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Life-cycle assessment of a multi-family residence built to passive house standard

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1 Abstract

LCA of buildings has become a distinguished field of LCA, and a number of previous studies have found that low energy buildings generally have better life cycle performance than conventional buildings. However, there has been a lack of studies comparing low energy buildings against passive buildings. The present study evaluates life cycle performance of two passive and two low energy buildings that are all part of the housing cooperative Løvåshagen in Bergen. Construction of the housing cooperative was completed in 2009 and measured material and operational data was used in a comprehensive LCA of the whole life cycle from cradle to grave, for twelve midpoint impact categories. The functional unit is a lifetime of fifty years of one square meter BRA of a building block apartment.

Heating for low energy apartments are provided by electric resistance heaters and heating cables in the bathroom floors, while hot water heating is provided by an electric water heater. Evacuated tube thermal collectors are located on the roofs and provide passive house room heating through hydronic radiators and hydronic floor heating. They also provide hot water heating for each apartment. When solar collector output is not sufficient, heating is supplied by electric resistance elements.

The LCA results show practically no difference between the climate change performances of the house models, and this is largely the result of a particularly low passive house performance. In simulation-based LCA literature there appears to be a trend of over-estimating the operational performance of passive and low energy buildings, and Løvåshagen is no exception. The measured electricity consumption is high, both compared to estimations and to the results of other, simulation-based, studies. The high consumption appears to be a result of a particularly low outdoor temperature for the year of the measured data. It is recommended to monitor the electricity consumption over the next few years of operation, and if it is not significantly reduced there is reason to suspect faults in building construction or in the solar collector system. In the case of no direct defects there is reason to re-evaluate the effectiveness of solar collectors for the climatic conditions of Bergen.

2 Sammendrag

LCA av bygninger har blitt en egen gren av LCA, og en rekke studier har funnet at lavenergihus generelt har en bedre ytelse enn konvensjonelle bygg. Så langt har det vært en mangel på studier som sammenligner lavenergihus med passivhus. Dette studiet analyserer borettslaget Løvåshagen i Bergen som består av to lavenergihus og to passivhus. Borettslaget ble ferdigstilt i 2009, og målte material- og forbruksdata har her blitt brukt i en vugge-grav LCA som tar for seg tolv utslippskategorier. Den funksjonelle enheten er en levetid på 50 år for 1 m² BRA i en boligblokk-leilighet.

Oppvarming av lavenergihus består av panelovner og varmekabler i baderomsgulv, mens varmtvann forsynes ved bruk av en elektrisk varmtvannstank. Solfangere er montert på hustak, og sørger for romoppvarming og varmtvann til passivhusene via et vannbårent distribusjonssystem. Når solfangerne ikke gir tilstrekkelig effekt, benyttes elektriske varmeelementer for å supplere systemet.

Analysen viser ingen tydelig forskjell i klimagassutslippene fra de to ulike hustypene, og dette er hovedsakelig et resultat av uventet høyt elektrisitetsforbruk i passivhusene. Det ser ut til at simuleringer og studier som baserer seg på dem har en tendens til å overvurdere energieffektiviteten i passiv- og lavenergihus. Det målte elektrisitetsforbruket ved Løvåshagen er høyt, både sammenlignet med forventede verdier og sammenlignet med resultater fra tidligere, simuleringsbaserte, studier. Det høye forbruket ser ut til å være et resultat av en særlig lav utendørstemperatur for måleåret. Det anbefales å overvåke elektrisitetsforbruket over de neste årene, og dersom de ikke reduseres betydelig er det grunnlag for å mistenke feil i bygningskonstruksjonen eller i solfangersystemene. Dersom ingen feil blir funnet, er det grunn til å revurdere bruken av solfangere, tatt de klimatiske forholdene i Bergen i betraktning.

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4 Introduction

The building sector is responsible for about 30% of energy demand globally, and about 40% of the energy demand in Norway (Dahlstrøm et al., 2012, Sartori et al., 2009). The reduction potential in the form of active and passive energy efficiency measures is substantial, and has been increasingly studied over the last few years. While such measures may reduce the operational energy demand significantly, some studies argue that the operational benefits are sometimes outweighed by the increased impacts embodied in building materials and components (Ramesh et al., 2010). A number of studies have employed the life cycle assessment tool (LCA) for comparing passive or low energy buildings with conventional buildings, but there is a lack of studies comparing low energy buildings against passive buildings. This is where the present study attempts to provide a contribution, by comparing two passive and two low energy multi-family buildings in Bergen. The buildings were all taken into use in 2009, and the availability of construction and operational data gives a basis for more reliable results than when using estimated data. Estimated data is most common in surveyed building LCA literature. As pointed out by Blengini and Di Carlo (2010), there is also less uncertainty associated with a comparative study of different building standards than when comparing the results of different individual studies with each other. Generally the present study is more detailed than what is common in building LCA literature, including study of more life cycle phases and a broader range of environmental indicators.

This thesis includes thirteen chapters. Chapter 5 gives an overview of previous literature on building life cycle assessment and a closer description of the contribution made by the present study. Chapter 6 includes a short presentation of the LCA method and how it is applied to the system of study. This system is then defined more closely in Chapter 7, before the details of the life cycle inventory is introduced in Chapter 0. Results are presented through the impact assessment in Chapter 9 before they are analyzed in Chapter 0. Finally, Chapter 11 interprets and discusses results before drawing conclusions and making suggestions for further work.

5 Literature review

5.1 Life cycle assessment of buildings

*A survey has been made of studies that focus on LCA methodology (*Table 5-1*), or that focus on LCA case studies of buildings (*Table 5-2*). This chapter starts by presenting the background for developing a specialized LCA methodology for buildings, and continues by introducing key concepts and characteristics of such LCAs. The general findings of the four overview studies [14]-[17] are then presented, and the case studies [4]-[13] are used to build upon these findings. It should be noted that the overview studies cover many of the same case studies, and that some of them include the case studies [4] and [5].*

Although LCA has been used in the building sector since 1990 (Review [15] and [16]), there is not yet an internationally recognized methodology for assessing and organizing LCA inventory data for buildings. As pointed out by [3], [6] and [16], this hinders direct comparison of results from different LCA case studies, and is an obstacle to the application of LCA within the building industry. LCA of buildings is particularly complex because buildings are more complex than most other products. There is complexity in the sheer number of building materials and component combinations used in a building and in the uniqueness of each particular building, but also in other ways. As explained by [16], the lifetime of buildings is long, which makes it difficult to predict the whole life cycle. Also, buildings may undergo changes throughout their life cycle, potentially leading to a significant structural difference between the building that is demolished at end of life and the building that was initially constructed. Further, while most other products do not have any significant impacts throughout their use phase, the operation stage of buildings is often the major contributor to total life cycle impacts. Finally, the number of stakeholders is high in the building industry, including designers, builders and users, among others. This means that a house may not be built or used according to the idea of the designers. Methodology for applying LCA to buildings is presented and discussed by several papers, including [1], [2], [3], [15] and [16].

ID	Year	Study	Description
[1]	2008	Vieira and Horvath	Surveys previous research on the end of life of products, discusses key end of life issues, and presents a method for environmental decision-making related to buildings
[2]	2008	Peuportier	Compares the application of seven European building LCA tools to a simple hypothetical building and a real case study building, and further applies the EQUER tool to the pre- and post-renovation states of a case study building in France
[3]	2010	Crawford et al.	Surveys literature analysing life cycle energy requirements of BMCC and presents a method for ranking building assemblies based on this attribute. The method is applied to eight residential construction assemblies

Table 5-1: Studies of LCA tools and and methodology

Abbreviations: BMCCs - Building Materials and Component Combindations

ID	Year	Study	Description	Multi-family	Life Cycle Phases			
					C	**M**	**O**	**E**
[4]	2002	Yohanis and Norton	Study of embodied, operational and total energy for a simulated office building built to Northern Irish technical standards	No	X		X	
[5]	2005	Asif et al.	Study of a semi detached house in Scotland, focusing on initial embodied energy in the materials wood, aluminium, glass, concrete and ceramic tiles	No	X			
[6]	2007	Itard and Klunder	Compares embodied, operational and total energy, as well as a number of environmental impacts, for the renewal options maintenance, consolidation, transformation and redevelopment for two typical cases of Dutch urban renewal	Yes	X	X	X	
[7]	2008	Thiers and Peuportier	Compares thermal and environmental assessment of passive house in France with that of a reference house built to the French thermal regulation standard	Yes	X		X	X
[8]	2009	Dodoo et al.	Compares CO_2 emissions of a concrete-frame building with those of a wooden-frame building, focusing on end of life management implications	Yes*	X			X
[9]	2010	Monahan and Powell	Compares the embodied carbon in a LE timber frame house in the UK with two alternative scenarios: (1) exchange of timber cladding for brick cladding, and (2) exchange of timber frame for masonry and timber cladding for bricks	No	X			
[10]	2010	Blengini and Di Carlo	Study of a number of environmental impacts for a LE family house built in Northern Italy, compared to the impacts of a more conventional house	No	X	X	X	X
[11]	2010	Gustavsson and Joelsson	Study of primary energy and CO_2 emissions for 11 scenarios for two LE and three conventional case study buildings in Sweden	Yes	X		X	
[12]	2011	Sørnes	Study of environmental impacts and primary energy resulting from four scenarios: one scenario for a house built to the Norwegian technical standard with a standard heating system, and three heating system scenarios for a house built to passive house standard	No	X	X	X	X
[13]	2011	Dahlstrøm	Cradle to grave LCAs of one house built to the Norwegian technical standard and one house built to passive house standard	No	X	X	X	X
		Overviews						
[14]	2007	Sartori and Hestnes	Literature survey covering 60 case studies studying the life cycle energy use of buildings. Discusses and compares embodied, operating and total life cycle energy for LE and conventional buildings					
[15]	2009	Ortiz et al.	Surveys a number of published building sector LCA studies, focusing on the development and accomplishments of LCA in the construction industry, in the period 2000-2007					
[16]	2009	Khasreen et al.	Reviews LCA from a building perspective and surveys a number of building sector LCA studies, focusing on the potentials for further development of LCA in the building sector.					
[17]	2010	Ramesh et al.	Surveys 73 building LCA case studies, discussing and comparing embodied, operating and total life cycle energy for conventional buildings and LE buildings using passive and active technologies					

Table 5-2: LCA case studies of the building sector

*Abbreviations: ID – Identification letter; C – Construction phase; M – Maintenance phase; O – Operation phase; E – End of life phase; *not specified, but useable floor area is large (1190 m2); LE – Low energy*

5.2 Concepts and characteristics

[15] and [16] discern between LCAs that include the whole process of the construction (WPC) and those that only include the building materials and component combinations (BMCC). WPC's do not only include the construction phase of a building, but typically also includes operation and end of life management. According to [16], the life cycle inventory (LCI) of a WPC typically includes, in addition to the BMCC, "the transport of materials and building components to site, the use of the building (as energy use), the waste of materials (sometimes), water consumption (sometimes), maintenance and replacement, demolition of the building, and transport of waste to the treatment site" ([16], p. 681). [14] and [17] describe the concepts of embodied energy as compared to operating energy. Embodied energy is defined as "the sum of all the energy needed to manufacture a good" ([14], p. 249), and is divided into initial embodied energy and recurring embodied energy. Initial embodied energy is the energy embodied in materials used in the construction phase, while recurring embodied energy is energy embodied in the materials used in the rehabilitation and maintenance phase. An emphasis is made on distinguishing between primary energy and end-use (delivered) energy. The latter determines "energy measured at the final use level" ([14], p. 249), while primary energy is the sum of the energy required to produce the end-use energy, measured at the natural resource level. According to [14], the standard practice among LCA studies is to provide the primary energy data.

5.3 Overview study results

The overview studies agree that operation generally is the most energy-intensive phase of a building's life cycle, and [17] find the relative contributions of embodied and operating energy to be in the range 10-20% and 80-90%, correspondingly. [14] demonstrates a mostly linear relationship between operating and total energy for the building case studies analysed. [14] and [17] conclude that the life cycle energy performance of low energy buildings is generally better than that of conventional ones, in spite of a higher embodied energy. [14] also find that passive (P) houses may achieve a great decrease in total life cycle energy use with only a slight increase in embodied energy. However, it points out a case study where the performance of a "self-sufficient" house, with a high degree of active energy efficiency technologies, was significantly worse than a passive house version. [17] points to this result, warning that an excessive use of passive and active energy efficiency technologies may be counterproductive. When comparing wood-based buildings with concrete-based buildings, study [15] finds that the latter results in the highest global warming and acidification impacts, a conclusion supported by the results of [16]. The latter emphasizes the need to "hold whole life-cycle assessment studies to establish the effect of alternative materials on the energy performance of the buildings, and to find the relationships between them" ([16], p. 695-696). Several reviewed studies comment on the tendency among LCA case studies to focus on energy consumption, and suggest that future studies would benefit from including analysis for a wide range of environmental loads, and for the whole life cycle ([10], [14], [15] and [16]).

5.4 Case study results

The findings of the overview studies are generally supported by the case studies presented in Table 5-2. Several studies find low energy and passive buildings to have better life cycle performance than conventional buildings, including [7], [10], [11], [12] and [13]. Several studies report that energy consumption is dominated by the operation phase, for LE as well as conventional buildings, and that the relative contribution of the construction phase is higher for LE houses ([12], [13], [16] and [19]).

[13] reports an operation phase relative contribution of 76% for a conventional house, and 67% for a P house. An exception to the domination of the operation phase is demonstrated by [10], where a majority of impacts for the LE building is found to stem from material components in the construction and maintenance phases, for a lifetime of 70 years. [11] points to a previous study that compared LCA results with input-output results for primary energy use and carbon emissions in the production phase of buildings. This study found substantially higher impacts when using the input-output methodology, likely due to truncation error for the LCA method. When the difference is added to the results of [11], the production phase turns out to have a higher contribution to total energy use than space heating in the operation phase.

Studies [8], [9] and [11] find wood to be a preferable frame construction material to concrete or masonry, in terms of life cycle energy use and carbon emissions. [5] and [9] find concrete to be the material with the highest embodied energy and embodied carbon correspondingly. Ceramic tiles and bricks also prove to be materials with significant relative impact contributions. [13] finds that the building elements with the highest contributions to climate change are (in descending order) floors (including floor separators), walls, roof, and groundwork/foundation, and [9] finds the most important elements to be the substructure, foundations and ground floor. For a timber-framed LE building, [9] finds that 82% of the embodied carbon for house construction is embodied in the construction materials themselves, the remainder embodied in energy used on the construction site, transportation of materials to site, and transportation of waste from site. The article points to an earlier study showing that 10-15% of the materials imported to a construction site was exported as waste (McGrath and Anderson, 2000), and a cradle to site LCA of the [9] building finds that 14% of the total embodied carbon originates from on-site waste production. Transportation to site is found to be responsible for only 2% of total embodied carbon, and the cradle to grave LCA conducted by [10] finds a similarly low impact contribution.

[6] compares the four maintenance options “maintenance, consolidation (insulation measures), transformation (change of floor plan to accord with new needs), and rebuilding (demolition of the old building and reconstruction with a new floor plan)” ([6], p. 266) for two housing blocks in Holland, and finds that transformation, when possible, is a significantly better option than rebuilding. Hence, it is suggested that new buildings be designed for flexibility, for instance by avoiding dependency on load-bearing inner walls, thus enabling easy removal of the walls. [11] finds that installation of envelope energy efficiency measures such as attic insulation and energy efficient windows has a substantial effect on the performance of a conventional wood-framed four storey apartment building. The choice of energy supply system is found to be even more important however, and use of biomass-based district heating results in more than 50% lower life cycle primary energy use than use of coal-based electrical resistance heating. For a twelve-storey concrete-framed LE building the result of making the same change is a decrease in life cycle primary energy use of roughly 40%. The use of solar thermal collectors for hot water heating is found to be efficient, but not more so than the use of a heat pump or district heating. Likewise, for the cradle to grave LCA of a P house, [12] finds the heating system solution of an air-to-water heat pump to be preferable when comparing with a solar collector system or a combination of electrical resistance heating and a wood stove. However, the solar collector system performs best for the climate change impact category.

5.5 Motivation for the present study

The present study is a full life cycle LCA that compares the environmental performance of flats in existing low energy buildings with flats in existing passive house buildings, all part of the same housing cooperative in Bergen, Norway. Such an LCA study is useful for various reasons. As indicated by previous literature (for instance [10], [15] and [16]) there is a lack of building life cycle assessments that include the whole life cycle of the buildings. Regarding the relevance of [10], it is stated that "the comparison between the life cycle impacts of the LEH [Low-Energy House] and the SH [Standard House] is probably the most meaningful part of the research […] it must be recalled that, despite the effects of uncertainty on the absolute accuracy of an LCA, comparative LCAs are relatively more accurate, as uncertainty is usually highly correlated between scenarios" ([10], p. 660). [10] and other comparative studies have generally concluded that low energy buildings outperform conventional ones, and a logical next step is then to compare low energy buildings with even more energy efficient ones; passive buildings. The number of such studies is even lower than the number of studies that compare LE and conventional buildings, and that is why the present study may be considered to be particularly relevant.

Under a list of good practice [2] states that one should "use product specific data when available with a consistent methodology, recent data being preferable" ([2], p. 6). The availability of the material inventories of Løvåshagen and the 2010 electricity consumption values for all apartments gives a good basis for LCA.

5.6 Chapter summary

LCA of buildings has become a distinguished field of LCA, mainly because of the high complexity of buildings. System boundaries for building LCAs differ substantially in terms of which elements, life cycle phases, and environmental loads that are included. There is a need for a common LCA framework for buildings, in order to increase the comparability and relevance of case studies. Low energy buildings generally have better life cycle performance than conventional buildings. The operation phase of buildings is usually the most impact-intensive, but the relative contribution is lower for LE and P houses than for conventional houses, due to a significantly lower operational energy use and a somewhat higher production material use. In general, concrete-based buildings are substantially more impact-intensive than wood-based ones.

6 Method

This chapter starts by giving an overview of the four stages of the LCA method and continues to describe the twelve impact categories used for the present study.

6.1 Life Cycle Assessment

The tool used for the analysis of Løvåshagen is life cycle assessment (LCA), as described in NS-EN ISO 14044:2006. An LCA includes four main stages:

6.1.1.1 Goal and scope definition

Central for this stage is statement of the reasons behind the study and the intended application, as well as descriptions of the product systems to be studied, the functional unit and system boundaries.

6.1.1.2 Life cycle inventory analysis (LCI)

According to the ISO standard “the qualitative and quantitative data for inclusion in the inventory shall be collected for each unit process that is included within the system boundary” (p. 16), “all calculation processes shall be explicitly documented and the assumptions made shall be clearly stated and explained” (p.17). Allocation should be avoided when possible, and otherwise it should be done in a way that reflects the underlying physical relations between the system’s inputs and outputs.

6.1.1.3 Life cycle impact assessment (LCIA)

As part of the LCIA it is considered mandatory to include selection of impact categories, category indicators and characterization models, as well as classification and characterization of results.

6.1.1.4 Life cycle interpretation

This stage includes identification of significant issues based on the LCI and LCIA results, taking into consideration completeness, sensitivity and consistency checks. Further, it includes conclusions, a description of limitations, and recommendations for the intended audience of the LCA.

6.2 LCIA Specifications

As described by Dahlstrøm (2011), “midpoint categories are problem oriented and based on a scientific background but can sometimes be difficult to interpret, while endpoint categories are damage oriented an easier to interpret, but have higher uncertainty” (Dahlstrøm 2011, p. 8). Although energy consumption and climate change impacts are often the focus of LCA studies, studying a wider range of impact categories gives a broader basis for decision-making. This has been considered a potential for improvement in the literature on building-related LCA, as pointed out in Chapter 5: Literature Review. For the impact assessment of the present study, twelve midpoint categories have been selected from the hierarchist version of the ReCiPe method (version 1.06). The twelve are described in Table 6-1 below, adopted from Dahlstrøm (2011). As pointed out in the literature review, it is common LCA practice to provide primary energy data, and this is provided in the present study through inclusion of the cumulative energy demand impact category. Although the study of a wide range of environmental indicators is desirable, it is still useful to limit the study somewhat, and for this reason some ReCiPe impact categories have been excluded. These categories are ozone depletion, ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, and fossil fuel depletion. They are considered to be less relevant for various reasons. As described by Dahlstrøm (2011), the first two are indicators of environmental problems that have less relevance for a study of buildings in the Norwegian context. Land use indicators are not included because of uncertainty for the Norwegian conditions, and fossil fuel depletion is replaced by cumulative energy demand, which includes both renewable and non-renewable energy. Dahlstrøm (2011) found that 98% of water use stemmed from the use phase. The system conditions for Dahlstrøm (2011) are considered to have much similarity those of the present study. For this reason, and because water consumption is not a major issue in Norway, the indicator has been excluded.

Impact category		*Unit*	*Description*
CC	**Climate change**	kg CO_2 eq	To air, global. Emissions who contributes to the greenhouse effect by increased infra-red radiative forcing in the atmosphere.
HT	**Human toxicity**	kg 1,4-DB eq	To urban air, site-sensitive. Effect of toxic substances to human environment. Air emissions of heavy metals are specifically large contributors
POF	**Photochemical oxidant formation**	kg NMVOC	To air, site-sensitive. Formation of ground-level ozone, indicated as "summer smog". "Ozone is a health hazard to humans because it can inflame airways and damage lungs" (Goedkoop et al., 2009).
PMF	**Particulate matter formation**	kg PM_{10} eq	To air, regional air quality. Particles in the air generated by mainly combustion of fossil fuels. Causes health problems for airways and lungs.
TA	**Terrestrial acidification**	kg SO_2 eq	To air, site-sensitive. Inorganic gases (sulfates, nitrates and phosphates) may dissolve in water and change acidity in, e.g., soil and groundwater. Acid rain.
FE ME	**Freshwater eutrophication** **Marine eutrophication**	kg P eq Kg N eq	Both to freshwater, site-sensitive. Nutrient-rich compounds released into water bodies. Can cause algal bloom which may lead to an adverse ecological effect.
TET	**Terrestrial ecotoxicity**	kg 1,4-DB eq	To industrial soil, site-sensitive. Risks of damage to ecosystems on land by emissions of toxic substances.
FET	**Freshwater ecotoxicity**	kg 1,4-DB eq	To freshwater, site-sensitive. Risks of damage to freshwater bodies, as a result of emissions of toxic substances to air, water and soil.
MET	**Marine ecotoxicity**	Kg 1,4-DB eq	To marine water, site-sensitive. Risks of damage to marine ecosystems by emissions of toxic substances.
MD	**Metal depletion**	kg Fe eq	The depletion of metals and minerals can be described as the decrease of available reserve of minerals due to extraction and use.
CED	**Cumulative energy demand**	GJ eq	Accumulated total primary energy required, fossil and renewable.

Table 6-1: Impact categories included for the present study

6.3 Chapter summary

LCA includes four stages: (1) Goal and scope definition, (2) LCI, (3) LCIA, and (4) interpretation. Twelve midpoint impact categories have been selected: Climate Change, Human Toxicity, Photochemical Oxidant Formation, Particulate Matter Formation, Terrestrial Acidification, Freshwater Eutrophication, Marine Eutrophication, Terrestrial Ecotoxicity, Freshwater Ecotoxicity, Marine Ecotoxicity, Metal Depletion, and Cumulative Energy Demand.

7 System Description

This chapter starts by presenting a description of the object of study – the Løvåshagen housing cooperative. It goes on to describe the functional unit and the system boundaries for the study.

7.1 Løvåshagen housing cooperative

The object of study is the Løvåshagen housing cooperative, located in Fyllingsdalen, Bergen. The cooperative includes 80 apartments, distributed on two houses built to low energy standard and two passive houses. The utility floor space (BRA) of apartments range from 50 m^2 to 96 m^2, with an average area of 81 m^2 (Thomsen et al., 2011). Aggregated BRA for the houses at Løvåshagen is 6475 m^2, or 9207 m^2 when including garages. The figure below provides an overview of the placement of the Løvåshagen buildings.

There appears to be some discrepancy between the area measure definitions and translations used by different sources (SSB, 2012a; SSB, 2012b; Müller, 2006; Sandberg et al., 2011). Because of this, the BRA used in the present study will be described more explicitly in the following paragraph.

> *BRA for houses includes the floor area within the outer walls, as defined by Statistics Norway (SSB, 2012b), and includes the indoor storage rooms displayed in Figure 1.2 but not the balconies. There is one indoor storage room per apartment, and on average this room has a floor area of 3.3 m2. Stairs, elevators and entrance balconies are located on the outside of the buildings, and are not included in the BRA. Hence, all house BRA is heated. The garages are not considered to be heated, but the garage floor space is referred to as BRA.*

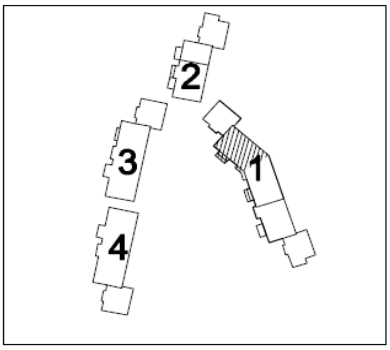


Figure 7.1: Building overview

Løvåshagen was projected by ByBo AS, and is one of Enova SF's example projects, or "Forbildeprosjekter". The label is used for buildings that Enova considers to be good examples in terms of using future-oriented solutions to achieve low energy use and a high partition of renewable energy sources (Enova SF, 2008). The construction of Løvåshagen was started in 2007 and completed in 2009.

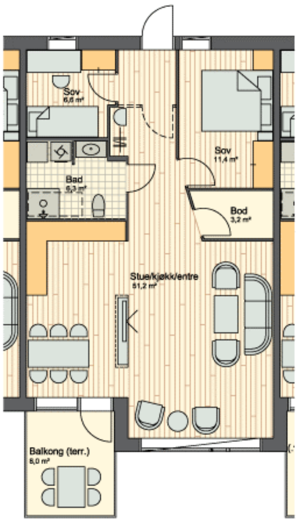


Figure 7.2: Apartment overview

Bills of material quantities used for the construction were provided by ByBo, in addition to technical drawings and electricity consumption data for 2009 and 2010.

7.1.1 Passive (P) houses

Houses 3 and 4 are built to passive house standard, and are almost identically constructed (only laterally inversed), as illustrated in figures 1.1 and 1.2. The houses have 2-3 floors and contain oriels clad in colored aluminium plates. Each house has a utility floor space of 1145 m2.

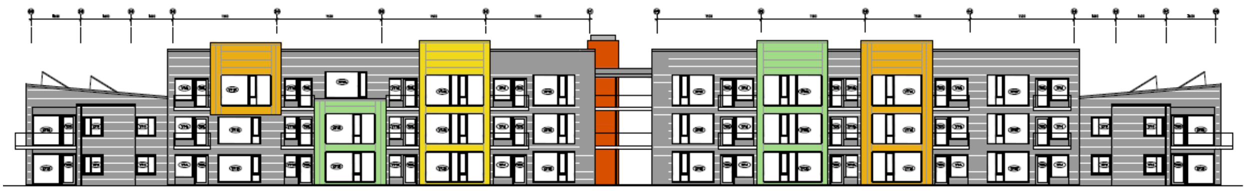


Figure 7.3: Façades, house 3 (left side) and house 4 (right side). Red column is the elevator house.

Wall insulation is 350 mm mineral wool, and 400 mm at the end walls. Roof insulation is 500 mm mineral wool. Evacuated tube solar thermal collectors are located on the roof, and provide floor heating and hot water heating for each apartment. All Løvåshagen houses have a balanced ventilation system with recovery units.

7.1.2 Low energy (LE) houses

Figure 7.4: Façade, house 1

Houses 1 and 2 are regarded as low energy houses, and the utility floor space areas are 2777 m^2 and 1408 m^2, correspondingly. The houses have 3-5 floors. Wall insulation thickness is 250 mm, and 300 mm at the end walls. Roof insulation thickness is 400 mm. Heating for each apartment is provided by an electric water heater, an electric radiator and heating cables in the bathroom floor.

Figure 7.5: Façade, house 2

7.1.3 Garages and garden facilities (G&G)

Garages are placed on two levels below the LE houses, but provide parking and storage space for everyone living at Løvåshagen. Because of this, they are not considered as part of any particular house, but as a separate element. BRA for garages total 2732 m^2 and they are assumed to be unheated, modelled as having no electricity consumption. Outdoor facilities at Løvåshagen include an automated vacuum waste collection system, playgrounds for children and other leisure areas, as well as garden stairs and walls. The vacuum waste collection system itself is not included in this study, only the structure containing this system. Likewise, playground installations are not included.

7.1.4 Electricity consumption

Figure 7.6 below displays the annual electricity consumption per square meter for each apartment, according to their placement in the buildings at Løvåshagen. The figure is a vertical cross-section where each apartment number is written in bold letters with the corresponding electricity consumption value underneath.

