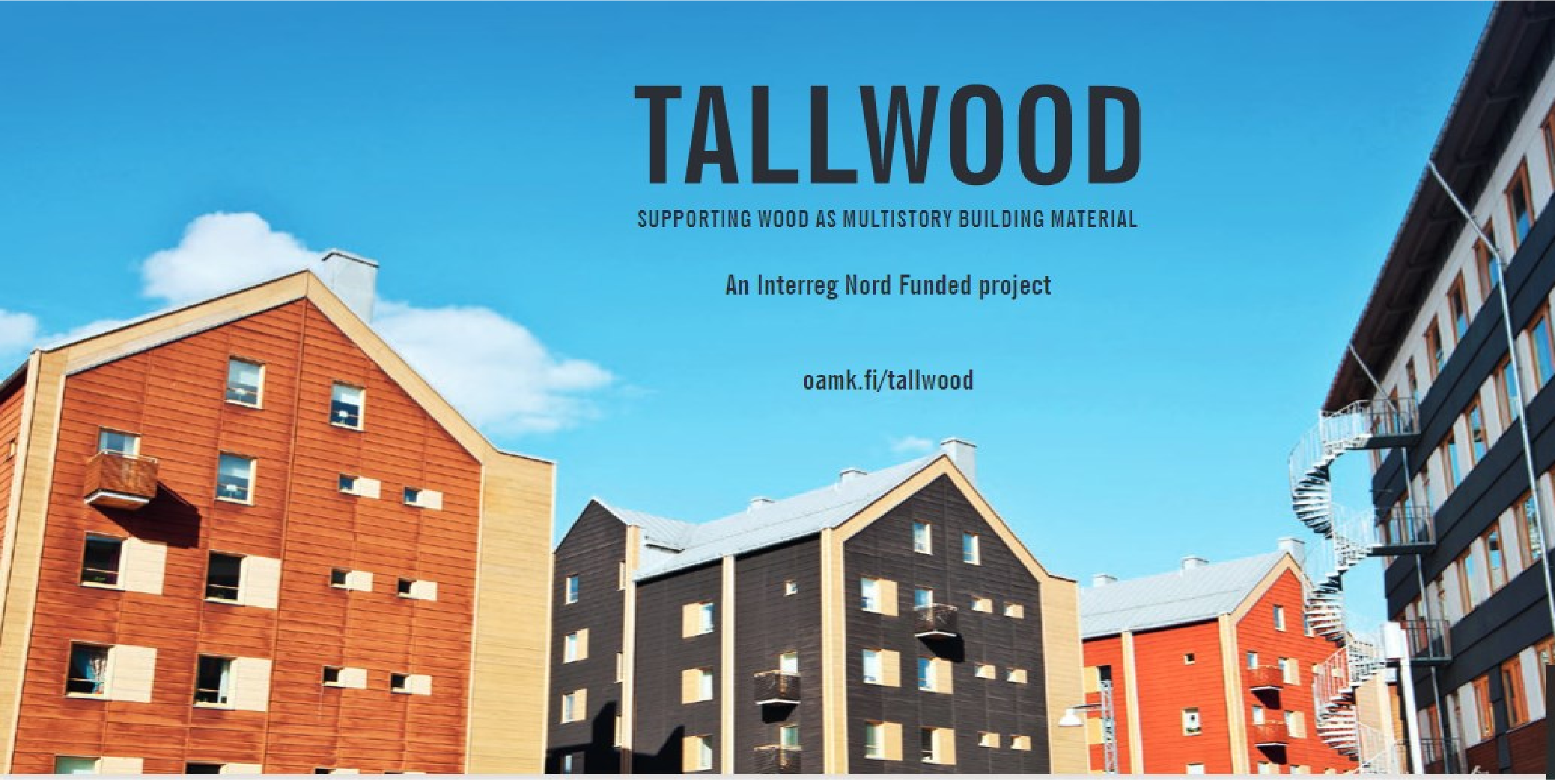


TALLWOOD: Towards LCA Reporting – Cross collaboration learning and understanding wooden buildings and performance measures

REPORT V 4.0

Authors: Dr Megan Palmer-Abbs (Lead) in Collaboration with Tallwood Project Partners

Contents

This Report is the result of collaboration work between a number of partners of the TALLWOOD project as follows:

Lead author, editor and LCA lead: Megan Palmer-Abbs (NRI)

Contributors: NRI team: Bjarne Lindeløv and Jarle Løvland (LCA contributor & project team)

RISE team: Sara Khanalizadehtaromi, Anders Gustafsson (LCA contributor & project team)

OULU team: Seppo Perälä, Vesa Pitsinki, Juho-Martti Vinkki, Antti Ukonmaanaho, and Arman M. Kouch (LCA contributor & project team)

LAPIN AMK Ferenc Kadar, Mourujärvi Katja, Valtteri Pirttinen (LCA contributor & project team).

Megan Palmer-Abbs (NRI)

01 Feb 0223

1 INTRODUCTION

The goal of the TALLWOOD project is to develop innovative solutions on how to use more wooden hybrid components in building and as structural elements of multistorey wooden buildings. These solutions will increase utilizing wood in multistorey/tall wooden buildings and consequently will reduce the carbon dioxide emissions and thus the environmental impact of building.

2 BACKGROUND

Research shows an excess of annual forest growth compared to annual harvesting especially in the Finnish, Swedish and Norwegian (particularly in northern regions) parts of the Nordic region. Nonetheless, the currently employed practices and technologies in the building industry demonstrate that there are even more opportunities to use wood in multistorey/tall buildings. The extra potential of using wood is not adopted significantly. There is a substantial need to prevent wood to be wasted and to be used effectively where it can environmentally and economically contribute the higher value. Therefore, the main goal of this project is to increase the usage of wood in multistorey/tall buildings solely or in a combination and/or hybrid way with other materials like concrete and steel particularly in structural elements.

Objectives

TALLWOOD will develop innovative solutions on how to use wooden hybrid elements in multistorey/ tall buildings. It will also explore and remove key barriers of the additional use of wood in construction. Furthermore, TALLWOOD will develop optimal cost-effective wooden hybrid solutions.

Impact

- A substantial knowledge transfer between the participating countries is established.
- Knowledge of using design and planning tools in wood construction and management is increased, thus enabling higher quality and shorter project terms.
- More compatible methods and systems help harmonizing building regulations between the countries and vice versa.
- Cross-border business in building industry and public sector services is increased by the higher interoperability of the information systems of different actors, thus resulting in more efficient use of Northern resources and more competition in the European building construction market.
- The increased use of wood resulting in cost-efficient wood/hybrid buildings.
- CO_2 emissions will be reduced.
- Energy efficiency and environmental issues will be improved.
- Knowledge of the public sector, supervision of buildings and other actors for planning multistorey/tall wood hybrid buildings will increase.

Work package 6 (WP6) of the TALLWOOD project was tasked 1) Supporting the development of LCA methods across the project partners, and 2) within the parameters of the project produce a Life Cycle Analysis (LCA) case study. The purpose of this report is to present the five case studies from collaboration partners for the TALLWOOD project. These outputs will include a description of the project location, design ethos and outcomes in terms of CO_2. Drawing from outputs from other WPs (WP3 Hybrid solutions and building component and WP4 Technical and scientific development) the report also links innovation and new knowledge to more sustainable building practices in wooden materials.

3. LITERATURE & NARRATIVE

The Construction industry has a significant environmental footprint consuming vast amounts of finite resources and responsible for circa 33% of all carbon emissions globally (Vestergaard Jensen, A and Craig, N , 2019). Buildings construction and operations accounted for 36% of global final energy use and nearly 40% of energy-related carbon dioxide (CO_2) emissions in 2017 (IEA and UNEP, 2018). Approximately 75% of all construction in Europe is residential (Hurmekoski, E, 2017).

Despite global political agreement to reduce harmful construction practices, progress has been very slow these past 20 years (Vestergaard Jensen, A and Craig, N, 2019; IEA AND UNEP, 2018). For example, the introduction of sustainable construction methodologies (e.g., Building Research Establishment Environmental Methodology (BREEAM), LEED, etc) has promoted some change in the right direction with flagship buildings and publicly funded projects. In terms of design principles, ten principal areas can be highlighted [Management, Health and Wellbeing, Energy, Transportation, Land Use and Ecology, Water Consumption, Materials, Waste management, Pollution, Innovation) (BRE,2021; EU, 2020). Whilst operational energy consumption has seen significant improvements (IEA and UNEP, 2018) the construction market has remained overall relatively unchanged in terms of the wider sustainable construction parameters (Vestergaard Jensen, A and Craig, N, 2019; IEA and UNEP, 2018). By this we mean mitigation of impacts from material resources and supply chain adjustments, design for deconstruction, waste reduction and biodiversity improvements, to name a few). It is also worthwhile noting a shift in the mainstream narrative surrounding sustainability. From the initial grappling with the three pillars of sustainability as per The Brundtland Report to current literature and associated discussion of sustainable circular design (UN, 1987; EU, 2020).

The impact of human activity on our planetary system(s) (e.g., climate change, resource depletion, biodiversity, etc) (IEA and UNEP, 2018) remains significant. Therefore, there is greater need than before to ensure decision making based on scientific fact is used to guide the construction industry towards more circular sustainable practices. Policy tools and instruments which inform, drive and encourage market change towards more circular design practices is required (United Nations, 2016). In this respect, the introduction of the Circular Building Design (EU, 2020) and increased use of Environmental Performance Certification (EPDs), LCA and related sustainable certification schemes (BRE, 2021, 2020, LEED, 2022; EU, 2020) simplifies and organises this complex field. The increased use of Life Cycle Analysis and policy instruments and tools is significant in driving this circular sustainable transition in construction. As is the funding of research and innovation projects such as TALLWOOD by the European Union[i] and national funding bodies e.g., Research Council of Norway.

Access to scientifically sound knowledge, methodologies and associated tools (BRE Green Guide, CAD, LCA modelling tools such as ONE CLICK, sustainable procurement, etc) bring decision making tools to mainstream whereby informed choices can be made in terms of sustainable circular design and 'best practices. (BRE, 2022, 2021; EU, 2020, ONE CLICK, 2022).

The use of wood in construction is promoted as part of the picture in reducing the impact of construction on the environment (Vestergaard and Craig , 2019; Gustafsson, 2019; ARUP, 2019). This approach relies upon a sustainable resource of wood. The UN policy review (2016) of the use of timber in construction '*Promoting sustainable building materials and the implications on the use of wood in buildings'* emphasised that most timber rich countries had effective sustainable wood management policies in place. However, these were in the main focused on production (ibid). In order to avoid the stagnation of promoting wood as a viable, competitive and sustainable building material, it is suggested a Life Cycle Assessment should be adopted (UN, 2016). By designing out key practices which are harmful and replacing these with more sustainable choices, the construction industry could significantly improve its environmental footprint (EU, 2020, IEA and UNEP, 2018). Part of this is the 'localising' of material resources in construction, timber construction lends itself well to this where an abundant and accessible supply is prevalent (Sweden and Finland, for example). The emergence of engineered wood products (EWP) such as Glue Laminated Timber (Glulam) and Cross Laminated Timber (CLT) in recent decades has *'increasingly been used also in large-scale construction'* (Hurmekoski, E , 2017). CLT, for example is light relative to its strength, and has a good capacity for thermal insulation and thermal storage (Gustafsson, A, 2019). The qualities of timber lend themselves very well to offsite construction (e.g., SIPS panels and fully integrated modular construction) (Vestergaard and Craig, 2019; UN, 2016; EU, 2020). In addition, reducing 'time on site' is known to offer significant cost savings and reduce waste in the construction phase (ARUP, 2019, (Gustafsson, A, 2019). These attributes make wood extremely competitive in the current construction market both in terms of environmental performance but also at a cost level. In addition, new timber-based materials also behave well under fire control tests, mitigating previous experiences with old construction methods and materials (Hurmekoski, E , 2017). From a circular economy perspective (Ellen MaCarthur, 2022; Raworth, K, 2018; United Nations, 2016) if managed appropriately, wood offers the ability to maximize the circulation of product, component, and material flows by reducing material input and waste, recycling, reuse, and sharing and maximize the value of materials (Gustafsson, A, 2019; BRE Global, 2022).

The following report is intended to add to narrtative about 'localising' the use of wood in construction in three northern areas in the Nordic Regions, namely norther Norway, Finland and Sweden.

3 LCA CASE STUDIES: an introduction

Five case studies were selected for the TALLWOOD project, each of varying designs. Two located in Norway (Ungdomskole Stokmarknes), two in Finland (Rovaniemi and Pudasjärvi) and one in Sweden (Skelleftea). It is understood the buildings were constructed within the last past 10 years.

Case study 1: DAS Kelo, Finland

Case study 2: Pudasjarven Hirsihovi, Finland

Case study 3: Ungdomsskole Stokmarknes, Norway

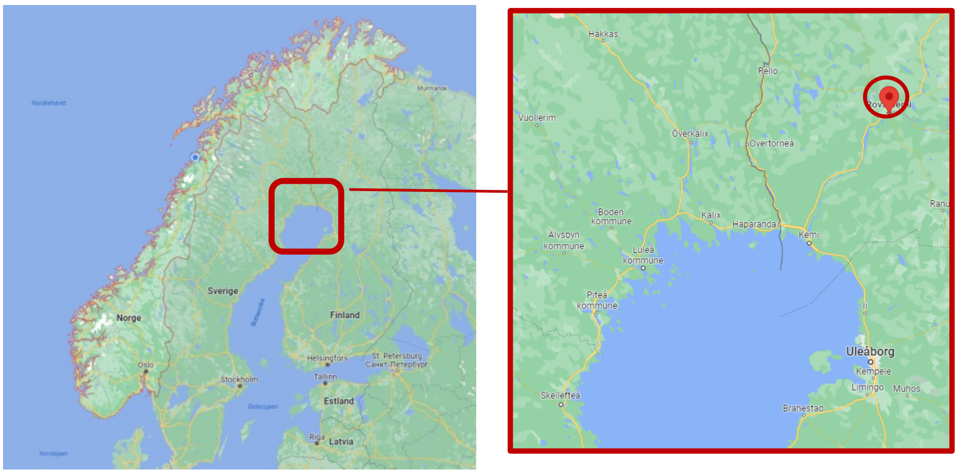
Case study 4: Alvsbacka Strand, Sweden

Each case study demonstrates particular characteristics associated with furthering of construction with wood. For example, Stokmarknes school benefitted from modular construction and CLT. Pudasjarven Hirsihovi applied a pioneering hybrid construction approach using digital design communications to speed up the factory construction process. Das Kelo (Rovaniemi) introduced space element approach a new technique for local builders whilst Alvsbacka Stranda (Skelleftea) adopted a CLT panel approach and environmental certification Miljöbyggnad Guld (Environmental Building Gold) approach)

3.1 Case study 1: DAS Kelo, Finland

Picture 1. DAS KELO (photo: Aaro Artto)

Romaniemi, is located in Finland's northernmost province, Lapland, and its southern part Peräpohjola and homeland of the indigenous Sami people. It is the administrative capital and commercial centre of the province and is located 6 km south of the Arctic circle. It is the second largest city in Finland next to Oulu, and the second most popular tourist destination next to Helsinki. The Das Kelo project is located in the city centre.



Map 1a & 1b: Source: Google Maps Finland and extract with Romaniemi in Northern Finland

The city is located in the municipality of Rovaniemen maalaiskunta, being a single entity as of January 2006. The urban area of Rovaniemi is roughly 59km2 with a population of 53 361. The surrounding areas houses up to 64,000 people. Many students live in the area due to the proximity to both the Lapland University and Lapland University of applied sciences.

DAS Kelo is the first CLT-built eight-storey student apartment building in Finland and Rovaniemi, also the most northerly wooden highrise building in Finland. It is a landmark for Rovaniemi in the middle of the campus area of the University of Lapland and Lapland University of Applied Sciences.

The implementation of the project included several actors, such as DAS (Domus Arctica Foundation) residents, student organizations, representatives of educational institutions, NEVE Oy (local energy company) and city officials.

3.2 Case study 2 Pudasjarven Hirsihovi Finland

Picture 2: Pudasjarven Hirsihovi

The Pudasjarven Hirsihovi project is located in Pudasjärvi, Finland in the northern part of the region of Northern Ostrobothnia. The central area of the city is called Kurenalus. Outside of Lapland, Pudasjärvi is boasts the largest total area of circa 5,867 km², of this 229km² is inland waters. It is the second largest city in Finland by area but due to its low population density, location and surrounding areas is considered rural.

Map 2a & 2b: Source: Google Maps Finland and extract with Pudasjärvi in Northern Finland

The main occupations of the city are largely based on the natural resources and their processing. Key industries include mechanical wood processing, tourism and rural entrepreneurship. The city boasts large companies in mechanical wood processing namely Kontiotuote and Profin. Kontiotuote Oy is a nationally significant supplier of log houses, Profin Oy is a supplier of windows and doors, whose products. Known for its Modern Log City project, Pudasjärvi has been pivotal in raising the profile of log construction in public construction. Based on this industry capability, preconditions have been established which underpin log construction research. The project was part of the University of Oulu's Modern Log City – New Architecture, Mass Customization and Life Cycle Economy of Log Buildings project. The Pudasjärvi site is the first of the log apartment buildings in Finland.

3.3 Case study 3: Ungdomsskole Stokmarknes, Norway

Picture 3: Ungdomsskole Stokmarknes

The small town of Stokmarknes is situated on the northern coast of the island of Hadseløya, Vesterålen and on the small, neighbouring island of Børøya. It is the administrative centre of Hadsel Municipality in Nordland County, Norway. The town covers an area of 2.47-square-kilometre (610-acre) with a population of 3,367 (2018). It is the administrative centre for the municipality.

It is linked by bridges to the island of Langøya to the north (Børøy Bridge and Hadsel Bridge). The Stokmarknes Airport (Skagen) is located on Langøya. By Norwegian standards this is a peripheral and remote location experiencing arctic and coastal weather conditions, including long dark winters. The Ungdomsskole Stokmarknes school is located in the town, housing the years 1-10 of the Norwegian education system (junior and senior school).

