwellings more sustainable is the environmental assessment of different sustainable energy systems for dwellings. Some forms of sustainable energy are best suited for (inter)national networks, some for neighbourhoods and some for individual buildings. An extensive environmental assessment of different types of sustainable energy on different geographical scales could provide deep insight into the future energy system. The local interaction between different systems that make use of the same heat or energy resources is another interesting topic of research.

Finally, the current research can be valorised by developing tools to help the various actors to decide on the right course of action, strategically, financially and environmentally. For example, a tool could be developed to enable housing associations and maintenance companies to calculate the environmental and economic consequences of different maintenance strategies (Itard *et al.*, 2010).

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# Summary

## Environmental impacts during the operational phase of residential buildings

*Inge Blom*

The United Nations Environmental Programme (UNEP) and the European Commission (EC) have identified the building sector as a key factor in reaching the Kyoto Protocol targets for reducing $CO_2$ emissions. The building sector consumes an estimated 30-40% of energy worldwide and around 36% in the European Union (EU): the non-residential sector accounts for 8.7% and the residential sector for 27.5% of the total.

The primary challenge posed by ecological sustainability is to ease the pressure on the environment amid a constantly rising world population and ever-increasing prosperity. This challenge calls for methods to formulate quantified targets for sustainable development and to measure and monitor progress. The life cycle assessment (LCA) approach, which can be applied to buildings, steps up to the challenge by analysing and quantifying the negative impact of material and energy flows on different environmental mechanisms. The life cycle of a building consists of three clearly distinguishable main phases: construction, operation and deconstruction.

The operational phase of a building spans multiple decades, which is why reducing the environmental impacts of buildings might be more effectively achieved by changing the way buildings are used and managed rather than by changing the building itself. To date, no comprehensive and detailed research has been published on this theme. There is a lack of knowledge regarding the environmental impacts of regularly occurring activities in the operational phase of dwellings, such as regular maintenance and renovation, and the relationship between building-related and user-related impacts is unclear.

### Objective and research questions

The objective of this research is to provide insight into the factors that cause the greatest environmental impacts in the operational phase of residential buildings and awareness of the long-term ecological consequences of decisions made in the design, construction and operational phases. The research further aims to contribute to the modelling of the operational phase of residential buildings in life cycle assessment (LCA) by indicating if it is possible to assess the ecological sustainability of residential buildings with reasonable accuracy according to a limited number of contributing factors. The acquired knowledge may help policymakers to develop effective policies and can steer further developments in research and building practice towards areas that have the most potential for improving the environmental performance of residential buildings. The research includes a sensitivity analysis for variations in standard operational behaviour patterns, since those variations may have great influence on the results. The aim of this research is to establish how great the influence of operational behaviour and assumed variations thereof are compared to other factors. Further research may include behavioural science to determine how and why people behave like they do and how to effectively promote ‘good’ behaviour.

The main research questions are:

1. *What are the environmental impacts related to the operational phase of residential buildings?*
2. *Which factors significantly contribute to the various environmental impact categories?*
3. *To what extent do changes in the variable parameters of the assessment affect the environmental impacts?*
4. *How can the environmental impacts in the operational phase be most effectively reduced?*

These research questions are applied to three main aspects of the operational phase of dwellings and the operational phase as a whole:

- maintenance and replacement of façade components (Chapter 2);
- maintenance, replacement and use of heating and ventilation systems (Chapter 3);
- building-related and user-related gas and electricity consumption (Chapter 4);
- operational phase of dwellings, including the replacement of bathroom, toilet and kitchen (Chapters 5 and 6).

The main aspects of the operational phase have been selected on the basis of the probability of high environmental impacts, given the high frequency of activities and the amount of energy, materials and waste.

**Research approach**

The environmental impacts occurring in the operational phase of dwellings are quantified by life cycle assessment (LCA) methodology. There are four steps in LCA, which consist of the definition of the goal and scope of the research; the inventory phase in which all relevant substance flows to and from the environment are inventoried; the impact assessment phase in which the impact of all substance flows is assessed; and the interpretation phase in which the results of the assessments are analysed in the light of the goal of the research. As a research methodology which is still in development, LCA will continue to be refined, improved and expanded for some time to come as a result of progressing insight. LCA methodology can be considered current best practice which is improving in time. The LCA is performed with the SimaPro software package and the input data for the calculations of the environmental impact come from the commercially available ecoinvent 2.0 database.

In order to assess the environmental impact of activities in the use phase of dwellings, the amount of materials needed for building products and systems and the energy consumption of climate systems are calculated with the aid of a Dutch reference building. The building selected for this research is the gallery flat constructed between 1966 and 1988 of which there are approximately 208,000 dwellings in the Netherlands, 67% of which are owned by housing associations and subject to regularly scheduled maintenance and replacement activities.

In order to show how environmental impact accumulates in time as a result of decisions made in the operational phase of the dwellings, the environmental assessment is performed by applying scenarios to the reference building. A scenario describes when activities, such as maintenance and replacements, take place. The gas and electricity consumption is calculated with Vabi EPA-W software, which is attested according to the Dutch standard for energy performance calculation tools, BRL 9501, which measures calculation methods against current best available practice.

## Results

The results of the environmental impact assessment of various scenarios for the operational phase of the reference dwelling presented in Chapter 5 show that when the technical measures that were proven effective in Chapters 2 and 3 are implemented – namely, applying high-efficiency glazing and climate systems and reducing maintenance and replacement activities – the environmental impact scores will fall by 2-30% depending on the impact category. When, in addition to the technical measures mentioned above, the user-related electricity consumption for appliances is reduced by 47% by decreasing the number of appliances in the dwelling and using appliances that are more energy efficient, the environmental impact scores will fall by 27-49%. Both of the above mentioned scenarios make use of the electricity mix supplied to Dutch households in 2004. They have also been calculated with a 2020 electricity mix in which 35% of the electricity is generated from sustainable renewable resources. The results show that the contribution to some environmental impact categories would then be further reduced by 15-18% (Abiotic depletion, Global warming, Ozone layer depletion and Photochemical oxidation), while others would increase compared with the 2004 electricity mix (slight increase for Human toxicity and notable increase for Eutrophication – 17%). The other impact scores have the same order of magnitude.

The results of the environmental impact assessment per contributing factor show that gas and electricity consumption causes 80-95% of the environmental impact in all categories except Fresh water aquatic ecotoxicity, which is dominated by material resources and processing of waste metals (65-80% of the total). Material resources account for about 5-20% of the contribution to the environmental impact categories. Some material resources and related production processes contribute considerably to specific impact categories.

Chapter 2 shows that extending the service life of façade components by

50% reduces the environmental impacts from the maintenance and replacement of façade components by 17-27% after 70 years. The reduced environmental impact stems from the fact that fewer façade components need to be produced and processed as waste during the operational phase of the dwelling. Additionally, transportation of maintenance workers to perform replacement activities is reduced. The effect of extending the service life of façade components increases slowly over time: after 150 years of dwelling operation, the environmental impact of the maintenance of façade components decreases by 24-35%.

The theoretical variations in occupant behaviour in this research have relatively little influence on the gas used for heating and hot tap water, therefore they have little influence on the environmental impacts of gas consumption. However, in practice the gas consumption of occupants living in identical dwellings may vary widely due to different temperature settings and ventilation habits. Electricity consumption is strongly related to user behaviour. Changes in behaviour, which in the context of this research mean changes in the number of appliances in the dwelling and their energy efficiency can reduce the environmental impacts of energy consumption by up to 60%.

### Main conclusions

The results show that it is not a specific group of activities that has the greatest influence on the environment, but rather factors that are involved in all kinds of activities, such as energy consumption and the use of high-impact material resources. Technical building measures which reduce heat demand, such as applying high efficiency glazing and more efficient climate systems, and measures which lengthen the service life of building components can reduce the environmental impact by up to 30%. The design of new buildings should focus on reducing the heat demand as much as possible, but careful attention should be paid to possible shifts and increases of environmental impacts when different types of energy are used, for example electricity instead of gas. Furthermore, the energy efficiency – particularly auxiliary electricity consumption – of relatively new space heating technology should be improved before applying it at a large scale. A 47% reduction of user-related energy consumption leads to up to 49% lower impact scores.

The environmental impacts of material resources can be reduced by extending the service life of building components, either by improving the design of the building or the component, or the maintenance. Furthermore, buildings should be designed with enough flexibility and adaptability to accommodate implementation of yet unknown future technology and changing functional preferences, thus building components and climate systems should be easily removed and replaced.

According to the results, it should be possible to asses the general ecological sustainability of residential buildings by a few factors, provided that a checklist of high-impact materials is available and it is known how much material is used in building components and systems.

The results of this research support the Three Step Strategy theory at the level of individual buildings, as it is more effective to reduce electricity consumption than to improve the environmental quality of the electricity supplied to the dwellings, especially given the rate at which the capacity of sustainable electricity production is currently growing, or to increase the energy efficiency of the building and its systems. Yet, the total annual energy consumption of Dutch households is expected to continue to rise for several reasons. Gas consumption is growing because of the increasing number of households, even though consumption per household is declining. Electricity consumption is rising due to the increasing number of households combined with increasing numbers of appliances in each household, even though most household appliances are becoming more energy-efficient all the time. Hence, it may be more effective in terms of the overall building stock to improve the environmental quality of the electricity supply by changing to different sources of generation or by developing new sustainable technology, as better-quality electricity would affect the environmental impacts of all households, while behavioural change is an individual decision and would only affect some of the dwellings. The share of sustainable electricity should, however, be substantial and the type of sustainable resource should be chosen carefully to ensure that a reduction in the environmental impact in one category does not take place at the expense of another.

The shift of environmental impact from one category to another can also be observed in other aspects of the research. It occurs, for example, when gas consumption is replaced by electricity, when energy efficiency is reached by applying more material resources in the dwelling, or when alternative building products made of different materials are chosen. Accordingly, this research stresses the importance of full-range environmental assessments that show the environmental impact embodied in building products as well as material and energy resources consumption and the full range of environmental impact categories. It has been apparent throughout the research that specific parts of the production processes and energy supply affect specific environmental impact categories. The score of specific impact categories could therefore be reduced by targeting specific areas of production and supply processes.

Finally, the environmental impacts from the operation of dwellings can only be reduced by concerted effort by the manufacturers of building products and services, the owners of residential buildings, maintenance companies, energy supply companies and, last but not least, the occupants.

## Recommendations for policy, practice and further research

Policies are made by different actors and serve different goals. The policies of housing associations on their dwelling stock should include environmental sustainability goals alongside strategic and financial goals. National and international government policy should aim to improve the energy efficiency of the older housing stock by stimulating the enhancement of the thermal quality of the outer shell of the building and the energy efficiency of the climate systems. Furthermore, the general development of electricity generated from sustainable resources should be stimulated and the share of sustainable electricity should grow much faster than in the current targets. Consumers who want to generate their own sustainable energy should be optimally supported through reliable measures. Additionally, the development and use of Environmental Product Declarations (EPD) for manufacturers of semi-manufactured products and end products should be stimulated, to provide insight in the environmental impacts in the supply chain of products.

There are many actors that influence the operational phase of dwellings. Owners of residential real-estate with low energetic quality can improve energy efficiency by using alternative façade components and more efficient climate systems. Occupants – particularly owner-occupiers – have a strong hand in the environmental impact of dwellings, but they cannot be held solely responsible for their actions. In the end, occupants are responsible for the amount of energy wasted through ignorance and energy used by appliances. New dwellings should be designed with the operational phase in mind, to shield the building from fast degradation and create possibilities for future technology. Building product manufacturers should improve the environmental quality of their products by, for example, eliminating high-impact parts, using recycled material, making the products easy to recycle or process as waste and using sustainable energy.

The research described in this thesis points to various avenues of further research. First, it could be extended by including the maintenance and replacement of other building components and other activities such as the introduction of new technology and building products. Second, the current work could be applied to different dwelling and construction types and dwellings in other countries. Furthermore, an extensive environmental assessment of different types of (sustainable) energy in different countries and at different geographical scales could provide deep insight into desired future energy systems. This thesis also provides leads for other types of research, such as fetailed life-cycle assessments of building components and climate systems; and analysis of the decision-making processes of various actors in the operational phase of dwellings. Finally, future life cycle assessments of buildings should focus on obtaining deeper and more detailed insight into the environmental effects related to the entire service life of buildings, focusing first on identifying the major contributors to environmental problems and systematically assessing the influence of different parameters on the environmental impact.

# Samenvatting

## Milieu-impacts in de gebruiksfase van woongebouwen

*Inge Blom*

Volgens United Nations Environmental Programme (UNEP) en de Europese Commissie (EC) speelt de bouwsector een sleutelrol in het behalen van de doelstellingen voor het reduceren van $CO_2$ emissies, zoals vastgesteld in het Kyoto Protocol. Wereldwijd komt een geschatte 30-40% van het totale energieverbruik voor rekening van de bouwsector. In de Europese Unie (EU) is de energievraag van gebouwen ongeveer 36% van het totale energieverbruik, waarvan 27,5% in de woningbouw en 8,7% in de utiliteitsbouw.

De grootste uitdaging met betrekking tot ecologische duurzaamheid is het verminderen van de milieubelasting bij een groeiende wereldbevolking en toenemende welvaart. Deze uitdaging vraagt om een methode om de milieu-impact kwantitatief vast te kunnen stellen, zodat de voortgang op het gebied van ecologische duurzaamheid kan worden gecontroleerd. Met behulp van levenscyclusanalyse (LCA), die kan worden toegepast op gebouwen, kan de negatieve invloed van materiaal- en energiestromen op verschillende milieukundige mechanismen gekwantificeerd en geanalyseerd worden. De levenscyclus van een gebouw bestaat uit drie hoofdfasen: de bouwfase, gebruiksfase en sloopfase.

De gebruiksfase van een gebouw beslaat meerdere decennia. Veranderingen in de manier waarop gebouwen worden gebruikt en beheerd zouden daarom effectiever milieu-impact kunnen verminderen dan veranderingen aan het gebouw zelf. Tot op heden is er over dit thema geen uitgebreid en gedetailleerd onderzoek gepubliceerd. Er is gebrek aan kennis over de milieu-impacts van regelmatig voorkomende gebeurtenissen in de gebruiksfase van woningen, zoals regulier onderhoud en renovaties, en de verhouding tussen gebouwgerelateerde en gebruikergerelateerde milieu-impact is onbekend.

### Doelstelling en onderzoeksvragen

Het doel van dit onderzoek is om inzicht te verschaffen in de factoren die de grootste milieu-impact veroorzaken in de gebruiksfase van woongebouwen en de gevolgen van besluiten in de ontwerp-, bouw- en gebruiksfase voor het milieu op lange termijn. Het onderzoek beoogt tevens een bijdrage te leveren aan het modelleren van de gebruiksfase van woongebouwen in levenscyclusanalyse (LCA) door aan te geven of het mogelijk is om met redelijke nauwkeurigheid de milieu-impact van woongebouwen te bepalen met behulp van een beperkt aantal factoren. De verkregen kennis kan beleidsmakers helpen om effectief beleid te ontwikkelen en kan richting geven aan ontwikkelingen in onderzoek en de praktijk in de bouwsector, zodat maatregelen die potentieel de grootste verbeteringen bieden worden uitgediept. Het onderzoek bevat een gevoeligheidsanalyse van variaties in standaard gebruiksgedrag, omdat die variaties een grote invloed kunnen hebben op de resultaten. Het doel van het onderzoek is om te bepalen hoe groot de invloed van gebruiksgedrag en aangenomen variaties daarop is vergeleken met andere factoren. Nader gedragswetenschappelijk onderzoek kan vervolgens worden ingezet om te bepalen hoe en waarom mensen zich gedragen zoals ze doen en hoe 'goed' gedrag kan worden gestimuleerd.

De hoofdonderzoeksvragen zijn:

1. *Wat zijn de milieu-impacts gerelateerd aan de gebruiksfase van woongebouwen?*
2. *Welke factoren dragen significant bij aan de verschillende impactcategorieën?*
3. *In welke mate beïnvloeden veranderingen van de variabele parameters in het onderzoek de milieu-impacts?*
4. *Wat is de effectiefste manier om de milieu-impacts in de gebruiksfase van woongebouwen te verminderen?*

## Onderzoeksmethode

Door middel van levenscyclusanalyse (LCA) worden de milieu-impacts die in de gebruiksfase van woningen optreden kwantitatief bepaald. Een LCA bestaat uit vier stappen, die bestaan uit het bepalen van de doel en reikwijdte van het onderzoek, de inventarisatie van alle relevante materiaal- en energiestromen van en naar het milieu, de analyse van de invloed van de materiaal- en energiestromen op het milieu; en de interpretatie van de resultaten van de analyse met betrekking tot het doel van het onderzoek. LCA is een onderzoeksmethode die nog volop in ontwikkeling is, maar kan worden beschouwd als de best beschikbare methode van het moment. Door voortschrijdend inzicht zal de methode in de toekomst nog worden verfijnd, verbeterd en uitgebreid. Voor de analyse is gebruik gemaakt van de software SimaPro en de milieugegevens van materialen en processen zijn ontleend aan de database ecoinvent.

Om de milieu-impacts van activiteiten in de gebruiksfase van woningen te kunnen bepalen is in het onderzoek gebruik gemaakt van een Nederlandse referentiewoning om de hoeveelheid materialen in bouwdelen en klimaatinstallaties te kunnen bepalen. De geselecteerde woning is een appartement in een galerijflat zoals deze werd gebouwd tussen 1966 en 1988, waarvan er in Nederland ongeveer 208.000 zijn. 67% van deze appartementen zijn in het bezit van woningcorporaties, waardoor onderhoud en vervanging van bouwdelen en klimaatinstallaties volgens een onderhoudsplan worden uitgevoerd. De gebruikscenario's voor de referentiewoning maken het ook mogelijk om de opeenstapeling van milieu-impacts als gevolg van activiteiten in de gebruiksfase in de tijd weer te geven. In een scenario staat aangegeven wanneer activiteiten zoals onderhoud en vervanging plaatsvinden. Het gas- en elektriciteitsverbruik in de woning is berekend met de gecertificeerde EPA-W software van Vabi, die ook wordt gebruikt om de energie prestatie coëfficiënt (EPC) van woningen te berekenen volgens BRL 9501.

**Resultaten**

De resultaten van de impact analyse van verschillende scenario's voor de gebruiksfase van de referentiewoning in Hoofdstuk 5 laten zien dat wanneer de technische maatregelen die effectief bleken in Hoofdstukken 2 en 3 worden geïmplementeerd – namelijk het toepassen van HR++ beglazing en efficiënte klimaatinstallaties en het reduceren van onderhoud en vervangingen – de milieu-impacts met 2 tot 30% zullen dalen, afhankelijk van de milieu-impactcategorie. Wanneer naast deze maatregelen ook het elektriciteitsverbruik van apparaten met 47% afneemt, bijvoorbeeld doordat bewoners kiezen voor een kleiner aantal energiezuinige apparaten in de woning te hebben, dan dalen de milieu-impacts met 27 tot 49%. In beide genoemde scenario's wordt gebruik gemaakt van de elektriciteitsmix zoals die in 2004 werd geleverd. Deze scenario's zijn ook uitgerekend met een mix voor 2020, waarin 35% van de elektriciteit wordt opgewekt uit duurzame bronnen. De resultaten laten zien dat de bijdrage tot sommige milieu-impactcategorieën dan verder zullen dalen met 15 tot 18% (Uitputting van abiotische grondstoffen, Klimaatverandering, Aantasting van de ozonlaag en Fotochemische oxidatie), maar andere bijdragen zullen stijgen (kleine stijging voor Humane toxiciteit, 17% voor Vermesting). De bijdragen aan de overige impactcategorieën blijft in de zelfde orde van grootte.

De resultaten van de analyse per factor laten zien dat gas- en elektriciteitsverbruik 80 tot 95% van de bijdrage aan alle impactcategorieën veroorzaken, behalve in de categorie Ecotoxiciteit zoet water, die wordt veroorzaakt door materiaalgebruik en het verwerken van metaal afval (65-80% van de totale bijdrage). Materiaalgebruik zorgt voor 5-20% van de bijdrage aan de impactcategorieën. Sommige materialen en gerelateerde productieprocessen dragen in belangrijke mate bij aan specifieke impactcategorieën.

In hoofdstuk 2 wordt aangetoond dat het met 50% verlengen van de levensduur van geveldelen de milieu-impact van onderhoud en vervangingen van geveldelen met 17-27% vermindert na 70 jaar woninggebruik. De reden voor de verminderde milieu-impacts is dat er minder geveldelen gemaakt en als afval verwerkt hoeven worden tijdens de gebruiksfase van de woning. Daarnaast wordt het transport van bouwvakkers ten behoeve van de vervanging van geveldelen verminderd. Het gunstige effect van het verlengen van de levensduur van geveldelen wordt groter naarmate de gebruiksfase langer duurt: na 150 jaar zijn de milieu-impacts verminderd met 24-35%.

De theoretische variaties in gebruikersgedrag in dit onderzoek hebben relatief weinig invloed op het gasverbruik voor verwarming en warm tapwater en hebben daarom weinig invloed op de milieu-impacts van gasverbruik. In de praktijk blijkt echter dat het gasverbruik van bewoners van identieke woningen erg verschillend kan zijn als gevolg van onder andere verschillende temperatuurinstellingen en ventilatiegedrag. Het elektriciteitsverbruik in woningen is sterk gerelateerd aan gebruikersgedrag. Gedragsveranderingen – in de context van dit onderzoek aanpassingen aan de hoeveelheid en de energiezuinigheid van apparatuur in de woning – kunnen de milieu-impacts van energieverbruik tot 60% verlagen.