House 1

	151	**152**	**153**	**154**			
	123	91	122	96			
141	**142**	**143**	**144**	**145**	**146**	**147**	
180	119	125	179	117	50	130	
131	**132**	**133**	**134**	**135**	**136**	**137**	**138**
145	73	84	187	71	77	139	138
121	**122**	**123**	**124**	**125**	**126**	**127**	**128**
80	136	166	115	118	114	179	154
111	**112**	**113**	**114**	**115**	**116**	**117**	**118**
173	89	208	302	156	140	152	171

House 2

		251	**252**
		99	74
	241	**242**	**243**
	110	115	116
231	**232**	**233**	**234**
116	107	111	116
221	**222**	**223**	**224**
145	161	52	104
211	**212**	**213**	**214**
235	215	124	110

House 3

	331	**332**	**333**	**334**
	66	107	159	117
321	**322**	**323**	**324**	**325**
114	169	79	103	124
311	**312**	**313**	**314**	**315**
162	132	122	166	163

House 4

431	**432**	**433**	**434**	
102	54	116	162	
421	**422**	**423**	**424**	**425**
165	79	92	96	113
411	**412**	**413**	**414**	**415**
87	126	150	143	110

Figure 7.6: Vertical view; 2010 Electricity consumption for each flat (KWh/m2)

According to SINTEF Byggforsk, the expected delivered energy needs for low energy and passive buildings are 60 and 100 KWH/m^2 correspondingly (SINTEF Byggforsk, 2006). In Figure 7.6, values marked in yellow meet the expected efficiency for low energy buildings, while values marked in green meet the expected efficiency for passive buildings. The ten highest values are marked with a red background, while the highest value for each passive house is marked with red text. A more easily readable overview of the consumption values is presented in Figure 7.7 below.

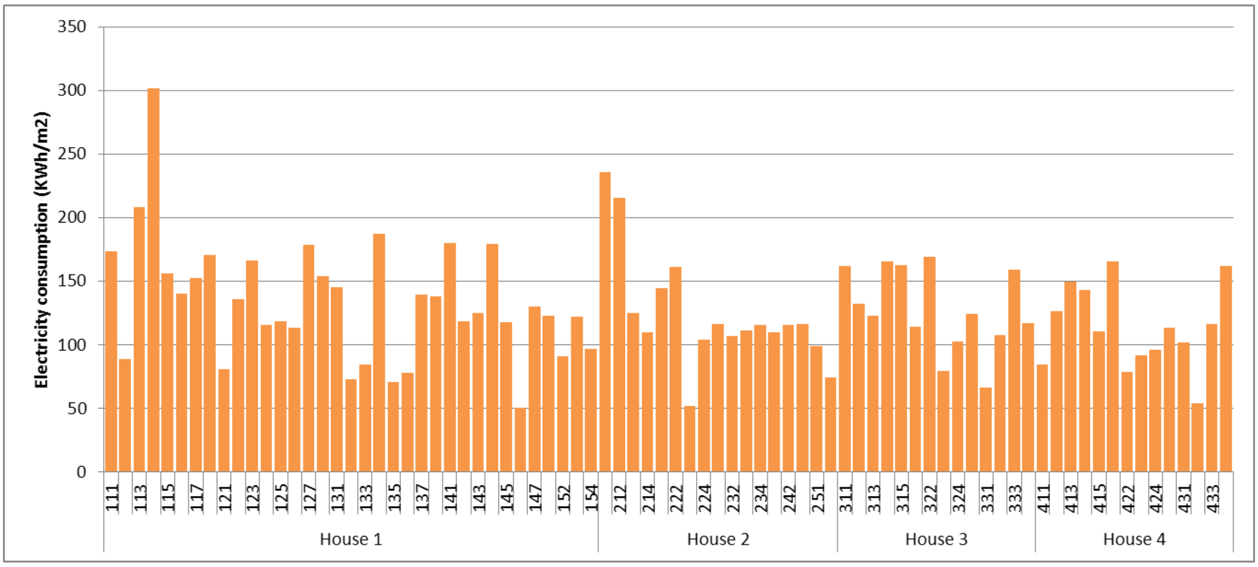


Figure 7.7: 2010 Electricity consumption per apartment

7.2 Functional unit

The following functional unit is used for the present study:

> *50 years of 1 m2 utility floor space (BRA) of a residential apartment in a block of flats, including the whole building life cycle: construction, maintenance, operational energy and water use, and end of life treatment.*

The functional unit is equal for all four houses. Although the G&G utility floor space is not residential apartment floor space, it is analysed along the same lines as the apartment houses, in order to give an understanding of the life cycle impacts from Løvåshagen as a whole. The presentation of results on a per square meter utility floor space basis enables comparison to other studies.

7.3 System boundaries

Figure 7.8 below shows the system boundaries for the present study. There are three main life cycle phases, including construction, house in use, and end of life management. The construction phase includes construction energy as well as waste generated from the over-ordering of materials, based on errors or bulk ordering of materials to the construction site. The use phase includes maintenance of building elements and operational water and electricity consumption, and the maintenance processes generate building material waste. Household waste generation is not included in the modelled system. The end of life management includes demolition of the buildings and generates building waste, which is transported to a sorting plant or an incineration plant. Residues from the incineration are transported to an inert material sanitary landfill. Materials produced from recycling, as well as recovered incineration energy, are not included in the system. Dotted lines represent flows that are not included. Diesel use for building machines used in the construction and demolition processes is included, as well as all electricity use on the construction site, mainly used for lighting and heating. Transport of workers and equipment to site is not included. The system boundaries include all the processes listed in Chapter 5 as typically included in a whole process of construction. According to [16], transport of equipment to site, the construction phase at the building site and construction waste are typically not included. Hence, the inclusion of construction work and electricity on site, as well as waste during construction distinguishes the present study from the general trend. The system elements are described further in Chapter 0: Life Cycle Inventory Analysis.

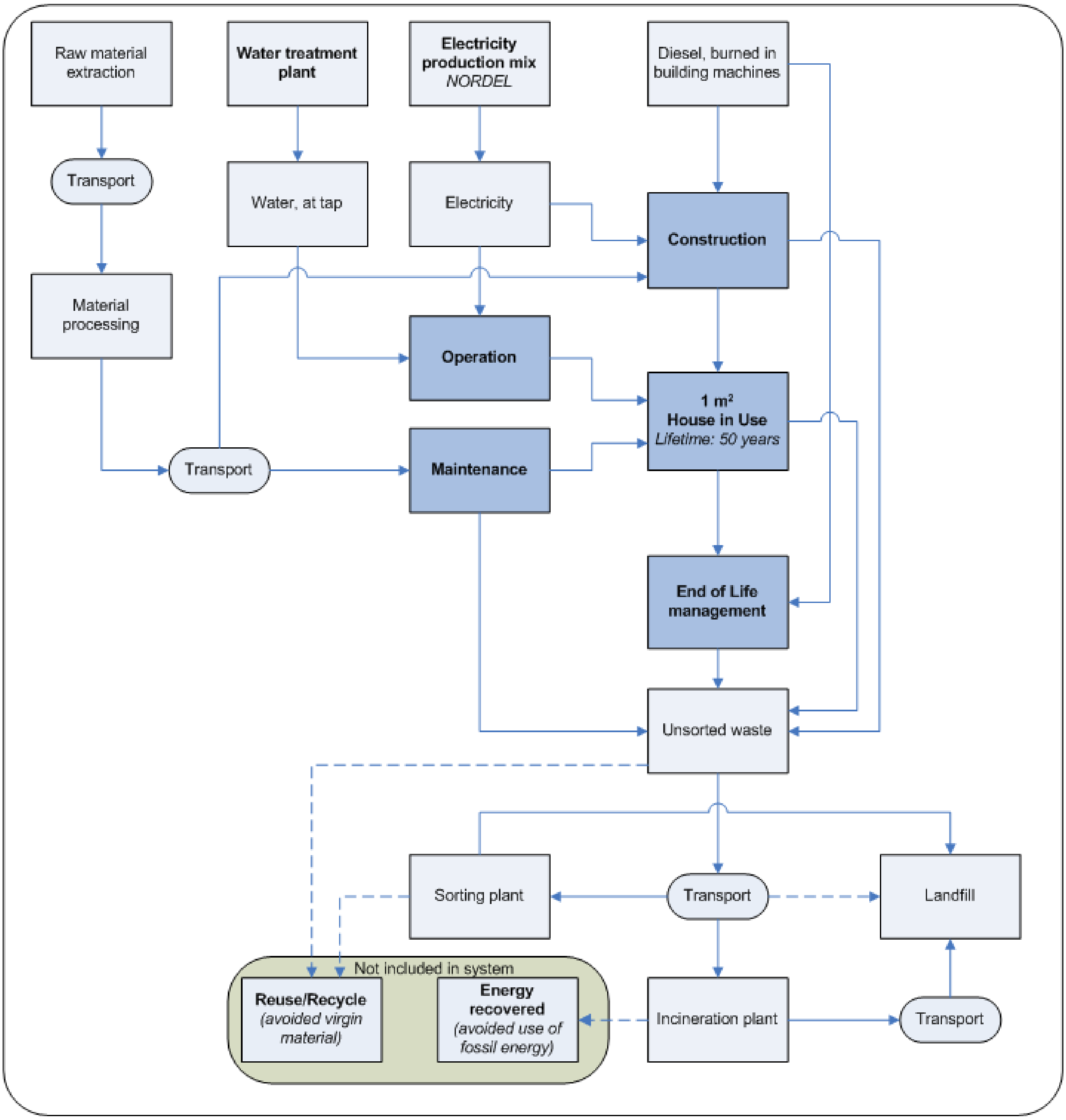


Figure 7.8: System boundaries

7.4 Chapter summary

The object of study is a housing cooperative in Bergen, categorized into five units: two passive house units, two low energy house units, and one unit comprising garage and garden facilities. The functional unit is 50 years of 1 m^2 BRA of a building block apartment, including the whole life cycle from cradle to grave.

8 Life Cycle Inventory Analysis

8.1 Phase 1: Construction

This section includes a description and categorization of the inventory for the construction phase of the system, from the day work was started on the building lot until the completion of the buildings. This comprises all building materials and component combinations used in the buildings, including excess materials being transported from site as waste, as well as energy used on site, and transportation of all materials to site and excess materials to a waste treatment plant.

Bills of material quantities (BOQ) for the buildings were provided by ByBo, and cover the majority of elements in the buildings. Some elements are not covered in BOQ, including materials for ventilation shafts and heat exchangers, electrical installations, solar thermal collector installations, plumbing, furnishing, and elevator machinery. For these elements, qualified assumptions have been made in order to achieve as complete an inventory as possible. It is assumed that the values given in BOQ amounts to the exact material quantities used in the buildings, not including potential over-ordering due to errors, bulk deliveries, etc. Cross-check calculations of material quantities based on technical drawings support the assumption that BOQ values are exact values.

8.1.1 Material transport and production

8.1.1.1 Transport of materials to site

All transport of materials to site is assumed to be done by a 20-28t lorry, fleet average. Materials were aggregated into two main categories, one for materials that were known to be produced in Norway, the other for materials that were not known to be produced in Norway. For the first category, transport distance was estimated using Oslo as point of origin, while Germany was used as point of origin for the second category. Some exceptions were made to this categorization, for materials that are used in particularly large quantities, materials that are known to be produced outside Europe, and a few others. For the exceptions, more accurate transport distances were used. Notable exceptions and their production locations are described in the table below. Distance estimations were made using Google Maps except for the case of sea transport from China, where the distance used by Moberg et al. (2007) was adopted.

Material	Production location
Aluminium sheets	Vik, Sogn
Concrete	Laksevåg, Bergen
Reinforcement steel	Mo i Rana,
Solar collection system	China
Windows	Moi, Rogaland

Table 8-1: Product location specifications

Construction materials and energy consumption have been aggregated and distributed on the following building element categories: Construction Energy & Transport, Floors, Foundation, Roof, Solar Collection System, Surface Finishes, Unheated Areas, Walls, Windows & Doors, and Electricity, Plumbing & Ventilation. In the following description of the elements, some values are represented with the notation A/B, where A is the value relevant for LE houses and B is the value relevant for P houses. The same categories apply to Garage & Garden as for the four houses, but they are described separately at the end, because their subcategories differ from the subcategories of the houses themselves.

8.1.1.2 Electricity used for material production

Where EcoInvent material processes have been used, the electricity used in the production process has been set according to its assumed production location, using either the Nordic (NORDEL), European (UCTE), or, for the solar collection system, the Chinese electricity mix. As for most of the EcoInvent material processes, medium voltage electricity is assumed to be used.

8.1.1.3 Note on concrete and concrete casting

Although different types of concrete were used at Løvåshagen, all concrete types are modeled using the EcoInvent process "Concrete, normal, at plant/CH U" with a density of 2380 kg/m^3. The subcontractor Strand AS did the concrete casting at Løvåshagen, using reusable casting frames of type Manto, delivered by Hans Mark AS. The casting frames consist of steel frames and plywood boards, and were stated to be reused approximately 350 times. Although the plywood boards are likely to need replacement much more frequently, they have only a very low environmental impact, and for simplicity they are assumed to have the same replacement rate as the steel. The reusability is accounted for by modeling impacts from casting frames as $\frac{1}{350}$ of their life cycle impacts. The casting frames are modules with fixed sizes, but for simplicity, impacts have been calculated assuming an exact fit of casting frames to concrete casting dimensions. For unconventional concrete structures, customized wood casting frames were used, and these are assumed to be discarded after a single use. Concrete casting is assumed to be produced in Germany.

8.1.2 Building element categories

8.1.2.1 Construction Energy & Transport

Information on energy use at the construction site was researched by contacting subcontractors involved in the project. The category includes subcategories fuel use, electricity use and excavated soil transport. Energy and transport in this category has been allocated among the five sections of Løvåshagen (four houses as well as the G&G), based on BRA.

8.1.2.1.1 Fuel consumption

The subcontractor Fyllingen Maskin was responsible for the groundwork at Løvåshagen, and provided information about total fuel use for this process. Based on statements from Fyllingen Maskin, the groundwork is assumed to have been the most fuel-intensive construction process by a good margin. Considering that construction energy is only a small portion of the life cycle energy use of Løvåshagen, other construction-related fuel consumption, including fuel for transport of workers to the construction site, has been excluded.

8.1.2.1.2 Electricity consumption

Information on electricity expenses at the Løvåshagen construction site, including expenses for use of machines, heating and lighting, was provided by the carpenter company, Byggmesteren. The average electricity price for 2007 and 2008 were then estimated, based on statistics from Statistics Norway, and used to calculate the energy consumption. According to Byggmesteren, the bulk of electricity expenses originated from heating and lighting, implying that energy use during the winter months were significantly higher than during the summer months. To account for this, electricity prices from the second quarter of the year were not included in calculating the average price.

8.1.2.1.3 Excavated soil transport

This category includes the transport of excavated soil from the construction site to a deposit, assuming a transport distance of 85 km, the same distance as to the waste treatment plant.

8.1.2.2 Floors

This category includes the subcategories ground level floor, level separator floors, bathroom floors level 2-5, and steel plates. The ground level is considered to be level 1. Surface finishes are not included in this category, as they are described in the category Surface Finishes.

8.1.2.2.1 Ground level floor

The ground floor consists of a 300/350 mm layer of EPS, covered by a vapor barrier and a 70 mm thick layer of reinforced concrete. The reinforcement is a steel net of type K189, and the concrete is of type B25. Information on materials for fastening and sealing vapor barrier joints were not available, and as their environmental impacts are extremely low compared to the overall impacts in this study, they have not been included in the analysis. The vapor barrier was assumed to consist of three-layered Umodan ESP. Information on the compressive strength of the EPS was not available, and the type S150 was assumed for all EPS used at Løvåshagen, unless described otherwise.

8.1.2.2.2 Level separator floors

Except for the bathroom areas (described below), the level separators at Løvåshagen consist of 250 mm reinforced concrete, covered by 6 mm Silencio insulation. Kitchen ceilings are covered by a layer of 13 mm plaster boards. There is a passageway through House 1 at ground level, and the floor above this passageway is insulated with 300 mm of mineral wool. It is assumed that all mineral wool in Løvåshagen is of type λ37.

8.1.2.2.3 Bathroom floors level 2-5

Bathroom floors for level 2-5 are described specifically, as the construction for bathrooms on these levels differs from the overall construction of the floors. The level separators for bathroom floors at level 2-5 are only 200 mm thick, but are covered by 20 mm EPS insulation and a 50 mm integral cast of reinforced concrete. The integral cast is of concrete B25 reinforced with a steel net K131. Ceilings in bathrooms include two layers of 13 mm plaster boards and 100 mm mineral wool for sound proofing.

8.1.2.2.4 Steel plates

This category includes steel plates casted into the concrete of the level separators.

8.1.2.3 Foundation

This category includes the subcategories footing, spot foundation, foundation wall and steel plates. In addition, the category ground level entrance balcony describes a concrete floor at ground level for LE houses, which is included in some simulation scenarios.

8.1.2.3.1 Footing

The footing is located underground, below the indoor walls that separate the apartments from each other, and consists of B30 concrete reinforced with ø12 and ø16 reinforcement steel. Where the separation walls are built on top of the garage, there is no footing. Because this exception is relevant for parts of the LE houses but not the P houses at Løvåshagen, a second scenario has been modeled, where the LE houses are given the same base construction as the P houses have. Using this, a comparison between the houses will be more valid.

8.1.2.3.2 Spot foundation

Spot foundation elements are concrete blocks that are typically located at corners and intersections of the foundation wall. The concrete is B30 and reinforced with ø16 and ø20 steel bars.

8.1.2.3.3 Foundation wall

BOQ discerns between foundation walls on the ground and foundation walls on the garage roof. Because it is apparent that the latter have been affected by their placement on top of the garage, the alternative scenario uses the same structure of foundation walls for the LE houses as for the P houses. For this scenario, the dimensions of the foundation walls have been used to calculate the amounts of concrete used.

8.1.2.3.4 Steel plates

This category includes steel plates used to reinforce foundation elements.

8.1.2.3.5 Ground level entrance balcony

Because this balcony only exists for LE houses, casted on top of the garage roof, the balcony is not included for the alternative foundation scenario. The entrance balcony consists of a 270-300 mm sloping layer of EPS, separating the garage roof from a 70 mm concrete floor, providing entrance to the LE houses. The concrete is of type B35, reinforced with a K189 steel net.

8.1.2.4 Roof

Roof includes the subcategories top level roof, roof gutter, and roof guard. There is also a roof hatch for each house, but these hatches have been ignored in the simulation, as their impact may be assumed to be negligible in this context.

8.1.2.4.1 Top level roof

This category includes all elements from the indoor ceiling of the top floor to the thatch on the external roof. This includes a layer of plaster boards, vapor barrier, 400/500 mm I-beams with mineral wool in between, wind barrier, roof thatch, wooden framework and wooden sheathing.

8.1.2.4.2 Roof gutter

The roof gutter is made of aluminium, with no surface finish. According to the webpages of gutter producers, no surface finish is necessary (Grøvik Verk, 2007). The BOQs provided values for the required length of the gutter. Technical drawings found at the gutter producer Grøvik's webpages were used to calculate the weight of aluminium required. The method for processing the aluminium is assumed to be sheet rolling.

8.1.2.4.3 Roof guard

BOQ roof guard values were provided in terms of required length. The type of roof guard was not specified, but the system was assumed to consist of Lobas SN G-22 rails connected by SN E-119 consoles with a center-to-center (c/c) distance of 800 mm. The material is assumed to be galvanized steel.

8.1.2.5 Solar collection system

This category includes the solar thermal collectors used for the passive houses and the heat distribution system associated with them.

Passive house apartments each have two panels of evacuated tube collectors of 3 m^2, in total 6 m2 per apartment, mounted on the roof. The solar thermal collection system has been adapted from Sørnes (2011), which used a system that was again adapted from EcoInvent. The modelled system includes 6 m2 of evacuated tube collectors, an expansion vessel, pumps, and heat carrier liquid (water and propylene glycol). Additionally, hydronic distribution pipes made of copper, insulated with elastomere, are included. Sørnes (2011) used 16 kg copper per hydronic heat distribution system, and the same has been assumed here – with one system per apartment. Lifetime for Evacuated Tube Collectors and distribution pipes are assumed to be 25 years, while it is assumed to be 10 years for pumps and heat carrier liquid. The EcoInvent process upon which the solar collection system process is based use 3.12 pumps, 57.0 kg water and 41.4 kg propylene glycol for a lifetime of 10 years, but do not differentiate between construction and maintenance for this lifetime. Because of this, the present model has assumed that the solar collection system requires the given values for the construction phase, and then again for maintenance every 10th year.

The solar collectors used at Løvåshagen were produced by the company Apricus (Rindal and Salvesen, 2008), whose production plant is in China. Hence, a transport distance from China was used. Moberg et al. (2007) used a sea transport distance of 15 000 km from China to Europe, and this was used also in the present study.

8.1.2.6 Surface Finishes

Surface finishes are grouped into the categories bathroom surfaces, fittings, oriel façades, painted surfaces, and parquet.

8.1.2.6.1 Bathroom surfaces

This subcategory includes materials used for surfaces of the bathroom floor and walls, namely tiles, tile glue, tile sealant, and waterproofing membrane. The waterproofing membrane is assumed to consist of Litex wet room boards (Litex AS, 2012).

8.1.2.6.2 Fittings (heated)

0,9 mm rolled aluminium fittings cover several areas where surfaces are adjoined, for instance where a balcony floor meets the external wall of the house. Such fittings also cover the bordering edge of the roof, and the frames and edges of doors and windows. BOQs specify the material to be aluminium in some instances, while others are left unspecified. Here, all instances are assumed to be rolled aluminium.

8.1.2.6.3 Oriel façades

The oriel façades are covered by coloured sheets of rolled aluminium, and the subcategory includes these sheets as well as the aluminium laths they are mounted on. Information on the aluminium sheets was provided by the manufacturer, Vik Industrier.

8.1.2.6.4 Painted surfaces (heated)

Many indoor- and outdoor surfaces have been painted or stained, and this category includes all the material used for painting or staining external and internal surfaces of heated areas. In the simulation, stain has also been modelled as paint, and all paint has been modelled as white. This is to limit the work load, as the only existing available EcoInvent process is white paint. Wærp et al. (2008) assumes that paint for outdoor walls is renewed every 8^{th} year in the use phase, and this renewal rate is assumed for all paint on painted surfaces.

8.1.2.6.5 Parquet

BOQs specify that the parquet is multi-layered, and covers all indoor dry-room floors except storage rooms. The parquet has been assumed to be three-layered, with each layer covered by two top coats of acrylic varnish, and a total parquet thickness of 14 mm. A lifetime of 20 years is assumed, based on Nebel et al. (2004) and Dahlstrøm (2011).

8.1.2.7 Unheated areas

Unheated areas include subcategories entrance balconies, terraces & balconies, elevator, painted surfaces, railings, stairs, and fittings (unheated).

8.1.2.7.1 Entrance balconies

This term covers the platforms that are used to enter the apartments, including floor tiles, tile glue and sealant, the roof of the top balcony, reinforced concrete columns supporting the entrance balconies, galvanized steel plates and bars for fastening the supporting columns to the entrance balconies, and galvanized steel bars for fastening the balconies to the rest of the house. The concrete is B35 and the steel bars are ø10, ø12 and ø20. Various steel plates are used, with thicknesses 5, 10 and 20 mm.

8.1.2.7.2 Terraces & balconies

This subcategory includes wooden supports and floor for the terraces and balconies, as well as ø10 and ø12 reinforced B45 concrete used for the balconies. Further, some places of the terrace floor are supported by reinforced blocks of concrete. There has been a lack of specifications for these blocks, but they have been assumed to be ø12 and ø16 reinforcement bars with B30 concrete. The placement of the blocks depends on the terrain on the ground below. In order to make the houses more comparable, the concrete blocks have been added in the simulation also to terrace areas that do not have them in reality. The amount of blocks added was determined based on the density of blocks for the houses that have them in reality.

8.1.2.7.3 Elevator house & machinery

House 1 and 2 have one elevator each, while houses 3 and 4 share one – impacts for the latter have been distributed evenly between the two houses. The elevator subcategory contains all materials in the elevator house, as well as the elevator machinery itself. The elevator house consists of ø10 and ø12 reinforced B35 concrete walls, floor and roof, with openings for the elevator doors. The exterior of the walls is insulated with a timber framed 100 mm layer of mineral wool, covered by 0,9 mm rolled aluminium sheets mounted on aluminium laths. A layer of EPS insulation combined with a vapor barrier covers the roof. The elevator pit walls have a plastic membrane and a 50 mm layer of EPS on the exterior. Elevator walls, roof and pit floor are all 200 mm thick. All elevator elements are included for their respective houses, with one exception; houses 1 and 2 have underground elevator levels for the garages, which are included in the G&G section, not the sections for their respective houses.

The elevator machinery was assumed to be of the type Schindler 3300, made for residential houses of up to 20 floors (Schindler, 2005). The EPD of a 5-floor version of the elevator was used to model the elevator. Production in Germany and a lifetime of 20 years was assumed.

8.1.2.7.4 Painted surfaces (unheated)

Unheated painted surfaces include surfaces on the underside of entrance balconies, on the supporting columns for entrance balconies, on elevator house walls and ceilings, and on storage room ceilings (including storage rooms inside the apartments, although these rooms are actually heated; no attempt has been made to disaggregate values for this, as impacts are very low). The same assumptions have been made as for section 8.1.2.6.4 (painted surfaces (heated)).

8.1.2.7.5 Railings

Løvåshagen has aluminium railings with glass elements for staircases and entrance balconies. Railings were assumed to consist of extruded aluminium posts and handrails framing glass sheets. Specifications for railings were found in the product catalogue of Alu-Railing AS (2012), and were used to calculate the quantities of aluminium and glass needed for the railings.

8.1.2.7.6 Stairs

The foundation for the stairs and the stairs themselves are included in this category. The foundation consists of ø16 and ø20 reinforced B30 concrete, and the same specifications have been assumed for the stairs themselves.

8.1.2.8 Fittings (unheated)

1 mm rolled aluminium fittings line the entrance balconies and stairwells. Also, Vik aluminium sheets cover the ceiling of the top entrance balconies.

8.1.2.9 Walls

This category includes the subcategories inner walls and outer walls.

8.1.2.9.1 Inner walls

Inner walls within each apartment are various models of pre-made Gyproc walls, including Gyproc GS 70/70 (600), Gyproc GS 95/95 (600), and their wet room versions (labeled “BPB” instead of “GS”). The walls consist of 13 mm plaster boards mounted on supporting columns as well as top and bottom rails of rolled steel. The wet room walls use special Gyproc GRIE plaster boards. In terms of impacts, the wet room plaster boards do not differ significantly from the standard plaster boards, and hence all boards have been modeled as standard boards. Wet room walls are insulated with mineral wool. Specifications for inner walls were found at the Gyproc website (Gyproc, 2012).

Inner walls separating apartments consist of 220 mm ø12 reinforced B30 concrete, and these walls appear to be the supporting walls of the buildings. Layers of 50 mm EPS are installed between the foundation walls and the inner walls to avoid thermal bridges. The inner walls category also includes some woodwork for nailing strips in the bathrooms.

8.1.2.9.2 Outer walls

From inside to outside, the outer walls consist of a layer of 13 mm plaster boards (two layers for wet room walls), a vapor barrier, wall insulation with wooden framework, 9 mm Gyproc GU-X plaster boards, a wind-proof layer and a layer of plywood boards. The wall insulation for P houses is one layer of 150 mm (200 mm for end walls) mineral wool, with one layer of 100 mm mineral wool on each side, totaling 350 mm (400 mm for end walls). The wall insulation for LE houses is an inner layer of 200 mm mineral wool and an outer layer of 50 mm (100 mm for end walls) mineral wool, totaling 250 mm (300 for end walls).

8.1.2.10 Windows & Doors

Due to lack of material data and in order to save time, material data for doors and windows were largely adopted from Dahlstrøm (2010) and Dahlstrøm (2011). The category includes the subcategories windows and doors.

8.1.2.10.1 Windows

More than 30 different window models are used, all variations of NorDan NTech passiv with a U-value of 0.7 W/m2K. Dahlstrøm (2010) analysed a specialized window of reference dimensions 1230 x 1480 mm and U-value 0.8, providing detailed material data for the window model. The window dimensions of the average window at Løvåshagen passive houses are 1620 x 1590 mm, and these are used for a reference window in the current study. Using the surface areas, the material data for Dahlstrøm's reference window was adapted and used to estimate the material requirements for the Løvåshagen reference window. In the simulation, all windows at Løvåshagen use the values for this window. The windows have an external aluminium cladding. Windows have been assumed to be produced at and transported from the NorDan production plant in Moi, in the southwestern part of Norway.

8.1.2.10.2 Doors

Several different door models are used at Løvåshagen, but they have been aggregated into the subcategories outer doors and inner doors. Although balcony doors have a larger portion of glass than other outer doors, they have been modeled using the same material quantities. The material data for doors was adopted from Dahlstrøm (2011), and include materials for door leaf, door frame, lining, paint, and hardware. Further details may be found in Dahlstrøm (2011, p. xxiii). Door production has been assumed to be in the Eastern part of Norway.

8.1.2.11 Electricity, Plumbing & Ventilation

Available information on the electricity and plumbing for Løvåshagen was very limited. Because of this, and because material use for these categories is very low in the overall perspective, estimates have been made based on other studies.