Map 3a&3b: Source: Google Maps Norway and extract with Stokmarknes area in NW Norway

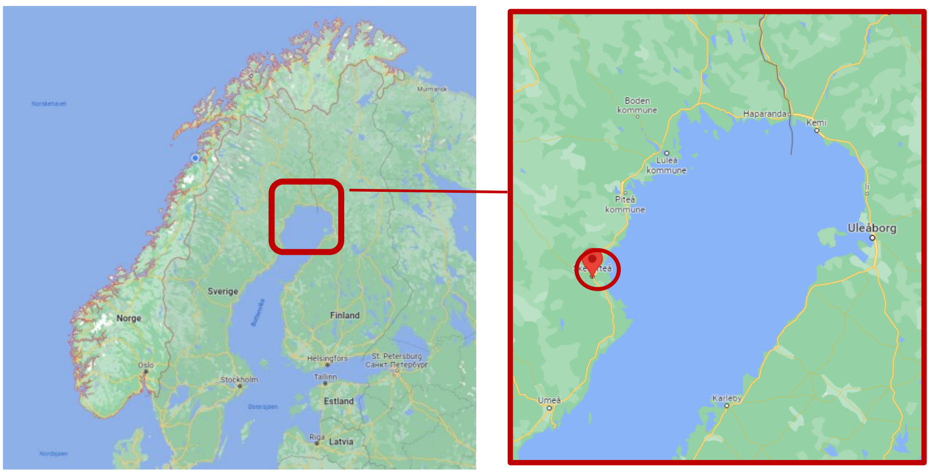
Stokmarknes school is a new school constructed from CLT in a response to national and local policy aspirations to build more sustainably with wood (Hurmekoski, E , 2017; United Nations, 2016). The idea for the project was developed around the same time as Indyr, Gildeskal project. To this end, it was part of the same regional push to develop more sustainable skills in the construction industry and pilot some schemes which could act as flagship projects in the use of timber in Nordland. Again, the objectives were to upskill current construction organisations, reduce supply chains and stimulate competition in sustainable construction.

3.4 Case Study 4 Alvsbacka Strand, Sweden

Picture 4: Source: trastad.se Älvsbacka strand, Skellefteå.

Skellefteå is a city in Västerbotten County, Sweden and is the administration centre of the Skellefteå Municipality boasting a population of 73,246 (2021).

Historically the city was industrial, mainly mineral extraction (especially gold). It is the second largest city in Västerbotten, located on Skellefte River. It is located around 15 kilometres (9.3 mi) from the Bothnian Bay and halfway between Umeå and Luleå. Skellefteå. Falmark is roughly 15km from Skellefteå where Skellefteå Airport is located. The surrounding region boasts southern Sami indigenous people and many natural resources, including timber.



Map 4a&4b: Source: Google Maps Sweden and extract with Skellefteå in NE Sweden on the Baltic

The local area benefits from natural resources such as timber, reflected in is core industries and research and development organisations such as RISE and Luleå University of Technology. R&D is closely aligned to the local timber industry covering areas such as testing and technical performance and skills training.

Recognised for its historical and contemporary wood construction skills, Skelleftea boasts the Lejonströmsbron wooden bridge which spans the Skellefte River and is the oldest wooden bridge in

Sweden. The city also boasts the contemporary Wood Hotel a 20 storey CLT building completed in 2021. The city has protected the old farmers housing (Bonnstan) and many other wooden structures remain making the city a mecca for wood construction. The Älvsbacka strand building is located in Skellefteå, in a nice residential area near the riverbank in central Skellefteå.

4 Section 4 Method

4.1 Objective of the TALLWOOD Life Cycle Analysis (LCA)

The WP 6 brief of the project sought LCA studies on a number of cases studies from the three Nordic countries (Norway, Sweden, and Finland). The intention of the LCA process of the TALLWOOD project was twofold, first to share knowledge and upskill partners in the LCA process, and second, to record a certain level of data about the building performance. Due to the nature of the project and timing of the involvement of the project partners with the case studies, the scope of the LCA study ONLY focuses on the building structure and does not include other LCA parameters available in the ONECLICK LCA tool. For example, building services and external site activities (see table 6.1.2).

Five studies were identified by project partners with four attaining suitable data for the LCA calculations (albeit with reduced scope). The studies were third party projects (mainly municipality partners) and either completed or near completion at the time of the TALLWOOD project. Close collaboration between the TALLWOOD project teams (NRI; RISE; OULU & LAPIN AMK) and local partners secured information on the design and construction.

The method for the LCA work in the project was actioned in four stages as follows:

Stage 1: Scoping of the project and understanding the context of the case studies.

Stage 2: Scoping the case studies and a suitable method for the LCA work.

Stage 3: Collection of Data.

Stage 4: Data analysis and report writing.

The following is a description of these activities.

4.2 Stage 1: Scoping of project

The scoping of the TALLWOOD case studies was collaborative process with all WP partners. This process started at the onset of the project with partners securing potential projects which reflected the core objectives of the TALLWOOD Project (namely timber and hybrid construction and potential to test for problematic issue of timber construction e.g., moisture control measures, noise abatement, and technical issues such as CLT strength). This stage of the project ran for approximately 2 years (2019-2021).

4.3 Stage 2: Scoping the case studies and a suitable method for the LCA work

Since 2020 NRI developed project case study templates for each partner to complete based on the stages of circular sustainable construction [A1-A3 (product stage) A4-A5 (construction process stage) B1-B5 (use stage) C1-C4 (end of life stage) and the potential for D (benefits beyond system (recycle, recovery and recycling potential). The template also included innovation sections, noise abatement, moisture management and robustness to map other aspects critical to improving wooden construction performance.

Parallel to this work a scoping exercise was undertaken to secure a suitable LCA methodology. It was not the intention of the project to produce an LCA tool. The scoping exercise included a literature review of current methods and tools which could support the required work. It was essential that the adopted LCA tool complied with EU accreditation system(s)and therefore could be considered a reasonable 'off the peg' tool for the TALLWOOD LCA calculations. Tools such as BREEAM and LEED were considered too niche for the task. Partner projects such as INTERREG project Indu-Zero offered linkages to colleagues at Strathclyde University who, with BRE, had co developed a new modelling tool - ESP-r. This tool had many capabilities not least the capability for LCA and building performance calculations (thermal modelling etc). However, the tool was considered too niche for the TALLWOOD project needs. ONE CLICK LCA was considered the best tool on the market as many aspects of the tool incorporated some capabilities seen in BREEAM and LEED processes. That said, it was acknowledged it did not offer a bespoke accreditation of the building(s) performance should therefore not be represented as an equal assessment tool to BREEAM or LEED (or similar).

THE ONE-CLICK LCA tool did offer access to tools such as the BRE Green Guide to Specifications (environmental performance of building elements) and was a BRE accredited tool to EN 15978 standards. The ONE CLICK LCA has been third party verified by ITB for compliancy with the following LCA standards: EN 15978, ISO 21931–1 and ISO 21929, and data requirements of ISO 14040 and EN 15804. The full compliancy documentation is available at

https://www.oneclicklca.com/support/faq-and-guidance/documentation/compliancy-and-certifications/.

The tool covered all the areas of the LCA parameters and offered extensive access to national data and Environmental Product Declaration data of products. If required, generic transportation data for the value chain could be drawn upon. However, given the location of projects in the High North of Nordic countries and local supply chains for some timber products, this was seen only as a backup should data be unavailable.

4.4 About the assessment software

The assessment has been carried out with ONE CLICK LCA software and the following narrative is an adaptation from the ONE-CLICK LCA methodology statement (sections 4.4-4.6). This has been used to ensure appropriate representation of the ONE-CLICK LCA method but is attributable to the organisation. The software holds 11 third party certifications and complies with over 30 certifications and standards for Life Cycle Assessment and Life Cycle Costing, including all versions of LEED and BREEAM. The software includes curated and verified global and local databases. The up to date list of integrated databases can be found here: https://www.oneclicklca.com/support/faq-and-guidance/documentation/database/.

ONE CLICK LCA has been third party verified by ITB for compliancy with the following LCA standards: EN 15978, ISO 21931–1 and ISO 21929, and data requirements of ISO 14040 and EN 15804. The full compliancy documentation is available at

https://www.oneclicklca.com/support/faq-and-guidance/documentation/compliancy-and-certifications/.

ITB is a certification organization and a Notified Body (EC registration nr. 1488) to the European Commission designated for construction product certification. Polish Accreditation Board assures the independence and impartiality of ITB services (Accreditation Certificates are: AB 023, AC 020, AC 072, AP 113). ITB activities are conducted in accordance with the requirements of the following assurance standards: ISO 9001, ISO/IEC 27001, ISO/IEC 17025, EN 45011, and ISO/IEC 17021.

The tool supports CML characterization methodology as well as TRACI characterization methodology. All the datasets in the tool comply with ISO 14040/14044 and most part also EN 15804 standard.

4.5 Life Cycle Assessment methodology

4.5.1 About Life Cycle Assessment for construction industry

As businesses, governments and consumers develop environmental awareness and sensitivity, focus of environmental impact reduction shifts to the industries responsible for the greatest impacts.

Construction, maintenance and use of buildings and civil engineering works generate ca. 35 % of the carbon emissions globally. Furthermore, the industry is responsible for one half of raw material extraction, and very significant amount of mass replacements and transfers. The sector is not only requested to reduce the impact on global warming, but also to reduce the raw material depletion, especially for non-renewable materials via circular economy measures.

Life Cycle Assessment is a science-based methodology for measuring environmental performance. It's based on international standards and rigorously defined public methodologies for quantifying environmental impacts, expressed in form of potential harm caused by activities to the biosphere, including atmosphere, soil and water bodies. Those impacts are expressed as "equivalent to" normalized unit, for example, one kilogram of carbon dioxide in case of global warming potential.

Life Cycle Assessment considers the whole life cycle of the building, including manufacturing, transport, use and final disposal of the resources required for the delivery of the building functions for the whole period which the assessment covers.

Most common impact category covered by LCA is the global warming potential, also referred to as the carbon footprint. It quantifies the impact of greenhouse gases heating the planet. Other common impact categories are ozone depletion, acidification, eutrophication and smog formation.

LCA methodology also supports other indicators which describe the use of resources and energy. Those are more typically expressed as kilograms of material, or megajoules in case of energy.

4.5.2 Applicable International and European Standards

All building and civil engineering works Life Cycle Assessments delivered by ONE CLICK LCA platform comply with the following International Standards.

ISO 14040 Environmental management. Life cycle assessment. Principles and framework

ISO 14044 Environmental management -- Life cycle assessment -- Requirements and guidelines

ISO 21930 Sustainability in buildings and civil engineering works -- Core rules for environmental product declarations of construction products and services

ONE CLICK LCA platform tools used in European context comply with following European Standards:

EN 15978 Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method.

EN 15804+A1 Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products

4.5.3 System boundary

The International Standard ISO 21930 and European Standard EN 15804 set out a common life-cycle model for building and construction works. The life-cycle model includes modular definitions for the life-cycle stages, allowing each stage to be compared in isolation with other projects.

The product stage information (A1-A3) is always represented combined for building level assessments, as are end of life stages (C1-C4) in most cases. Depending on the purpose of the LCA, other stages may be omitted or be replaced with a scenario in absence of detailed information.

The actual life cycle stages used in the report are outlines in this chapter (chapter 6) with additional project specific details clarified in chapter 8.

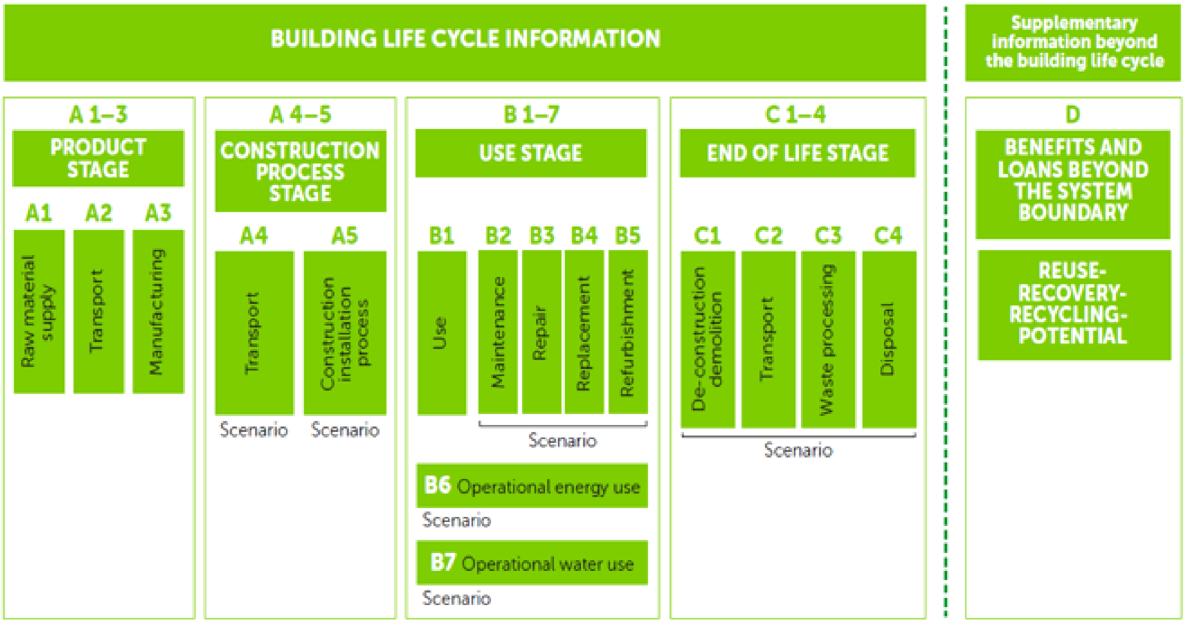


Figure 4.1: Source: ONE CLICK reporting tool: Building Life Cycle Information and life cycle stages.

4.5.4 Methodology and impact categories

LCA results are obtained using methodology called characterisation, which describes environmental impact of a given emission. ONE CLICK LCA implements multiple characterisation methodologies. When no specific methodology is mandated, ONE CLICK LCA implements for European customers the CML 4.1. IA characterisation methodology (as set out in EN 15804+A1), and for North American customers the TRACI 2.1. methodology defined by United States Environmental Protection Agency.

Impact category	Unit(s)	Description
Global warming potential	kgCO2 eq	Describes changes in local, regional, or global surface temperatures caused by an increased concentration of greenhouse gases in the atmosphere. Greenhouse gas emissions from fossil fuel burning are strongly correlated with acidification & smog. Called "carbon footprint".
Acidification potential	$kgSO_2$ eq	Describes the acidifying effect of substances in the environment. Substances such as carbon dioxide dissolve readily in water, increasing the acidity and leading to damage to water ecosystems.
Eutrophication potential	CML: $kgPO_4$-eq TRACI: kgNeq	Describes the effect of adding mineral nutrients to soil or water, which causes certain species to dominate an ecosystem, compromising the survival of other species and sometimes resulting in die-off of entire animal populations.
Ozone depletion potential	$kgCFC_{11}$eq	Describes the effect of substances in the atmosphere to degrade the ozone layer, which absorbs and prevents harmful solar UV rays from reaching Earth's surface.
Formation of ozone of lower atmosphere ("tropospheric")	CML: kgC_2H_4eq TRACI: kgO^3eq	Describes the effect of substances in the atmosphere to create photochemical smog. Also known as summer smog.

Table 4.1: SOURCE: ONE CLICK Reporting tool: Other impact categories follow the requirements of their respective certification systems or tools.

4.6 Analysis scope, data sources and assumptions

4.6.1 Scope applied for this study.

The LCA assessments in this study follow the BREEAM Mat 01 Life Cycle Assessment requirements, for the building for life span of 60 years. The scope for the LCA studies in this report have been calculated retrospectively at the post construction stage of each project. Therefore, some of the data typically collected at the early stages of such projects have not been available (e.g., construction site activities). Where possible ONE CLICK generic data has been used to make 'assumptions' for missing data. In general, these areas are material transportation, site construction activities, material replacement and end of life scenarios. Some of the case study projects benefited from local resources and offsite construction and it is assumed these savings would not be accounted for in the ONE CLICK tool. Mechanical and Engineering works have also been discounted due to limited data access. These parameters are discussed in context for each case study in section 5.

N.B. It is suggested a wider scope of LCA assessment is undertaken which covers all of the LCA parameters (external site and biodiversity, etc) offering greater scope to benchmark the project against other LCA assessments.

4.7 Data sources

The analysis has been performed relying on the following data sources for building information:

Data type	Data source
Material quantities (A1-A3)	Construction drawings, bills of quantities and BIM models as delivered by the client and the designers acting on the clients behalf.
Material transport distances (A4)	Regionally applicable transportation scenarios from ONE CLICK LCA. Those represent regionally typical transportation distances and methods for product types, which are relevant when no decisions on suppliers are made.
Construction and installation (A5)	Impacts are based on conservative default values from ONE CLICK LCA.
Material impacts in use (B1-B5)	Material service lives are based on the typical values for the materials in question, which have been reviewed for relevance for the project. The values have been adjusted where necessary. Material maintenance and repair activities have not been included in the scope; materials have been assumed to be replaced in their entirety at the end of their service life.
Use phase energy consumption (B6)	Impacts are based on annual consumption data received from each project team and partners. Typically, from Building Management System (BMS) outputs
Use phase water consumption (B7)	Impacts are based on annual consumption data received from each project team and partners. Typically, from Building Management System (BMS) outputs
End of life impacts (C1-C4)	End of life impacts are based on ONE CLICK LCA's scenarios which represent the typical end of life processing for material types in compliance with the requirements of the EN 15804+A1.

4.8 Stage 3: Collection of Data.

Megan Palmer-Abbs (NRI) has extensive experience of LCA assessments in industry and established the scope and support measures for the collection of data required to complete the LCA assessments (e.g., excel data collection sheets). The data collection was an iterative process between the project partners (RISE, OULU, Lapin, and Nordland project partners (county governor and construction companies). Data was collected, reviewed, and final agreement of completed data confirmed). This ensured both quality control of the data and a comparative data collection process was applied.

Simultaneously, project partners who were new to calculating LCA undertook LCA training with ONE CLICK suitable to use the ONE CLICK LCA software for their LCA.[1] Where required Megan Palmer-Abbs (NRI) liaised and supported project partners on scope of LCA, data gathering and final outputs.

NRI undertook the LCA tests for two case studies namely Stokmarknes (Norway) and Skelleftea (Sweden). The Swedish case study was conducted in close cooperation with partners RISE. Whilst partners Oulu (Case study 2: Pudasjarven Hirsihovi) and Lapin AMK (Case Study 1: Das Kelo) undertook the Finnish LCA tests, running similar data collection methods, data entry and project parameters respectively.

