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ABSTRACT

A variety of life cycle assessment (LCA) calculation methods and rules exist in European countries for building performance evaluation based on new-build. However, the increased focus on the retention and renovation of the existing building stock raises questions about the appropriateness of these the methods and rules when applied to renovation cases. Using a real renovation case, Danish, Finnish and Swedish LCA-based greenhouse gas emissions (GHGe) assessments are assessed for how they position building renovation in relation to demolition and new-build reference values. The influence of these three different methods is examined for future development policies. Results show that upfront emissions for renovation are significantly lower for all approaches. The Swedish approach had the lowest GHG emissions compared with a scenario with demolition and new-build due to the method, which only includes upfront emissions of new materials. The Danish and Finnish renovation cases each performed worse in comparison with the new-build future emissions, specifically from operational energy use. Therefore, method development should consider incentives for upfront and future emissions. Furthermore, methods could account for the existing materials in the building, which are included in the Danish and Finnish approaches. This would provide incentive for renovation and reuse.

POLICY RELEVANCE

Future policymaking needs to consider the influence of LCA methods on climate impact assessment of building renovations. The temporal differences occur when renovation is compared with demolition and new-build. Policy needs to take account of these temporal differences for apportioning GHG emissions between upfront and future emissions. A key question is whether existing materials should be included in the assessment as this would incentivise the reuse of these materials. Differences in accounting for the impacts of biogenic carbon in materials yields different results. This is a key issue in carbon accounting and will influence future practice.

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building assessment method; building regulation; demolition; greenhouse gas (GHG) emissions; life cycle assessment (LCA); policymaking; refurbishment; renovation

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1. INTRODUCTION

The construction and operation of buildings are using vast amounts of resources and are accountable for 38% of greenhouse gas emissions (GHGe) globally (UNEP 2020). Hence, building and construction activities are important to reach policy targets for climate as well as circular material use (Giesekam *et al.* 2018). In recent years, climate considerations for buildings have expanded beyond operational energy use to include the embodied impacts of buildings. This is often addressed via standardised life cycle assessment (LCA), which is a commonly applied method for assessing life cycle embodied and operational environmental impacts (CEN 2012b). The LCA of buildings exists in several voluntary green building certification schemes, and recently mandatory life cycle-based climate declarations, have also become part of building regulations in several European countries, such as France, Sweden, Denmark and Finland (OneClickLCA 2022).

As part of preparing for regulation, each country defined context-specific methods and rules for how to conduct the building LCA, based on EN 15978 (CEN 2012b). Additionally, comprehensive research activities in each country have investigated the current performance of new buildings, *i.e.* statistically derived GHGe reference values for different building types. The reference values can serve as benchmarks to show the level of reference for new-builds. They can be further used in a policy context, where negotiated limit values may be introduced in regulation to specify the minimum performance requirements (Lützkendorf & Balouktsi 2023).

The LCA-based method and rules development in the Nordic countries of Sweden, Denmark and Finland have been characterised by a high level of knowledge exchange and explicit intentions for some level of harmonisation. However, each national approach, including its methods and rules definitions, is still very context specific due to preconditions of industry practices as well as applicability (Rasmussen & Birgisdóttir 2016). For instance, the scope of life cycle stages varies, as well as the scope of inventory elements to include in the assessment (Rasmussen *et al.* 2023). One thing that the Nordic approaches have in common, though, is the development focus on new buildings: each method is developed with regulation for new buildings in mind, and the complementary reference values are likewise associated with the performances of new-build. A key concern in the construction of new buildings is the high level of resources used and embodied GHGe emitted 'upfront', *i.e.* from production of materials, their transport and installation into the building (Birgisdottir *et al.* 2017; Röck *et al.* 2019). These upfront emissions are a direct threat to the immediate cuts in GHGe needed to keep the global temperature around 1.5°C (IPCC 2023). Strategies for reducing GHGe from the building and construction activities thus have the upfront emissions as well as the whole life cycle perspective to take into account.