### Hoofdconclusies

De resultaten laten zien dat het niet een bepaalde groep van activiteiten is die de grootste invloed op het milieu heeft, maar factoren die betrokken zijn bij allerlei activiteiten, zoals het energieverbruik en het gebruik van materialen met grote impact. De milieu-impacts kunnen tot 30% verlaagd worden met behulp van technische maatregelen om de warmtevraag te verminderen, zoals het toepassen van HR++ beglazing en efficiëntere klimaatinstallaties, en maatregelen die de levensduur van bouwdelen verlengen. Het ontwerp van nieuwe gebouwen moet gericht zijn op het zoveel mogelijk verminderen van de warmtevraag, maar er moet zorgvuldig aandacht worden besteed aan mogelijke verschuivingen en verhogingen van de milieu-impacts wanneer alternatieve soorten energie worden gebruikt, bijvoorbeeld elektriciteit in plaats van gas. Bovendien moet de energie-efficiëntie van relatief nieuwe ruimteverwarmingstechnologie worden verbeterd alvorens het op grote schaal wordt toegepast, met name op het gebied van benodigde elektrische hulpenergie. De impact scores kunnen met maximaal 49% worden verminderd door het verlagen van het elektriciteitsverbruik van bewoners.

De milieu-impact van materiaalgebruik kan worden verminderd door de levensduur van bouwdelen te verlengen, hetzij door het verbeteren van het ontwerp van het gebouw of het bouwdeel, hetzij door beter onderhoud. Bovendien moeten gebouwen worden ontworpen met voldoende flexibiliteit en aanpasbaarheid aan nog onbekende toekomstige technologie en veranderende functionele voorkeuren, door bouwdelen en klimaatinstallaties gemakkelijk te kunnen verwijderen en vervangen.

De resultaten van het onderzoek laten zien dat het mogelijk moet zijn om de ecologische duurzaamheid van een woning te beoordelen met behulp van een beperkt aantal factoren, mits er een checklist van materialen met grote milieu-impact beschikbaar is en het bekend is hoeveel materiaal wordt gebruikt voor de productie van bouwdelen en klimaatinstallaties.

Op de schaal van individuele gebouwen ondersteunen de resultaten van dit onderzoek de Three Step Strategy: het blijkt efficiënter om het elektriciteitsverbruik in de woning te verminderen dan om de energie-efficiëntie van het gebouw en de klimaatinstallaties te verbeteren of de milieukwaliteit van de geleverde elektriciteit te verbeteren, vooral gezien de snelheid waarmee de capaciteit van elektriciteit uit duurzame bronnen momenteel groeit. De verwachting is dat het totale jaarlijkse energieverbruik van Nederlandse huishoudens zal blijven stijgen: gasverbruik groeit vanwege de toename van het aantal huishoudens, ook al neemt het verbruik per huishouden af, en elektriciteitsverbruik stijgt als gevolg van het groeiende aantal huishoudens in combinatie met een toenemend aantal apparaten per huishouden, hoewel de meeste huishoudelijke apparaten steeds energiezuiniger worden. Op de schaal van de totale woningvoorraad is het echter efficiënter om de milieukwaliteit van de elektriciteitsvoorziening te verbeteren door elektriciteit uit andere bronnen op te wekken of door nieuwe, duurzame technologie te ontwikkelen, aangezien een betere kwaliteit elektriciteit invloed heeft op de milieu-impacts van alle huishoudens, terwijl gedragsverandering een individuele beslissing is en alleen van invloed op de eigen woning. Het aandeel duurzaam opgewekte elektriciteit moet echter aanzienlijk stijgen en het type duurzame energiebronnen moet zorgvuldig worden gekozen om ervoor te zorgen dat een vermindering van de milieu-impact in de ene impactcategorie niet ten koste gaat van een andere categorie.

In andere aspecten van het onderzoek is ook sprake van een verschuiving van milieu-impacts van de ene categorie naar de andere, bijvoorbeeld wanneer gasverbruik wordt vervangen door elektriciteit, wanneer meer materialen moeten worden gebruikt om de energie-efficiëntie van de woning te verbeteren, of wanneer wordt gekozen voor alternatieve bouwdelen gemaakt van andere materialen. Dit onderzoek benadrukt het belang van analyses over het hele spectrum van impactcategorieën, die kijken naar alle materiaal- en energiestromen. Uit het onderzoek wordt duidelijk dat specifieke onderdelen van de productieprocessen en de energievoorziening bijdragen aan specifieke milieu-impactcategorieën. Deze impacts kunnen worden verlaagd door gericht productie en transportprocessen te verbeteren.

Ten slotte kunnen de milieu-impacts in de gebruiksfase van woningen alleen worden verminderd door gezamenlijke inspanning van de fabrikanten van bouwproducten en klimaatinstallaties, de eigenaars van woongebouwen, onderhoudsbedrijven, energiebedrijven en, last but not least, de bewoners.

### Aanbevelingen voor beleid, bouwpraktijk en vervolgonderzoek

Er zijn verschillende actoren die beleid maken, dat in ieder geval zijn eigen doel dient. Het voorraadbeleid van woningcorporaties zou naast strategische en financiële overwegingen ook ecologische duurzaamheid moeten omvatten. Nationaal en international beleid zou zich tot doel moeten stellen om de energie-efficiëntie van de bestaande oudere woningvoorraad te verbeteren, bijvoorbeeld door technische verbeteringen van de scheidingsconstructie en verbetering van de energie-efficiëntie van klimaatinstallaties te stimuleren. Daarnaast zou de ontwikkeling van uit duurzame bronnen opgewekte elektriciteit moeten worden gestimuleerd en het aandeel duurzame elektriciteit zou veel sneller moeten groeien dan de huidige doelstelling. Consumenten die hun eigen duurzame energie willen opwekken moeten zo goed mogelijk ondersteund worden door betrouwbare en blijvende maatregelen. De ontwikkeling van milieurelevante product informatie (MRPI) of Environmental Product Declarations (EPD) op Europees niveau moet worden voortgezet, zodat inzicht ontstaat in de milieu-impact in de toeleveringsketen van bouwproducten.

In de gebruiksfase van woningen zijn vele actoren actief die invloed hebben op de milieu-impact van de woning. Eigenaren van woongebouwen met een lage energie-efficiëntie kunnen de milieu-impact van de woningen verminderen door het vervangen van bouwdelen, zoals het aanbrengen van HR$^{++}$ beglazing in plaats van gewoon dubbel glas, en het aanbrengen van efficiëntere klimaatinstallaties. Bewoners van woningen, eigenaar-bewoners in het bijzonder, spelen een grote rol in de milieu-impact van woningen, ook al kunnen zij niet volledig verantwoordelijk worden gehouden voor hun daden. Zij zijn echter wel verantwoordelijk voor de hoeveelheid verspilde energie door onwetendheid of energiegebruik van apparaten in huis. Tijdens het ontwerp van nieuwe woningen moet al rekening worden gehouden met het vermijden van milieu-impact in de gebruiksfase, bijvoorbeeld door bouwdelen zo goed mogelijk te beschermen tegen klimaatinvloeden en door rekening te houden met het feit dat klimaatinstallaties bijvoorbeeld vervangen worden door nieuwe technologie. Producenten van bouwproducten kunnen hun producten milieuvriendelijker maken door bijvoorbeeld onderdelen met een grote milieu-impact te vervangen, gerecycled materiaal te gebruiken, het product geschikt te maken voor recycling en duurzaam opgewekte energie te gebruiken in het productieproces.

Het onderzoek in dit proefschrift geeft aanleiding tot verschillende richtingen van vervolgonderzoek. Ten eerste kan het huidige onderzoek worden uitgebreid door onderhoud en vervanging van andere gebouwdelen of vervangingen door nieuwe producten en technologie te analyseren. Een meer gedetailleerde levenscyclusanalyse van bouwproducten en klimaatinstallaties kan meer inzicht bieden in Ten tweede kan ter vergelijking gelijksoortig onderzoek worden gedaan naar andere woningtypen, constructiemethoden en woningen in andere landen. Ten derde kan een uitgebreide analyse van de milieu-impact van andere typen (duurzaam opgewekte) energie in verschillende landen en op verschillende schaalniveaus het nodige inzicht bieden voor toekomstige energievoorzieningen. Dit proefschrift geeft ook aanleiding tot andere typen onderzoek, zoals gedetailleerde levenscyclusanalyses van bouwproducten en klimaatinstallaties, en analyse van besluitvormingsprocessen van verschillende actoren in de gebruiksfase van woningen.

# Appendix 1 Environmental impact categories

## Introduction

This appendix describes the nine environmental impact categories from the CML baseline 2000 LCA methodology that are considered in this research. The information has been derived from Guinée (2002), unless otherwise indicated. Of each environmental impact category, a description of the effect and its possible consequences for humans and ecosystems is given, as well as the unit in which the environmental impact score is expressed. The impact of each substance flow is calculated by comparing it to the impact of a reference substance in each impact category, then adding the impact of all substances to obtain an impact score. The exact calculation of the environmental impact scores and alternative methods can be found in the Handbook on Life Cycle Assessment (Guinée, 2002).

The contribution to an environmental impact category represents a potential effect on the environment. A lower score is better, because the impact on the environment is lower. Each particle of substance flows may contribute to several of the considered environmental problems, but generally not at the same time. For example, some ozone depleting substances are also greenhouse gases. However, ozone layer depletion is a chemical process in which the ozone layer depleting substance is transformed, after which it is no longer a greenhouse gas. The entire substance flow is counted in both environmental impact categories.

## Abiotic depletion

The impact category abiotic depletion is a measure for the global depletion of natural, non-living resources. Abiotic resources can be divided into three categories: deposits, which are not regenerated within the human life span and thus can only be depleted (fossil fuels, minerals); funds, which can be regenerated within the human life span and thus can be used or depleted if use is faster than regeneration (groundwater, soil); and flows, of which a more or less constant supply is available and thus can only be used (wind, water, solar energy) (Heijungs *et al.*, 1997). Depletion is defined as decreasing the amount of available resources without replacement (deposits), or decreasing the amount of available resources faster than they can be replaced by nature (funds). The consequences of Abiotic resource depletion are that the resources are no longer available and the extraction may cause severe disruptions to ecosystems. The impact score is expressed in kg antimony equivalent [kg Sb eq].

Abiotic depletion is currently calculated based on ultimate reserves of deposits, the volume of which is a factor of high uncertainty. Other methods are still debated, since scarcity and the economic value of resources is now not taken into account. Furthermore, since funds and competitive flows do not have ultimate reserves, the methodology does not suit those resources well. In the future, the methodology for depletion of resources may be split up to cover different types of resources. Furthermore, the list of characterisation factors for resources is being expanded and adapted to progressing knowledge about the amount of resources available. The characterisation factors are currently based on elements rather than resources.

### Global warming

The global warming impact category is a measure for the emission of substances that absorb heat radiation in the global atmosphere. The emission of these substances may have an adverse effect on the health of ecosystems and humans, as well as the earth's temperature. The impact score is expressed in kg carbon dioxide ($CO_2$) equivalents.

There are some uncertainties in the calculation of the impact score. These uncertainties concern the time frame of the effect, background concentrations of greenhouse gases and the global warming potential of ozone layer depleting substances. The uncertainties are known and accepted by the Intergovernmental Panel on Climate Change (IPCC).

### Ozone layer depletion

The impact category ozone layer depletion is a measure for the emission of substances that can deplete ozone in the stratosphere. This causes the ozone layer to thin, which will lead to higher fractions of solar UV-B radiation reaching the earth's surface. UV-B radiation is harmful to human health and ecosystems. The reference substance is trichlorofluoromethane (CFC-11).

The calculation of ozone layer depletion is widely accepted and used. The uncertainties are known and accepted by the World Meteorological Organisation (WMO). Knowledge should be gained on the relationship between ozone depletion potential and global warming potential, since many ozone depleting substances are also greenhouse gases. Therefore, part of the substance emission may contribute to depletion of the ozone layer, while another part may contribute to global warming.

### Photochemical oxidation

In contrast with ozone layer depletion in the stratosphere, photochemical oxidation deals with the formation of ozone and other reactive chemicals in the troposphere, near the earth's surface. Photo-oxidants may be formed through photochemical oxidation of Volatile Organic Compounds (VOCs) and carbon monoxide (CO), in the presence of ultraviolet light and nitrogen oxides ($NO_x$). Photo-oxidant formation is also known as summer smog, Los Angeles smog or secondary air pollution. It can affect the health of humans and ecosystems and crops may be damaged. The reference substance for photochemical oxidation is ethylene ($C_2H_4$).

The photochemical oxidation calculation method and characterisation methods are widely used. There are some uncertainties concerning the differences in characterisation factors determined by different methods. The old characterisation factors were based on average potential, while the new characterisation factors are based on marginal potential compared with background levels.

### Human toxicity

The impact category human toxicity covers the effect of toxic substances present in the environment on human health. Human toxicity includes so-called winter smog, or London smog, which constitutes of high level of inorganic compounds, carbon monoxide and sulphur compounds at ground level. This type of smog may cause bronchial irritation and coughing. The CML method excludes the impact of exposure to toxic substances at work. The reference substance for the ecotoxicity impact categories is 1,4 dichlorobenzene (1,4-DB).

The human toxicity impact category is complicated and subject of ongoing scientific debate. Toxic substances may influence humans directly by breathing in air bound substances or drinking contaminated water, or indirectly through consumption of plants and animals that have taken up toxins from the environment. The effect of toxins depends on concentration of substances, exposure to them, the risk of exposure, and physical characteristics of people. In the future, it is expected that toxicity factors of more substances may become known and the modelling of the environmental mechanisms will be further developed.

### Fresh water aquatic ecotoxicity and Terrestrial ecotoxicity

The fresh water aquatic and terrestrial ecotoxicity impact categories refer to the impact of toxic substances on fresh water ecosystems and terrestrial (soil) ecosystems respectively. The reference substance for the ecotoxicity impact categories is 1,4 dichlorobenzene (1,4-DB).

The ecotoxicity impact categories are complicated and subject of ongoing scientific debate, because toxic substances tend to travel trough different types of ecosystems (air, water, soil), spread out and some may degrade. Furthermore, many species are affected in several ways. All species and possible effects of toxins in ecosystems are currently considered to be of equal value, which may be debated. Currently, substances emitted to one type of ecosystem are assumed to only impact that specific ecosystem and the characterisation factors used are global. In the future, more detailed models of migration of toxic substances, concentrations of substances, fate and exposure modelling will become available, as well as models for other ecosystems.

### Acidification

The acidification impact category is a measure for the local presence of acidic elements in ecosystems. The most important acidic elements are sulphur dioxide ($SO_2$), nitrogen oxides ($NO_x$) and nitrogen-hydrogen compounds

($NH_x$). Depending on the ecosystem involved, the consequences of acidification range from degrading building materials, forest decline and fish mortality. The reference substance for this impact category is sulphur dioxide ($SO_2$).

The current calculation of acidification uses European characterisation factors for $SO_2$, $NH_3$ and $NO_x$. The uncertainty of this method is low, but could be lower if generic characterisation factors are used, which cover more substances. Acidification is a local environmental impact and has a different effect in different ecosystems, therefore the modelling of local environmental mechanisms could be more detailed in the future.

### Eutrophication

The eutrophication impact category is a measure for substances' potential contribution to the formation of biomass. It covers the impact of local high levels of nutrients in ecosystems, the most important of which are the chemical elements nitrogen (N) and phosphorus (P). A high level of nutrients may cause increased biomass production in aquatic and terrestrial ecosystems, such as algae in water systems, at the expense of other organisms. Consequentially, fresh water may become unsuitable as a source of drinking water and the composition of species in a certain area may change. The reference substance for this impact category is phosphate ($PO_4^{3-}$).

Eutrophication is a widely used impact category. Characterisation factors are available for many substances containing bio-available nitrogen and phosphorus, taking into account the chemical oxygen demand (COD) to form biomass. Eutrophication is a localized effect and can affect aquatic and terrestrial ecosystems. Fate and exposure of the substances is not yet included. In the future, more detailed models of the eutrophication effects in different ecosystems should be developed. The characterisation factors are generic, but could be localized. The current uncertainty margins of the impact category are low.

## References

Guinée, J.B., 2002, **Handbook on Life Cycle Assessment – Operational Guide to the ISO Standards, Eco-efficiency in Industry and Science** (Dordrecht: Kluwer Academic Publishers).

Heijungs, R., J.B. Guinée and G. Huppes, 1997, **Impact categories for natural resources and land use** (Leiden: Centre of Environmental Science (CML)).

# Appendix 2 Results Chapter 2

This appendix contains the results related to Chapter 2. The description of the scenarios can be found in Table 2.2.

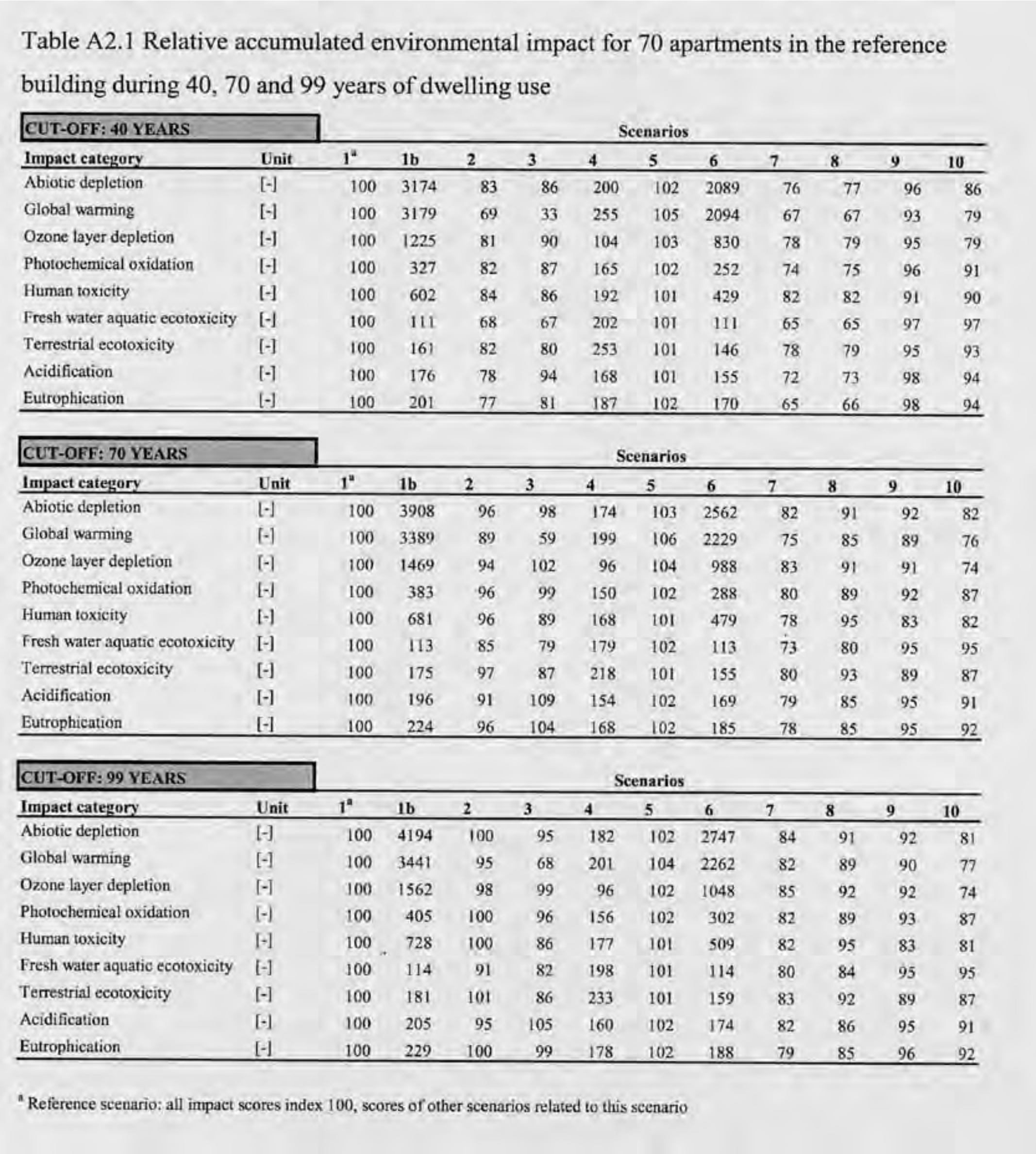


Table A2.1 Relative accumulated environmental impact for 70 apartments in the reference building during 40, 70 and 99 years of dwelling use

| **CUT-OFF: 40 YEARS** | | **Scenarios** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Impact category** | **Unit** | **1[a]** | **1b** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
| Abiotic depletion | [-] | 100 | 3174 | 83 | 86 | 200 | 102 | 2089 | 76 | 77 | 96 | 86 |
| Global warming | [-] | 100 | 3179 | 69 | 33 | 255 | 105 | 2094 | 67 | 67 | 93 | 79 |
| Ozone layer depletion | [-] | 100 | 1225 | 81 | 90 | 104 | 103 | 830 | 78 | 79 | 95 | 79 |
| Photochemical oxidation | [-] | 100 | 327 | 82 | 87 | 165 | 102 | 252 | 74 | 75 | 96 | 91 |
| Human toxicity | [-] | 100 | 602 | 84 | 86 | 192 | 101 | 429 | 82 | 82 | 91 | 90 |
| Fresh water aquatic ecotoxicity | [-] | 100 | 111 | 68 | 67 | 202 | 101 | 111 | 65 | 65 | 97 | 97 |
| Terrestrial ecotoxicity | [-] | 100 | 161 | 82 | 80 | 253 | 101 | 146 | 78 | 79 | 95 | 93 |
| Acidification | [-] | 100 | 176 | 78 | 94 | 168 | 101 | 155 | 72 | 73 | 98 | 94 |
| Eutrophication | [-] | 100 | 201 | 77 | 81 | 187 | 102 | 170 | 65 | 66 | 98 | 94 |

| **CUT-OFF: 70 YEARS** | | **Scenarios** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Impact category** | **Unit** | **1[a]** | **1b** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
| Abiotic depletion | [-] | 100 | 3908 | 96 | 98 | 174 | 103 | 2562 | 82 | 91 | 92 | 82 |
| Global warming | [-] | 100 | 3389 | 89 | 59 | 199 | 106 | 2229 | 75 | 85 | 89 | 76 |
| Ozone layer depletion | [-] | 100 | 1469 | 94 | 102 | 96 | 104 | 988 | 83 | 91 | 91 | 74 |
| Photochemical oxidation | [-] | 100 | 383 | 96 | 99 | 150 | 102 | 288 | 80 | 89 | 92 | 87 |
| Human toxicity | [-] | 100 | 681 | 96 | 89 | 168 | 101 | 479 | 78 | 95 | 83 | 82 |
| Fresh water aquatic ecotoxicity | [-] | 100 | 113 | 85 | 79 | 179 | 102 | 113 | 73 | 80 | 95 | 95 |
| Terrestrial ecotoxicity | [-] | 100 | 175 | 97 | 87 | 218 | 101 | 155 | 80 | 93 | 89 | 87 |
| Acidification | [-] | 100 | 196 | 91 | 109 | 154 | 102 | 169 | 79 | 85 | 95 | 91 |
| Eutrophication | [-] | 100 | 224 | 96 | 104 | 168 | 102 | 185 | 78 | 85 | 95 | 92 |

| **CUT-OFF: 99 YEARS** | | **Scenarios** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Impact category** | **Unit** | **1[a]** | **1b** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
| Abiotic depletion | [-] | 100 | 4194 | 100 | 95 | 182 | 102 | 2747 | 84 | 91 | 92 | 81 |
| Global warming | [-] | 100 | 3441 | 95 | 68 | 201 | 104 | 2262 | 82 | 89 | 90 | 77 |
| Ozone layer depletion | [-] | 100 | 1562 | 98 | 99 | 96 | 102 | 1048 | 85 | 92 | 92 | 74 |
| Photochemical oxidation | [-] | 100 | 405 | 100 | 96 | 156 | 102 | 302 | 82 | 89 | 93 | 87 |
| Human toxicity | [-] | 100 | 728 | 100 | 86 | 177 | 101 | 509 | 82 | 95 | 83 | 81 |
| Fresh water aquatic ecotoxicity | [-] | 100 | 114 | 91 | 82 | 198 | 101 | 114 | 80 | 84 | 95 | 95 |
| Terrestrial ecotoxicity | [-] | 100 | 181 | 101 | 86 | 233 | 101 | 159 | 83 | 92 | 89 | 87 |
| Acidification | [-] | 100 | 205 | 95 | 105 | 160 | 102 | 174 | 82 | 86 | 95 | 91 |
| Eutrophication | [-] | 100 | 229 | 100 | 99 | 178 | 102 | 188 | 79 | 85 | 96 | 92 |