4.9 Stage 4: Data analysis and report writing.

The data entry stage consisted of a number of steps 1) cleaning up the project data suitable for entry in to the ONECLICK Tool, and 2) Setting up the LCC and LCA parameters in the ONE CLICK tool suitable for each partner to enter their data in a similar method and complete the validation checks in the LCA tools.

Data outputs covered [A1-A3 (product stage) A4-A5 (construction process stage) B1-B5 (use stage) C1-C4 (end of life stage). Stage D (benefits beyond system (recycle, recovery and recycling potential) if applicable are reported in the relevant case study. All case study outputs from the ONE CLICK LCA tool were checked for anomalies and amended where required. Data analysis was then undertaken, the findings of which are presented in section five of this report and a summary in section 6.

[1] ONE CLICK training: *The tool and support services provided by ONE CLICK delivered training and a support suitable for professional with some skills in construction and acted as an upskill and learning task for the LCA methodology.*

5 LCA STUDY

5.1 Case study 1: DAS Kelo, Finland

5.1.1 BRIEFING

The DAS Kelo project objective was to provide a student-residential apartment building close to the campus areas. The core aim of the design for DAS Kelo was that it should be cost-effective, energy-efficient, and a healthy place to live.

DAS and the City of Rovaniemi wanted to improve the attractiveness of the campus area by creating an ecological and innovative high-rise building. In meeting this aim, the DAS Kelo building adopted space elements or an offsite modular construction approach. At the time, this was a relatively new way of building wooden high-rise buildings in Finland.

A multifunctional building, the first floor comprised of the offices of the Domus Arctica Foundation (DAS), storage facilities, technical facilities, common areas, a washroom, and an air-raid shelter. Floors two to eight accommodated the student studio apartments of 25,5m2, 30,5m2 and 31.5m2 each fitted with French balconies. The eighth floor also benefited from social space, namely a common sauna, and common areas and a cooling balcony with a gross floor area of 4 583 m2.

5.1.2 INNOVATION

The approach to this project sought to maximise the use of modular offsite construction, thus reducing overhead costs and weather-related delays on the project. The project design approach used four different space elements that made it very cost-effective. Where structures could not be constructed under factory conditions on site innovation was used to minimise negative impacts e.g., delays or damage due to adverse weather conditions. Using an innovative project management approach, the project adopted an interesting method to protect the construction site, and this reduce climatic impact on the materials. The offsite preconstructed roof elements were erected and used as a roofing (protection system) for the construction of the eight-storey space element assembly. This was achieved by assembling the roof and then using it as a canopy for each floor as the space elements were brought onto site. As each floor was completed the roof was raised to enable the assembly of the next floor until such time as the final roof position was achieved.

High quality energy performance has been achieved by fitting modern house automation, solar panels, and heat recovery from the wastewater.

5.1.3 LCA ANALYSIS

The post construction LCA analysis was carried out on the 21/10/2022 using the ONE CLICK LCA tool v Version: 0.7.1, Database version: 7.6. An LCA, LCC and embodied carbon analysis was completed. Only basic construction data was offered by partners LAPIN AMK due to the nature of the project. Between 80-90% of total materials for each building element was assessed, these being the largest by volume for the building. Due to limited information certain elements were not accounted for or where out of scope for the project e.g., external areas and services. Some parameters have been calculated using the ONE CLICK generic data: namely the transport leg from resource origin to manufacturer, building services and life span of materials. Most data sets used were from Finland and locally resourced data. Where local supplier data could not be found the nearest material profile from the ONE CLICK LCA data base.

It is acknowledged that the offsite construction element of the design approach may not be fully accounted for by the ONE CLICK tool. In real terms there may therefore be some deviation from the final ONE CLICK calculations.

5.1.4 OUTCOMES

OUTPUTS from the ONE CLICK LCA tool indicate a rating of 183 kg/CO_2e/yr which is significantly below the benchmark for the A rating of <250 kg/CO_2e/yr. The total assessed carbon for the project was 2 965 TONS CO_2 and 12.94 kg CO_2/m^2/year with a social carbon cost of 148 231€.

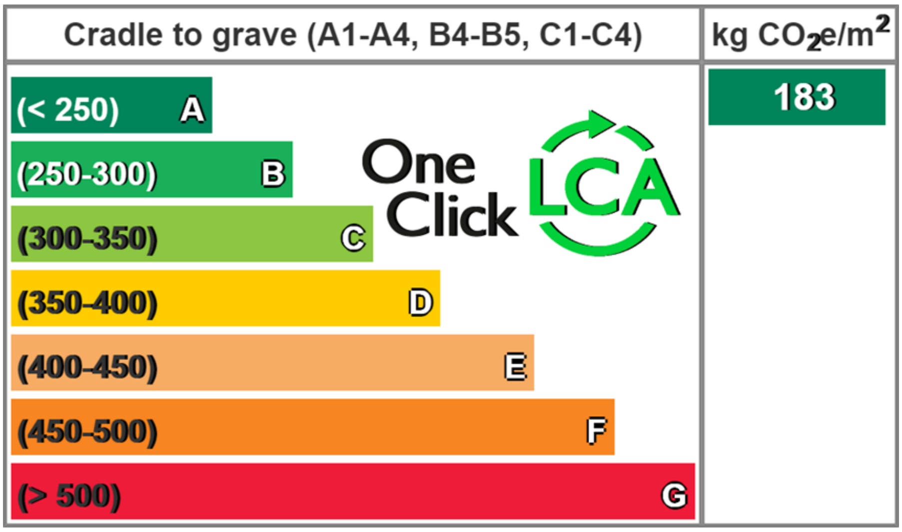


Illustration 5.1a DAS Kelo Embedded carbon: CO_2 rating

As illustrated in table 5.1a (below) The breakdown of the data reveals that (C1-C4) End of Life management accounted for 8.7 kg/CO_2e, (B7) water use 5.39kg/CO_2e, (A1-3), construction site processes 4.93 kg/CO_2e (A1-3), construction installation process (A5) 4.83 kg/CO_2e, with material replacement and refurbishment (B4-B5) 2.61 kg/CO_2e.

All other elements were relatively small contributors to the carbon LCA of the building.

In terms of other environmental impacts, energy consumption (B6) is the largest contributor to acidification at 9.49 kg SO_2e, construction /installation (A5) to eutrophication at 4.31 kg PO_2e and water use (B7) to ozone depletion at 5.89 kg CFC11e. Whilst material replacement and refurbishment (B4-5) is the largest contributor to lower atmospheric formation of ozone at 6.52 kg Ethanee and water use (B7) at 6.02 MJ.

Best performance was end of life (C1-4) for acidification at 1.38 kg SO_2e, ozone depletion at 1.19 kg CFC11e and ozone at 1.06 kg Ethanee. Whilst material replacement/refurbishment (B4-5) performed well for eutrophication at 1,34kg PO_2e and energy consumption (B6) for abiotic depletion potential at 1.91 MJ).

Life-Cycle Assessment for Level(s) in compliancy with EN 15978 Download Results Summary

	Result category	Global warming kg CO_2e	Biogenic carbon storage kg CO_2e bio	Ozone Depletion kg CFC11e	Acidification kg SO_2e	Eutrophication kg PO_4e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ	
A1-A3	Construction Materials	4,83E5	9,26E5	3,66E-1	1,55E3	3,71E2	1,5E2	1,19E2	5,63E6	Details
A4	Transportation to site	2,04E4		3,91E-3	8,09E1	1,75E1	1,55E0	1,18E2	5,19E5	Details
A5	Construction/installation process	4,93E4		3,21E-3	1,52E2	4,31E1	1,34E1	1,65E1	5,79E5	Details
B1	Use phase									Hide empty
B3	Repair	0E0		0E0	0E0	0E0	0E0	0E0	0E0	Details
B4-B5	Material replacement and refurbishment	2,61E5		3,44E-1	6,11E2	1,34E2	6,52E1	1,15E2	2,38E6	Details
B6	Energy consumption	2,01E6		4,22E-1	9,49E3	1,58E3	4,59E2	7,44E-1	1,91E7	Details
B7	Water use	5,39E4		5,89E-3	2,92E2	1,48E2	1,31E1	1,9E-1	6,02E5	Details
C1-C4	End of life	8,7E4		1,19E-3	1,38E2	3,79E1	1,06E1	4,51E1	3,31E5	Details
D	External impacts (not included in totals)	-4,95E5		-7,16E-4	-4,64E2	-9,6E1	-4,15E1	-2,7E-1	-6,37E6	Details
	Total	**2,96E6**	**9,26E5**	**1,15E0**	**1,23E4**	**2,33E3**	**7,13E2**	**4,14E2**	**2,92E7**	
	Results per denominator									
	Per gross internal floor area m2 / year	1,29E1	4,04E0	5E-6	5,37E-2	1,02E-2	3,11E-3	1,81E-3	1,27E2	
	Per gross internal floor area m2	6,47E2	2,02E2	2,5E-4	2,69E0	5,09E-1	1,56E-1	9,03E-2	6,36E3	

Table 5.1a DAS Kelo Life Cycle Assessment

Of the main construction activities Chart 5.1a indicates that largest contributor to the LCA of CO2e are the Energy (64.5%), construction materials (18.2%), replacement of materials (9.8%) and construction activities (1.8%). All other contributing activities formed less than 7% of the total CO2 contributions for the building phase of the project.

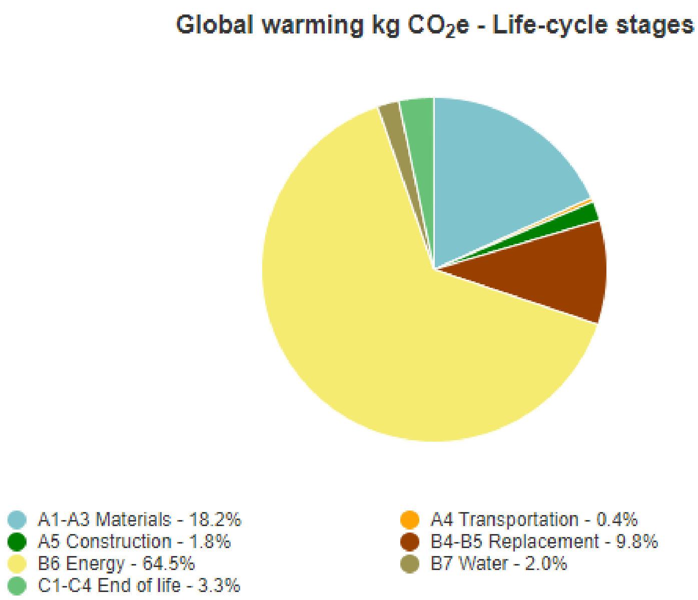


Chart 5.1a DAS Kelo Use Global Warming contribution per construction material (CO2e) : Stages A1-C4

The largest contributor to global warming (kg CO2e) by building element (Chart 5.1b) was the energy use (67.8%), concrete elements [roof decks, floor slabs, beams and roof] (16.6%), other structures (5.5%) and windows/doors (4.1%).

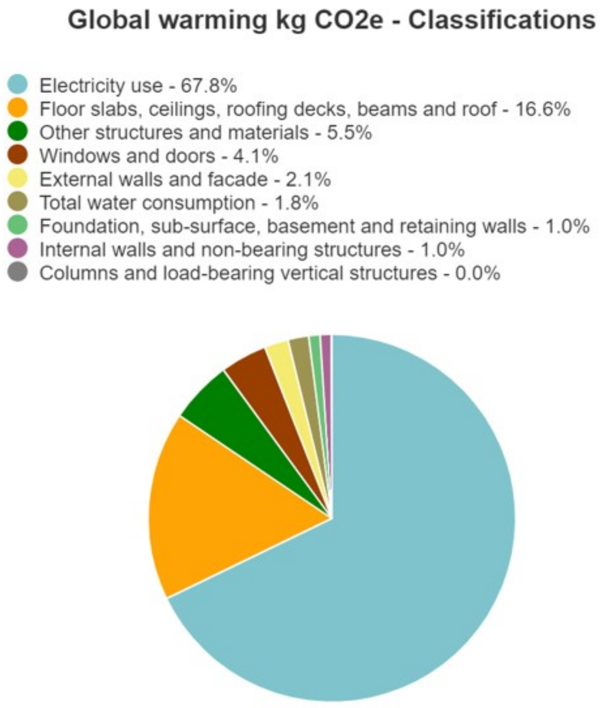


Chart 5.1b DAS Kelo Global Warming contribution per building element (CO2e): Stages A1-C4

By resource type (Chart 5.2c) the highest % of CO2 is attributable to the utilities (69.9%), flooring (8.6%), wood (6.6%), concrete elements (4.2%) and windows (4.1%).

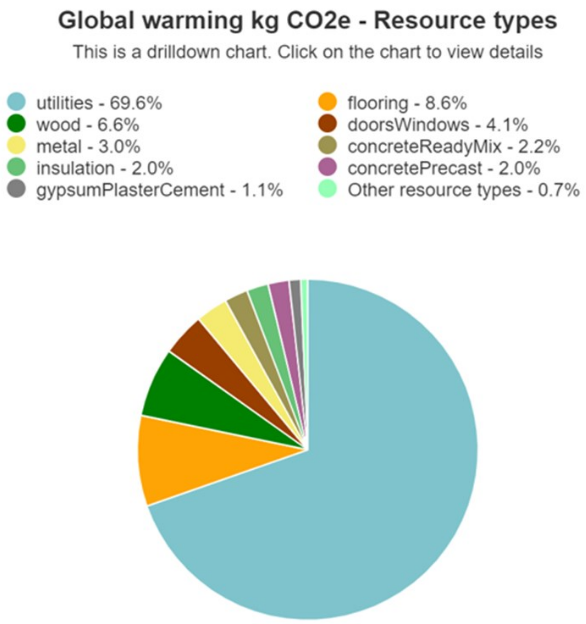


Chart 5.1c DAS Kelo Use Global Warming contribution per resource type (CO2e) : Stages A1-C4

5.1.5 CONCLUSION

The assessed building structure has performed well in terms of GHG and Carbon emissions for LCA stages A1 to C4 (cradle to grave). Though external works and building services were not included in the calculation it is possible this would be balanced out by the fact that many timber related products were resourced and manufactured locally. In the main, most of the construction was offsite being partly modularised (e.g., CLT panels brought and assembled on site). This included the kitchens, cupboards, and bathroom equipment.

It is likely the high building energy use is due to the multiple use of the building for both business offices (floor 1) and student living (floors 2-8). This hybrid construction includes a concrete structure for the first floor which supports the CLT modular structures present from floors 2-8. These two factors are most likely the reason for the high global warming contribution of these elements.

The better performing elements in terms of global warming were materials resourcing, replacement of materials and transport and in use water and energy use. These contributing factors support the A rating of the project whose outputs are assessed at **2 965 TONS CO_2** and **12.94 kg CO_2/m^2/year** with a **social carbon cost of 148 231€.**

In terms of other environmental impacts, best performance was end of life (C1-4) for **acidification 1.38 kg SO_2e, ozone depletion 1.19 kg CFC11e and ozone 1.06 kg Ethanee.** Whilst material replacement/refurbishment (B4-5) performed well for **eutrophication 1,34kg PO_2e** and energy consumption (B6) for abiotic depletion potential at **1.91 MJ).**

5.2 Case study 2 Pudasjarven Hirsihovi Finland

5.2.1 BRIEFING

Pudasjärven Hirsihovi is the name for two four-storied buildings in the city centre of Pudasjärvi. Located right next to the city hall, the finished complex will have a total of 53 two room with five 80 m2 commercial premises on the first floor, Pudasjarven Hirsihovi has a gross floor area (GFA) 3158 m2.

The apartment buildings in the centre of Pudasjärvi were built with a hybrid structure, in which the frame of the house was made from precast concrete elements and the outer casing was constructed from unstressed SmartLog logs supplied from Pudasjärvi-based Kontiotuote.

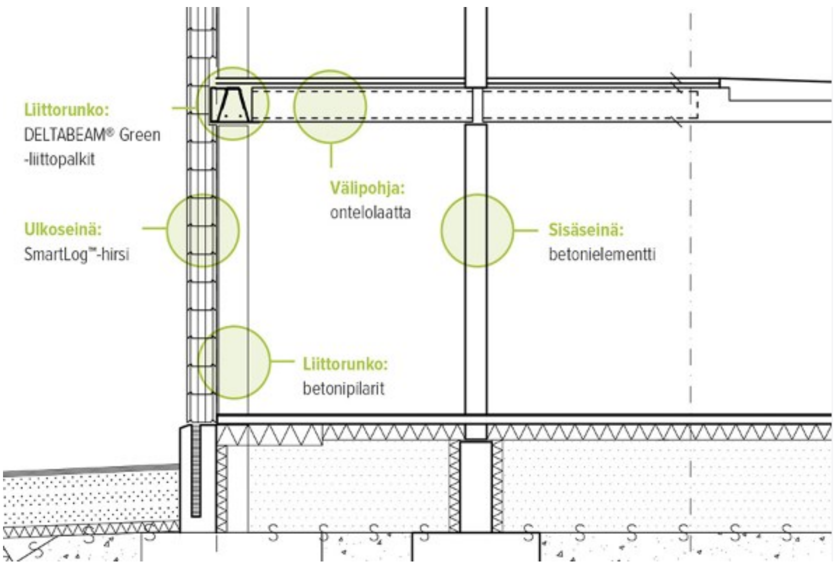


Diagram 1: Source: Peikko: Cutting photo of a hybrid structure.

Approximately a EUR 9.5 million project, the construction of the log apartment buildings sought to promote log construction as a viable option for apartment buildings. Some 700 m3 of logs were used for the apartment buildings in Hirsihovi. The outer walls of residential buildings are made with a 275 mm thick and 275 mm high unstressed SmartLog log with some of the partitions were also made from logs.

The first floor of the buildings offers commercial premises for future and current entrepreneurs, five commercial premises measuring approximately 80 m2. A major part of the apartments are studios and two-room apartments, 53 in total ranging from studio to family apartments.

BIM was used in the design process and facilitated risk management and work management both in production and on site. In addition, the use of BIM was a valuable tool for the log manufacturer Kontiotuote. The combination model provided the initial data, for example, for the further design of log openings and thus for the export of data directly to the log mill's machine.

Special attention has been paid to moisture control and the protection of logs during construction.

