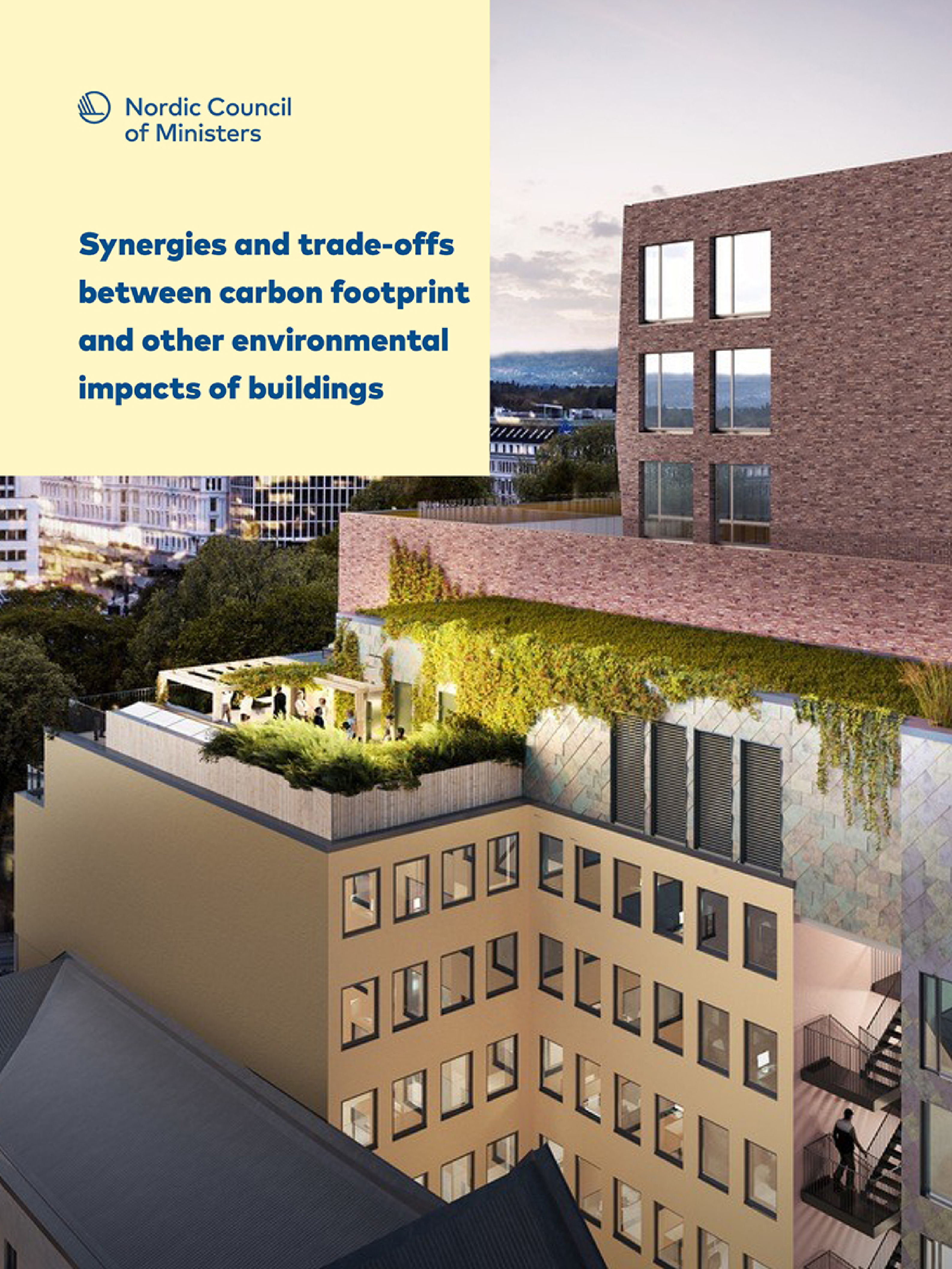
Nordic Council of Ministers

Synergies and trade-offs between carbon footprint and other environmental impacts of buildings



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Preface

Low-carbon and circular building construction are receiving increasing attention on the EU and Nordic policy agendas to overcome unsustainable production and consumption patterns. The role of public procurement in promoting low-carbon and circular construction has been recognized but not fully exploited opportunity by cities and municipalities to reach their objectives of carbon neutrality and resource-efficiency. Climate change and circular economy are focused on also in the current Programme for Nordic co-operation on Environment and Climate 2019–2024.

Today, many national action plans and legislation related to low-carbon public construction already set targets that stimulate the calculation of carbon footprint of buildings as well as higher recycling rate for construction materials and waste reduction in building sector. Also, EU's green public procurement criteria, circular procurement criteria developed by Green Building Council, and Nordic eco-label exist for buildings, which could help procuring units to conduct low-carbon and circular public building projects.

Albeit several examples in low-carbon and circular public procurement exist, the extent to which low-carbon and circular aspects provide synergies in terms of the total environmental impacts of the building, has remained unexplored. This study, Synergies and trade-offs between carbon footprint and other environmental impacts of buildings (SynTra), defines the framework and approaches how low-carbon and circular buildings can be acquired and presents some case studies in the Nordic and Baltic countries. In addition, the study explores potential trade-offs in applying low-carbon and circularity targets.

Low-carbon and circular construction will most likely remain one of the priority areas also in future Nordic co-operation. The Nordic countries could also become frontrunners in low-carbon and circular public construction and establish common guidelines, as numerous procurement cases promoting the low-carbon and circular construction and a shared interest in this matter already exist.

This study was carried out in Nordic co-operation by Finnish Environment Institute (SYKE), Norwegian University of Science and Technology (NTNU), Asplan Viak and Tallin University of Technology (TALTECH). The project was financed by the Nordic Council of Ministers, administrated by the Nordic working group for Climate and Air (NKL). We would also like to thank Senate Group in Finland, Eki Karjalainen at Ramboll Finland Oy and Anna Huostila at Green Building Partners for their contribution in the case study.

Authors' have contributed into the report in the following manner:

1. Introduction	Alhola
2. Literature review	Sankelo
3. Case study: Finland	Sankelo
4. Case study: Norway	Borg, Chartrand, Andresen
5. Case study: Estonia	Aljas, Kertsmik, Lylykangas
6. Conclusions from the case studies	All authors
7. Public procurement highlights	Alhola
8. Concluding remarks	Alhola, Sankelo

Summary

Low-carbon and circular public procurement aims at reducing climate emissions, promoting value retention, closed material loops and savings in resource use. This can be achieved for example by favouring re-manufacturing and re-using of products and materials several times in a circular manner without causing increase in emissions or other harmful environmental impacts. In the construction and renovation of buildings, attention is paid to the planning phase as well as minimizing material and demolition waste and recycling waste appropriately. In the construction of road infrastructure, significant savings in material and money could be achieved by utilising secondary materials from the site or nearby.

This study examined and illustrated the approaches of low-carbon and circular construction and their synergies and trade-offs. Three examples of circular construction were identified in Finland, Norway and Estonia. Emissions and potential emission savings were calculated in the context of circular solutions in these case studies. The Finnish case study represented a new construction, where renovation and re-use of materials were considered as one possible means of lowering the building carbon footprint. The Norwegian case was an example of a construction that was designed with a high degree of re-used and re-usable materials, following principles of circularity. The Estonian case utilized the building information models from the architect and the structural engineers of the building.

The cases showed that in order to achieve substantial emission savings, the amount of re-use must be extensive, and likely encompass load-bearing structures. In such a case, the re-use aspects and their possibilities must be considered in the new building design from the start. The pre-demolition audit for the existing building should pay explicit attention towards using load-bearing structures, and investigate their possibilities.

The cases examined in this study imply that low-carbon and circular construction can be promoted through public procurement. Re-use of building materials can bring about a siginificant decrease in building climate impact, first through pilot projects and later on hopefully as a matter of course. A new construction with very extensive building part re-use is not possible in every case, but in many cases the existing building might be saved, or at least the building frame spared. This is an option that should be explored first and foremost, because it is higher on the circularity hierarchy. If new construction is absolutely necessary, choosing wood as the frame material also has potential for significant emission reductions. Energy choices also play an important role in a low-carbon building construction.

Advanced planning, market dialogue and co-operation between different actors in supply chains is important for the future development of low-carbon and circular procurement. It is necessary to address the overall chain of manufacturers, suppliers, logistics, reprocessing and end markets as well as consumers. In addition, the education of procurers is essential for the focusing of the most important aspects and for the adoption of meaningful new practices.

1. Introduction

Climate change mitigation and sustainable use of the Earth's resources, among other goals of Sustainable Development Agenda2030, are focused on in the Nordic Strategy for Sustainable Development 2013–2025. The Paris Agreement (December 2015) signatory countries have agreed to accelerate global mitigation efforts to limit the increase in the global average temperature to 1.5°C. In consistence with the long-term temperature goal of the Paris Agreement, the Nordic countries have in 2019 signed the Declaration on Nordic Carbon Neutrality, whereby they commit themselves to working towards carbon neutrality. The vision of Nordic co-operation is that the Nordic region will become the most sustainable and integrated region in the world by 2030. Nordic countries have each set their own target years for reaching net zero emissions: Finland by 2035, Iceland by 2040, Sweden by 2045, Norway and Denmark by 2050.

In addition, the European Green Deal investment plan provides a framework to facilitate public and private investments needed for the transition to a climate-neutral, green, competitive, and inclusive economy (European Commission, 2019). Public investments will likely to be accelerated also by the recovery and rebuild of economies after the Covid-19 crisis and the war in Ukraine. Building stock is not only important in itself: it can bring flexibility and add resilience to the overall energy system. It is now crucial to target the public money in low-carbon and resource-efficient solutions, to enable the transition away from the use of fossil fuels in production and carbon intensive materials in construction.

1.1 The building sector has great potential to contribute to climate targets

The Nordic goal of being global leaders and advocates for climate action cannot be reached without effecting a rapid change in ways of building, renovating, and living, without compromising the safety, affordability and quality of the built environment (Nordic Declaration on Low-carbon Construction and Circular Principles in the Construction Sector, 2019). Indeed, building construction has been recognized as one of the key sectors in tackling climate change. Globally, buildings and construction are estimated to account for 36% of final energy use and 39% of energy-related CO_2 emissions (UN Environment and International Energy Agency, 2017). An estimate used by the EU is that within the EU, buildings represent 40% of energy consumption and 36% of CO_2 emissions (European Commission, 2020).

Energy efficient buildings are receiving increasing attention to reduce the carbon emissions in the built environment. According to the UN Environment, the energy intensity of the buildings must improve by an average of 30% across the globe by 2030 (compared to the situation in 2015), for the world to be on track to fulfill the Paris Agreement (UN Environment and International Energy Agency, 2017). In addition to improving the use-phase energy efficiency, it is crucial that attention should be paid to the whole life-cycle of the building, especially to the embodied emissions of the construction materials. Materials used in new construction are often highly carbon intensive. A relatively recent study (Material economics, 2018) reveals that the production of materials such as aluminum, steel, cement, and plastics, which are heavily used in the construction sector, could alone exceed the remaining carbon budget calculated in relation to achieving the 1.5 °C climate target. It is suggested that circular approaches in these heavy industries could reduce CO_2 emissions from materials production in the EU by 56% by 2050. (Material economics, 2018) In addition to the process of producing construction materials, attention should be paid to the reduction of material consumption, and re-use or recycling of existing materials, i.e., solutions that promote circular economy (Ellen MacArthur Foundation, 2015).

1.2 Carbon footprint calculation – Capturing the life-cycle impacts of buildings

The EU level regulation related to energy performance and nearly zero-energy buildings obligates all member states to implement building energy efficiency regulation in their national legislation. As a part of the European Green Deal and Fit for 55 package, aiming for emission reduction of 22% by 2030, the European commission has drafted a major revision for the Energy Performance of Buildings Directive (EPBD). The draft proposes that the building life-cycle carbon footprint is assessed and declared for all new buildings starting from 2030, and for buildings with a floor area larger than 2000 m^2 starting from 2027. The life-cycle climate impact must be assessed according to European standards: European Commissions' Level(s) provides a suitable framework for the assessment, and national methodologies can be used if they fulfil the criteria specified within the Level(s) guidelines. (European Commission, 2021)

Several European countries and especially the Nordic countries are already developing their national methodologies and preparing to regulate the emissions occurring before or after the building use-phase. In October 2019, a collaborative Nordic working group for LCA, climate and buildings was established, and Nordic Climate Forum for Construction was organized, to begin the work for Nordic harmonization on building life-cycle climate impact regulation, as well as to develop practical applications of LCA methods for construction (Swedish Life-cycle Center, 2019).

Finland is to implement building life-cycle carbon footprint (CF) regulation in the national building code by 2025, and Ministry of the Environment has established a national framework for the CF calculation, which has recently been piloted and commented. The development of a Finnish national emission database, containing emission data on building materials, construction, transport and waste management, was established in 2021 (Finnish Ministry of the Environment, 2021). In Norway, the regulation authorities have commissioned several studies to prepare for introducing embodied carbon requirements in the building code (Asplan Viak 2018, 2020), and some voluntary schemes / programmes have already implemented such criteria (e.g. futurebuilt.no, byggalliansen.no). From July 2021, the Norwegian building regulation includes a requirement to do a CF calculation for new residential blocks and commercial buildings. In Estonia, the Ministry of Finance and Communications has also started the preparations for a national building CF regulation.

1.3 Building materials matter and their importance is increasing

As buildings become more energy efficient, and as the ambient energy systems gradually decarbonize, embodied emissions form an increasing portion of the building life-cycle carbon footprint. In modern energy-effective buildings, the share of the embodied emissions can exceed 50% of the building life-cycle CF (e.g. Ibn-Mohammed et al. 2013; Azari & Abbasabadi 2018; Wiik et al. 2020; Zimmerman et al. 2020). In case of a truly net zero energy building, emissions from the use-phase are zero, and 100% of the life-cycle emissions consist of pre- or post-use emissions, largely from the embodied emissions in construction materials. The next step in decarbonizing the building stock would be to construct net energy positive buildings, and thus compensate for the initially occurring embodied emissions[1].

Aside from pilot projects, net zero energy buildings or plus energy buildings are currently rarities. However, the embodied emissions should already receive great attention on the building level. With the share of embodied emissions already being approximately 50% or more of a modern building's CF, tackling the embodied emissions in new building construction is an effective tool for decreasing the large emission impacts of the whole construction material industry.

1.4 Public procurers should take the lead towards low-carbon construction

Public sector is expected to lead the way towards low-carbon and circular buildings, areas, and cities by procuring sustainable works, services and solutions (Nordic Council of Ministers, 2019). Public procurement covers almost 20% of the EU's GDP, and it has been recognized as essential in attaining various environmental and social goals (European Commission, 2010). However, its potential has not been utilized to full extent (Alhola, 2012; Alhola & Kaljonen, 2017). In Finland, for example, public procurement and investments cause around 20% of the total consumption-based carbon footprint, which equaled 8.3 million tons carbon dioxide equivalent in the year 2015. The highest emissions result from public procurement of heating and electricity, construction and maintenance services for buildings and areas, as well as travel and transport services. (Nissinen & Savolainen, 2019) These expenditures contribute to the overall emissions of the built environment.

Municipalities are aware of the climate change mitigation potential of the construction sector, as well as of the upcoming CF regulation. Many cities and other public organizations are currently formulating strategies and procurement guidelines accordingly, which indicates their strategic commitment to reach climate targets (e.g., Towards Carbon Neutral Municipalities and Regions (Canemure) -network[2]). Several pilot projects and other real-life examples of low-carbon buildings – comprising both the embodied emissions and the building use-phase – can also be found in the European and Nordic countries. For example, the FutureBuilt

1. The Norwegian Project Powerhouse is attempting this: https://www.powerhouse.no/en/
2. https://www.hiilineutraalisuomi.fi/en-US/Canemure

programme in Norway is a sustained effort to lower the built environment CF by means of public procurement. The programme started in 2010 and is a close cooperation between municipalities, researchers, and industry. In 50+ case buildings, including both new construction and renovations, the aim is to reduce the building carbon footprint by 50%. Since the programme commenced in 2010, this target has been reached and verified in many finished building cases. (FutureBuilt, 2019)

Another recent example indicates that important decisions should be made already in the planning phase to reach low emission level and other sustainability targets. A municipal school building in Kuopio, Eastern Finland achieved a CF for its chosen design option (wood frame, heat pump, PV) which was 44% lower than for the 'standard' building practice (concrete frame, district heating, no PV) (Alhola et al. 2019). Although good examples exist in the field of low-carbon and circular procurement, they have so far been pilots rather than a systematic way of procuring public buildings.

As concluded from the earlier studies of low-carbon and circular procurement (Alhola et al. 2019; Alhola et al. 2017) and from KEINO[3] consortium's co-operative and practical work with several Finnish municipalities assisting them in the tendering process of low-carbon buildings, it has been observed that municipalities have many environmental and functional objectives they wish the building to fulfill. In addition to improving the building energy efficiency or lowering the building CF, they may wish the buildings to have a longer life span, to be more flexible to future alterations, to allow more user groups and extended usage hours, to support sustainable modes of traffic, and to interact intelligently with the ambient energy grids. However, it is not necessarily clear to the procurers how to weigh the different objectives, and which ones are likely to have the largest environmental impact. Lack of knowledge is probably one of the reasons why sustainable procuring patterns and innovative procurement diffusion is slow (Alhola, 2012; Alhola & Kaljonen, 2017).

There already exist EU-level and national guidance and criteria sets as well as Swan Eco-label criteria for buildings, that stimulate the procurement of low-carbon and circular buildings in public tender competition[4]. Also, in addition to the development of LCA based CF calculation methods, building embodied carbon is already reported, rated, or limited in several building certifications or other building-related initiatives, both nationally and internationally. A recent compilation recognizes a total of 15 different Nordic certificates, methods, pilot programmes or other initiatives for quantifying and/or reducing the embodied emissions in buildings. These include RT Environment tool (Ympäristötyökalu, *in Finnish*) and the national CF assessment method in Finland, BREEAM NOR and Statsbygg requirements in Norway, BREEAM SE and Miljöbyggnad in Sweden and DK-DGNB and Bolig+ in Denmark. (Bionova Oy, 2018).

No single indicator will encompass all sustainability targets, and the procuring authority in the municipality may use a multitude of environmental criteria in the procurement process. In case the criteria overlap, this can create unnecessary calculation effort for all parties of the tendering process. The objectives set for the

3. KEINO Competence Centre for Sustainable and Innovative Public Procurement is a consortium of research organizations and public procurement bodies, steered and funded by the Finnish Ministry of Economic Affairs and Employment.
4. E.g., procurement criteria for circular buildings, Finnish Green Building Council (FGBC, 2018)

building may also be in conflict, in which case all targets cannot be realized, no matter how carefully the criteria are selected. Indeed, a recent review paper on building sector circular economy & GHG emissions (Gallego-Schmid et al. 2020) concludes that circular economy solutions in the building sector do not necessarily result in emission reductions, and that case-by-case quantification is crucial. The authors also point out that despite a growing number of publications on building sector circular economy, there is a scarcity in quantitatively analyzing the links between circular economy and greenhouse gas emissions.

However, the benefits of circular approaches are strengthened by the fact that many of these measures do work well together. For example, reducing the materials intensity of buildings reduces the total amount of steel needed, which secondary steel production needs to grow less to meet the demand. Likewise, new business models that boost the value realized from each product can drastically improve the economics of measures to make products more materials efficient. Cumulatively, these opportunities can result in a step change in resource efficiency and low-carbon-built environment.

This report aims to provide public procurers with objective information on:

- To what extent building CF considers the most important environmental aspects of buildings and can be used as a tool to define sustainable buildings.
- In which cases the building CF could be limited or even in conflict with other building sustainability measures.
- How sensitive the building CF is for the underlying assumptions (e.g., emission profiles, sectoral allocation of emissions, time weighting of emissions).

2. Low-carbon and circular construction of buildings

In the discourse of building sustainability, design philosophies such *as circularity*, *adaptability*, *flexibility* and *longevity* are sometimes used almost synonymously. Frequently they are also equated with building *low-carbon footprint*.

One example of this rhetoric is found in a recent EU review of building carbon footprint regulation. In the review, performed by Buildings Performance Institute Europe (BPIE), low building carbon footprint is equated with circularity, and this in turn is equated with a multitude of other desirable building characteristics:

> *The principles and action to mitigate whole-life emissions are the same as improving circularity (e. g. re-use, reduce, avoid over-specifications, consider local aspects and passive solutions, improve building resilience, flexibility and adaptability, extend the lifespan of buildings and components, improve recyclability).* (BPIE 2021, p. 15)

The implicit claim is that lowering building carbon footprint requires precisely the same actions as improving building circularity. If this were always the case, procuring low-carbon buildings would be simple. By demanding that contractors construct long-lived, adaptable buildings, with re-used and recyclable building materials, the public procurer could obtain low-carbon buildings almost automatically. And perhaps also the other way around: by demanding low-carbon buildings, the public procurer would also secure buildings that are flexible, adaptable, and in line with circular economy and circular building principles.

However, there are some grounds to question such a broad generalization. While low-carbon footprint, circularity, flexibility, adaptability and longevity may coincide for some building designs, they do not always do so. In some cases, designing a building with some beneficial characteristic (e.g., longevity, adaptability) may result in poorer performance in other characteristics (e.g., carbon footprint, resource demand). Research findings that demonstrate this are reviewed in this report section.

Conflicts between environmental goals are not merely a question of imperfect building design, which could be perfected with more detailed information or more sophisticated optimization. True trade-offs can appear, where the building procurer must choose, or at least prioritize, between different environmental goals.

Prioritizing is of course familiar in the field of public procurement, or indeed any construction activity, where funds and other resources are limited. The procurer always faces possible trade-offs between life-cycle costs, functionality, user preferences, aesthetics and environmental performance. These need not always be in conflict: a building that is in some aspect excellent for the environment – for example, a low-carbon building – can have reasonable life-cycle costs, good overall functionality, beautiful architecture and happy users. But it is important to be aware that "good environmental performance" embodies various environmental goals, and these goals do not always support each other.

2.1 Building circularity strategies

Askar et al. (2021) have reviewed the concepts of building adaptability and resilience, which they link closely with each other. They present an array of adaptability and resiliency strategies, with examples of appropriate design solutions. These include:

- **Robustness / Longevity / Durability**: Overdesigning structural capacity. Structures should be designed to sustain the worst-case scenario.
- **Redundancy**: Providing the building with backup generators and multiple water supply systems. Sufficient floor height for different uses.
- **Passive survivability**: Thermal massiveness, green roofs and other green surfaces, enclosed courtyards, adaptive building envelope (e.g. active renewable energy production elements).

These are just a few of the adaptability resiliency strategies and measures found in the reviewed literature. In total, Askar et al. recognize 19 different dimensions of adaptability, with partial overlap. The chosen examples illustrate that at least some building adaptability / flexibility strategies are likely to increase the building carbon footprint. For example, a massive building with ample floor height and multiple supply systems may be well designed for longevity but may also cause high carbon emissions before the use-phase.

Another recent review article (Eberhardt et al., 2020) categorizes different building design strategies for reaching a circular economy. The authors find 16 circularity strategies, which have some overlap with the above-mentioned adaptability strategies listed in Askar et al. (2021). Strategies such as modularity, standardization, flexibility and building component accessibility can be seen as directly representing circularity, or belonging to the category of adaptability, which can be seen as a building circularity strategy itself.

Eberhardt et al. (2020) remark that strategies to reduce emissions by building circularity are interconnected and overlapping, and they can lead to either positive or negative results. Even where it seems highly likely that a particular circularity strategy also reduces carbon emissions, there is a scarcity of quantitative case studies to support the conclusion. And when case studies exist, their documentation and calculation methods vary so widely, that it is not easy to draw robust conclusions based on them. This finding indicates that there is an urgent need for more case studies on the interconnections between building circularity and low-carbon design.

In a Finnish context, Huuhka (2019) has reviewed the synergies between building circularity and low building carbon footprint. The report lists 19 different building circularity strategies, which can contribute to lowering the climate impact. Although the study focuses on synergies, it does identify some possible trade-offs. For example, designing a compact building lessens the climate impact from building materials, but the building adaptability and flexibility may suffer. And whereas re-using building parts is a low-carbon activity, producing new building parts from recycled material is not necessarily so. It is concluded that the relationships between circularity, renewability, climate impacts and other environmental benefits are not straightforward, and these goals can sometimes be in conflict. (Huuhka, 2019)

2.2 Building longevity strategies

The trade-off between longevity and building carbon footprint may be an especially problematic one. Continued use of existing buildings is in accord with circular economy: utilizing existing spaces and resources is preferable to material recycling. And if the continued use of existing buildings brings less pressure to construct new buildings, this also lowers the emissions from the construction sector. But in case a new building is being constructed anyway, will designing for longevity truly lower the life-cycle carbon footprint of that specific building? This depends on multiple factors, but the question can be simplified to: does the strive for longevity cause more emissions before the use-phase; and if so, will this "carbon debt" be paid during the building lifetime?

In principle, the benefits from constructing a durable building may justify higher emissions before the use-phase. If the building will truly become a long-lived one, the carbon debt will likely be paid. However, if the building is dismantled before the end of its useful lifetime, perhaps the extra emissions from sturdy materials or massive structure will never be compensated by building longevity, and they end up being just extra emissions.

In Finland, buildings are often demolished before they reach their full useful lifespan. Finnish demolished residential buildings are 58 years old in average, and other demolished buildings are only 43 years old in average. A significant share of demolition stems from other causes than building age or condition. Demolition is often driven by financial motives, such as the owner wishing to clear the plot for sale. (Huuhka & Lahdensivu, 2016.) Such findings indicate that designing for longevity does not help to lower carbon emissions, if the buildings are not allowed to reach their attainable useful life-time. The proposed emission savings from longevity need a specific context to be realized.