8.1.2.11.1 Electricity

This category includes one fuse box for each apartment, double outlet sockets, and electric wires insulated with PVC. It also includes one 1 KW electric panel heater for each LE apartment, with product data adopted from Sørnes (2011), and an assumed lifetime of 25 years. The quantities of electrical wiring required were calculated based on the dimensions of each house, where an assumption was made of one circuit around each room as well as 10 cables stretching from roof to ground. Quantities of outlet sockets were adopted from the passive house used in Dahlstrøm (2011), and adjusted based on gross floor area. The LE houses have heating cables in the bathroom floors, but these were not included in the model, because no good product data on heating cables was found, and because impacts are assumed to be relatively low.

8.1.2.11.2 Plumbing

This category includes hot water heaters, PE pipes, and PP sewage pipes of diameters 40, 110 and 125 mm. In addition, the subcategory includes one hydronic steel radiator per apartment for P houses. According to technical drawings, one pipe of each size runs the length of each house at Løvåshagen. Sewage pipes were also assumed to run from bathrooms and kitchens to the storage room in each apartment, and from the storage rooms to ground. High pressure PE pipes are assumed to run from ground to storage rooms and from storage rooms to bathrooms and kitchens.

The hot water tanks are assumed to be of the type 200 mL OSO Ecoline Twin Coil RTV VE, which is specialized for heat pumps and solar collectors, and material data was collected from product data found at the OSO webpage (OSO, 2010) and from personal communication with the company. One heater was assumed per apartment, and for simplicity, the same hot water heater was assumed for LE houses as for P houses. According to the OSO web site, their hot water heaters have an average lifetime of 26 years (OSO, 2012).

8.1.2.11.3 Ventilation

The ventilation system consists of two main elements: ventilation ducts and heat recovery units. Ventilation ducts were assumed to be steel spiral-seam ducts with diameters of 125 mm, and lengths were measured on technical drawings for one apartment and extrapolated for all of Løvåshagen. Heat recovery units at Løvåshagen were of the type Flexit SL4 RE EC, but because environmental product information was lacking for this unit, values were estimated based on product data for a different unit: Systemair VR 400 DCV/B (Systemair AS, 2012). A lifetime of 25 years was assumed for heat recovery units and ventilation ducts.

8.1.3 Garage & Garden

The following paragraphs describe the construction element categories for processes that are not part of any particular house, grouped into the Garage & Garden (G&G) section. The categories Electricity, Plumbing & Ventilation and Construction Energy & Transport are not described *specifically, because the first category is considered as having no elements for G&G, while the second category is modeled exactly the same for G&G as for the houses.*

8.1.3.1 Floors

This category includes a 70 mm reinforced concrete floor and a vapour proof layer for the lowest level of the garage as well as 40 mm porous asphalt floors on both levels of the garage. The only existing asphalt process in EcoInvent version 2.2 is mastic asphalt. Hence, a search for EPDs on porous asphalt was made, but no results were found to be adequately comprehensive. Hence, the mastic asphalt of EcoInvent was used for simulations.

8.1.3.2 Foundation

This category includes concrete footing of type B30 reinforced with ø12 and ø16 steel bars, ø16 and ø20 reinforced B30 concrete spot foundations, and ø10 and ø12 reinforced B30 concrete foundation walls, all part of the garage.

8.1.3.3 Roof

The roof category includes 280 mm reinforced concrete level separators between level 0 and level 1 of the garage, a reinforced concrete roof above level 1, 50 mm EPS insulation on top of the roof as well as 20 mm in some level separator joints, and a glued vapour proof membrane between the roof and the EPS insulation. The reinforcement steel bars are ø10, ø12 and ø20 and the concrete is B35.

8.1.3.4 Surface Finishes

This category includes paint for external concrete surfaces that are not below ground as well as paint for wooden espaliers mounted on these surfaces.

8.1.3.5 Unheated Areas

This category name is somewhat misleading for G&G, as all G&G elements are considered to be unheated. The category includes a B35 concrete structure reinforced with ø16 steel bars, for installation of a vacuum garbage disposal system. The garbage disposal system itself is not included in this analysis. Unheated areas also include garden walls and stairs and elevator shafts for the garage levels, both containing ø16 reinforced B35 concrete.

8.1.3.6 Walls

Walls of the garage contain 200 mm B35 concrete reinforced with ø12 steel bars, with an external layer of 50 mm EPS insulation. Between the garage roof and the walls resting upon it, there is an 80 mm thick layer of XPS, which is also included in this category. Further, the category includes ø16 reinforced B35 concrete columns supporting the garage roof and level separators, as well as a light expanded clay aggregate (LECA) wall mounted on the outside of the garage walls, covered by a wooden espalier.

8.1.3.7 Windows & Doors

There are no windows in the garage, but there are two garage doors as well as wire doors and fences used for storage rooms in the garage area. All of this is included in the Windows & Doors category. There was a lack of specifications for these elements in the BOQ, and thus the garage doors were assumed to be of the type Prolid Overhead Sectional Door, while the wire fences and doors were assumed to be of ø1.8 steel wires with 50 x 50 mm meshes. The garage doors were modelled based on an EPD found on the Swedish Prido website (Prido, 2010).

8.1.4 Waste during construction (WDC)

According to Monahan and Powell (2010), error- and contingency-related over ordering for a UK construction site typically amounts to approximately 10% of all materials brought to a construction site, "with 10-15% of the materials imported to a construction site being exported as waste" (Monahan and Powell 2010, p. 2). In the present study, waste generated during construction has been assumed to amount to 10% of total materials brought to site, implying that the BOQ quantities amount to 90% of total materials brought to site. Elements and materials that may be expected to be delivered in exact quantities are not assumed to generate WDC, for instance windows and doors. All waste, including WDC is assumed to be transported to a waste treatment plant located 85 km from Løvåshagen. For more information on waste transport and treatment, see section 8.3. WDC is grouped in the same building element categories as the materials and components used in the Løvåshagen buildings.

8.1.5 Section Summary

The construction phase at Løvåshagen includes energy used on the construction site, cradle to site production of building components and of waste generated during construction, and transport and management of this waste. The construction phase is grouped into the element categories Construction Energy & Transport, Floors, Foundation, Roof, Solar Collection System, Surface Finishes, Unheated Areas, Walls, Windows & Doors, and Electricity, Plumbing & Ventilation, as well as corresponding WDC categories for the mentioned building component element categories.

8.2 Phase 2: House in use

This section presents the inventory for the house in use phase, starting with a description of electricity and water use during house operation, followed by a description of the maintenance of Løvåshagen.

8.2.1 Operation

The operation phase of Løvåshagen has been modeled to include electricity and water consumption for the house apartments and for the elevators. Although the G&G also will have some consumption, this has not been included in the scope of this study.

8.2.1.1 Electricity use

Final energy use data at Løvåshagen for 2009 and 2010 were provided by ByBo, for all apartments in the four houses. 2009 values are considered unreliable, because most apartments were still being moved into at this point, and some apartments might have been used as display apartments by the estate agents. Hence, the 2010 values are extrapolated for the whole lifetime of 50 years, and the monthly consumption is presented in Figure 6.2 below. It should be noted that 2010 was a very cold year in the western part of Norway, as indicated in Figure 8.1, indicating that the electricity consumption values are likely to be unnaturally high.

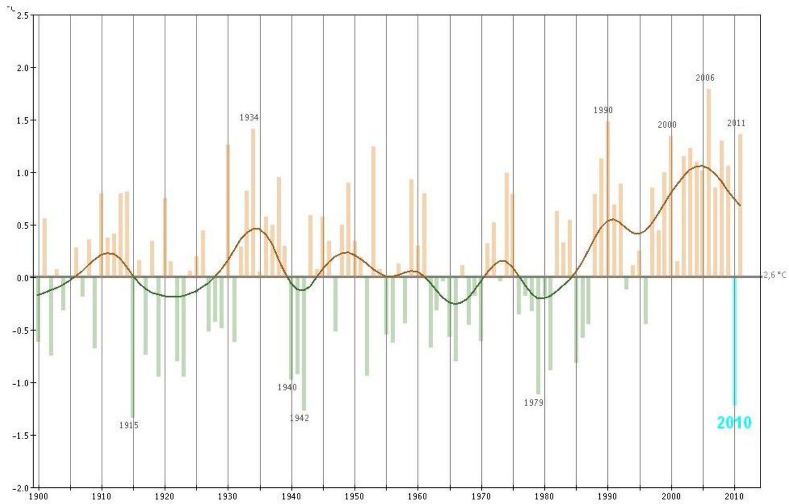
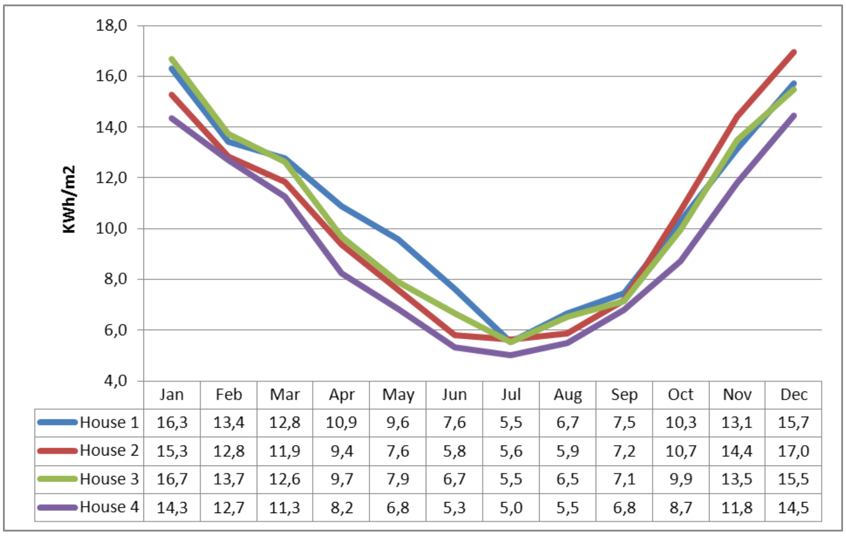


Figure 8.1: Deviations from normal temperature for the period 1900-2011

Degree-day adjustment of the electricity consumption was considered and discarded. This decision was based on the unsuccessful search for a reliable source providing the portion of temperature-dependent energy consumption in low energy and passive buildings – a factor that significantly influences the degree-day adjusted values (Enova SF, 1999). Figure 8.2 below displays the monthly 2010 electricity consumption for the four houses at Løvåshagen.

Electricity use for elevators is assumed as not included in the electricity use provided by ByBo. Hence, the consumption over the lifetime of the houses was estimated by extrapolating the annual electricity consumption, found in the environmental fact sheet provided by Schindler, over the lifetime of 50 years. Electricity use at Løvåshagen is modeled to be using the Nordic electricity mix, through the EcoInvent process “Electricity, low voltage, production NORDEL, at grid/NORDEL U”.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
House 1	16,3	13,4	12,8	10,9	9,6	7,6	5,5	6,7	7,5	10,3	13,1	15,7
House 2	15,3	12,8	11,9	9,4	7,6	5,8	5,6	5,9	7,2	10,7	14,4	17,0
House 3	16,7	13,7	12,6	9,7	7,9	6,7	5,5	6,5	7,1	9,9	13,5	15,5
House 4	14,3	12,7	11,3	8,2	6,8	5,3	5,0	5,5	6,8	8,7	11,8	14,5

Figure 8.2: Monthly electricity consumption per house, 2010

8.2.1.2 Water use

According to Statistics Norway, the average water consumption in Norway is 212 L per person per day. The water consumption for each house at Løvåshagen was calculated using this value combined with the number of persons living in each house. The number of beds in each apartment was used for estimating the number of persons in each house. The resulting total water consumption at Løvåshagen was found to be 20 million L per year.

8.2.2 Maintenance

The table below presents the maintenance assumed for Løvåshagen. Most are elements that need to be renewed throughout the lifetime of Løvåshagen. Additionally, elevators and the solar collection system need maintenance throughout their respective lifetimes. According to the producer Schindler, Elevators require input of some small quantities of steel, aluminium, lead and wiring board. This material input is included in the maintenance element Elevator machinery. As described in section 8.1.2.5, the solar collection system is modeled to require replacement of pumps and heat carrier liquid every 10th year. In the table below, this replacement is extrapolated for 25 years and incorporated in the Solar Collection System maintenance process.

Element	Lifetime [yr]	Life cycles [n]	Elements renewed
Bathroom surfaces	30	2	All elements of section 8.1.2.6.1: Bathroom Surfaces
Doors	30	2	All elements of section 8.1.2.10.2: Doors
Elevator machinery	25	2	Elevator machinery, in section 8.1.2.7.3: Elevator house & machinery
Roof	30	2	Woodwork, wind-proof layer and roof thatch, in section 8.1.2.4.1: Top level roof, as well as the sections Rain gutters and Roof guards
Paint	8	7	All elements of section 8.1.2.6.4: Painted Surfaces (heated)
Parquet	20	3	All elements of section 8.1.2.6.5: Parquet
Heating system	25	2	LE: Hot water tanks and electrical heaters, in sections 8.1.2.11.2: Plumbing and 8.1.2.11.1:

			Electricity P: Hot water tanks and hydronic radiators, in section 8.1.2.11.2: Plumbing
Ventilation system	25	2	All elements of section 8.1.2.11.3: Ventilation
Solar Collection System	25	2	All elements of section 8.1.2.5: Solar Collection System
Windows	30	2	All elements of section 8.1.2.10.1: Windows

Table 8-2: Maintenance descriptions for building elements at Løvåshagen

8.2.3 Section summary

Electricity use during operation is based on the 2010 values for Løvåshagen, while water use is estimated based on statistics from Statistics Norway. Maintenance is required for bathroom surfaces, doors, windows, elevator machinery, roof, paint, parquet, heating systems, ventilation systems, and solar collection systems.

8.3 Phase 3: End of Life management

This section describes the inventory for the end of life management at Løvåshagen. The end of life (EOL) phase is categorized using the same elements as the construction phase, where each EOL category includes EOL transport and waste treatment of the materials from its corresponding construction category. The construction energy & transport category is replaced by the EOL category "demolition energy".

8.3.1 Demolition Energy

Several companies in the Bergen area were asked for information on fuel requirements for the demolition of Løvåshagen, and the two companies Transport & Maskin AS and VestaFjell AS provided estimates. The highest of the fuel use estimates was an average of 4.0 L per demolished m^2, and this value was used for calculations. VestaFjell AS estimated that the demolition of Løvåshagen would take approximately 3½ months, using a 30 ton excavator. Other energy use for demolition is not included, because it is assumed to be dwarfed by excavator fuel use.

8.3.2 Waste transport and treatment

Two waste treatment solutions are assumed used for waste from Løvåshagen; incineration with energy recovery is assumed used when applicable, for instance for plastic- and wood-based materials, while other materials are modeled to be transported to a sorting plant. No material recycling is assumed.

Dahlstrøm (2011) points to a study by Avfall Norge (Raadal and Modahl, 2009) that determines an average transport distance from waste source to incineration plant of 85 km. This distance was in the present study assumed for all waste being transported from demolition site to waste treatment site.

8.3.3 Section summary

The end of life inventory is categorized identical to the construction inventory, except that the construction category Construction Energy & Transport is replaced by Demolition Energy. Values for this category were estimated based on information from Bergen-based companies.

9 Life Cycle Impact Assessment

9.1 Total Life Cycle Impacts

This section presents the total aggregated results for Løvåshagen as a whole, first using midpoint indicators and then using an endpoint indicator. Midpoint results are presented both in aggregated form and distributed on the five units of the housing cooperative.

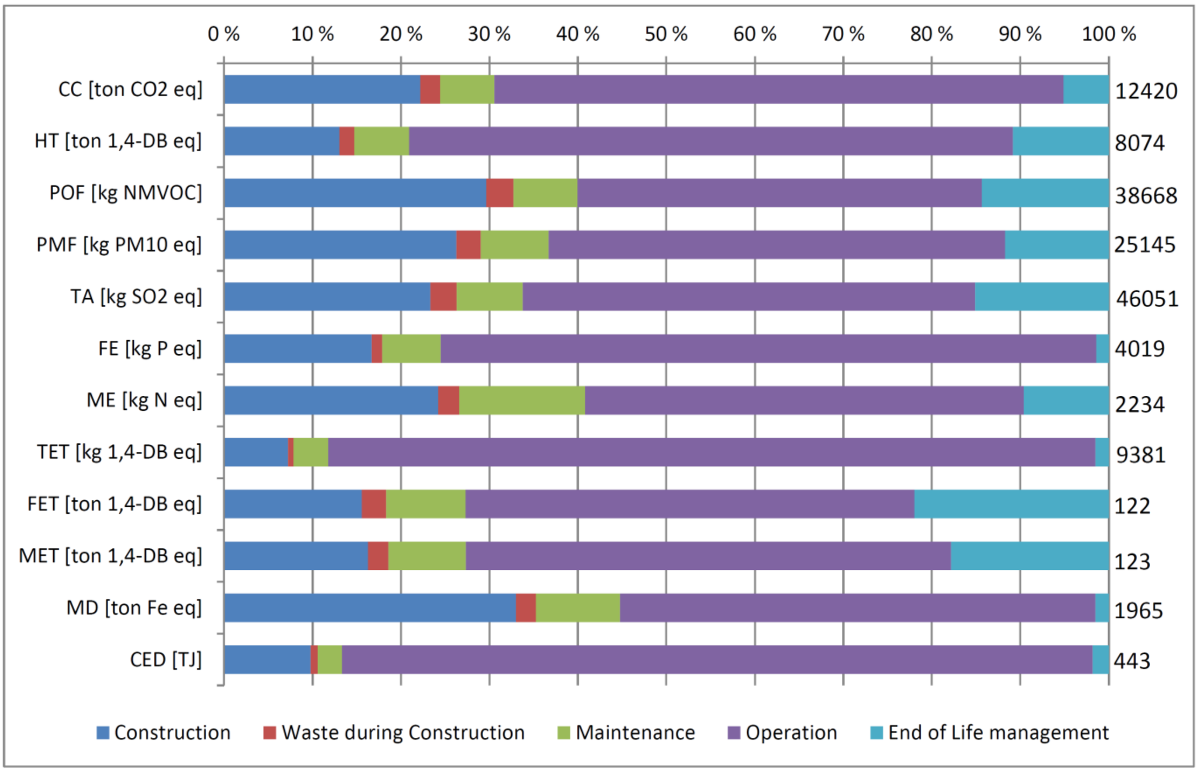


Figure 9.1: Total life cycle impacts for Løvåshagen

The aggregated life cycle impacts for a lifetime of 50 years for Løvåshagen Borettslag are displayed in the figure above, and include the four houses as well as garages and other constructions on the lot, such as garden walls and stairs. Impacts are distributed on the five sections Construction, Waste during Construction (WDC), Maintenance, Operation, and End of Life management (EOL), which are described further in Chapter 0. The Climate Change impact category totals 12420 ton CO2-equivalents, or 1.9 ton CO2-equivalents per m^2 BRA. Roughly 64% of these impacts originate from Operation, 22% from Construction, 6% from Maintenance, 5% from EOL, and 2% from WDC. Operation is the most impact-intensive section for all impact categories. Operation and Maintenance combined constitute the use phase of the houses, which accounts for an impact category average of 69% of impacts.

Figure 9.2 below displays the total characterized life cycle impacts per BRA disaggregated into the four houses and Garage & Garden, where the latter includes all constructions on the lot that are not part of one particular house. Although the garages are placed under houses 1 and 2, they are used by all, and are hence not considered to be part of any particular house. Results are normalized to the

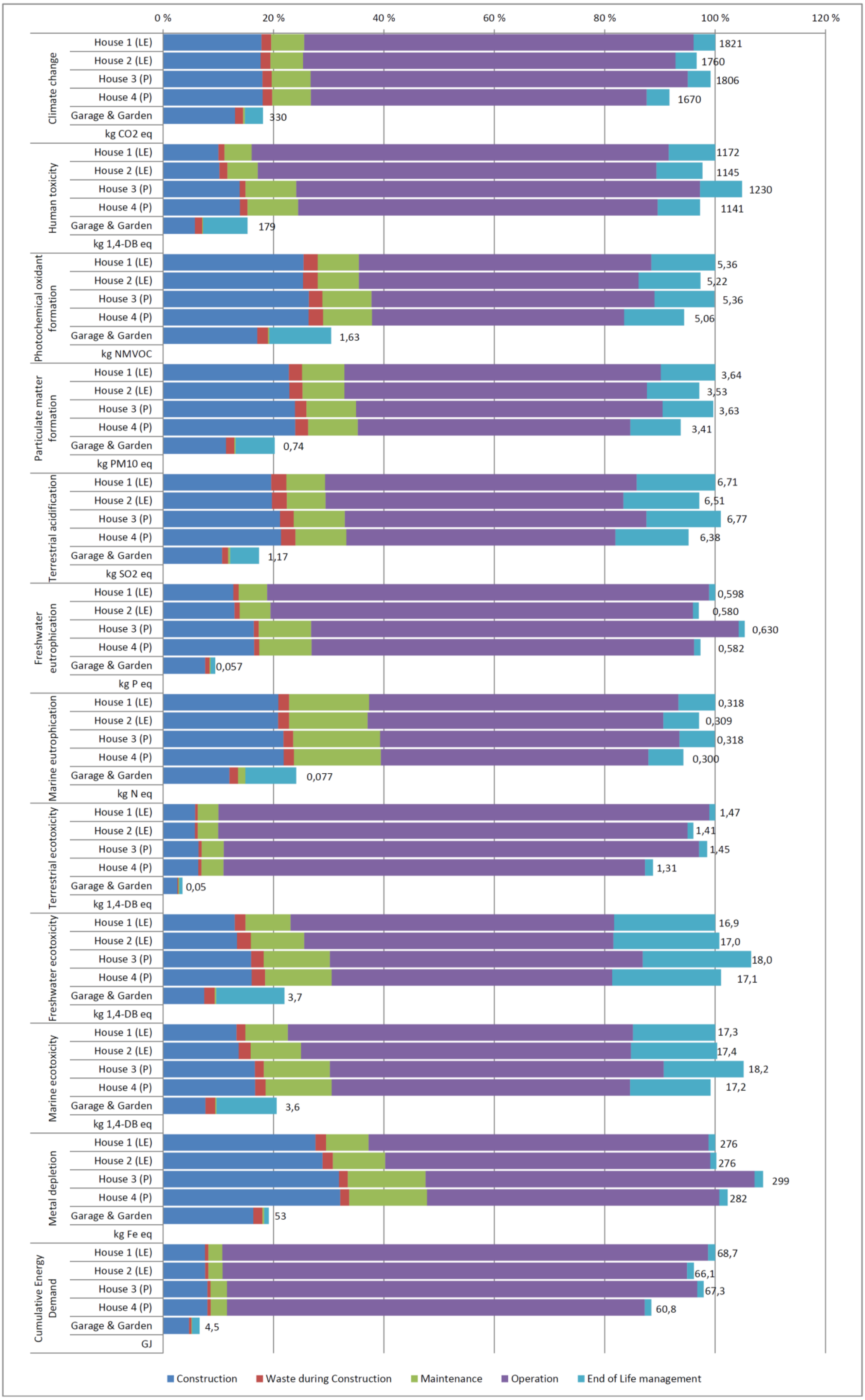


Figure 9.2: Characterized life cycle impacts per m^2 BRA at Løvåshagen, equal foundation scenario

impacts of house 1. As described in Chapter 0, an optional construction scenario was created in order to make the houses more comparable, where all houses were considered to have the same foundation solution as house 3. Figure 9.2 is for this scenario, which means that results differ slightly from the actual impacts originating from the Løvåshagen constructions. However, the difference is very small, and do not affect the Maintenance and Operation.

Houses 1, 2 and 3 contribute the most to Climate Change, all with 1.8 ton CO2-eq/m^2. House 4 contributes 1.7 ton CO2-eq/m^2, and Garage & Garden contributes 0.33 ton CO2-eq/m^2. In other words, the difference between P and LE houses is practically negligible. This is surprising, as one would expect the passive houses to have significantly lower impacts than the low energy houses.

The general trend for other impact categories reflects that of climate change, with houses 1 and 3 having the highest impacts per square meter, followed by houses 2 and 4. Notable exceptions to this are for the metal depletion as well as the marine and freshwater ecotoxicity categories. Here, house 3 has significantly higher impacts than the rest, which are nearly at the same level.

Differences between the P and LE houses for impact potentials of the construction phase are lower than might be expected. As pointed out in Chapter 5, the trend from previous studies is that the relative contribution of the construction phase increases with the energy-efficiency of buildings, but for climate change impacts at Løvåshagen, there is little indication of this. For impact categories such as human toxicity and freshwater eutrophication, the effect is more apparent.

9.1.1 Endpoint indicator

A single score indicator for each building is a more understandable way of presenting results, and hence a single score endpoint indicator is provided in the figure below. The indicator used is Europe ReCiPe H/A, hierarchist average, version 1.06, which “refers to the normalization values of Europe, with the average weighting set” (Dahlstrøm, 2011). Results are presented per square meter BRA and normalized to the result of House 1.

Results are displayed as two columns per building, where the left column shows the endpoint score distributed on the impact categories climate change human health, human toxicity, particulate matter formation, climate change ecosystems, agricultural land occupation, natural land transformation, fossil depletion, and others. The others category include ozone depletion, photochemical oxidant formation, ionising radiation, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, urban land occupation, and metal depletion. The right column shows the endpoint score distributed on the categories damage to human health, damage to ecosystems, and damage to resource availability.

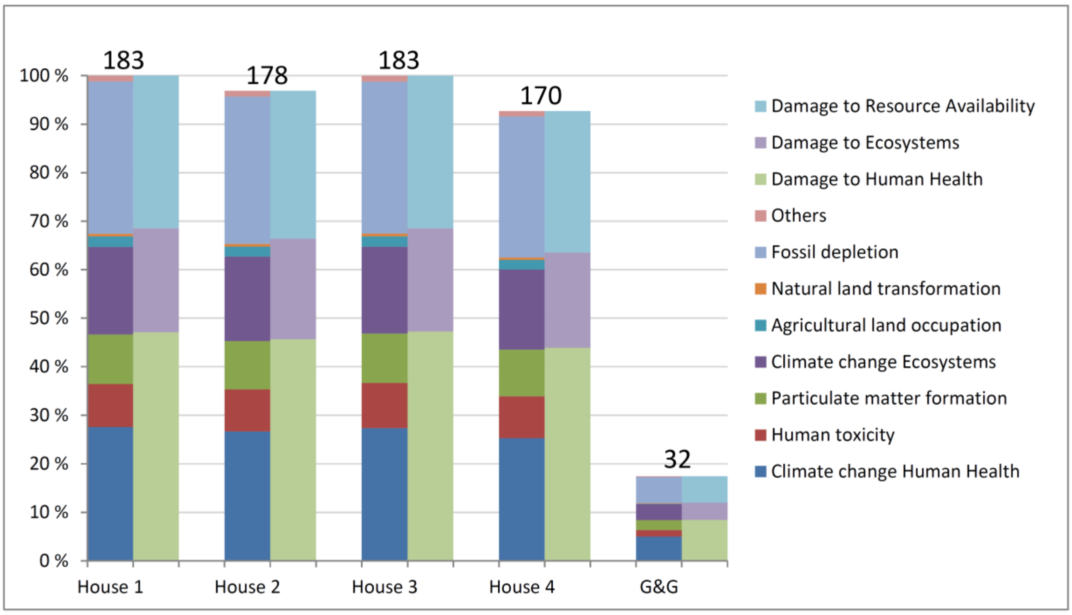


Figure 9.3: Endpoint indicator scores for each building unit at Løvåshagen, equal foundation scenario

The figure shows that House 1 and House 3 both have 183 points per square meter, followed by House 2 at 178 Pt/m^2, House 4 at 170 Pt/m^2, and G&G at 32 Pt/m^2. Thus, the life cycle performance of one P house and one LE house becomes exactly the same when using this endpoint indicator, while the P house average performs less than 3 % better than the LE house average. Among the impact categories in the left column, fossil depletion is the major contributor, with 31% of relative contributions in all cases, closely followed by climate change human health (27-29%) and then climate change ecosystems (18-19%). For the right column, damage to human health has the highest contribution (47-48%), followed by damage to resource availability (31%), and damage to ecosystems (20-21%).

9.1.2 Section summary

The operation phase of Løvåshagen is clearly the most impact-intensive, followed by the construction and end of life phases. There is practically no difference between the climate change performances of the house models, although one passive house performs slightly better than the other houses. For other categories, the differences are small, with the exception that House 3 performs slightly worse for some toxicity and eutrophication categories.

9.2 Results disaggregated

The characterized results are here presented in disaggregated form, starting with disaggregation of climate change impacts over time, and continuing with a closer inspection of each life cycle phase.

9.2.1 Disaggregated over time

As suggested by literature in the building LCA field (Itard and Klunder, 2007), the climate change results are in this section presented as a time function. The figure below shows the climate change impacts per square meter BRA from the elements of Løvåshagen, disaggregated over time, with annual impact contributions on the left vertical axis and accumulated impacts on the right axis. The bulk of impacts occur in year 0, with the construction of Løvåshagen, and in year 50, with the demolition of the housing cooperative. The LE house average impact values for these two years are

355 and 95 kg CO_2 eq/m^2 correspondingly, and the P averages are 359 and 99 kg CO_2 eq/m^2 correspondingly. Another significant contribution occurs in year 30, with the renewal of bathroom surfaces, doors, windows, and roof, as well as end of life management for the outdated components. Significant climate change impacts for G&G occur only in year 0 and year 50, due to low maintenance impacts and the assumption of no operational impacts.