[a] Reference scenario: all impact scores index 100, scores of other scenarios related to this scenario

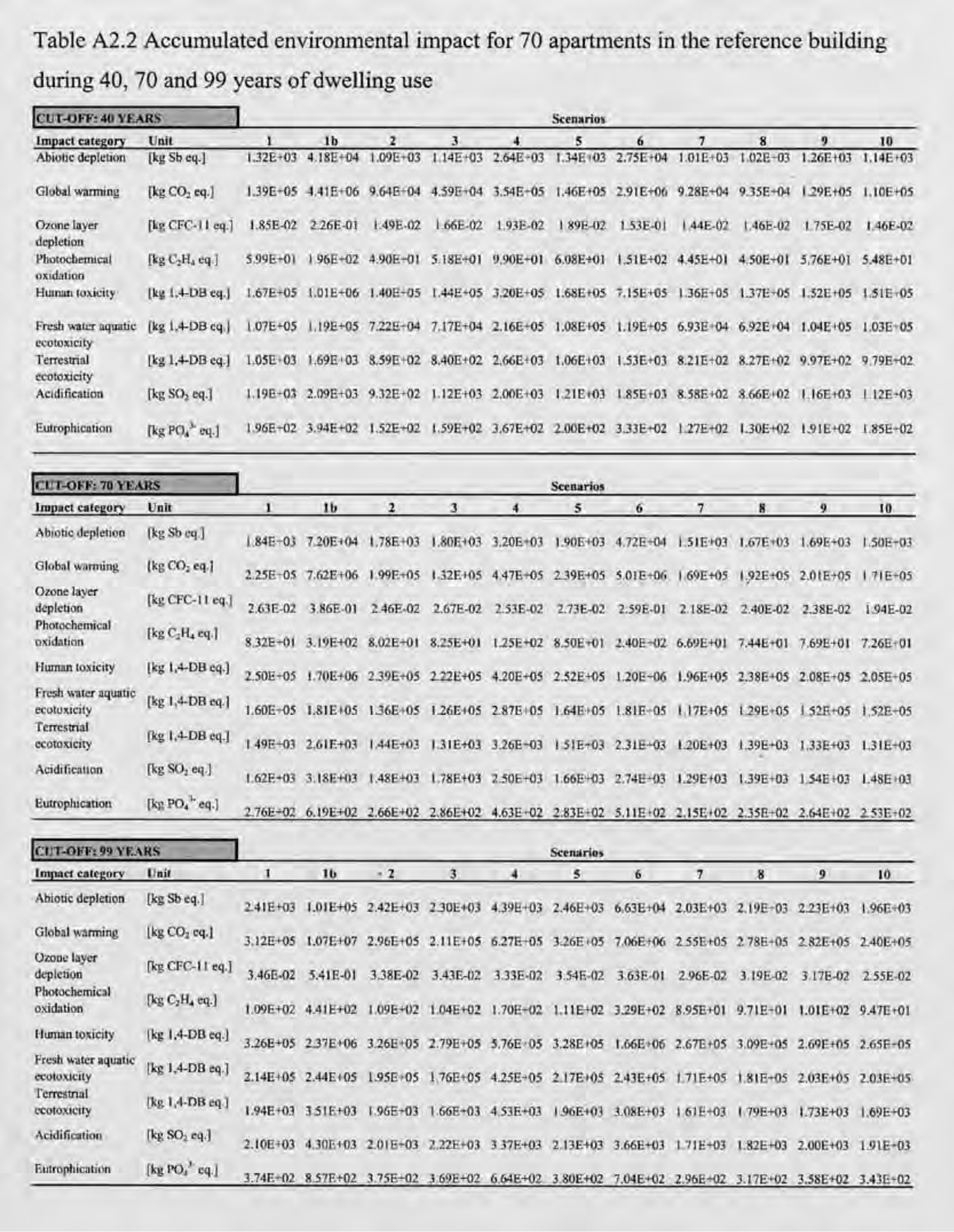


Table A2.2 Accumulated environmental impact for 70 apartments in the reference building during 40, 70 and 99 years of dwelling use

| **CUT-OFF: 40 YEARS** | | **Scenarios** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Impact category** | **Unit** | **1** | **1b** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
| Abiotic depletion | [kg Sb eq.] | 1.32E+03 | 4.18E+04 | 1.09E+03 | 1.14E+03 | 2.64E+03 | 1.34E+03 | 2.75E+04 | 1.01E+03 | 1.02E+03 | 1.26E+03 | 1.14E+03 |
| Global warming | [kg CO$_2$ eq.] | 1.39E+05 | 4.41E+06 | 9.64E+04 | 4.59E+04 | 3.54E+05 | 1.46E+05 | 2.91E+06 | 9.28E+04 | 9.35E+04 | 1.29E+05 | 1.10E+05 |
| Ozone layer depletion | [kg CFC-11 eq.] | 1.85E-02 | 2.26E-01 | 1.49E-02 | 1.66E-02 | 1.93E-02 | 1.89E-02 | 1.53E-01 | 1.44E-02 | 1.46E-02 | 1.75E-02 | 1.46E-02 |
| Photochemical oxidation | [kg C$_2$H$_4$ eq.] | 5.99E+01 | 1.96E+02 | 4.90E+01 | 5.18E+01 | 9.90E+01 | 6.08E+01 | 1.51E+02 | 4.45E+01 | 4.50E+01 | 5.76E+01 | 5.48E+01 |
| Human toxicity | [kg 1,4-DB eq.] | 1.67E+05 | 1.01E+06 | 1.40E+05 | 1.44E+05 | 3.20E+05 | 1.68E+05 | 7.15E+05 | 1.36E+05 | 1.37E+05 | 1.52E+05 | 1.51E+05 |
| Fresh water aquatic ecotoxicity | [kg 1,4-DB eq.] | 1.07E+05 | 1.19E+05 | 7.22E+04 | 7.17E+04 | 2.16E+05 | 1.08E+05 | 1.19E+05 | 6.93E+04 | 6.92E+04 | 1.04E+05 | 1.03E+05 |
| Terrestrial ecotoxicity | [kg 1,4-DB eq.] | 1.05E+03 | 1.69E+03 | 8.59E+02 | 8.40E+02 | 2.66E+03 | 1.06E+03 | 1.53E+03 | 8.21E+02 | 8.27E+02 | 9.97E+02 | 9.79E+02 |
| Acidification | [kg SO$_2$ eq.] | 1.19E+03 | 2.09E+03 | 9.32E+02 | 1.12E+03 | 2.00E+03 | 1.21E+03 | 1.85E+03 | 8.58E+02 | 8.66E+02 | 1.16E+03 | 1.12E+03 |
| Eutrophication | [kg PO$_4^{3-}$ eq.] | 1.96E+02 | 3.94E+02 | 1.52E+02 | 1.59E+02 | 3.67E+02 | 2.00E+02 | 3.33E+02 | 1.27E+02 | 1.30E+02 | 1.91E+02 | 1.85E+02 |

| **CUT-OFF: 70 YEARS** | | **Scenarios** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Impact category** | **Unit** | **1** | **1b** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
| Abiotic depletion | [kg Sb eq.] | 1.84E+03 | 7.20E+04 | 1.78E+03 | 1.80E+03 | 3.20E+03 | 1.90E+03 | 4.72E+04 | 1.51E+03 | 1.67E+03 | 1.69E+03 | 1.50E+03 |
| Global warming | [kg CO$_2$ eq.] | 2.25E+05 | 7.62E+06 | 1.99E+05 | 1.32E+05 | 4.47E+05 | 2.39E+05 | 5.01E+06 | 1.69E+05 | 1.92E+05 | 2.01E+05 | 1.71E+05 |
| Ozone layer depletion | [kg CFC-11 eq.] | 2.63E-02 | 3.86E-01 | 2.46E-02 | 2.67E-02 | 2.53E-02 | 2.73E-02 | 2.59E-01 | 2.18E-02 | 2.40E-02 | 2.38E-02 | 1.94E-02 |
| Photochemical oxidation | [kg C$_2$H$_4$ eq.] | 8.32E+01 | 3.19E+02 | 8.02E+01 | 8.25E+01 | 1.25E+02 | 8.50E+01 | 2.40E+02 | 6.69E+01 | 7.44E+01 | 7.69E+01 | 7.26E+01 |
| Human toxicity | [kg 1,4-DB eq.] | 2.50E+05 | 1.70E+06 | 2.39E+05 | 2.22E+05 | 4.20E+05 | 2.52E+05 | 1.20E+06 | 1.96E+05 | 2.38E+05 | 2.08E+05 | 2.05E+05 |
| Fresh water aquatic ecotoxicity | [kg 1,4-DB eq.] | 1.60E+05 | 1.81E+05 | 1.36E+05 | 1.26E+05 | 2.87E+05 | 1.64E+05 | 1.81E+05 | 1.17E+05 | 1.29E+05 | 1.52E+05 | 1.52E+05 |
| Terrestrial ecotoxicity | [kg 1,4-DB eq.] | 1.49E+03 | 2.61E+03 | 1.44E+03 | 1.31E+03 | 3.26E+03 | 1.51E+03 | 2.31E+03 | 1.20E+03 | 1.39E+03 | 1.33E+03 | 1.31E+03 |
| Acidification | [kg SO$_2$ eq.] | 1.62E+03 | 3.18E+03 | 1.48E+03 | 1.78E+03 | 2.50E+03 | 1.66E+03 | 2.74E+03 | 1.29E+03 | 1.39E+03 | 1.54E+03 | 1.48E+03 |
| Eutrophication | [kg PO$_4^{3-}$ eq.] | 2.76E+02 | 6.19E+02 | 2.66E+02 | 2.86E+02 | 4.63E+02 | 2.83E+02 | 5.11E+02 | 2.15E+02 | 2.35E+02 | 2.64E+02 | 2.53E+02 |

| **CUT-OFF: 99 YEARS** | | **Scenarios** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Impact category** | **Unit** | **1** | **1b** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
| Abiotic depletion | [kg Sb eq.] | 2.41E+03 | 1.01E+05 | 2.42E+03 | 2.30E+03 | 4.39E+03 | 2.46E+03 | 6.63E+04 | 2.03E+03 | 2.19E+03 | 2.23E+03 | 1.96E+03 |
| Global warming | [kg CO$_2$ eq.] | 3.12E+05 | 1.07E+07 | 2.96E+05 | 2.11E+05 | 6.27E+05 | 3.26E+05 | 7.06E+06 | 2.55E+05 | 2.78E+05 | 2.82E+05 | 2.40E+05 |
| Ozone layer depletion | [kg CFC-11 eq.] | 3.46E-02 | 5.41E-01 | 3.38E-02 | 3.43E-02 | 3.33E-02 | 3.54E-02 | 3.63E-01 | 2.96E-02 | 3.19E-02 | 3.17E-02 | 2.55E-02 |
| Photochemical oxidation | [kg C$_2$H$_4$ eq.] | 1.09E+02 | 4.41E+02 | 1.09E+02 | 1.04E+02 | 1.70E+02 | 1.11E+02 | 3.29E+02 | 8.95E+01 | 9.71E+01 | 1.01E+02 | 9.47E+01 |
| Human toxicity | [kg 1,4-DB eq.] | 3.26E+05 | 2.37E+06 | 3.26E+05 | 2.79E+05 | 5.76E+05 | 3.28E+05 | 1.66E+06 | 2.67E+05 | 3.09E+05 | 2.69E+05 | 2.65E+05 |
| Fresh water aquatic ecotoxicity | [kg 1,4-DB eq.] | 2.14E+05 | 2.44E+05 | 1.95E+05 | 1.76E+05 | 4.25E+05 | 2.17E+05 | 2.43E+05 | 1.71E+05 | 1.81E+05 | 2.03E+05 | 2.03E+05 |
| Terrestrial ecotoxicity | [kg 1,4-DB eq.] | 1.94E+03 | 3.51E+03 | 1.96E+03 | 1.66E+03 | 4.53E+03 | 1.96E+03 | 3.08E+03 | 1.61E+03 | 1.79E+03 | 1.73E+03 | 1.69E+03 |
| Acidification | [kg SO$_2$ eq.] | 2.10E+03 | 4.30E+03 | 2.01E+03 | 2.22E+03 | 3.37E+03 | 2.13E+03 | 3.66E+03 | 1.71E+03 | 1.82E+03 | 2.00E+03 | 1.91E+03 |
| Eutrophication | [kg PO$_4^{3-}$ eq.] | 3.74E+02 | 8.57E+02 | 3.75E+02 | 3.69E+02 | 6.64E+02 | 3.80E+02 | 7.04E+02 | 2.96E+02 | 3.17E+02 | 3.58E+02 | 3.43E+02 |

**Table A2.3 Relative accumulated environmental impact (in %) caused by different factors after 70 years of dwelling operation, per environmental impact category**

| | Abiotic depletion | | Global warming | | Ozone layer depletion | | Photochemcial oxidation | | Human toxicity | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Scenario** | **1** | **4** | **1** | **4** | **1** | **4** | **1** | **4** | **1** | **4** |
| Timber | 10 | - | -18 | - | 9 | - | 12 | - | 6 | - |
| Paint | 4 | - | 4 | - | 5 | - | 3 | - | 1 | - |
| PVC | - | 54 | - | 48 | - | 25 | - | 44 | - | 43 |
| Transport | 17 | 3 | 22 | 4 | 28 | 10 | 9 | 2 | 2 | 0 |
| Glazing | 50 | 33 | 67 | 38 | 46 | 54 | 54 | 41 | 38 | 26 |
| Polysulfide sealant | 3 | - | 5 | - | 3 | - | 4 | - | 2 | - |
| Rubber sealant | - | 1 | - | 1 | - | 2 | - | 0 | - | 0 |
| Hinges and locks | 15 | 9 | 20 | 10 | 9 | 10 | 19 | 13 | 51 | 30 |
| **Total** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** |

| **- continued** | Fresh water aq. Ecotoxicity | | Terrestrial ecotoxicity | | Acidification | | Eutrophication | |
|---|---|---|---|---|---|---|---|---|
| **Scenario** | **1** | **4** | **1** | **4** | **1** | **4** | **1** | **4** |
| Timber | 2 | - | 9 | - | 9 | - | 14 | - |
| Paint | 2 | - | 2 | - | 3 | - | 4 | - |
| PVC | - | 44 | - | 58 | - | 41 | - | 51 |
| Transport | 0 | 0 | 3 | 0 | 6 | 1 | 6 | 1 |
| Glazing | 73 | 45 | 47 | 25 | 68 | 50 | 62 | 42 |
| Polysulfide sealant | 5 | - | 3 | - | 3 | - | 4 | - |
| Rubber sealant | - | 0 | - | 0 | - | 0 | - | 0 |
| Hinges and locks | 18 | 10 | 37 | 17 | 11 | 7 | 10 | 6 |
| **Total** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** |

# Appendix 3 Results Chapter 3

This appendix contains the results related to Chapter 3. The description of the scenarios can be found in Tables 3.2 and 3.5.

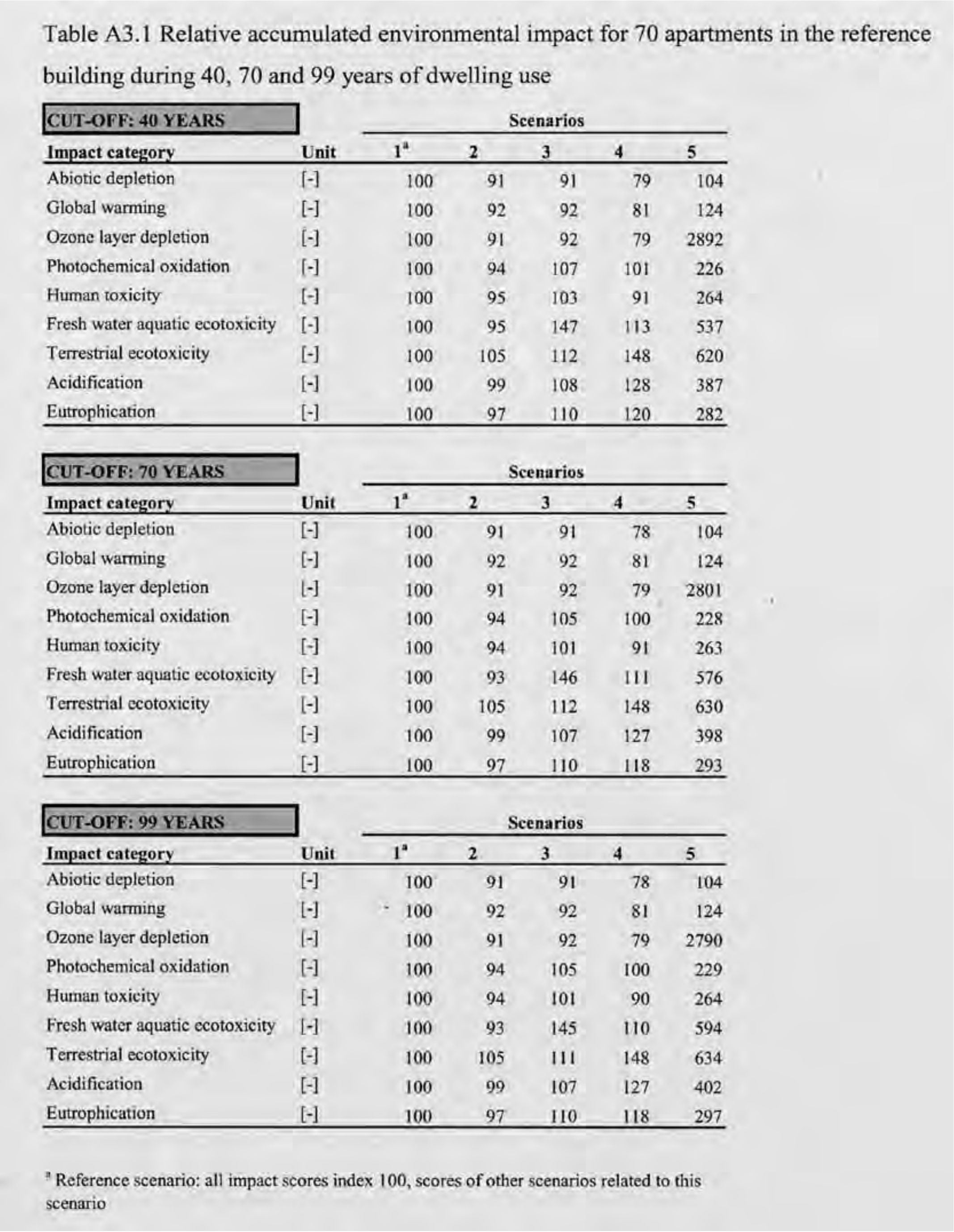


Table A3.1 Relative accumulated environmental impact for 70 apartments in the reference building during 40, 70 and 99 years of dwelling use

| **CUT-OFF: 40 YEARS** | | **Scenarios** | | | | |
|---|---|---|---|---|---|---|
| **Impact category** | **Unit** | **1[a]** | **2** | **3** | **4** | **5** |
| Abiotic depletion | [-] | 100 | 91 | 91 | 79 | 104 |
| Global warming | [-] | 100 | 92 | 92 | 81 | 124 |
| Ozone layer depletion | [-] | 100 | 91 | 92 | 79 | 2892 |
| Photochemical oxidation | [-] | 100 | 94 | 107 | 101 | 226 |
| Human toxicity | [-] | 100 | 95 | 103 | 91 | 264 |
| Fresh water aquatic ecotoxicity | [-] | 100 | 95 | 147 | 113 | 537 |
| Terrestrial ecotoxicity | [-] | 100 | 105 | 112 | 148 | 620 |
| Acidification | [-] | 100 | 99 | 108 | 128 | 387 |
| Eutrophication | [-] | 100 | 97 | 110 | 120 | 282 |

| **CUT-OFF: 70 YEARS** | | **Scenarios** | | | | |
|---|---|---|---|---|---|---|
| **Impact category** | **Unit** | **1[a]** | **2** | **3** | **4** | **5** |
| Abiotic depletion | [-] | 100 | 91 | 91 | 78 | 104 |
| Global warming | [-] | 100 | 92 | 92 | 81 | 124 |
| Ozone layer depletion | [-] | 100 | 91 | 92 | 79 | 2801 |
| Photochemical oxidation | [-] | 100 | 94 | 105 | 100 | 228 |
| Human toxicity | [-] | 100 | 94 | 101 | 91 | 263 |
| Fresh water aquatic ecotoxicity | [-] | 100 | 93 | 146 | 111 | 576 |
| Terrestrial ecotoxicity | [-] | 100 | 105 | 112 | 148 | 630 |
| Acidification | [-] | 100 | 99 | 107 | 127 | 398 |
| Eutrophication | [-] | 100 | 97 | 110 | 118 | 293 |

| **CUT-OFF: 99 YEARS** | | **Scenarios** | | | | |
|---|---|---|---|---|---|---|
| **Impact category** | **Unit** | **1[a]** | **2** | **3** | **4** | **5** |
| Abiotic depletion | [-] | 100 | 91 | 91 | 78 | 104 |
| Global warming | [-] | 100 | 92 | 92 | 81 | 124 |
| Ozone layer depletion | [-] | 100 | 91 | 92 | 79 | 2790 |
| Photochemical oxidation | [-] | 100 | 94 | 105 | 100 | 229 |
| Human toxicity | [-] | 100 | 94 | 101 | 90 | 264 |
| Fresh water aquatic ecotoxicity | [-] | 100 | 93 | 145 | 110 | 594 |
| Terrestrial ecotoxicity | [-] | 100 | 105 | 111 | 148 | 634 |
| Acidification | [-] | 100 | 99 | 107 | 127 | 402 |
| Eutrophication | [-] | 100 | 97 | 110 | 118 | 297 |