The timing of allowable emissions is a crucial consideration. Nations of the world are quickly running out of time to meet the 2 °C goal of the Paris agreement, let alone the 1.5 °C goal. According to the current commitments by the 191 Paris agreement parties, necessary emission reductions are not in sight: instead, the global emissions are set to increase by 16% by 2030, compared with 2010. This suggests a warming track of 2.7 °C by the end of the century. (UN Secretariat, 2021)

The challenge is not first and foremost in reaching a political target: the urgency is fundamentally physical. If heating the climate pushes Earth systems (ocean currents, ice sheets, rainforests, permafrost) over their so-called tipping points, it is predicted to set off abrupt and irreversible changes, which tend to heat the climate further (Lenton et al., 2008, 2019). If the human industrial societies fail to drastically cut their emissions in a short time perspective (10–20 years), they may eventually face such extreme climate conditions, that there is little use trying to envision the fate of a building 100 years from now. In fact, the climate crisis is now widely recognized as an existential threat for humankind (e. g. UN Secretary-General, 2021). In such an urgent situation, lengthening the life-time of existing buildings should take a clear precedence over constructing new buildings.

For example, Birgisdottir et al. (2016) report a case study, where a Japanese library in an earthquake-prone area was designed for 100 years rather than 60 years. Design life-time extension was acquired by adding more concrete to the structure. This caused more emissions before the use-phase, but it was calculated that in the time period between 60–100 years, the carbon debt would be paid back. Whether or not emission saving happens depends entirely on the conditions that prevail 60–100 years from now, and there is much uncertainty involved. It should be stressed that building user safety is also a key consideration and having earthquake-resistant buildings in an earthquake zone is important. This is a good example of two goals – earthquake safety and low building carbon footprint – that may be in synergy (given a long enough lifetime) or may be in conflict, involving a trade-off.

Because there is uncertainty in attaining long-term emission savings from long-lived buildings, and a risk that constructing them might lead to higher up-front emissions, one possible circularity strategy is to intentionally construct buildings for a short use time. Eberhardt et al. (2020) present short use time as one of the building circularity strategies, an opposite strategy to building longevity. Buildings can be designed for a short lifetime and constructed to be light and easily dismantled. After the first designed use-time, the elements can be re-used in other buildings. Examples of this kind of buildings are e.g., a town-hall in Netherlands, which is designed to be re-located after 20 years, and a sports facility constructed for the Olympic games and dismantled for other purposes after the event (Eberhardt et al., 2020).

2.3 Own renewable energy production

There is a potential trade-off between renewable energy production and low building carbon footprint. Own renewable energy production lowers the need for delivered energy, and it can help to attain nearly zero energy, net zero energy or even off-grid buildings. Whether or not such buildings also have a low life-cycle carbon footprint, is by no means clear.

A common mode for own renewable energy production in buildings is solar electricity. Photovoltaic panels are often visible on the outside of the building, and they give a visual indication that renewable energy is part of the building design. When a public procurer sets out to construct a low-carbon building, PV panels are often considered as one of the readily available, commercially mature technologies for lowering the building carbon footprint. This is reasonable from the energy efficiency point of view: on-site solar energy production is a cost-effective way of improving the building energy efficiency, also in public buildings (e.g., Niemelä et al., 2016; Sankelo et al., 2019). However, the embodied emissions of solar PV can be high, and they have other environmental drawbacks (e.g. use of scarce minerals, toxic pollution at the site of production).

In a Norwegian case study by Kjendseth et al. (2018), building PV system was the second largest factor in building embodied emissions, contributing as much as 20% on average. In comparison, building services such as sanitary, heating, cooling and ventilation facilities, contributed 9% on average. The building envelope contributed 65% of the embodied emissions, when considered as one entity. In case the building envelope was considered in its separate parts (founding, walls, roof, etc.), in 4 out of 6 case buildings solar PV was the single largest source of embodied emissions, larger than any other envelope part. Total life-cycle emissions were not calculated in this study, but the authors conclude that when constructing energy-effective buildings, the embodied carbon should be evaluated. Otherwise, there is a risk that lowering operational emissions will only shift the emissions into a different building life-cycle stage.

Alhola et al. (2019) have assessed a public procurement case – a low-carbon school –

where solar PV was employed as one of the low-carbon strategies. Different design strategies were evaluated with the assessment method by the Finnish Ministry of the Environment (Kuittinen, 2019), following the version of the method that was published at the time. It was found that by installing solar PV, the school carbon footprint was lowered by 2%. After this study was conducted, the Finnish building CF assessment method was altered, with updated grid emission scenarios and solar panel embodied emissions. With the revised method, the assessment was less favorable for solar PV installation. Using the revised method, Keskisalo et al. (2021) found that solar PV system for a residential building did not manage to pay back its carbon debt within the 50-year calculation period. Only when assuming a constant (year 2020) value for electricity emissions – which is not consistent with the Finnish national assessment method – the solar PV installation paid back its carbon debt and lowered the overall building CF.

Vares et al. (2016) assessed three building designs with own renewable energy production and compared their total emissions (operational + embodied) against a business-as-usual (BAU) building with no renewable energy generation. The modelled building designs were:

- A net zero energy building, annually feeding as much energy into the grid as it takes out
- An off-grid building, demanding no energy from the ambient energy grid
- A building that supplies all its heating needs by solar heat
- BAU: a building receiving all its energy (electricity + district heat) from the grid

Several renewable generation technologies were considered (GSHP, free cooling, solar PV, solar thermal), as well as storage options.

All modelled building designs with renewable energy production had higher embodied emissions (emissions from pre-use phase) than the building without renewable energy production. This is not surprising: production of on-site energy and storage technology is carbon intensive. From life-cycle emission point of view, the question is then whether the operational emissions (emissions from use phase) are low enough to pay this "carbon debt" (i.e., the extra emissions occurring in the building phase are balanced by equal or even larger emission savings in the use phase).

It was found that on a 25-year calculation period, the off-grid building causes a total of 12–170% more GHG emissions than the comparison building. In other words, the off-grid case-study building does not manage to pay its carbon debt. This is largely because of high embodied emissions in the storage technologies. The other two building designs succeed better: net zero energy building causes 31–39% and solar heat building 31–32% less GHG emissions in total than the BAU building. In their case, the carbon debt is paid. In conclusion: own renewable energy production lowers the building carbon footprint, unless the strategy goes as far as to attain complete energy sufficiency by storage technologies. (Vares et al., 2016.)

However, the above assessment was performed with the assumption that emissions from the grid stay at a constant level during the 25-year calculation period. This is not consistent with many current building CF assessment methods. If district heating and electricity become cleaner in the 25-year period, as they are predicted to do, the overall benefit from own renewable energy production dwindles. In such a case, it is less clear if the net-zero building or the solar heated building are better building designs than the BAU design, from the life-cycle emissions point of view. The future outlook of the grid energy plays a large role in deciding which building designs to choose today.

The dynamics of diminishing grid emissions and building life-cycle carbon footprint was also explored by Parkin et al. (2020). They modelled numerically, how on-site PV production lowers the need for building operational energy, but on the other hand increases the embodied energy. They concluded that operational energy carbon metrics and life-cycle carbon metrics do not mirror each other: improving performance of one may cause poorer performance of the other. They also note that the divergence, or trade-off, is likely to increase with time, at least in the regions where the grid electricity is increasingly decarbonized. (Parkin et al., 2020.)

The fast decarbonization of grid energy is happening in many countries, and the public procurer increasingly faces these considerations, while making decisions about low-carbon buildings. In some Nordic countries, grid electricity already has a high share of renewables: the extreme example is Norway, with 98% of electricity originating from renewable sources[5]. In such a context, it should be carefully assessed if own renewable energy production decreases or in fact increases the building life-cycle carbon footprint.

2.4 Connecting circularity, carbon emissions and biodiversity

Focusing on GHG emissions is not enough, even when the whole building life-cycle is accounted for. If only the global warming potential is considered, there is a risk of causing significant environmental burden in other impact categories, such as resource depletion. This risk has received increasing attention lately (see e.g., Heinonen et al., 2016; Andersen et al., 2020), especially as the on-going loss of biodiversity is clearly linked to the depletion of natural resources. Building circularity strategies help to curb the resource demand, but which circularity strategies are the most efficient in protecting biodiversity? And are these strategies also beneficial in lowering the building carbon footprint?

In the Finnish context, Ruokamo et al. (2021) have assessed circular economy strategies both in terms of GHG emissions and biodiversity. Building circularity is considered one of the key aspects of circular economy, because the building sector is a major GHG emitter and natural resource consumer in Finland as well as globally. Ruokamo et al. have classified building circularity strategies according to their impact both on carbon emissions and biodiversity. By such a classification effort, it is possible to distinguish which circularity strategies have the most significant potential in lowering carbon emissions, while preserving biodiversity.

According to Ruokamo et al., the building circularity strategies with the largest potential climate benefits are:

- Using less concrete by optimizing concrete structures
- Re-using concrete building parts instead of recycling the concrete

5. https://www.regjeringen.no/en/topics/energy/renewable-energy/renewable-energy-production-in-norway/id2343462/

- Using low-carbon concrete with recycled binder materials
- Using less steel by optimizing steel structures
- Re-using metal building parts instead of recycling the metal
- Replacing concrete with timber
- Re-using or recycling timber building parts instead of burning them
- Building less space by optimizing space use (e. g. flexibility)
- Renovating buildings instead of demolition and new construction

Most of these strategies also ranked with the highest benefit in halting biodiversity loss. The exception is replacing concrete with timber, which may have negative consequences on forest ecosystems biodiversity. Lowest climate benefits resulted from:

- Recycling concrete demolition waste into landscaping
- Recycling concrete demolition waste into concrete manufacturing
- Recycling land removed from building site into landscaping

These actions are also not the highest-ranking in biodiversity protection: recycling concrete has potential for small biodiversity benefit, whereas recycling land has potential for only moderate benefit. (Ruokamo et al., 2021)

In conclusion, there are several building circularity strategies that benefit both biodiversity and climate. The strategies can overlap, but they can also be mutually exclusive. For example, optimizing the use of space also helps to optimize the use of building materials. However, saving the building from demolition and re-using the building parts cannot happen simultaneously. And if the building materials are recycled, this means they cannot be re-used as they are; these are mutually exclusive strategies.

In terms of public procurement, there is a risk that a weak circular strategy can receive too much attention and override stronger ones. For example, demolition of an existing building can be (seemingly) justified by recycling building materials and land masses before new construction takes place. Considered by sheer weight, it can seem like a large portion of the old building is recycled, and the strategy can falsely appear a strong one. But in the light of research, the climate benefits of preserving the existing building would be high, whereas the benefit from recycling building materials may be only moderate or even low. More case studies help to assess such scenarios, and this is one of the goals for the SynTra project.

3. Case study: Court Campus, Vantaa, Finland

A building life-cycle carbon footprint assessment was made for a new building located at the Court Campus in Kielotie 21, Vantaa. The assessment was performed at Finnish Environmental Institute SYKE, as a part of SynTra research project. Case study building in Kielotie 21 was examined in cooperation with Senate Properties (Senaatti), who are the owners of the current buildings at the site and responsible for the construction project. Due to the confidential nature of the activities within these buildings, detailed drawings or designs are not disclosed in this report.

The case study building is a new construction under planning phase. Currently there are two buildings on-site, housing police and court functions, and these are connected by a walking corridor. According to the preliminary plans, the new building will replace the existing police office building. The new building will house office spaces and court rooms for district court, while existing court premises will be thoroughly renovated and extended at the site. The functions of the existing police station will be replaced in another location. Because the planning process is still underway, the final configuration of the buildings and their functions may still change, and the results of this assessment may not apply.

Motivation for the study was to assess the possibilities of circular economy approaches for lowering the building CF. For identifying the circular economy potential of the project, a demolition audit in the currently existing building was carried out by a third party (Oy Insinööri Studio). The demolition audit report was available for the assessment. Several scenarios were considered in the assessment, concerning energy and material choices as well as circular economy actions.

The assessment was performed with OneClickLCA web-based tool, with the help of CarbonDesign tool. Drawings, planning documents and demolition audit report were made available through Senate Properties. A building model in IDA-ICE 4.8 modelling software, made by a third party (Ramboll), was also available for the building CF assessment.

Because of the early planning stage, the building CF assessment is only a preliminary one. Senate Properties should update the CF assessment as a part of the further planning process, when energy and material choices are considered in more detail. The results illustrate the magnitude of different design choices in lowering the building carbon footprint and help to compare different scenarios for developing the Court Campus.

3.1 Data and methods

3.1.1 Assessment method

Building CF assessment was made with the assessment method proposed by Finnish Ministry of the Environment, comprehensively explained in Kuittinen (2019) and Ministry of the Environment (2021). The Finnish national assessment method is based on the European Commission Level(s) method and European standards for sustainable construction and building life-cycle analysis (e.g., EN 15643, EN 15978, EN 15804, EN ISO 14067).

Building life-cycle is generally assessed in three modules: before use (A), during use (B) and after use (C). Figure 1 shows the life-cycle stages as they are defined in the European methodologies.

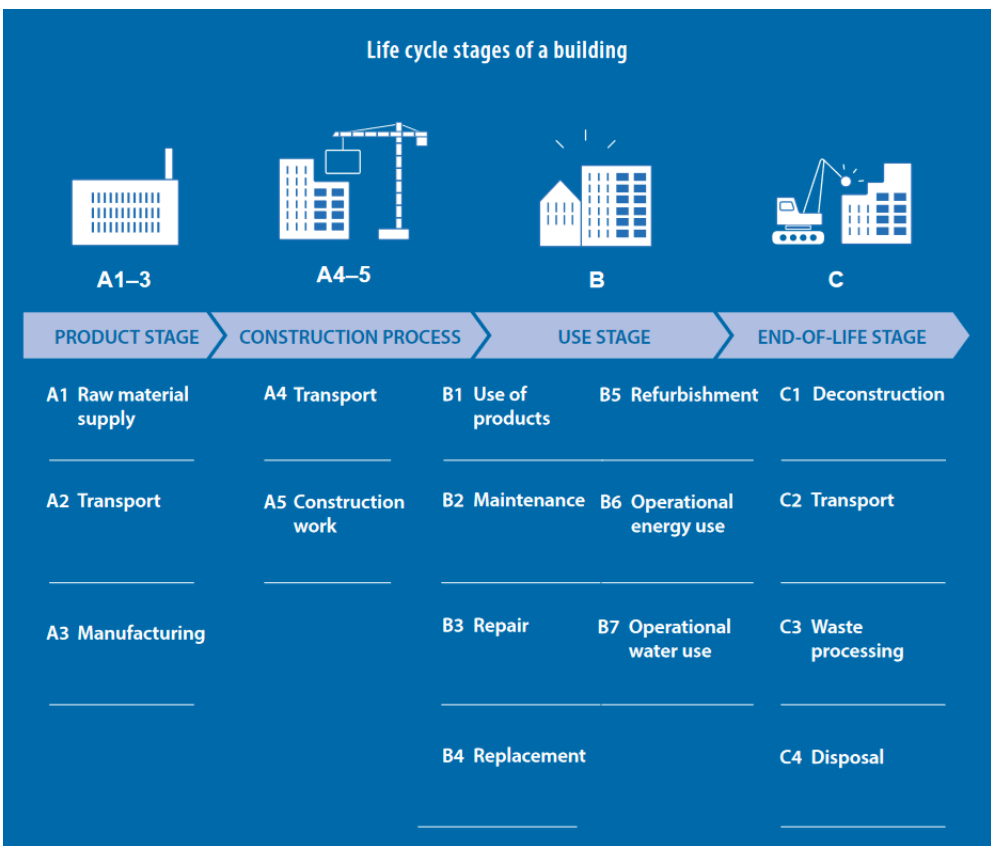

Figure 1. Building life-cycle stages A-C. Figure based on Kuittinen et al. (2019).

Table 1 shows the system boundary according to the Finnish national assessment method, with respect to modules A–D and their sub-modules.

Table 1. System boundaries of the Finnish national building life-cycle assessment method.

Module	Finnish national assessment method (proposed)
A1–A3 Manufacture of products	• Included • Assessed with project-specific data
A4–A5 Transport to site and construction process	• Included • Can be assessed with constant emission factor (expressed as kg CO_{2e}/m^2)
B1–B2 Use and maintenance of products	• Not included
B3–B4 Replacement of products	• Included • Production of replacement materials assessed with project-specific data • Energy consumption of replacements can be as-sessed with constant emission factor (expressed as kg CO_{2e}/m^2)
B5 Refurbishment	• Not included • For a significant renovation, a separate assessment may be required in the future
B6 Operational energy use	• Included • Assessed with project-specific consumption and national emission factors
B7 Operational water use	• Not included
C1–C4 End-of-life stage: demolition, transport, waste processing, disposal	• Included • Can be assessed with constant emission factor (expressed as kg CO_{2e}/m^2)
D Benefits outside the building life-cycle	• Not included in the building carbon footprint, but included in the assessment method • Should be declared separately under the title of "Building carbon handprint"

Module D, or the climate benefits occurring outside the system boundary, is also included in the Finnish assessment method, under the name "Building carbon handprint". In Finland, module D includes effects such as:

- biogenic carbon storage
- material re-use after building life-time
- renewable energy exported into the grid
- carbonatization occurring in concrete building materials

According to the Finnish national method, results from module D are given as additional information. Module D is not part of building carbon footprint, and it should not be subtracted from modules A–C. In this assessment of the Finnish case study, we are only concerned with modules A–C, because these constitute the actual building carbon footprint.

Building CF was assessed for a period of 50 years, as proposed in the method by the Ministry of the Environment, and by the European Level(s)-method. Although the assessment is carried out for a period of 50 years, building design lifetime and building actual lifetime may be different. National construction emission database CO2data (http://co2data.fi), maintained by Finnish Environmental Institute, was utilized for the generic energy and materials emissions, where necessary.

The Finnish national CF method does not assume any time discounting for greenhouse gas emissions: emissions 50 years from now are weighted equally to emissions today. Emissions from energy production are assumed to have a decreasing trend. The emission trends are discussed in more detail in connection with sensitivity analysis.

The building in the Finnish case study is in design phase, and there is no exact information on the chosen materials. At this stage, it would be highly speculative to assign differing scenarios for the demolition phase of the building. The Finnish method allows using a constant value for the emissions arising from module C, and this approach has been chosen here. In all cases, emissions from module C are given a constant value of 33.5 kg CO_{2e} / m^2. Divided by 50 years, this results in 0.67 kg CO_{2e} / m^2 a. Differences between different design scenarios arise solely from modules A and B, since module C is assumed constant and module D ("carbon handprint") is outside the scope of this assessment.

3.1.2 Building model

A building model made with IDA-ICE 4.8 was utilized in the CF assessment. IDA-ICE model was based on architectural drawings available in March 2021 and created by Eki Karjalainen at Ramboll Finland. With permission from Senate Properties, Ramboll Finland allowed the use of the model in this research project. Possible errors resulting from further use and modification of the model are the responsibility of the authors of this report.

Architectural plans for the Court Campus were modified in October 2021 and a part of the extension was removed from the updated plans. Figure 2 shows the model originally received from Ramboll. The larger building outlined on the right is an existing building that likely will be thoroughly renovated. The inverted L-shaped extension was the planned new construction, according to the planning situation in March 2021.

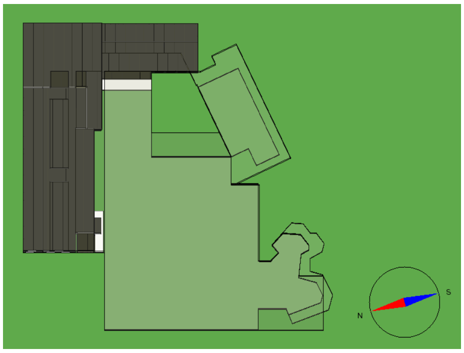

Figure 2. Original building model, Eki Karjalainen / Ramboll.

Figure 3 shows the outline of the extension in the new drawings (section III in Figure 3). The new building has been somewhat altered from the earlier version.

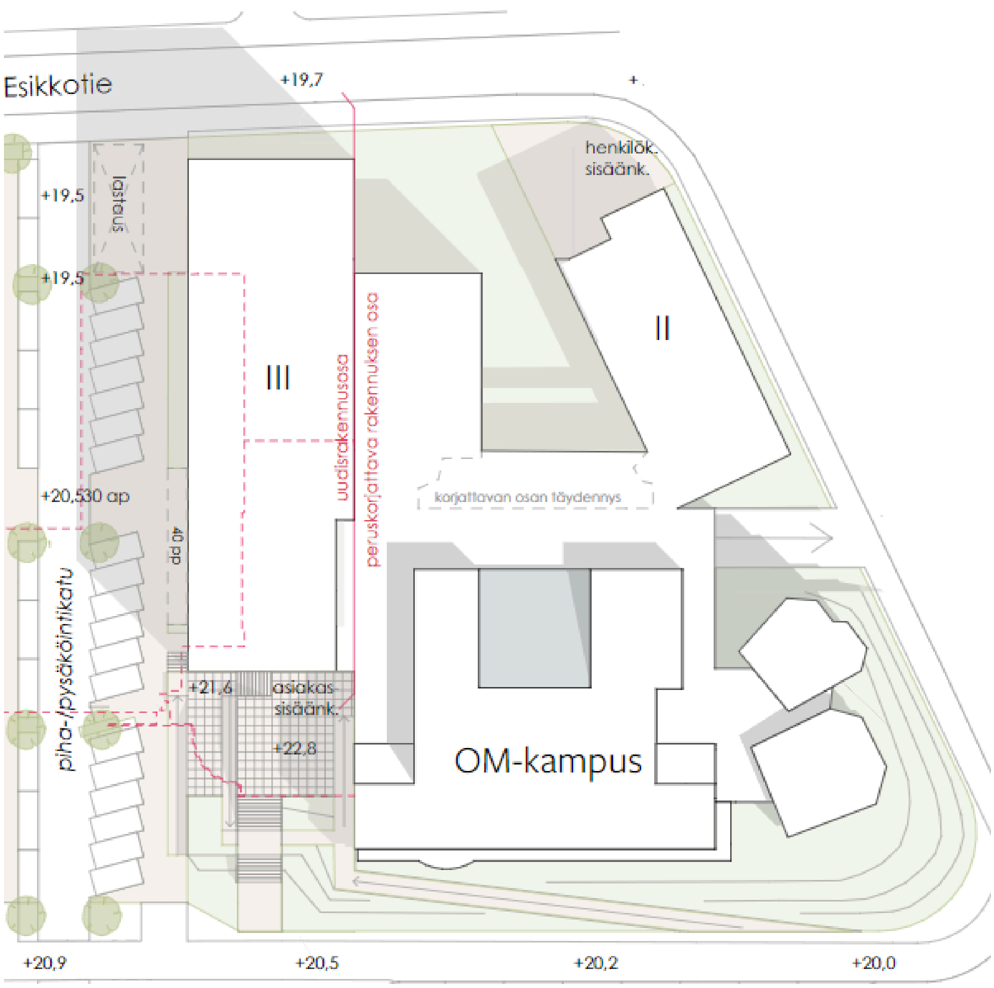

Figure 3. Extension in the current drawings (Senaatti Properties).

For the purposes of this CF assessment, the existing IDA-ICE model was truncated to represent the current planning situation. Figures 4 and 5 show the extension in the new, modified model. Heated net area of the new building part is now 2968 m^2. This is assumed to be 90% of the gross area, so gross area is assumed to be 3298 m^2.

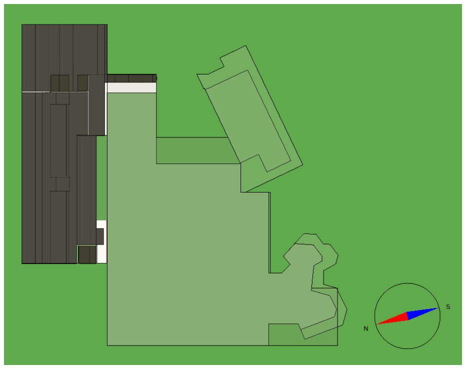

Figure 4. New version of the model originally made by Eki Karjalainen / Ramboll. Top view.

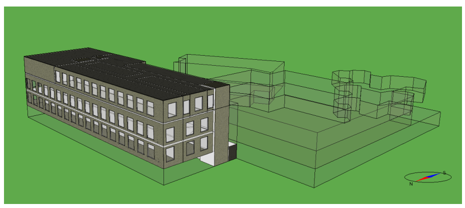

Figure 5. New version of the model originally made by Eki Karjalainen / Ramboll. Side view.

The new truncated model was used for energy simulations and as a source of quantitative input data for OneClickLCA. Information on building part areas was retrieved from the model.

Because the CF assessment is based on the truncated version of the model and did not start from the newly updated architectural plans, likely the modified model is somewhat out of date. This is not a critical issue for the preliminary CF assessment. When the building materials are not yet chosen, and the final choice of the energy system is not yet made, there are in any case several uncertainties present, likely larger than the exact shape of the building. All areas and volumes are in any case subject to change, as the planning process advances.

3.1.3 Building materials

A design tool for OneClickLCA, called Carbon Designer, was utilized to establish the different building CF scenarios. Input data for Carbon Designer was derived from the IDA-ICE building model and planning documents, as explained previously.

Because of the early planning phase, several assumptions had to be made concerning the design and building parts (e.g. the amount of window area). These assumptions were checked with Senate Properties representatives and the leading architect.

Table 2 shows the input data entered into OneClickLCA, for establishing the material use.

Table 2. Material quantity input data for the OneClickLCA building CF calculation.