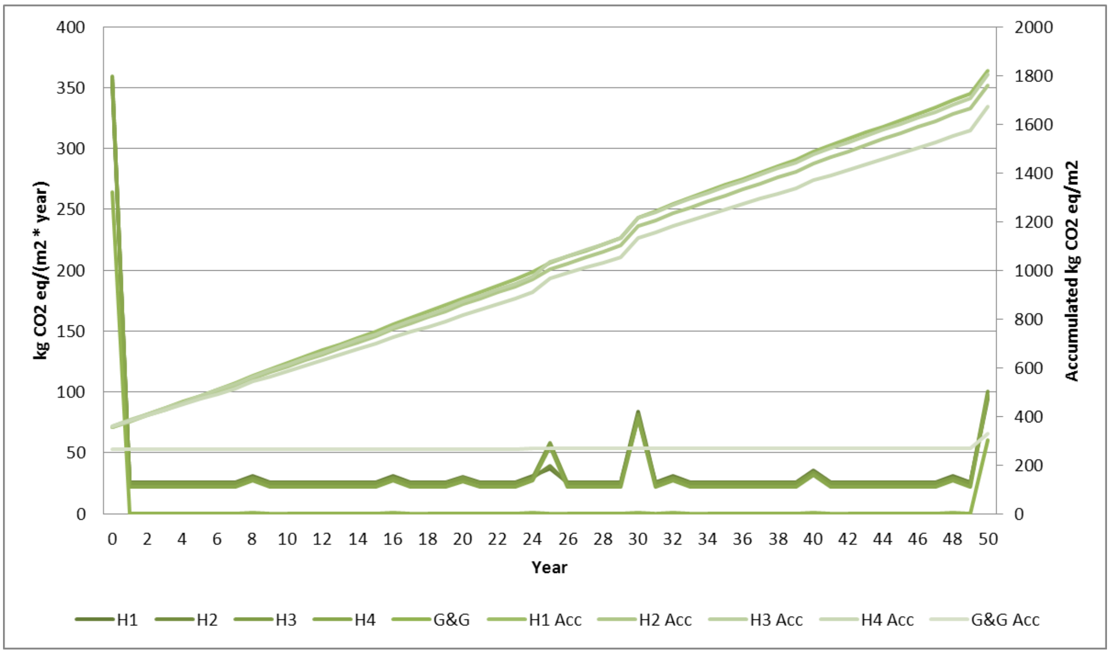


Figure 9.4: Annual and accumulated climate change impacts per building unit, equal foundation scenario

The accumulated impact plots of the houses follow each other closely, but have slightly different slopes, due to the differences in operational emissions. The leap in year 25 is slightly higher for the passive buildings, due to the replacement of the solar collection system. This difference is more apparent in the plot for the annual emissions, where the P peak is significantly higher than the LE peak.

As pointed out in the first part of this section, the climate change differences of construction are surprisingly small at Løvåshagen, and this is apparent also in the time function above. The difference between P and LE houses is noticeable for the annual impact potential plots, but not for the accumulated plots.

9.2.2 Disaggregated over life cycle phases

9.2.2.1 Construction and Waste during Construction

Figure 9.5 below shows impacts per m^2 BRA originating from energy and materials used for house construction. Results are distributed on the building element categories that were introduced in Chapter 0, and normalized to the impacts of House 1. For the climate change category, total impacts from House 1 are 324 kg CO2-eq/m^2, and impacts from other houses differ by up to a few per cent of this, while impacts from Garage & Garden is at 73% of the House 1 impacts. The most significant element category is Floors, with a house average relative contribution of 29% for the climate change category. For the G&G, Roof is the most important category by far (contributing 52%), but as it includes the floor separator between the two garage floors, the result supports the trend of Floors being the most impact-intensive category. Floors and G&G Roof include large quantities of reinforced concrete, which is known as one of the more impact-intensive construction materials, and may be assumed to be the main source of these elements' importance.

Overall, Walls is the element category with the highest relative contribution (17%). Almost equally important are Floors (16%) and Unheated Areas (15%), followed by Roof (14%), Construction Process (12%), Surface Finishes (8%), Windows/Doors (6%), Solar System (5%), Electricity & Plumbing (4%), and Foundation (2%).

For toxicity impact categories, the passive houses have significantly higher impacts than the low energy houses, and closer inspection reveals that the solar system makes the larger part of the difference (Appendix 13.1.1). A study of the solar collection systems indicates that the important component in this respect is copper, used for the evacuated tube collectors and the distribution pipes. Another house model difference is that Floors generally have a higher proportion of impacts for low energy houses than for passive houses, and this is likely to originate from the fact that the former are five level buildings, while the latter only have three levels. More levels mean a higher proportion of concrete per m^2, as the level separators have a significantly thicker concrete layer than the ground floor does.

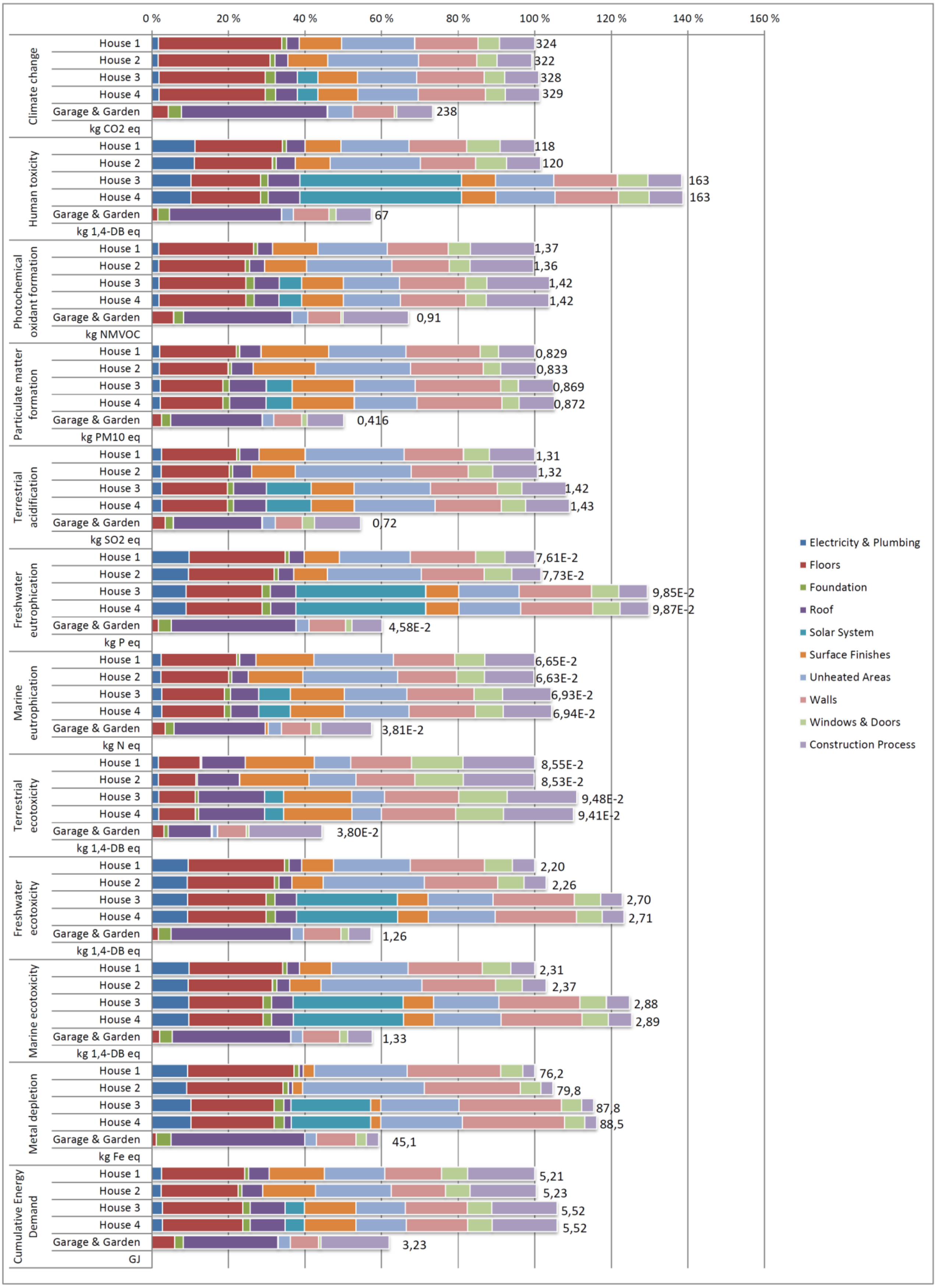


Figure 9.5: Characterized Construction impacts per m^2 BRA at Løvåshagen, equal foundation scenario

9.2.2.2 Maintenance

Figure 9.7: Characterized Maintenance impacts per m^2 BRA at Løvåshagen illustrates impacts per BRA from the maintenance phase for Løvåshagen, normalized to the impacts of House 1. Maintenance of the passive houses is significantly more impact-intensive than the low energy houses, for all impact categories. Both P houses have a 17% higher climate change potential than House 1, at 128 kg CO_2-eq/m^2, while the houses 1 and 2 are at 109 and 108 kg CO_2-eq/m^2 correspondingly. The greatest difference between the house models is for the human toxicity category, where both P houses have 46% higher impacts than House 1. The significant difference between the house models stem mainly from the maintenance of the solar collection systems, which is necessary for the P houses. It is clear that this maintenance process has particularly high toxicity, ecotoxicity and freshwater eutrophication potentials.

For the houses, maintenance of bathroom surfaces and renewal of painted surfaces contribute the most to climate change, with relative contributions of 21-28 % and 23-28 % correspondingly. Paint is also the major contributor to marine eutrophication, with 50-58 % of the impacts, while Bathroom Surfaces are the major contributor to photochemical oxidant formation (24-33%), particulate matter formation (34-45 %), and cumulative energy demand (21-27%). Maintenance of Elevator Machinery is among the most impact-intensive processes for human-, marine- and freshwater (eco) toxicity, as well as for metal depletion. For these categories, it is superseded only by maintenance for the Solar Collection System, where it is applicable. Maintenance of Doors, Roof, Parquet, Heating System, Ventilation System and Windows are of low to medium impact-intensity without dominating any categories. The only exception is Parquet, which dominates terrestrial ecotoxicity. Maintenance for G&G is close to negligible compared to maintenance for the houses. It includes two processes only, and emissions from Paint dominate all emission categories save metal depletion, which is dominated by Doors.

9.2.2.3 Operation

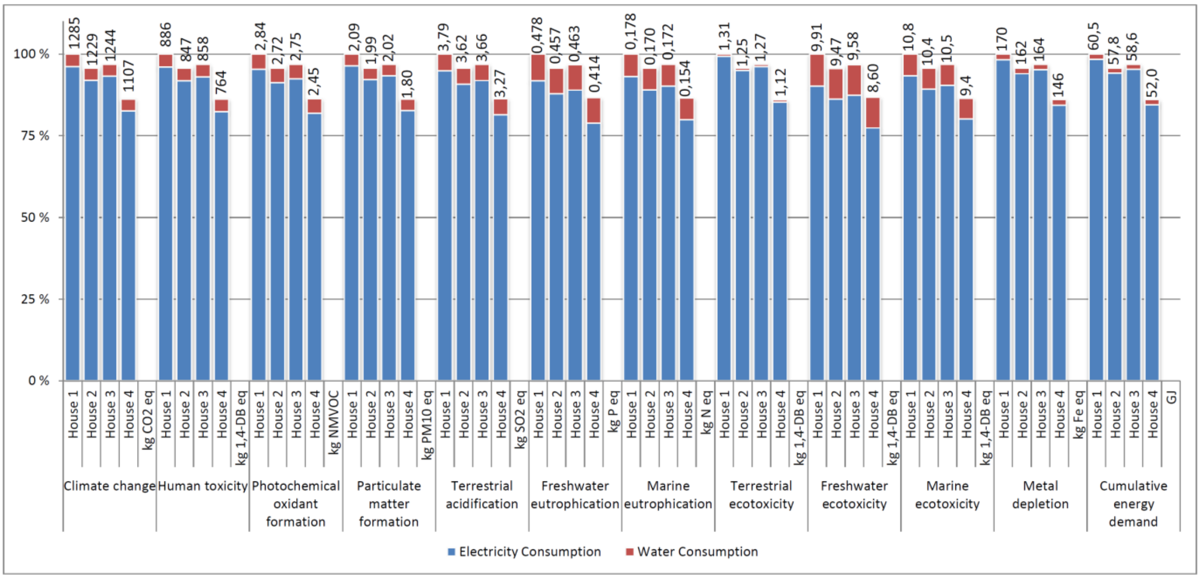


Figure 9.6: Characterized Operation impacts per m^2 BRA at Løvåshagen

The figure above displays impact potentials of the Operation section, normalized to the impacts of House 1. Not surprisingly, electricity consumption dominates all impact categories, with water consumption contributing averagely 5% of impacts. The small difference in total impacts that was seen for the total life cycle impacts in section 9.1 is also evident here. Average climate change impacts are 1.26 ton CO_2-eq/m^2 for LE houses and 1.18 ton CO_2-eq/m^2 for P

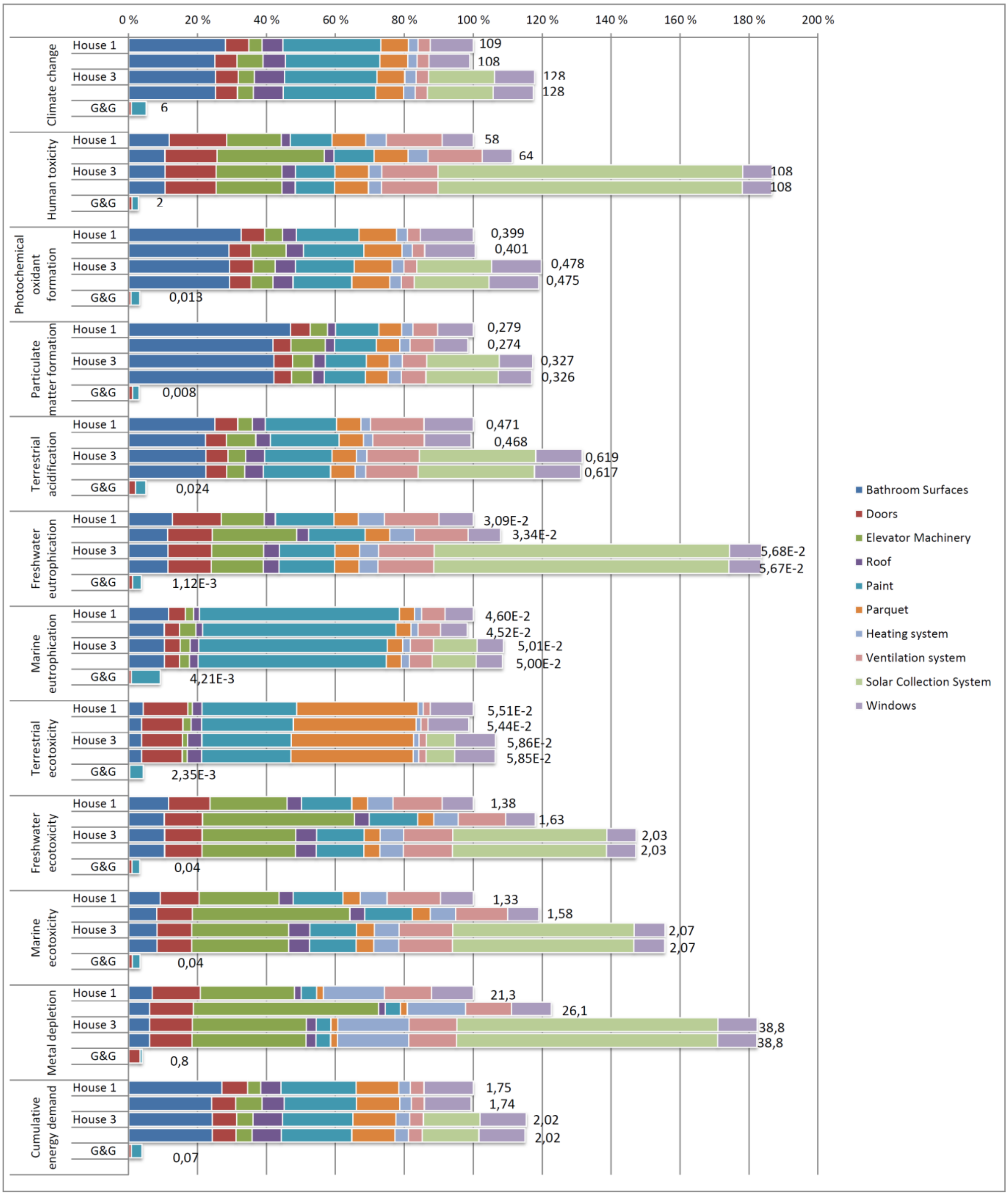


Figure 9.7: Characterized Maintenance impacts per m^2 BRA at Løvåshagen

houses, equalling P impacts at 94 % of LE impacts. House 4 stands out slightly, with a climate change impact potential that is nearly 15% lower than that of House 1. However, House 3 has a practically identical construction to that of House 4, and has only 4 % lower impacts than House 1. The difference between the performances of the P houses is basically a result of different user patterns, indicating the importance of this factor in reducing emissions. Results for other impact categories reflect the pattern observed for climate change.

9.2.2.4 End of Life Management

Figure 9.8 below displays impact potentials per BRA for the end of life management section, normalized to the impacts of House 1. The climate change impact potentials for P houses are 6% and 7% higher than that of House 1, while the G&G impact potential is 15% lower. Likewise, the P houses are slightly more impact-intensive than the LE houses for the impact categories freshwater eutrophication and freshwater ecotoxicity, while they are significantly more impact-intensive for the terrestrial ecotoxicity and metal depletion categories. It is apparent that the main difference for the first category stems from materials in the Floors category. A study of the process tree (Appendix 13.1.2) for the category shows that the bulk of the impact potential is from expanded polystyrene, which is the insulation under the ground level floor. This insulation element is 50 mm thicker for the P houses than for the LE houses, indicating a significantly higher material use per BRA. The difference for the metal depletion category originates from end of life treatment of the solar collection system that is installed for the P houses.

Compared to other life cycle phase sections, G&G has particularly high relative impact contributions for EOL. For this section, G&G's normalized impacts span from a minimum of 37% for terrestrial acidification to 139% for marine eutrophication. The Roof element category is generally the most significant contributor, for instance for climate change, where it contributes 50% of the G&G impacts. A closer inspection of the process tree (Appendix 13.1.3) finds that concrete disposal and transport is the main reason for the relative importance of the Roof category. As described in the LCI of this study, the Roof category for G&G includes concrete level separators, which for the houses are included in the Floors category. This is the main reason why the mentioned element categories are the most important for their respective Løvåshagen building units.

9.2.3 Section summary

Climate change impact differences for the construction phase are small, but for other impact categories, the passive houses stand out with higher impact potentials, originating mainly from the solar collection systems. The same trend is reflected, only stronger, for maintenance impacts. Passive houses have significantly higher end of life impacts in the categories terrestrial ecotoxicity and metal depletion. EPS insulation and solar collection systems appear to be important contributors for these categories.

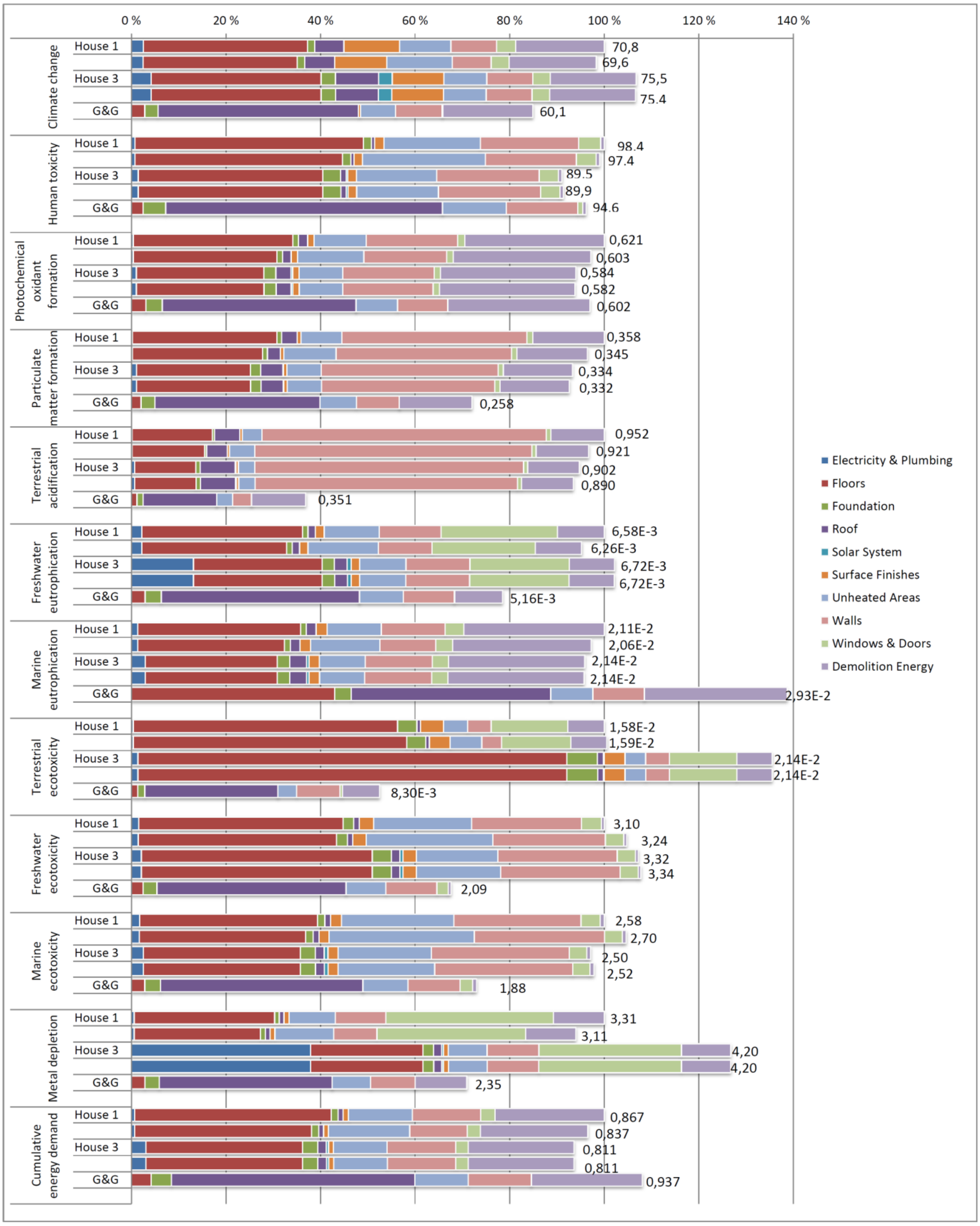


Figure 9.8: Characterized EOL impacts per m^2 BRA at Løvåshagen, equal foundation scenario

10 Analysis

The following chapter starts with an advanced contribution analysis, containing a closer inspection of which construction processes that contribute most to the various impact categories. It also contains an inspection of the climate change impacts originating from transportation in the various life cycle phases.

10.1 Advanced Contribution Analysis

In order to better understand which processes and stressors contribute to the various impact categories, an advanced contribution analysis has been performed. The five most impact-intensive processes and the three most impact-intensive stressors in each impact category have been found and studied more closely, using the process contribution analysis and process tree tools provided by the LCA software SimaPro. The advanced contribution analysis has been undertaken for Løvåshagen as an entity, not for the individual houses, and is based on the Løvåshagen scenario model that is closest to reality, not the scenario where house elements are adjusted for a better comparison (see Chapter 0 for details). It includes all elements described in Chapter 7, and the life cycle sections Construction, WDC, Maintenance and EOL. Because operation is responsible for such a large portion of the impacts from Løvåshagen, it would dwarf other life cycle sections, which is the reason why it is excluded in the present analysis.

“Løvåshagen Road Transport” is the process covering all transport of materials from production gates to the Løvåshagen construction site, and all waste from the site to the waste treatment plant at end of life.

10.1.1 Climate Change

Process		Contribution
Clinker, at plant/CH U		21 %
Løvåshagen Road Transport		11 %
Diesel, burned in building machine/GLO U		6 %
Pig iron, at plant/GLO U		6 %
Epoxy resin, liquid, at plant/RER U		4 %
Stressor	**Compartment**	**Contribution**
Carbon dioxide, fossil	Air	93 %
Methane, fossil	Air	5 %
Dinitrogen monoxide	Air	1 %

Table 10-1: Relative contributions to climate change

The processes that contribute most to climate change are Clinker, at plant, Løvåshagen Road Transport, and Diesel, burned in building machine, with 21%, 11%, and 6% of impact potentials respectively. Clinker is a central component in the Portland cement that is used in concrete, and several studies have found concrete to be one of the most impact-intensive construction materials in use (Vieira and Horvath, 2008; Asif et al., 2005). A study of the process tree for climate change, found in appendix 13.1.4, confirms that the high climate change contribution of clinker at Løvåshagen is because it is a component of concrete. The high impacts of Løvåshagen Road Transport and Diesel burned in building machines demonstrate that fossil fuel consumption is a central contributor to climate change also in this study. The two most important stressors are Carbon dioxide (93%) and Methane (5%).

10.1.2 Toxicity

Process		HT	TE	FE	ME
		Contribution			
Disposal, inert material, 0% water, to sanitary landfill/CH U		28 %		23 %	24 %
Disposal, sulfidic tailings, off-site/GLO U		21 %		10 %	10 %
Disposal, spoil from coal mining, in surface landfill/GLO U		7 %			7 %
Steel, electric, un- and low-alloyed, at plant/RER U - NORDEL		7 %			
Disposal, steel, 0% water, to municipal incineration/CH U		6 %		16 %	17 %
Disposal, wood ash mixture, pure, 0% water, to landfarming/CH U			53 %		
Soy beans IP, at farm/CH U			9 %		
Disposal, expanded polystyrene, 5% water, to municipal incineration/CH U			7 %	9 %	
Disposal, drilling waste, 71.5% water, to landfarming/CH U			7 %		
Løvåshagen Road Transport			5 %		
Disposal, nickel smelter slag, 0% water, to residual material landfill/CH U				9 %	9 %
		Contribution			
Stressor	**Compartment**	**HT**	**TE**	**FE**	**ME**
Manganese	Water	54 %		14 %	15 %
Arsenic, ion	Water	15 %			
Mercury	Air	10 %			
Phosphorus	Soil		60 %		
Bromine	Water		9 %		
Metolachlor	Soil		8 %		
Nickel, ion	Water			47 %	50 %
Vanadium, ion	Water			11 %	11 %

Table 10-2: The five processes and the three stressors that contribute most to Human Toxicity (HT), Terrestrial Ecotoxicity (TE), Freshwater Ecotoxicity (FE), and Marine Ecotoxicity (ME)

The table above displays the five processes with the highest relative contributions to the human toxicity and the ecotoxicity impact categories. Disposal of inert material is the highest of the five presented processes for HT, FE, and ME, with relative contributions of 28%, 23%, and 24% respectively. A study of the process trees (appendix 13.1.5, 13.1.6, 13.1.7) show that disposal of concrete is the central process behind the importance of inert material disposal. Disposal of sulfidic tailings has the second highest contribution for HT (21%) and the third highest for FE (11%) and ME (11%). The importance of this process at Løvåshagen is mainly due to copper use. Significant amounts of copper are used for several processes, where the highest impacts originate from electronics, evacuated tube collectors and copper tubes. The second most important process for FE and ME is the disposal of steel, with contributions of 16% and 17% respectively. A closer inspection (appendix 13.1.8) shows that the importance of this process originates from steel used in elevators and columns. For the TE category, the disposal of wood ash dominates with 53% of impacts. Closer inspection shows that the impacts originate mainly from parquet production and from electricity used at the building site and in Nordic material production. By comparison with wood ash, the remaining processes contribute little to TE, and the second highest contribution is from soy beans (9%), through the use of soya oil in paint (appendix 13.1.9).

The stressor that contributes most to TE is Phosphorus emitted to soil (60%), while Nickel ions to the water compartment is the dominating contributor to FE (47%) and ME (50%). HT is dominated by Manganese emitted to water (54%), which is also the second highest contributor to FE and ME, with 14% and 15% of impacts for each category, correspondingly.