Circularity and best use of timber was considered and with all wood used in log production obtained from within a radius of about 100 kilometers, it was felt this was upheld. In addition, side streams of log production, such as wood chips and sawdust, were used for local district heat production.

As much timber as possible has been left open internally to benefit aesthetically from the natural finish.

5.2.2 INNOVATION

Pudasjärvi's Hirsihovi is a pioneering hybrid construction project combining steel, concrete, and wood. The frame is supported by Peikko's DELTABEAM® Green composite beams made of recycled steel and Betroc's concrete pillars. The outer walls are clad by Kontiotuote's unstressed log sheathing. In an open-minded building model, the strongest properties of different materials are combined with ecological thinking.

The main structures of the building were:

- Exterior walls unstressed solid lamella log, Kontio Smart Log.
- Bottom floor reinforced concrete slab with ground clearance.
- Intermediate floor hollow-core slab.
- Top floor load-bearing hollow-core slab, wooden roof supports, gable roof, bitumen cream.
- Foundations reinforced concrete plinth and antura foundation.
- Load-bearing structures load bearing reinforced concrete partitions.
- Light partitions lamellar log, and AKO element (concrete).
- Balcony reinforced concrete element.

5.2.3 LCA Analysis

The post construction LCA analysis was carried out on the 25/11/2022 using the ONE CLICK LCA tool v Version: 0.7.1, Database version: 7.6. An LCA, LCC and embodied carbon analysis was completed. Due to the nature of the project only basic construction data was available and assessed. Between 80-90% of total materials for each building element was accounted for in the assessment. This being the largest contributing materials by volume for each area. Most data sets used were from Finland and locally resourced materials. Due to the timing of this assessment and accessibility to time sensitive data information for some building elements was not available e.g., transportation to site (A4), construction site activities (A5), external areas (D) and services. To this end, certain parameters have been calculated using generic data from the ONE CLICK tool: namely the life span of materials. All other areas are not accounted for in this assessment.

5.2.4 OUTCOMES

OUTPUTS from the ONE CLICK LCA tool indicate a rating of C at 314 kg/CO_2e/m^2 which is slightly above the minimum benchmark for the of 300 kg/CO_2e/yr (B rating). An overall reduction of 14 kg/CO_2e/m^2 against the building performance would be required to achieve a B rating. The total assessed carbon for the project was 5 718 TONS CO_2 and 34.09 kg CO_2/m^2/year with a social carbon cost of 285 911€.

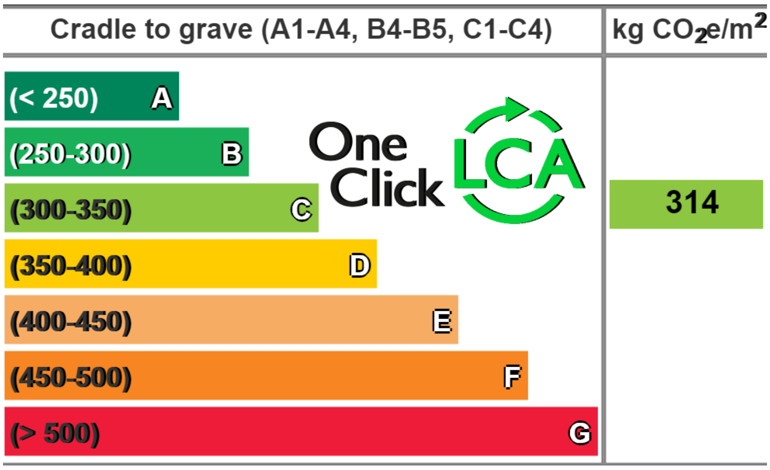


Illustration 5.2a Pudasjarven Hirsihovi Embedded carbon: CO_2 rating

As illustrated in table 5.2a (below) in terms of global warming, the data illustrates that the largest contributing areas were maintenance and material replacement (B1-B5) 9.85 kg/CO_2e, construction materials 7.4 kg/CO_2e and energy consumption (in use) 4.62 kg/CO_2e.

All other elements were relatively small contributors to the carbon LCA of the building.

In terms of other environmental impacts, maintenance and material replacement (B1-5) is the largest contributor to acidification at 3.49 kg SO_2e, eutrophication at 7.31 kg PO_2e and ozone depletion at 4.07 kg CFC11e. Whilst energy consumption (B6) is the largest contributor to lower atmospheric formation of ozone at 6.58 kg Ethanee and total use of primary energy use (B6) at 9.31 MJ.

Best performance in this respect were water use (B7) for acidification at 1.57 kg SO_2e and energy consumption (B6) for ozone depletion at 1.92 kg CFC11e, construction materials (A1-3) for lower atmospheric ozone formation at 1.35kg Ethanee and for eutrophication at 2.5 kg PO_2.

Life cycle assessment results

Download Results Summary

	Result category	Global warming kg CO_2e	Acidification kg SO_2e	Eutrophication kg PO_4e	Ozone Depletion kg CFC11e	Formation of ozone of lower atmosphere kg Ethenee	Total use of primary energy ex. raw materials MJ	Biogenic carbon storage kg CO_2e bio	
A1-A3	Construction Materials	7,4E5	1,67E3	2,5E2	3,2E-2	1,35E2	5,85E6	1,7E6	Details
A4	Transportation to site								Hide empty
A5	Construction/installation process								Hide empty
B1-B5	Maintenance and material replacement	9,85E4	3,49E2	7,31E1	4,07E-3	2,63E1	1,14E6		Details
B6	Energy consumption	4,62E6	1,62E4	2,02E3	1,92E-1	6,46E2	9,31E7		Details
B7	Water use	2,24E5	1,57E3	4,49E3	2,26E-2	6,58E1	4,05E6		Details
C1-C4	End of life	3,89E4	2,01E2	5,74E1	4,5E-3	5,72E0	6,26E5		Details
D	External impacts (not included in totals)	-1,16E5	-2,22E2	-3,12E1	-2,44E-3	-3,56E1	-7,82E5		Details
	Total	**5,72E6**	**2E4**	**6,9E3**	**2,55E-1**	**8,79E2**	**1,05E8**	**1,7E6**	
	Results per denominator								
	Heated net area 2660.0 m^2	2,15E3	7,52E0	2,59E0	9,6E-5	3,31E-1	3,94E4	6,37E2	
	Gross Internal Floor Area (IPMS/RICS) 2796.0 m^2	2,05E3	7,16E0	2,47E0	9,13E-5	3,15E-1	3,75E4	6,06E2	

Table 5.2a Pudasjarven Hirsihovi Life Cycle Assessment Results

The global warming potential by Life Cycle Stages (Chart 5.3a) illustrates that energy (B6) is the largest contributor (80.7%), with materials (A1-3) (12.9%). The remaining elements attribute to less than 7% of the total building global warming potential over the life of the building (60 years).

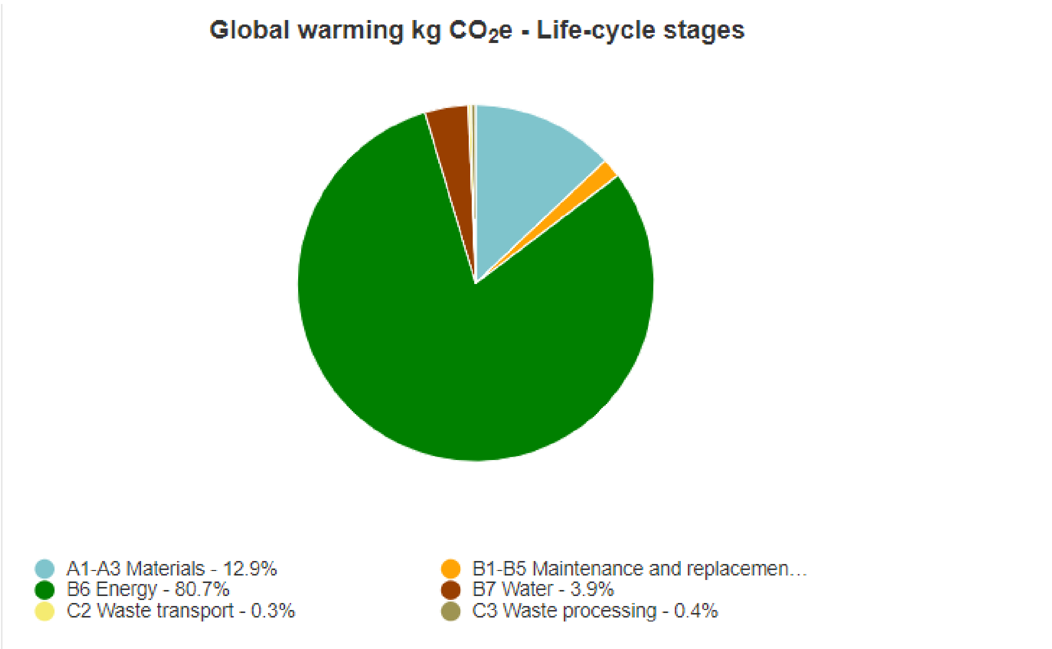


Chart 5.3a i Pudasjarven Hirsihovi Global Warming contribution per construction element l (CO2e/m2/a) : Stages A1-C4

The largest contributor to this buildings CO2e (Charts 5.3b i-iv) are the district heating (74.6%), electricity consumption (6.1%) at the in-use phase. Other high contributing elements include the Foundation, sub-surface, basement (5.2%), total water consumption (3.9%) and floor slabs, ceilings and roof decking (2.8%). Remaining elements account for 7.4% of the CO2e.

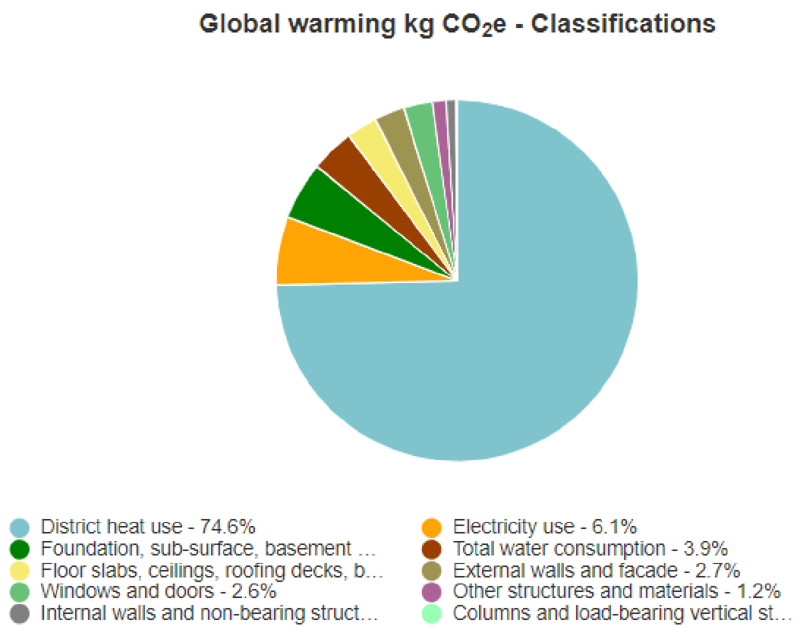


Chart 5.2b i Pudasjarven Hirsihovi Global Warming contribution per construction element (CO2e/m2/a): Stages A1-C4

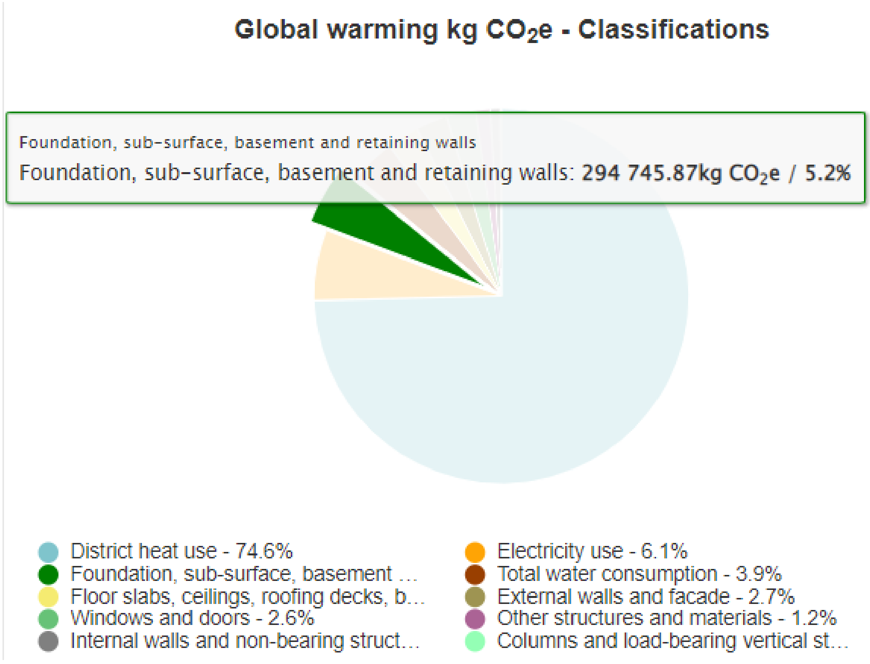


Chart 5.2b iiPudasjarven Hirsihovi Global Warming contribution per construction element (CO2e/m2/a): Stages A1-C4

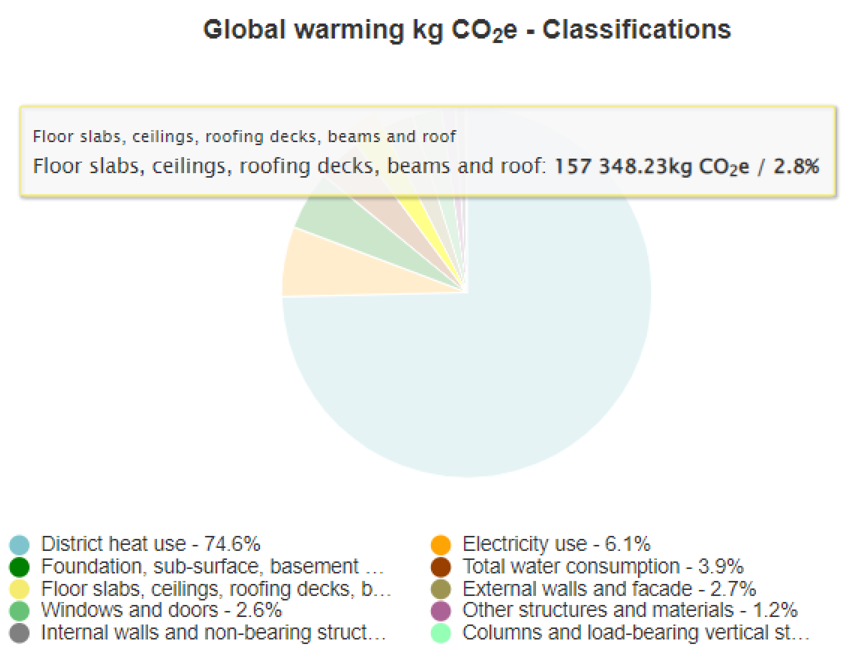


Chart 5.2b iii: Pudasjarven Hirsihovi Global Warming contribution per construction element (CO2e/m2/a): Stages A1-C4

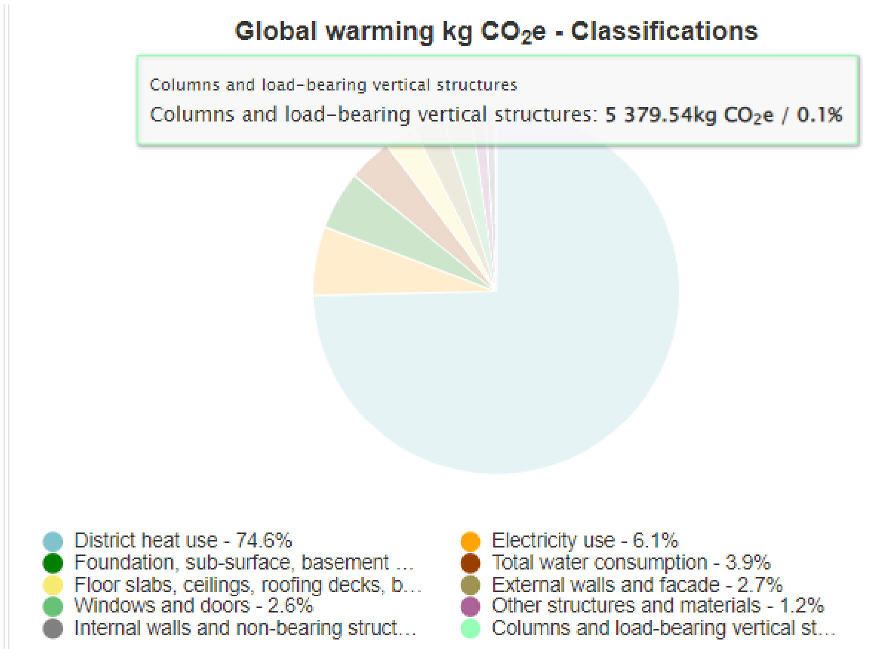


Chart 5.2b iv: Pudasjarven Hirsihovi Global Warming contribution per construction element (CO2e/m2/a): Stages A1-C4

By resource type (Chart 5.3c i-iv) the highest % of CO2e is attributable to the district heating 74.6%), electricity (6.1%), CLT, glulam and LVL (4.0%), ready mix concrete for external walls and floors (2.8%) and beams and pillars (0.8%), structural concrete (1.6%) [Total concrete 5.2%], other resource types (unspecified) (3.9%) and windows (1.7%). The remaining materials contribute to 3% of CO2e.