Building part	
Base floor	944 m^2
External roof	944 m^2
Internal slab	1888 m^2
Internal ceiling	2832 m^2
Internal floor	2832 m^2
External wall area	1238 m^2
Non-load bearing internal walls (assumed 70% of all internal walls)	4289 m^2
Load-bearing internal walls (assumed 30% of all internal walls)	1838 m^2
Internal doors (assumed 30 wooden doors, 1.0 m x 2.1 m in size)	63 m^2
Total length of concrete pillars (above ground)	259 m
Total length of concrete beams	432 m
Internal walls finishing	7364 m^2
Window area	328 m^2
Permafrost insulation (along building circumference)	140 m
Balconies	none
Public shelter	none
External doors	22 m^2
Height of stairwell & elevator shaft	11.4 m

In this assessment, the basic scenario is assumed to be a steel-reinforced concrete building, with a beam and pillar construction, hollow-core concrete elements for slabs and sandwich concrete elements for external walls. This represents a typical new office building in Finland. Effects from choosing wood (CLT) as the main building material will be explored in its own scenario. In the case of CLT frame scenario, the façade is assumed to be made of timber.

Another scenario to be examined is a concrete building where all suitable concrete is replaced by low-emission concrete, which has 40% of the binders replaced by recycled material. The use of recycled material results in 32% lower climate impact, compared with conventional concrete. This represents a type of low-emission concrete likely to be already available in the Finnish market.

Note that in all scenarios, the building is assumed to require a founding of 20 m concrete piles, reinforced with steel. The currently standing police office building has a concrete slab foundation, with steel-enforced concrete piles. According to the briefing meetings with Senate Properties and Oy Insinööri Studio, these are possibly cohesion piles not anchored to the bedrock, and certainly they are massive in size (the ground at the site is unstable). When new consruction requires a lot of stabilizing works or structures below the foundations, this can also become a major climate impact. Therefore the foundation piles are included in the assessment.

3.1.4 Building energy use

As a part of the planning process, an earlier energy simulation study was performed at Ramboll Finland, to investigate how the new building can fulfill the energy efficiency requirements for RTS Environmental Classification[6]. In the simulations, the main heating system was district heating, and the following energy efficiency measures were considered:

- Energy efficient lighting and ventilation
- Need-based, VAV (variable air volume) ventilation in the meeting rooms
- Ventilation heat recovery efficiency 70% ... 80%
- Solar PV production

In all cases, the building E-number[7] fulfilled the RTS classification level 3 criterion of 87 kWh_E/m^2a or below. In the most energy efficient case, with ventilation heat recovery efficiency chosen as 80%, the building reached E-number 79 kWh_E/m^2a. This included the effect from solar PV production.

In this building CF assessment, the most energy efficient case with 80% ventilation heat recovery is assumed as the starting point. An energy effective building was chosen for the basic scenario, because the building will possibly seek the RTS Environmental Classification. However, the basic scenario is modelled here first without solar PV. The carbon footprint effects from own solar PV production are explored separately in its own scenario, because the embodied emissions of solar panels are an interesting area of investigation. A separate energy scenario is also created for choosing a heat-pump based main heating system.

Simulating the building energy use with the truncated model, and without the solar PV, results in E-number **83 kWh_E/m^2a**. Annual district heating and electricity consumption are given in Table 3. Figure 6 shows how the yearly energy demand is distributed within the building. Figure 7 shows the monthly energy demand.

Table 3. Modelled energy use and E-number in different energy scenarios.

	District heating kWh/m^2a	District heating kWh/a	Electricity kWh/m^2a	Electricity kWh/a	E-number kWh_E/m^2a
District heating basic case	36.5	108332	53.6	159085	83
District heating + 18 kWP PV (100 m^2)	36.5	108332	48.8	144838	77
GSHP	0	0	65.8	195294	79

6. A Finnish building environmental classification: https://cer.rts.fi/en/rts-environmental-classification/
7. In Finland, the building energy efficiency is expressed with E-number. See Ministry of the Environment, 2017.

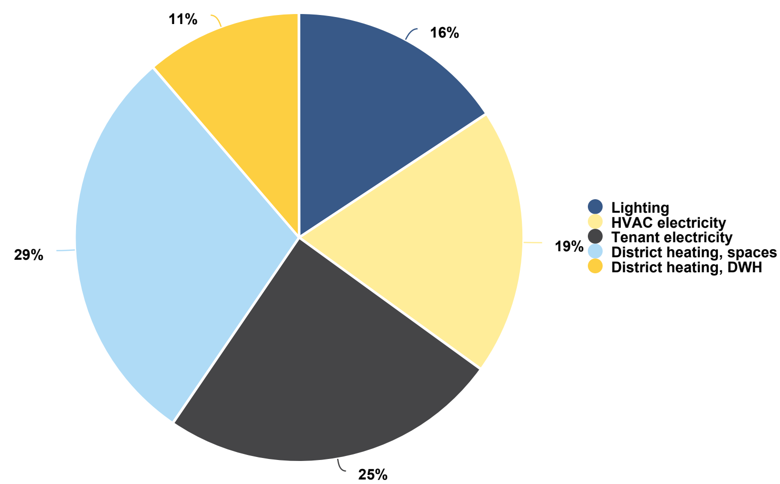

Figure 6. Distribution of yearly energy demand in the case study building, basic case with district heating, modelled by IDA-ICE 4.81.

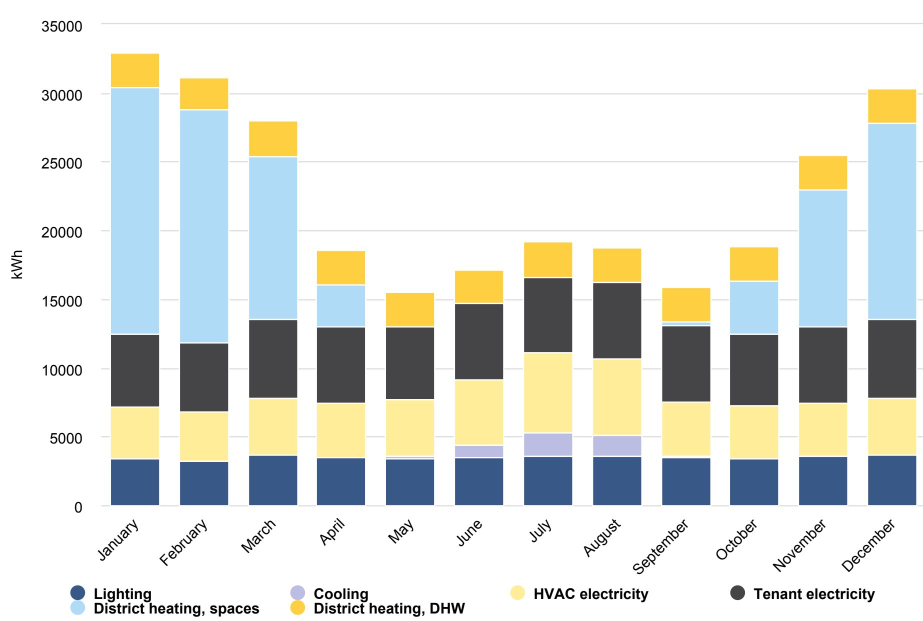

Figure 7. Monthly energy demand within the case study building, basic case with district heating, modelled with IDA-ICE 4.81.

In a separate scenario, a solar PV system is added, with capacity of **18 kW$_p$**. This is assumed to consist of **100 m^2** of solar panels, with efficiency 16.6%, directed 15° from south, at an inclination of 45°. For solar PV system embodied emissions, a value of 11.75 kg CO_{2e} / kg (or 141 kg CO_{2e}/m^2) is chosen. According to the OneClickLCA tool and Ecoinvent as data source, this value represents a typical solar panel system installed in Finland. It is more optimistic than the value used by the SYKE CO2data database, where typical / conservative values are 19 / 23 kg CO_{2e} /kg.

The roof of the extension has an area of **944 m^2**. With help of drawings and Helsinki Region Environmental Services solar energy GIS map (Helsinki Region Environmental

Services HSY), it is estimated that up to **560 m²** of the roof area is suitable for solar PV production. A system requiring 100 m^2 is therefore a realistic assumption, in terms of roof space. At the same time, here it is assumed that the system is not largely over-dimensioned.

With this system size, the yearly PV production is modelled with IDA-ICE at **18112 kWh**. According to the model, 83% of the production is consumed in the building. 17% of the produced solar energy is expected to be fed into the grid, unless it can be used in the old building part. This is considered a realistic dimensioning of the installation. More electricity use on-site can also occur e.g., for charging electric vehicles on the premises, so the actual amount of energy fed into the grid might be lower. Figure 8 shows the monthly energy demand of the building with 18 kW_p of solar PV. Exported solar electricity is shown in the graph, but not included in the building CF assessment (it falls under "Building Carbon Handprint"). The properties of the modelled solar PV system are summarized in Table 4.

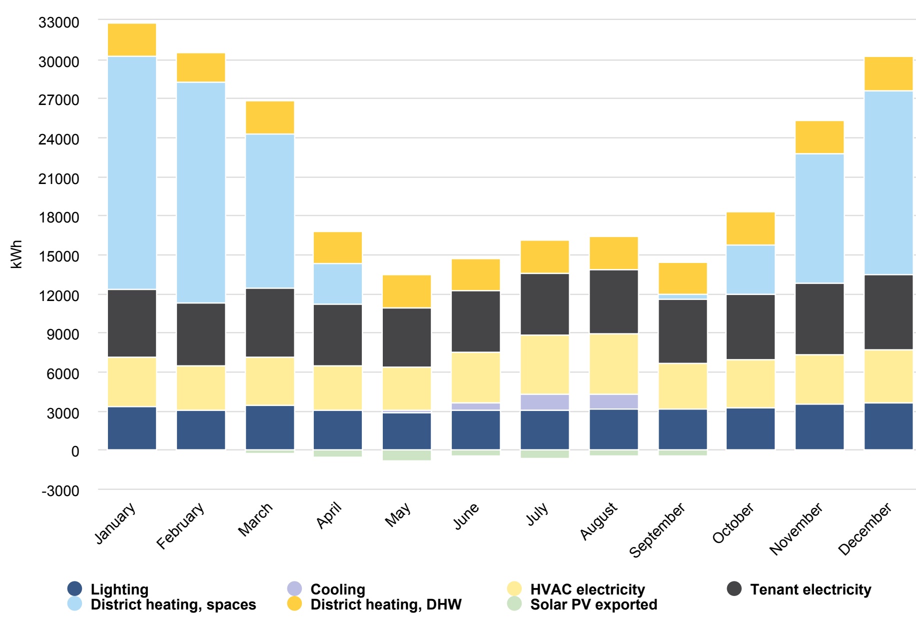

Figure 8. Monthly energy demand within the case study building, in case of 18 kW_p solar PV installation. Modelled with IDA-ICE 4.81.

Table 4. The modelled solar PV system in the Court Campus case study building.

Site	Area	Efficiency	Capacity	Tilt	Orientation	Embodied emissions	Yearly production	Self-consumption
Roof	100 m^2	16.6%	18 kW_p	45°	15°	141 kg CO_{2e}/m^2	18112 kWh	83%

Another separate energy scenario investigates a choice of ground-source heat pump (GSHP) for the main heating option. With the shape of the building altered from the previous drawings, there is more space available for boreholes. By a rough estimate, the premises could accommodate 13 boreholes (see Figure 9). Assuming borehole depth of 200 m and annual heat production of 100 kWh/m, this arrangement has the potential to yield **260 MWh** annually.

According to the energy model, the district heat consumption for the new building part is estimated at **108332 kWh / a** (see Table 2), so the borehole capacity would be sufficient. However, this is not a suggestion for final GSHP system sizing, just an initial reality check of the GSHP potential.

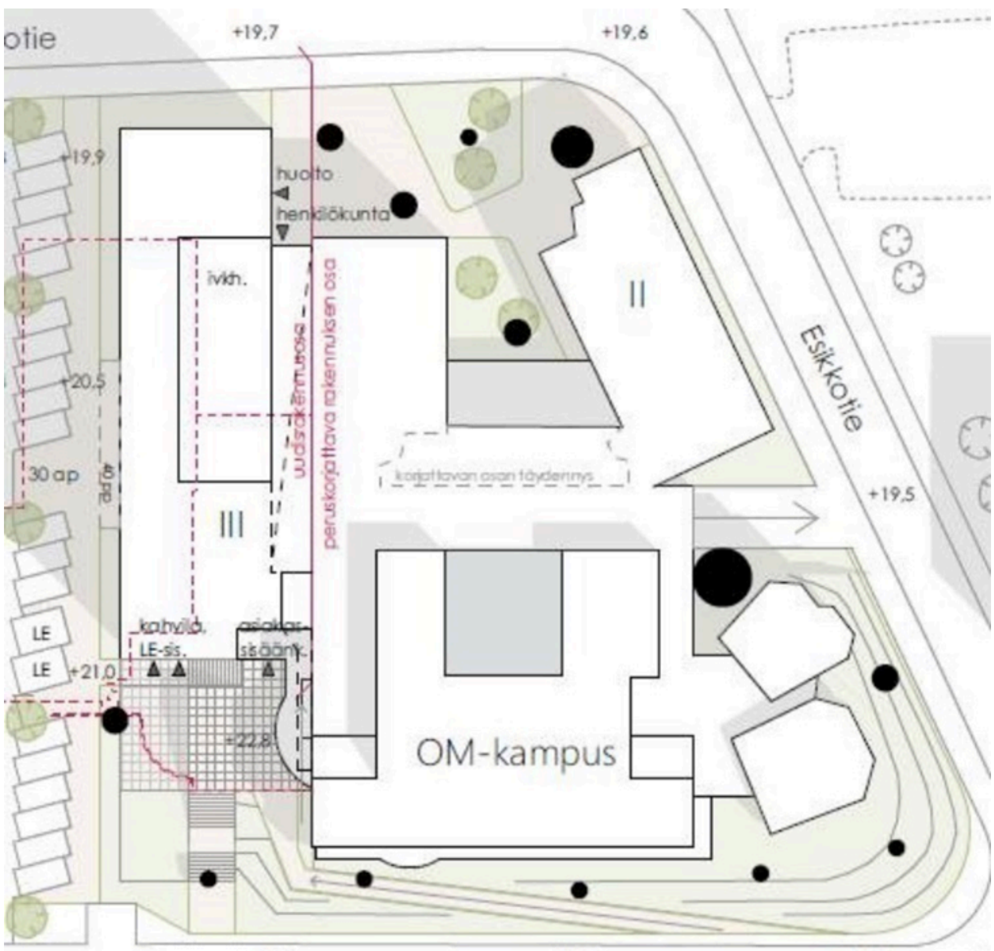

Figure 9. Borehole placement, a rough estimate.

Assuming a year-round coefficient of performance of 3, which is a typical or even conservative value, a rough estimate is made for the annual delivered electricity need in case of GSHP system (see Table 3). According to the IDA-ICE building energy simulation, the maximum required heating power is **160 kW**, and this is used for the GSHP dimensioning. Again, this is not a system dimensioning recommendation, but a rough estimate used in the building CF assessment.

Embodied emissions for the GSPH system are assumed to be 59.0 kg CO_{2e} / kW. The value is from OneClickLCA / Ecoinvent database and covers only the heat pump equipment: heat exchangers, compressors, valves and expansion vessel. It does not include the heat distribution system inside the building. However, the heat distribution system (water-based radiators) is already covered in the calculations, as the district heating option must also have heat distribution.

In case the building surroundings are for some reason unsuitable for GSHP boreholes, another heat pump -based heating option would be an industrial-size air-to-water heat pump (AWHP). A separate scenario is not made for AWPH, because embodied emission information for AWHP was only available for smaller heat pumps suitable for detached houses, approximately 5 kW systems. No current and usable embodied emission data was found for larger AWPH systems suitable for service buildings.

3.1.5 Circular building solutions

A key motivation for this assessment was to explore the possibilities of circular building practices and their potential in lowering the building carbon footprint. According to the circular economy hierarchy, it is better to entirely avoid waste creation, if possible. If waste is inevitable, re-using is better than recycling bulk material. Landfilling should be the last option.

Applying these principles to the building stock, the solution at the top of the circularity hierarchy is to continue the use of existing buildings. Even when a complete renovation is needed, and a building needs to be stripped to the frame, saving the building frame is beneficial from the emission and material use point of view. If saving the old building is impossible, then disassembling the building and re-using all suitable building parts is preferable to recycling the materials in bulk.

To find out which building parts from the demolished building may be suited for re-use, a demolition audit was carried out by Oy Insinööri Studio, including inspections at the premises. The audit classified the building materials into four categories, according to the recommended destination:

- Re-use
- Recycling as bulk material
- Energy production
- Disposal

For most of the materials (concrete, gypsum, brick, metal, glass) the recommended destination was recycling as bulk material. Some hazardous waste (lead-containing building parts, pressure impregnated wood, electrical waste) should be disposed to proper facilities. Wood, paper, cardboard or plastic waste was considered suited to burning for energy. Table 5 lists the building parts that were identified for potential re-use.

Table 5. Re-usable building parts identified in the demolition audit.

Building part	Dimensions	Amount
Wooden internal doors	0.94 m x 2.1 m	10
Aluminium frame sliding doors, each in 2 parts (sliding part and stationary part)	2.4 m x 2.2 m	2
Aluminium frame glass door in 2 parts	1.0 m x 2.1 m	1
Glass sliding door	1.05 m x 2.1 m	1
Glass door with metal frame	1.0 m x 2.1 m	1
Internal glass wall	2.17 m x 2.10 m	2
Internal glass wall	1.2 m x 3.0 m	3
Internal glass wall	0.8 m x 1.0 m	1

There is a total of **36.7 m^2** of internal doors and **20.7 m^2** of internal glass walls in re-usable condition. Some equipment or smaller building parts were also deemed re-usable: e.g., one toilet seat and some toilet sinks in good condition. However, equipment this size is not included in the building carbon footprint assessment, and their effect would be very small in any case.

The audit did not find re-use possibilities for load-bearing structures or any part of the building frame. The benefits of re-using the building frame are considered later in this report.

Circular building, limited scenario

For the possible circular solutions, several scenarios were again constructed. In the first scenario, only those building parts are re-used that can be salvaged from the disassembled building and were considered to be in re-usable condition. In practice, this means that **36.7 m^2** of internal doors are assumed to be re-used, and **20.7 m^2** of internal walls are assumed to be replaced with glass walls.

This assessment does not consider the practicalities of e.g. replacing internal walls with re-used glass walls. If such circular solutions are chosen, they must be carefully considered in the building architectural design at a sufficiently early stage. The re-used building parts should be clearly marked and carefully disassembled from the demolished building. A storage solution must also be found, preferably on-site, to avoid creating transport emissions. These considerations, however, are out of scope of this assessment.

Circular building, extensive scenario

Because the amount of re-usable building parts from the demolished building is very small, a more extensive – and much more speculative – circular building scenario was created for the sake of comparison. Here, the following solutions are employed:

- **Old windows for internal walls**: According to Oy Insinööri Studio, the demolished building part has approximately **550 m^2** of windows (glass area). With wood frames included, the combined glass + frame area is approximately **1100 m^2**. Because of energy efficiency considerations, the old windows cannot be re-used as windows. According to the building condition evaluation and the demolition audit, the wooden window frames are also in poor condition.

  In a very optimistic scenario, a portion of the windows – those in the best condition – might be used to replace some internal walls. Such solution again requires careful architectural design at a sufficiently early stage. Likely, it also requires some restoration of the window frames, which may be labor-intensive and costly.

  If both inner and outer frames could be re-purposed along with the glass, the overall area of glass + frame combination would be 1100 m^2. However, it is likely a significant part of the windows is in too poor a condition, or otherwise unsuitable. For the purpose of the scenario, it is assumed that **550 m^2** of internal walls could be replaced with re-used windows, with some combination of glass parts, inner frames and outer frames.

- **Re-used concrete elements:** At the time of performing this assessment, the Finnish online circular building material marketplace Materiaalitori (https://www.materiaalitori.fi) had 1100 m^2 of concrete hollow-core slabs available (thickness 265 mm), disassembled from a demolition site. These were considered non-harmful waste. In an optimistic spirit, it is considered that such an offer might come around again, and that the hollow-core slabs might be re-used for the police office's new construction. The building model has **944 m^2** of hollow-core slabs with thickness 265 mm in the ceiling, and the re-used slabs are assumed to be utilized there, replacing this demand in full.

  Practical considerations arise from re-use of building frame parts: are they structurally sound, and do they contain anything potentially harmful? How can the soundness and harmlessness be examined, and who guarantees the suitability for new end-users? Again, these questions are out of scope for the report at hand.

3.1.6 Combined actions scenario

As the last scenario, several actions are combined to bring about an even larger reduction in building carbon footprint. The chosen actions are CLT frame with timber lining, low-carbon concrete in the foundation piles, ground-source heat pump and limited building part circularity. Extensive building part circularity was not chosen here, because the extensive circularity scenario was highly speculative, employing re-used building parts that may not be available in the right form or quantity. To keep the combined actions scenario less speculative and more realistic, only those re-usable building parts were accepted that have already been identified as available. In this manner, all technologies and solutions in the combined actions scenario are already on the market or otherwise available.

Installing solar PV was initially considered as one action in the combined actions scenario. When it emerged, that solar PV did not lower the building CF (see the results section), it was left out from the combined actions scenario. The combined actions scenario represents design choices that are at least moderately effective, and realistically attainable in the project at hand.

3.1.7 Scenario summary

Table 6 summarizes the different carbon footprint scenarios assessed in this study. The resulting carbon footprints are presented and discussed in the next chapter. In these scenarios, the building foundation and supporting piles are not yet considered.

Table 6. Summary of the building CF scenarios employed in the assessment.

Scenario	
Basic scenario	Concrete frame
	District heating
Energy scenario: PV	Concrete frame
	District heating
	Solar PV, 18 kW_p
Energy scenario: GSHP	Concrete frame
	GSHP, 160 kW
Material scenario: low-carbon concrete	Concrete frame
	Low-carbon concrete (40% recycled material)
	District heating
Material scenario: CLT	CLT frame
	Timber lining
	District heating
Circular scenario: limited	Concrete frame
	District heating
	Limited re-use of building parts
Circular economy scenario: extensive	Concrete frame
	District heating
	Extensive re-use of building parts
Combined actions scenario	CLT frame
	Timber lining
	Low-carbon concrete in foundations
	GSHP, 160 kW
	Limited re-use of building parts

3.2 Results and discussion

3.2.1 Scenario results

Figure 10 shows the resulting building life-cycle carbon footprint for 8 different scenarios, expressed in kg CO_{2e} per m^2 annually. Table 7 shows the results in more detail. Note that in all cases, module C is assessed as constant value, given in the Finnish national emission database. The differences between the scenarios appear in foundations, module A (before use) or module B (during use). Because the building is in the design phase, and no product details are available, there is not sufficient data to assess the end-of-use emissions more closely.

Emissions from the 20 m concrete and steel pile foundation are shown separately, because the potential in re-using the foundation was specifically raised in discussions with the partners. The figure illustrates how large portion of module A emissions arise from the foundation piles.

It should be noted that while the Finnish Ministry of the Enviroment carbon footprint assessment method includes the foundation piles, the possible limit values for the new construction do not include them. In case the legislation comes to force as it is now proposed, the new construction will not receive any "penalty" from installing new concrete piles, no matter how long or massive. To reduce the project's climate impact and absolute emissions, they are in any case a very relevant design aspect to be considered, even though the eventual law might not mandate it.

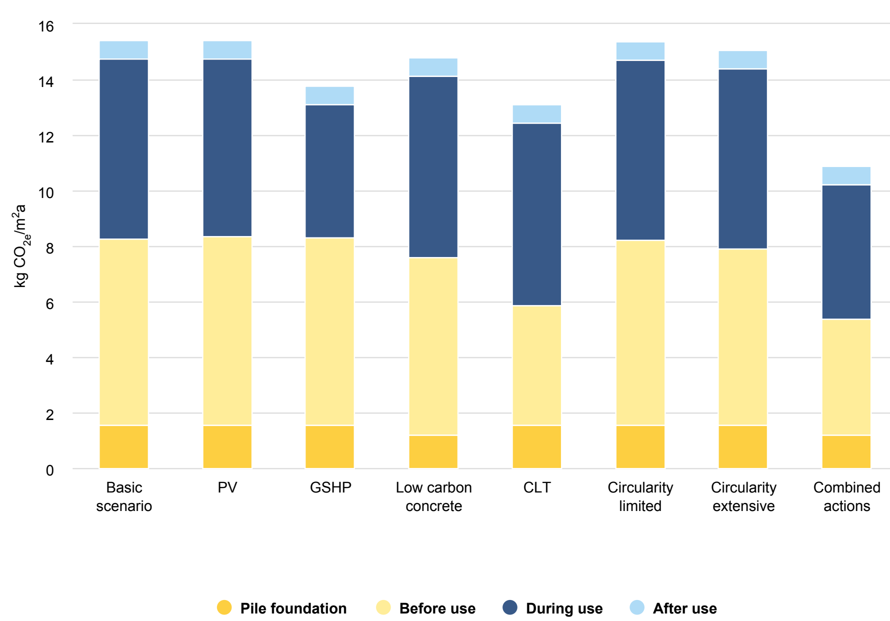

Figure 10. Building carbon footprint calculated for 50 years, for new construction with a foundation of 20 m steel-reinforced concrete piles.

Table 7. Numerical summary of the results shown in Figure 10.