10.1.3 Photochemical Oxidant Formation

Process		Contribution
Løvåshagen Road Transport		24 %
Diesel, burned in building machine/GLO U		21 %
Clinker, at plant/CH U		6 %
Epoxy resin, liquid, at plant/RER U		5 %
Natural gas, vented/GLO U		3 %
Stressor	**Compartment**	**Contribution**
Nitrogen oxides	Air	76 %
NMVOC, non-methane volatile organic compounds, unsp	Air	13 %
Sulfur dioxide	Air	5 %

Table 10-3: Relative contributions to photochemical oxidant formation

Two processes dominate contributions to photochemical oxidant formation, namely Løvåshagen transport (24%) and diesel burned in building machines (21%), resulting in altogether 45% of impacts originating from processes dominated by diesel fuel consumption. The stressors that cause these impacts are mainly Nitrogen oxides emitted to air, responsible for 76% of impacts, and non-methane volatile organic compounds (NMVOC), responsible for 13% of impacts.

10.1.4 Particulate Matter Formation

Process		Contribution
Løvåshagen Road Transport		10 %
Diesel, burned in building machine/GLO U		10 %
Iron ore, 46% Fe, at mine/GLO U		10 %
Ceramic tiles, at regional storage/CH U - UCTE		8 %
Disposal, gypsum, 19.4% water, to sanitary landfill/CH U		7 %
Stressor	**Compartment**	**Contribution**
Nitrogen oxides	Air	29 %
Particulates, > 2.5 um, and < 10um	Air	25 %
Particulates, < 2.5 um	Air	25 %

Table 10-4: Relative contributions to particulate matter formation

The most impact-intensive processes for particulate matter formation are Løvåshagen Road Transport, diesel burned in building machines, and iron ore, all with relative contributions of 10%. Notably, diesel consumption through the use of vehicles and building machines is responsible for a large portion of impact potentials, in the same manner as for previously described impact categories. Stressors emitted to air dominate as contributors, with Nitrogen oxides responsible for 29% of impacts and particulates up to 10 um responsible for 50% of impacts.

10.1.5 Terrestrial Acidification

Process		Contribution
Disposal, gypsum, 19.4% water, to sanitary landfill/CH U		19 %
Løvåshagen Road Transport		13 %
Diesel, burned in building machine/GLO U		10 %
Clinker, at plant/CH U		5 %
Epoxy resin, liquid, at plant/RER U		4 %
Stressor	**Compartment**	**Contribution**
Sulfur dioxide	Air	54 %
Nitrogen oxides	Air	40 %
Ammonia	Air	7 %

Table 10-5: Relative contributions to terrestrial acidification

The disposal of gypsum is responsible for 19% of impacts to terrestrial acidification. A study of the process tree shows that more than 99% of the input for gypsum disposal originates from gypsum plaster boards, used in walls and roofs at Løvåshagen. Road transport and use of building machines are once again important contributors, responsible for 23% of impacts to terrestrial acidification. Important stressors are SO_2 and NO_x to air, with contributions of 54% and 40% correspondingly.

10.1.6 Freshwater Eutrophication

Process		Contribution
Disposal, sulfidic tailings, off-site/GLO U		30 %
Disposal, spoil from coal mining, in surface landfill/GLO U		29 %
Disposal, spoil from lignite mining, in surface landfill/GLO U		22 %
Disposal, basic oxygen furnace wastes, 0% water, to residual material landfill/		7 %
Titanium dioxide, chloride process, at plant/RER S		3 %
Stressor	**Compartment**	**Contribution**
Phosphate	Water	99,0 %
Phosphorus	Soil	0,5 %
Phosphorus	Water	0,4 %

Table 10-6: Relative contributions to freshwater eutrophication

Disposal of sulfidic tailings, of spoil from coal mining and of spoil from lignite mining are responsible for altogether 81% of freshwater eutrophication impact potentials. The first of these processes, with 30% of contributions, originate from copper use in the manner described in the toxicity section of this chapter. The second process, coal mining, contributing 29%, mainly originates from use of reinforcement steel, and partly through the use of rock wool insulation (appendix 13.1.10). Disposal of spoil from lignite mining contributes 22% and originates mainly from production processes in non-Nordic European countries, through the use of the UCTE electricity mix (appendix 13.1.11). Phosphate emitted to the water compartment is responsible for 99% of impacts, while phosphorus emitted to soil and water is responsible for roughly 1% of impacts altogether.

10.1.7 Marine Eutrophication

Process		Contribution
Løvåshagen Road Transport		15 %
Diesel, burned in building machine/GLO U		13 %
Soy beans IP, at farm/CH U		11 %
Green manure IP, until march/CH U		8 %
Disposal, spoil from coal mining, in surface landfill/GLO U		6 %
Stressor	**Compartment**	**Contribution**
Nitrogen oxides	Air	55 %
Nitrate	Water	34 %
Ammonia	Air	5 %

Table 10-7: Relative contributions to marine eutrophication

Contributions to marine eutrophication are dominated by the previously described transport and building machine processes, altogether responsible for 28% of impacts. The soy bean process is the third most important contributor, with 11%. As described in the toxicity section, this is mainly through the use of paint at Løvåshagen. Stressor contribution is mainly divided between Nitrogen oxides to air (55%) and Nitrates to water (34%).

10.1.8 Metal Depletion

Process		Contribution
Iron ore, 46% Fe, at mine/GLO U		39 %
Ferronickel, 25% Ni, at plant/GLO U		12 %
Manganese concentrate, at beneficiation/GLO U		11 %
Copper concentrate, at beneficiation/RER U		8 %
Chromite, ore concentrate, at beneficiation/GLO U		7 %
Stressor	**Compartment**	**Contribution**
Iron, 46% in ore, 25% in crude ore, in ground	Raw	42 %
Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	Raw	13 %
Manganese, 35.7% in sedimentary deposit, 14.2% in crud	Raw	12 %

Table 10-8: Relative contributions to metal depletion

The main contributor to metal depletion is iron ore, responsible for 39% of impact potentials, and mainly used in reinforcement steel (appendix 13.1.12). Steel use in elevators and steel columns are also important sources of iron ore extraction. All of the three steel-based elements are important drivers behind the second and third highest contributors to metal depletion, namely Manganese concentrate and Ferronickel, responsible for 12% and 13% of impact potentials, correspondingly. The stressors for metal depletion are the raw metals themselves, and the most important stressors are iron, nickel and manganese, with relative contributions equal to that of their respective processes.

10.1.9 Cumulative Energy Demand

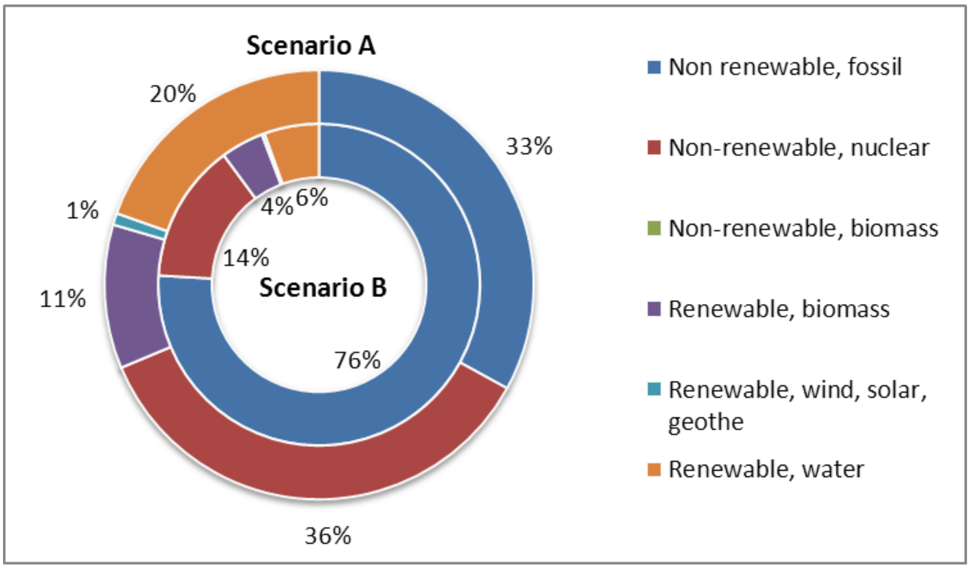


Figure 10.1: Relative distribution of primary energy sources

The figure above displays the cumulative energy demand for two cases; the outer ring shows the relative distributions of energy sources for the whole life cycle of Løvåshagen (scenario A), while the inner ring shows the same distribution for all life cycle sections except Operation (scenario B). It is evident that the non-renewable energy share is high for both cases: 69% for scenario A and 90% for scenario B. Accordingly, the shares of renewable energy are 32% for scenario A and 10% for scenario B. The shares of energy originating from wind, solar and geothermal, as well as the shares originating from non-renewable biomass, are practically negligible. The renewable energy shares are divided into roughly one third of biomass and two thirds of water, for both scenarios.

10.1.10 Transport

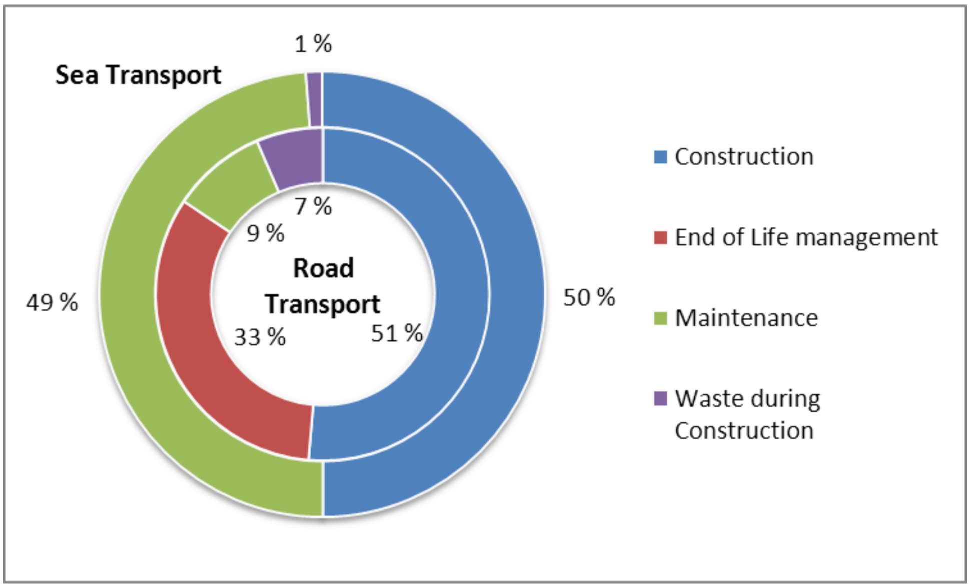


Figure 10.2: Relative contributions of life cycle phases to total climate change transport impacts

The figure above presents the disaggregation of climate change impacts originating from transportation of materials to the building site and waste to a waste treatment plant.

Sea transport is represented by the outer circle and totals 1.5 ton CO_2-eq, while road transport is represented by the inner circle, and totals 494.1 ton CO_2-eq. In total, this equals 4 % of the total climate change impacts of Løvåshagen. The four sections of the graph represent their respective life cycle sections, described in Chapter 9. Operation is not included here, as there is no transport associated with it. The results show that transport of materials to the construction site is responsible for close to half of the impacts, both for road and for sea transport. The Waste during Construction section includes transport of excess materials to and from the construction site, and contributes only little, being responsible for 1% of sea transport and 7% of road transport impacts. WDC and Construction are both included in the construction phase for Løvåshagen, which adds up to a relative contribution of 51% for sea transport and 58% for road transport. There is no sea transport associated with end of life management, as the waste treatment plant is assumed to be reached over land. EOL road transport is responsible for one third of total road transport. The contribution of Maintenance transport is 49% for sea and only 9% for road. A study of the process tree indicates that the large contribution of Maintenance for sea transport is due to the transport of solar collector systems from China, which is the origin of 81% of the transportation (appendix 13.1.13). A study of the tree for Construction indicates that the solar collector transportation is responsible for the larger part (79%) of the contribution also to sea transport for this section (appendix 13.1.14). For Construction road transport, the main driver is the Groundwork process, which includes the transportation of excavated soil from the construction site to a waste deposit (appendix 13.1.15).

10.1.11 Section summary

Clinker used in concrete is the main contributor to the climate change, and is also a significant contributor to a couple of other impact categories. Overall, transportation and fuel use in building machines are the most important impact sources. Copper is an important source of toxicity impacts from Løvåshagen. Almost 70% of cumulative energy demand is from non-renewable energy sources. Transportation of solar collection systems from China contribute substantially to climate change impacts from sea transport, while transportation of excavated soil to a waste deposit is the highest contributor to the impacts of land transportation.

10.2 Sensitivity Analysis

In order to understand the implications of changes in the modelled system, a sensitivity analysis has been performed. It contains two sections:

A. *Sensitivity to changes in the electricity mix has been studied, by comparing results using the Norwegian (NO), Nordic (NORDEL) and European (UCTE) electricity mixes.*
B. *The effect of using a special concrete based on low-carbon cement has been estimated and compared with the base scenario.*

10.2.1 Electricity mix

The effect of using different electricity mixes for the Construction and Operation phases, described in Chapter 0, has been studied for the three electricity alternatives Norwegian, Nordic and European. The EcoInvent processes used have impact potentials of 18 g CO_2 eq/KWh, 190 g CO_2 eq/KWh, and 594 g CO_2 eq/KWh, correspondingly (EcoInvent database, 2010). In the sensitivity analysis, these are labelled NO, NOR, and EU, correspondingly (in order to minimize the space used for graphs). The electricity used for material production and end of life management are kept constant, at their default values. Average impacts per square meter for the two low energy (LE) houses have been compared with average impacts per square meter for the two passive (P) houses, for each of the three electricity mix alternatives. Impacts are distributed on the same five sections that have been used previously; Construction, WDC, Maintenance, Operation, and EOL. Results are displayed in Figure 10.4 below, normalized to the impacts of the LE average with the Nordic (NOR) electricity mix.

It is apparent that climate change impacts when using the European electricity mix is more than twice as high as when using the Nordic electricity mix, while the impacts for the Norwegian electricity mix are less than half as for the Nordic mix. Interestingly, the passive houses have the highest impacts when using the Norwegian mix, while the low energy houses have the highest impacts when using the Nordic or European mixes. A closer inspection of climate change impacts for the Norwegian mix, displayed in Figure 10.3 below, shows that the higher Construction, Maintenance and EOL impacts for passive houses outweighs the lower Operation and WDC impacts they have, leading to total impact potentials of 684 kg CO_2 eq/m^2 for LE houses and 703 kg CO_2 eq/m^2 for P houses. The central difference compared to the other electricity mixes is that the impact potential of Operation is extremely low for the Norwegian mix. The relative importance of Operation compared to the other life cycle sections is also significantly lower for the Norwegian mix than for the European and Nordic mixes. These results demonstrate the importance of the electricity mix in determining the benefit of building a more energy-efficient house; when using a mix with low climate change impact potentials such as the Norwegian one, the importance of house operation diminishes, while the importance of the materials used for construction and maintenance increases. With a more impact-intensive electricity mix, the relative benefit of the passive house increases, reaching its highest for the European mix in this scenario.

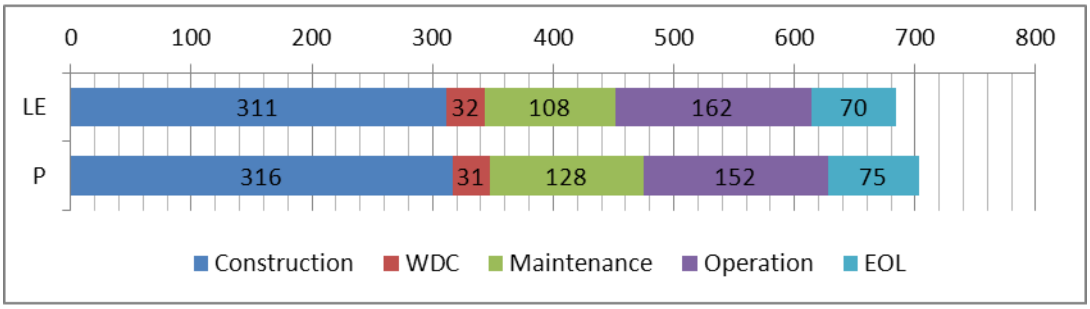


Figure 10.3: Climate change impacts for the Norwegian electricity mix

The other impact categories show a similar trend as the climate change category, with 20-60% lower impacts for the Norwegian mix, and higher impacts for the European mix, spanning from only a few per cent higher to almost seven times higher. An exception to this pattern is the results for terrestrial ecotoxicity (TET), where the Nordic electricity mix results in the highest impacts, and the other mixes are 60-80% lower. A study of the process tree of the Nordic electricity consumption (appendix 13.1.16) shows that the bulk of the impact potential for TET stems from the Finnish and the Swedish electricity production. According to Dones et al. (2007) the central factor that separates Finnish and Swedish production from that of Norway and Denmark is the amount of nuclear based electricity production, and Finland also has a high share of biomass based electricity production. A quick comparison of the Nordic and the European countries shows that the average shares of nuclear based and biomass based electricity production are significantly higher among the Nordic countries than among other European countries. It is probable that the relatively high TET impacts for the Nordic mix stems from electricity production based on these energy sources.

In the case of the European mix, the passive house average performs better than the low energy house average for all impact categories save metal depletion, where the LE average performs slightly better. Hence, when considering the European electricity mix, the passive house is clearly preferable. For the Norwegian mix, the LE average has slightly lower impacts for all categories save cumulative energy demand, where the P average performs somewhat better. In the same manner as previously described for the climate change impact category, the Operation section becomes less dominating when using the low-impact Norwegian energy mix. Thus, the performance advantage held by the LE house average for other life cycle sections outweighs the advantage of the P house average for the Operation section. Hence, the LE house average is slightly preferable to the P house average when using the Norwegian electricity mix. For the Nordic mix, the differences are less, and the house models alternate having the lowest impacts. Hence, it is more difficult to declare one alternative as preferable.

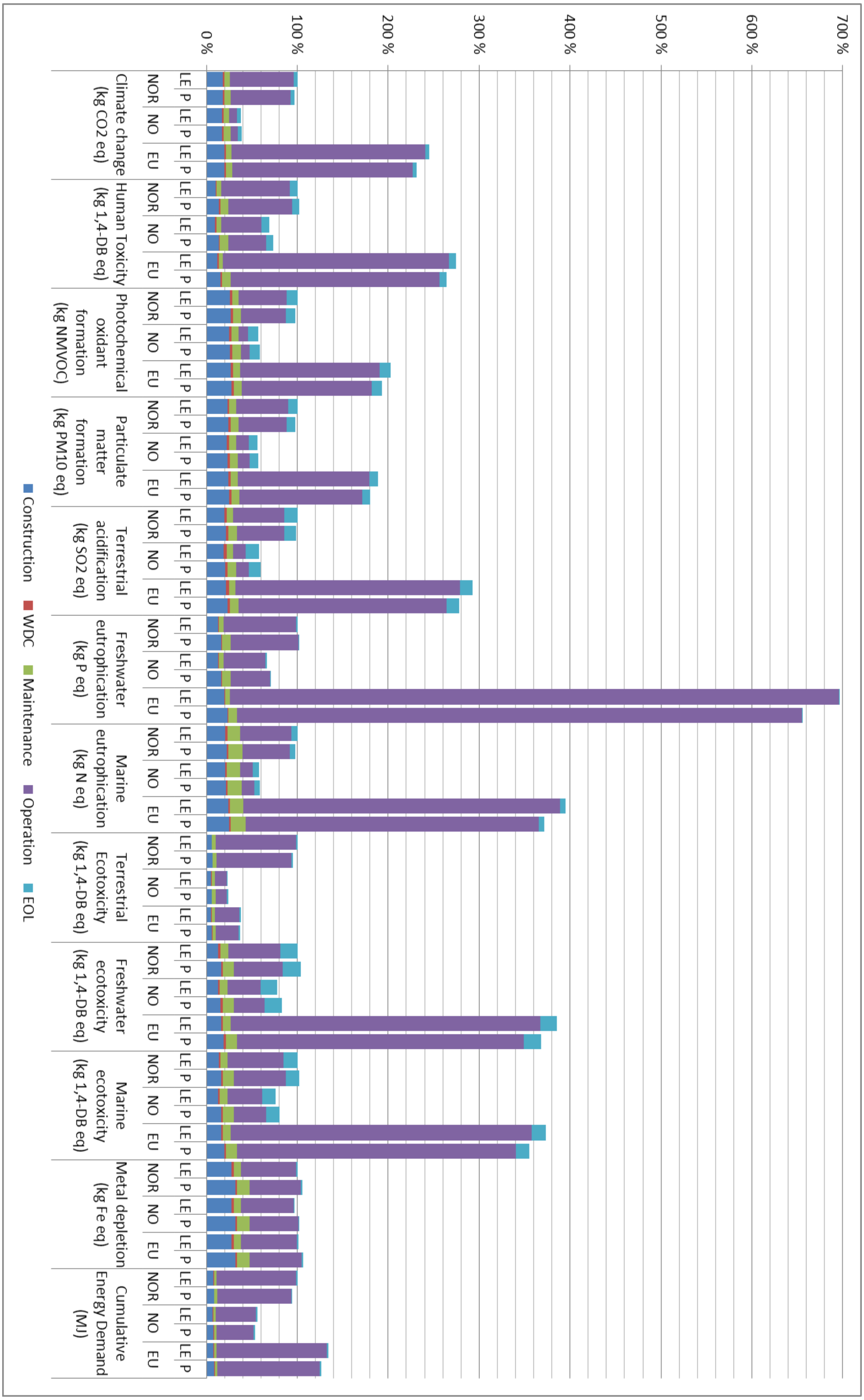


Figure 10.4: Characterized average impacts per house model for Nordic, Norwegian and European electricity mixes, equal foundation scenario

10.2.2 Low-carbon concrete

The effect of replacing standard Portland cement in the concrete at Løvåshagen with special low-carbon cement, produced by Norcem, has been estimated, based on the cradle to gate EPD for this cement (NEPD, 2011). The low-carbon cement has a climate change impact potential of 488 g CO_2 eq/ m^2, while the Portland cement originally used has a potential of 821 g CO_2 eq/ m^2, a difference of roughly 40% (EcoInvent, 2010). The resulting climate change impacts for the whole life cycle are presented in Figure 10.5 below, given as CO_2 equivalents per m^2 BRA and normalized to the results of the low-carbon case for House 1.

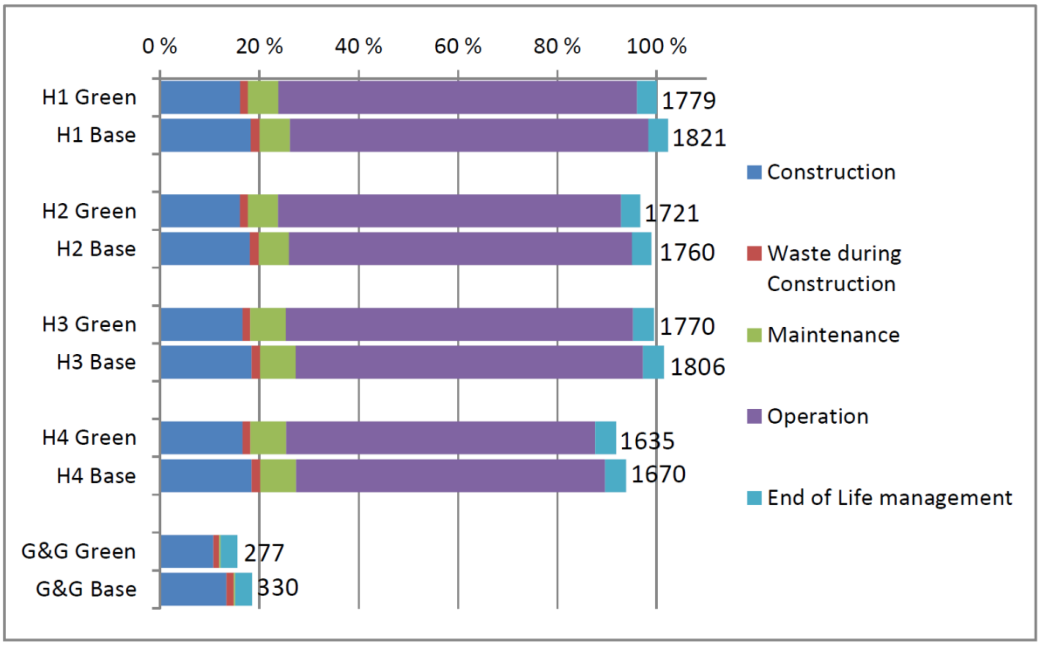


Figure 10.5: Comparison of climate change impacts for green and base scenario

The life cycle impact reduction for each house is in the range 2-3%, while the reduction for G&G is more than 16%. The relative contribution of the Construction section increases by 1-3%. Change of concrete affects only Construction and WDC, not the other phases (the same waste treatment process is used for green concrete as for the base case). In order to better understand the effect on the Construction phase, the disaggregated results have been calculated and are presented in Figure 10.6. The relative reduction of climate change impacts for each house is 10-11%, while it is 20% for G&G. For Floors, the house element category with the highest relative contribution, there is a relative contribution reduction of 3-4%, while the equivalent reduction is 3% for the G&G element category with the highest relative share (Roof). These element categories are among the most concrete-intensive at Løvåshagen.

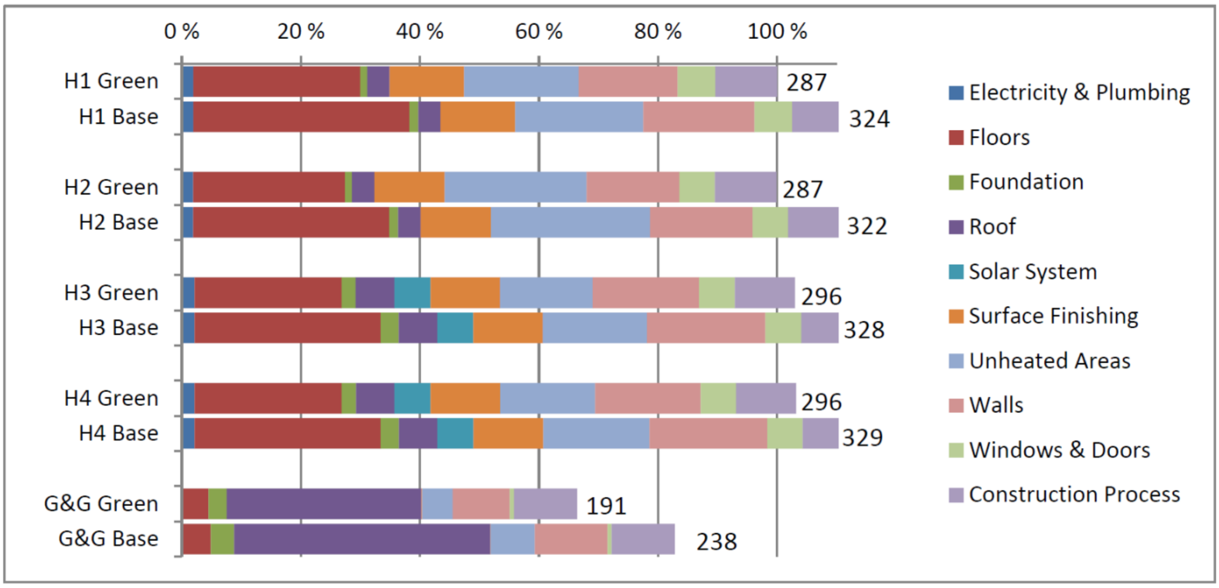


Figure 10.6: Comparison of climate change impacts for green and base scenario, construction phase

For the Løvåshagen average, the replacement of normal concrete with low-carbon concrete results in a 12% reduction of initial embodied carbon, from 308 kg CO_2 eq/ m^2 to 271 kg CO_2 eq/ m^2. The new average P performance is 296 kg CO_2 eq/ m^2, and the new average LE performance is 287 CO_2 eq/ m^2, indicating 3% lower initial embodied carbon for the LE houses than for the P houses. This difference is only 2% for the base case. For the whole life cycle performance, the new average climate change impact potentials are 1.70 (P) and 1.75 (LE) ton CO_2 eq/ m^2, placing P emissions at 97% of LE emissions. This difference is equal to the result for standard concrete. It may be concluded that use of a low-carbon concrete leads to a noticeable decrease in initial embodied carbon, but it is practically negligible for the life cycle perspective.

10.2.3 Section summary

Environmental performance differences between LE and P houses are very small when considering the Norwegian or Nordic electricity mix, while there is a notable difference in favour of the P houses when considering the European mix. The replacement of standard concrete with a low-carbon concrete leads to a slight decrease in initial embodied carbon, but the improvement in the whole life cycle perspective is practically unnoticeable.

11 Discussion

This chapter discusses the LCA results and compares them with other studies. It contains four sections: (1) Evaluations of primary energy and climate change impacts (2) Evaluations of impacts other than CC and CED (3) Uncertainty, and (3) Conclusions and further work.

11.1 Evaluations of primary energy and climate change impacts

This section starts by comparing the energy and carbon impacts with those of other studies and then examines the operational electricity consumption at Løvåshagen. Operational energy use is then compared with results from other studies, and then the same is done for embodied energy.