[a] Reference scenario: all impact scores index 100, scores of other scenarios related to this scenario

Table A3.2 Accumulated environmental impact for 70 apartments in the reference building during 40, 70 and 99 years of dwelling use

| **CUT-OFF: 40 YEARS** | | **Scenarios** | | | | |
|---|---|---|---|---|---|---|
| **Impact category** | **Unit** | **1** | **2** | **3** | **4** | **5** |
| Abiotic depletion | [kg Sb eq.] | 5.34E+04 | 4.85E+04 | 4.87E+04 | 4.19E+04 | 5.55E+04 |
| Global warming | [kg $CO_2$ eq.] | 5.85E+06 | 5.35E+06 | 5.39E+06 | 4.75E+06 | 7.24E+06 |
| Ozone layer depletion | [kg CFC-11 eq.] | 2.76E-01 | 2.52E-01 | 2.55E-01 | 2.18E-01 | 7.99E+00 |
| Photochemical oxidation | [kg $C_2H_4$ eq.] | 2.77E+02 | 2.61E+02 | 2.95E+02 | 2.78E+02 | 6.25E+02 |
| Human toxicity | [kg 1,4-DB eq.] | 1.49E+06 | 1.40E+06 | 1.53E+06 | 1.36E+06 | 3.92E+06 |
| Fresh water aquatic ecotoxicity | [kg 1,4-DB eq.] | 1.61E+05 | 1.52E+05 | 2.36E+05 | 1.82E+05 | 8.63E+05 |
| Terrestrial ecotoxicity | [kg 1,4-DB eq.] | 1.54E+04 | 1.62E+04 | 1.73E+04 | 2.28E+04 | 9.56E+04 |
| Acidification | [kg $SO_2$ eq.] | 3.45E+03 | 3.42E+03 | 3.74E+03 | 4.42E+03 | 1.34E+04 |
| Eutrophication | [kg $PO_4^{3-}$ eq.] | 5.93E+02 | 5.78E+02 | 6.52E+02 | 7.12E+02 | 1.68E+03 |

| **CUT-OFF: 70 YEARS** | | **Scenarios** | | | | |
|---|---|---|---|---|---|---|
| **Impact category** | **Unit** | **1** | **2** | **3** | **4** | **5** |
| Abiotic depletion | [kg Sb eq.] | 9.21E+04 | 8.38E+04 | 8.39E+04 | 7.22E+04 | 9.56E+04 |
| Global warming | [kg $CO_2$ eq.] | 1.01E+07 | 9.24E+06 | 9.29E+06 | 8.19E+06 | 1.25E+07 |
| Ozone layer depletion | [kg CFC-11 eq.] | 4.76E-01 | 4.33E-01 | 4.38E-01 | 3.75E-01 | 1.33E+01 |
| Photochemical oxidation | [kg $C_2H_4$ eq.] | 4.65E+02 | 4.38E+02 | 4.89E+02 | 4.64E+02 | 1.06E+03 |
| Human toxicity | [kg 1,4-DB eq.] | 2.50E+06 | 2.36E+06 | 2.54E+06 | 2.27E+06 | 6.58E+06 |
| Fresh water aquatic ecotoxicity | [kg 1,4-DB eq.] | 2.69E+05 | 2.51E+05 | 3.92E+05 | 2.98E+05 | 1.55E+06 |
| Terrestrial ecotoxicity | [kg 1,4-DB eq.] | 2.61E+04 | 2.75E+04 | 2.91E+04 | 3.87E+04 | 1.65E+05 |
| Acidification | [kg $SO_2$ eq.] | 5.72E+03 | 5.67E+03 | 6.14E+03 | 7.27E+03 | 2.27E+04 |
| Eutrophication | [kg $PO_4^{3-}$ eq.] | 9.80E+02 | 9.53E+02 | 1.07E+03 | 1.16E+03 | 2.87E+03 |

| **CUT-OFF: 99 YEARS** | | **Scenarios** | | | | |
|---|---|---|---|---|---|---|
| **Impact category** | **Unit** | **1** | **2** | **3** | **4** | **5** |
| Abiotic depletion | [kg Sb eq.] | 1.30E+05 | 1.18E+05 | 1.18E+05 | 1.02E+05 | 1.34E+05 |
| Global warming | [kg $CO_2$ eq.] | 1.42E+07 | 1.30E+07 | 1.31E+07 | 1.15E+07 | 1.76E+07 |
| Ozone layer depletion | [kg CFC-11 eq.] | 6.69E-01 | 6.09E-01 | 6.15E-01 | 5.26E-01 | 1.87E+01 |
| Photochemical oxidation | [kg $C_2H_4$ eq.] | 6.48E+02 | 6.10E+02 | 6.78E+02 | 6.45E+02 | 1.48E+03 |
| Human toxicity | [kg 1,4-DB eq.] | 3.49E+06 | 3.28E+06 | 3.52E+06 | 3.15E+06 | 9.21E+06 |
| Fresh water aquatic ecotoxicity | [kg 1,4-DB eq.] | 3.77E+05 | 3.49E+05 | 5.46E+05 | 4.13E+05 | 2.24E+06 |
| Terrestrial ecotoxicity | [kg 1,4-DB eq.] | 3.65E+04 | 3.84E+04 | 4.06E+04 | 5.42E+04 | 2.31E+05 |
| Acidification | [kg $SO_2$ eq.] | 7.92E+03 | 7.85E+03 | 8.47E+03 | 1.00E+04 | 3.19E+04 |
| Eutrophication | [kg $PO_4^{3-}$ eq.] | 1.36E+03 | 1.32E+03 | 1.49E+03 | 1.59E+03 | 4.03E+03 |

Table A3.3 Relative accumulated environmental impact caused by different factors after 40 years of dwelling operation, per environmental impact category

| CUT-OFF: 40 YEARS **ABIOTIC DEPLETION** | **Scenarios** | | | | |
|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** |
| | [%] | [%] | [%] | [%] | [%] |
| Ventilation system | 0 | 0 | 0 | 2 | 2 |
| Heat distribution | 1 | 1 | 3 | 2 | 13 |
| Boiler | 1 | 1 | 1 | 2 | - |
| Heat pump | - | - | - | - | 20 |
| Electricity | 14 | 17 | 16 | 4 | 65 |
| Gas | 84 | 81 | 79 | 90 | - |
| TOTAL | 100 | 100 | 100 | 100 | 100 |

| CUT-OFF: 40 YEARS **GLOBAL WARMING** | **Scenarios** | | | | |
|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** |
| | [%] | [%] | [%] | [%] | [%] |
| Ventilation system | 0 | 1 | 1 | 3 | 2 |
| Heat distribution | 1 | 1 | 3 | 2 | 12 |
| Boiler | 1 | 1 | 1 | 2 | - |
| Heat pump | - | - | - | - | 25 |
| Electricity | 16 | 19 | 19 | 5 | 61 |
| Gas | 81 | 77 | 76 | 88 | - |
| TOTAL | 100 | 100 | 100 | 100 | 100 |

| CUT-OFF: 40 YEARS **OZONE LAYER DEPLETION** | **Scenarios** | | | | |
|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** |
| | [%] | [%] | [%] | [%] | [%] |
| Ventilation system | 1 | 1 | 1 | 4 | 0 |
| Heat distribution | 2 | 2 | 5 | 3 | 0 |
| Boiler | 3 | 3 | 3 | 4 | - |
| Heat pump | - | - | - | - | 98 |
| Electricity | 12 | 14 | 14 | 19 | 2 |
| Gas | 83 | 80 | 78 | 70 | - |
| TOTAL | 100 | 100 | 100 | 100 | 100 |

| CUT-OFF: 40 YEARS<br>**HUMAN TOXICITY** | **Scenarios** | | | | |
|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** |
| | [%] | [%] | [%] | [%] | [%] |
| Ventilation system | 3 | 3 | 3 | 8 | 1 |
| Heat distribution | 8 | 8 | 16 | 9 | 6 |
| Boiler | 13 | 15 | 13 | 15 | - |
| Heat pump | - | - | - | - | 57 |
| Electricity | 14 | 16 | 15 | 24 | 37 |
| Gas | 62 | 58 | 52 | 44 | - |
| TOTAL | 100 | 100 | 100 | 100 | 100 |

| CUT-OFF: 40 YEARS<br>**FRESH WATER AQUATIC ECOTOX** | **Scenarios** | | | | |
|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** |
| | [%] | [%] | [%] | [%] | [%] |
| Ventilation system | 11 | 11 | 7 | 22 | 2 |
| Heat distribution | 37 | 39 | 61 | 30 | 15 |
| Boiler | 35 | 31 | 20 | 24 | - |
| Heat pump | - | - | - | - | 65 |
| Electricity | 9 | 10 | 7 | 19 | 18 |
| Gas | 8 | 8 | 5 | 4 | - |
| TOTAL | 100 | 100 | 100 | 100 | 100 |

| CUT-OFF: 40 YEARS<br>**TERRESTRIAL ECOTOXICITY** | **Scenarios** | | | | |
|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** |
| | [%] | [%] | [%] | [%] | [%] |
| Ventilation system | 3 | 3 | 2 | 23 | 2 |
| Heat distribution | 6 | 6 | 12 | 20 | 12 |
| Boiler | 7 | 5 | 5 | 17 | - |
| Heat pump | - | - | - | - | 43 |
| Electricity | 80 | 83 | 77 | 31 | 43 |
| Gas | 5 | 4 | 4 | 9 | - |
| TOTAL | 100 | 100 | 100 | 100 | 100 |

| CUT-OFF: 40 YEARS<br>**PHOTOCHEMICAL OXIDATION** | **Scenarios** | | | | |
|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** |
| | [%] | [%] | [%] | [%] | [%] |
| Ventilation system | 4 | 4 | 3 | 13 | 2 |
| Heat distribution | 10 | 11 | 22 | 12 | 13 |
| Boiler | 9 | 9 | 8 | 10 | - |
| Heat pump | - | - | - | - | 26 |
| Electricity | 22 | 26 | 23 | 25 | 59 |
| Gas | 54 | 51 | 44 | 40 | - |
| TOTAL | 100 | 100 | 100 | 100 | 100 |

| CUT-OFF: 40 YEARS<br>**ACIDIFICATION** | **Scenarios** | | | | |
|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** |
| | [%] | [%] | [%] | [%] | [%] |
| Ventilation system | 9 | 10 | 9 | 28 | 4 |
| Heat distribution | 8 | 9 | 17 | 10 | 8 |
| Boiler | 12 | 11 | 10 | 12 | - |
| Heat pump | - | - | - | - | 32 |
| Electricity | 42 | 46 | 42 | 30 | 56 |
| Gas | 29 | 26 | 23 | 21 | - |
| TOTAL | 100 | 100 | 100 | 100 | 100 |

| CUT-OFF: 40 YEARS<br>**EUTROPHICATION** | **Scenarios** | | | | |
|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** |
| | [%] | [%] | [%] | [%] | [%] |
| Ventilation system | 11 | 11 | 10 | 30 | 7 |
| Heat distribution | 13 | 13 | 23 | 14 | 15 |
| Boiler | 9 | 8 | 7 | 9 | - |
| Heat pump | - | - | - | - | 22 |
| Electricity | 31 | 35 | 31 | 21 | 57 |
| Gas | 37 | 33 | 29 | 26 | - |
| TOTAL | 100 | 100 | 100 | 100 | 100 |

# Appendix 4 Results Chapter 4

This appendix contains the results related to Chapter 4. The description of the scenarios can be found in Tables 4.2 and 4.3.

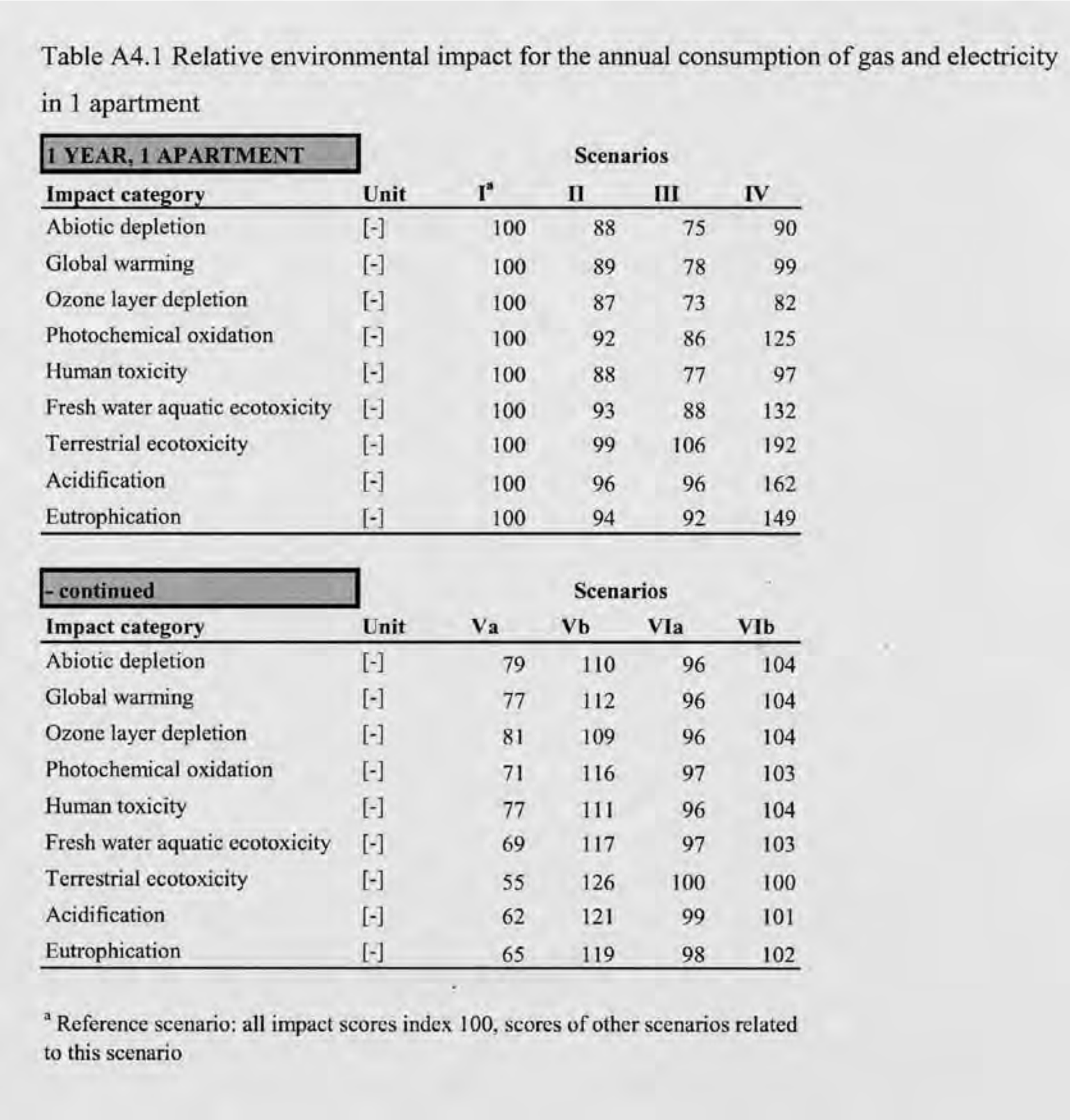


Table A4.1 Relative environmental impact for the annual consumption of gas and electricity in 1 apartment

| **1 YEAR, 1 APARTMENT** | | **Scenarios** | | | |
|---|---|---|---|---|---|
| **Impact category** | **Unit** | **I[a]** | **II** | **III** | **IV** |
| Abiotic depletion | [-] | 100 | 88 | 75 | 90 |
| Global warming | [-] | 100 | 89 | 78 | 99 |
| Ozone layer depletion | [-] | 100 | 87 | 73 | 82 |
| Photochemical oxidation | [-] | 100 | 92 | 86 | 125 |
| Human toxicity | [-] | 100 | 88 | 77 | 97 |
| Fresh water aquatic ecotoxicity | [-] | 100 | 93 | 88 | 132 |
| Terrestrial ecotoxicity | [-] | 100 | 99 | 106 | 192 |
| Acidification | [-] | 100 | 96 | 96 | 162 |
| Eutrophication | [-] | 100 | 94 | 92 | 149 |

| **- continued** | | **Scenarios** | | | |
|---|---|---|---|---|---|
| **Impact category** | **Unit** | **Va** | **Vb** | **VIa** | **VIb** |
| Abiotic depletion | [-] | 79 | 110 | 96 | 104 |
| Global warming | [-] | 77 | 112 | 96 | 104 |
| Ozone layer depletion | [-] | 81 | 109 | 96 | 104 |
| Photochemical oxidation | [-] | 71 | 116 | 97 | 103 |
| Human toxicity | [-] | 77 | 111 | 96 | 104 |
| Fresh water aquatic ecotoxicity | [-] | 69 | 117 | 97 | 103 |
| Terrestrial ecotoxicity | [-] | 55 | 126 | 100 | 100 |
| Acidification | [-] | 62 | 121 | 99 | 101 |
| Eutrophication | [-] | 65 | 119 | 98 | 102 |

[a] Reference scenario: all impact scores index 100, scores of other scenarios related to this scenario