Scenario	Pile foundation kg CO_{2e}/m^2a	Before use (A1–A5) kg CO_{2e}/m^2a	During use (B3–B4, B6) kg CO_{2e}/m^2a	After use (C) kg CO_{2e}/m^2a	In total (A–C) + foundations kg CO_{2e}/m^2a	Comparison with basic scenario %
Basic scenario	1.54	6.71	6.51	0.67	15.43	100
PV	1.54	6.81	6.41	0.67	15.43	100
GSHP	1.54	6.77	4.78	0.67	13.76	89
Low-carbon concrete	1.20	6.41	6.51	0.67	14.78	96
CLT	1.54	4.31	6.60	0.67	13.11	85
Circularity limited	1.54	6.69	6.49	0.67	15.40	100
Circularity extensive	1.54	6.35	6.49	0.67	15.05	98
Combined actions	1.20	4.18	4.85	0.67	10.90	71

According to this assessment, the biggest effect on the building CF arises from the choice of the main building material. Choosing wood as the frame material is more effective than choosing low-carbon concrete. Building with a CLT frame had **15%** lower CF than building with a concrete frame. Using low-emission concrete, the building CF is lowered by **4%**. Half of this contribution results from the building frame itself and half from the foundation piles, which are also assumed to be made of low-carbon concrete.

The low-carbon concrete used in the assessment had 40% of recycled materials in the binders, resulting in 32% smaller CO_2 emissions than the variety with no recycled binders. There is some potential for using even lower-emission concrete, especially if the project owner is willing to embark on a pilot project. For example, in Norway there has been public procurer pilot project using concrete with 70% lower emission than the standard comparison value (Alhola et al. 2021). The low-emission concretes have some characteristics that must be carefully considered in the construction, such as longer hardening time, which may affect the construction schedule. New products with geopolymer concrete are also likely to enter the market and broaden the choice of low-carbon concretes. There is likely still much room to improve the low-carbon concrete option, but out of currently available technologies, wood construction lowers the building CF more effectively.

The re-use of building materials had a negligible effect in the building CF, when limiting the assessment to the building parts that were flagged as re-usable in the demolition audit. Re-using the internal doors and internal glass walls brought a saving of **0.03 kg CO_{2e} /m^2a** (see Table 7), a difference that is seen only in the 2nd decimal. Such limited re-use plays no tangible role in lowering the building CF.

The extensive re-use scenario, with a substantial number of windows used as internal walls and with re-used concrete elements for the roof slab, brought a saving of **2%** in the building CF. This scenario is optimistic: it is assumed that the external windows can be integrated into the new building design as internal walls, and the frames renovated (by hand) if necessary. The re-used concrete elements were available at the time of writing the report, but this was coincidental. Such suitable elements might not be available for re-use at a later point, and even if they were, according to the project leading architect there might be health and safety concerns in using them.

Energy-wise, using a heat pump -based heating system is an effective way to reduce building CF. Choosing GSHP as the main heating system has the potential to lower the building CF by **11%**. In this assessment, solar PV system does not lower the building carbon footprint: emission savings from the building use phase are cancelled by the embodied emissions from solar panel manufacturing. This happened even though the embodied emissions for the solar PV system were optimistic rather than conservative, according to the OneClickLCA database. The result is in line with findings in e.g. Keskisalo et al. (2021).

The final scenario combined wood as the main building material, low-carbon concrete in the foundations, GSHP as the main heating option and limited re-use of building parts. In this scenario, the building CF was lowered by **29%**. If this seems a modest decrease, it should be noted that the percentual emissions savings are dependent on the point of comparison. In this case, even the basic scenario is an energy effective building, with E-number 83 kWh_E/m^2a, which nearly attains the Finnish energy class A (limit value 80 kWh_E/m^2a). In the other energy scenarios (PV, GSHP), the building is estimated to reach energy class A, but even the basic scenario of comparison is not far away from reaching it. Compared with a less energy effective building, energy solutions may bring about even more emissions savings from the use-phase.

Energy effective starting point partly explains, why the most effective single action is the choice of wood as main building material. The choice of heat pump as main heating system yields the second largest reduction in the building CF. In some other assessments (e.g., Bionova, 2021), choosing a heat-pump -based main heating system is found to be the choice with the largest effect on the building CF. In those cases, the basic point of comparison is often a building that barely fulfils the energy efficiency regulations but does not exceed them.

3.2.2 Re-using the concrete founding piles

The concrete founding piles form a substantial contribution to the new construction building CF. Assuming that the new building requires 20 m long steel-reinforced concrete piles, the carbon footprint grows by **1.54 kg CO_{2e} /m^2a**, or **1.20 kg CO_{2e} /m^2a** in case low-carbon concrete is utilized for the foundation (see Table 7, scenarios Low-carbon concrete and Combined actions).

To increase the degree of circularity in the new construction, perhaps the founding piles themselves could be left in place and re-used, in case this is technically feasible. This is an option that was raised in discussions with Senaatti Properties. This option was also discussed in e-mail conversations with the designers (InnovArch / Vahanen Yhtiöt). The following considerations were raised:

- Design life-time for the foundations was 50 years, which they are already approaching. However, the initial design life-time does not reveal the condition

of the foundations: they may have usable life-time left.
- Physical and technical state of the foundations should be ascertained with approved, standardized methods.
- Re-using the foundations limits the possibilities of the new design: the straightforward option is to situate the new building directly on top of the old foundations.
- It may be possible to utilize the old foundations, even in case the new building is not situated directly on top them. In that case, new horizontal beam structures are required to transmit the force to the remaining piles. A substantial amount of building materials would be required for the new horizontal structures. Another option is to leave the old piles in place and situate the new building partially on top the old foundations, letting the old piles carry part of the load. In that case, some new piles are needed, and it may be challenging to combine the new founding structures with the old (e.g. different design life-times).

In the Estonian case study building, the foundations and concrete base floor slab were in fact preserved, and a new building was constructed on top of them (see chapter 5.1).

3.2.3 Re-using the building frame

As discussed above, preserving the old piles is not feasible, if they are in poor condition. However, they are a massive structure of steel-reinfoced concrete, constructed in 1988. It is entirely within realistic possibilities that the foundations are structurally sound, and can be re-used.

Using the old foundations creates some limitations for the new design. If the old piles are to be used for carrying the load, the new construction should be situated on top of them, or else the load must be transferred via horizontal beams. This in itself requires a substantial amount of concrete.

This raises a further question: if the old foundations are still usable, is it also possible to preserve the concrete building frame, entirely or partially? Preserving the old frame limits the possibilities of the new design, but re-using the foundations is also a limiting factor. If re-use of old foundations is an option, and if the limitations are accepted, it would be logical to consider preserving the entire frame. This would be the truly circular bulding solution. Preserving the old frame also has potential health and safety concerns, which should be carefully investigated.

This assessment has already shown that re-use of some individual building parts has a very small effect on the building CF. On the other hand, collecting a substantial amount of building materials for the new construction has several challenges connected with e.g., design, logistics, temporary storage and user health and safety. Re-using the entire building frame where it stands is taking building circularity to the higher level, and according to previous studies, can benefit both climate and project economy. According to a recent study on renovation climate impacts and costs, renovation is not only better for climate, it is also more cost-optimal than demolition and new construction (Huuhka et al., 2021).

The option of saving the existing building frame cannot be assessed here as one scenario among the others: it is a different design philosophy entirely, not directly comparable. For a thorough assessment, architectural plans and models for the renovation option should be compared with the new construction option. Because such treatment is impossible for this assessment – there isn't sufficient data – just a very coarse initial estimate is performed here.

The starting point is the existing building model with 20 m pile foundation, but with the assumption that both frame and piles are re-used. The re-used parts are:

- Foundations
- Piles under the foundations
- Concrete pillars and beams
- All concrete slabs (hollow-core elements)
- Inner layers of the external wall sandwich-elements

It is further assumed that the outer layer and the insulation are stripped away from the external wall sandwich elements, and new insulation + new façade material are introduced. New insulation is assumed to be rock wool, and the new façade material is timber.

Leaving the old building frame standing is a different project entirely than constructing a new one. Figure 11 shows how the existing buildings are currently located. This can be contrasted with Figure 3, which showed the planned location of the new construction.

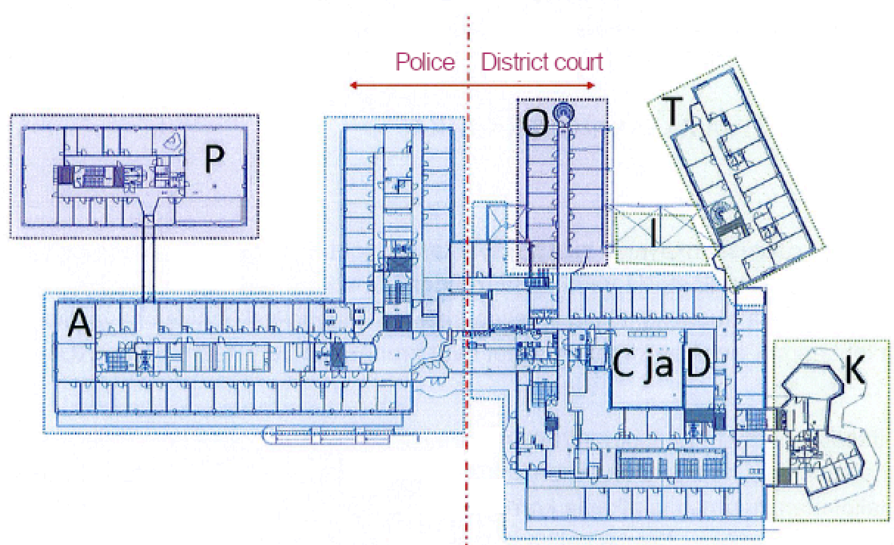

Figure 11. Current placement of Court campus buildings. Bluecolour indicates construction year 1988, purple colour 1994 and green colour 2003.

According to the plan, the new construction would be located adjacent to the courthouse, sharing a wall with the courthouse. Currently the police offices are in a separate building, with a walking corridor in between. When modelling the new construction scenarios, it was in every case assumed that the south wall between the police premises and the courthouse is an internal wall, with heated space on the courthouse side. This diminished the heat flow through the south wall, decreased the heating demand and thus improved the energy efficiency.

To make the re-used frame scenario more closely truthful, the south wall is now turned into an external wall. The U-values of the model building envelope are also changed into poorer U-values, better representing the properties of the old frame. The U-values used here – both for new and old frame – are the same that were used for simulation in the Ramboll energy efficiency report (see Table 8). The old windows were assumed to be changed in any case, so the windows received a U-value of 1.0 W / m^2 K, also in the old frame re-use scenario. (This is a conservative estimate, since new energy-efficient windows can have U-values down to 0.6 W / m^2 K.)

Table 8. Building envelope U-values used in the energy simulations.

	New construction W / m^2 K	Old building frame spared, insulation not improved W / m^2 K	Old building frame spared, insulation improved W / m^2 K
External walls	0.17	0.28	0.17
External roof	0.09	0.22	0.22
External floor	0.17	0.22	0.22
Windows	1.0	1.0	1.0

If the building concrete frame were spared, likely some improvements could be made to the building envelope insulation. Here it was assumed that the inner layers of the old sandwich elements would be saved, the outer layers would be stripped away, and the insulation replaced. In such a case, adding more insulation to the external walls carries no significant cost increase: labour is by far the more expensive factor. Another option is to leave the old sandwich elements in place and add a new wooden element on the surface. If applicable, this spares the labour and cost from stripping the outer layers, and also improves the external wall U-value.

To reflect the possible insulation upgrade, another scenario is created. Here the old frame and pile foundations are spared, and some improvements are made on the building envelope U-values. It was already assumed that the windows were replaced with modern windows, and it was also assumed that 220 mm of mineral wool was installed into the external wall, to replace the old insulation stripped from the sandwich element. With 30 mm more mineral wool, and with a wood outer lining, the modelled U-value of the renovated wall reaches 0.17 W /m^2 K. The windows are still modelled with U-value 1.0 W /m^2 K. The external wall and external roof U-values are assumed to stay at 0.22 W /m^2 K (see Table 8).

Even if the old building frame is spared, it is possible to update the building energy systems. To investigate this, one more scenario is created where the frame is spared, insulation is improved, and the main heating system is retrospectivey changed into GSHP. Again, yearly COP of 3.0 is assumed. In this scenario, the sizing of the GSHP system must be changed from 160 kW to 170 kW, because the insulation is poorer and heat demand is greater than in the new building case. Again, the energy demand in each case is investigated with the IDA-ICE model, with modified U-values and wall configurations.

Table 9 summarises the new scenarios, and Table 10 shows the modelled energy use in each of the scenarios.

Table 9. Summary of the new scenarios for re-using the building frame.

Scenario	
Basic scenario with piles, identical to basic scenario in Figure 10: represents new construction where piles and frame are not re-used	Concrete frame
	District heating
	20 m pile foundation
	Wall shared with court house
	U-values as in new construction (Table 8)
Re-using the frame and piles, windows changed, no improvement on the insulation	Concrete frame
	District heating
	20 m pile foundation
	Wall not shared with court house
	Windows changed (1.0 W /m2 K)
	Otherwise U-values as in old building (Table 8)
Re-using the frame and piles, windows changed, improved insulation in external walls, no improvement on external roof and floor	Concrete frame
	District heating
	20 m pile foundation
	Wall not shared with court house
	Windows changed (1.0 W /m^2 K)
	U-values for external walls improved (0.17 W /m^2 K)
	U-values for external roof and external floor remain as in old building (0.22 W /m2 K)
New combined actions scenario: Re-using the frame and piles, windows changed, improved insulation in external walls, no improvement on external roof and floor, GSHP as the new main heating system	Concrete frame
	GSHP (COP 3, 170 kW)
	20 m pile foundation
	Wall not shared with court house
	Windows changed (1.0 W /m^2 K)
	U-values for external walls improved (0.17 W /m^2 K)
	U-values for external roof and external floor remain as in old building (0.22 W /m^2 K)

Table 10. Modelled energy use and E-number in new scenarios for sparing the building concrete frame.

Scenario	District heating kWh/m²a	District heating kWh/a	Electricity kWh/m²a	Electricity kWh/a	E-number kWh_E/m^2a
District heating, basic scenario with piles, new construction	36.5	108332	53.6	159085	83
District heating, re-using frame	53.4	153695	54.7	157647	93
District heating, re-using frame, better insulation	46.1	132688	54.8	157793	89
GSHP, re-using frame, better insulation	0	0	70.2	208255	85

Results from the new scenarios are presented in Figure 12 and Table 11.

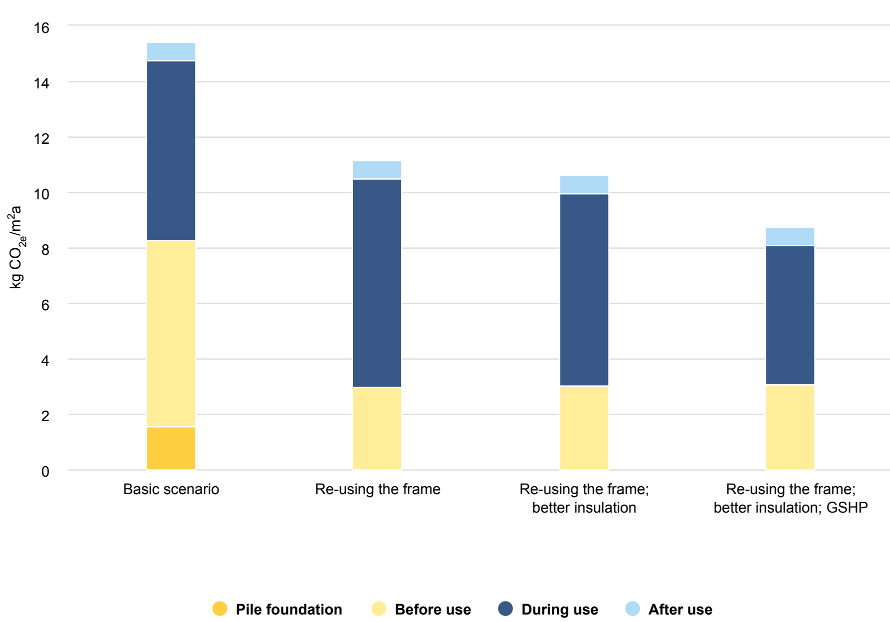

Figure 12. Building carbon footprint calculated for 50 years. Basic scenario is new construction with 20 m concrete piles, the other scenarios illustrate the effect from saving the building foundations and frame.

Table 11. Numerical summary of results shown in Figure 12.

Scenario	Pile foundation	Before use (A)	During use (B)	After use (C)	In total (A–C) + foundations	Comparison with basic scenario
	kg CO_{2e}/m^2a	kg CO_{2e}/m^2a	kg CO_{2e}/m^2a	kg CO_{2e}/m^2a	kg CO_{2e}/m^2a	%
Basic scenario with piles	1.54	6.71	6.51	0.67	15.43	100
Re-using the frame	0	2.99	7.51	0.67	11.17	72
Re-using the frame, better insulation	0	3.01	6.94	0.67	10.62	69
Re-using the frame, better insulation, GSHP	0	3.07	5.01	0.67	8.76	57

In the new scenarios, re-using the building frame lowers the building CF by **28%**, even when the insulation of the external walls is not improved. Emissions in the use phase (module B) grow by 15%, but the emissions before use (module A) are 55% lower, which is more than compensates for the poorer energy efficiency. If the frame is spared and insulation of the external walls is improved, the building life-cycle carbon footprint decreases by **31%**.

In case of new construction (see results in Figure 10 and Table 7), maximum emissions savings of 29% were obtained by taking all feasible actions together (CTL for frame, GSHP for heating system, low-carbon concrete for foundation, limited re-use of building parts). Although scenarios for sparing the building frame and scenarios for new construction cannot be directly compared, and all results are preliminary without more specific input data, it can be at least speculated that re-using the building frame can bring about emission savings in the same magnitude as very comprehensive low-carbon design for a new construction.

Finally, re-using the frame and choosing GSHP as the new heating system, the life-cycle CF decreases by a total of **43%**. This is the biggest estimated saving potential in all the scenarios considered here. By using the old building frame, the energy efficiency is somewhat poorer, but switching into a lower-emission energy source helps to decrease the emissions from the use-phase. As a result, emissions from module A and module B are both lower than in the basic scenario, where a new building is constructed.

3.2.4 Sensitivity to emission scenarios

Building carbon footprint results depend on the chosen assessment method: this renders the comparisons between different assessments difficult. Säynäjoki et al. (2019) have reviewed building LCA assessments for the pre-use phase. They conclude the results are highly dependent on the chosen method and the subjective choices of the person(s) carrying out the assessment. Similar conclusions are reached by Röck et al. (2020). If carbon footprints of different buildings are compared, they should be assessed with similar methodology, otherwise benchmarking is not reliable.

Building LCA is perhaps best suited in comparing different design options for the same building, using the same assessment method and same metodological choices. However, even in such a case, the question of methodology choice is relevant. Special attention should be paid to the method of use-phase emission calculation, because that has significant potential to affect the result. This is demonstrated by a sensitivity analysis performed in relation to the energy emissions.

In the Finnish national building CF method, both district heating and electricity emissions are assumed to have a diminishing trend, due to the decarbonization of the energy sector. The assumption of decreasing emissions on the production-side affects the results. Finland is also a country with a lot of CHP (combined heat and power) production, and there are different ways of allocating greenhouse gas emissions between heat and power. In the Finnish method, the emissions are allocated with benefit allocation, which gives slightly different results than energy allocation (for the allocation methods, see e.g. Koreneff, 2018 and the references therein).

To demonstrate the effects of these methodological choices, 4 sensivity scenarios are compared. First one is again the basic scenario, familiar from previous results. The basic scenario employs benefit allocation and a diminishing emission trend, as instructed by the Finnish national CF assessment method. New scenario Sensitivity 1 assumes benefit allocation, but keeps the emissions constant in time. Scenarios Sensitivity 3 and 4 assume energy allocation, with diminishing emissions (Sensitivity 3) or no diminishing trend (Sensitivity 4).

Figures 13 and 14 show the emission trends assumed in the Finnish national building CF assessment method. In this report, the building is assumed to be erected in 2022 and decommissioned in 2072.

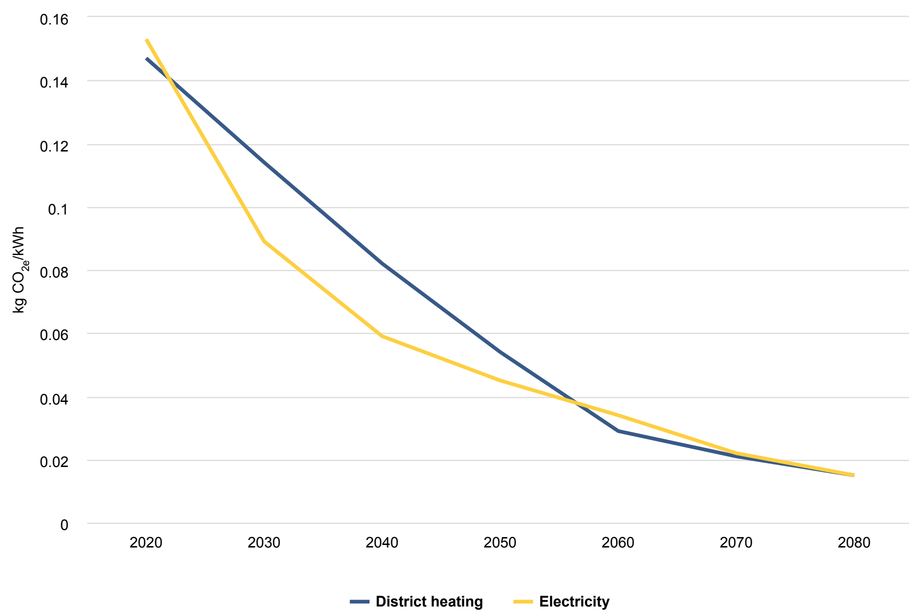

Figure 13. Decreasing emission trend according to the Finnish national building CF assessment method, benefit allocation. Source: CO2data.fi.

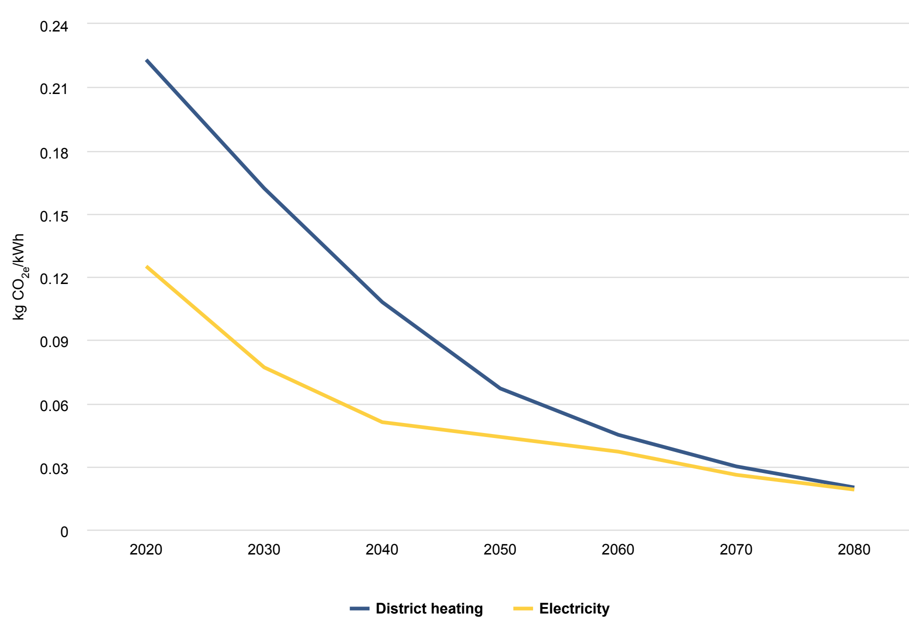

Figure 14. Decreasing emission trend according to the Finnish national building CF assessment method, energy allocation. Source: CO2data.fi.

Table 12 summarizes the sensitivity scenarios and their results. Assuming energy allocation instead of benefit allocation (Sensitivity 2) increases the building CF by **4%**. The methodological choice of assessing the building CF with constant year 2022 emissions increases the building CF by **45%** (Sensitivity 1) or **53%** (Sensitivity 3), depending on the allocation method. This very large variation shows the important role of methodology choice: the result is highly sensitive to the assumptions about energy emissions and their future trend.

Table 12. Sensitivity analysis for different emission allocation methods and trends.

	Benefit allocation	Energy allocation	Diminishing trend	Constant 2022 emissions	In total (A-C) + foundations	Relation to basic scenario
					kg CO_{2e}/m^2a	%
Basic scenario	X		X		15.43	100
Sensitivity 1	X			X	22.31	145
Sensitivity 2		X	X		16.07	104
Sensitivity 3		X		X	23.55	153

For example, if the case Finnish study were based on Sensitivity 1 scenario, where emissions are assumed to continue on the 2022 level until 2072, the results of various design choices would have been as follows:

- Adding 18 kW_p of solar PV
- Choosing GSHP as the heating option
- Choosing CLT as the frame material

If the emissions are assumed to stay constant, solar PV installation manages to pay its "carbon debt", and a low-carbon heating solution becomes the single most effective action to lower the building carbon footprint.

3.2.5 Key takeaways

The Finnish case study represents a new construction, where renovation and re-use of materials are considered as one possible means of lowering the building carbon footprint. As a first step towards building circularity, the existing building – possibly to be demolished – was reviewed in a pre-demolition audit. Although the pre-demolition audit is positive step towards circularity, the research shows that when only small number of building parts are flagged for possible re-use, the effect on building carbon footprint is negligible.

To achieve substantial emission savings, the amount of re-use must be extensive, and likely encompass load-bearing structures. In such a case, the re-use aspects and their possibilities must be considered in the new building design from the start. The pre-demolition audit for the existing building should pay explicit attention towards using load-bearing structures, and investigate their re-use possibilities. The project should be geared towards tackling and solving the challenges related to finding, transporting, storing and finally utilizing second-hand building parts in a safe manner. This cannot be performed along the sidelines, or as an afterthought.

Another option is to preserve the existing building, if possible. In light of this case study, preserving the building frame has potential for large emission savings. In the more extensive re-use scenario, the building CF was decreased by 2%. By sparing the old building frame, the climate impact of the construction project was decreased by 28% or more, depending on the renovation option: the outcome is better by an order of magnitude.