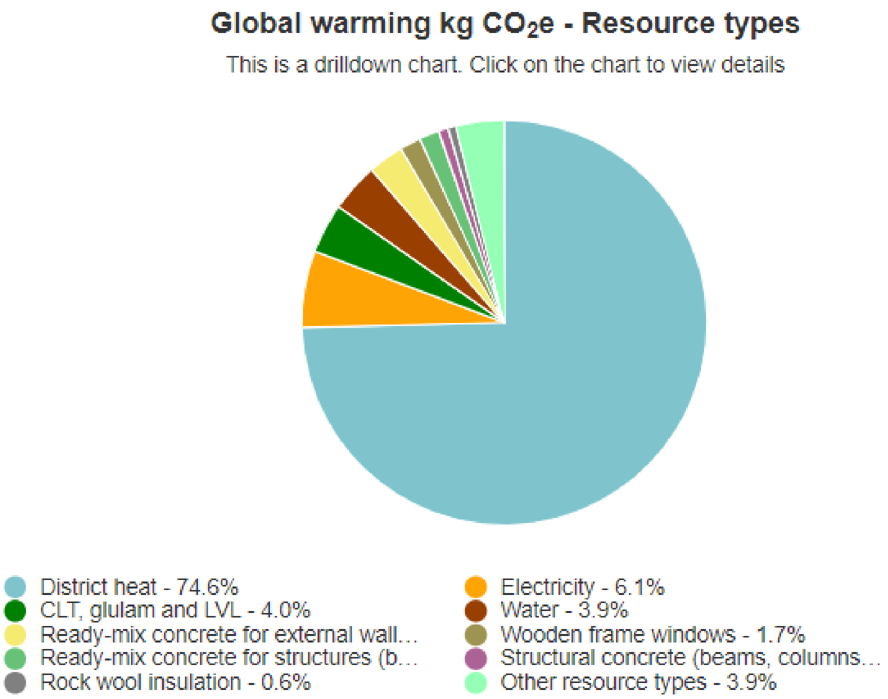


Chart 5.2c i Pudasjarven Hirsihovi Global Warming contribution per resource type (CO2e/m2/a): Stages A1-C4

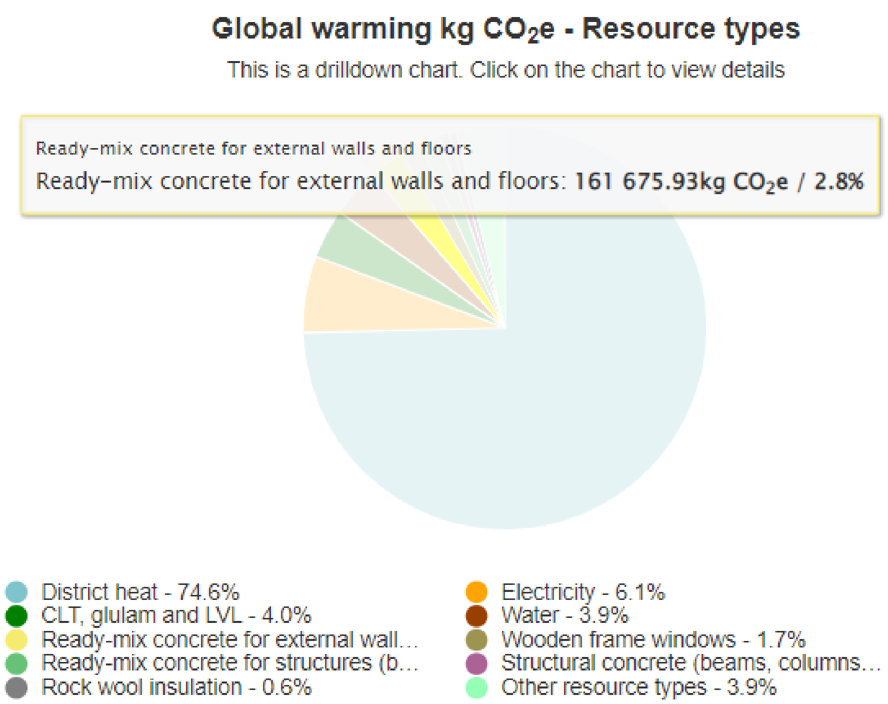


Chart 5.2c ii Pudasjarven Hirsihovi Global Warming contribution per resource type (CO2e/m2/a): Stages A1-C4

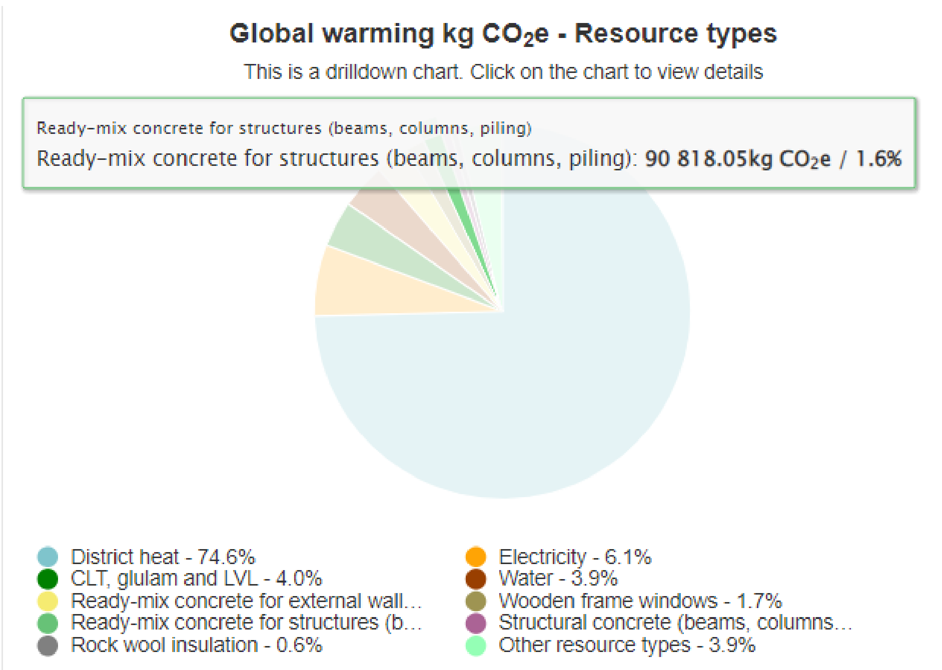


Chart 5.2c iii Pudasjarven Hirsihovi Global Warming contribution per resource type (CO2e/m2/a): Stages A1-C4

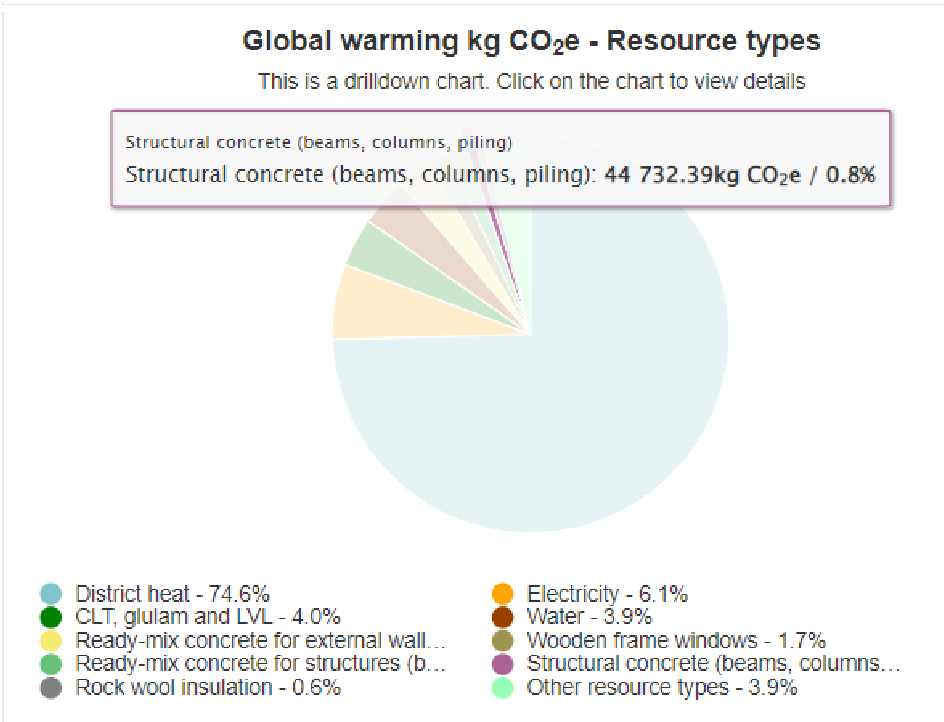


Chart 5.2c iv Pudasjarven Hirsihovi Global Warming contribution per resource type (CO2e/m2/a): Stages A1-C4

5.2.5 CONCLUSION

The assessed building structure has performed to a level **C rating** in terms of GHG and Carbon emissions for LCA stages A1 to C4 (cradle to grave). Actual data for external works were not included in the calculation. However, unlike the other assessments building services were included in the LCA data. A hybrid building using concrete and timber (CLT / Glulam) the building construction performed well, however the energy use of the building is a high contributor to the $CO_2/m_2/a$. The building is a large construction of 3 157,5 m2, five commercial premises (80m2/unit) and 53 two-room apartments (family & studio). The building would therefore be used for a significant proportion of the day and therefore reflects the high energy use.

The ONE CLICK LCA assessment does confirm that the design, materials choices, replacement of materials, waste transportation and energy performed well. These contributing factors support the C rating for the project, attributing to **2 519 TONS CO_2** and **15.02 kg CO_2/m2/year** with a social carbon cost of **125 960 €.**

In terms of other environmental impacts, best performance in this respect were water use (B7) for **acidification at 1.57 kg SO_2e** and energy consumption (B6) for **ozone depletion at 1.92 kg CFC11e,** construction materials (A1-3) **for ozone at 1.35kg Ethanee** and for **eutrophication at 2.5 kg PO_2.**

5.3 Case study 3: Ungdomsskole Stokmarknes, Norway

5.3.1 BRIEFING

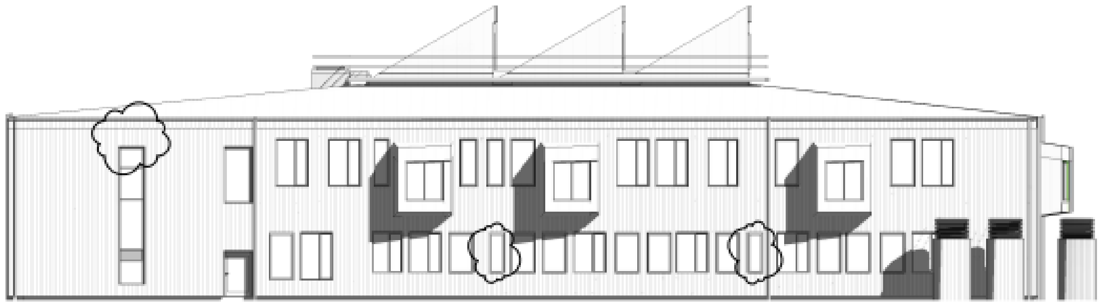
The region of Nordland and associated municipalities are striving to achieve greater sustainability in their building stock. Part of this objective is the need to upskill the local workforce through knowledge exchange and pilot projects. The Stokmarknes project is one of the early construction projects procured to enable this sustainability transformation in the construction industry in Nordland, Norway.

The objective of the project for the owner of the project, Hadsel municipality, was to design and build an effective new school building that as fit for purpose both in terms of sustainable construction and education needs for the 21st Century e.g., for modern education needs for today and future.

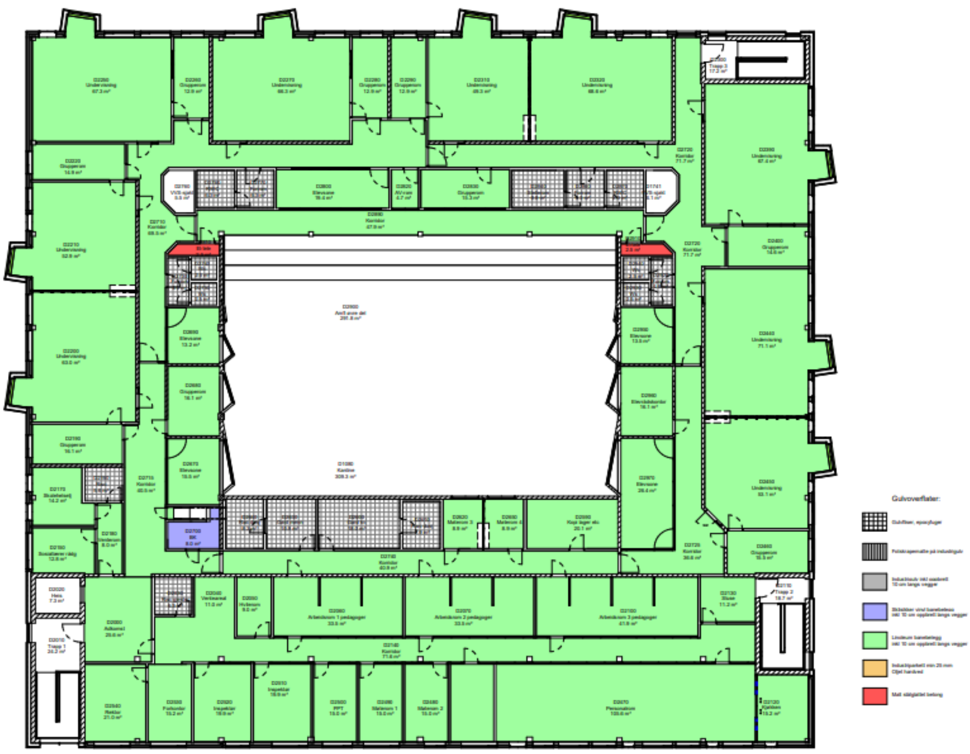
The successful construction team were tasked with designing and new school building within an existing campus that achieved passive house levels of performance (energy class B) and was CLT construction. CLT was considered a sustainable material resource and skills in working with this material were limited in Nordland. The final design was for a two-storey building with provision of teaching and learning spaces and communal areas suitable for community spaces. The comprised of teaching spaces which included specialist rooms (e.g., music spaces), hospitality and service spaces around the central atrium with three stairwells for access. The gross floor area of 3996m2.

The inclusion of CLT in the procurement of the project was considered an upskilling task for the construction industry. Learnings would include understanding how to design and construct the new school using CLT. Of particular consideration was understanding and actioning the storage and on-site tasks to avoid moisture ingress. As a new construction technique, the construction team also required support and upskilling in how to build for optimum noise abatement. To this end an acoustician was involved and construction methods adapted to achieve the correct building standards.

Drawing 5.3.1: Ungdomsskole Stokmarknes Elevations A F D 300 North



Drawing 5.3.2: Ungdomsskole Stokmarknes Elevations A F D 300 Øst



Drawing 5.3. 3: Ungdomsskole Stokmarknes Floor Plan 2 A G D 120

The CLT was procured by the subcontractors from Austria and the energy system design took cognisance of Norway policy to incorporate local renewables for energy provision – thus leaving the grid based hydroelectric for industry use. This report does NOT assess the Life Cycle Analysis and associated ground works for the renewable energy systems.

5.3.2 INNOVATION

The project sought to use this pilot as a learning project for local industry and as such collaboration and learning from the County Governor of Nordland seems to be relevant e.g., procurement of timber from nearest suppliers. Other new ways of working for the contractor were:

- The use of CLT for the first time with local builders and learning 'best practices'.
- Transferring knowledge from Passive House projects to larger projects
- Overcoming technical construction issues to achieve 'best practice' in acoustics for the school.
- Construction: Bearing construction CLT and prefabricated outer walls and roof elements. All facades are covered with burned Ore Pine.
- Energy standard: Passive house standards and the use of Hydro Electric for grid-based energy use.
- Heating: 32 geothermal energy wells for hot water heating and solar panels on roof.

5.3.3 LCA ANALYSIS

The post construction LCA analysis was carried out on the 08/10/2022 using the ONE CLICK LCA tool v Version: 0.7.1, Database version: 7.6. An LCA, LCC and embodied carbon analysis was completed. Only basic construction data was offered by collaboration partners due to the nature of the project. Between 80-90% of total building materials by element were assessed, these being the highest by volume for the building. Due to lack of information certain elements were not accounted for or where out of scope for the project e.g., external areas, services and fixtures and fittings. Some parameters have been calculated using the ONE CLICK generic data: namely some of the transport leg from resource origin to manufacturer and life span of materials. Most data sets used were from Norway and locally resourced data. Where local supplier data could not be found the nearest material profile was used and the result is determined by the ONE CLICK LCA tool.

It also acknowledged that the offsite construction and renewable energy elements of the design approach may not be fully accounted for by the ONE CLICK tool. There may therefore be some deviation from the final ONE CLICK calculations should this be assessed.

5.3.4 OUTCOMES

OUTPUTS from the ONE CLICK LCA tool indicate a rating of A at **161** kg/CO_2e/yr which is below the benchmark for the A rating of < **200** kg/CO_2e/yr. The total assessed carbon for the project was **720 TONS CO_2** and **3.02 kg CO_2/m2/year** with a social carbon cost of **3 6 016€.**

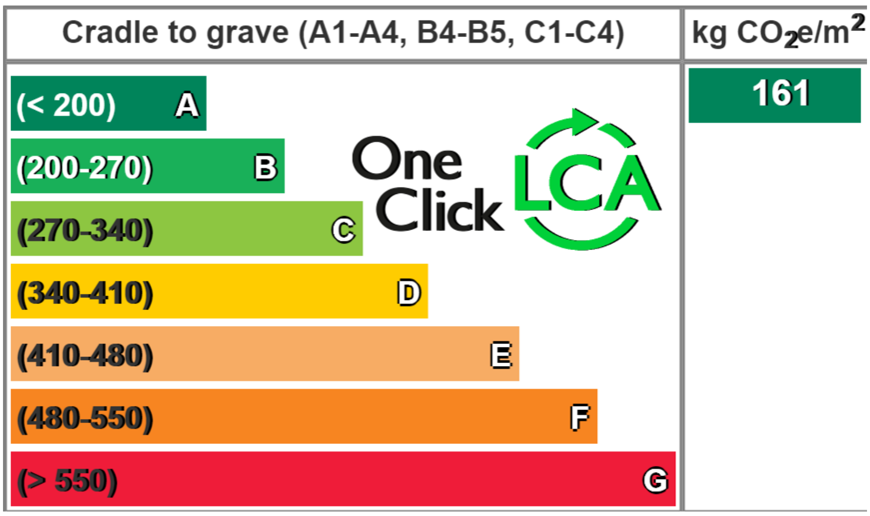


Illustration 5.3a Embedded carbon: Ungdomsskole Stokmarknes CO2 rating

As illustrated in table 5.4a (below) The breakdown of the data reveals that the end-of-life activities contributed to 6.02 kg/CO2e, transportation to site 4.92 kg/CO2e, construction site processes 4.84kg/CO2e, material replacement and refurbishment 2.36kg/CO2e whilst construction materials account for 1.23 kg/CO2e.

All other elements were relatively small contributors to the carbon LCA of the building.