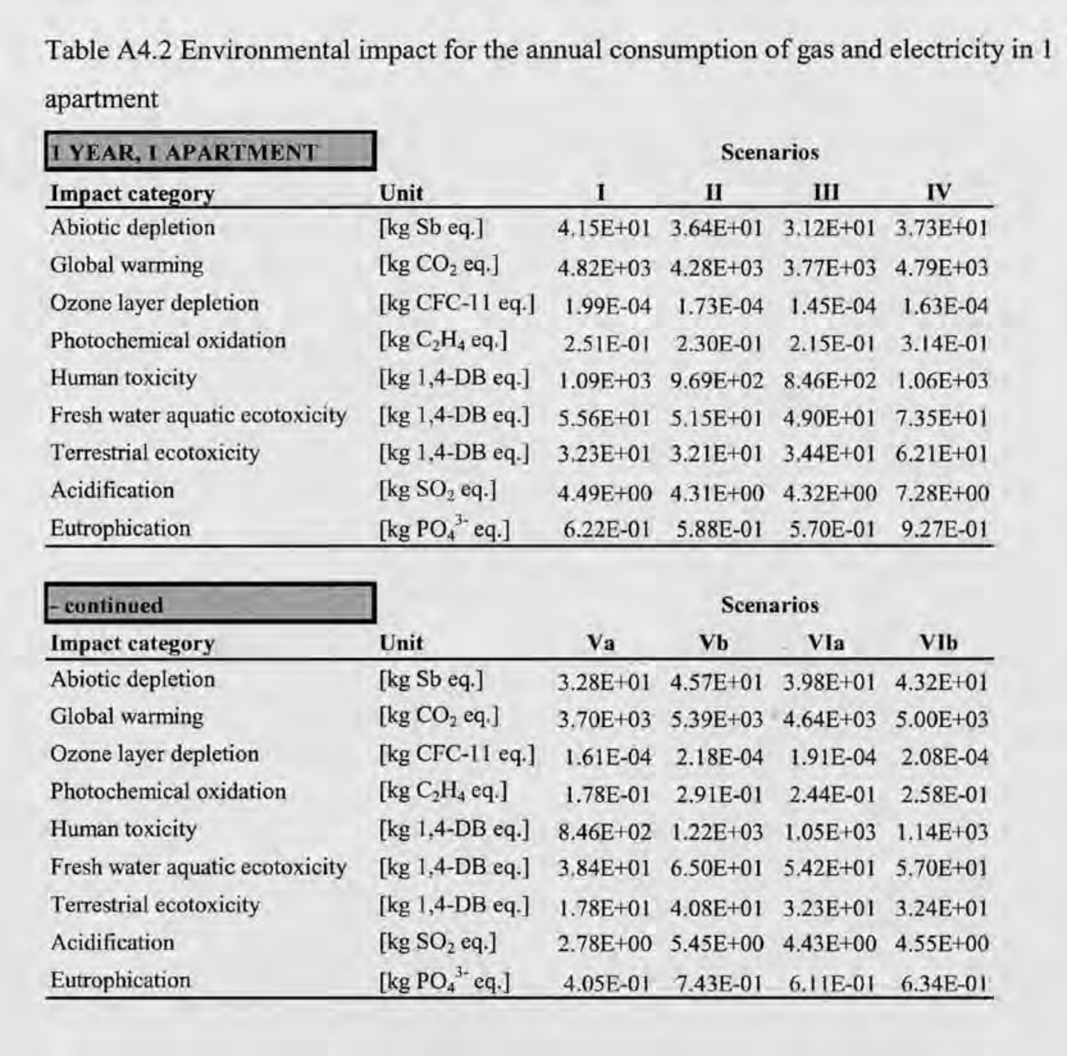


Table A4.2 Environmental impact for the annual consumption of gas and electricity in 1 apartment

| 1 YEAR, 1 APARTMENT | | Scenarios | | | |
|---|---|---|---|---|---|
| **Impact category** | **Unit** | **I** | **II** | **III** | **IV** |
| Abiotic depletion | [kg Sb eq.] | 4.15E+01 | 3.64E+01 | 3.12E+01 | 3.73E+01 |
| Global warming | [kg $CO_2$ eq.] | 4.82E+03 | 4.28E+03 | 3.77E+03 | 4.79E+03 |
| Ozone layer depletion | [kg CFC-11 eq.] | 1.99E-04 | 1.73E-04 | 1.45E-04 | 1.63E-04 |
| Photochemical oxidation | [kg $C_2H_4$ eq.] | 2.51E-01 | 2.30E-01 | 2.15E-01 | 3.14E-01 |
| Human toxicity | [kg 1,4-DB eq.] | 1.09E+03 | 9.69E+02 | 8.46E+02 | 1.06E+03 |
| Fresh water aquatic ecotoxicity | [kg 1,4-DB eq.] | 5.56E+01 | 5.15E+01 | 4.90E+01 | 7.35E+01 |
| Terrestrial ecotoxicity | [kg 1,4-DB eq.] | 3.23E+01 | 3.21E+01 | 3.44E+01 | 6.21E+01 |
| Acidification | [kg $SO_2$ eq.] | 4.49E+00 | 4.31E+00 | 4.32E+00 | 7.28E+00 |
| Eutrophication | [kg $PO_4^{3-}$ eq.] | 6.22E-01 | 5.88E-01 | 5.70E-01 | 9.27E-01 |

| - continued | | Scenarios | | | |
|---|---|---|---|---|---|
| **Impact category** | **Unit** | **Va** | **Vb** | **VIa** | **VIb** |
| Abiotic depletion | [kg Sb eq.] | 3.28E+01 | 4.57E+01 | 3.98E+01 | 4.32E+01 |
| Global warming | [kg $CO_2$ eq.] | 3.70E+03 | 5.39E+03 | 4.64E+03 | 5.00E+03 |
| Ozone layer depletion | [kg CFC-11 eq.] | 1.61E-04 | 2.18E-04 | 1.91E-04 | 2.08E-04 |
| Photochemical oxidation | [kg $C_2H_4$ eq.] | 1.78E-01 | 2.91E-01 | 2.44E-01 | 2.58E-01 |
| Human toxicity | [kg 1,4-DB eq.] | 8.46E+02 | 1.22E+03 | 1.05E+03 | 1.14E+03 |
| Fresh water aquatic ecotoxicity | [kg 1,4-DB eq.] | 3.84E+01 | 6.50E+01 | 5.42E+01 | 5.70E+01 |
| Terrestrial ecotoxicity | [kg 1,4-DB eq.] | 1.78E+01 | 4.08E+01 | 3.23E+01 | 3.24E+01 |
| Acidification | [kg $SO_2$ eq.] | 2.78E+00 | 5.45E+00 | 4.43E+00 | 4.55E+00 |
| Eutrophication | [kg $PO_4^{3-}$ eq.] | 4.05E-01 | 7.43E-01 | 6.11E-01 | 6.34E-01 |

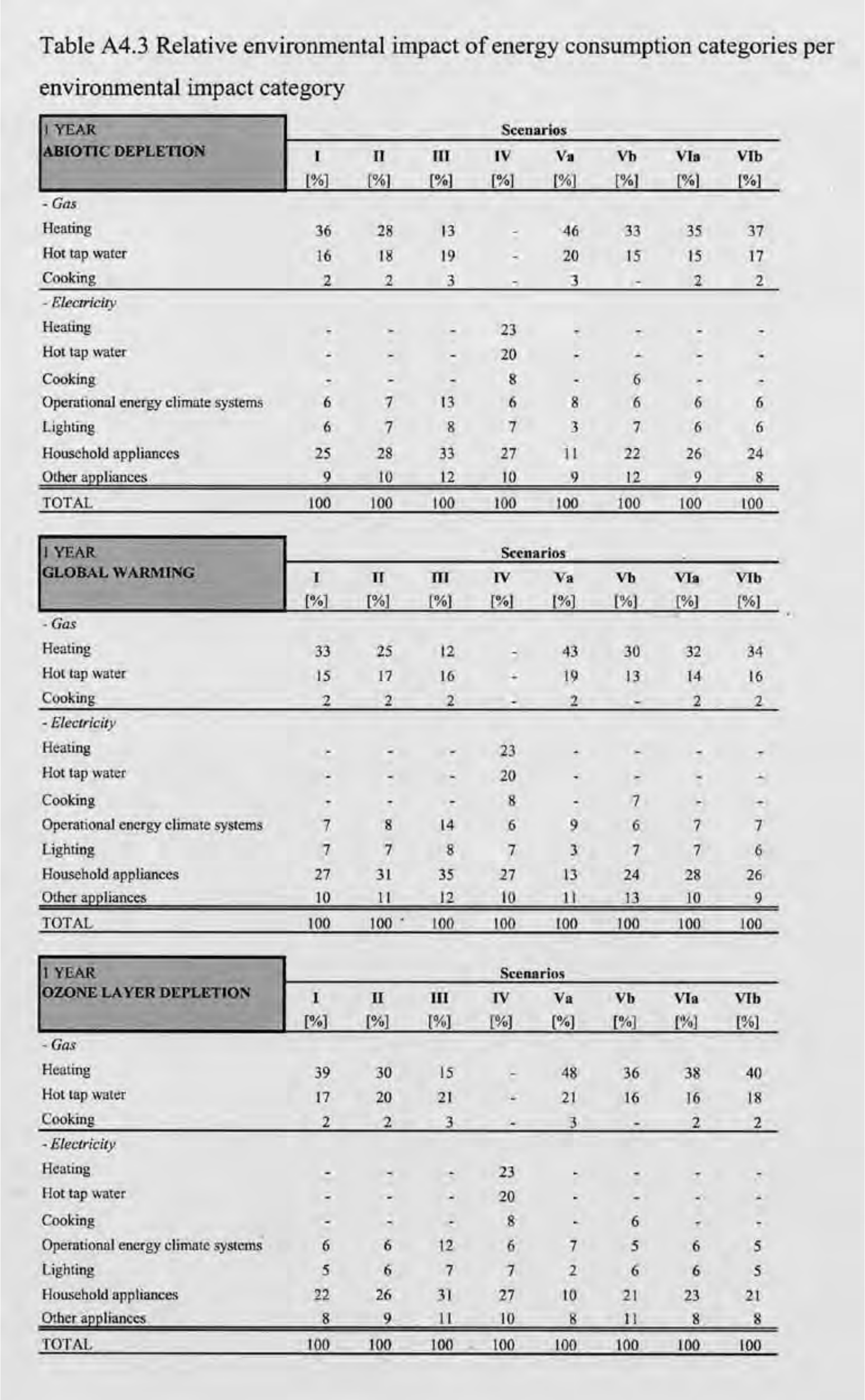


Table A4.3 Relative environmental impact of energy consumption categories per environmental impact category

| 1 YEAR<br>ABIOTIC DEPLETION | Scenarios | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | Va | Vb | VIa | VIb |
| | [%] | [%] | [%] | [%] | [%] | [%] | [%] | [%] |
| *- Gas* | | | | | | | | |
| Heating | 36 | 28 | 13 | - | 46 | 33 | 35 | 37 |
| Hot tap water | 16 | 18 | 19 | - | 20 | 15 | 15 | 17 |
| Cooking | 2 | 2 | 3 | - | 3 | - | 2 | 2 |
| *- Electricity* | | | | | | | | |
| Heating | - | - | - | 23 | - | - | - | - |
| Hot tap water | - | - | - | 20 | - | - | - | - |
| Cooking | - | - | - | 8 | - | 6 | - | - |
| Operational energy climate systems | 6 | 7 | 13 | 6 | 8 | 6 | 6 | 6 |
| Lighting | 6 | 7 | 8 | 7 | 3 | 7 | 6 | 6 |
| Household appliances | 25 | 28 | 33 | 27 | 11 | 22 | 26 | 24 |
| Other appliances | 9 | 10 | 12 | 10 | 9 | 12 | 9 | 8 |
| TOTAL | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

| 1 YEAR<br>GLOBAL WARMING | Scenarios | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | Va | Vb | VIa | VIb |
| | [%] | [%] | [%] | [%] | [%] | [%] | [%] | [%] |
| *- Gas* | | | | | | | | |
| Heating | 33 | 25 | 12 | - | 43 | 30 | 32 | 34 |
| Hot tap water | 15 | 17 | 16 | - | 19 | 13 | 14 | 16 |
| Cooking | 2 | 2 | 2 | - | 2 | - | 2 | 2 |
| *- Electricity* | | | | | | | | |
| Heating | - | - | - | 23 | - | - | - | - |
| Hot tap water | - | - | - | 20 | - | - | - | - |
| Cooking | - | - | - | 8 | - | 7 | - | - |
| Operational energy climate systems | 7 | 8 | 14 | 6 | 9 | 6 | 7 | 7 |
| Lighting | 7 | 7 | 8 | 7 | 3 | 7 | 7 | 6 |
| Household appliances | 27 | 31 | 35 | 27 | 13 | 24 | 28 | 26 |
| Other appliances | 10 | 11 | 12 | 10 | 11 | 13 | 10 | 9 |
| TOTAL | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

| 1 YEAR<br>OZONE LAYER DEPLETION | Scenarios | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | Va | Vb | VIa | VIb |
| | [%] | [%] | [%] | [%] | [%] | [%] | [%] | [%] |
| *- Gas* | | | | | | | | |
| Heating | 39 | 30 | 15 | - | 48 | 36 | 38 | 40 |
| Hot tap water | 17 | 20 | 21 | - | 21 | 16 | 16 | 18 |
| Cooking | 2 | 2 | 3 | - | 3 | - | 2 | 2 |
| *- Electricity* | | | | | | | | |
| Heating | - | - | - | 23 | - | - | - | - |
| Hot tap water | - | - | - | 20 | - | - | - | - |
| Cooking | - | - | - | 8 | - | 6 | - | - |
| Operational energy climate systems | 6 | 6 | 12 | 6 | 7 | 5 | 6 | 5 |
| Lighting | 5 | 6 | 7 | 7 | 2 | 6 | 6 | 5 |
| Household appliances | 22 | 26 | 31 | 27 | 10 | 21 | 23 | 21 |
| Other appliances | 8 | 9 | 11 | 10 | 8 | 11 | 8 | 8 |
| TOTAL | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

| 1 YEAR<br>HUMAN TOXICITY | Scenarios | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | Va | Vb | VIa | VIb |
| | [%] | [%] | [%] | [%] | [%] | [%] | [%] | [%] |
| *- Gas* | | | | | | | | |
| Heating | 34 | 26 | 12 | - | 0 | 31 | 33 | 35 |
| Hot tap water | 15 | 17 | 17 | - | 0 | 14 | 14 | 16 |
| Cooking | 2 | 2 | 2 | - | 0 | - | 2 | 2 |
| *- Electricity* | | | | | | | | |
| Heating | - | - | - | 23 | - | - | - | - |
| Hot tap water | - | - | - | 20 | - | - | - | - |
| Cooking | - | - | - | 8 | - | 7 | - | - |
| Operational energy climate s; | 7 | 8 | 14 | 6 | 6 | 6 | 7 | 6 |
| Lighting | 6 | 7 | 8 | 7 | 7 | 7 | 7 | 6 |
| Household appliances | 26 | 30 | 34 | 27 | 27 | 24 | 28 | 25 |
| Other appliances | 9 | 11 | 12 | 10 | 10 | 12 | 10 | 9 |
| TOTAL | 100 | 100 | 100 | 100 | 50 | 100 | 100 | 100 |

| 1 YEAR<br>FRESH WATER AQUATIC ECOTOX | Scenarios | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | Va | Vb | VIa | VIb |
| | [%] | [%] | [%] | [%] | [%] | [%] | [%] | [%] |
| *- Gas* | | | | | | | | |
| Heating | 22 | 16 | 7 | - | 32 | 19 | 21 | 23 |
| Hot tap water | 10 | 11 | 10 | - | 14 | 8 | 9 | 10 |
| Cooking | 1 | 1 | 1 | - | 2 | - | 1 | 1 |
| *- Electricity* | | | | | | | | |
| Heating | - | - | - | 23 | - | - | - | - |
| Hot tap water | - | - | - | 20 | - | - | - | - |
| Cooking | - | - | - | 8 | - | 9 | - | - |
| Operational energy climate s; | 9 | 10 | 16 | 6 | 13 | 8 | 9 | 9 |
| Lighting | 9 | 9 | 10 | 7 | 4 | 9 | 9 | 9 |
| Household appliances | 36 | 39 | 41 | 27 | 19 | 31 | 37 | 35 |
| Other appliances | 13 | 14 | 15 | 10 | 16 | 16 | 13 | 13 |
| TOTAL | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

| 1 YEAR<br>TERRESTRIAL ECOTOX | Scenarios | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | Va | Vb | VIa | VIb |
| | [%] | [%] | [%] | [%] | [%] | [%] | [%] | [%] |
| *- Gas* | | | | | | | | |
| Heating | 2 | 1 | 0 | - | 3 | 2 | 2 | 2 |
| Hot tap water | 1 | 1 | 1 | - | 2 | 1 | 1 | 1 |
| Cooking | 0 | 0 | 0 | - | 0 | - | 0 | 0 |
| *- Electricity* | | | | | | | | |
| Heating | - | - | - | 23 | - | - | - | - |
| Hot tap water | - | - | - | 20 | - | - | - | - |
| Cooking | - | - | - | 8 | - | 12 | - | - |
| Operational energy climate s; | 13 | 13 | 20 | 6 | 24 | 10 | 13 | 13 |
| Lighting | 13 | 13 | 12 | 7 | 8 | 12 | 13 | 13 |
| Household appliances | 53 | 53 | 49 | 27 | 34 | 42 | 53 | 52 |
| Other appliances | 19 | 19 | 18 | 10 | 29 | 22 | 19 | 19 |
| TOTAL | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

| 1 YEAR<br>**PHOTOCHEMICAL OXIDATION** | **Scenarios** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **I** | **II** | **III** | **IV** | **Va** | **Vb** | **VIa** | **VIb** |
| | [%] | [%] | [%] | [%] | [%] | [%] | [%] | [%] |
| *- Gas* | | | | | | | | |
| Heating | 25 | 18 | 8 | - | 35 | 21 | 23 | 26 |
| Hot tap water | 11 | 12 | 11 | - | 15 | 9 | 10 | 12 |
| Cooking | 1 | 1 | 2 | - | 2 | - | 1 | 1 |
| *- Electricity* | | | | | | | | |
| Heating | - | - | - | 23 | - | - | - | - |
| Hot tap water | - | - | - | 20 | - | - | - | - |
| Cooking | - | - | - | 8 | - | 8 | - | - |
| Operational energy climate s | 9 | 9 | 16 | 6 | 12 | 7 | 9 | 8 |
| Lighting | 8 | 9 | 10 | 7 | 4 | 9 | 9 | 8 |
| Household appliances | 34 | 37 | 40 | 27 | 17 | 30 | 35 | 33 |
| Other appliances | 12 | 13 | 14 | 10 | 15 | 15 | 13 | 12 |
| TOTAL | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

| 1 YEAR<br>**ACIDIFICATION** | **Scenarios** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **I** | **II** | **III** | **IV** | **Va** | **Vb** | **VIa** | **VIb** |
| | [%] | [%] | [%] | [%] | [%] | [%] | [%] | [%] |
| *- Gas* | | | | | | | | |
| Heating | 12 | 8 | 3 | - | 19 | 10 | 11 | 13 |
| Hot tap water | 5 | 6 | 4 | - | 9 | 4 | 5 | 6 |
| Cooking | 1 | 1 | 1 | - | 1 | - | 1 | 1 |
| *- Electricity* | | | | | | | | |
| Heating | - | - | - | 23 | - | - | - | - |
| Hot tap water | - | - | - | 20 | - | - | - | - |
| Cooking | - | - | - | 8 | - | 10 | - | - |
| Operational energy climate s | 11 | 12 | 18 | 6 | 18 | 9 | 11 | 11 |
| Lighting | 11 | 11 | 11 | 7 | 6 | 11 | 11 | 11 |
| Household appliances | 44 | 46 | 46 | 27 | 26 | 37 | 45 | 44 |
| Other appliances | 16 | 16 | 16 | 10 | 22 | 19 | 16 | 16 |
| TOTAL | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

| 1 YEAR<br>**EUTROPHICATION** | **Scenarios** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **I** | **II** | **III** | **IV** | **Va** | **Vb** | **VIa** | **VIb** |
| | [%] | [%] | [%] | [%] | [%] | [%] | [%] | [%] |
| *- Gas* | | | | | | | | |
| Heating | 16 | 12 | 4 | - | 25 | 39 | 16 | 17 |
| Hot tap water | 7 | 8 | 6 | - | 11 | 17 | 7 | 8 |
| Cooking | 1 | 1 | 1 | - | 1 | - | 1 | 1 |
| *- Electricity* | | | | | | | | |
| Heating | - | - | - | 23 | - | - | - | - |
| Hot tap water | - | - | - | 20 | - | - | - | - |
| Cooking | - | - | - | 8 | - | 5 | - | - |
| Operational energy climate s | 10 | 11 | 18 | 6 | 16 | 5 | 10 | 10 |
| Lighting | 10 | 10 | 11 | 7 | 5 | 6 | 10 | 10 |
| Household appliances | 41 | 43 | 44 | 27 | 22 | 19 | 42 | 40 |
| Other appliances | 15 | 15 | 16 | 10 | 19 | 10 | 15 | 14 |
| TOTAL | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

Table A4.4 Relative environmental impact of the supply of 1 kWh of electricity in the Netherlands (NL, index 100), Belgium (BE), Germany (DE), France (FR), Norway (NO) and the United Kingdom (UK); and 1 kWh of electricity from centralised wind power and solar power (photovoltaic cells)

| **1 kWh electricity** | | **Supply mix in countries** | | | | | | **Sustainable resources** | |
|---|---|---|---|---|---|---|---|---|---|
| **Impact category** | **Unit** | **NL** | **BE** | **DE** | **FR** | **NO** | **UK** | **Wind** | **Solar** |
| Abiotic depletion | [-] | 100 | 46 | 93 | 13 | 5 | 93 | 2 | 10 |
| Global warming | [-] | 100 | 50 | 99 | 15 | 6 | 94 | 2 | 11 |
| Ozone layer depletion | [-] | 100 | 94 | 111 | 20 | 11 | 63 | 3 | 60 |
| Photochemical oxidation | [-] | 100 | 105 | 107 | 56 | 23 | 203 | 8 | 50 |
| Human toxicity | [-] | 100 | 85 | 88 | 65 | 52 | 107 | 34 | 80 |
| Fresh water aquatic ecotoxicity | [-] | 100 | 78 | 248 | 79 | 45 | 141 | 94 | 141 |
| Terrestrial ecotoxicity | [-] | 100 | 99 | 104 | 99 | 97 | 105 | 2 | 6 |
| Acidification | [-] | 100 | 107 | 98 | 62 | 21 | 218 | 5 | 35 |
| Eutrophication | [-] | 100 | 65 | 76 | 32 | 11 | 124 | 5 | 32 |
| Ionising radiation | [-] | 100 | 641 | 284 | 1084 | 44 | 272 | 2 | 21 |

# Appendix 5 Results Chapter 5

This appendix contains the results related to Chapter 5. The description of the scenarios can be found in Table 5.3.