It should be noted, however, that 2% is by no means an upper limit for the usefulness of circularity. This will be demonstrated by the results from the Norwegian case study. In the Finnish case, 2% represents the effect from a fairly extensive re-use scenario, but not one where re-use of building parts is a central consideration, guiding the design from the start. In order to explore such a scenario, more project-specific data would have been needed. In this research report, the Norwegian case study represents a case where extensive re-use was piloted, and this was guiding the project from the beginning.

One of the research questions was to find out whether the circularity actions have trade-offs: can they also increase the building carbon footprint? In case the old building frame is re-used, and insulation is not improved at all, there is a trade-off happening in the building use-phase. Emissions from new construction are avoided, but energy efficiency is poorer and heat demand is higher than for new building. However, in the life-cycle perspective, the significant decrease in embodied emissions more than compensates for the poorer insulation. Overall, it can be said that saving the building frame is good for both circularity and climate. In case it is also the cost-optimal choice, as in a previous study (Huuhka et al., 2021), this solution has the potential to be the win-win-win -solution: winner in terms of material use, climate and costs. The cost assessment is outside the scope of this report and should be considered separately.

One way of spotting the possible trade-offs is to consider the expenditure of effort. It is concluded that building circularity can lower the building carbon footprint, but – in case of a new construction – not necessarily very much. At this stage, it requires a pilot project with a pioneering spirit to solve the challenges inherent in a very extensive building part re-use. Such new construction pilot projects are welcome and needed, and they will pave the way for more circular construction sector. However, there are other choices that can bring about large effects in building CF in the more immediate time frame, and there should be enough effort left to expend towards these actions.

In this case study, choosing a low-carbon building material has potential to lower the building CF by 15%, and choosing a low-carbon heating system can lower the building CF by 11%. The building procurer should not spend a disproportionate amount of effort in considering material recycling or small-scale re-use, and neglect the very real – and commercially mature – possibilities of low-carbon materials and energy systems. In other words: if the procurer wants a new low-carbon building, and if they are not able to make re-use the central philosophy and guiding principle of the project, they should first and foremost spend their time and effort towards choosing low-carbon building materials and clean heating systems. Because planning and staff resources are limited, there is a trade-off involved in spending a lot of effort with small-scale recycling and re-use actions, and not enough effort in e.g. thorough exploration and optimization of building energy solutions.

Whatever the chosen scenario, wasteful use of heating energy is never recommended. In case the old building frame is spared, a thorough renovation is an opportunity to update and improve the building energy systems, and perhaps also change the main heating system. Exploring all the possible energy renovation options is beyond the scope of this study: here the energy scenarios are very much simplified. For example, it was assumed that the ground-source heat pump system covered the entire need for heating energy. In reality, such sizing may not be the optimal solution. In a study by Niemelä et al. (2017), the optimal heating solution for a renovated office building was to install a GSHP system alongside the old district heating system. Other hybrid systems might also be considered. It is strongly recommended that the possibilities of renovation are assessed with a thorough energy optimization, where a wide combination of energy renovation actions is taken as a starting point.

It should be stressed once more, that the carbon footprint calculation performed here for the renovation option is an estimate with a lot of uncertainty. The calculations had to be based on the new building model, because there were no detailed plans for possible renovation. Although the new building model was modified to represent the old building frame, e.g. by changing the U-values, the treatment carries a lot of assumptions and simplifications. Some assumptions were optimistic: for example, it was assumed that the ventilation could be made as energy-efficient as in the new building. Other assumptions were on the conservative side: for example, new windows can in reality have better U-value than 1.0 W /m^2 K.

While the material and energy choices are not yet made, there are major uncertainties present in any case, even in the case of new construction. The results here are tentative: they illustrate the relative magnitude of the choices in materials, energy and circularity domains. If there is to be a new construction, choices of main building material and main heating system carry more importance than re-using some individual building parts as a part of new construction. However, if circularity is taken to the level of preserving the entire building frame, this can be the decision with potentially the largest climate benefits. There is a possible trade-off between saving heating energy emissions and saving embodied emissions, but in the life-cycle view, avoiding the carbon peak is the more climate-friendly option. In light of this, preserving the existing building frame is highly recommendable from both climate and circularity point of view.

4 Case study: Kristian August gate 13, Oslo, Norway

The goal of this study is to assess the carbon footprint of an office building in Oslo, Norway with the use of life-cycle assessment (LCA). This study investigates the effect of:

- Building type: new construction versus refurbishment
- Re-use: re-use of construction materials in a new building life-cycle versus new materials
- Energy solution: energy use with different energy production technologies
- Methodology: conventional LCA methodology versus time-weighted methodology discounting carbon emissions happening at a later stage of the building's lifetime

The building assessed in this study is Kristian August gate 13 (KA 13). This office building from the 1950s was rehabilitated and extended, both with a high degree of re-used materials and products. The eight-storey building was completed in 2021. It was designed by MAD arkitekter and is owned by Entra ASA. An overview of the refurbishment and new construction parts of the building is shown in Table 13. More information on KA 13 and lessons learned from re-use can be found in the project report by Entra ASA (2021).

Table 13. Overview of the case study

Kristian August gate 13	Refurbishment	New construction
Building type	Refurbishment with a high degree of re-used materials	New construction with a high degree of re-used materials
Useful floor area (m^2)*	3350	700
Gross area (m^2)	3905	857
Number of users	153	41
Project phase	As built 2021	As built 2021
Construction materials	Steel and concrete	Steel and concrete
Energy supply	100% district heating for room heating, ventilation, and domestic hot water	100% district heating for room heating, ventilation, and domestic hot water
Re-use	Preserved existing materials: 80% of building weight Re-used materials from donor buildings: 8% of added material weight	Re-used materials from donor buildings: 34% of added material weight
Reusability	Reusable materials: 4% of added material weight	Reusable materials: 22% of added material weight

*Useful floor area is used to present results per square meter in this report.

4.1 Data and methods

4.1.1 Assessment method

The assessment of KA 13 was performed using Life-cycle Assessment as a methodology with a modular approach in line with EN 15978 "Sustainability of construction works – Assessment of environmental performance of buildings" (ES, 2011).

The modular lifecycle approach measures the impacts from cradle to grave for the four main phases of the building life-cycle: 1) the product stage (module A1–A3); 2) the construction process stage (module A4–A5); 3) the use stage (module B1–B8); and 4) the end-of-life stage (C1–C4). In addition, the benefits related to re-use, recovery, recycling and export of self-produced energy are calculated in module D. The assessment was done over a 60-year lifetime period.

Conventional and dynamic methods

Two different methods were used to assess KA13: 1) NS 3720 "Method for greenhouse gas calculations for buildings" (SN, 2018); and 2) FutureBuilt ZERO method (Resch et al., 2020).

The Norwegian standard NS 3720:2018 is the conventional method used in Norway to quantify greenhouse gas emissions over the lifetime of a building. NS 3720 is based on the international standard EN 15978.

The FutureBuilt ZERO method was developed by FutureBuilt, a programme that supports climate friendly urban development in Oslo and five surrounding municipalities. FutureBuilt ZERO follows the principles in NS 3720, but introduces additional concepts such as time-weighting, technology advancement and biogenic carbon. The main differences in the two methods are summarized in Table 14. The comparison is based on the findings from a ZEN case study by Resch et al. (2022).

Table 14. Comparison between NS 3720 and FutureBuilt ZERO

Methodology	Conventional – NS 3720	Dynamic – FutureBuilt ZERO
Future technology	Includes future technology advancement in power and heat production.	Includes technology advancement for all emission sources, for energy and materials. This puts more weight on emissions that happen today rather than emissions that happen in the future.
Time-weighting	No time-weighting. Uses static LCA method (GWP 100) no matter when the emissions happen.	Emissions are weighted based on when the emissions happen (dynamic LCA). The emissions contribution to global warming over a 100-year period from construction are included. Global warming impacts further than 100 years in the future are omitted. Emissions that happen in the future contribute less to global warming in the analysis period than emissions that happen today.
Biogenic Carbon	Uptake of biogenic carbon in wood happens before cutting (year 0). Stored biogenic carbon is calculated according to NS-EN 16485, with uptake happening in module A1 and emissions in module C3–C4. Net impact of uptake and emissions of biogenic carbon is 0.	Uptake of biogenic carbon happens as a consequence of cutting, during the building's lifetime. Trees and biomass will gradually store carbon, leading to a carbon storage effect. There is a cap to how much of this effect can be written in the account (100% of combustion emissions and 75% of production emissions). Biogenic carbon storage is reported in module B1.
Allocation of emissions from waste treatment (district heating)	Allocates combustion emissions from energy recovery to the creator of the waste (polluters pay principle).	50/50 allocation of combustion emissions between waste sector and energy sector. This gives higher emissions from waste combustion in district heating and lower emissions from waste treatment of building materials.
Module D	Consequences of exported energy, reusability and material and energy recovery are reported separate from the main results in module D.	Includes consequences of exported energy and reusability in the main results.
Emission factors for materials	Specific data from EPD's and studies of carbon footprint of re-used materials.	Same emission factors as in the conventional method (NS 3720).
Emission factors for energy use	Electricity - European consumption mix (EU28+Norway), assuming a gradual, yearly reduction in fossil fuels towards 2050. Gives an average emission factor of 119 gCO2e/kWh over 60 years.	Same, but when accounting for time-weighting, the average emission factor over 60 years is 84 g CO2e/kWh.
	Heat - District heating and cooling is dependent on the energy source of the specific district heating facility. Emissions from heat by waste incineration is treated as «zero emissions». Gives an average emission factor of 11 g CO2e/kWh over 60 years, based on the mix of energy carriers used to produce district heating in Oslo.	Same, but emissions from heat by waste incineration are allocated 50/50 between waste sector and energy sector. Gives an average emission factor of 82 g CO2e/kWh over 60 years.

System boundaries

The modules included in the assessment of KA13 with NS 3720 and FutureBuilt ZERO are presented in Table 15.

Table 15. System boundaries

Module	Conventional – NS 3720	Dynamic – FutureBuilt ZERO
A1–A3 Raw material extraction, transport to manufac-turing and manufacturing	Included	Included
A4 Transport to site	Included	Included
A5 Construction process	Not included	Not included
B1 Use of products	Not included	Uptake of biogenic carbon during the building's life-time included
B2–B3 Maintenance and reparation	Not included	Not included
B4–B5 Manufacturing and transport of replaced materials	Included	Included
B6 Energy use	Included	Included
B7–B8 Water use and transport in use	Not included	Not included
C1–C2, C4 Deconstruction, demolition, transport, and disposal	Not included	Not included
C3 Waste processing	Included	Included
D Other benefits	Not included	Reusability of materials and exported energy produced on site included

Tools

ByggLCA v.1.2, an MS Excel workbook-based life-cycle assessment tool developed by Asplan Viak, was used to assess the environmental impact of KA13 with the NS 3720 method. FutureBuilt has developed their own Excel-based tool which was used for the FutureBuilt ZERO method.

4.1.2 Building model

An as-built BIM building model designed by MAD arkitekter was used to retrieve material information and quantities for the assessment. The model was completed in September 2020 and includes both architectural and structural elements. Architectural and structural drawings were used to supplement the construction of walls, floors, and roofs.

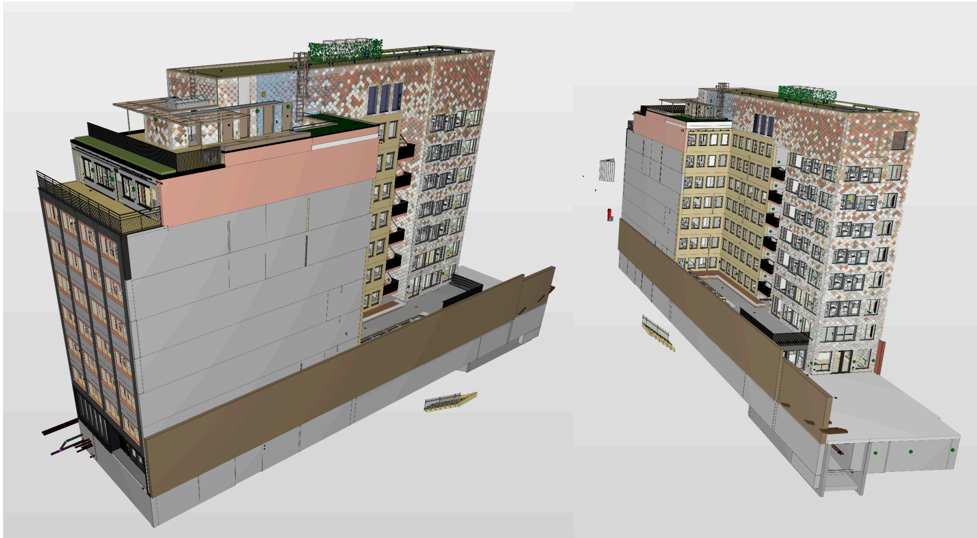

Figure 15. Building model of Kristian August gate 13. Model: MAD arkitekter

4.1.3 Building materials

Input data for building materials was extracted from the building model with the Solibri Office software. Table 16 shows the input data for material use for refurbishment and new construction.

Table 16. Material quantity input data

Building component	Material	Quantity		Unit	Re-used	Reusable
		Refurbishment	New construction			
Foundations	Steel core piles	0	75 600.00	kg		
Structure	Steel beam, L, U and I profile	819.00	7480.00	kg		
	Steel beam, L, U and I profile	9368.00	2371.00	kg	X	
	Steel beam hollow profile	3462.00	2061.00	kg		
	Steel beam hollow profile	2945.00	24 458.00	kg	X	
	Concrete columns	0.31	0	m^3		
	Reinforcement steel for columns	31.40	0	kg		
Exterior walls	Load-bearing concrete wall	96.24	16.77	m^3		
	Reinforcement steel for wall	9624.00	3354.00	kg		
	13 mm gypsum	173.89	402.00	m^2		
	15 mm fire gypsum	10.24	143.00	m^2		
	48–200 mm insulation	44.18	60.58	m^3		
	9 mm GU plate	108.72	0	m^2		

	23+48 mm wood plate	10.87	2.72	m³		
	118–250 mm Leca bloc	0.63	36.25	m³		
	250 mm brick	0	34.00	m³	X	X
	250 mm insulation for brick	0	34.00	m³		
	250 mm insulation for brick	0	36.25	m³	X	
	70 mm wood stud	18.38	0	kg		
	Vapour barrier	108.72	272.00	m²		
	250–300 mm Leca Isoblokk	16.51	46.71	m²		
	Glass façade	11.00	0	m²	X	
	Glass façade	15.00	0	m²		
	Windows	231.83	104.00	m²		
	Windows		87.00	m²	X	
	Door, aluminium with glass	10.00	6.00	unit		
	Door, wood	1.00	0	unit		
	Façade cladding	223.78	472.22	m²	X	X
Interior walls	13mm gypsum	2099.20	139.84	m²		
	70–100 mm wood stud	1992.34	56.63	kg		
	70–100 mm insulation	29.99	3.02	m³		
	200 mm TEWO	88.67	8.19	m²		X
	Door, wood	32.00	4.00	unit		
	Door, wood with glass	8.00	2.00	unit		
	Door, metal	14.00	6.00	unit		
	Paint	1292.32	0	m²		
	15 mm fire gypsum	485.71	0	m²		
	118–150 mm Leca bloc	16.72	0	m³		
	Ceramic tiles	80.00	0	m²		
	Adhesive for tiles	669.6	0	m²		
	Membrane	186.00	0	m²		
	50 mm steel stud	477.30	0	kg		
	15 mm plywood	450.00	0	m²		
	13 mm gypsum	750.88	0	m²	X	
	15 mm fire gypsum	62.04	0	m²	X	
	70–100 mm insulation	9.56	0	m³	X	
	70–100 mm wood stud	462.56	0	kg	X	
	15 mm plywood	275.54	0	m²	X	

	Ceramic tiles	106.00	0	m²	X	
	Glass surface	255.00	0	m²		
Floors	Hollow core slab	0	127.83	m²		
	Hollow core slab	0	254.43	m²	X	
	Screed	0.06	1.58	m³		
	Concrete, casted over hollow core slab	8.31	12.92	m³		
	Concrete casted slab	91.42	4.57	m³		
	Wood flooring	41.69	88.34	m²		
	Carpet tiles	1622.00	541.00	m²		X
	Brick	0	8.84	m³		
	Ceramic tiles, 5mm	87.50	0	m²		
	Adhesive for tiles	87.50	0	m²		
	Membrane	87.50	142.57	m²		
	40–90 mm insulation	0	18.53	m³		
	Acoustic ceiling, 25 mm	4.75	8.36	m³		X
	Mineral wool ceiling, 50 mm	9.51	16.72	m³		
	Acoustic ceiling, 25 mm	36.57	1.36	m³	X	X
	Mineral wool ceiling, 50 mm	73.14	2.72	m³	X	
	SonaSpray	392.34	113.32	m²		
	Reinforcement steel for slab	5.50	883.93	kg		
Roof	30 mm fire insulation	4.30	2.94	m³		
	40–225 mm insulation	294.45	29.56	m³		
	Corrugated steel plates 10kg/m2	1380.00	0	kg		
	Vapour barrier	131.67	0	m²		
	Stone tiles	0	1.70	m³	X	X
	Sedum roof plan 10	172.00	49.02	m²		
	Roofing	400.25	0	m²		
	Terrasse flooring, 28 mm	192.01	0	m²		
	Skylight	13.51	0	m²		
	Fittings, parapet	7.81	0	m²		
Stairs	Concrete stairs	0.98	2.11	m³		
	Steel stairs	0	2922.00	kg		

Re-use of materials

Having high environmental ambitions, the project had as a goal to achieve a high degree of re-use of building components, including load-bearing structures. Exterior walls in the existing property were mainly retained except for windows. The new building extension, consisting of eight floors and a roof terrasse, was designed to include re-used materials as much as possible while providing good quality products. The market for re-use of materials in Norway is still under development and used materials from over 25 buildings in demolition or renovation processes were used in the project. Most materials were retrieved within a 5-kilometer radius from the project, as shown in Figure 16.

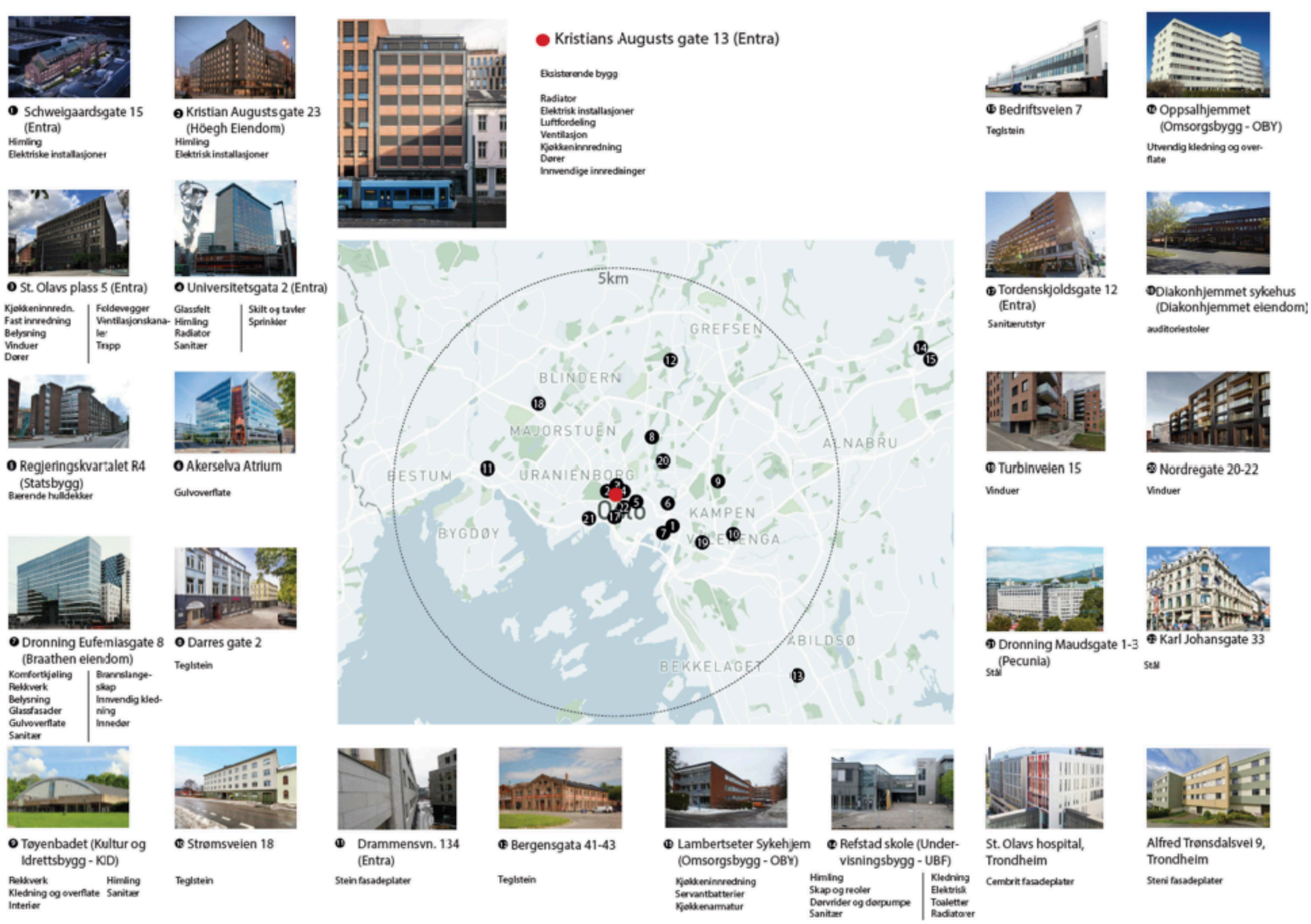

Figure 16. Map of donor buildings in Oslo. Illustration: MAD arkitekter

Figure 17 illustrates the re-used building components on a typical floor.

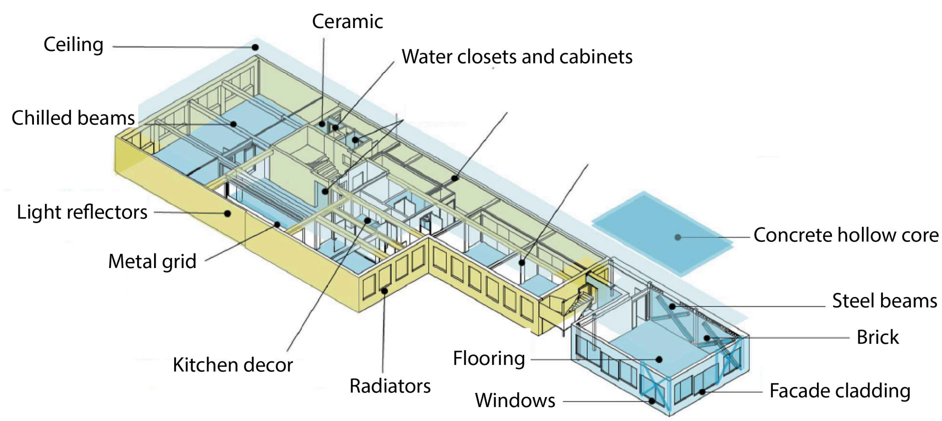

Figure 17. Re-used components on a typical floor. Illustration: MAD arkitekter

Overall, re-use of local components from the existing building constitutes about 80% of the total weight of the materials in the building. Use of re-used materials from donor buildings account for 15% of the weight of added materials to the building under the refurbishment and new construction as illustrated in Figure 18. Re-used materials are identified in Table 16.

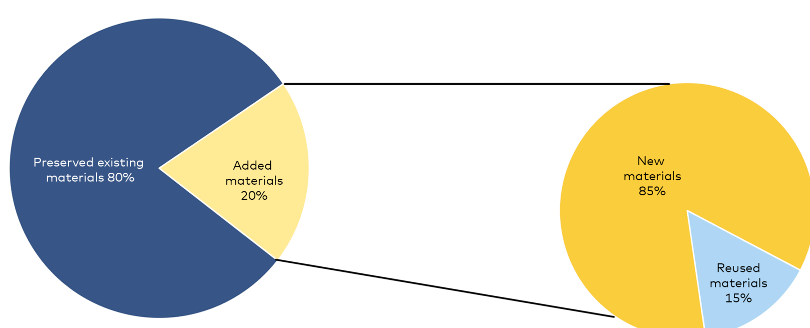

Figure 18. Distribution of material type per percent of building weight

Re-use of materials is accounted for in both NS 3720 and FutureBuilt ZERO methods in the modules A1–A3 and A4. Product-specific emission factors were used as much as possible. For most re-used materials, the findings from the Master's thesis "Re-use of building materials and products in a sustainable perspective" by Høydahl and Walter (2020) were used. For re-used materials with no emission data, a standard reduction factor of 80% was used for the material production phase (A1–A3).

Re-usability of materials

In addition to using re-used materials, the project also focused on using materials that are easily re-usable at the end of life of a building. Re-usability can apply to both used and new elements that have been added to the project. For a component to be re-usable, one should consider the following:

- Robust and homogenous materials without substances that are harmful to health and the environment
- Reversible connections between components so that these can be safely dismantled
- Layered construction so that components can be dismantled independently of adjacent layers.

The share of re-usable materials accounts for 15% of the total mass of added materials in the refurbishment / new construction process. Re-usable materials are identified in Table 16. Re-usability is accounted for in the FutureBuilt ZERO method under the module D.

4.1.4 Building energy use

Building energy use was simulated in SIMIEN v.6.015[8], a simulation tool for calculating energy consumption and assessing indoor climate. The building was modelled in two parts: refurbishment and new construction. The specific energy demand per end-use is presented in Table 17.