In terms of other environmental impacts, transportation to site (A4) is the largest contributor to **acidification at 7.62 kg SO2e,** water use (B7) to **eutrophication at 8.01 kg PO2e,** and construction site processes (A5) to **ozone depletion at 7.01 kg CFC11e-,** lower atmospheric formation of **ozone at 8.24 kg Ethanee and abiotic depletion potential at 6.71 MJ.**

Best performance in this respect were water use (B7) for **acidification 1.81 kg SO2e, end of life (C1-4) for ozone depletion 1.05 kg CFC11e, energy consumption for lower atmospheric ozone formation at 2.99 kg Ethanee.** Whilst material c construction materials (A1-3) performed well for **eutrophication 1.04kg PO2e** and construction materials (A1-3) for abiotic depletion potential at **1.47 MJ.**

Life-Cycle Assessment for Level(s) in compliancy with EN 15978

Download Results Summary

	Result category	Global warming kg CO_2e	Biogenic carbon storage kg CO_2e bio	Ozone Depletion kg CFC11e	Acidification kg SO_2e	Eutrophication kg PO_4e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ	
A1-A3	Construction Materials	1,23E5	1,2E5	4,36E-3	4,98E2	1,04E2	3,23E1	9,94E-1	1,47E6	Details
A4	Transportation to site	4,92E5		8,3E-2	7,62E2	1,57E2	7,22E1	1,05E2	6,67E6	Details
A5	Construction/installation process	4,84E4		7,01E-3	9,52E1	2,34E1	8,24E0	1,63E1	6,71E5	Details
B1	Use phase									Hide empty
B3	Repair	0E0		0E0	0E0	0E0	0E0	0E0	0E0	Details
B4-B5	Material replacement and refurbishment	2,36E4		2,22E-3	1,89E2	1,95E1	8,58E0	1,71E1	4,06E5	Details
B6	Energy consumption	1,72E3		1,53E-4	6,53E0	1,26E0	2,99E-1	2,37E-2	2,25E4	Details
B7	Water use	2,59E4		2,61E-3	1,81E2	5,19E2	7,59E0	1,13E-1	2,47E5	Details
C1-C4	End of life	6,02E3		1,05E-3	3,26E1	8,01E0	7,01E-1	3,27E1	1,46E5	Details
D	External impacts (not included in totals)	-2,3E4		-6,89E-4	-1,07E2	-2,55E1	-4,74E0	-3,79E0	-8,32E4	Details
	Total	**7,2E5**	**1,2E5**	**1E-1**	**1,76E3**	**8,31E2**	**1,3E2**	**1,73E2**	**9,64E6**	
	Results per denominator									
	Per gross internal floor area m2 / year	3,02E0	5,03E-1	4,21E-7	7,4E-3	3,49E-3	5,45E-4	7,25E-4	4,04E1	
	Per gross internal floor area m2	1,81E2	3,02E1	2,53E-5	4,44E-1	2,09E-1	3,27E-2	4,35E-2	2,43E3	

Table 5.3a Ungdomsskole Stokmarknes Life Cycle Assessment

Of the main construction activities Chart 5.3a indicates that largest contributor to the LCA of CO2e are the transport of materials (68.2%), materials (17.1%), construction activities (6.7%) and replacement of materials (3.3%). All other contributing activities formed less than 5% of the total CO2 contributions for the building phase of the project. Waste transportation (0.6%), Energy (0.2%) and waste processing (0.2%) perform well. 100% of the energy will be from renewable sources and replacement or reuse of building elements would be mainly timber or concrete. The former is low impact at this stage and the latter is expected to last 60 years.

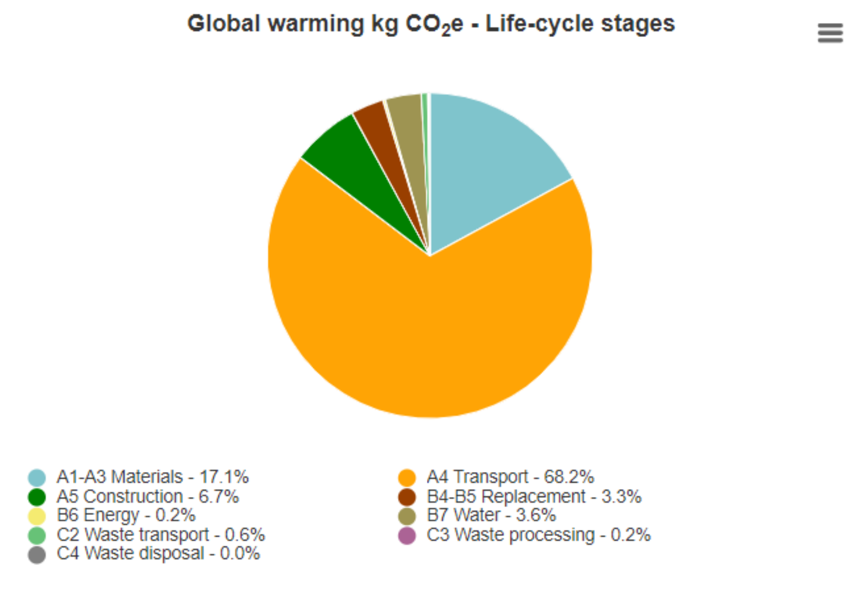


Chart 5.3a Ungdomsskole Stokmarknes Use Global Warming contribution per construction material (CO2e): Stages A1-C4

From the design brief and data it is expected the largest contributor to this by building element is the Upper floors (47.5%), external walls with integral CLT structure (16.6%), foundations (substructure) (11.2%), roof (5.2%), facades /openings (5%), external faces (4.1%) and internal walls/ partitions (4%) (Chart 5.3b). The construction site scenarios (2.6%) were calculated by the ONE CLICK LCA data sets. It is the view of this reporter that certain aspects of the CLT offsite construction and site works for geothermal energy system installation will not be accounted for, both positively and negatively. The data should be considered with this in mind.

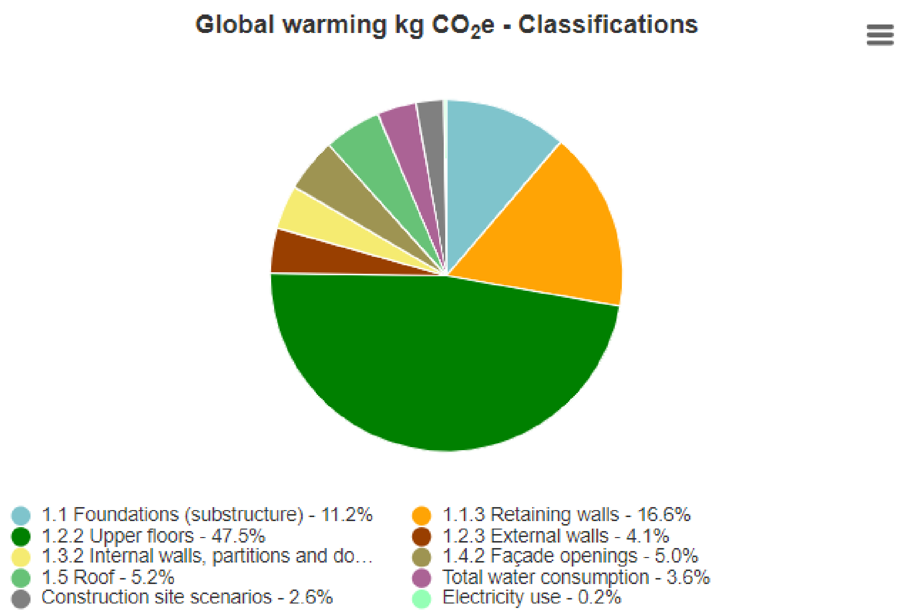


Chart 5.3b Use Global Warming contribution per building element (CO2e) : Stages A1-C4

By resource type (Chart 5.3c) the highest % of CO2 is attributable to the concrete works (74.7%) and gypsum plaster & board (6.4%), rockwool insulation (6.1%), wood (incl. CLT) (1.4%), windows (5%), with construction site activities (2.6%) (N.B. no data on ground works for geothermal installation).

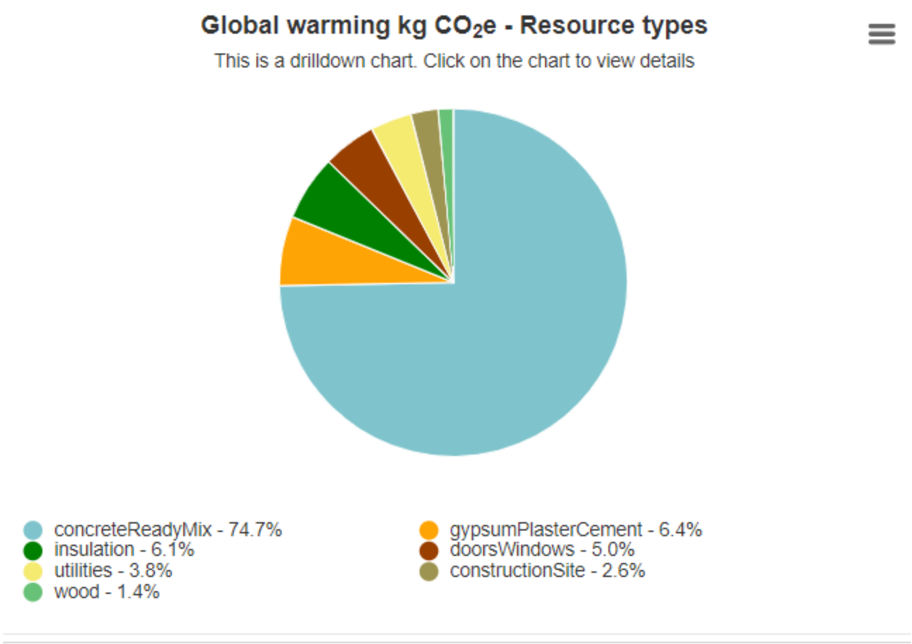


Chart 5.3c Ungdomsskole Stokmarknes Use Global Warming contribution per resource type (CO_2e) : Stages A1-C4

5.3.5 CONCLUSION

The assessed building structure has performed well in terms of GHG and Carbon emissions for LCA stages A1 to C4 (cradle to grave). Actual data for external works and building services were not included in the calculation. It is possible some of carbon attributable to these activities could be balanced out by the fact that the building will be run on renewable energy sources (e.g., renewables, hydro, etc) but without a full LCA calculation on these parameters (e.g., accounting for embodied carbon and ground works for the geothermal heating system), the outcome of this remains inconclusive. The building design has achieved good performance levels, however the procurement of CLT from Austria has significantly added to the transportation related carbon. More locally resourced CLT would improve the performance further.

The ONE CLICK LCA assessment does confirm that the design, materials choices, replacement of materials, waste transportation and energy performed well. These contributing factors support the A rating of the project whose outputs are assessed at 720 TONS CO_2 and 3.02 kg $CO_2/m^2/year$ with a social carbon cost of 36 016€.

All other elements were relatively small contributors to the carbon LCA of the building.

Best performance in this respect were water use (B7) for acidification 1.81 kg SO_2e, end of life (C1-4) for ozone depletion 1.05 kg CFC11e, energy consumption for lower atmospheric ozone formation at 2.99 kg Ethanee. Whilst material c construction materials (A1-3) performed well for eutrophication 1.04kg PO_2e and construction materials (A1-3) for abiotic depletion potential at 1.47 MJ.

For future projects it is recommended earlier LCA scoping is undertaken which embodies a wider scope of the LCA parameters (services, external sites and biodiversity, etc). Undertaking this approach would offer greater scope to benchmark the project against other assessments using LCA methodologies.

5.4 Case Study 4 Alvsbacka Strand, Sweden

5.4.1 BRIEFING

Picture 5: Source: Sara Kh. Taromi: Älvsbacka Strand Buildings, Skellefteå, Sweden.

As the result of Skellefteå municipality's environmental and sustainable development goal, Skellefteå is a leader in sustainable timber construction. The Älvsbacka strand residential building designed by White Arkitekter and located in Skellefteå was part of the EU project Concerto-SESAC, whose goal is to reduce the amount of carbon dioxide, among other things, by building energy-efficient homes. The total energy consumption for transmission, ventilation and hot water must be less than 95 kWh per sqm and year. Conserto-SESAC also limits the total electricity use for lighting, cooling, heating, and air conditioning to less than 20 kWh per sqm and year. The project has benefited from earlier investment by the municipality in mains fed renewable energy infrastructure and energy supply for both the apartments but also local manufacturing suppliers.

The Älvsbacka strand building has 18 apartments spread over six floors with one upper recessed penthouse with storage and guest accommodation. With the load bearing structure of CLT panels and volume elements for kitchens and bathrooms, the project aimed at high degree of industrialization and prefabrication. The gross floor area is 2128 m2 and the apartments where sold as condominiums.

5.4.2 INNOVATION

With a diligent approach towards sustainability the project has achieved environmental certification Miljöbyggnad Guld (Environmental Building Gold) and was the first in northern Sweden.

In terms of innovation the project boasts the use of high degree of prefabrication and industrialization. It is estimated this saved up to four weeks on site construction, reducing construction time after the laying of foundations from 22 to 18 weeks. With associated cost savings both economically and environmentally.

CLT panels were used in the load-bearing structure, volume elements for kitchen and bathrooms, and Glulam facades.

To encourage energy savings at the 'in use stage' the developer installed meters for cold and hot water, heating, and electricity for each apartment. It is understood that personal control of energy and resources consumption increases the more conscious use of resources – hence metering of the services will have a behavioural learning aspect for residents. The reason is that it is considered that the desire to save energy is more easily justified if individuals control their own energy use and costs.

5.4.3 LCA ANALYSIS

The post construction LCA analysis was carried out on the 08/10/2022 using the ONE CLICK LCA tool v Version: 0.7.1, Database version: 7.6. An LCA, LCC and embodied carbon analysis was completed. Only basic construction data was offered by partners RISE due to the nature of the project. Between 80-90% of total building materials by element were assessed, these being the highest by volume for the building. Due to lack of information certain elements were not accounted for or where out of scope for the project e.g., external areas, services and fixtures and fittings. Windows were unknown so a wooden window with paint finish for the 168 windows was substituted from Swedish generic data in ONE CLICK tool. Some parameters have been calculated using the ONE CLICK generic data: namely building services and life span of materials. Most data sets used were from Sweden and locally resourced data. Where local supplier data could not be found the nearest material profile was used and the result is determined by the ONE CLICK LCA data base.

It also acknowledged that the offsite construction element of the design approach may not be fully accounted for by the ONE CLICK tool. There may therefore be some deviation from the final ONE CLICK calculations.

5.4.4 OUTCOMES

OUTPUTS from the ONE CLICK LCA tool indicate a rating of A at 120 kg/CO_2e/yr which is significantly below the benchmark for the A rating of <220 kg/CO_2e/yr. The total assessed carbon for the project was 322TONS CO_2 and 2.52 kg CO_2/m2/year with a social carbon cost of 16 094 €.

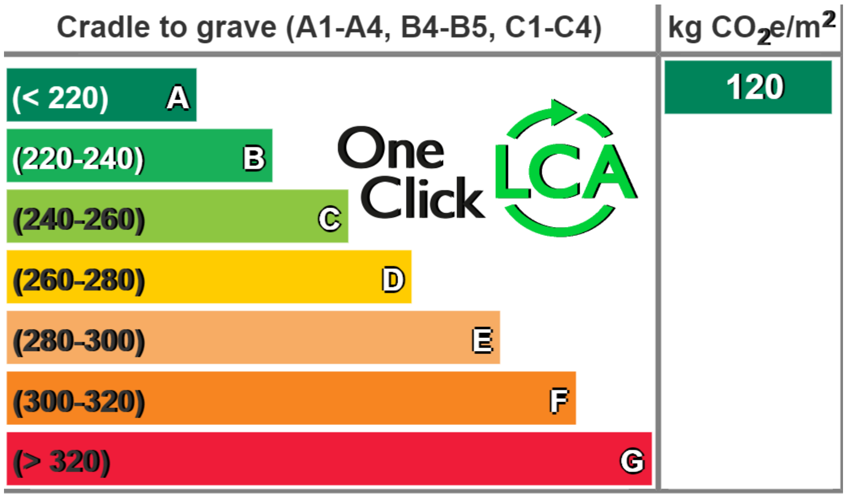


Illustration 5.4a Embedded carbon: Alvsbacka Strand CO2 rating

As illustrated in table 5.5a (below) The breakdown of the data reveals that construction site processes 6.17 kg/CO2e, transportation to site 5.52 kg/CO2e, construction materials account for 2.09 kg/CO2e, and material replacement and refurbishment 3 kg/CO2e. Whilst the end-of-life activities contributed to 1.2 kg/CO2e.

All other elements were relatively small contributors to the carbon LCA of the building.

In terms of other environmental impacts, construction materials (A1-3) is the largest contributor to acidification 8.88 kg SO2e and construction /installation processes (A5) to ozone depletion 7.49 kg CFC11e, eutrophication 3.87 kg PO2e and abiotic depletion potential at 8.46 MJ. Whilst transportation to site (A4) is the largest contributor to lower atmospheric formation of ozone at 5.57 kg Ethanee.

Best performance in this respect were construction /installation processes (A5) for acidification at 1.64 kg SO2e and formation of lower atmosphere ozone at 1.01 kg Ethanee. Whilst transportation to site (A4) for ozone depletion at 1.01 kg CFC11e and for abiotic depletion potential at 1.17 MJ, with energy consumption (B6) for eutrophication at 1.15kg PO2e.