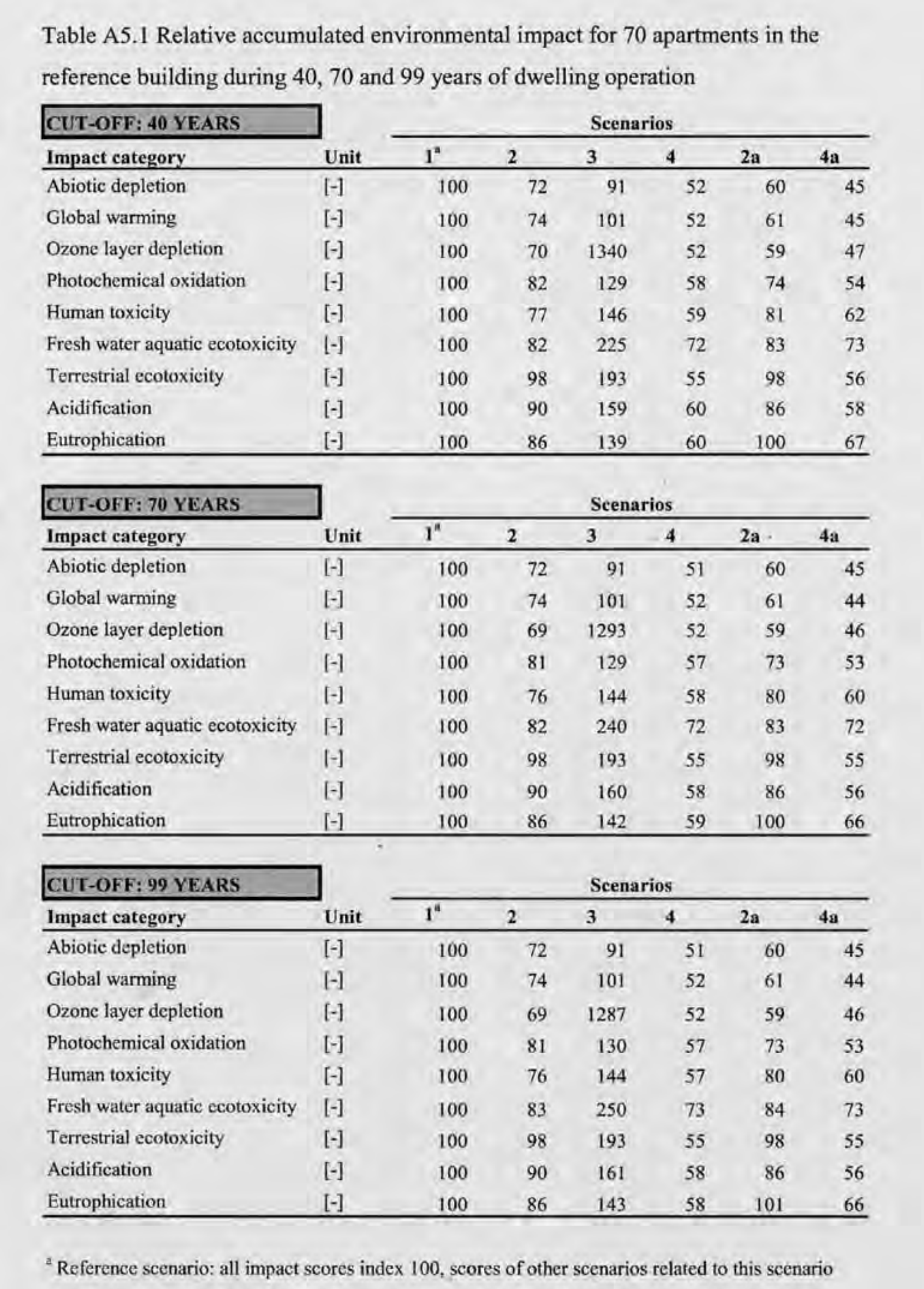


Table A5.1 Relative accumulated environmental impact for 70 apartments in the reference building during 40, 70 and 99 years of dwelling operation

**CUT-OFF: 40 YEARS**

| | | Scenarios | | | | | |
|---|---|---|---|---|---|---|---|
| **Impact category** | **Unit** | **1[a]** | **2** | **3** | **4** | **2a** | **4a** |
| Abiotic depletion | [-] | 100 | 72 | 91 | 52 | 60 | 45 |
| Global warming | [-] | 100 | 74 | 101 | 52 | 61 | 45 |
| Ozone layer depletion | [-] | 100 | 70 | 1340 | 52 | 59 | 47 |
| Photochemical oxidation | [-] | 100 | 82 | 129 | 58 | 74 | 54 |
| Human toxicity | [-] | 100 | 77 | 146 | 59 | 81 | 62 |
| Fresh water aquatic ecotoxicity | [-] | 100 | 82 | 225 | 72 | 83 | 73 |
| Terrestrial ecotoxicity | [-] | 100 | 98 | 193 | 55 | 98 | 56 |
| Acidification | [-] | 100 | 90 | 159 | 60 | 86 | 58 |
| Eutrophication | [-] | 100 | 86 | 139 | 60 | 100 | 67 |

**CUT-OFF: 70 YEARS**

| | | Scenarios | | | | | |
|---|---|---|---|---|---|---|---|
| **Impact category** | **Unit** | **1[a]** | **2** | **3** | **4** | **2a** | **4a** |
| Abiotic depletion | [-] | 100 | 72 | 91 | 51 | 60 | 45 |
| Global warming | [-] | 100 | 74 | 101 | 52 | 61 | 44 |
| Ozone layer depletion | [-] | 100 | 69 | 1293 | 52 | 59 | 46 |
| Photochemical oxidation | [-] | 100 | 81 | 129 | 57 | 73 | 53 |
| Human toxicity | [-] | 100 | 76 | 144 | 58 | 80 | 60 |
| Fresh water aquatic ecotoxicity | [-] | 100 | 82 | 240 | 72 | 83 | 72 |
| Terrestrial ecotoxicity | [-] | 100 | 98 | 193 | 55 | 98 | 55 |
| Acidification | [-] | 100 | 90 | 160 | 58 | 86 | 56 |
| Eutrophication | [-] | 100 | 86 | 142 | 59 | 100 | 66 |

**CUT-OFF: 99 YEARS**

| | | Scenarios | | | | | |
|---|---|---|---|---|---|---|---|
| **Impact category** | **Unit** | **1[a]** | **2** | **3** | **4** | **2a** | **4a** |
| Abiotic depletion | [-] | 100 | 72 | 91 | 51 | 60 | 45 |
| Global warming | [-] | 100 | 74 | 101 | 52 | 61 | 44 |
| Ozone layer depletion | [-] | 100 | 69 | 1287 | 52 | 59 | 46 |
| Photochemical oxidation | [-] | 100 | 81 | 130 | 57 | 73 | 53 |
| Human toxicity | [-] | 100 | 76 | 144 | 57 | 80 | 60 |
| Fresh water aquatic ecotoxicity | [-] | 100 | 83 | 250 | 73 | 84 | 73 |
| Terrestrial ecotoxicity | [-] | 100 | 98 | 193 | 55 | 98 | 55 |
| Acidification | [-] | 100 | 90 | 161 | 58 | 86 | 56 |
| Eutrophication | [-] | 100 | 86 | 143 | 58 | 101 | 66 |

[a] Reference scenario: all impact scores index 100, scores of other scenarios related to this scenario

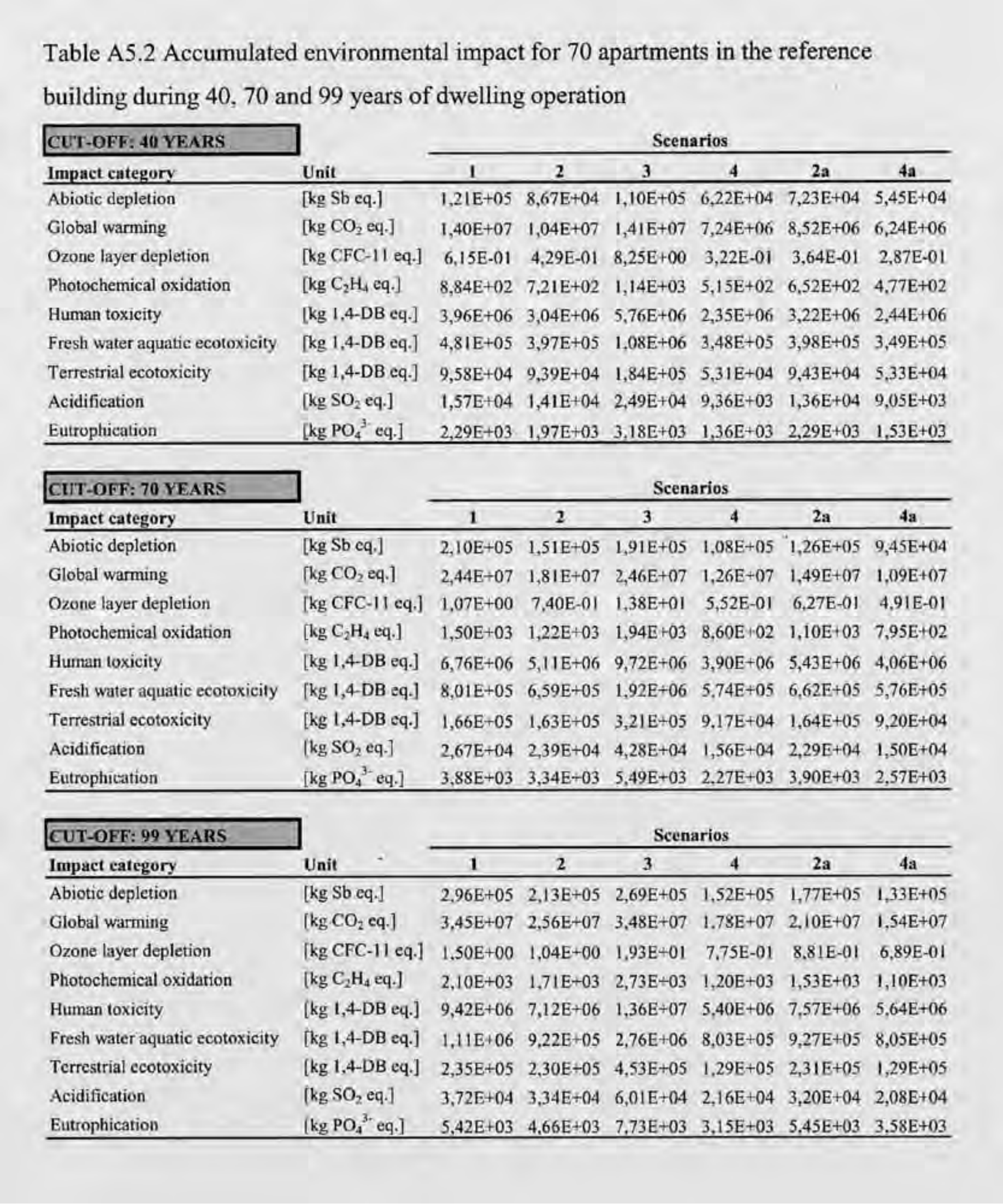


Table A5.2 Accumulated environmental impact for 70 apartments in the reference building during 40, 70 and 99 years of dwelling operation

**CUT-OFF: 40 YEARS**

| | | Scenarios | | | | | |
|---|---|---|---|---|---|---|---|
| **Impact category** | **Unit** | **1** | **2** | **3** | **4** | **2a** | **4a** |
| Abiotic depletion | [kg Sb eq.] | 1,21E+05 | 8,67E+04 | 1,10E+05 | 6,22E+04 | 7,23E+04 | 5,45E+04 |
| Global warming | [kg $CO_2$ eq.] | 1,40E+07 | 1,04E+07 | 1,41E+07 | 7,24E+06 | 8,52E+06 | 6,24E+06 |
| Ozone layer depletion | [kg CFC-11 eq.] | 6,15E-01 | 4,29E-01 | 8,25E+00 | 3,22E-01 | 3,64E-01 | 2,87E-01 |
| Photochemical oxidation | [kg $C_2H_4$ eq.] | 8,84E+02 | 7,21E+02 | 1,14E+03 | 5,15E+02 | 6,52E+02 | 4,77E+02 |
| Human toxicity | [kg 1,4-DB eq.] | 3,96E+06 | 3,04E+06 | 5,76E+06 | 2,35E+06 | 3,22E+06 | 2,44E+06 |
| Fresh water aquatic ecotoxicity | [kg 1,4-DB eq.] | 4,81E+05 | 3,97E+05 | 1,08E+06 | 3,48E+05 | 3,98E+05 | 3,49E+05 |
| Terrestrial ecotoxicity | [kg 1,4-DB eq.] | 9,58E+04 | 9,39E+04 | 1,84E+05 | 5,31E+04 | 9,43E+04 | 5,33E+04 |
| Acidification | [kg $SO_2$ eq.] | 1,57E+04 | 1,41E+04 | 2,49E+04 | 9,36E+03 | 1,36E+04 | 9,05E+03 |
| Eutrophication | [kg $PO_4^{3-}$ eq.] | 2,29E+03 | 1,97E+03 | 3,18E+03 | 1,36E+03 | 2,29E+03 | 1,53E+03 |

**CUT-OFF: 70 YEARS**

| | | Scenarios | | | | | |
|---|---|---|---|---|---|---|---|
| **Impact category** | **Unit** | **1** | **2** | **3** | **4** | **2a** | **4a** |
| Abiotic depletion | [kg Sb eq.] | 2,10E+05 | 1,51E+05 | 1,91E+05 | 1,08E+05 | 1,26E+05 | 9,45E+04 |
| Global warming | [kg $CO_2$ eq.] | 2,44E+07 | 1,81E+07 | 2,46E+07 | 1,26E+07 | 1,49E+07 | 1,09E+07 |
| Ozone layer depletion | [kg CFC-11 eq.] | 1,07E+00 | 7,40E-01 | 1,38E+01 | 5,52E-01 | 6,27E-01 | 4,91E-01 |
| Photochemical oxidation | [kg $C_2H_4$ eq.] | 1,50E+03 | 1,22E+03 | 1,94E+03 | 8,60E+02 | 1,10E+03 | 7,95E+02 |
| Human toxicity | [kg 1,4-DB eq.] | 6,76E+06 | 5,11E+06 | 9,72E+06 | 3,90E+06 | 5,43E+06 | 4,06E+06 |
| Fresh water aquatic ecotoxicity | [kg 1,4-DB eq.] | 8,01E+05 | 6,59E+05 | 1,92E+06 | 5,74E+05 | 6,62E+05 | 5,76E+05 |
| Terrestrial ecotoxicity | [kg 1,4-DB eq.] | 1,66E+05 | 1,63E+05 | 3,21E+05 | 9,17E+04 | 1,64E+05 | 9,20E+04 |
| Acidification | [kg $SO_2$ eq.] | 2,67E+04 | 2,39E+04 | 4,28E+04 | 1,56E+04 | 2,29E+04 | 1,50E+04 |
| Eutrophication | [kg $PO_4^{3-}$ eq.] | 3,88E+03 | 3,34E+03 | 5,49E+03 | 2,27E+03 | 3,90E+03 | 2,57E+03 |

**CUT-OFF: 99 YEARS**

| | | Scenarios | | | | | |
|---|---|---|---|---|---|---|---|
| **Impact category** | **Unit** | **1** | **2** | **3** | **4** | **2a** | **4a** |
| Abiotic depletion | [kg Sb eq.] | 2,96E+05 | 2,13E+05 | 2,69E+05 | 1,52E+05 | 1,77E+05 | 1,33E+05 |
| Global warming | [kg $CO_2$ eq.] | 3,45E+07 | 2,56E+07 | 3,48E+07 | 1,78E+07 | 2,10E+07 | 1,54E+07 |
| Ozone layer depletion | [kg CFC-11 eq.] | 1,50E+00 | 1,04E+00 | 1,93E+01 | 7,75E-01 | 8,81E-01 | 6,89E-01 |
| Photochemical oxidation | [kg $C_2H_4$ eq.] | 2,10E+03 | 1,71E+03 | 2,73E+03 | 1,20E+03 | 1,53E+03 | 1,10E+03 |
| Human toxicity | [kg 1,4-DB eq.] | 9,42E+06 | 7,12E+06 | 1,36E+07 | 5,40E+06 | 7,57E+06 | 5,64E+06 |
| Fresh water aquatic ecotoxicity | [kg 1,4-DB eq.] | 1,11E+06 | 9,22E+05 | 2,76E+06 | 8,03E+05 | 9,27E+05 | 8,05E+05 |
| Terrestrial ecotoxicity | [kg 1,4-DB eq.] | 2,35E+05 | 2,30E+05 | 4,53E+05 | 1,29E+05 | 2,31E+05 | 1,29E+05 |
| Acidification | [kg $SO_2$ eq.] | 3,72E+04 | 3,34E+04 | 6,01E+04 | 2,16E+04 | 3,20E+04 | 2,08E+04 |
| Eutrophication | [kg $PO_4^{3-}$ eq.] | 5,42E+03 | 4,66E+03 | 7,73E+03 | 3,15E+03 | 5,45E+03 | 3,58E+03 |

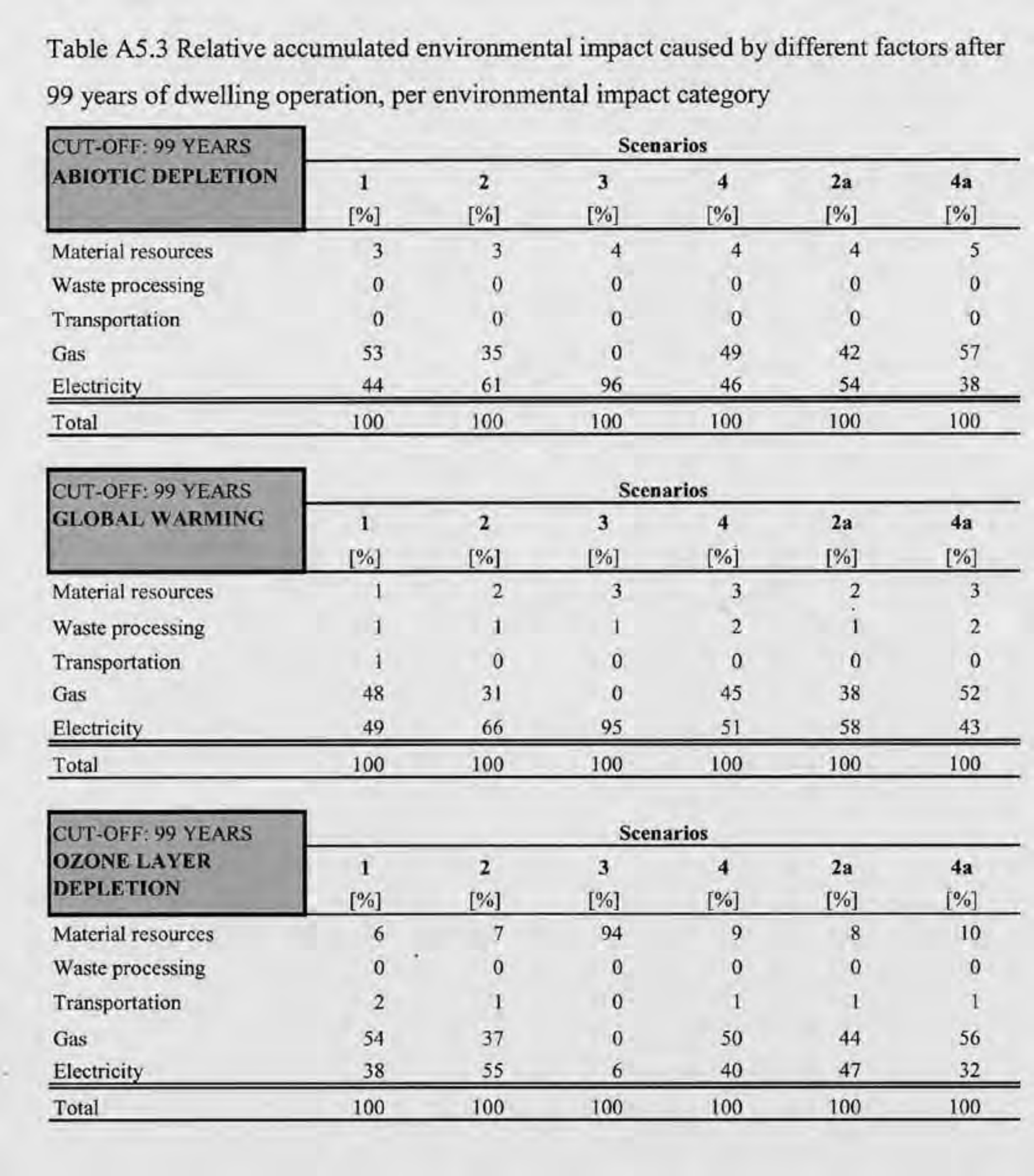
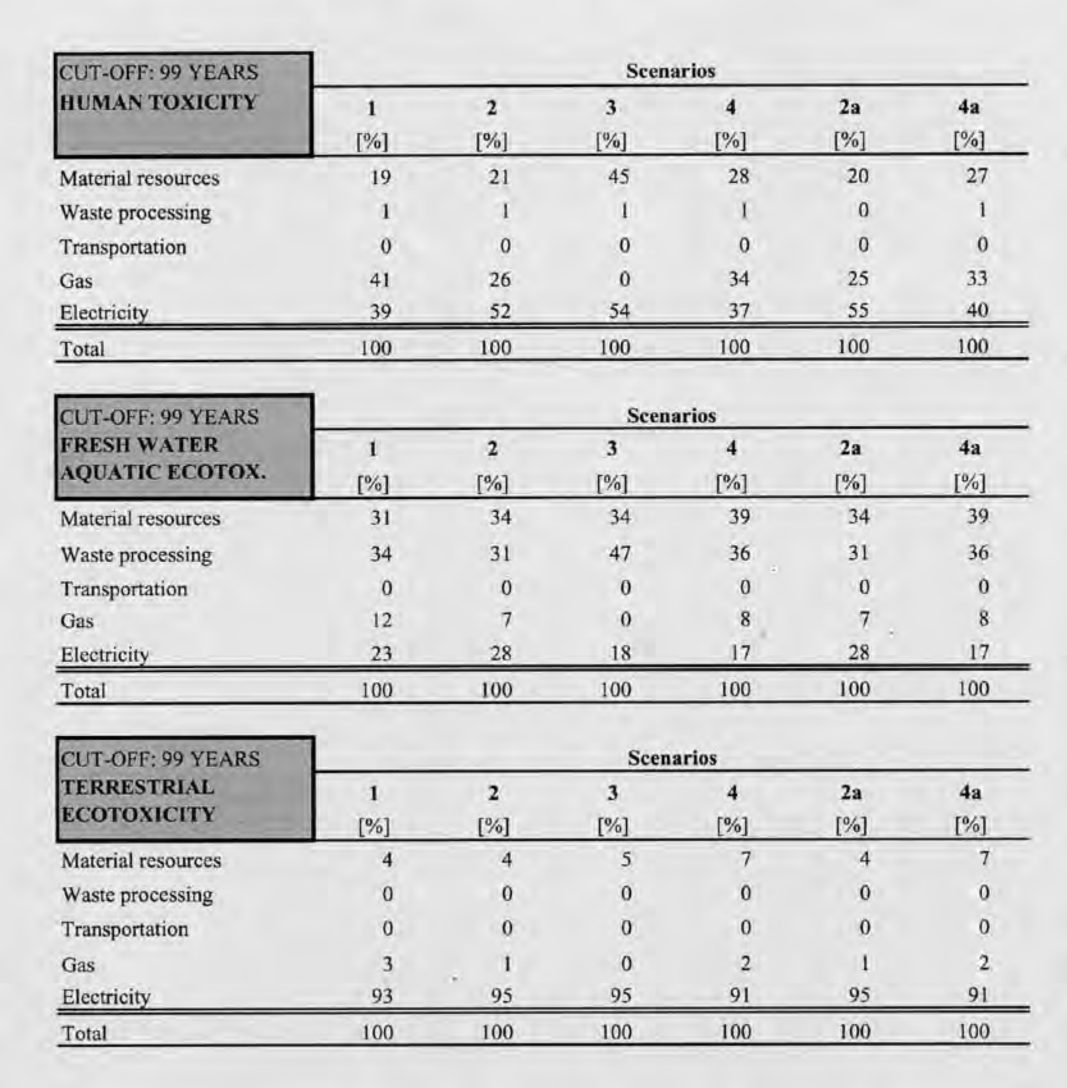