Table 17. Annual specific energy demand per end-use

Specific energy demand (kWh/m^2/year)	Refurbishment	New construction	Whole building
Space heating	19.6	16.1	19.0
Ventilation heating	10.2	10.2	10.2
Domestic water heating	7.0	5.0	6.7
Fans	12.1	11.1	11.9
Pumps	3.1	1.6	2.8
Lighting	28.0	20.0	26.6
Technical equipment	48.2	34.5	45.8
Room cooling	15.3	6.4	13.8
Ventilation cooling	4.8	4.1	4.7
Total	**148.3**	**109.0**	**141.5**

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Since most of the existing structure has been preserved, the exterior walls (concrete and Siporex) were insulated to a small extent without compromising the expression of the façade or risking frost and moisture issues due to changed temperature conditions. Although the passive solutions were implemented and technical systems optimized, the refurbished part of the building does not meet the current national regulatory requirements for new building energy use (TEK17) (DIBK, 2017). The new extension, however, meets the energy use requirements.

Figure 19 illustrates the distribution of energy demand per end-use in the building. Technical equipment accounts for about one-third of the total energy demand, followed by lighting with 19%. Heating end-uses account for 25%, while cooling end-uses account for 20%.

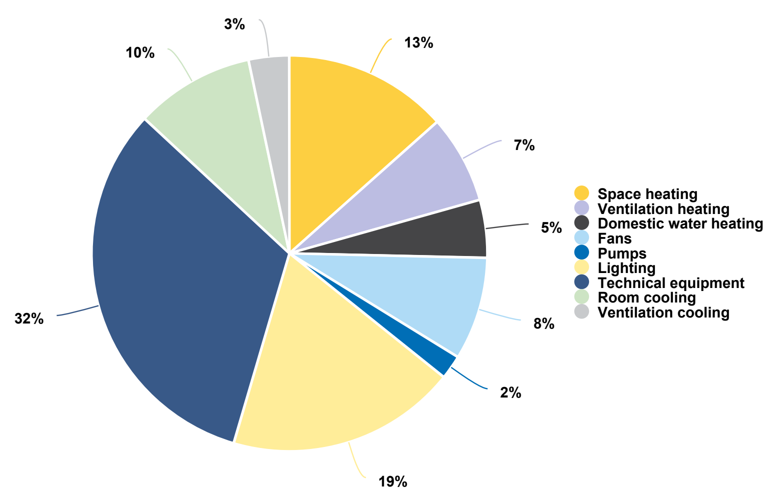

Figure 19. Distribution of energy demand per end-use

In the early stages of the project, a preliminary study was conducted to assess the possible energy source and system solutions. As a result of this study, it was decided to continue with the existing solution which consists of district heating and electric cooling (direct expansion or dry cooler). The system efficiency of each energy solution is shown in Table 18 and the resulting annual specific energy delivered in Table 19. Electricity accounts for the about two-third of the total energy delivered to the building, and district heating for one-third.

Table 18. Energy sources and systems

System	Description
Heating system	100% district heating, system efficiency 88 %
Cooling system	100% electric cooling, system efficiency 245 %
Electricity	100% electricity grid, system efficiency 100 %

Table 19. Annual specific energy delivered

Annual specific energy delivered (kWh/ m^2/year)	Refurbishment	New construction	Whole building
Electricity from the grid	99.6	71.5	94.8
District heating	41.8	35.6	40.7
Total	**141.4**	**107.1**	**135.5**

4.1.5 Scenarios

Five different scenarios were assessed in this study, both with NS 3720 and FutureBuilt ZERO methods.

First, the climate footprint of the building "as built", was assessed (Scenario 0). The "as built" scenario for both materials and energy solution is described in sections 5.1.3 and 5.1.4. The building has a high degree of re-use of building components and uses district heating as the heating source. The footprint of the new construction was compared to that of the refurbished construction.

Then, the same building, but with new materials instead of re-used materials, was compared to the as built solution to assess the impact of re-using materials in both the refurbished and new parts (Scenario 1). The emissions in the production phase (A1-A3) and transportation to building (A4) phase were adjusted accordingly. In the case of refurbishment, a scenario without re-use is a scenario where the existing structure is not preserved, but rather demolished and built with new materials. The carbon footprint per square meter of the new construction part was therefore used for the refurbishment. In addition, emissions from demolishment of the existing structure (C1–C4) were accounted for. The emission per square meter for demolishment is assumed to be 53 kg CO_{2e} according to an LCA study of a brick building from the 1950s conducted by Zimmermann et al. (2020).

Lastly, alternative scenarios for the energy solution were investigated: use of solar photovoltaic (PV) panels (Scenario 2), use of a ground-source heat pump (GSHP) (Scenario 3), and a combination of both (Scenario 4).

Table 20. Scenarios assessed in the study

NS 3720 and FutureBuilt ZERO methods	New construction	Refurbishment	Whole building
Scenario 0: As built with high degree of re-use and district heating	X	X	
Scenario 1: Without re-use	X	X	
Scenario 2: With solar PV			X
Scenario 3: With GSHP			X
Scenario 4: With solar PV and GSHP			X

Alternative energy scenarios

The first energy alternative investigated is solar panels. Considering the limited roof space, façades were also considered in this case. The roof, as well as the south-west and south-east façade are well exposed to sun. The building to the east is lower, allowing sun to reach the south-east façade. A total of 148 m^2 of PV panels are placed on the roof at an angle of 10 degrees in the east-west direction, while 259 m^2 are placed on the façade. Panels with a wattage of 200 kW_p/m^2 and a shading factor of 10% were assumed as part of this study.

Table 21. Dimensioning of solar PV system

	Area (m^2)	Tilt angle	Orientation	Capacity installed (kW_p)
Roof	148	10°	East-West	29.6
South-East façade	189	90°	34°	37.8
South-West façade	70	90°	214°	14.0

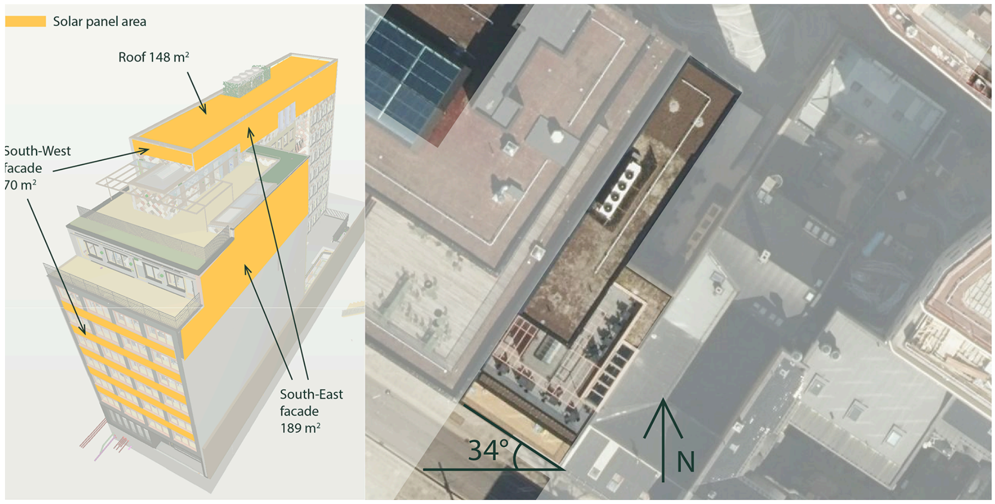

Figure 20. Placement of solar PV

The solar panel assessment was performed in "Lønnsom solenergi", an Excel-based tool developed by Asplan Viak. The calculation showed that the PV system produces 46 780 kWh per year and covers 14% of the total electricity use of the building. Less than 1% of the total electricity produced by the PV system is exported. The monthly distribution of electricity produced by the PV system and the building electricity use is shown in Figure 21. FutureBuilt ZERO accounts for the exported solar electricity in module D, while it is outside the system boundaries in the case of NS 3720.

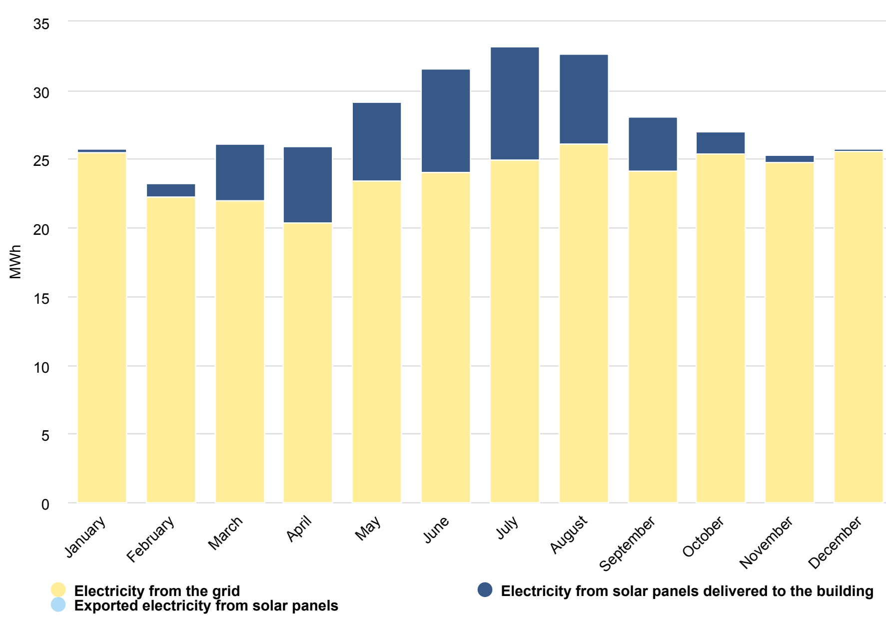

Figure 21. Monthly electricity production from solar PV and electricity use

The emissions from material use for the PV system is included in the analysis. The emission factor is based on LCA from Louwen et al. (2016). This includes emissions from the mounting system and inverters. Solar PVs are assumed to have a lifetime of 30 years, requiring one replacement over a 60-year period. NS 3720 and FutureBuilt ZERO have different methods to calculate the emissions from solar panels at the time of replacement. FutureBuilt accounts for technology advancement and time-weighting, resulting in a 53% reduction in production emissions at time of replacement, whereas NS 3720 uses the same factor at both installation and replacement. It is assumed that solar panels are produced in Asia.

The second energy alternative investigated is a ground-source heat pump (GSHP) as the main heating system. It is assumed that the heat pump provides 95% of the yearly heating demand. The total capacity of the heat pump is roughly estimated at 76 kW, with four 300-meter-deep boreholes. A conservative year-round coefficient of performance of 3.0 was assumed.

Emissions from the production of the heat pump and boreholes are accounted for in the analysis. The emission factors for material production are taken from the Ecoinvent database. It is assumed that the equipment is produced in Europe.

The parameters used in the calculations are shown Table 22.

Table 22. Parameters and assumptions per energy system

System	Dimension	Lifetime	Weight	Transport distance	A1-A3 emission factor
Solar PV	81 kW_p	30 years	4.4 tonnes	20 000 km	680 kg CO_{2e}/kW_p
GSHP	76 kW	25 years	0.6 tonnes	2000 km	46.1 kg CO_{2e}/kW
Boreholes	4 x 300 m	60 years	5.7 tonnes	2000 km	6.3 kg CO_{2e}/m

The annual specific energy delivered to the building per energy source and scenario is shown in Table 23.

Table 23. Annual specific energy delivered per scenario

Annual specific energy delivered (kWh/m^2a)	Electricity from the grid	Electricity from solar PV	District heating	Total
Scenario 0 As built	94.8	0	40.7	135.5
Scenario 2 Solar PV	83.6	11.2	40.7	135.5
Scenario 3 GSHP	93.4	0	2.0	106.8
Scenario 4 Solar PV + GSHP	82.2	11.2	2.0	106.8

4.2 Results and discussion

4.2.1 Scenario results

Scenario 0 As built

The carbon footprint of the building "as built" is presented in Table 24 and Figure 22. Results are presented per module, per method, and per construction type. Results are expressed in kg CO_{2e} per square meter annually.

Overall, the refurbished portion has a slightly lower carbon footprint per square meter than the new portion. Less materials were needed for the refurbishment, thanks to the high number of preserved elements from the existing building. Preserving the existing structure comes, however, with a cost in terms of energy efficiency in this case. Less insulation was added to the existing structure than required to meet the regulations, resulting in a building consuming more energy than a new construction. Emissions from energy use (B6) account for most of the total emissions for the two construction types. These findings apply for both NS 3720 and FutureBuilt ZERO methods.

Using the FutureBuilt ZERO method results in a lower carbon footprint than NS 3720: 6% lower for new construction and 8% for refurbishment. For both new construction and refurbishment, module B1–B5 accounts for most of the difference in results, mostly due to time weighting and technology advancement in FutureBuilt ZERO. For refurbishment, module B6 (energy use) also contributes to a lower carbon footprint with the FutureBuilt ZERO method, where time-weighting results in a lower average electricity emission factor. The emissions from A1–A4 are the same in both cases. The emissions from C3 and D account for a small share of the total emissions. The FutureBuilt method results in higher emissions from C3 due to the allocation of emissions from waste incineration. On the other hand, FutureBuilt has lower emissions from module D since that module is included in the assessment as opposed to NS 3720.

Table 24. Results for as-built scenario

Carbon foot-print (kg CO_{2e}/m^2a)	Refurbishment			New construction		
	NS 3720	FutureBuilt ZERO	Comparison	NS 3720	FutureBuilt ZERO	Comparison
A1–A3	0.95	0.95	0%	4.93	4.93	0%
A4	0.12	0.12	0%	0.73	0.73	0%
A5	0.11	0.13	+20%	0.57	0.59	+5%
B1–B5	1.09	0.47	-57%	1.42	0.43	-70%
B6	12.30	11.75	-4%	8.89	8.88	0%
C3	0.01	0.03	+432%	0.02	0.04	+68%
D	0.00	-0.01	-	0.00	-0.03	-
Sum	14.57	13.43	-8%	16.56	15.57	-6%

Figure 22. Carbon footprint for refurbishment and new construction, as-built scenario

Scenario 1 Without re-use

The carbon footprint of the building with and without re-used materials is presented in Table 25 and Figure 23 with NS 3720, and in Table 26 and Figure 24 with FutureBuilt ZERO.

Results show that use of re-used materials is an effective strategy to reduce the greenhouse gas emissions of a building. Re-use leads to a 31% reduction for refurbishment and 20% for new construction with both methods. Emissions from materials are reduced by 35% for new construction and by 81% for refurbishment with NS 3720, and by respectively 37% and 85% with FutureBuilt ZERO. In the case of new construction, the emissions from energy use are assumed to be the same with or without re-use. For refurbishment however, it is assumed that by having a new rather than a re-used structure, the building could be fully insulated. Re-use therefore results in a 38% increase in emissions from energy use for refurbishment with NS 3720 and 32% increase with FutureBuilt ZERO.

Table 25. Results with and without re-use, NS 3720

Carbon footprint ($kg\ CO_{2e}/m^2a$)	Refurbishment			New construction		
	Without re-use	With re-use	Comparison	Without re-use	With re-use	Comparison
C1–C4	0.88	0.00	-100%	0.00	0.00	-
A1–A3	6.84	0.95	-86%	7.18	4.93	-31%
A4	1.85	0.12	-94%	1.95	0.73	-62%
A5	0.87	0.11	-88%	0.91	0.57	-38%
B1–B5	1.62	1.09	-32%	1.70	1.42	-16%
B6	8.89	12.30	+38%	8.89	8.89	0%
C3	0.02	0.01	-74%	0.02	0.02	0%
D	0.00	0.00	-	0.00	0.00	-
Sum	20.97	14.57	-31%	20.65	16.56	-20%

Table 26. Results with and without re-use, FutureBuilt ZERO

Carbon footprint ($kg\ CO_{2e}/m^2a$)	Refurbishment			New construction		
	Without re-use	With re-use	Comparison	Without re-use	With re-use	Comparison
C1–C4	0.88	0,00	-100%	0.00	0.00	-
A1–A3	6.84	0.95	-86%	7.18	4.93	-31%
A4	1.85	0.12	-94%	1.95	0.73	-62%
A5	0.89	0.13	-86%	0.94	0.59	-37%
B1–B5	0.53	0.47	-12%	0.56	0.43	-24%
B6	8.88	11.75	+32%	8.88	8.88	0%
C3	0.04	0.03	-17%	0.04	0.04	0%
D	-0.07	-0.01	-82%	-0.07	-0.03	-60%
Sum	19.85	13.43	-32%	19.48	15.57	-20%

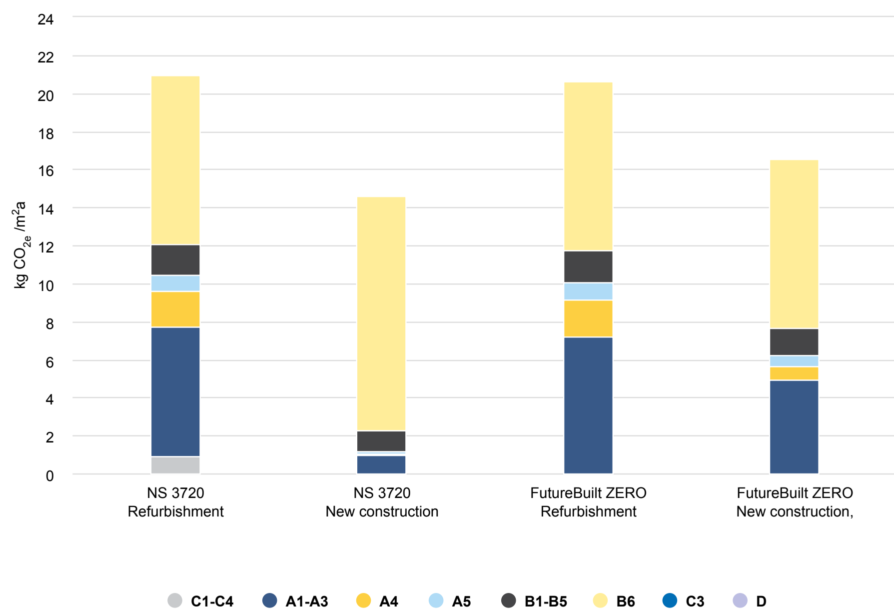

Figure 23. Effect of re-use, NS 3720

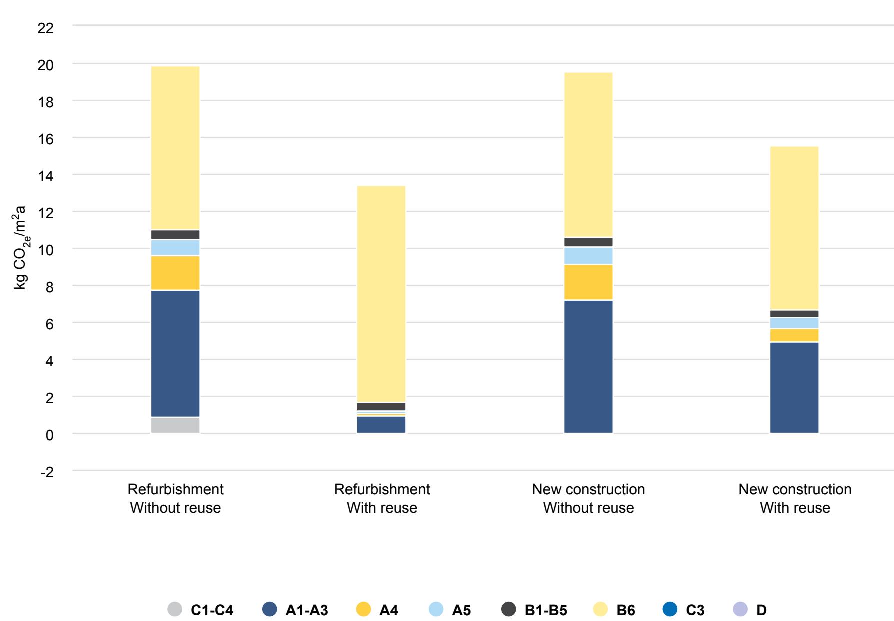

Figure 24. Effect of re-use, FutureBuilt ZERO

Scenarios 2–4 Alternative energy solutions

The resulting carbon footprint of including a PV system (scenario 2), a ground-source heat pump (GSHP) as main heating system (scenario 3), and a combination of both (scenario 4) is presented in Table 27 and Figure 25 with NS 3720 (NS), and in Table 28 and Figure 26 with FutureBuilt ZERO (FB).

Installing a PV system results in a decrease in emissions from energy use (11% reduction with NS and 8% with FB), but an increase in emissions from material use (15% increase with NS and 12% with FB). Overall, the emissions saved from energy use surpass the increase in emissions from material use, leading to a total reduction of 6% with NS 3720 and 4% with FutureBuilt ZERO in carbon footprint. Since only

1% of the electricity produced by the PV system is being exported, there is insignificant benefits in module D with the FutureBuilt ZERO method.

Using a GSHP as the main heating system results in an increase (6%) in carbon footprint when using NS 3720. In addition to leading to an increase in emissions from material use (3%), this alternative also leads to an increase in emissions from energy use (6%). Having a GSHP increases on the one hand electricity use but decreases district heating use on the other hand. Since the emission factor for district heating is lower than that of electricity in NS 3720, having a GSHP results in an increase in carbon footprint. This is however not the case when using the FutureBuilt ZERO methodology. In that case, the total carbon footprint is decreased by 16%. The increase in emissions from material use is the same as for NS 3720, but the decrease in emissions from energy use reaches 21% because the emission factors from electricity and district heating are in the same range. It should be noted that heating accounts for only 25% of the total energy demand of the building. For an office building, most of the energy demand is used by technical equipment and lighting. Having a heating system with higher efficiency therefore has a less significant impact than on a building having a relatively larger share of heating demand.

When combining the PV and GSHP systems, the reduction in carbon footprint with GSHP and the increased footprint with the PV system are cancelled out for NS 3720. With FutureBuilt ZERO, benefits from both energy alternatives add up to a total reduction of 21% in carbon footprint. It should be noted that the energy alternatives included in this case study are based on rough dimensioning estimates.

Table 27. Results per energy alternative, NS 3720

Carbon footprint (kg CO_{2e}/m^2a)	Scenario 0 As built	Scenario 2 Solar PV		Scenario 3 GSHP		Scenario 4 Solar PV + GSHP	
	Footprint	Footprint	Comparison with Scenario 0	Footprint	Comparison with Scenario 0	Footprint	Comparison with Scenario 0
A1–A3	1.64	1.87	+14%	1.68	+3%	1.91	+17%
A4	0.19	0.23	+22%	0.23	+24%	0.24	+26%
A5	0.22	0.21	-6%	0.19	-14%	0.21	-4%
B1–B5	1.15	1.38	+20%	1.18	+3%	1.41	+23%
B6	11.71	10.38	-11%	12.46	+6%	11.14	-5%
C3	0.01	0.01	+0%	0.01	+0%	0.01	+0%
D	0.00	0.00	-	0.00	-	0.00	-
Sum	14.91	14.07	-6%	15.76	+6%	14.92	+0%

Table 28. Results per energy alternative, FutureBuilt ZERO

Carbon footprint (kg CO_{2e}/m^2a)	Scenario 0 As built	Scenario 2 Solar PV		Scenario 3 GSHP		Scenario 4 Solar PV + GSHP	
	Footprint	Footprint	Comparison with Scenario 0	Footprint	Comparison with Scenario 0	Footprint	Comparison with Scenario 0
A1–A3	1.64	1.87	+14%	1.68	+3%	1.91	+17%
A4	0.22	0.23	+2%	0.23	+4%	0.24	+6%
A5	0.21	0.23	+11%	0.21	+3%	0.24	+14%
B1–B5	0.46	0.53	+14%	0.48	+4%	0.55	+18%
B6	11.25	10.32	-8%	8.92	-21%	7.99	-29%
C3	0.03	0.03	+1%	0.03	+0%	0.03	+1%
D	-0.02	-0.02	+24%	-0.02	+0%	-0.02	+24%
Sum	13.80	13.19	-4%	11.55	-16%	10.93	-21%

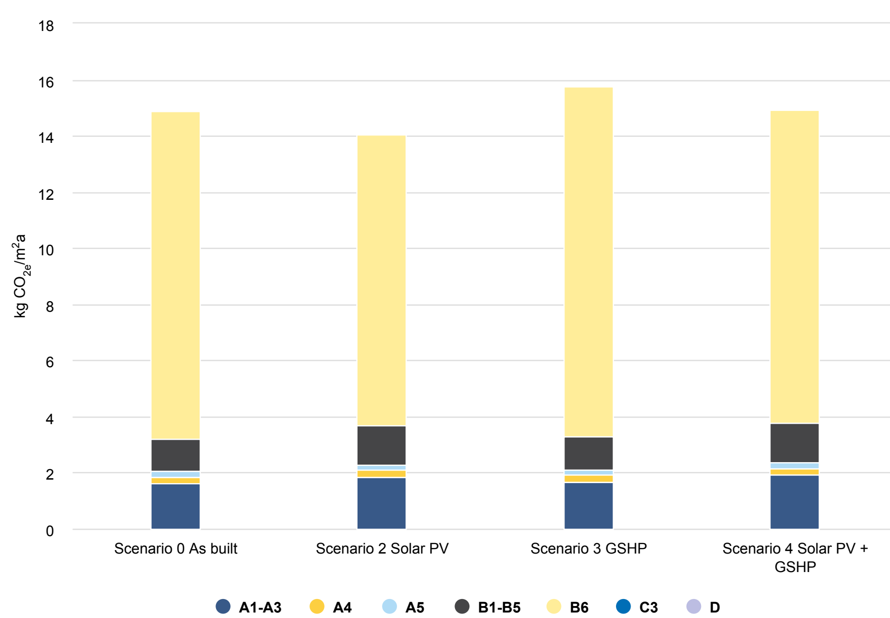

Figure 25. Effect of energy solution, NS 3720

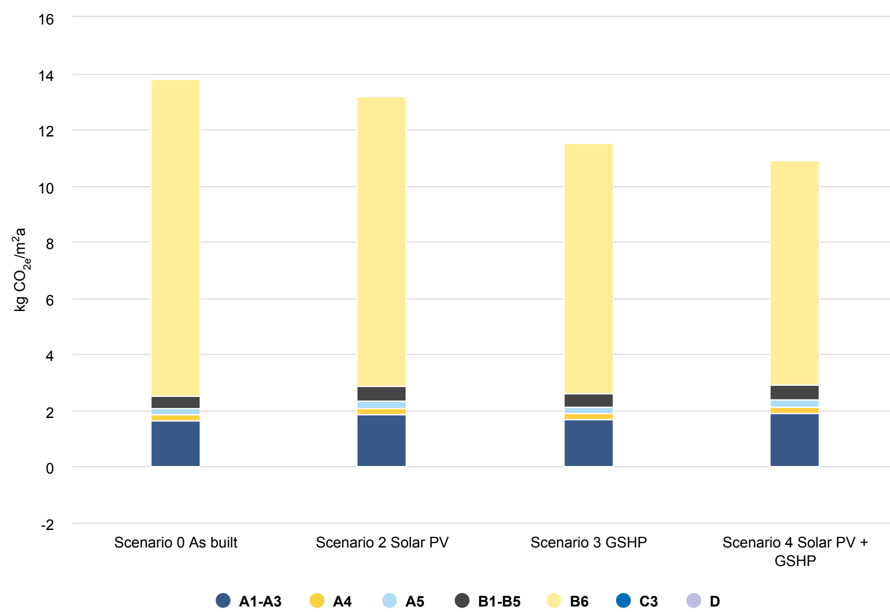

Figure 26. Effect of energy solution, FutureBuilt ZERO

4.2.2 Sensitivity to emission scenarios

As discussed in section 5.2.1, the energy source emission factors have a significant role to play in whether an alternative is beneficial from a carbon footprint perspective.