Life-Cycle Assessment for Level(s) in compliancy with EN 15978 Download Results Summary

	Result category	Global warming kg CO_2e	Biogenic carbon storage kg CO_2e bio	Ozone Depletion kg CFC11e	Acidification kg SO_2e	Eutrophication kg PO_4e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
A1-A3	Construction Materials	2,09E5	7,61E5	7,45E-3	8,88E2	1,63E2	1,01E2	6,03E0	2,62E6
A4	Transportation to site	5,52E3		1,01E-3	1,72E1	3,69E0	5,57E-1	2,1E1	1,17E5
A5	Construction/installation process	6,17E4		7,49E-3	1,64E2	3,87E1	1,98E1	9,51E0	8,46E5
B1	Use phase	-7,2E0		0E0	0E0	0E0	0E0	0E0	0E0
B3	Repair	0E0		0E0	0E0	0E0	0E0	0E0	0E0
B4-B5	Material replacement and refurbishment	3E4		2,28E-3	1,77E2	1,82E1	1,23E1	5,7E0	3,65E5
B6	Energy consumption	7,61E2		4,45E-5	4,67E0	1,15E0	1,74E-1	1,94E-3	1,91E4
B7	Water use	2,49E3		2,51E-4	1,74E1	4,99E1	7,31E-1	1,08E-2	2,37E4
C1-C4	End of life	1,2E4		1,61E-3	8,12E1	2,4E1	2,31E0	3,99E1	2,2E5
D	External impacts (not included in totals)	-1,25E5		-3,35E-3	-1,27E3	-2,82E2	-5,89E1	-3,6E0	-7,24E5
	Total	**3,22E5**	**7,61E5**	**2,01E-2**	**1,35E3**	**2,99E2**	**1,37E2**	**8,22E1**	**4,22E6**
	Results per denominator								
	Per gross internal floor area m2 / year	2,52E0	5,96E0	1,58E-7	1,06E-2	2,34E-3	1,07E-3	6,44E-4	3,3E1
	Per gross internal floor area m2	1,51E2	3,58E2	9,46E-6	6,34E-1	1,4E-1	6,44E-2	3,86E-2	1,98E3

Table 5.4a Alvsbacka Strand Life Cycle Assessment

Of the main construction activities Chart 5.4a indicates that largest contributor to the LCA of CO_2e are the construction materials (65.1%), construction activities (19.2%) and replacement of materials (9.3%). All other contributing activities formed less than 7% of the total CO_2 contributions for the building phase of the project.

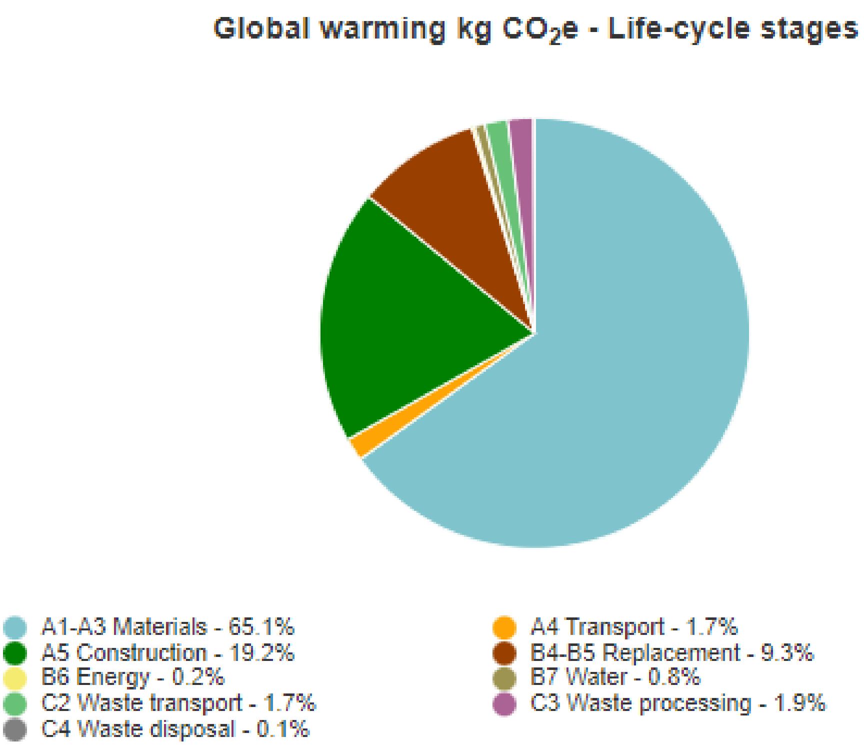


Chart 5.4a Alvsbacka Strand Use Global Warming contribution per construction material (CO_2e) : Stages A1-C4

From the design brief and data, it is expected the largest contributor to this by building element is the external walls with integral CLT structure (54.1%) (Chart 5.5b). The substituted windows (Wood windows with paint finish) are the next biggest contributor (16.1%) but it is noted these are set to average performance and may not truly represent the project design. The construction site scenarios were calculated by the ONE CLICK LCA data sets and may not fully reflect the CLT offsite construction and should be treated with caution as no actual data was available for this activity.

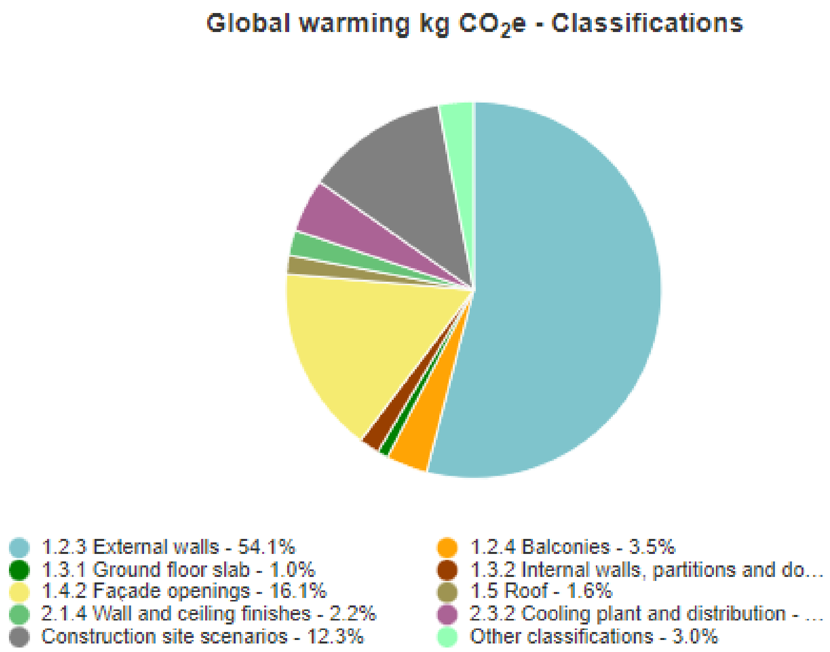


Chart 5.4b Alvsbacka Strand Use Global Warming contribution per building element (CO2e) : Stages A1-C4

By resource type (Chart 5.5c) the highest % of CO2 is attributable to the rockwool insulation (32%), wood (incl. CLT) (21.3%), windows (16.1%), with construction site activities (12.3%).

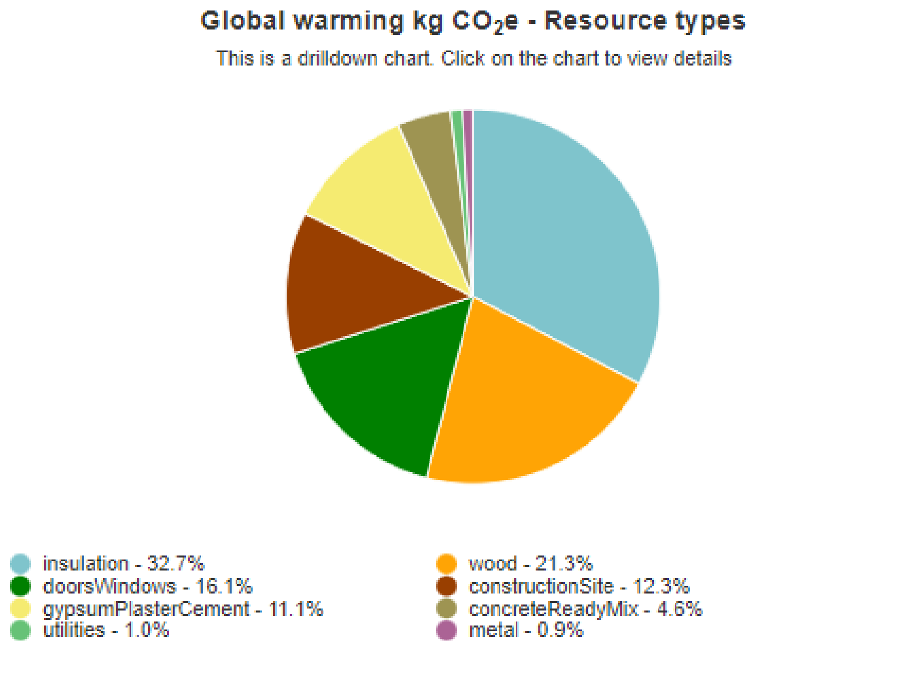


Chart 5.4c Alvsbacka Strand Use Global Warming contribution per resource type (CO2e) : Stages A1-C4

5.4.5 CONCLUSION

The assessed building structure has performed well in terms of GHG and Carbon emissions for LCA stages A1 to C4 (cradle to grave). Though external works and building services were not included in the calculation it is possible this would be balanced out by the fact that local energy resources are manufactured using renewable energy sources (e.g., renewables, hydro, etc) and that the construction, in the main, was offsite being partly modularised (e.g., CLT panels brought and assembled on site). In this respect the project has also benefitted from the established national wood management policy and associated wood businesses and innovation from the immediate area of Skelleftea. In addition, the project achieved certification 'gold' in the Miljöbyggnad, offering an additional sensitivity check to the overall sustainability check for the Älvsbacka strand project.

The ONE CLICK LCA assessment does confirm that the design, materials resourcing, replacement of materials and transport and in use water and energy perform well. These contributing factors support the A rating of the project whose outputs are assessed at **322TONS CO2** and **2.52 kg CO2/m2/year** with a social carbon cost of **16 094 €.**

In terms of other environmental impacts, best performance in this respect were construction /installation processes (A5) for **acidification at 1.64 kg SO2e** and **formation of lower atmosphere ozone at 1.01 kg Ethanee**. Whilst transportation to site (A4) for **ozone depletion at 1.01 kg CFC11e** and **for abiotic depletion potential at 1.17 MJ,** with energy consumption (B6) for **eutrophication at 1.15kg PO2e.**

Further reading of the Miljöbyggnad undertaken by the main contractor achieves much of this requirement for a full LCA but sits outwith the TALLWOOD project.

6 DISCUSSION

6.1 LCA discussion and lessons learnt from project site visits.

This section offers discussion on the LCA of the four case study projects and lessons learnt from project site visits. The initial purpose of the LCA study was to offer a comparator study between projects (project and national levels). However, a number of contributing factors means a comparative study is not meaningfully achievable. These factors are variability of the construction type and design and the availability and quality of data e.g., design and materials. That said, some specific and generic learnings can be formed through observations of the LCA outputs and project site visits. This section presents project specific learnings taken from the LCA outputs (section 6.1.1) and some observations from innovative working practices enabled by local activities (section 6.1.2).

6.1.1 LCA discussion for four case studies

Table 6.1.1 and 6.1.2 illustrate the scope of each case study design and performance characteristics and scope of the LCA assessments respectively.

In terms of the design and building performance characteristics all buildings used a significant proportion of CLT & timber in the design. The scope of design of each building varies in terms of design and utilisation of concrete and steel elements, gross floor area, building use and therefore LCA results. Two buildings used a more significant percentage of timber in the main structures (Alvsbacka Strand and Ungdomsskole Stokmarknes). Whilst two utilised steel and or concrete extensively in their first floor and structural elements (Das Kelo and Pudasjarven Hirsihovi). The largest buildings by gross floor area were Pudasjarven Hirsihovi (hybrid design with CLT with standard Finnish mains energy systems) attaining a C rating and Ungdomsskole Stokmarknes (mainly CLT with 100% renewable energy systems) attaining an A rating. However, as no data was assessed for transportation of materials to site and site processes for Pudasjarven Hirsihovi and offsite construction was not accounted for in Ungdomsskole Stokmarknes, it would be unwise to draw too many conclusions from this data.

Projects	Characteristics of buildings					
	Gross Floor Area	No. of floors	Space utilisation	Operational rate /day	Energy systems	Design features
DAS Kelo	4583m2	8	Office premises and 103 apartments (3 973m2)and rooftop social space (saunas, meeting areas)	Business and residential hours plus services	Mains standard (Finland) & waste water heat recovery system	• No basement • Ground floor concrete • Upper floors CLT • The adopted CLT modular building systems, prefabricated offsite enabled a fast construction program, dramatically reduced labour costs.
Pudasjarven Hirsihovi	3158m2	2 buildings	Office premises and 53 two room apartments	Business and residential hours plus services	Mains standard (Finland)	• Outer layer from non-settling Kontio SmartLogs (dimensions 275x275mm). Log structure is attached to the intermediate floors as well as to the ends of load-bearing walls. • Non-load-bearing adjoining walls also made from logs. • Aiming for improvements in the indoor air quality with the use of logs
Ungdomsskole Stokkmarknes	3996m2	2	Teaching, social and services spaces	Education hours plus community use out of hours	100% onsite renewable energy	• The use of CLT for the first time with local builders and learning 'best practices'. • Transferring knowledge from Passive House projects to larger projects • Overcoming technical construction issues to achieve 'best practice' in acoustics for the school. • Construction: Bearing construction CLT and prefabricated outer walls and roof elements. All facades are covered with burned Ore Pine. • Energy standard: Passive house standards and the use of Hydro Electric for grid-based energy use. • Heating: 32 geothermal energy wells for hot water heating and solar panels on roof. • Knowledge learning project for industry
Alvsbacka Strand	2128m2	6	Apartments and services	Residential only	100% municipality supplied renewable energy	• Significance of use of CLT • The project aimed at high degree of industrialization and prefabrication. • Shortened assembly time (from 22 weeks after foundation is ready it was reduced to 18 weeks) • Energy consumption 20% lower than estimated. • The project is part of the EU project Concerto-SESAC, whose goal is to reduce the amount of carbon dioxide, among other things by building energy-efficient homes. The total energy consumption for transmission, ventilation and hot water must be <95 kWh per sqm and year. Due to this, more energy-efficient equipment than usual has been chosen. • Conserto-SESAC also limits the total electricity use for lighting, cooling, heating, and air conditioning to <20 kWh per sqm and year. • To limit energy use in the homes, the developer has chosen to install meters for cold and hot water, heating, and electricity in each apartment separately. The reason is that it is considered that the desire to save energy is more easily justified if you control the energy cost yourself.

Table 6.1.1: TALLWOOD Characteristics of building and decision making.

Regarding the LCA data (table 6.1.2), the majority of Life Cycle Stages were covered (A1-C4) in all cases studies. Stages B1 (Use) and B2 (Maintenance) were not covered in Das Kelo, Ungdomsskole Stokmarknes, with B2 (Maintenance) omitted in Alvsbacka Strand. Stages A4 (Construction transportation) and A5 (Construction installation process) were not covered in Pudasjarven Hirsihovi. D was not accounted for in the overall table outputs.

Tallwood LCA Case study summary table (x denotes covered in LCA / ** areas not calculated by one click data)															
Project	**LCA areas**														
	Product stage			Construction Stage		Use Stage					End of Life Stage				Benefits and Loans beyond system boundary
	A1 Raw material	**A2 Transportation**	**A3 manufacturing**	**A4 Transportation**	**A5 Construction installation process**	**B1 Use**	**B 2 maintenance**	**B3 Repair**	**B4 Replacement**	**B 5 Refurbishment**	**C1 De construction demolition**	**C2 Transportation**	**C3 Waste processing**	**C4 Disposal**	**Reuse- recovery – recycling potential**
						B6 Operational Energy			**B7 Operational water use**						
DAS Kelo	x	x **	x	x	x	–	–	x	x	x	x	x	x	x	Not included in totals
						x			x						
Pudasjarven Hirsihovi	x	x	x	–	–	x	x	x	x	x	x	x	x	x	Not included in totals
						x			x						
Ungdomsskole Stokkmarknes	x	x **	x	x **	x	–	–	x	x	x	x	x	x	x	Not included in totals
						x			x						
Alvsbacka Strand	x	x **	x	x **	x	x	–	x	x	x	x	x	x	x	Not included in totals
						x			x						

Table 6.1.2TALLWOOD Scope of LCA Assessment summary table

Table 6.1.3 illustrate the overall outcomes of the CO_2/year/m2 and social cost of the building performance and here we can make some comparisons. In terms of CO_2 emissions/year/m2 over 60 years the three projects achieved A ratings for their LCA assessment and associated kg/CO_2/year, namely Das Kelo(183kg/CO_2/year), Ungdomsskole Stokmarknes (1610kg/CO_2/year) and Alvsbacka Strand (120kg/CO_2/year). Alvsbacka Strand is the better performing building of the three, this is most likely attributable to a very high use of CLT, existing renewable energy infrastructure and high local resource utilisation. Whilst Pudasjarven Hirsihovi utilised much locally resourced CLT it was a two-building project and did not benefit from renewable energy systems so attained just in to the C rating at 314 kg/CO_2/yr (14kg less of CO_2/year would have achieved a B rating <300 kg/CO_2/year). These outcomes are reflected in the social cost of the buildings e.g., Alvsbacka Strand achieving 16 094€ whilst Pudasjarven Hirsihovi achieved 285 922€. However, if we were to assess just one building for the Pudasjarven Hirsihovi project it may be said the project would have achieved 50% less impact at 157 kg/CO_2/year an A rating, with 2 859 TONS CO_2, 17.045 CO_2/m2/year and a social cost of 14 2 955 € (table 6.1.3) and a gross floor area of 1 579m2 (Table 6.1.1).

Project	LCA rating and kg/CO2e/yr	Assessed carbon / TONS CO2	CO2/year/m2 over 60years	Social cost
DAS Kelo	A at 183	2 965	12.94 kg CO2/m2/year	148 231€.
Pudasjarven Hirsihovi	C at 314	5718	34.09 kg CO2/m2/year	285 911€
Ungdomsskole Stokkmarknes	A at 161	720	3.02 kg CO2/m2/year	36 016€.
Alvsbacka Strand	A at 120	322	2.52 kg CO2/m2/year	16 094 €.

Table 6.1.3 Summary of LCA outcome ratings, CO_2/year over 60 years, social cost

The following sections present and summary of the individual case studies.

6.1.1.1 Case study 1: DAS Kelo, Finland:

A block of 103 apartments over 8 floors with office accommodation on the first floor, Das Kelo has a gross floor area (GFA) 4583 m2. Design parameters were for a hybrid building that used a high volume of timber on a concrete ground floor.

The overall CO_2 levels per year for Das Kelo were **183 kg/CO2e/yr** which is significantly below the benchmark for the **A rating of < 250 kg/CO2e/yr.** The CO_2 outputs were assessed at **2 965 TONS** equalling **12.94 CO2/m2/year** over a 60-year period and a **social cost of €148 231.**

The better performing elements in terms of global warming were materials resourcing, replacement of materials and transport and in use water and energy use.