Table A5.3 Relative accumulated environmental impact caused by different factors after 99 years of dwelling operation, per environmental impact category

| CUT-OFF: 99 YEARS **ABIOTIC DEPLETION** | **Scenarios** | | | | | |
|---|---|---|---|---|---|---|
| | **1**<br>[%] | **2**<br>[%] | **3**<br>[%] | **4**<br>[%] | **2a**<br>[%] | **4a**<br>[%] |
| Material resources | 3 | 3 | 4 | 4 | 4 | 5 |
| Waste processing | 0 | 0 | 0 | 0 | 0 | 0 |
| Transportation | 0 | 0 | 0 | 0 | 0 | 0 |
| Gas | 53 | 35 | 0 | 49 | 42 | 57 |
| Electricity | 44 | 61 | 96 | 46 | 54 | 38 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 |

| CUT-OFF: 99 YEARS **GLOBAL WARMING** | **Scenarios** | | | | | |
|---|---|---|---|---|---|---|
| | **1**<br>[%] | **2**<br>[%] | **3**<br>[%] | **4**<br>[%] | **2a**<br>[%] | **4a**<br>[%] |
| Material resources | 1 | 2 | 3 | 3 | 2 | 3 |
| Waste processing | 1 | 1 | 1 | 2 | 1 | 2 |
| Transportation | 1 | 0 | 0 | 0 | 0 | 0 |
| Gas | 48 | 31 | 0 | 45 | 38 | 52 |
| Electricity | 49 | 66 | 95 | 51 | 58 | 43 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 |

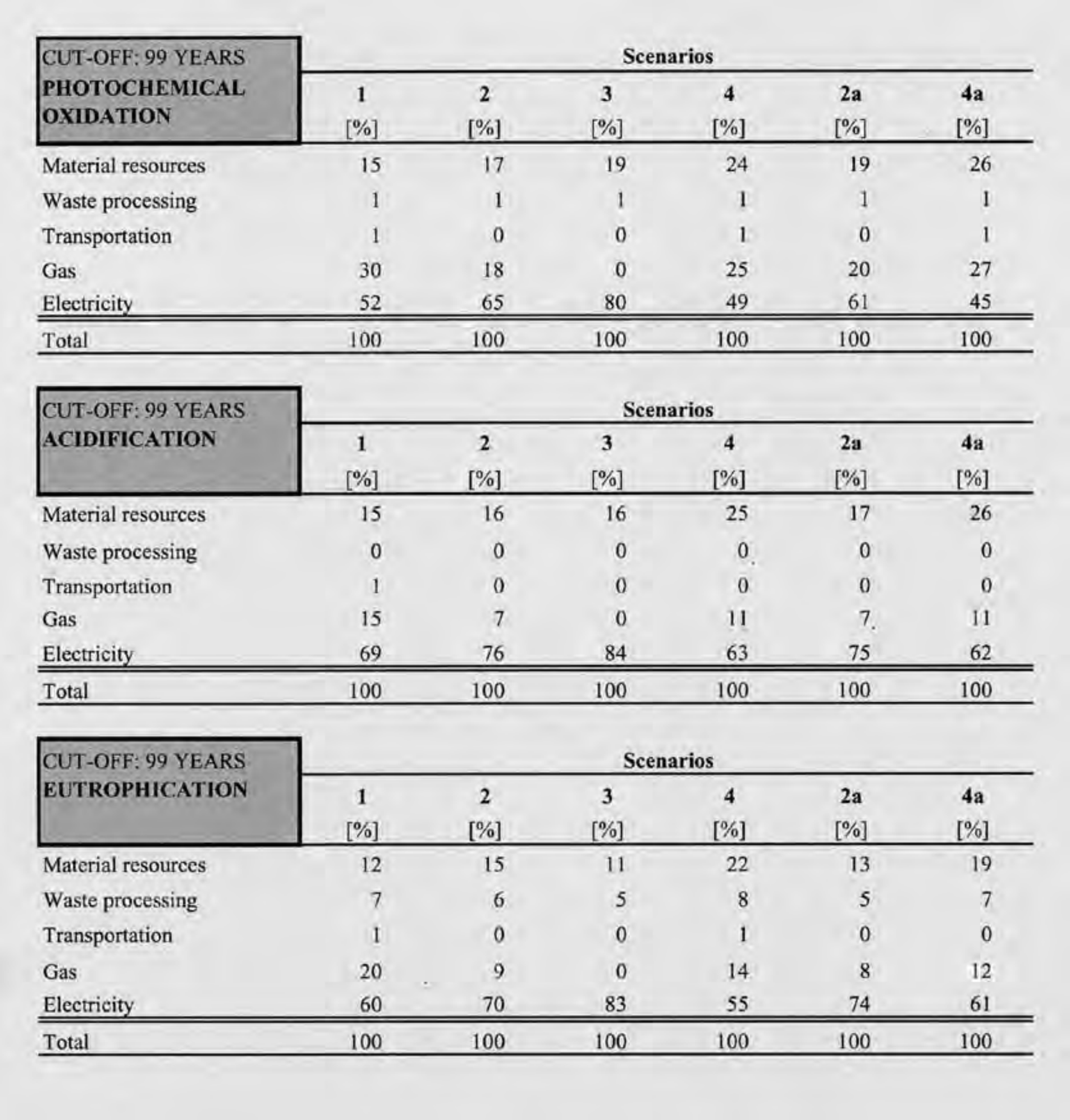
| CUT-OFF: 99 YEARS **OZONE LAYER DEPLETION** | **Scenarios** | | | | | |
|---|---|---|---|---|---|---|
| | **1**<br>[%] | **2**<br>[%] | **3**<br>[%] | **4**<br>[%] | **2a**<br>[%] | **4a**<br>[%] |
| Material resources | 6 | 7 | 94 | 9 | 8 | 10 |
| Waste processing | 0 | 0 | 0 | 0 | 0 | 0 |
| Transportation | 2 | 1 | 0 | 1 | 1 | 1 |
| Gas | 54 | 37 | 0 | 50 | 44 | 56 |
| Electricity | 38 | 55 | 6 | 40 | 47 | 32 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 |



| CUT-OFF: 99 YEARS<br>**HUMAN TOXICITY** | **Scenarios** | | | | | |
|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **2a** | **4a** |
| | [%] | [%] | [%] | [%] | [%] | [%] |
| Material resources | 19 | 21 | 45 | 28 | 20 | 27 |
| Waste processing | 1 | 1 | 1 | 1 | 0 | 1 |
| Transportation | 0 | 0 | 0 | 0 | 0 | 0 |
| Gas | 41 | 26 | 0 | 34 | 25 | 33 |
| Electricity | 39 | 52 | 54 | 37 | 55 | 40 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 |

| CUT-OFF: 99 YEARS<br>**FRESH WATER AQUATIC ECOTOX.** | **Scenarios** | | | | | |
|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **2a** | **4a** |
| | [%] | [%] | [%] | [%] | [%] | [%] |
| Material resources | 31 | 34 | 34 | 39 | 34 | 39 |
| Waste processing | 34 | 31 | 47 | 36 | 31 | 36 |
| Transportation | 0 | 0 | 0 | 0 | 0 | 0 |
| Gas | 12 | 7 | 0 | 8 | 7 | 8 |
| Electricity | 23 | 28 | 18 | 17 | 28 | 17 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 |

| CUT-OFF: 99 YEARS<br>**TERRESTRIAL ECOTOXICITY** | **Scenarios** | | | | | |
|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **2a** | **4a** |
| | [%] | [%] | [%] | [%] | [%] | [%] |
| Material resources | 4 | 4 | 5 | 7 | 4 | 7 |
| Waste processing | 0 | 0 | 0 | 0 | 0 | 0 |
| Transportation | 0 | 0 | 0 | 0 | 0 | 0 |
| Gas | 3 | 1 | 0 | 2 | 1 | 2 |
| Electricity | 93 | 95 | 95 | 91 | 95 | 91 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 |



| CUT-OFF: 99 YEARS<br>**PHOTOCHEMICAL OXIDATION** | **Scenarios** | | | | | |
|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **2a** | **4a** |
| | [%] | [%] | [%] | [%] | [%] | [%] |
| Material resources | 15 | 17 | 19 | 24 | 19 | 26 |
| Waste processing | 1 | 1 | 1 | 1 | 1 | 1 |
| Transportation | 1 | 0 | 0 | 1 | 0 | 1 |
| Gas | 30 | 18 | 0 | 25 | 20 | 27 |
| Electricity | 52 | 65 | 80 | 49 | 61 | 45 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 |

| CUT-OFF: 99 YEARS<br>**ACIDIFICATION** | **Scenarios** | | | | | |
|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **2a** | **4a** |
| | [%] | [%] | [%] | [%] | [%] | [%] |
| Material resources | 15 | 16 | 16 | 25 | 17 | 26 |
| Waste processing | 0 | 0 | 0 | 0 | 0 | 0 |
| Transportation | 1 | 0 | 0 | 0 | 0 | 0 |
| Gas | 15 | 7 | 0 | 11 | 7 | 11 |
| Electricity | 69 | 76 | 84 | 63 | 75 | 62 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 |

| CUT-OFF: 99 YEARS<br>**EUTROPHICATION** | **Scenarios** | | | | | |
|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **2a** | **4a** |
| | [%] | [%] | [%] | [%] | [%] | [%] |
| Material resources | 12 | 15 | 11 | 22 | 13 | 19 |
| Waste processing | 7 | 6 | 5 | 8 | 5 | 7 |
| Transportation | 1 | 0 | 0 | 1 | 0 | 0 |
| Gas | 20 | 9 | 0 | 14 | 8 | 12 |
| Electricity | 60 | 70 | 83 | 55 | 74 | 61 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 |

Table A5.4 Relative accumulated environmental impact caused by different factors after 99 years of dwelling operation excluding gas and electricity consumption, per environmental impact category

| CUT-OFF: 99 YEARS<br>**ABIOTIC DEPLETION** | | **Scenarios** | | |
|---|---|---|---|---|
| | | **1**<br>[%] | **2, 4**<br>[%] | **3**<br>[%] |
| Material resources | Façade components | 22 | 24 | 15 |
| | Climate systems | 24 | 43 | 64 |
| | Kitchen and bathroom | 41 | 29 | 18 |
| Waste processing | Façade components | 0 | 0 | 0 |
| | Climate systems | 0 | 0 | 0 |
| | Kitchen and bathroom | 0 | 0 | 0 |
| Transportation | Façade components | 5 | 1 | 1 |
| | Climate systems | 5 | 3 | 1 |
| | Kitchen and bathroom | 3 | 1 | 0 |
| Total | | 100 | 100 | 100 |

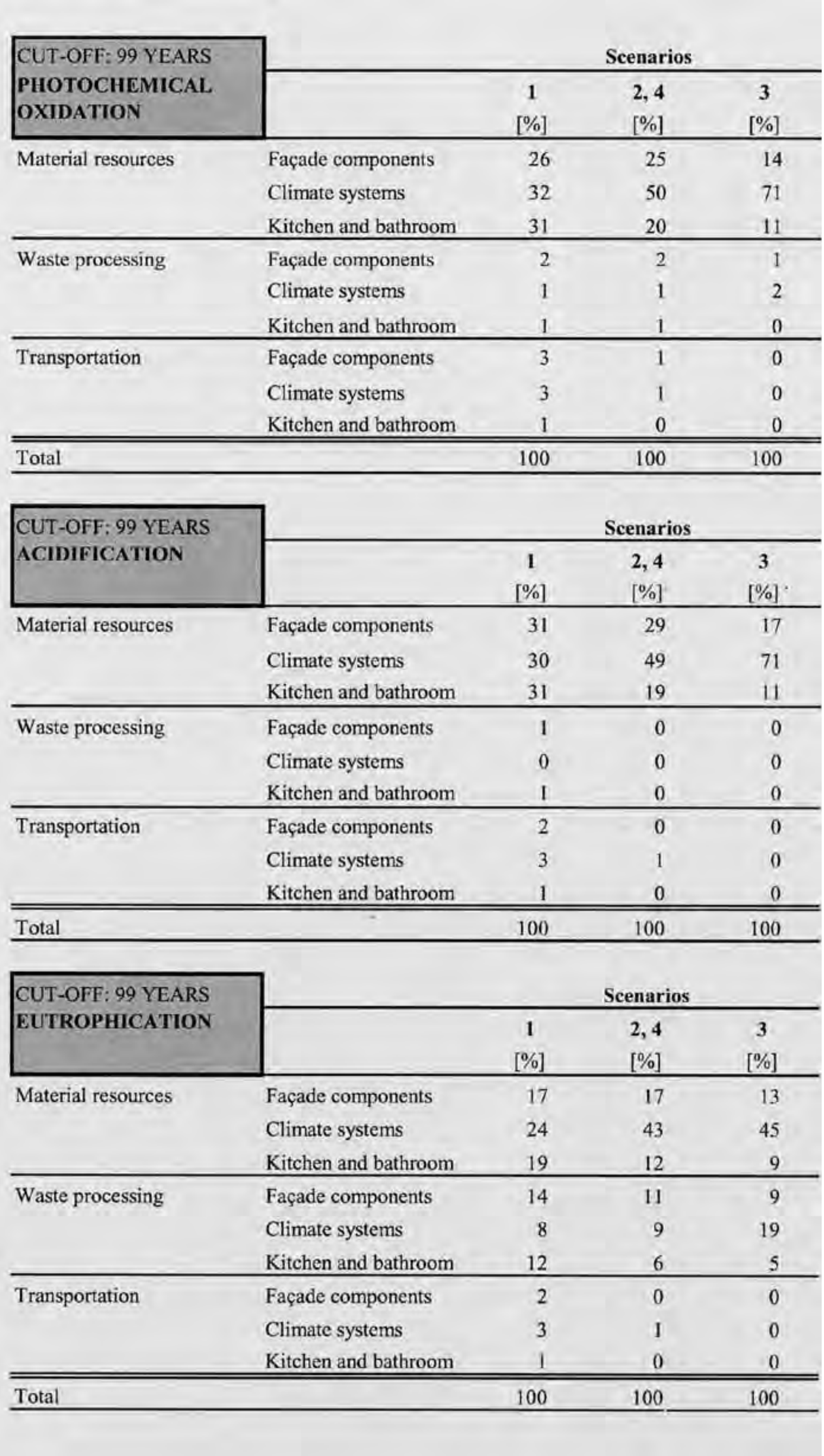
| CUT-OFF: 99 YEARS<br>**GLOBAL WARMING** | | **Scenarios** | | |
|---|---|---|---|---|
| | | **1**<br>[%] | **2, 4**<br>[%] | **3**<br>[%] |
| Material resources | Façade components | 5 | 8 | 4 |
| | Climate systems | 23 | 42 | 63 |
| | Kitchen and bathroom | 13 | 11 | 6 |
| Waste processing | Façade components | 17 | 14 | 8 |
| | Climate systems | 5 | 6 | 10 |
| | Kitchen and bathroom | 22 | 13 | 7 |
| Transportation | Façade components | 6 | 1 | 1 |
| | Climate systems | 7 | 3 | 1 |
| | Kitchen and bathroom | 3 | 1 | 0 |
| Total | | 100 | 100 | 100 |

| CUT-OFF: 99 YEARS<br>**OZONE LAYER DEPLETION** | | **Scenarios** | | |
|---|---|---|---|---|
| | | **1**<br>[%] | **2, 4**<br>[%] | **3**<br>[%] |
| Material resources | Façade components | 21 | 25 | 0 |
| | Climate systems | 17 | 36 | 100 |
| | Kitchen and bathroom | 38 | 30 | 0 |
| Waste processing | Façade components | 0 | 0 | 0 |
| | Climate systems | 0 | 0 | 0 |
| | Kitchen and bathroom | 1 | 0 | 0 |
| Transportation | Façade components | 9 | 2 | 0 |
| | Climate systems | 10 | 5 | 0 |
| | Kitchen and bathroom | 5 | 1 | 0 |
| Total | | 100 | 100 | 100 |

| CUT-OFF: 99 YEARS<br>**HUMAN TOXICITY** | | **Scenarios** | | |
|---|---|---|---|---|
| | | **1** | **2, 4** | **3** |
| | | [%] | [%] | [%] |
| Material resources | Façade components | 16 | 15 | 4 |
| | Climate systems | 38 | 56 | 88 |
| | Kitchen and bathroom | 42 | 26 | 7 |
| Waste processing | Façade components | 1 | 1 | 0 |
| | Climate systems | 1 | 1 | 1 |
| | Kitchen and bathroom | 1 | 1 | 0 |
| Transportation | Façade components | 0 | 0 | 0 |
| | Climate systems | 0 | 0 | 0 |
| | Kitchen and bathroom | 0 | 0 | 0 |
| Total | | 100 | 100 | 100 |

| CUT-OFF: 99 YEARS<br>**FRESH WATER AQUATIC ECOTOX.** | | **Scenarios** | | |
|---|---|---|---|---|
| | | **1** | **2, 4** | **3** |
| | | [%] | [%] | [%] |
| Material resources | Façade components | 9 | 8 | 2 |
| | Climate systems | 23 | 34 | 37 |
| | Kitchen and bathroom | 16 | 10 | 3 |
| Waste processing | Façade components | 21 | 20 | 5 |
| | Climate systems | 20 | 22 | 51 |
| | Kitchen and bathroom | 12 | 7 | 2 |
| Transportation | Façade components | 0 | 0 | 0 |
| | Climate systems | 0 | 0 | 0 |
| | Kitchen and bathroom | 0 | 0 | 0 |
| Total | | 100 | 100 | 100 |

| CUT-OFF: 99 YEARS<br>**TERRESTRIAL ECOTOXICITY** | | **Scenarios** | | |
|---|---|---|---|---|
| | | **1** | **2, 4** | **3** |
| | | [%] | [%] | [%] |
| Material resources | Façade components | 17 | 16 | 6 |
| | Climate systems | 45 | 60 | 84 |
| | Kitchen and bathroom | 35 | 22 | 9 |
| Waste processing | Façade components | 1 | 1 | 0 |
| | Climate systems | 0 | 1 | 1 |
| | Kitchen and bathroom | 1 | 0 | 0 |
| Transportation | Façade components | 1 | 0 | 0 |
| | Climate systems | 1 | 0 | 0 |
| | Kitchen and bathroom | 0 | 0 | 0 |
| Total | | 100 | 100 | 100 |



| CUT-OFF: 99 YEARS<br>**PHOTOCHEMICAL OXIDATION** | | **Scenarios** | | |
|---|---|---|---|---|
| | | **1** | **2, 4** | **3** |
| | | [%] | [%] | [%] |
| Material resources | Façade components | 26 | 25 | 14 |
| | Climate systems | 32 | 50 | 71 |
| | Kitchen and bathroom | 31 | 20 | 11 |
| Waste processing | Façade components | 2 | 2 | 1 |
| | Climate systems | 1 | 1 | 2 |
| | Kitchen and bathroom | 1 | 1 | 0 |
| Transportation | Façade components | 3 | 1 | 0 |
| | Climate systems | 3 | 1 | 0 |
| | Kitchen and bathroom | 1 | 0 | 0 |
| Total | | 100 | 100 | 100 |

| CUT-OFF: 99 YEARS<br>**ACIDIFICATION** | | **Scenarios** | | |
|---|---|---|---|---|
| | | **1** | **2, 4** | **3** |
| | | [%] | [%] | [%] |
| Material resources | Façade components | 31 | 29 | 17 |
| | Climate systems | 30 | 49 | 71 |
| | Kitchen and bathroom | 31 | 19 | 11 |
| Waste processing | Façade components | 1 | 0 | 0 |
| | Climate systems | 0 | 0 | 0 |
| | Kitchen and bathroom | 1 | 0 | 0 |
| Transportation | Façade components | 2 | 0 | 0 |
| | Climate systems | 3 | 1 | 0 |
| | Kitchen and bathroom | 1 | 0 | 0 |
| Total | | 100 | 100 | 100 |

| CUT-OFF: 99 YEARS<br>**EUTROPHICATION** | | **Scenarios** | | |
|---|---|---|---|---|
| | | **1** | **2, 4** | **3** |
| | | [%] | [%] | [%] |
| Material resources | Façade components | 17 | 17 | 13 |
| | Climate systems | 24 | 43 | 45 |
| | Kitchen and bathroom | 19 | 12 | 9 |
| Waste processing | Façade components | 14 | 11 | 9 |
| | Climate systems | 8 | 9 | 19 |
| | Kitchen and bathroom | 12 | 6 | 5 |
| Transportation | Façade components | 2 | 0 | 0 |
| | Climate systems | 3 | 1 | 0 |
| | Kitchen and bathroom | 1 | 0 | 0 |
| Total | | 100 | 100 | 100 |