Norwegian electricity mix in NS 3720

According to NS 3720, the carbon footprint of energy use (module B6) shall be calculated for two different scenarios for emissions from electricity. The main scenario, as described in section 5.1.1, is based on an electricity mix with a development over 60 years in line with the EU zero emission target for electricity production by 2050 as shown in Figure 27. This results in an average emission factor of 119 g CO_{2e} per kWh. The second scenario corresponds to a domestic Norwegian electricity mix, which is of 18 g CO_{2e} per kWh over 60 years.

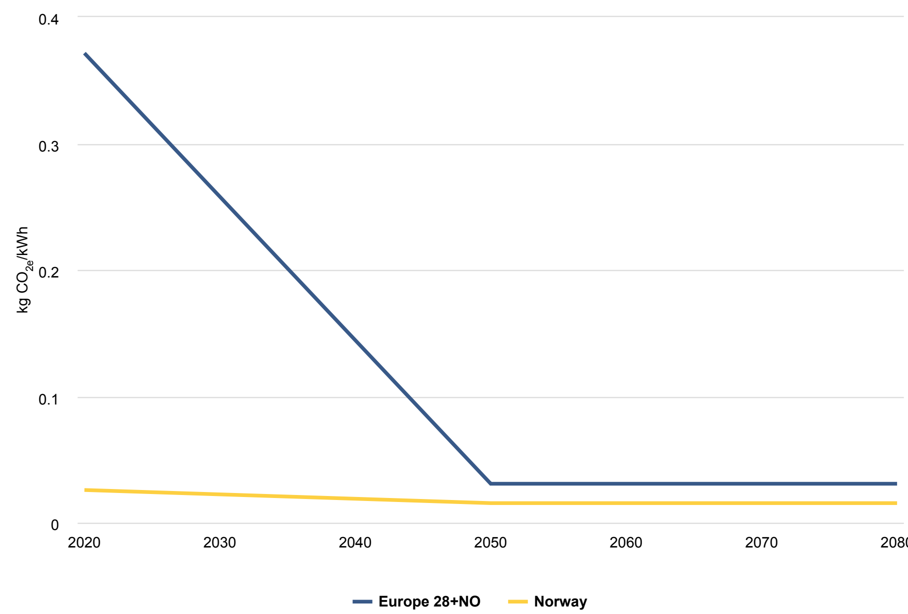

Figure 27. Decreasing emission trend per electricity mix

Table 29 presents results for the effect of re-use with the Norwegian electricity mix. When comparing the building with and without re-use, results show that using the Norwegian mix results in a higher decrease in total carbon footprint (67% for refurbishment and 30% for new construction) since energy use accounts for a lower share of the total emissions.

Table 29. Results for effect of re-use with Norwegian electricity mix, NS 3720

Carbon footprint (kg CO_{2e}/m^2a)	Refurbishment			New construction		
	Without re-use	With re-use	Comparison	Without re-use	With re-use	Comparison
C1–C4	0.88	0.00	-100%	0.00	0.00	-
A1–A3	6.84	0.95	-86%	7.18	4.93	-31%
A4	1.85	0.12	-94%	1.95	0.73	-62%
A5	0.87	0.11	-88%	0.91	0.57	-38%
B1–B5	1.62	1.09	-32%	1.70	1.42	-16%
B6	1.69	2.27	+34%	1.69	1.69	0%
C3	0.02	0.01	-74%	0.02	0.02	0%
D	0.00	0.00	-	0.00	0.00	-
Sum	13.77	4.55	-67%	13.45	9.36	-30%

Table 30 presents results for the effect of energy solution with a Norwegian electricity mix. As opposed to using a European mix, the use of the PV system leads to an increase in total carbon footprint (5%), while the use of a GSHP leads to a decrease (3%). A combination of both systems results in a 2% increase in carbon footprint.

Table 30. Results for energy alternatives with Norwegian electricity mix, NS 3720

Carbon footprint (kg CO_{2e}/m^2a)	Scenario 0 As built	Scenario 2 Solar PV		Scenario 3 GSHP		Scenario 4 Solar PV + GSHP	
	Footprint	Footprint	Comparison with Scenario 0	Footprint	Comparison with Scenario 0	Footprint	Comparison with Scenario 0
C1–C4	0.00	0.00	-	0.00	-	0.00	-
A1–A3	1.64	1.87	+14%	1.68	+3%	1.91	+17%
A4	0.19	0.23	+22%	0.23	+24%	0.24	+26%
A5	0.22	0.21	-6%	0.19	-14%	0.21	-4%
B1–B5	1.15	1.38	+20%	1.18	+3%	1.41	+23%
B6	2.17	1.97	-9%	1.93	-11%	1.73	-20%
C3	0.01	0.01	+0%	0.01	+0%	0.01	+0%
D	0.00	0.00	-	0.00	-	0.00	-
Sum	5.38	5.66	+5%	3.30	-3%	5.51	2%

Comparison between NS 3720 and FutureBuilt ZERO

In addition to the electricity mix chosen, time-weighting can play a significant role when using an average emission factor over a 60-year period. Although FutureBuilt ZERO follows NS 3720 in terms of technological development in electricity mix, it also includes a time-weighting factor, where emissions happening in the future count less than emissions happening in the present. This results in an average emission factor for electricity which is 29% lower than that of NS 3720.

The emissions from waste incineration that are included in district heating (energy recovery) in use phase (B6) are allocated 50/50 between the waste sector and the energy sector in FutureBuilt ZERO. NS3720 allocates all emissions from energy recovery to the waste sector and with a view to waste incineration included in district heating as zero emissions (100/0). Although FutureBuilt uses time-weighting, the emission factor for district heating is 645% higher than that of NS 3720. For buildings highly relying on district heating, this will result in a higher total emission using the FutureBuilt ZERO method.

4.2.3 Key takeaways

This case study revealed that re-use of materials can significantly reduce the carbon footprint of a building, up to 30% for refurbishment and 20% for new construction. Kristian August gate 13 was designed with a high degree of re-used and reusable materials, following principles of circularity. This case is however not considered as a common practice in Norway as of today. Re-use of materials is a practice that require further research, development, and practice.

The impact of energy efficiency measures is highly dependent on the method chosen and the emission factor for energy use. A dynamic LCA methodology (FutureBuilt ZERO), discounting emissions happening in the future, is better suited for decision-making in reducing carbon emissions in the short term. The dynamic method gives a higher priority of using re-used materials and low-carbon materials. Time-weighting favours refurbishment over new construction, but there is a trade-off between decreased emissions from materials and increased energy use, and thus emissions in the long term. Energy efficiency measures are not prioritized as much as re-use of materials, but both the PV system and the heat pump system give a net benefit over the building lifetime. Especially for the PV system, there is between increasing material emissions in the short term, and reducing emissions from energy use in the long term.

5. Case study: Mäemaja building, Tallinn, Estonia

5.1 Description of the building

A life-cycle carbon footprint assessment was carried out for the Mäemaja building (Figure 28) in the Mustamäe campus area in Tallinn. Mäemaja (hilltop building) is a flagship project of Tallinn University of Technology. The building provides premises for structural and road engineering, HVAC and building physics laboratories with some auditoriums. Similarly to the Finnish and Norwegian case studies, the Estonian case study includes re-use of existing structures and new construction aiming at a low CF. The basic information of the building is presented in Table 31.

Table 31. Basic information on Mäemaja educational building

Address	Harju county, Tallinn, Mustamäe district, Mäepealse tn 3
Type	Educational building
Architect	Tõnu Laigu, Allis Mehide, Kristjan Lind
Interior architect	Tarmo Piirmets
Landscape architects	Kadi Nigul, Kristian Nigul
Lighting designer	Marko Kuusik
Year of completion	2021
No of storeys (above ground)	3
No of storeys (under ground)	1
Height (m)	17.8
Length (m)	50.1
Width (m)	43.1
Depth (m)	3.2
Heated floor area (m²)	3 497
Gross internal floor area (m²)	4 068

Figure 28. Mäemaja, Tallinn, Mäepealse 3. Photo: Vallo Vahesaar

A test hall, built in 1986, was thoroughly renovated and extended with a three-story office part in 2021 (Figure 29). The solutions aiming at reducing the environmental load included 1) partial use of the existing building 2) new construction with a timber frame 3) installation of a PV system on the roofs.

The preserved parts of the old test hall included the foundation, the rooms in the basement, the thick concrete floor slab of the actual test hall, the light-weight concrete exterior walls and the steel roof trusses. The top layer of the test hall floor slab was damaged and uneven, and had rails that had become unnecessary. Therefore, about 40 mm of concrete was removed and a new layer of flooring screed was cast with an EPO layer on the top. New hydro isolation, thermal insulation and an outer crust of reinforced concrete were added onto the existing foundation.

The building extension has three floors with a CLT structure, including columns, beams and slabs on the top of a concrete basement floor. The CLT slabs of intermediate floors have a concrete layer on top. The primary staircase is of timber, and the second stairwell has a concrete structure. The long exterior wall of the office has a light timber frame. The load-bearing CLT panel is mainly exposed to interior. Most of the façades are covered with metal sheet panels but the main entrance side of the building is clad with wooden boards. Windows and glass façades have aluminium profiles.

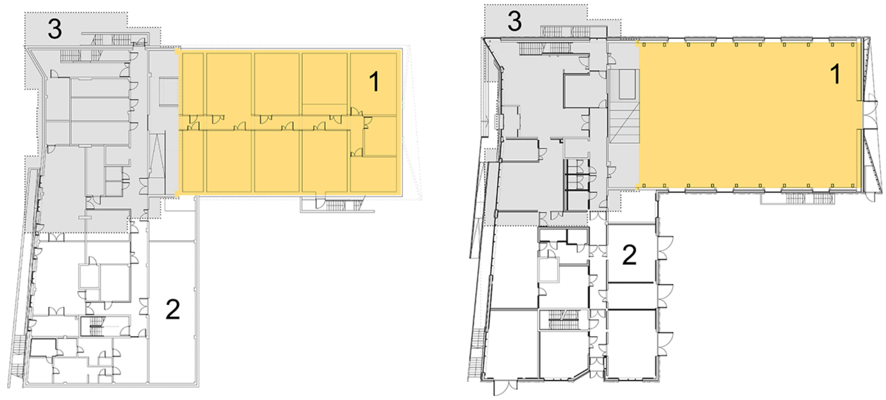

Figure 29. Basement (left) and the ground floor plan, Mäemaja building. The structures of the old test hall (1) were mainly preserved and spaces with poor functionality (3) demolished. New, larger office part (2) was construced with a CLT timber frame.

Figure 30. New extension has a load-bearing timber frame that is partly exposed to the interior. Photo: Tõnu Laigu

The heating system is district heating. Mechanical supply and exhaust heat recovery ventilation is in most of rooms demand controlled, and room conditioning is implemented with water radiators and active chilled beams. LED lighting applies occupancy sensors in many rooms. The entire roof surface area is covered with photovoltaic panels in an angle that is optimized for maximum annual output.

The installed PV capacity at Mäepealse 3 is as follows:

- Test Hall roof:
    - 104 panels (Q.PEAK DUO-G7)
    - 330 W/panel
    - 34.3 kW
- New Building roof:
    - 88 panels (Q.PEAK DUO-G7)
    - 330 W/panel
    - 29.0 kW
- **TOTAL:**
    - **192 panels** (Q.PEAK DUO-G7)
    - **330 W/panel**
    - **63.3 kW**

5.2 Data and methods

5.2.1 Methods and tools

The Estonian method for assessing the CF for new construction was developed in 2021 and published by the Estonian Ministry of Economic Affairs and Communications in the spring of 2022 (Kalamees et al. 2021); thus the CF assessment was not applied during the design stage. This case study applies the new method and evaluates the viability of the chosen strategies from the CF perspective in the Estonian context.

The LCA for this report was carried out by the researchers of Tallinn University of Technology TalTech with the OneClickLCA tool, as a part of the SynTra research project. The simulation of delivered energy as well as the analysis of photovoltaic output and load match were carried out with IDA-ICE 4.8, utilizing the building information models from the architect and the structural engineers of the building.

The Estonian national CF assessment method is based on the European standards on sustainable construction and building life-cycle assessment (EN 15643, EN 15978, EN 15804, EN ISO 14067). However, it is important to notice that at the time of this study, the Estonian database of the generic CO_2 emission factors for construction materials only provides values for 47 most common Estonian construction materials. The number of environmental product declarations (EPDs) for Estonian construction materials and products is very limited.

Table 32 shows the system boundary according to the Estonian national CF assessment method, with respect to modules A–D and their sub-modules.

Table 32. System boundaries of the Estonian national building life-cycle assessment method.

Module	Scope of the Estonian method
A1–A3 Product phase	• Included • Assessed with project-specific data
A4–A5 Transport to site and construction process	• Included • Assessed with the default transportation distances in the Estonian materials database
B1–B3 Use, maintenance and repair of products	• Not included
B4 Replacements	• Included • Assessed based on the default service life of materials in the Estonian materials database
B5 Refurbishment	• Not included • No major refurbishments expected during the life span of 50 years
B6 Operational energy use	• Included • Assessed with project-specific values for delivered energy, national emission factors and the national decarbonisation scenario for energy carriers
B7 Operational water use	• Not included
C1–C4 End-of-life stage: demolition, transport, waste processing, disposal	• Included • Assessed with default factors from the Estonian materials database

The current version of the Estonian CF assessment method only includes a limited number of aspects for Module D, excluding impacts such as:

- biogenic carbon storage
- material re-use after building life-time
- renewable energy exported into the grids
- carbonatization occurring in concrete building materials.

In accordance with the European standards on life-cycle assessment – and respectively to the Finnish CF method – the result from module D is declared as additional information. Thus, module D is not part of building CF.

Building CF was assessed for a period of 50 years, in accordance with the national assessment method. Generic Estonian CO_{2e} emission factors were applied for the assessment of material-related greenhouse gas emissions. The module B6 applies the current Estonian scenario for the CO_{2e} emission factors of the grid electricity and district heating (Table 33). The module D emissions are reported separately.

Table 33. Estonia's electricity and district heating CO_{2e} emission factor scenario (Mändmets & Štõkov 2021).

kg CO_{2e}/kWh	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
Grid electricity	0.717	0.637	0.509	0.425	0.359	0.344	0.32	0.27	0.22	0.17	0.11
District heating	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11

5.2.2 Building model

A detailed building information model and several sub-models were created during the design and construction process. A combination of structural engineering and architecture models were used for this study. The materials and components remaining from the existing building were excluded from the life-cycle assessment. The simulation of energy performance applied an as-built model of the Mäemaja building. Possible errors resulting from application and modification of the model are the responsibility of the authors of this report.

5.2.3 Building materials

All underground structures are constructed of reinforced concrete. The test hall part of the basement is a preserved structure from 1986, and the basement under the office is a new concrete construction. The U-values of the building envelope are presented in Table 34. Table 35 shows the input data for OneClickLCA.

Table 34. Surface materials and the U-values of the building envelope.

Building envelope	Area (m^2)	U ($W/(m^2K)$)
Walls above ground	1598.27	0.12
Walls below ground	405.8	0.14
Roof	1288.38	0.09
Floor towards ground	1251.15	0.14
Floor towards amb. air	32.27	1.91

Table 35. Material quantity input data for the OneClickLCA building CF calculation.

Building part	m²
Base floor	1158
External roof	1407
Internal slab	639
Internal ceiling	402
Internal floor	1197
External wall area	2177
Non-load bearing internal walls	2206
Load-bearing internal walls	945
Internal doors	183
Total length of concrete beams	647
Internal walls finishing	6304
Window area	572
Frost insulation around the building perimeter	185
External doors	36

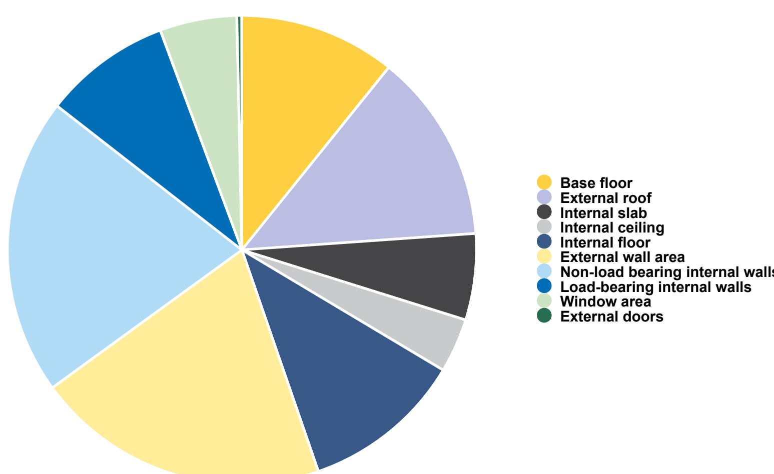

Figure 31. The surface areas of the building parts (m²).

5.2.4 Operational energy use

The total heated floor area is 3 497 m^2 and the gross internal floor area is 4 068 m^2. The delivered energy and the annual photovoltaic output were calculated in the IDA Indoor Climate and Energy simulation environment.

Delivered energy

As a whole, including both the new and renovated parts, the Mäemaja building meets the Estonian new building NZEB requirement that is 100 kWh/(m^2a) of primary energy, including the electricity for appliances (small power plug loads) that are included on the top of minimum energy uses in the Estonian calculation method.

According to the simulation, the delivered energy is:

Heating, kWh/a	156 881
Cooling, kWh/a	2 776
HVAC, kWh/a	20 193
Lighting, kWh/a	21 221
Equipment, kWh/a	17 996
Heating of water, kWh/a	34 974.

The primary energy factors are:

District heating	0.9
Electricity	2.0.

Thus, the total annual primary energy consumption is 85.0 kWh/(m^2a). According to the Estonian practise, tenant electricity (plug-in electricity) is included in delivered energy. As in Finland, the national method differs here from the guidelines of EN 15978.

Photovoltaic output

The annual photovoltaic electricity generated totals 56 206 kWh/a. The share of exported electricity is 26 914 kWh/a (47.9%). The GWP for A1–A3 for the monocrystalline PV panels was assumed 23 kg CO_{2e}/kg.

Due to the energy use profile (educational building) of the building, the share of exported electricity is relatively high with the full photovoltaic capacity (Figure 32). During the summer season the building cannot use the output of the system and up to 49% of the photovoltaic output is exported – and thus excluded from CF. With GSHP, annual delivered electricity increases, but the share of exported PV electricity remains high (44%) due to mismatch between the electricity demand and the PV output. However, from the CF perspective, it still seems beneficial to use as much roof surface area for photovoltaic panels as possible. The value of exported electricity is further highlighted if carbon offsets are accounted for, for example when assessing the organizational carbon footprint for the university. It should be also noted that during the first 25 years (the expected service life of the photovoltaic system) the photovoltaic energy replaces very carbon-intensive grid electricity, and the actual environmental benefit during the life of this panel investment is much higher than the result shows.

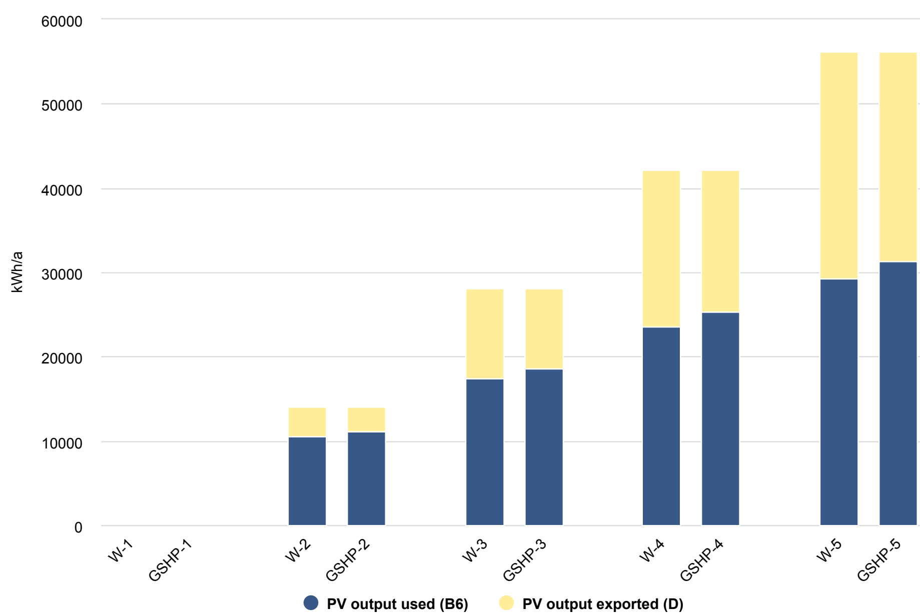

Figure 32. Photovoltaic system output, the shares of own use and export with district heating (left column) and GSHP (right column) and with various PV system dimensioning.

5.2.5 Scenarios

The use of preserved building components was calculated for all scenarios and the average was compared with the other measures of the study. The scenario W-5 is the as-built solution. Scenario W-1 equals to the current building without a photovoltaic system. The size of the photovoltaic system grows step-by-step from W-1 to W-5. The load bearing structure remains timber.

In the GSHP scenarios, district heating is replaced with a ground source heat pump. The coefficients for performance and distribution losses were set according to the building documentation and the relevant Estonian calculation guidelines as follows:

GSHP: COP 4.2 for heating of spaces + 3% distribution losses

GSHP: COP 2.7 for the heating of water

GSHP: COP 27 for cooling, including 10% of distribution and condensation losses

District heating: 3% distribution losses for the heating of spaces

Chiller: 5.5 (in accordance with the project documentation).

In the W-scenarios, the size of the photovoltaic system grows step-by-step from GSHP-1 to GSHP-5. The construction materials remain unchanged, but the embodied emissions for PV system are added.

In the C scenarios, the load-bearing CLT frame is replaced with reinforced concrete, and the size of the photovoltaic system grows step-by-step from C–1 to C–5, similarly to the previous W-scenarios. The U-values and the air tightness (q_{50}) of the building envelope are assumed the same as with the CLT frame, but the increase in thermal mass has a minor impact on the heating energy demand.

5.3 Results and discussion

5.3.1 Scenario results

Tables 36–38 below show the impact of the utilization of old test hall structures on the CF. For the various scenarios, the total CF reduction gained by preserving old structures totals 7–8%.

Table 36. W-scenarios and the reduction gained by material reuse in module A, in product phase emissions (A1–A3) and in the total CF of the Mäemaja building; timber frame and district heating.

Reduction (%) by material reuse	W-1	W-2	W-3	W-4	W-5
floor and foundation					
module A	14.6	14.4	14.2	14.0	13.8
modules A1-A3	14.0	13.8	13.6	13.4	13.2
total CF	6.1	6.2	6.3	6.4	6.5
all preserved components					
module A	16.1	15.9	15.7	15.5	15.3
modules A1-A3	15.5	15.2	15.0	14.8	14.6

Table 37. GSHP-scenarios and the reduction gained by material reuse in module A, in product phase emissions (A1–A3) and in the total CF of the Mäemaja building; timber frame and district heating.

Reduction (%) by material reuse	GSHP-1	GSHP-2	GSHP-3	GSW-4	GSHP-5
floor and foundation					
module A	14.6	14.4	14.2	14.0	13.8
modules A1-A3	14.0	13.8	13.6	13.4	13.2
total CF	6.4	6.6	6.7	6.8	6.9
all preserved components					
module A	16.1	15.9	15.7	15.5	15.3
modules A1-A3	15.5	15.2	15.0	14.8	14.6

Table 38. C-scenarios and the reduction gained by material reuse in module A, in product phase emissions (A1–A3) and in the total CF of the Mäemaja building; timber frame and district heating.