Of the main construction activities Chart 5.1a indicates that **largest contributor** to the LCA of CO2e were the **Energy (64.5%),** construction materials (18.2%), replacement of materials (9.8%) and construction activities (1.8%).

Whilst energy consumption (B6) is the largest contributor to **acidification at 9.49 kg SO2e,** construction /installation (A5) to **eutrophication at 4.31 kg PO2e** and water use (B7) to **ozone depletion at 5.89 kg CFC11e**. With material replacement and refurbishment (B4-5) the largest contributor to lower atmospheric formation of **ozone at 6.52 kg Ethanee** and water use (B7) at **6.02 MJ (Table 5.1a).**

In terms of other environmental indicators the best performance areas were end of life (C1-4) for **acidification 1.38 kg SO2e, ozone depletion 1.19 kg CFC11e and ozone 1.06 kg Ethanee.** Whilst material replacement/refurbishment (B4-5) performed well for **eutrophication 1,34kg PO2e** and energy consumption (B6) for abiotic depletion potential at **1.91 MJ).**

6.1.1.2 Case study 2 Pudasjarven Hirsihovi Finland:

Pudasjärven Hirsihovi is the name for two four-storied buildings in the city centre of Pudasjärvi. Located right next to the city hall, the finished complex will have a total of 53 two room with five 80 m2 commercial premises on the first floor, Pudasjarven Hirsihovi has a gross floor area (GFA) 3158 m2. Design parameters were for a hybrid building that used a high volume of timber whilst incorporating of hybrid (steel and concrete) for lower floor sections and some structural elements. on a concrete ground floor.

The overall CO2 emissions per year were **314 kg/CO2e/m2** with a C rating. An overall reduction of **14 kg/CO2e/m2** against the building performance would be required to achieve a B rating. The total assessed carbon for the project was **5 718 TONS CO2** and **34.09 kg CO2/m2/year** with a **social carbon cost of 285 911€.**

The global warming potential by Life Cycle Stages (Chart 5.3a) illustrates that **energy (B6)** is **the largest contributor (80.7%),** with materials (A1-3) **(12.9%).** The remaining elements attribute to less than 7% of the total building global warming potential over the life of the building (60 years).

In terms of other environmental impacts, the best performance in this respect were water use (B7) for **acidification at 1.57 kg SO2e** and energy consumption (B6) for **ozone depletion at 1.92 kg CFC11e,** construction materials (A1-3) **for lower atmospheric ozone formation at 1.35kg Ethanee** and for **eutrophication at 2.5 kg PO2.**

The worst performance areas were maintenance and material replacement (B1-5) is the largest contributor to **acidification at 3.49 kg SO2e**, **eutrophication at 7.31 kg PO2e** and **ozone depletion at 4.07 kg CFC11e**. Whilst energy consumption (B6) is the largest contributor to lower atmospheric formation of **ozone at 6.58 kg Ethanee** and total use of primary energy use (B6) at **9.31 MJ.**

Standard Finnish mains energy supply parameters were used for the operational and construction energy processes.

6.1.1.3 Case study 3: Ungdomsskole Stokmarknes, Norway:

The final design was for a two-storey building with provision of teaching and learning spaces and communal areas suitable for community spaces. The comprised of teaching spaces which included specialist rooms (e.g., music spaces), hospitality and service spaces around the central atrium with three stairwells for access. The gross floor area of 3996m2.

The overall CO2 emissions were **161** kg/CO2e/yr which is below the benchmark for the A rating of < **250** kg/CO2e/yr.

The LCA assessment confirms that the design, materials choices, replacement of materials, waste transportation and energy performed well. These contributing factors support the **A rating of the project** whose outputs are assessed at **720 TONS CO2** and **3.02 kg CO2/m2/year** with a social carbon cost of **36 016€.**

Of the main construction activities Chart 5.4a indicates that **largest contributor** to the LCA of CO2e are the **transport of materials (68.2%),** materials (17.1%), construction activities (6.7%) and replacement of materials (3.3%). All other contributing activities formed less than 5% of the total CO2 contributions for the building phase of the project. Waste transportation (0.6%), Energy (0.2%) and waste processing

(0.2%) perform well. 100% of the energy will be from renewable sources and replacement or reuse of building elements would be mainly timber or concrete.

In terms of other environmental impacts, the best performance in this respect were water use (B7) for acidification 1.81 kg SO2e, end of life (C1-4) for ozone depletion 1.05 kg CFC11e, energy consumption for lower atmospheric ozone formation at 2.99 kg Ethanee. Whilst material c construction materials (A1-3) performed well for eutrophication 1.04kg PO2e and construction materials (A1-3) for abiotic depletion potential at 1.47 MJ.

6.1.1.4 Case Study 4 Alvsbacka Strand, Sweden:

The Älvsbacka strand building has 18 apartments spread over six floors with one upper recessed penthouse with storage and guest accommodation. With the load bearing structure of CLT panels and volume elements for kitchens and bathrooms, the project aimed at high degree of industrialization and prefabrication. The gross floor area is 2128 m2 and the apartments where sold as condominiums.

The overall CO2 for the assessment indicates a rating of A 120 kg/CO2e/yr which is significantly below the benchmark for the A rating of <250 kg/CO2e/yr.

Of the main construction activities Chart 5.5a indicates that largest contributor to the LCA of CO2e are the construction materials (65.1%), construction activities (19.2%) and replacement of materials (9.3%). All other contributing activities formed less than 7% of the total CO2 contributions for the building phase of the project.

The LCA assessment confirms that the design, materials resourcing, replacement of materials and transport and in use water and energy perform well. These contributing factors support the A rating of the project whose outputs are assessed at 322TONS CO2 and 2.52 kg CO2/m2/year with a social carbon cost of 16 094 €.

All other elements were relatively small contributors to the carbon LCA of the building.

In terms of other environmental impacts, construction materials (A1-3) is the largest contributor to acidification 8.88 kg SO2e and construction /installation processes (A5) to ozone depletion 7.49 kg CFC11e, eutrophication 3.87 kg PO2e and abiotic depletion potential at 8.46 MJ. Whilst transportation to site (A4) is the largest contributor to lower atmospheric formation of ozone at 5.57 kg Ethanee.

Best performance in this respect were construction /installation processes (A5) for acidification at 1.64 kg SO2e and formation of lower atmosphere ozone at 1.01 kg Ethanee. Whilst transportation to site (A4) for ozone depletion at 1.01 kg CFC11e and for abiotic depletion potential at 1.17 MJ, with energy consumption (B6) for eutrophication at 1.15kg PO2e.

6.1.2 Lessons learnt from case studies.

The following section offers an overview of lessons learnt from the TALLWOOD project.

Agents as drivers for Change: Throughout the TALLWOOD project it has been evident that key figures have stimulated and steered the drive (policy actors, industry leaders and academia) to use more wood in sustainable tall buildings. This focus has enabled a deeper and wider focus on certain sustainable construction related factors in 'what' and 'how' sustainable construction is and the relationship of this to wooden construction techniques. Collaboration has enabled new learning and relationships in procuring materials and reducing the length of value chains for timber. The retrospective use of the LCA will offer some important insights which both challenge and underpin the aspiration to use more wood in reducing of the environmental impact from these new buildings over their lifetime (cradle to grave).

Role of multi collaboration projects and knowledge exchange: a number of site visits where undertaken parallel to the LCA work, each offering sound insights to the use of wood and the associated skills and expertise this encompassed. The site visit of WOODCo near Oulu enabled first-hand the observation of modular construction of nearly completed one bedroom apartment units from floor assembly through to fixture, fittings and liveable spaces. Completing up to six units per day. The visit to the WOOD Hotel, Skelleftea and associated presentations illustrated how grand design and robust engineering practices could take wooden construction to both architecturally significant design and the achievement of fully accredited sustainability credentials. The Bankgata school multipurpose hall development, Bodø was an example of competitive procurement practices and how wooden construction was competitive both in terms of cost and building performance. These projects (and others not included in this narrative) are an illustration of how collaboration and knowledge exchange play a significant role on enabling cross border and innovative ways of working.

Reimagining the use of Timber in Construction: The use of national and local policy interventions and policy actors has enabled new ways of buildings to be trialled in Norway and industry upskilling to take place. e.g., policy actors' tacit knowledge in supply chains in Northern Nordic regions has replaced the need to import from distanced suppliers (southern Norway and Austria). Linkages with other projects can enable even further insights as to how sustainable construction, associated skills development and relevant circular value chains can be attained. For example, Cityloops is a project that Bodø partners also benefit from and brings further knowledge to sustainable construction. Sustainable procurement and LCA are key components of circular economy and areas that TALLWOOD construction can showcase performance if undertaken at the earliest stage of the project inception.

Efficiencies and advances in operational and management systems: the TALLWODD projects have also showcased modular construction and best practice in reducing the ingress of moisture during the construction phase by using innovative protection methods such as offsite construction and the use of canopies during the shorter on-site periods (e.g., use of tent domes and the roof structure as a canopy). This careful preplanning has enabled the maximisation on techniques such as BIM design, offsite construction and site sheltering techniques to reduce the environmental impacts on the wooden elements.

Future proofing the industry: sustainability and service model value chain creation: The case studies evidence that the local resourcing of materials has a positive impact on LCA outcomes. Where careful consideration has been undertaken and local value chains are available, performance has achieved an overall A rating showcasing low impact credentials for the construction materials and transportation to site (e.g., For most of the projects the services and renewable energy plans sat out with the assessment. Where existing infrastructure and associated renewable energy systems used, and building services installation was minimal (e.g., Hydro-electric in Alvsbacka Strand, Sweden), it is likely little variation in the LCA would be incurred. However, in more remote settings, where new infrastructure was required with significant ground works, it would be expected that the site works and LCA would have some negative implications for the LCA (e.g., Ungdomsskole Stokmarknes). It is therefore relevant to reflect upon regional infrastructure provision and the relationship with site specific LCA scope. As LCA should be transparent linkages with wider renewable energy plans should be taken in to account of the true accountability and impact of individual buildings (and their surroundings) be provided. This is a shortcoming of existing LCA tools and may be tackled at a municipality level.

Procurement and management: practices are essential for any project and enable tight controls on a project, this included design creep. Using accreditation systems drives a greater focus on project management, design parameters and therefore budget control. This includes aspects encountered in some TALLWOOD projects such as resource sourcing and site management. For example, the use of locally resourced timber and established wood-based industry coupled with established renewable energy services greatly lowers the environmental impact of the new apartments in Skelleftea. In Finland, equally the use of local timber resources and associated established wood-based industries is a driving force for innovation in this area. The example being, a 3D modular construction assembly system which can produce up to six completed apartment units in a working day (collaboration site visit to WOODCON, Oulu). These units are simply craned into position onsite.

Lessons learnt: The role of LCA and how to use it for future decision making: The TALLWOOD project sought to use LCA to substantiate how the case study buildings showcased the use of wood in tall wooden buildings. The review of the buildings was completed as a retrospective activity. Whilst this has added some value to the projects under discussion, optimal use of LCA tools (e.g., BREEAM, LEED and OneClick) should be undertaken at the design and planning stage and support decision making from site choice and design inception stages onwards. In the UK this is considered RIBA Stage A/B under the RIBA stages. Establishing the LCA at this early stage is essential and makes full use of tools such as ONE CLICK , BREEAM and LEED and enables the designing out of unproven technologies and decisions. Staring at this stage would enable the inclusion of actual data for all LCA stages A1 – D. The LCA tools can be used to develop digital twins and analysis of best practice at the design stage thus offsetting expensive and low performing environmental practices. That said, one project did undertake an environmental LCA assessment, namely Case Study 4 Alvsbacka Strand, Sweden – achieving a 'gold' award. The TALLWOOD project can learn from this approach for successive work.

7 CONCLUSION

The TALLWOOD project sought to identify and showcase best practice in tall wooden buildings. The selection of buildings was to include optimal use of timber including hybrid building design. The case studies illustrate a varied approach to achieving this objective e.g., offsite modular construction, use of BIM to optimise design and build activities, local timber-based industries, and the involvement of research actors in problem solving for the industries.

A number of key points are concluded from the LCA work and associated activities. These are that undertaking LCA is central to soundly baselining project performance and that this must be implemented at the earliest stage of the project. This is recommended at the site choice and design scoping stage.

Procurement is pivotal to securing the correct project protocols, team and project objectives. By this it is meant that from the design ideation stage key professionals should be involved to 'trouble shoot' and 'optimise' the environmental performance of the building and associated site management.

This approach should be guided by an appropriate system which is accredited and based on scientific fact to avoid 'urban myths' of what circular and sustainable construction is e.g., design, energy systems, management and procurement of materials.

We recommend a full LCA (60 years) is required for energy systems for the project and that this is linked to the national and local energy policy but is a project specific activity. Again, this will enable scientifically sound decisions.

We recognise that a policy which drives sustainable construction is a positive thing for TALLWOOD buildings and welcome further LCA practice in furthering this. It is recommended that all actors involved in LCA at the municipality level are fully trained and familiar with LCA, sustainability and circular economy. This is to ensure any procurement of future projects where LCA is part of the bid process is fully understood. Lack of upskilling in this area could be problematic as the parameters of any LCA require sound science and system boundaries to make informed, fair and just decisions.

The report highlights the 'best practice' adopted in the projects that are commonly understood to improve sustainable construction. These are sound policy and informed professionals, the use of sound design practices (modular construction, BIM tools and LCA) and short procurement value chains. The project also showcases the positive impact of collaboration with the private and public sector with research and development professionals. Projects such as TALLWOOD act as a conduit for knowledge exchange and learning in 'best practice' in a complex and every changing world.

The project has also identified that investment in services infrastructure (energy and water) affects the outcome of LCA on specific projects both negatively and positively. Full accountability should be taken in how energy services are provided at a site and municipality level. LCA should be a requirement for both in determining bets options and associated impacts (economic, environmental and social).

In terms of parallel technical testing activities, further benefits to building performance can be achieved which improve the 'in use experience' of the building users. The technical tests (moisture and robustness) illustrate a growing technical expertise and capability in wood construction which is furthering the knowledge for the industry. The work represented in the TALLWOOD project illustrates the level of collaboration between academia and industry in the resolution of 'real life' issues for society. The furtherance of knowledge in these problematic areas underpins innovative ways of working in future projects which include the sue of new wood products such as CLT and modular construction (e.g., SIPS panels, 3D moles (apartment spaces) and balconies). There is potential to reduce materials in modular construction if approached in a specific design approach thus improving the sustainability credentials of material embedded carbon in the wooden elements of buildings.

The technical reports on moisture ingress, control and monitoring widen our understanding of moisture behaviour in wooden construction in different spaces and locations of these spaces in buildings. This information is useful in future designs in terms of location on certain rooms and associated functionalities and best practice in material use and monitoring for moisture control in building structures.

In summary the LCA for the TALLWOOD project and associated activities of the project have contributed to broadening and deepening our understanding of TALLWOOD buildings. Whilst wider scope and earlier onboarding of the LCA process is required, the LCA assessment does indicate areas of good practice and those where improvements should be made. Locally resourced timber is part of this best practice but overall, fully integrating LCA into building ideation, design and management practices (including procurement) is key to achieving high performing sustainable buildings. This should be underpinned by training for those involved in these work areas to enable good decision making and avoid misinformed choices or 'greenwashing'.

References

ARUP, 2019. *Rethinking Timber Buildings*, London : ARUP.

Building Resarch Establishment, 2022. *BREEAM worldwide.* [Online]
Available at: https://www.breeam.com/worldwide/
[Accessed 20 January 2022].

Building Research Establishment, 2021. *BREEAM NOR New Constrution V6.9*, London BRE GLobal

BRE Global., 2023. *BRE Background to the Green Guide to Specification.* [Online]
Available at: https://tools.bregroup.com/greenguide/page.jsp?id=2069
[Accessed 07 March 2022].

ONE CLICK., 2022. *One Click LCA.* [Online]
Available at: https://www.oneclicklca.com/
[Accessed 05 October 2021].

Ellen MaCarthur, 2022. *Business and the circular economy.* [Online]
Available at: https://ellenmacarthurfoundation.org/resources/business/overview
[Accessed 25 January 2022].

European Commission , 2020. *Circular Economy Principles for Building Design,* Brussels: European Commission.

Food and Agriculture Organisation (United Nations), 2016. *Promoting sustainbale building materials and the impications on the use of wood in buildings,* s.l.: United Nations.

Global, B. R. E., 2022. *BRE Global Green Guide to Specifications.* [Online]
Available at: https://tools.bregroup.com/greenguide/podpage.jsp?id=2126

Gustafsson, A (RISE) and Berg, S (LTU), 2021. *Stabilization of volumes – optimization (Final Report).* [Online]
Available at:
https://www.oamk.fi/images/Hankkeet/TallWood/Publications/stabilization_of_volumes_optimization_final.pdf
[Accessed 2nd September 2022].

Gustafsson, A, 2019. *The CLT Handbook,* Skelleftea: RISE.

H. E., 2017. *How can wood construction reduce environmental degradation?,* s.l.: European Forestry Institute .

IEA and UNEP, 2018. *2018 Global Status Report Towards a zero-emission, efficient and resilient buildings and construction sector,* Nairobi, Kenya: International Energy Agency and the United Nations Environment Programme.

Kádár, Ferenc , 2021. *Implementation of new measurement methods in wood construction; Case DAS Kelo..* [Online]
Available at: https://blogi.eoppimispalvelut.fi/lumenlehti/2021/10/26/implementation-of-new-measurement-methods-in-wood-construction-case-das-kelo/
[Accessed 10th September 2022].

LEED, 2022. *LEED Healthy, highly efficient,.* [Online]
Available at: https://leed.usgbc.org/
[Accessed 02 September July 2022].

Mavi, R; Gengatharen, D; Mavi, N; Hughes, R; Campb, 2021. *Sustainability in Construction Projects: A Systematic Literature Review,* Basel, Switzerland : Sustainability.

Raworth, K, 2018. *Doughnut Economics : Seven Ways to Think Like a 21st-Century Economist.* London : Cornerstone.

United Nations, 2016. *Promoting sustainable building materials and the implications on the use of wood in buildings.,* Geneva: United Nations.

Vestergaard Jensen, A and Craig, N , 2019. *Wood in Construction 25 Cases of Nordic Good Practice* , Copenhagen : Nordic Concil of Ministers.