Figure 11.1 below displays climate change (CC) and primary energy (CED) results from the present study and several other case studies that include the full life cycle of residential buildings. For Løvåshagen, average values for each house model is used, based on the foundation wall scenario that was used for comparing the house models. Results are normalized to the Løvåshagen measured LE house average. The estimated Løvåshagen case is the result of using annual electricity consumptions of 74 and 101 KWh/m^2 for P and LE houses correspondingly, while keeping the rest of the system equal to the base case scenario. According to Enova SF (2008), the mentioned values were the pre-construction estimated delivered electrical energy needs for Løvåshagen. Dahlstrøm et al. (2012) is based on the master theses Dahlstrøm (2011) and Sørnes (2011), and evaluates four heating system alternatives for two versions of a wood-framed single-family house in the western part of Norway. One house version (T) is built to the Norwegian Building Code from 2010 while the other (P) is built to the Norwegian Passive house standard NS 3700. The four heating system alternatives are (0) electricity resistance heating, (1) electricity and wood, (2), electricity and a solar collector system, and (3) an air-water heat pump system. It would have been interesting to do a closer investigation of the effects of different heating and ventilation systems for Løvåshagen, but this would require building a complete simulation model, and this has been considered too time-consuming, given that measured electricity consumption values were available. However, the possible effect of alternative heating systems is discussed later in this chapter.

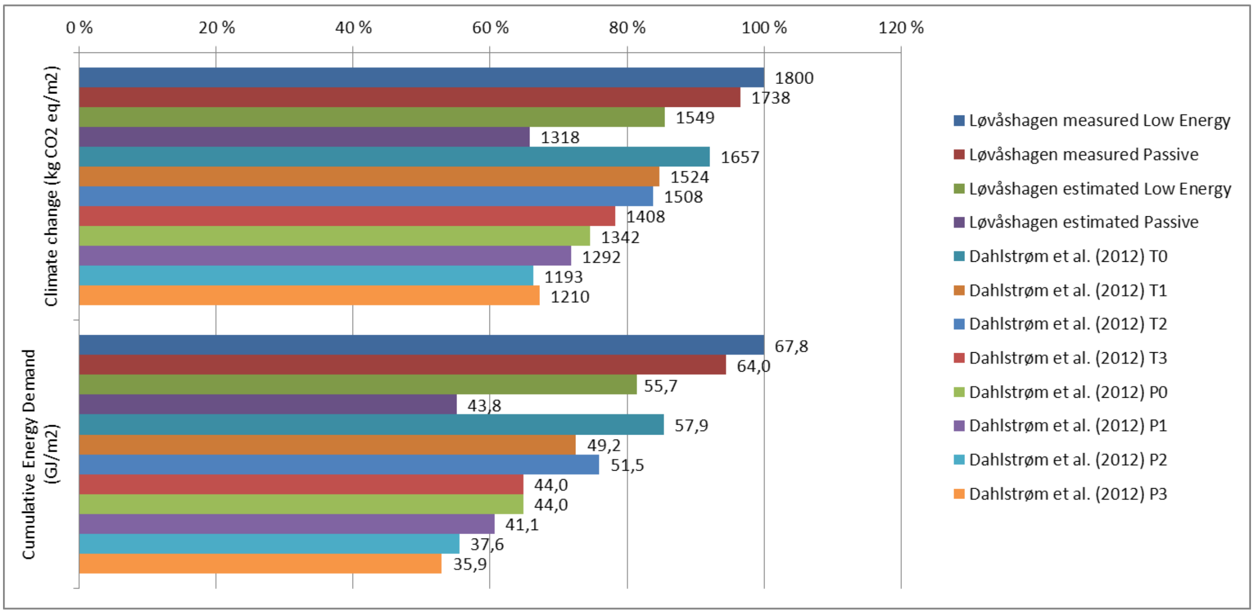


Figure 11.1: LCA case study results per BRA

It is apparent that the estimated Løvåshagen passive house case and the P2 and P3 cases have the best performance. It is also apparent that the Løvåshagen estimated case is far better than the Løvåshagen measured case, indicating that the actual performance is far lower than expected. The Løvåshagen measured buildings have lower performance than all other cases, even than the T0 conventional house with electric resistance heating. The difference between the measured and estimated Løvåshagen cases indicates that the operational electricity consumption is a central factor behind the poor measured performance. Hence, the measured electricity consumption is studied more closely below.

As illustrated in Figure 7.7: 2010 Electricity consumption per apartment, the difference between average LE and passive house consumption is very small, with values of 127 and 121 KWh/m^2 correspondingly. This reflects the small difference between the life cycle performances of the two house models, another indication of the strong influence of electricity consumption on life cycle performance. LE consumption is in the range 50-302 KWh/m^2, while P consumption is in the range 54-169 KWh/m^2. Thus it is evident that although the average consumption does not differ much between the house models, the peak consumption differs substantially. There appears to be no clear pattern to where the most energy efficient buildings are situated, except for a slight tendency for them to be on levels 2-5, not on the ground level. There is one clear tendency in that the ten *least* energy efficient apartments are in the LE houses. Four of the ten highest consumptions are for apartments that border on the passage through House 1. Increased air flow through the passage could possibly be a factor behind the high consumption.

11.1.1 Delivered energy and other studies

Figure 11.2 below displays estimated and measured annual delivered operational energy per m^2 BRA for four Nordic cases of multi-family buildings. For Løvåshagen the estimated values are the ones previously used in Figure 11.1, taken from Enova SF (2008). The red sections of the columns represent energy provided by solar thermal collectors, and are relevant for the Løvåshagen and Lindås passive buildings. Articles on Løvåshagen (Rindal and Salvesen 2008, Thomsen et al. 2011) have estimated the annual effect of the solar collection systems to be 17 KWh/m^2. No measurement of this was available. Data for the Karlstad passive building is taken from Persson (2008) and Thormark (2006), while data for the Lindås passive building is taken from Wall (2005). Lindås consists of 20 terrace houses using balanced ventilation systems with heat recovery, electric resistance heating, and solar collectors for hot water heating. Karlstad consists of 44 apartments in a 12-storey building using balanced ventilation systems with heat recovery and a hydronic system for floor and hot water heating, with the heat sources district heating and heat pumps.

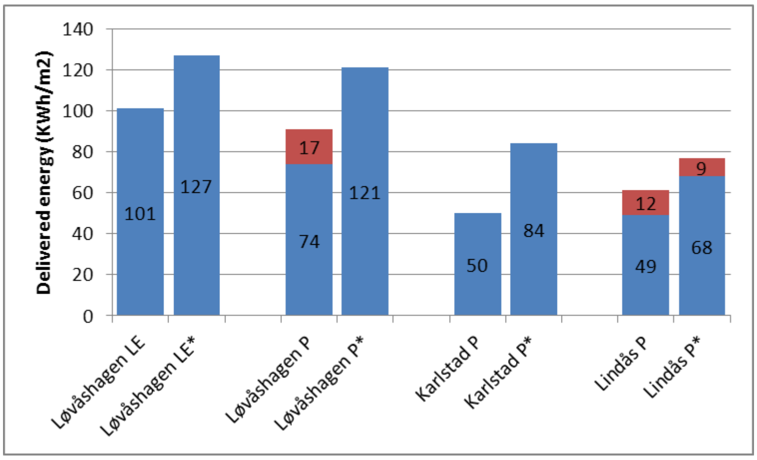


Figure 11.2: Annual delivered energy per square meter BRA
Explanation: *Based on measured values; LE - Low energy; P - Passive

Interestingly, actual energy consumption values are consequently higher than estimations. Although the Løvåshagen consumption is at a significantly higher level than the other studies, the relative estimation errors are in the same range as for the other studies, with 26% for Løvåshagen LE, 64% for Løvåshagen P, 68% for Karlstad P, and 28% for Lindås P.

11.1.1.1 Solar collectors

The results presented in Figure 11.2 show that the Lindås solar collectors had a lower output than expected. The results of the present study give reason to believe that this is the case also for the Løvåshagen solar collectors. Adding the estimated delivered solar collector energy to the measured electricity consumption would bring the average energy consumption of the P houses up to 138 KWh/m^2, a significantly higher level than the LE houses. Such a result is counterintuitive, as the P houses are better insulated than the LE houses. In a survey of various available solar thermal collector solutions, Kalogirou (2004) noted that the benefits of evacuated tube collectors are "greatly reduced when conditions become unfavourable during cold, cloudy and windy days" (Kalogirou, 2004, page 246). This gives reason to believe that that the low temperature of 2010 led to a particularly low performance for the installed solar thermal collectors.

11.1.1.2 Other heating systems

In a comparison of heating system solutions for several Swedish case study buildings, including the Lindås and Karlstad buildings described above, Gustavsson and Joelsson (2010) found that "the choice of energy supply system had a greater effect on the primary energy use than the energy-efficiency house envelope measures" (Gustavsson and Joelsson 2010, page 219). As mentioned in the literature review, solar collectors were found to be efficient, but not as efficient as heat pumps or district heating. Electric resistance heating was found to be the worst solution. It should be noted that the assumed electricity mix of the mentioned study had a higher impact per KWh than the mix used in the present study. The results presented in Figure 11.1 find solutions with heat pumps and solar collectors have the highest performance. Although it is difficult to predict the effect alternative heating systems would have on Løvåshagen without a full simulation, these results indicate that most heating system solutions would be preferable to the electric resistance heating used in the LE buildings, particularly when considering the relatively high energy use at Løvåshagen. The suspected low performance of the solar collection system also gives reason to believe that heat pumps or district heating would be preferable; such solutions are less dependent on climatic conditions.

11.1.2 Embodied energy

Apart from the operation phase, the construction phase is the largest contributor to the CC and CED categories. Figure 11.3 below shows embodied primary energy and carbon per m^2 BRA for the Løvåshagen buildings, as well as for the Lindås and Karlstad P buildings, and the conventional (C) and passive buildings of studied by Dahlstrøm (2011). Only primary energy values were found for Lindås P and Karlstad P. These values are estimated from graphs in Gustavsson and Joelsson (2010), and may be inaccurate. All values are normalized to Løvåshagen LE.

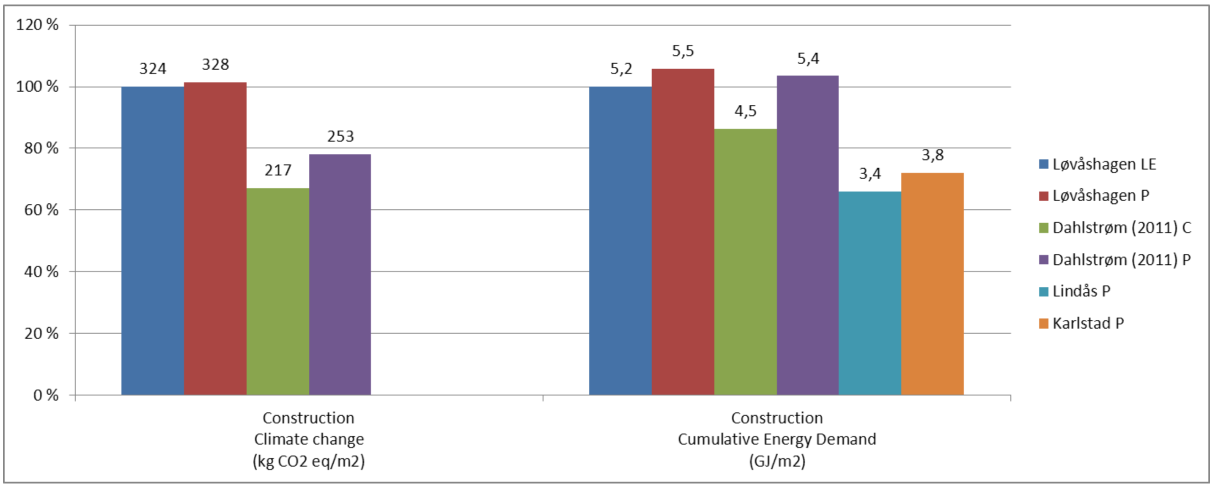


Figure 11.3: Construction phase impacts per BRA

Embodied energy for the Løvåshagen buildings is the highest, followed by those of Dahlstrøm (2011), Karlstad, and Lindås. The fact that Lindås performs the best is surprising, given that this is also the building with the lowest measured operational energy use. However, details of the calculation of the embodied energy for Lindås P and Karlstad P were not available, and there is a higher uncertainty associated with these values. Still, these buildings outperform the Løvåshagen ones by a good margin, and it is also surprising that embodied carbon and energy is higher for the single-family house than for the multi-family house cases. One possible reason behind the lower performance of Løvåshagen is that the building cores are made of concrete, while all of the other case studies except Karlstad P are wood buildings. The advanced contribution analysis showed that concrete was a central contributor to the relevant categories. On the other hand, the sensitivity analysis showed only a slight performance increase for the system when using a concrete type based on low-carbon cement that implied an almost 40% reduction of CO_2 impacts per kg. Further, the Karlstad P building has a frame of reinforced concrete while having a much higher performance than the Løvåshagen buildings. One factor that may play an important part in this is the fact that the present study and Dahlstrøm (2011) included the construction process at the building site, which is often excluded in other studies, according to Khasreen et al. (2009). This theory is supported by the fact that both the present study and Dahlstrøm (2011) found fuel use in building machines to be an important contributor to the climate change impact category. The lack of transparency in the Karlstad and Lindås calculations gives little ground to make any decisive conclusions, but it is probable that the high Løvåshagen impacts are the result of the relatively high detail of the LCA and of the choice of concrete as a building material.

11.1.3 Comparison discussion

Overall, the high impacts of Løvåshagen deviate from estimations and from results found by previous literature. Wall (2005) explained discrepancy between estimated and measured operational energy use by unexpectedly high indoor temperature and household electricity use, as well as unexpectedly low solar collector output. As discussed above, there is reason to believe that the solar collector output has been significantly lower than expected also for Løvåshagen. Findings of Thomsen et al. (2011) and Enova SF (2011) give reason to believe that the other explanations given by Wall (2005) are valid explanations also for the discrepancies noted in the present study. For instance, an interviewed Løvåshagen resident explicitly stated that her family keeps a higher indoor temperature in their Løvåshagen apartment than they did in their previous dwelling (Enova, 2011). These findings indicate a tendency to over-estimate the performance of passive multi-family buildings.

The comparisons of Figure 11.2 show that also the estimations for Løvåshagen were at a significantly higher level than the estimations of the Swedish case studies. It appears that the level of ambition was lower, but that the deviation from expectations was to the same relative degree as for the Swedish buildings. The comparison with the single-family case studies of Dahlstrøm et al. (2012) found the estimation cases for Løvåshagen to perform reasonably well. It is possible that measurements for the cases of Dahlstrøm et al. (2012) would find similar errors as those of the multi-family case studies in Figure 11.2. In conclusion, the ambition level of Løvåshagen appears to have been in line with those of single-family energy efficient houses in Scandinavia, although not as high as the ambition level of multi-family energy efficient houses in the region. Also, the results fall short of the ambitions, but the relative error is not larger than for other studies. Although a higher ambition level might have been fortunate, an excessive use of technologies for reducing energy demand could be counterproductive, as pointed out by Ramesh et al. (2010) and Sartori and Hestnes (2007). The lack of other complete life cycle assessments of multi-family dwellings makes it difficult to determine whether this would be the case for Løvåshagen. It would be advisable to gather more operational consumption data from Løvåshagen before coming to any drastic conclusions.

Estimations and previous literature indicated that the difference between Løvåshagen LE and P buildings should have been larger. However, literature has only compared LE or P buildings with conventional buildings, not with each other. Although both building models fail to meet estimated performance, the estimated error is far larger for the P building than for the LE building. Hence, it would be interesting learn more about the performance of the solar collection systems for 2010 as compared to years that have more normal climatic conditions. There is also a possibility of building defects, such as a too low air-tightness, which may lead to substantially lowered energy efficiency in passive houses (Rockwool AS, 2012).

11.1.4 Section summary

Generally, the Løvåshagen buildings are outperformed by the buildings of other studies, even some conventional ones, and the P building in particular performs worse than expected. Some of the background for this is the use of measured operational data from a particularly cold year and a strong suspicion that this reduced the solar collectors' output substantially. It is seen that energy use estimations in literature are often optimistic. There is also a relatively high level of detail for the present study compared to other studies. If the energy consumption at Løvåshagen is not lowered significantly throughout the next few years, it would be advisable to check the buildings and solar collectors for faults.

11.2 Evaluations of impacts other than CC and CED

Although climate change and primary energy are important impact categories and normally the focus of building LCAs, it is useful to also evaluate the results in terms of other environmental indicators. This section examines results for these indicators and the driving factors behind them.

11.2.1 Solar collection systems

The disaggregated life cycle impacts show that solar collection systems stand out as important contributors, especially for toxicity and eutrophication categories. The advanced contribution analysis showed that this was to a large extent due to copper use, embodied in the hydronic distribution pipes as well as in the evacuated tube collectors themselves. The model for the solar collector systems was based on the one used by Sørnes (2011). As might be expected, the study found a similarly high relative contribution to the mentioned impact categories for the solar collector materials. For the present study, the same length of copper pipes was assumed per apartment as the one used by Sørnes (2011) for a single-family house. A closer study of literature on distribution pipe length for larger solar collection systems (Stucki and Jungbluth, 2010) found that a system of the size used by Løvåshagen is expected to require only about half of the copper that was originally used in modelling. Simulations with the corrected copper use resulted in a reduction of solar collection system impacts of up to 20% for some impact categories. Solar collection systems were found to be particularly high contributors in the maintenance phase, and a corrected copper use has the highest effect for this phase, at most leading to a 10% reduction of passive house human toxicity impacts. However, the passive houses still have substantially higher impacts than low energy houses. In the life cycle perspective, the largest effect is for passive house human toxicity impacts, which are reduced by almost 2%. Climate change and cumulative energy demand categories are practically unaffected. Hence, the corrected copper use do not change the conclusions made so far. Even with the corrected values, copper use in solar collectors, distribution systems and electrical installations is still a central contributor. If one considers toxicity and eutrophication impacts to be important, the copper used in solar collectors is an argument against using the technology, unless one is able to find solutions with other materials. Not many studies compare heating systems in terms of impacts other than CC and CED, but the comparison made by Sørnes (2011) indicates that among the studied solutions, electric resistance heaters in combination with wood stove heating is best for the toxicity categories, while an air-water heat pump is better for other categories. For Løvåshagen, the high eutrophication and toxicity impacts related to solar collectors lead to significantly lower life cycle performance for House 3 than for the LE houses.

11.2.2 Fuel consumption and construction materials

11.2.2.1 Concrete

Concrete is a central factor behind human toxicity (HT), freshwater ecotoxicity (FET) and marine ecotoxicity (MET) impacts. The largest quantities of concrete are used in the level separators and supporting walls of the buildings. As indicated when discussing embodied CC and CED, a good solution for reducing concrete-related impacts would be to substitute as much of the material as possible with other materials. Although the effect of low-carbon concrete was only studied for CC, a quick comparison shows that the low-carbon concrete is even better for the HT, FET and MET categories, reducing impacts by up to 40% (appendix 13.1.17).

11.2.2.2 Fuel consumption

The advanced contribution analysis showed that fuel consumption, both through the use of building machines and transportation of materials and waste, was an important contributor to several impact categories, including photochemical oxidant formation (POF), particulate matter formation (PMF), terrestrial acidification (TA), and marine eutrophication (ME). Although fuel consumption is also a significant contributor for the CC category, the high relevance for the other mentioned categories emphasizes the importance of minimizing transport distances and machine use on site. It also shows that it is important to include on-site fuel consumption in building LCAs.

11.2.2.3 Steel and gypsum

Steel use for elevators, columns and reinforcement of concrete was shown to be an important source of metal depletion (MD), and the disposal of it was shown to be a major contributor to MET and FET. Reduction of concrete use, as previously suggested, would help reduce these impacts. Other possible measures include substituting steel columns in the inner walls with other materials if possible. Apart from the steel columns, these walls consist mainly of gypsum plaster boards, which are the major material contributor to terrestrial acidification. The substitution of the inner wall materials with other materials, for instance wood, could improve the performance for several impact categories. However, as described in Dahlstrøm (2011), the impacts from gypsum are substantially lowered if the gypsum is disposed of in an inert material landfill rather than in a sorting plant, as is assumed here.

11.2.2.4 Paint

Because of the relatively high maintenance rate for paint, soya oil use was shown to be a significant contributor to terrestrial ecotoxicity and marine eutrophication. Hence, it could be beneficial to employ measures that reduce the need for maintenance of painted surfaces. Aluminium is often used for its low maintenance attributes, but it is also an impact-intensive material for some categories, and the benefits would have to be evaluated against the costs of using the material.

11.2.3 Section summary

Some of the embodied environmental loads of Løvåshagen could be significantly reduced by substituting selected building materials with less impact-intensive materials. Impact-intensive materials include copper, concrete, steel, paint and gypsum. Wood is a potential good substitution material for concrete and gypsum. Copper use may be reduced by exploring alternatives for the solar collectors. Fuel use should also be minimized by reducing transport distances and machine use on site, while also looking into alternative technologies.

11.3 Uncertainty

This section discusses the uncertainty related to the different elements of this study.

11.3.1 Construction and demolition

Modelled energy use for the construction phase was based on information from the contractors at Løvåshagen. For electricity consumption, only information on aggregated expenses was received, and there is significant uncertainty associated with the conversion to KWh, due to fluctuations in energy prices. Fuel use uncertainty is also significant, as the consumption was calculated using the total hours of machine use and an estimate of average diesel use per hour for the building machines. For demolition data, uncertainty is substantial, as building lifetime is long, and because the estimate of one company was more than four times as high as the estimate of the other. The highest of the two estimates was chosen, and this value also corresponded well to the one used by Dahlstrøm (2011).

11.3.2 Transportation

Transport distances were estimated based on assumed production locations. Although uncertainty has been reduced by research on probable production locations, there is still significant uncertainty involved. Distances are only rough estimates. As mentioned in the advanced contribution analysis, transport of excavated soil from the construction site is a main driver of road transport. This is mostly due to the large mass of this soil, and is sensitive to the transport distance value. It is possible that this distance is shorter than assumed, potentially affecting results.

11.3.3 Material data

The EcoInvent database is the basis for most materials used in the present study. Processes that are assumed to be produced in a specific country have adopted the electricity mix of the relevant country for the first process "round". Using concrete as an example, this means that the Nordic (NORDEL) electricity mix has been used for the production of concrete, while the production of clinker and other materials use the default European (UCTE) electricity mix. Wood material processes have been based on the work of Dahlstrøm (2011), which again was based on the Mikado Project (Wærp et al. 2008).

Bills of material quantities (BOQ) were used for the material inventory. These were the source of information also for the workers that constructed Løvåshagen, and may thus be considered reliable. Still, they are only pre-construction estimates, and a number of building element descriptions contained errors or had too low detail for use. Hence, the establishment of the material inventory required making a large number of assumptions regarding material dimensions, quantities, and compositions. The availability of technical drawings meant that qualified assumptions were possible, thus reducing the uncertainty somewhat, but the uncertainty of the material inventory is still significant. This is especially true for elements that were not described in BOQ, including elevators, heat exchangers, ventilation systems, electrical installations, plumbing, and heat distribution systems. Uncertainty related to windows and doors is also significant, as simplifications were made during the calculations of the involved material quantities. The foundation wall scenario used for comparison of LE and P results estimated material quantities for a similar LE foundation wall solution based on the P solution and technical drawings, and has some related uncertainty. However, the difference between the two foundation wall scenarios was relatively small.

11.3.4 Lifetime and maintenance

The building lifetimes have been assumed to be 50 years. This is equal to the assumption made by Dahlstrøm et al. (2012), Gustavsson and Joelsson (2010), and a number of other studies (Ramesh et al., 2010). However, there is significant uncertainty related to this factor, and it has very high influence on life cycle performance. Maintenance and renewal rates of components also have significant uncertainty, and some components have substantial life cycle influence, for instance solar collection systems.

11.3.5 Operational energy consumption

As Figure 11.2 illustrates, there is a lot of uncertainty associated with estimating energy demand based on simulations or statistical data. Even though measured data is generally preferable, there is still high uncertainty associated with using measured annual values to predict consumption for the whole lifetime of a building. Energy consumption depends on many factors and varies significantly over time. Climate and temperature are obviously important influential factors, but the individual behaviour of house residents is also very important, as emphasized by Wall (2005), Peuportier (2008) and Novakovic et al. (2007). The influence of these two factors on the uncertainty will be discussed further below. There is some uncertainty regarding the effect of the difference in the ground below the buildings; P houses are built on the ground, while the LE houses are built partially on top of the garages. No signs have been spotted that would indicate a significant effect of this, but it is potentially an influence.

11.3.5.1 Climatic variations

Climatic variations over time are difficult to predict, and they have an essential influence on electricity consumption. The present analysis is based on energy consumption data from 2010, which was the coldest year in several decades for the part of Norway where Løvåshagen is located. Hence, extrapolation over the entire lifetime can be somewhat misleading, especially when taking into consideration that global average temperature is rising.

11.3.5.2 Residential behaviour

2010 was the first year that Løvåshagen was fully in use. It is probable that the residents of Løvåshagen lived in conventional buildings before they moved to the housing cooperative and thus that their energy consumption habits were tuned to less energy efficient buildings. Hence, consumption patterns may change significantly over the next few years of operation, as residents adjust their habits and learn to better use the heating and ventilation systems. Peuportier (2008) pointed out that “it is essential to inform the occupants about the function of equipment, put at their disposal, so that they can use them in an optimal manner: e.g. heating and ventilation systems, water equipment, waste collection” (Peuportier, 2008, p. 10). Optimal electricity consumption requires instructing residents on how to properly use the heating and ventilation systems. A study of user evaluations of Løvåshagen (Thomsen et al. 2011) reported some feelings of confusion and lack of control over such systems, indicating that information might have been lacking. Enova SF (2011) quoted one resident of Løvåshagen explicitly stating that their apartment came with a user manual, but that they have never looked at it.

11.3.6 Waste

There is high uncertainty related to waste treatment, because most of the waste is originated at end of life, which is assumed to be in year 2059. Because of this, it is not possible to know much about material sorting and waste treatment for this phase. Waste has been assumed to be transported to a sorting or incineration plant, with no recycling. Focus on recycling has been increasing over the last few years, and it is very likely that large portions of the building materials are recycled. However, there is high uncertainty related to the shares of materials that are recycled and the technologies used for this. There is also uncertainty related to allocation of the benefits of such recycling. The currently used waste treatment solution may be considered to be a worst case scenario.

11.3.7 Section summary

There is always significant uncertainty associated with a full life cycle building LCA, and the present study is no exception. Uncertainty has been reduced somewhat by using measured operational data and building component information from the projecting companies. However, the uncertainties are still significant, especially regarding processes occurring in the future. This is related to unpredictability of human behaviour, climatic conditions, waste treatment methods, and allocation methodology for recycling.

11.4 Conclusions and further work

This section sums up the discussion chapter, draws conclusions and suggests potentials for improvement and further work.

The performance of the Løvåshagen buildings is lower than that of other case study buildings, even than some conventional single-family buildings. The difference between the Løvåshagen house models is also less than expected, mostly due to a particularly low passive house performance. It is suspected that this originated from an exceptionally low solar collector performance for the year of the measured consumption data. There is significant uncertainty related to this data, due to unpredictability of climatic conditions and human behaviour. The overall low performance compared to literature may further be explained by a higher level of detail for this LCA and a suspected general trend of over-estimating the performance of buildings.

Assumption on electricity mix highly influences the results, and the performance difference between the house models becomes significantly higher when assuming the European mix than when assuming a Nordic or Norwegian mix. Replacement of normal concrete with a low-carbon version leads to significantly lowered embodied carbon, but it is of little significance in the life cycle perspective. Substituting concrete with wood could be efficient for reducing CC impacts, and even more efficient for reducing toxicity impacts. Alternative solar collector solutions, or alternatives to solar collectors, could be good for reducing toxicity and eutrophication impacts. Waste treatment methods should be evaluated as an alternative to material substitution, as they can have a central influence on life cycle impacts.

Energy consumption at Løvåshagen should be monitored and evaluated over the course of the next few years of operation. If the consumption is not reduced, there is reason to suspect faults in the buildings or solar collection system. In the case of continued high consumption and no element defects, the energy estimations for Løvåshagen may be regarded as unrealistic. It is probable that choice of heat pumps or district heating would have been more efficient than solar collection systems and electric resistance heating. In any event, the study of Løvåshagen gives little ground to recommend increasing construction standard from low energy to passive.

There is need for further LCA studies of multi-family dwellings, and of studies comparing low energy houses with passive houses. It is recommended to include all life cycle phases, and to include energy use at the construction and demolition site. It is also recommended to analyse a broad spectre of environmental impacts, because important aspects of material and element choices may otherwise be missed. In order to increase the comparability of case studies, one should strive to make studies as transparent as possible.