Recently, the focus is starting to change from new-build to renovation of existing constructions. Agendas of circular economy and net-zero GHGe are widely being set as a basis for European Union policy initiatives for more sustainable construction (Kylili & Fokaides 2017; Sala *et al.* 2021), pushing towards increased importance of building renovation as a key strategy to reduce impacts rapidly. Examples of this are the Renovation Wave initiatives and the revised Energy Performance in Buildings Directive where LCA-based whole-life carbon assessments are introduced alongside the establishment of Renovation Passports for existing buildings (European Commission 2020, 2021).

A growing number of scientific publications present LCA-based assessments of building renovations (Fahlstedt *et al.* 2022). Typically, the studies assess renovation cases in their own right (Galimshina *et al.* 2022; Ghose *et al.* 2017; Shirazi & Ashuri 2020) or compared with reference numbers from new-build (Marique & Rossi 2018; Schwartz *et al.* 2018). Key methodological issues have also been highlighted in the existing literature, such as those concerning the allocation of impacts between systems (Hasik *et al.* 2019; Obrecht *et al.* 2021; Zimmermann *et al.* 2022), or the environmental payback times of material investments (Asdrubali *et al.* 2019; Brown *et al.* 2014; Passer *et al.* 2016; Valančius *et al.* 2018). However, it has not been investigated in detail to what degree the current national LCA-based approaches developed for new-build are fit for use in GHGe assessments of renovations. There may be challenges in the methods and rules definitions that are specifically challenging when assessing renovation. With the increased focus on integrating LCA requirements in building legislation, assessments of renovation projects are still an evolving field of practice and policy, and the limits and incentives in renovation LCA for policymaking are not apparent in the current literature.

The aim of this paper is to analyse how the existing Swedish, Danish and Finnish approaches to LCA-based GHGe assessments perform in renovation projects, to investigate their influence on renovation versus demolition and new-build, and to reflect upon methodological challenges specific to the renovation context.

The scope of LCA approaches for analysis are set to the Nordic countries of Denmark, Sweden and Finland as an example of a region where methodological coordination and knowledge-sharing have been an explicit focus of the policymaking. The scope of the three countries enables a geographically equivalent context, since climatic conditions and building practice are similar in Denmark and in the southern areas of Sweden and Finland. Thus, in this study a generic refurbishment case for energy demand reductions in a multi-family building is assessed with the three different LCA-based approaches used in the three regulations, respectively. The results are analysed and discussed to answer the following research questions:

- How does the renovation case position itself against demolition and new-build in the three approaches?
- Which method-related aspects concerning upfront and future GHGe are important to highlight for future development of methods?

2. METHODS

LCA-based GHGe assessment is performed on a building renovation case. The assessment is carried out by using the Swedish, Danish and Finnish LCA approaches, all of which are still under development. These approaches are used to investigate how the case positions itself against demolition and new-build. The performance level of the new-build is statistically derived reference values from the respective countries.

The study compares the steering effects and incentives for renovation promoted by the different approaches. The national LCA-based approaches have inherent differences, and it falls outside the scope of this study to discuss the method-related differences in absolute values between the three different approaches. However, key methodological aspects of the approaches will be discussed and considered for future development.

2.1 ASSESSMENT METHOD ACCORDING TO THE NATIONAL APPROACHES

The European standard EN 15978 (CEN 2012b) is followed for assessing GHGe due to buildings' life cycle. The standard focuses on the impact category global warming potential (GWP), also referred to as climate impact. This impact category has a large political focus and is the most used in legislation (Butera *et al.* 2021). The national approaches used in this paper include the following:

- The 'Swedish approach' is the method for GHGe assessment for the climate declaration for new-build, in effect from 1 January 2022 (The Swedish Parliament 2021). There are currently no requirements for renovation in legislation, but it was chosen to use the same limited scope (modules A1–A5) and method to define the Swedish approach in this paper.
- The 'Danish approach' follows the method from the voluntary sustainability class for new-build and renovation in Denmark (Danish Transport Construction and Housing Authority 2020).
- The 'Finnish approach' is the proposed method (Ministry of the Environment 2022) for a mandatory climate declaration for new-build or deep renovation projects, which will be required from 2025 onwards.