Reduction (%) by material reuse	C-1	C-2	C-3	C-4	C-5
floor and foundation					
module A	13.6	13.4	13.2	13.1	12.9
modules A1-A3	12.9	12.8	12.6	12.4	12.3
total CF	6.0	6.1	6.2	6.3	6.3
all preserved components					
module A	15.0	14.8	14.7	14.5	14.3
modules A1-A3	14.3	14.1	13.9	13.7	13.6

Figure 33 and Tables 39–41 present the various scenarios and the respective carbon footprints. The CF of the Estonian case study (as-built, W-5) is 25.97 $kgCO_{2e}/m^2a$. Replacing the district heating system with a ground source heat pump would further reduce the CF down to 24.38 $kgCO_{2e}/m^2a$ (GSHP-5). With a load-bearing reinforced concrete frame, CF is 26.48 $kgCO_{2e}/m^2a$ (C-5), as the CO_{2e} emissions for the modules A1–A3 increase, but thermal mass reduces heating energy demand by 3%.

The CF reduction of timber construction totals 1.5–1.9% only (in comparison with reinforced concrete, with district heating), depending on the size of the photovoltaic system.

The high carbon-intensity of the Estonian grid electricity is reflected in the results – in the cases of both photovoltaic panels and the ground source heat pump (GSHP).

An effective ground source heat pump could further reduce the carbon footprint. However, it is important to notice that the current Estonian scenario for the energy carriers assumes a radical reduction in the CO_{2e} emission factor for the grid electricity but no future changes for district heating.

It appears that material reuse, load-bearing timber frame and photovoltaic capacity are viable measures for reducing CF, although a large share of PV output is exported in this case.

Table 39. The impact of photovoltaic system size in a timber-frame building with district heating.

$kgCO_{2e}/m^2a$	Wood frame, district heating				
Scenario	**W-1**	**W-2**	**W-3**	**W-4**	**W-5**
Nr of PV panels	0	48	96	144	192
A1–A3	8.14	8.26	8.38	8.50	8.62
A4	0.50	0.50	0.50	0.50	0.51
A5	0.44	0.44	0.44	0.44	0.44
B4	2.16	2.40	2.64	2.87	3.11
B6	15.74	14.61	13.88	13.23	12.63
C1–C4	0.66	0.66	0.66	0.66	0.66
CF (total)	**27.65**	**26.88**	**26.51**	**26.21**	**25.97**
reduction (%)	0	2.79	4.13	5.20	6.08
D	-1.72	-1.72	-1.72	-1.72	-1.72

Table 40. The impact of photovoltaic system size in a timber-frame building with ground source heat pump.

$kgCO_{2e}/m^2a$	Wood frame, GSHP				
Scenario	**GSHP-1**	**GSHP-2**	**GSHP-3**	**GSW-4**	**GSHP-5**
Nr of PV panels	0	48	96	144	192
A1–A3	8.14	8.26	8.38	8.50	8.62
A4	0.50	0.50	0.50	0.50	0.51
A5	0.44	0.44	0.44	0.44	0.44
B4	2.16	2.40	2.64	2.87	3.11
B6	14.38	13.19	12.41	11.70	11.05
C1–C4	0.66	0.66	0.66	0.66	0.66
CF (total)	**26.29**	**25.46**	**25.03**	**24.67**	**24.38**
reduction (%)	4.93	7.92	9.46	10.76	11.81
D	-1.72	-1.72	-1.72	-1.72	-1.72

Table 41. The impact of photovoltaic system size in a concrete-frame building with district heating.

$kgCO_{2e}/m^2a$	Concrete frame, district heating				
Scenario	**C-1**	**C-2**	**C-3**	**C-4**	**C-5**
Nr of PV panels	0	48	96	144	192
A1–A3	8.81	8.93	9.05	9.17	9.28
A4	0.57	0.57	0.57	0.57	0.57
A5	0.38	0.38	0.38	0.38	0.38
B4	2.16	2.40	2.64	2.87	3.11
B6	15.44	14.33	13.60	12.94	12.43
C1–C4	0.70	0.70	0.70	0.70	0.70
CF (total)	**28.06**	**27.31**	**26.93**	**26.62**	**26.48**
reduction (%)	-1.48	1.24	2.61	3.71	4.25
D	-1.69	-1.69	-1.69	-1.69	-1.69

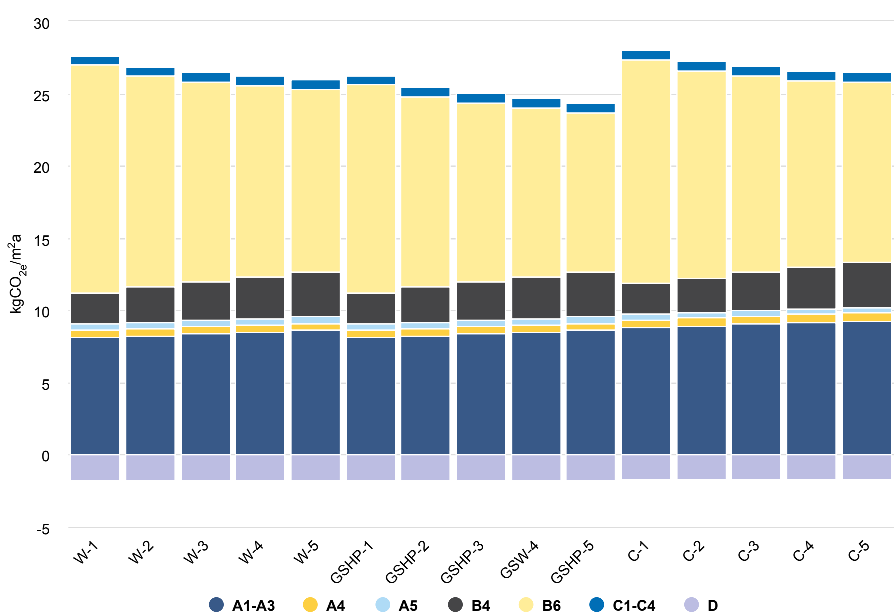

Figure 33. Building carbon footprint for various scenarios.

5.3.2 Sensitivity to emission scenarios

Estonia has one of the most carbon intensive energy grids of all IEA countries, due to the dominant role of oil shale (*põlevkivi*) in the energy sector (IEA 2019) (Figure 34). The current Estonian scenario is most likely subject to updates, because the existing factor data is not complete and is not based on the current climate neutrality commitment for 2050.

Figure 33 shows the current scenarios for the energy carriers in Estonia. Based on the results, applying GSHP instead of the district heating of Tallinn would reduce CF. However, the result is sensitive to the scenarios considering the decarbonisation of energy carriers. If the current scenario for the Estonian grid electricity is updated to better match with the climate commitments, the average factor for the next 50 years is likely reduced, and the results will be better for GSHP. Respectively, the benefits of PV will be reduced with the updated scenario, as the solar energy will replace less carbon-intensive grid electricity.

It should be further noticed that the Estonian scenario assumes no changes in the CO_{2e} emission factor for district heating. As in Finland, all district heating systems in the whole country are given one emission factor and one scenario, although in reality district heating systems apply different kind of fuels and technologies, and there may be great variation between the CO_{2e} emission factors of local district heating systems. Over the next 50 years, there will be also investments that improve the environmental performance of local district heating systems, but these are not taken into account in this scenario.

It should be also noted that the current scenario covers only the years from 2020 to 2070, and needs an update also for this reason. In this study, a linear development is assumed to continue in the emission factor for the Estonian grid electricity and district heating after 2070.

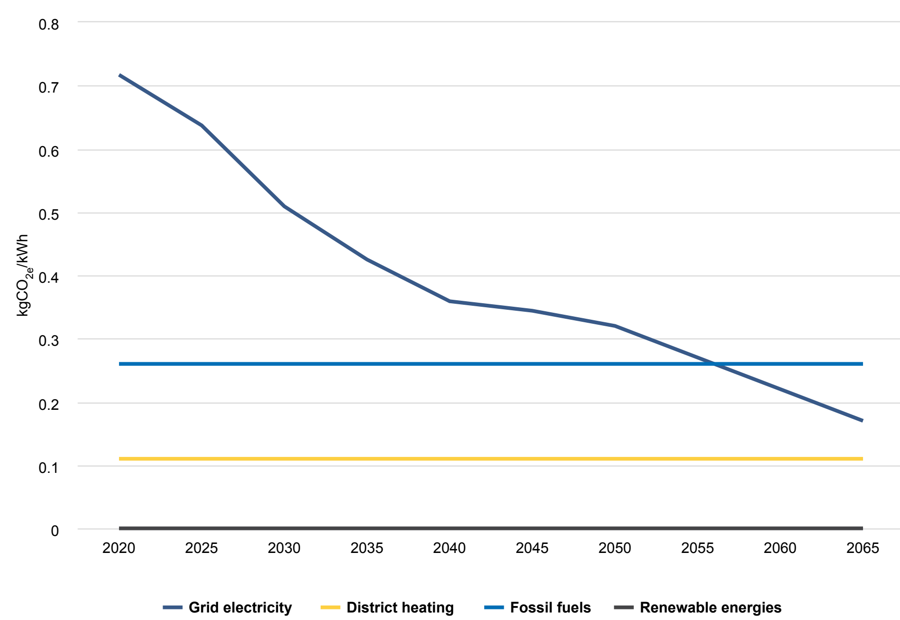

Figure 34. Current scenario for the decarbonisation of the grid electricity and district heating in Estonia (Mändmets & Štõkov 2021).

5.3.3 Key takeaways

Benefits of the utilization of old structures

Although the B6 module (operational energy use) tends to dominate the building CFs in Estonia, the utilization of old building structures shows a significant reduction potential in this study. Most of the savings are delivered by utilization of the existing underground concrete structures, the foundation and the test hall floor slab. The sandy soil in Mustamäe requires neither stabilization nor a heavy foundation. Solutions designed for a more difficult soil type, such as a pile foundation, would mean even higher savings.

Benefits of on-site solar electricity production

The energy consumption profile applied for the study follows the Estonian standard for educational buildings, which assumes that during the summer season the use is only 10% of the usual. Despite this assumption, the Estonian case study shows that with carbon-intensive grid electricity, the benefits of on-site renewable electricity production are obvious for CF. As the grid electricity emission factor is expected to rapidly decline, the major benefits of PV investment materialize during the service life of the first PV system (25 years), before the first replacement. This fact becomes visible when the results are examined annually, applying the annual expected EF for grid electricity instead of the 50- year average. According to the current scenario, the average annual CO_{2e} emission factor for the Estonian grid electricity is 0.485 $kgCO_{2e}$/kWh for 2021–2046 and 0.237 $kgCO_{2e}$/kWh for 2047–2072.

The embodied emissions of PV systems remain the same, even if the orientation of the panels would not be optimal. Thus, the orientation and shading of the PV system are crucial for the environmental benefits and the carbon balance between the embodied emissions and the emissions from operational energy. Poorly oriented or shaded systems have the same embodied emissions but less output to compensate the carbon-intensive grid electricity.

With the consumption profile of Mäemaja (educational building), demand side management (DSM), aiming at better load match, would make better use of the PV investment and further reduce the building CF. Although the excess energy is only reported in module D and excluded from the carbon footprint of a building, it may be beneficial in a wider context.

Energy scenarios

There is great variation in the CO_{2e} emission factors of national electricity grids and the assumptions regarding their future developments. The results of LCA are highly sensitive to these underlying assumptions.

The CFs of Estonian buildings are dominated by the B6 module (operational energy use) based on delivered energy. It would be possible to follow the standard EN 15978 (or the LEVEL(S) framework) and apply no scenarios for energy carriers, but in that case the energy-related emissions would dominate the CF result even more, and the share of material-related climate impacts would be most likely seriously underestimated over the life of the building. The national scenarios for energy carriers are created with different kinds of assumptions, and already after a 10-year time horizon, development is very difficult to predict.

The CF analysis of the Mäemaja building seems to confirm that specification of load-bearing materials and on-site renewable energy generation are viable measures to reduce the building CF, also in the Estonian context. The weight of material-related emissions is naturally higher in countries with a lower CO_{2e} emissions for grid electricity.

Although the energy scenario assumes a major reduction in the future emission factor for electricity, this is not taken into account in the emissions accounted for material replacements. Grid electricity consumption is one component in the processes that are assessed, and therefore in reality any reductions in the grid electricity emission factor will reduce also the emissions of future material replacements and related transportation. Material replacements also have a service life that often exceeds the 50-year life span of the building. In this respect, the Norwegian FutureBuilt ZERO method seems more accurate methodology than most national LCA frameworks.

6. Conclusions from the case studies

As expected, direct comparisons between Finnish, Estonian and Norwegian cases are not feasible, because of the differences in assessment methods. The methodologies have different calculation periods (Finland and Estonia 50 years, Norway 60 years) and emission profiles. The three case-study countries are good examples of differing electricity emission profiles: Norway has very high renewable share in electricity production, while Estonia has high share of fossil-based production. Finland falls between these two. Norwegian FutureBuilt ZERO method employs time-weighting of emissions, while the Finnish and Estonian methods or the Norwegian NS 3720 method do not. Comparable results could be achieved for example by applying the LEVEL(S) methodology for all case studies.

Despite the methodological differences, the building CFs fall roughly within the same range. In the Finnish basic new consruction scenario, the building CF is **15.43 $kgCO_{2e}/m^2a$**. In the Norwegian new construction scenario, assessed without re-use and with the NS 3720 method, the building CF is **20.65 $kgCO_{2e}/m^2a$,** which is 34% higher than the Finnish result. Although both case study buildings are multi-storey office buildings, they differ from each other in design, and part of the difference in their CFs stems from the different building designs. However, a substantial part of the variation likely results from the assessment methods. The Norwegian basic case assumes European electricity emission scenario, which has higher CO_2 emissions than in the Finnish national method. When the Norwegian assessment is performed with the Norwegian electricity mix, the building CF is brought down to **13.45 $kgCO_{2e}/m^2a$**, which is 13% lower than in the Finnish case study. The Estonian case differs slightly from the two others in functionality: in addition to office spaces, it also includes a test hall and auditoriums. As an educational building, its energy use profile differs from office buildings. The CF of the Estonian case study (as-built) is **22.32 $kgCO_{2e}/m^2a$.** Replacing the district heating system with a ground source heat pump would further reduce the CF down to **20.93 $kgCO_{2e}/m^2a$.**

The most striking contrast between the Finnish and the Norwegian cases is the effect from the building material re-use. In the Norwegian case, re-used construction materials helped to lower the new construction climate impact by **20%**. This was made possible by employing a substantial amount of re-used materials: they totalled 34% of material weight, and included load-bearing structures. This is in contrast to the Finnish case, where the currently foreseeable re-use of materials is limited to a small number of doors and internal wall elements. Such small-scale re-use is not expected to impact the building carbon footprint. In the more comprehensive – and more speculative – re-use scenario, the impact was increased to **2%**. The Estonian case study made use of the existing foundation and an extremely thick concrete floor slab of the former test hall.

The important takeaway message is that in the Norwegian case study, material re-use was realized to a very comprehensive degree, and the design for re-use was incorporated into the project from the start. The Norwegian case study building is already erected, and the CF calculation was based on actual material and product choices. This is an encouraging circularity example for other countries: re-use of building materials can bring about a siginificant decrease in building climate impact, first through pilot projects and later on hopefully as a matter of course. In a different context and with a different assessment method, the impact of re-use may not be exactly 20%, but it has the potential to be much more signicifant than 2%.

Encouragement can be found also from the Finnish case study: if an existing building can be renovated and its life-time extended, the emission savings could be up to 28% or more, depending on the chosen renovation option. A new construction with very extensive building part re-use is not possible in every case, but in many cases the existing building might be saved, or at least the building frame spared. This is an option that should be explored first and foremost, because it is higher on the circularity hierarchy. If new construction is absolutely necessary, choosing wood as the frame material also has potential for significant emission reductions.

Energy choices also play an important role in a low-carbon building construction. All three case studies considered utilizing a ground-source heat pump for heat production, and PV systems to cover part of the electricity need. When considering the energy options, it is evident that the assessment method plays a large role in shaping the results.

In the Finnish case study, the embodied emissions of the PV system cancel out the emissions savings during the use phase, and the effect on the building CF is **0%**. This happens because the emissions from the Finnish electricity mix are low to start with, and projected to diminish in the future. If the emissions are assumed to continue at the present-day level, PV installation lowers the building CF by **3%**. With the current emission scenario, the PV system of the Estonian case study reduces the building CF by **6%,** although only 52% of the total annual output is used in the building. In the Norwegian case study, higher (European mix) emissions are assumed for the electricity, and with such a methodology solar PV can bring about savings of **4–6%**. However, when assuming the domestic Norwegian electricity mix and subsequent emissions, the solar PV installation increases the building CF by **5%.**

All case studies demonstrate that the usefulness of PV in decreasing the building CF depends strongly on the chosen assessment method. However, in both cases it can be concluded that the use of PV systems may not lead to a very large decrease in life cycle greenhouse gas emission, at least not in countries where electricity emissions are low to start with. Norway is a prime example of such a country, producing 92% of its electricity by hydropower and wind[9]. Finland produces 69% of its electricity by hydropower, wind and nuclear power, and in total, more than 50% of Finland's electricity is renewable[10].

The case of solar PV is a good example why the whole life-cycle assessment is essential for developing truly low-carbon building sector. When the building energy demand is assessed alone, solar PV installations are automatically beneficial, because they lower the need for delivered energy. The benefit is not as clear, when the embodied emissions are included in the assessment: indeed, the impact of solar

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9. https://www.statista.com/statistics/1025497/distribution-of-electricity-production-in-norway-by-source/
10. https://www.stat.fi/til/salatuo/2020/salatuo_2020_2021-11-02_tie_001_en.html

PV installation can turn from beneficial to harmful. From the climate point of view, solar PV is a safer choice in regions where the grid electricity has very high emissions, such as Estonia. Even in the Estonia case study, with a large solar PV system, the effect from solar PV alone – a reduction of 6% – is not nearly enough to warrant a low-carbon building by itself. More solutions are needed, both in material and technology solutions.

The effect from low-carbon heating system is also very much dependent on the methodology, especially on the emission factors and scenarios employed for district heating. In the Finnish case study, ground-source heat pump solution decreases the building CF by **11%**, in comparison with district heating. In the Estonian case, the respective reduction would be **6%.** Assessed with the Norwegian NS 3720 method, GSHP does not decrease the building CF, but rather increases it by **6%**. The result stems from the very low emissions used for Oslo region district heating. Oslo district heating system has a high share of heat produced by waste incineration (64% in 2018[11]), and in the NS 3720 assessment, the emissions from waste incineration are allocated 100% in the waste sector. This results in very low overall emissions in district heating, which in turn does not encourace heating solutions relying on electricity. The Norwegian NS 3720 method, using the European mix for electricity and assigning all waste incineration emissions to waste sector, appears to be particularly unfavorable to heat pump -based solutions.

If the Norwegian case study buildind is assessed with the FutureBuilt ZERO method, where the waste incineration emissions are assigned to waste and energy sectors 50% / 50%, the heat pump case is altered. Now the effect of GSHP in the building CF is **-16%**, compared with district heating. This is closer to the Finnish result of -11%, which was attained by using the national average emissions for district heating. Clearly the choice of the method, and particularly the emission coefficients, has a profound effect on the heating system choice.

It should be remembered that the differences in results do not stem from merely technical details of calculation methods. When comparing the building CF assessments across different countries or regions, the energy systems are in fact physically different, and they may have different future outlooks due to the various national energy policies. This has a bearing on whether the circular economy actions and carbon emission savings are in synergy or involve trade-offs.

The solution with great potential for emission savings is preserving the old building as largely as possible, instead of constructing a new one. In the Finnish case study, this scenario decreased the building CF by **28%** or more, depending on the chosen renovation option. For this approach, circularity and low-carbon strategies are in synergy: preserving the load-bearing structures is beneficial for both material use and climate.

11. https://www.klimaoslo.no/2019/10/16/district-heating-from-sewage/

7. Public procurement highlights

In circular construction, the most important decisions are made in the preparation and planning of construction procurement. Thus, the ***needs assessment and planning*** are emphasized in circular public procurement. In the needs assessment, the public organization has a possibility to influence the preservation and/or renovation of the old building instead of demolition and constructing a new building. In the planning phase, decisive decisions are made about the need for space, the flexibility of the space, and the choice of materials. If the procuring unit acquires the planning from a consultant or similar, it must be ensured that the designer has sufficient expertise on circular economy solutions. Expertise is needed for example on the architectural and structural design, such as multipurpose facilities that can be modified. In addition, expertise on life-cycle modelling of the building as well as circular tendering criteria, are needed. The circular construction project itself may be complex, and stakeholders must be committed in early phase of the project. For example, land use planning supports circular and low-carbon building.

The expertise of a designer or a consultant can be clarified in advance, for example, by requesting information or references of the design of similar solutions. Despite this, public buyers or experts preparing the project and public tender competition rarely have all the relevant information available for a specific project or have enough time to carefully consider which procurement criteria or suitability requirements would best serve the desired outcome. Therefore, ***market analysis and dialogue*** are effective ways to get information on relevant solutions and bring the customer and the procurers together to consider how circular and low-carbon targets can be achieved in a construction project with a successful outcome. Market information is needed for example on construction products with recycled content or products that could replace their carbon-intensive counterparts, such as low-carbon concrete. The re-use of concrete, brick, steel and unprocessed lumber may already be possible from a safety or health point of view. However, the re-use of demolished components has to date faced challenges due to the of CE marking. (VNK, 2022)

Circular construction involves also other issues to be resolved. For example, who is responsible for the quality, chemical content and harmlessness of re-used products? The supplier shall also be able to demonstrate that the re-usable product is suitable for use and the characteristics required of the product are realized. It may also be time-wise challenging to organize the re-use of materials, i.e. the supply and demand may not always encounter. ***Interim storage and processing*** could be needed for re-used and released material on sites. Logistics is another matter; if re-used parts and materials are moved over long distances, more emissions might be emitted. Thus, other actors in addition to the procurer and supplier may be needed, such as a ***mass coordination***. This encompasses the balance of surplus construction material and soil that is released in sites and might be used in upcoming projects.

Advanced planning and assessment of expected benefits in terms of savings and reductions of CO_2 emissions is needed in all circular construction procurements. Carbon footprint calculations can be used to make comparisons. Advanced planning is important in order to direct the effort on real impacts that really matter in terms of material and emission savings, instead of paying attention to detail.

It is recommended that extending the lifetime of existing buildings is explored first and foremost. If saving the existing building frame is not feasible, only then effort should be directed into re-using building parts in new construction. For the new construction, the choices of main building material and main heating system are likely much more significant – at least by an order of magnitude – than any limited re-use of building parts. If significant climate benefits are to be gained from circularity in new construction, re-use of building parts should be extensive, and encompass load-bearing structures. In such a case, circularity and re-use should guide the design process from the start.

A potential trade-off might take place between employing small-scale and large-scale solutions. If much time and energy are expended on advancing small-scale circularity, such as re-using individual building parts, there is a potential danger that this effort is absent from advancing the more significant solutions with bigger emission saving potential. Therefore, a holistic understanding of the impacts and benefits, is important. Based on that it is easier to determine the correct requirements, criteria and conditions for recyclable material in the calls for tender and contract. If there is no such information on benefits or impacts on circular solutions to emission reductions, it is worth focusing primarily on energy efficiency in the tender competition and award criteria. With energy efficiency solutions, emission reductions can be achieved in a more straightforward manner and with less effort. However, if there is a clear indication of benefits gained by circular solutions, they should be considered in the competition phase. In addition, circular components and parts already available in the market, should be addressed.

8. Concluding remarks

Circular public construction is receiving more attention and public procurers need objective information on the relation of low-carbon and circular construction. This information should be utilized in the procurement process i.e., to define sustainability objectives, set them as tendering criteria and to monitor the fulfillment of the criteria during the contract period. In addition, public procurers should understand the relation of a single public building to the overall areal planning and decision making. In our study, we focused on the synergies and trade-offs of building construction, but more studies could be needed to assess the synergies and trade-offs of construction in a broader scope also including the land use, traffic solutions and related functions of the building into the examination. This may include for example, the catering, cleaning and maintenance operation in a public building.

One reason why circular construction patterns have so far been relatively slow may be the lack of experience and information among procurers and suppliers on how to carry out a circular construction project. This study provided insights in to the circular and low-carbon aspects of public procurement. The managerial implication of the study is to show the importance of advanced planning in understanding the level of potential emission reductions, based on which the procurer can prioritize energy efficiency and circular solutions. First priority is to save the materials and preserve the construction that already exist, if possible. It may also be that the procurers have negative preconceptions about using products that are made of recycled materials, or these products simply do not exist on the market. Thus, public procurers need more information on the market possibilities and this information can be gained through market analysis and dialogue. Simultaneously, recycled products and materials as well as product specific data about emissions and other life-cycle based environmental data must also develop further. The increased use of low-carbon and circular procurement also depends on how the operating conditions develop. If an efficient service provider network or after-markets exist, circular procurement is more attractive. In addition, other impacts such as impacts on biodiversity should be considered.

Political initiatives (e.g. circular economy packages) as well as legislation will likely put pressure on market actors to introduce more circular and low-carbon planning solutions and circular construction products in the coming years. These initiatives emphasize the low-carbon and circular approach as a prominent part in the construction planning processes in public organizations. They also call for a life-cycle perspective when identifying significant environmental aspects and goals for construction procurement and procurement procedures. Thus, in the rapidly developing area there is a need for objective information and information providers such as procurement competence centres, e.g., KEINO.

To promote low-carbon and circular construction procurement and the systemic change towards circular economy and less use of raw materials, procurers will need to establish an ongoing market dialogue and collaboration with businesses and other actors. It is important to create circular economy -based new businesses and industrial value chains in which more companies are involved, as well as to develop related logistics (Alhola et al. 2019). Enhancing co-operation and dialogue between target groups in the planning and procurement of low-carbon and circular construction could be one of the priority areas in future Nordic co-operation. The Nordic countries could become frontrunners in low-carbon and circular construction and establish common guidelines for public procurement, as numerous procurement cases in this area already exist.

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Cases from Finland, Norway and Estonia

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