Figure A5.1 Accumulated contribution to abiotic depletion during 99 years of dwelling operation

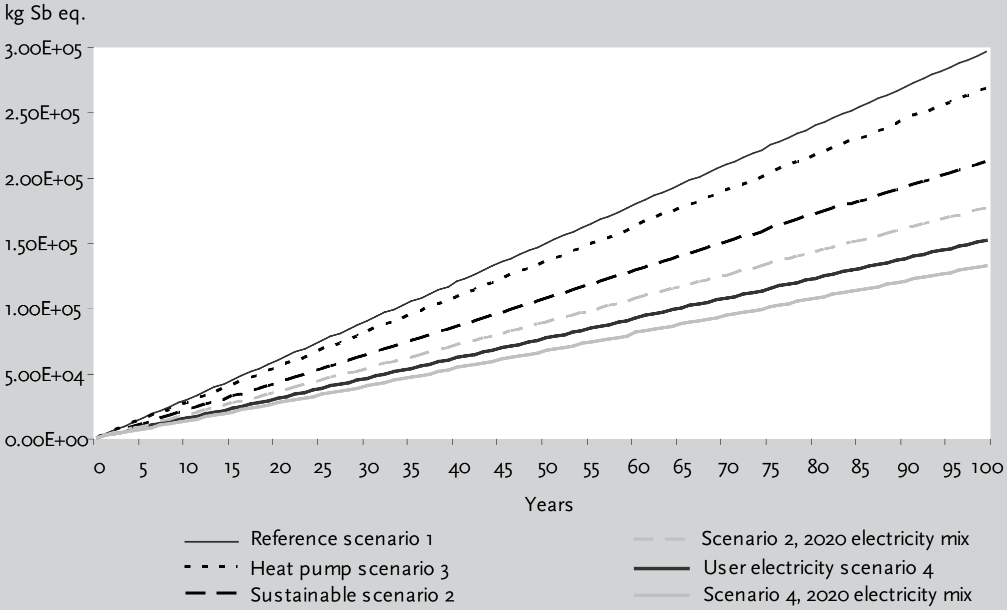
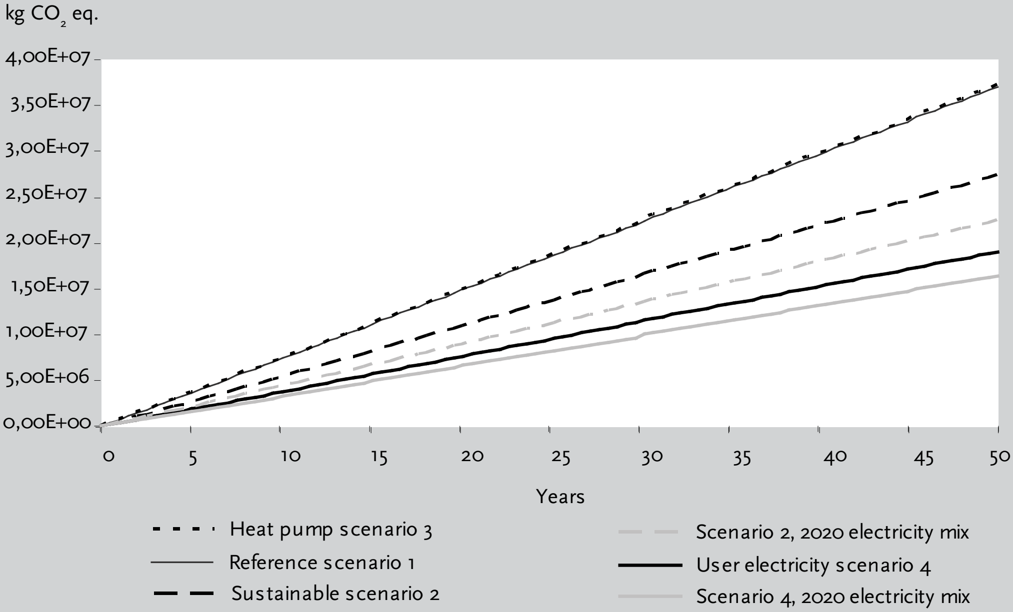
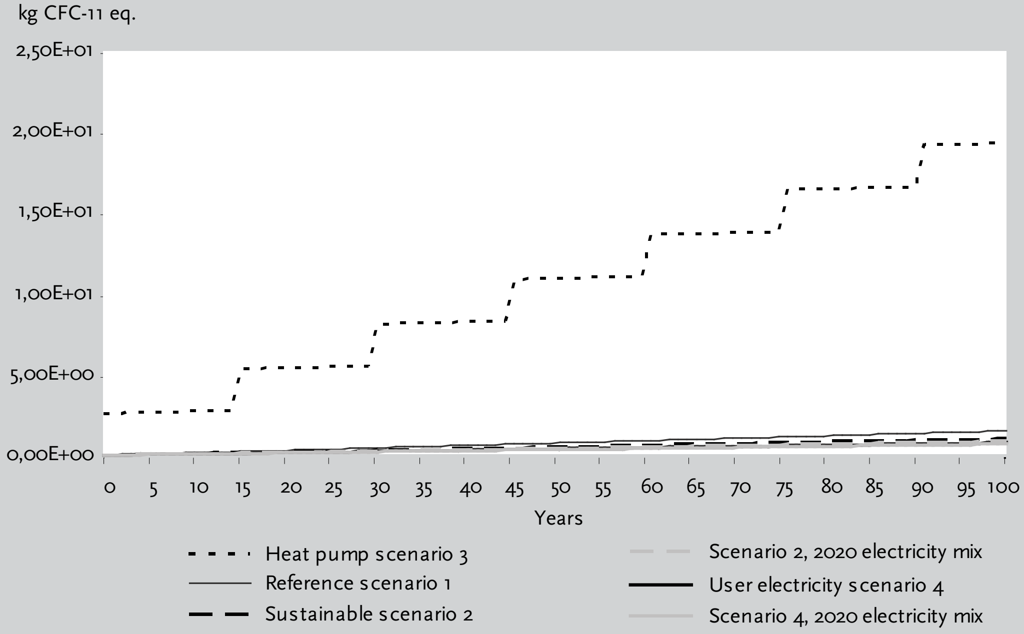


Figure A5.2 Accumulated contribution to global warming during 99 years of dwelling operation



## Figure A5.3 Accumulated contribution to ozone layer depletion during 99 years of dwelling operation



## Figure A5.4 Accumulated contribution to human toxicity during 99 years of dwelling operation

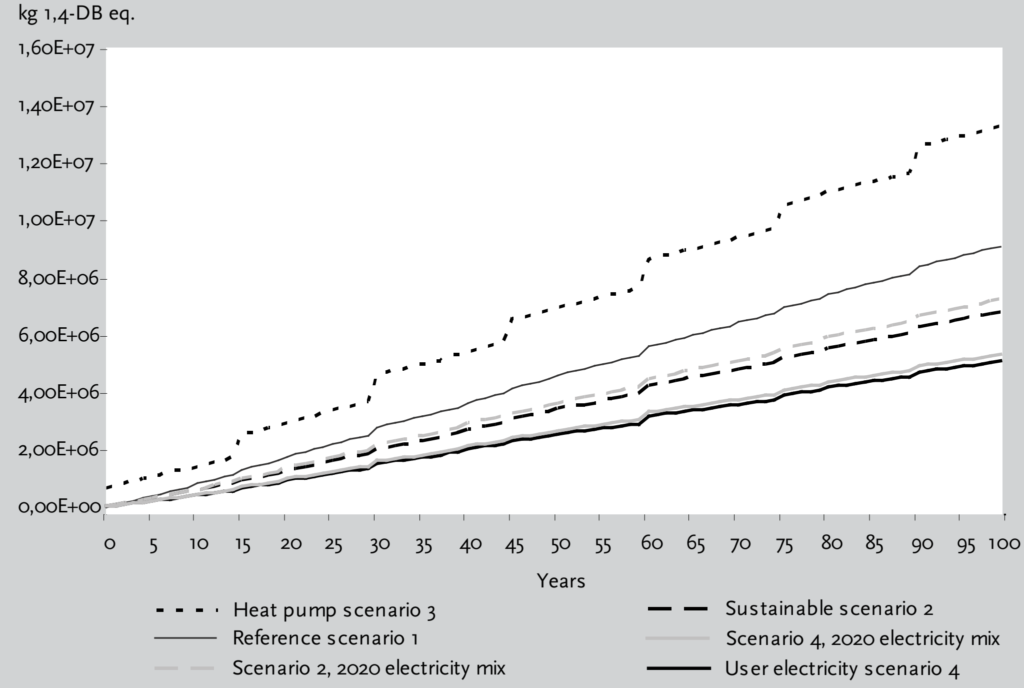


Figure A5.5 Accumulated contribution to fresh water aquatic ecotoxicity during 99 years of dwelling operation

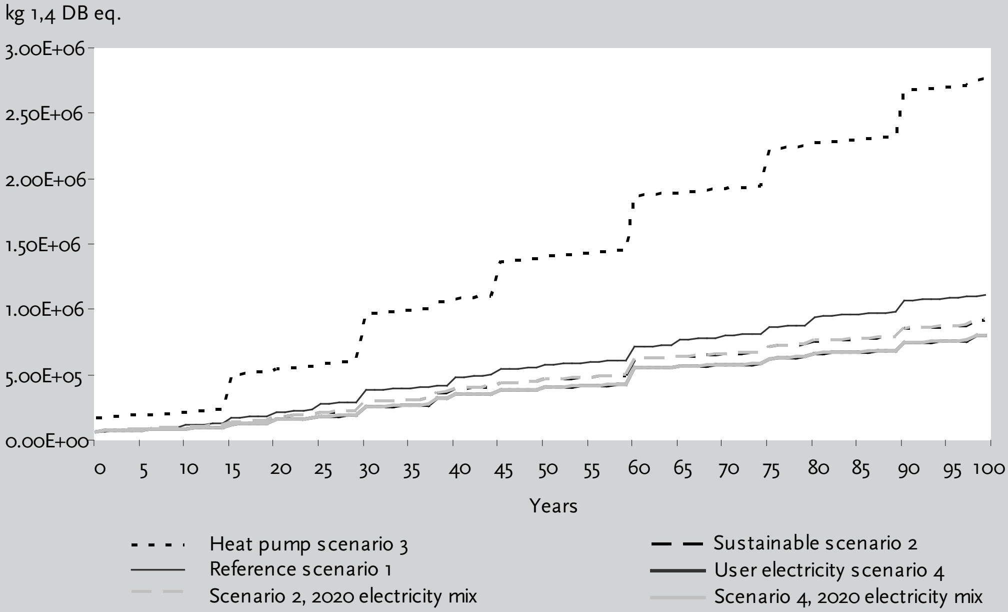


Figure A5.6 Accumulated contribution to terrestrial ecotoxicity during 99 years of dwelling operation

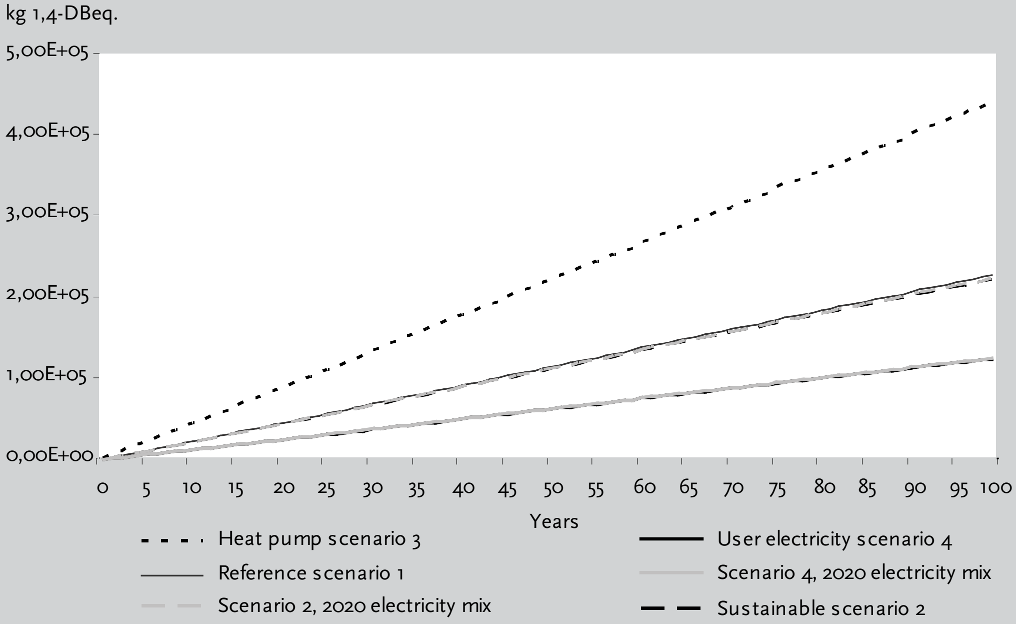


Figure A5.7 Accumulated contribution to photochemical oxidation during 99 years of dwelling operation

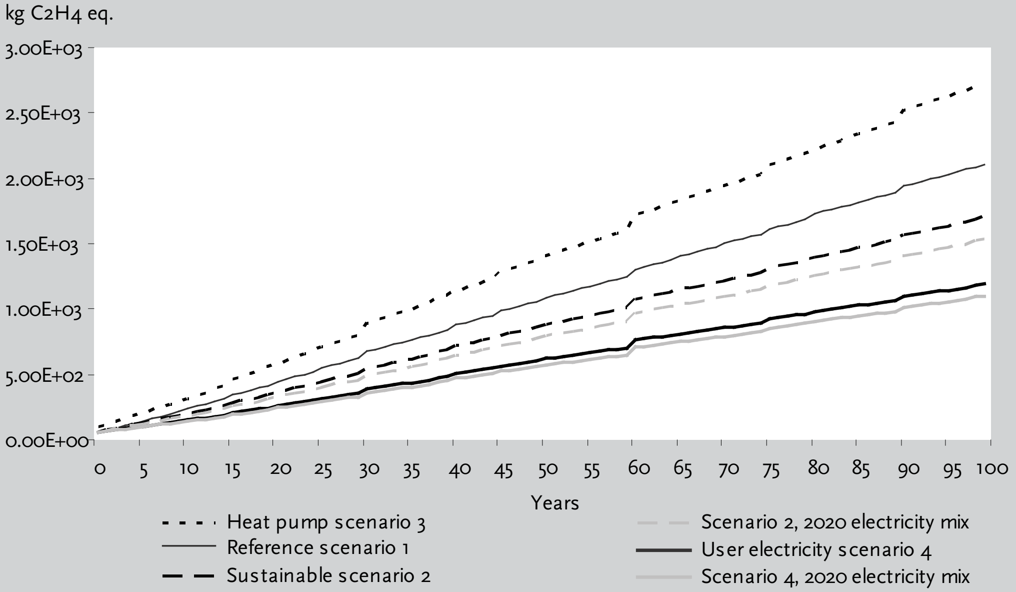


Figure A5.8 Accumulated contribution to acidification during 99 years of dwelling operation

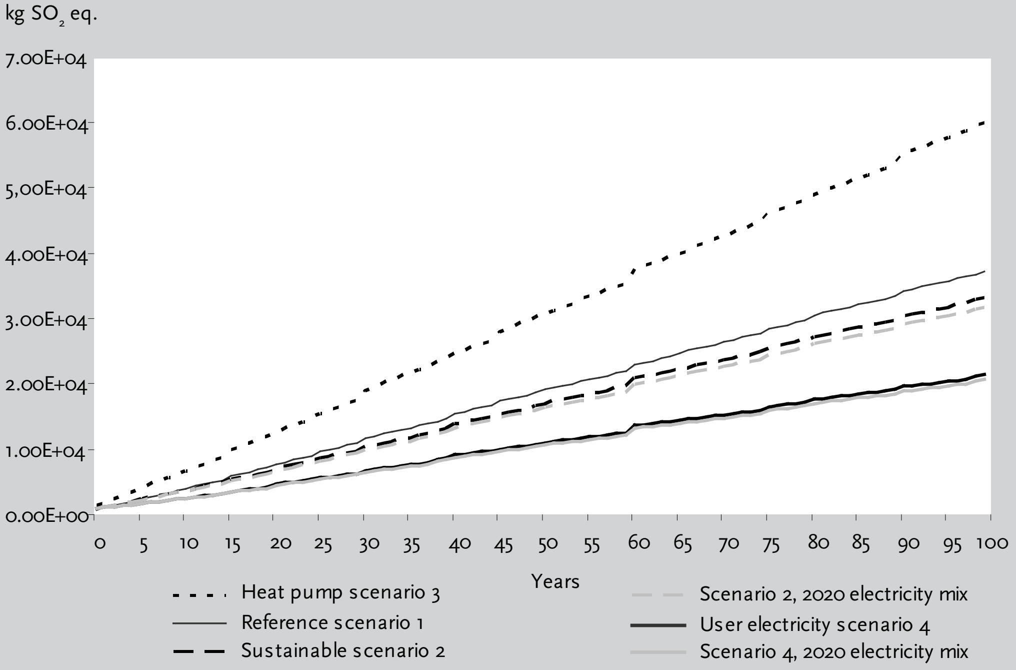
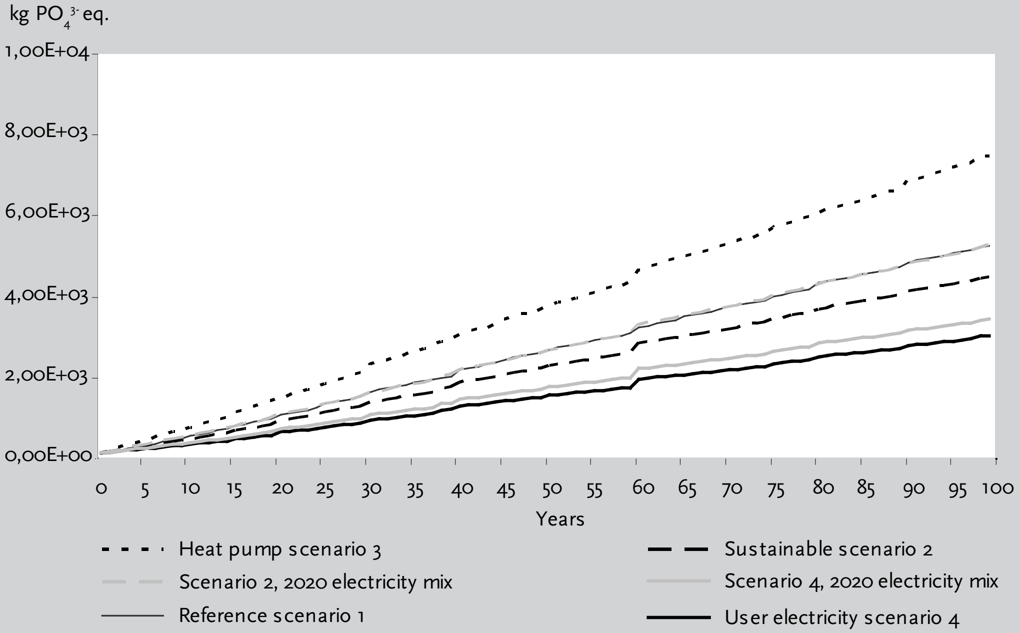


Figure A5.9 Accumulated contribution to eutrophication during 99 years of dwelling operation



# Curriculum vitae

Inge Blom (8 January 1981) was born in Eindhoven, but spent the conscious part of her childhood in Oirschot. After attending secondary school at Heerbeeck College in Best, she returned to Eindhoven in 1999 to study building physics at Eindhoven University of Technology, faculty of Architecture. During her studies, she worked as an intern for BDA Geveladvies at an overview of maintenance strategies for different materials used in façades. Through conducting comparative research on two versions of the LCA calculation tool Eco-Quantum her interest in LCA methodology and sustainable building was established. After completing her thesis Aanzet tot een nieuw LCA-model voor gebouwen she obtained her Master's Degree in 2005. In 2006, the work was followed by PhD research at OTB Research Institute for the Built Environment of Delft University of Technology. During her work in Delft, she co-authored a series of books about different façade systems – 'GevelReeks' – for BDA Geveladvies. In 2010 she completed her PhD dissertation and left OTB to take up a position as project engineer for sustainable energy systems with the engineering company Witteveen+Bos.

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To date, the focus in the field of sustainable building has been on new building design. However, existing residential buildings inflict great environmental burden through three causes: continuous energy consumption, regular building maintenance and replacements.

This publication analyses and compares these three causes of environmental burden and shows that material resources needed for replacements generally have a limited potential to reduce environmental impact. Reducing energy consumption for climate control and electrical appliances is much more effective. According to the author, sustainable measures should be tested for shifts in the kind of environmental impact caused due to the use of alternative types of energy resources and altered material quantities. The sustainability of the electricity supply is essential to decrease the total environmental impact of the residential building stock.

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