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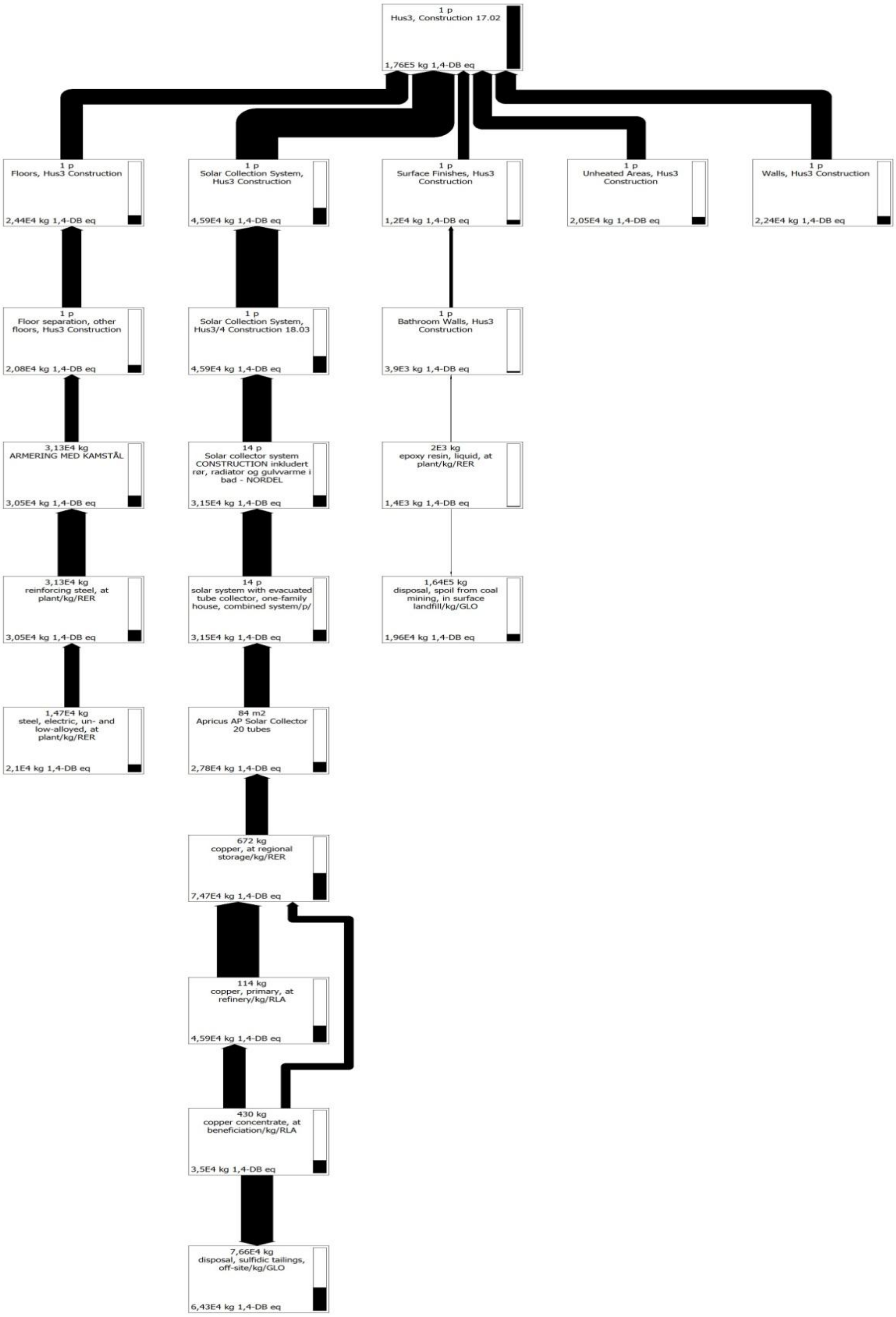
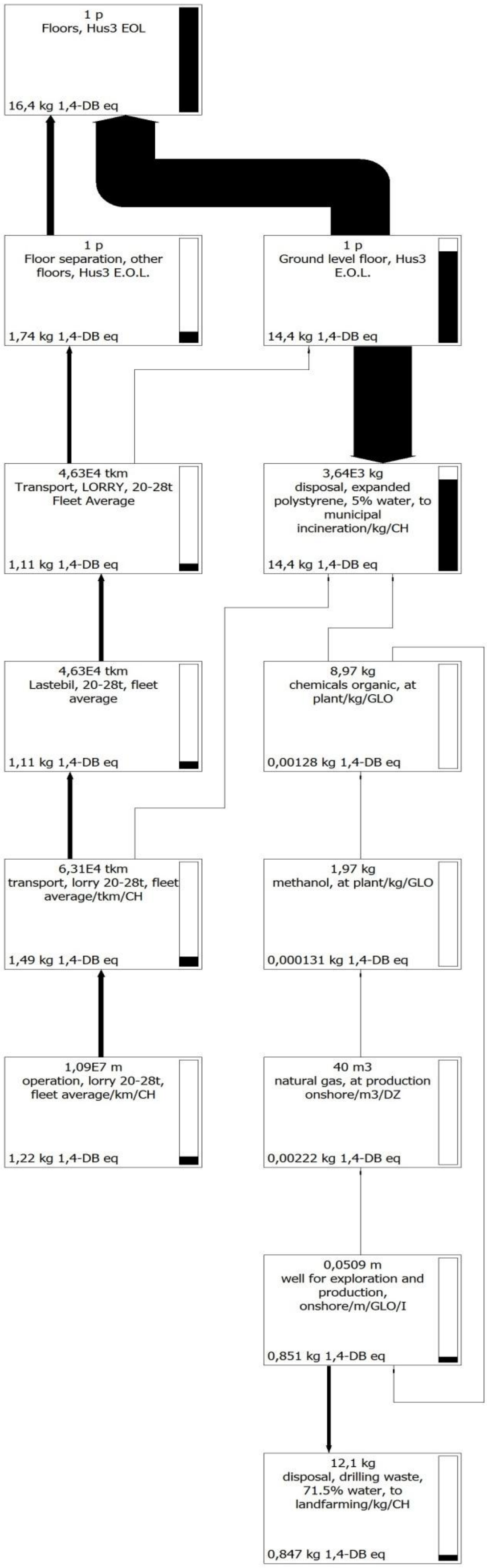
13 Appendix

13.1 Process trees

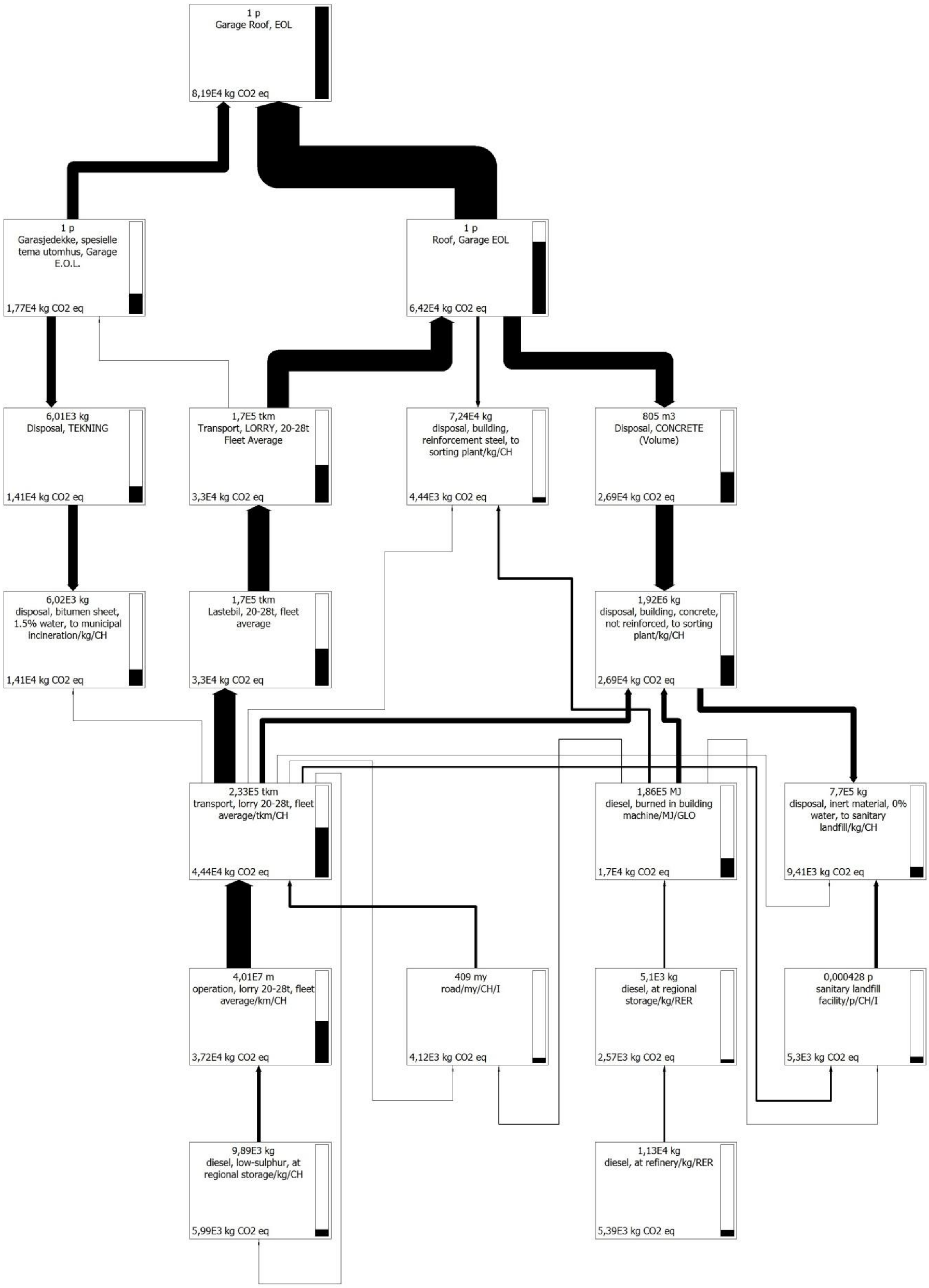
13.1.1 Human Toxicity Impacts, House 3 Construction



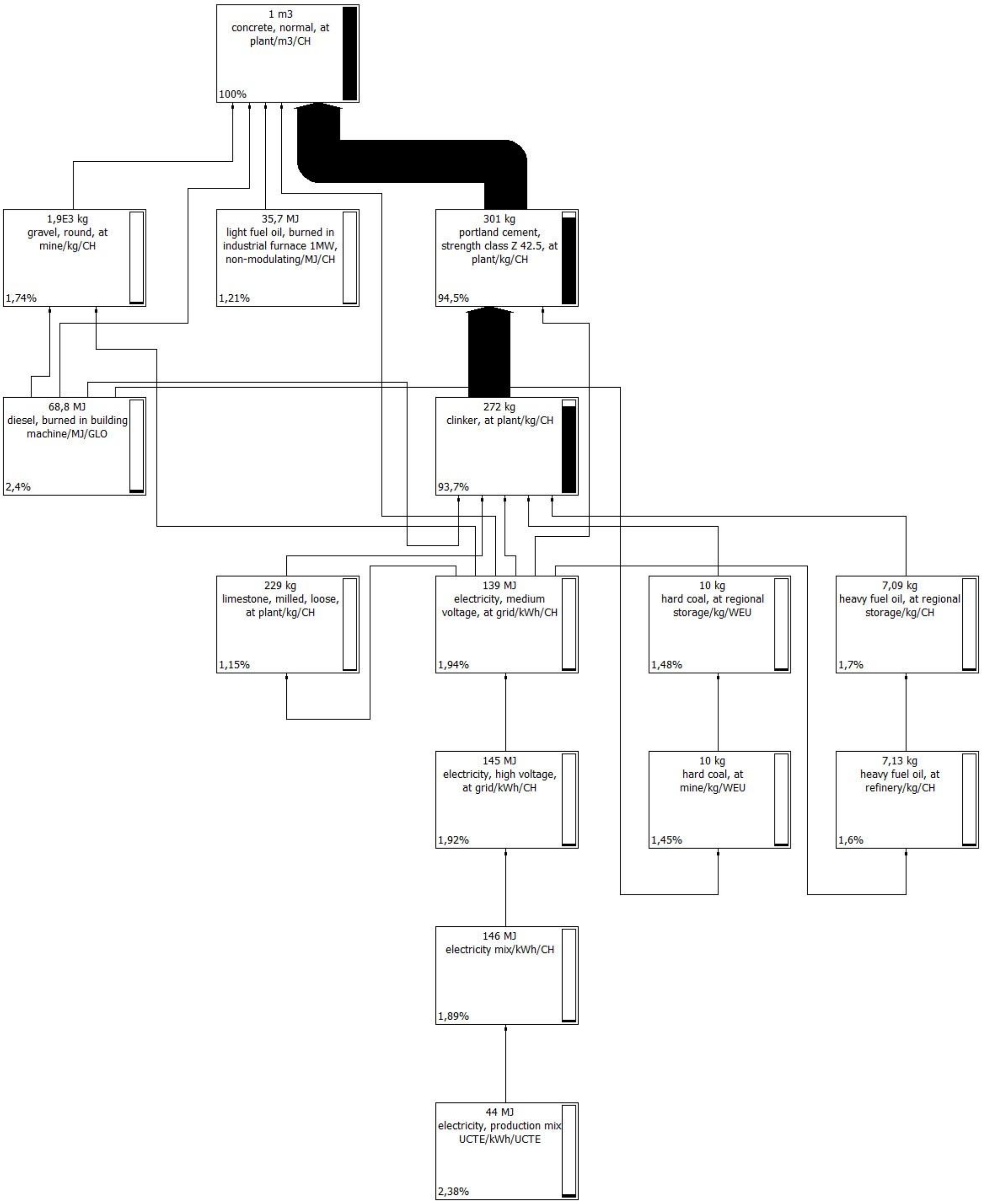
13.1.2 Human Toxicity Impacts, House 3 Floors EOL



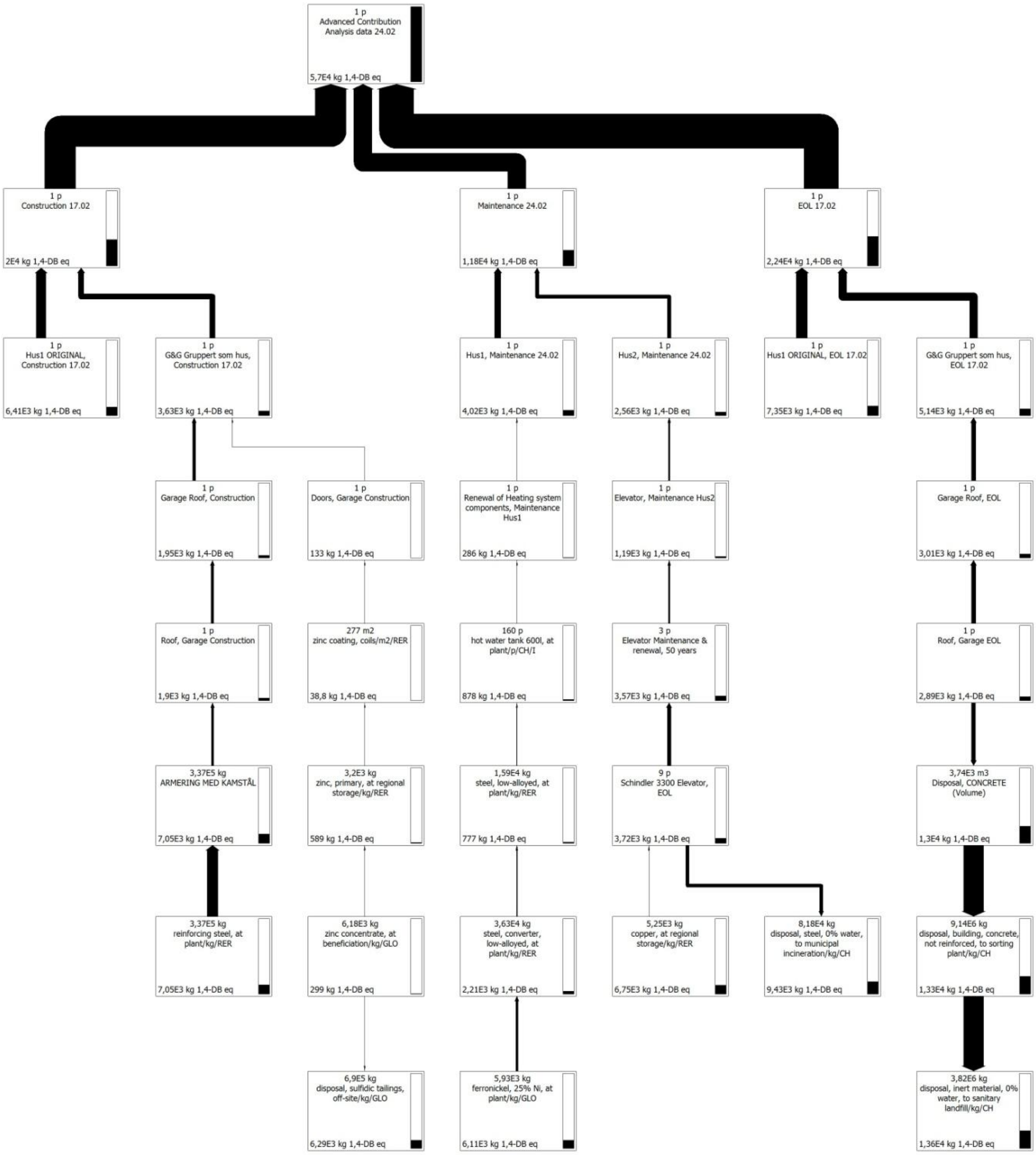
13.1.3 Climate Change Impacts, G&G Roof EOL



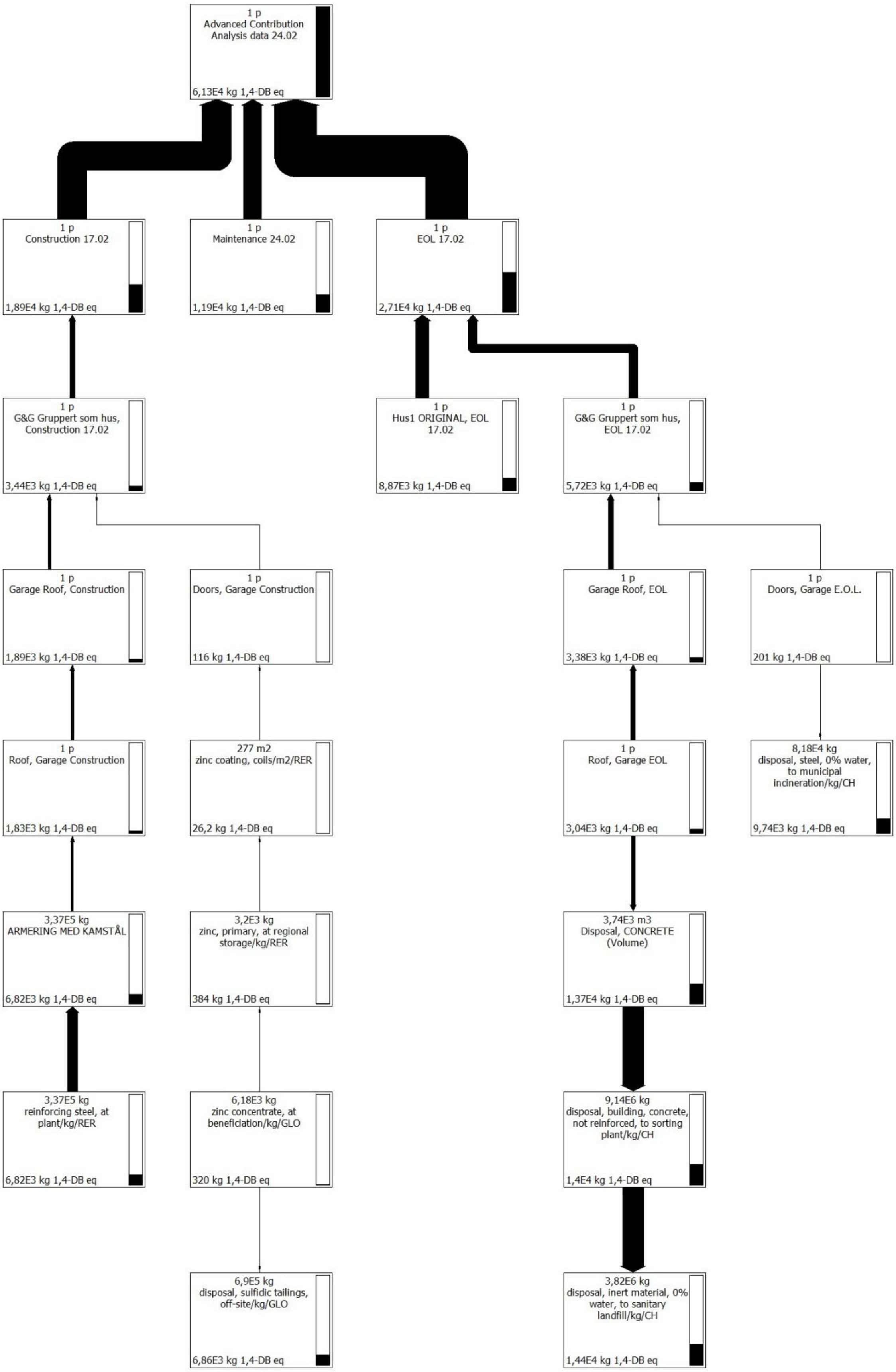
13.1.4 Climate Change Impacts, Concrete



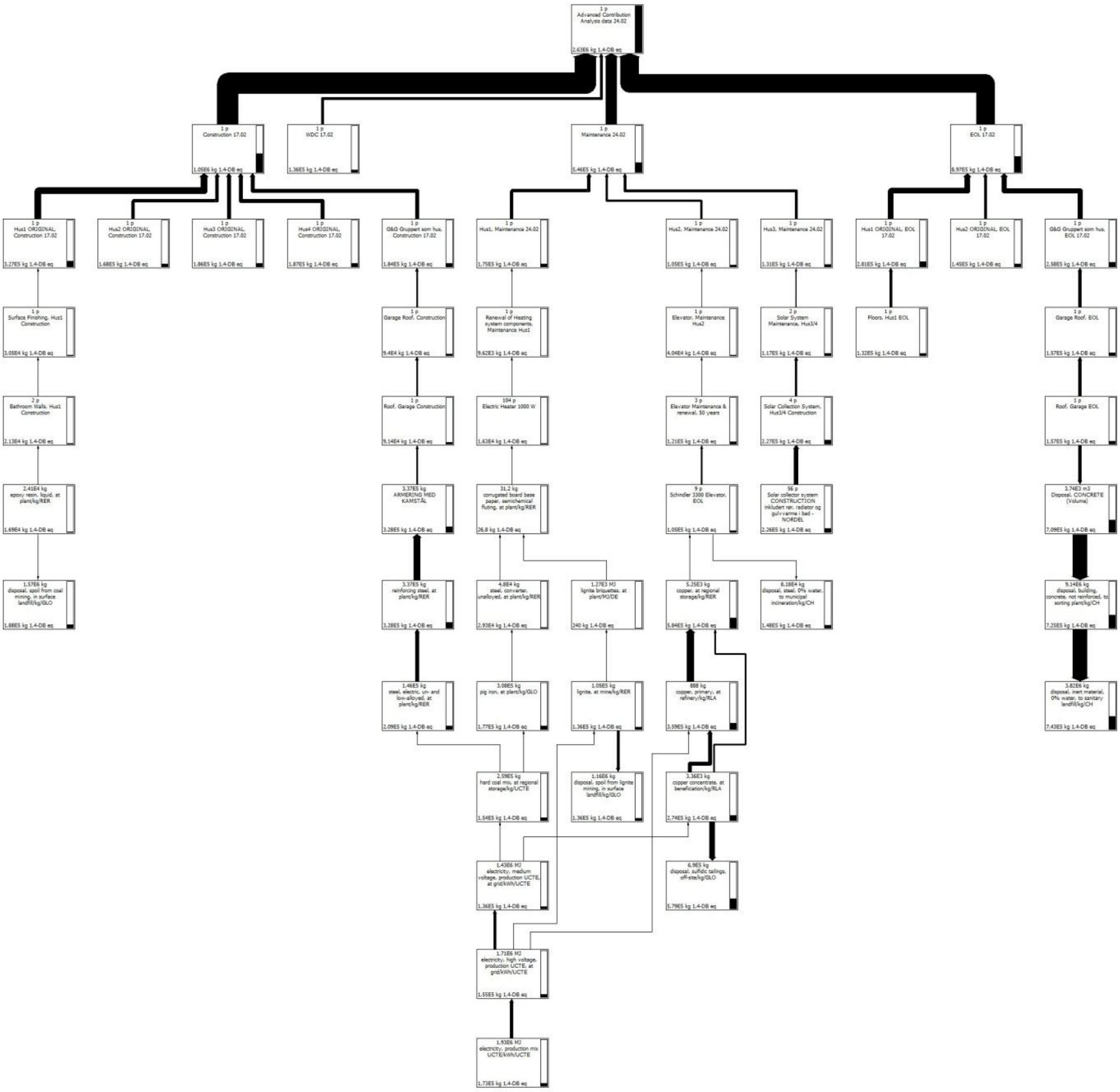
13.1.5 Marine Ecotoxicity Impacts, Advanced Contribution Analysis



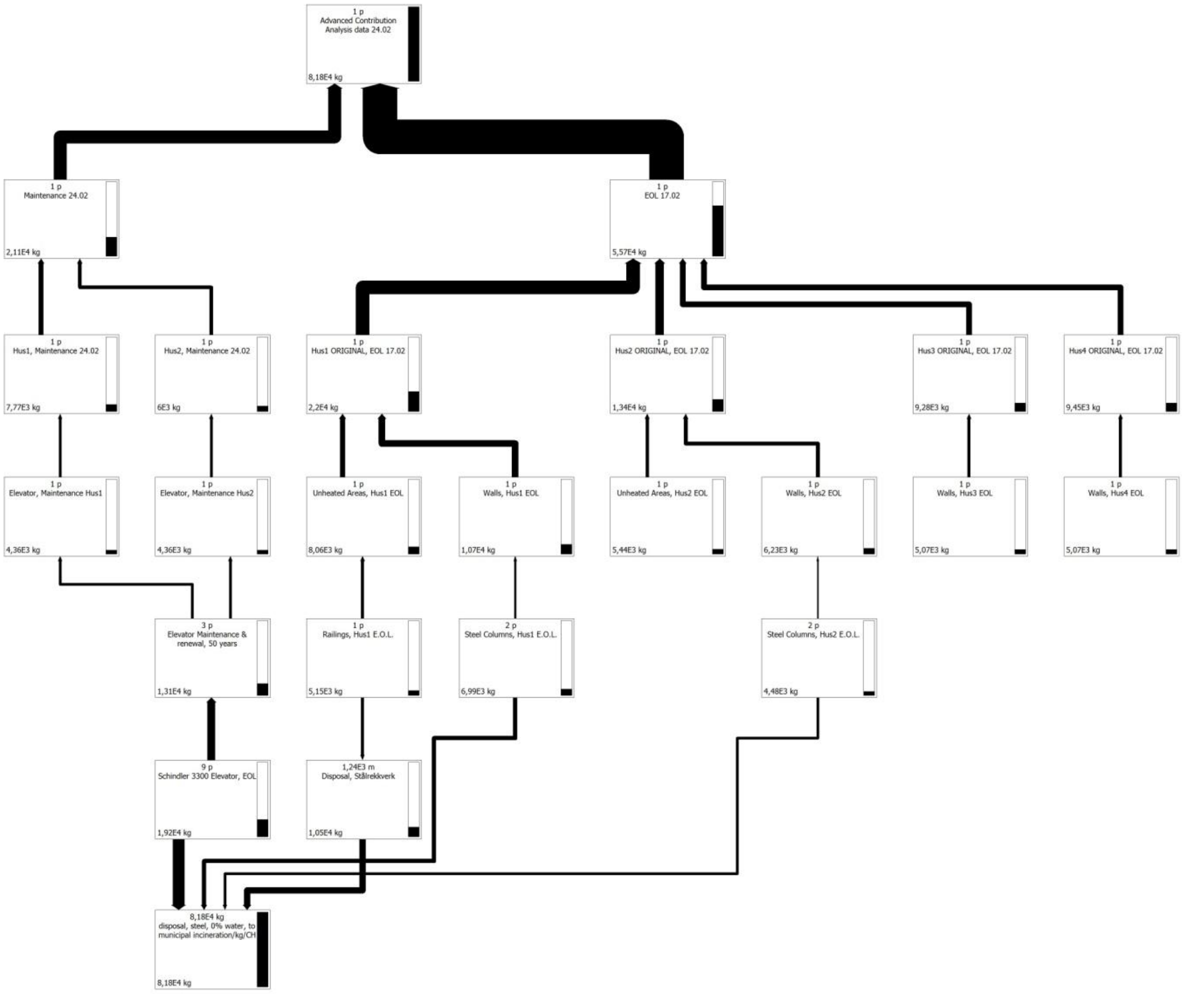
13.1.6 Freshwater Ecotoxicity Impacts, Advanced Contribution Analysis



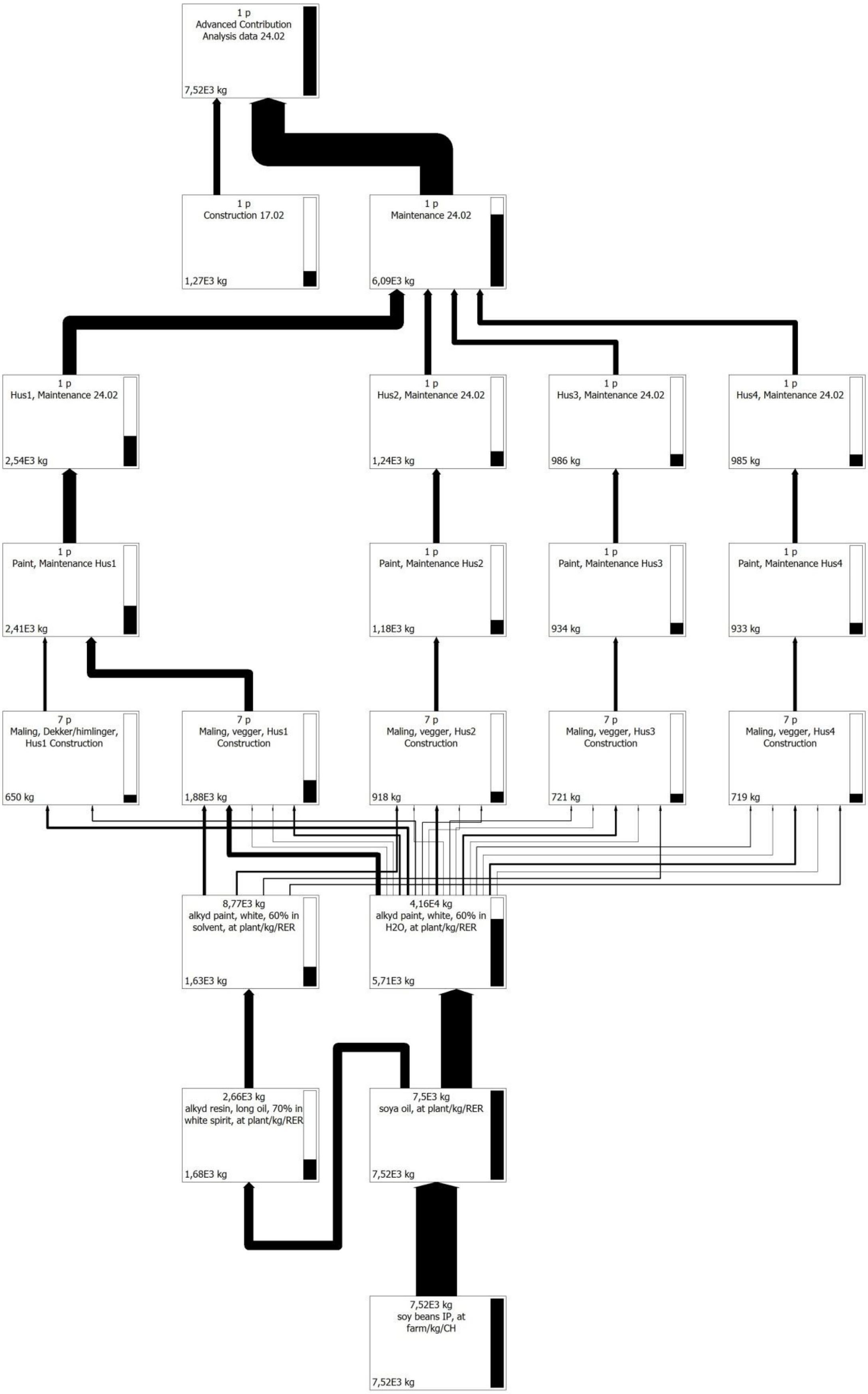
13.1.7 Human Toxicity Impacts, Advanced Contribution Analysis



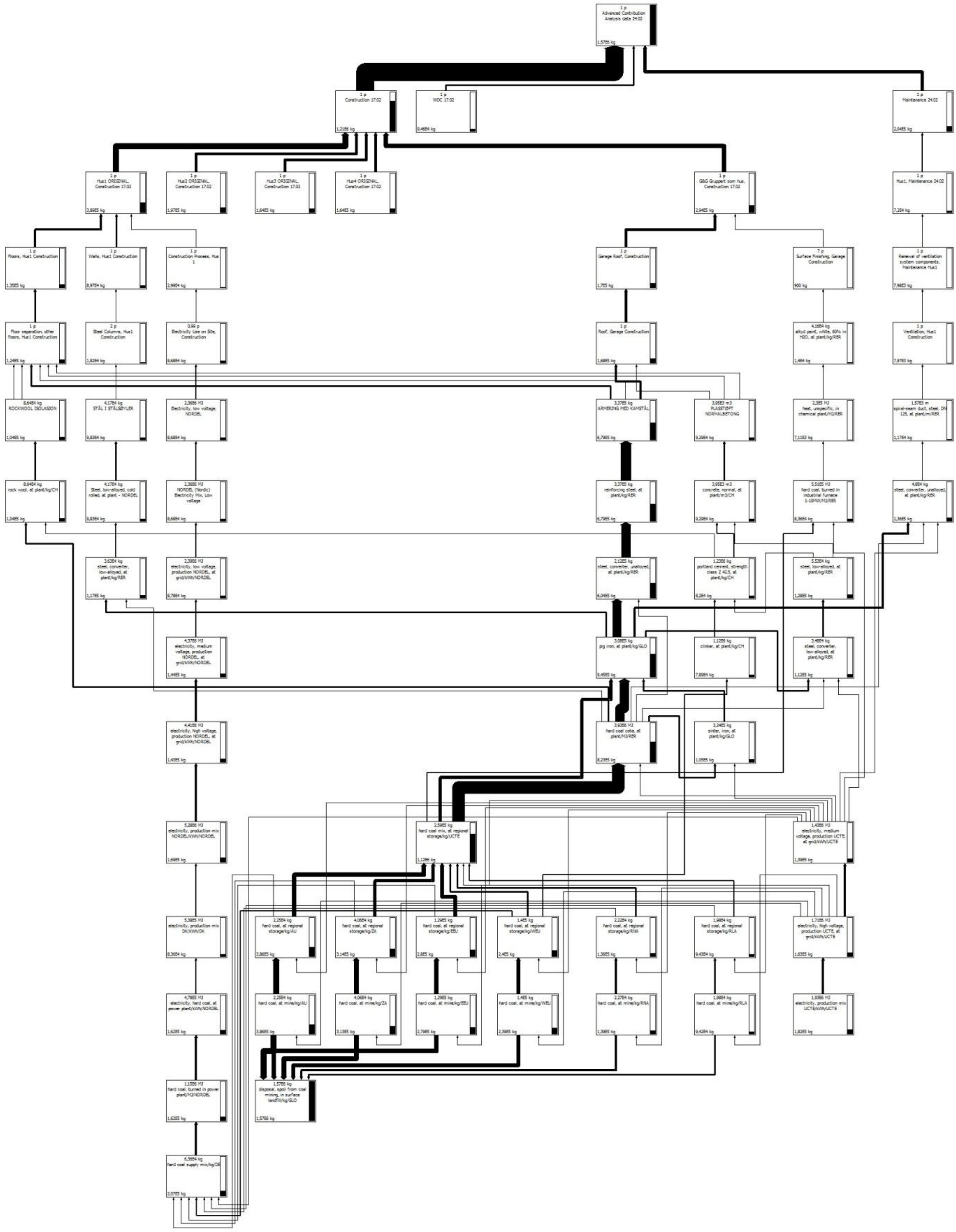
13.1.8 Steel Flow, Advanced Contribution Analysis



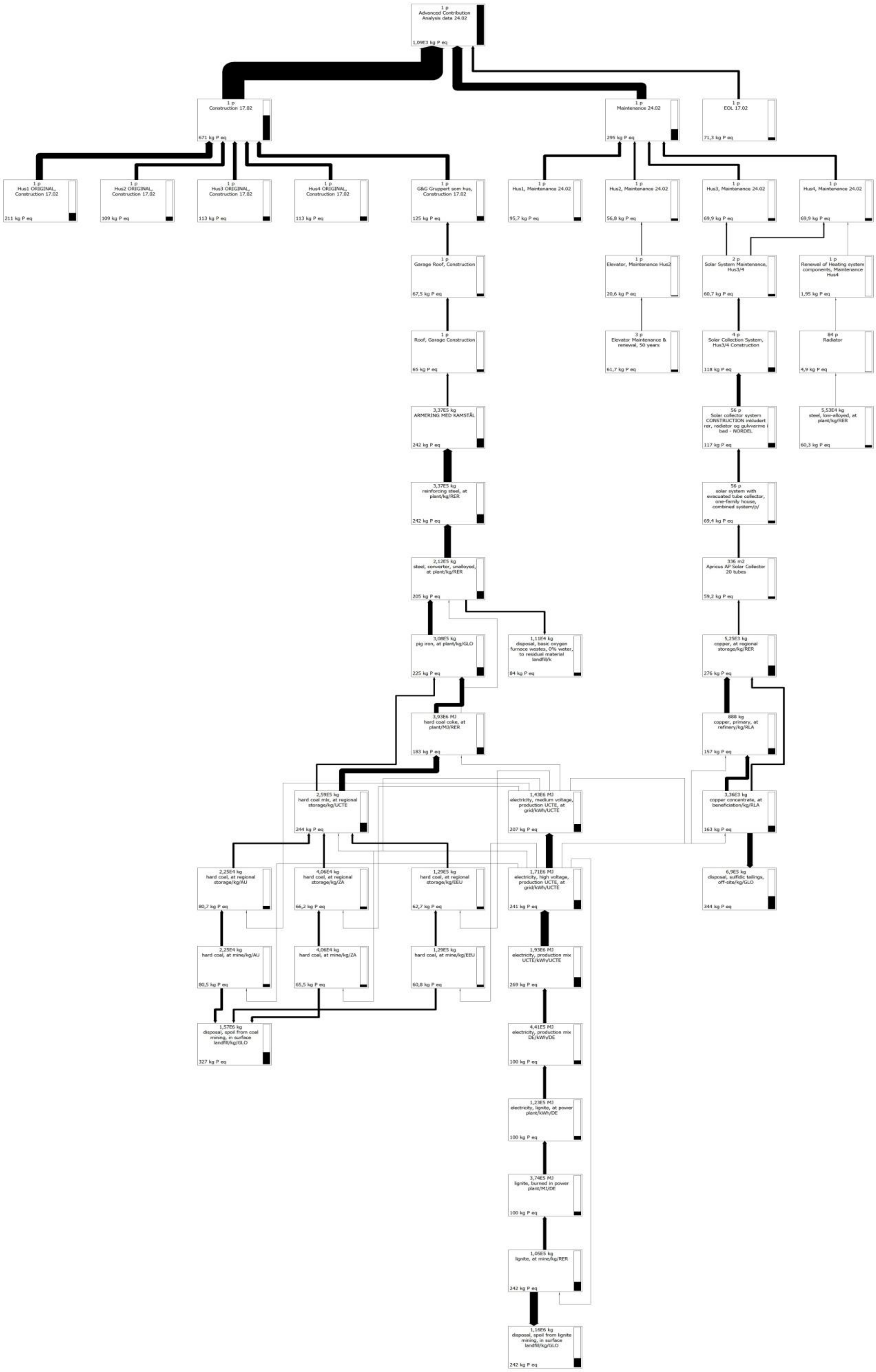
13.1.9 Terrestrial Ecotoxicity Impacts, Advanced Contribution Analysis



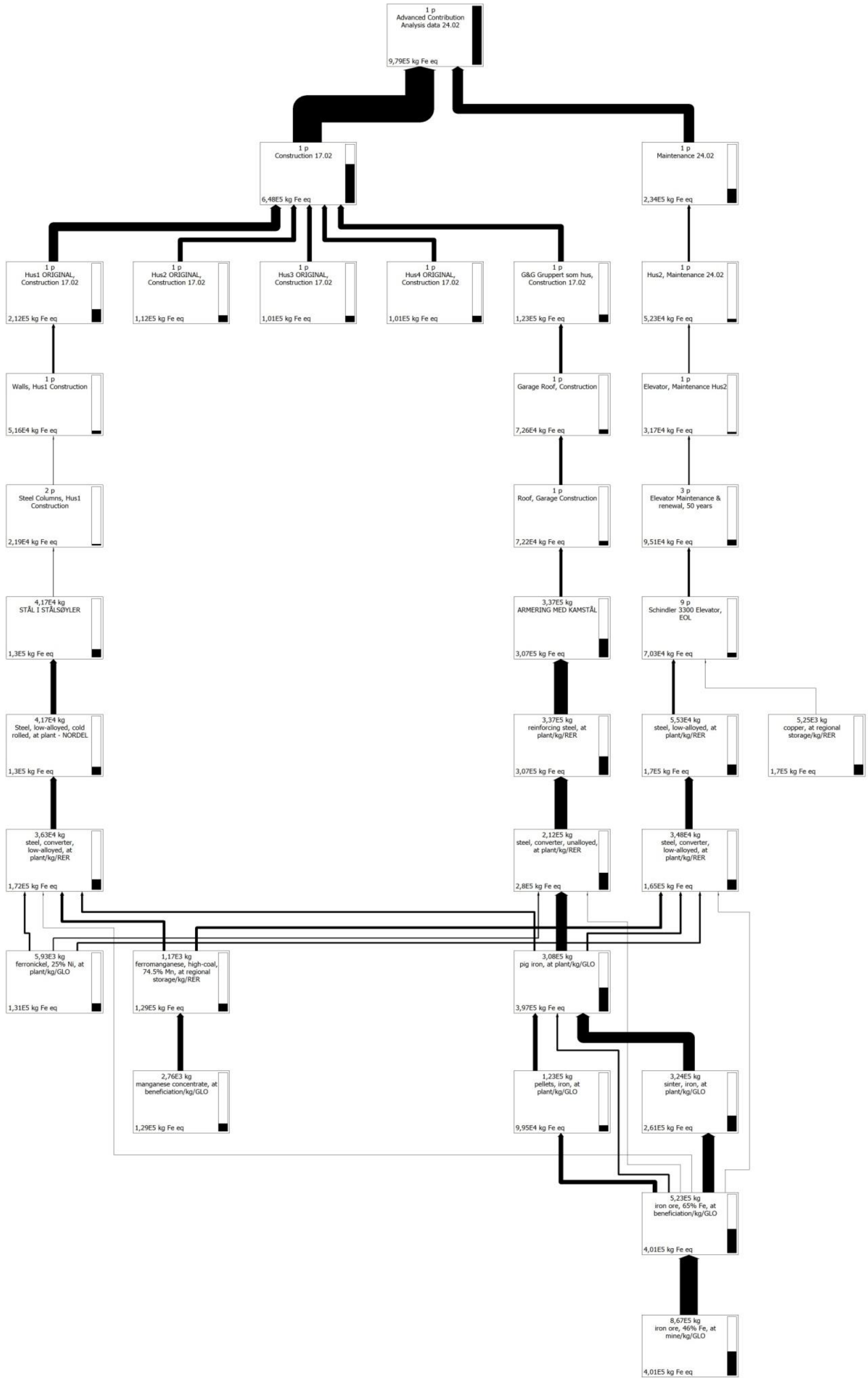
13.1.10 Flow of Disposal, Spoil from Coal Mining



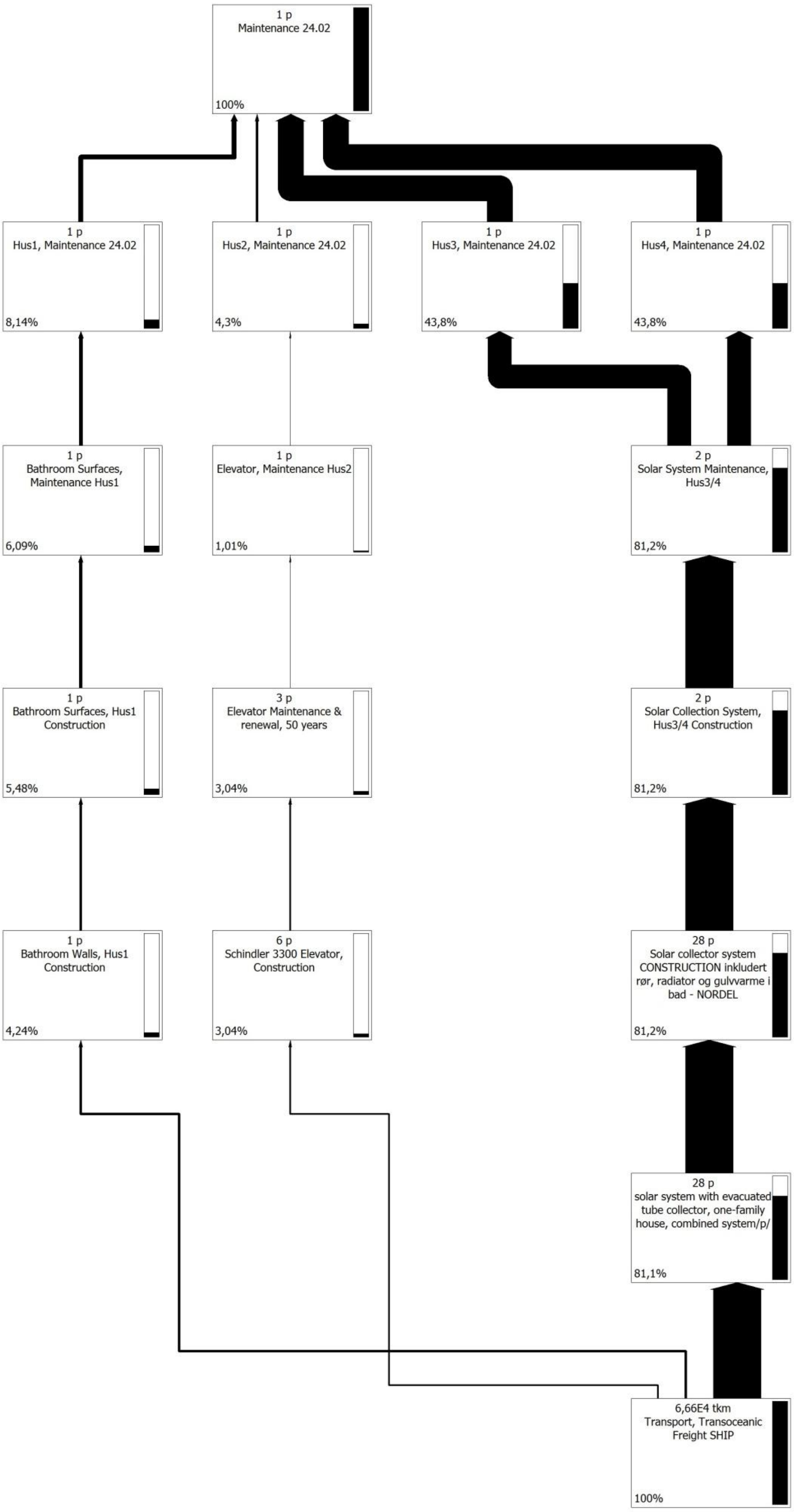
13.1.11 Freshwater Eutrophication Impacts, Advanced Contribution Analysis



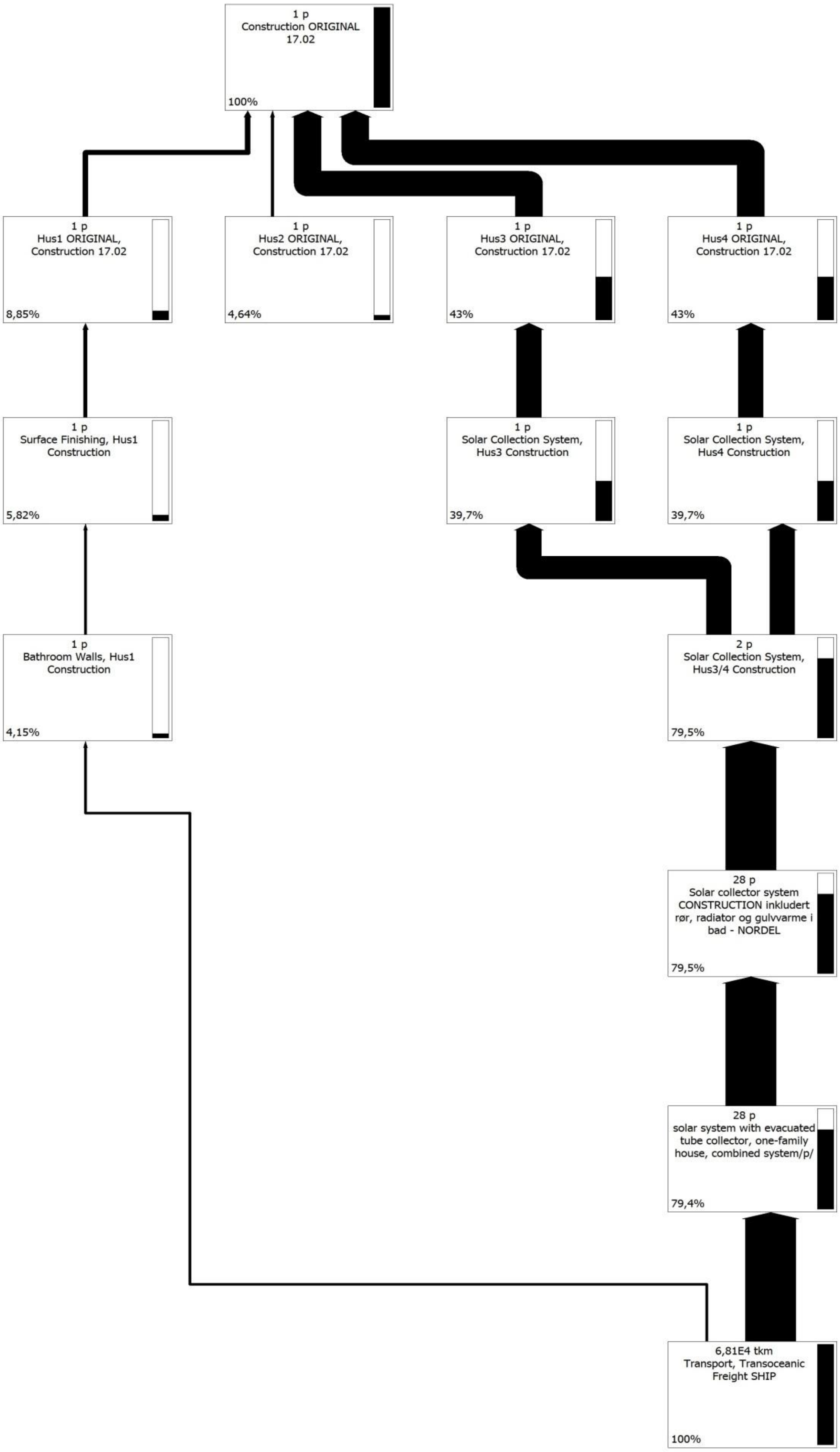
13.1.12 Metal Depletion Impacts, Advanced Contribution Analysis



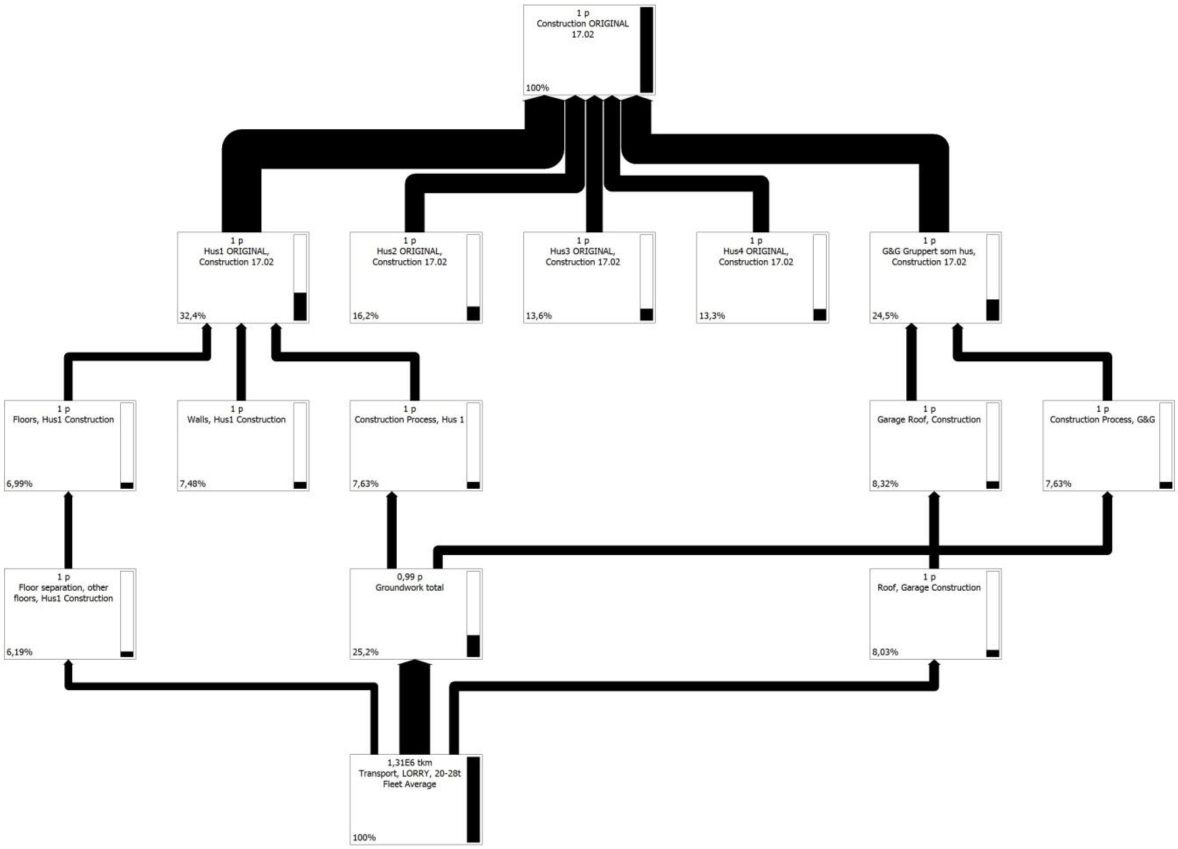
13.1.13 Sea Transportation Flow, Maintenance



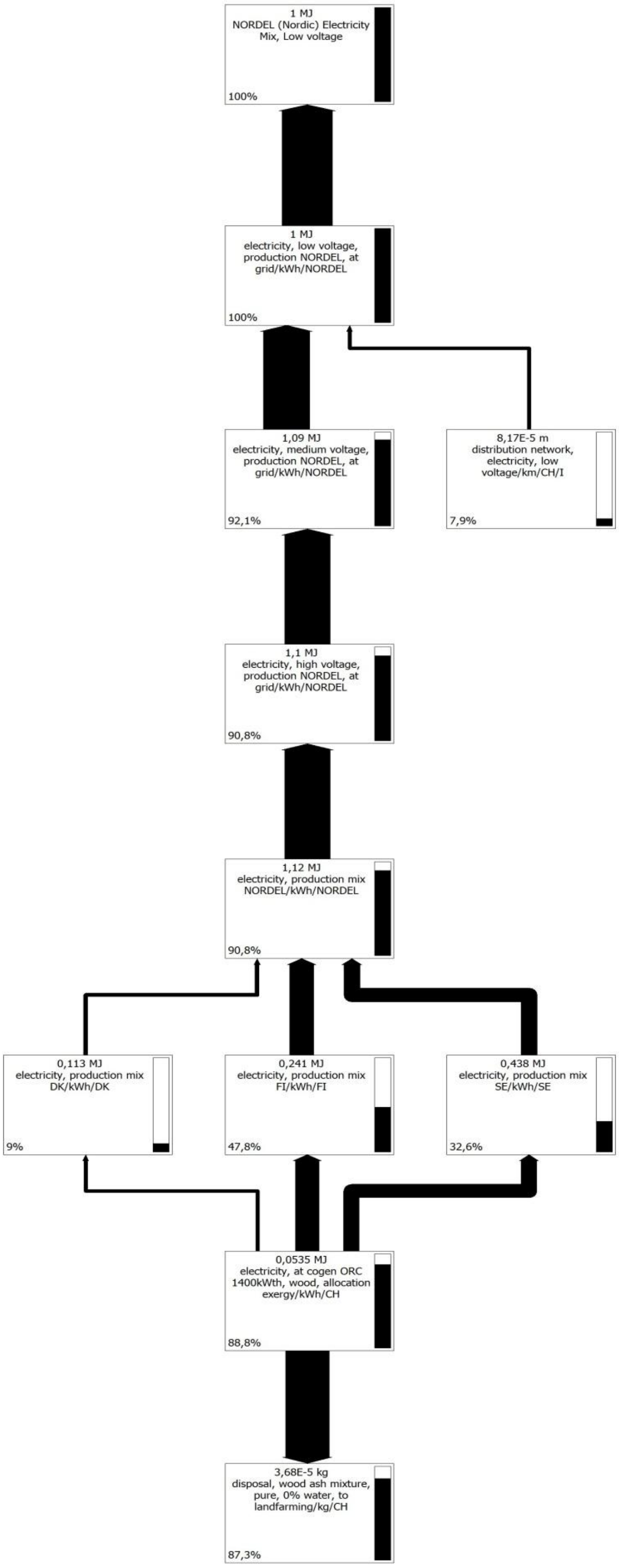
13.1.14 Sea Transportation Flow, Construction



13.1.15 Road Transportation Flow, Construction



13.1.16 Terrestrial Ecotoxicity Impacts, Nordic Electricity Mix



13.1.17 Comparison of Concrete Impacts