Note that the national approaches are all subject to ongoing development and changes, in terms of both methodological configurations and background data for assessments. The investigation for this paper thus reflects the state of play for the approaches in use at the beginning of 2023. The approaches represent three levels of completeness in terms of both life cycles stages and the type of building components (existing and new materials) included in the assessment. This is illustrated in Table 1, which shows the life cycle stages included in the three national approaches. Table 2 describes the assessment methods for each approach based on the standard EN 15978 (CEN 2012b). It describes the methodological choices and calculation rules that are specific to the three approaches.

2.2 DESCRIPTION OF THE RENOVATION CASE

The case consists of a group of multifamily building blocks with a concrete structure from 1972. Details on the building properties can be found in Table 3. The buildings were renovated for energy efficiency purposes, and balconies expanded. The renovation project also included the removal of asbestos from the parapets. All renovation actions are listed in Table 4. All quantities from new materials can be found in the supplemental data online. This case is a real renovation project of Danish building blocks and was selected for the comparative analysis because it is considered representative for all three countries (Denmark, Sweden, Finland), as a generic multifamily building from the 1970s using prefabricated concrete elements. Furthermore, the renovation actions are typical of the construction type and commonly undertaken in all compared countries. The energy use of the building is based on the Danish energy demand calculation (Danish Building Regulations 2023) for the Danish climate. The energy use before and after renovation is listed in Table 5.

2.3 ASSESSMENT OF THE RENOVATION CASE:

As previously explained, the national methods presented in Table 2 were followed to perform the GHGe assessments. However, the details of the case described above demand modelling adjustments of the national approaches. Further specifications on the modeling are presented in Table 6, and quantities from new and existing materials are in the supplemental data online.

2.4 COMPARISON WITH DEMOLITION AND NEW-BUILD

To understand how the renovation case compares with demolition and new-build, a comparable 'demolition and new-build' scenario is developed. This is done by using statistically derived reference values for new-build based on representative case samples in each country under study (Table 7). Reference values refer to values aiming at neutrally representing current new-build climate performance in the study countries (Malmqvist *et al.* 2023). To be consistent with each country's approach, these reference values were retrieved from published reports supervised by official institutions, in which the choice of statistical values considered to be representative are in line with the ISO (2021) standard. However, while the Finnish report (Granlund Oy 2021) communicates reference values using mean values, the Danish report (Zimmermann *et al.* 2021) communicates results with median values. The Swedish report communicates both mean and median values, which are almost identical (Malmqvist *et al.* 2023).

The reference values also differ in the reference units in which they are communicated (Table 7). The Swedish approach uses gross floor area, the Finnish uses heated floor area, and the Danish uses a weighted combination of both. Furthermore, Denmark's and Finland's reference units are divided by the reference study period (RSP).

The method and unit differences in the national reference values means they are not easily compared. However, the purpose of this study is not to compare reference values, but to understand their influence on renovation projects within their national contexts. Therefore, the reference values are adjusted to the case building: the reference values are multiplied by the corresponding floor areas of the case and the RSP for the Danish and Finnish values. These case-specific reference values are shown in Table 7.

Table 1: Life cycle modules included in the national approaches in Sweden (SE), Denmark (DK), and Finland (FI).

Note: Existing materials area shown as 'disposed' and 'remaining' depending on if they are disposed as part of upfront emissions, or remain in the building after the renovation. Modules $C3_{di}$, $C4_{di}$ and D_{di} are used in the Danish approach to separate end-of-life emissions from disposed materials. In the Finnish approach, these are included in A5 and D.

New = new materials added in the renovation; Disposed = materials removed during the renovation process; Remaining = materials kept in the building after renovation; Op. energy = operational energy use of the building.

		WASTE PROCESS	DIS-POSAL	BENEFITS/ LOADS	PRODUCT STAGE	TRANS-PORT	CONSTRUC-TION	USE	MAINTEN-ANCE	RE-PAIR	REPLACE-MENT	REFUR-BISHMENT	OP EN-ERGY USE	OP WATER USE	DECON-STRUCTION	TRANS-PORT	WASTE PROCESS	DIS-POSAL	BENEFITS/ LOADS
		$C3_{di}$	$C4_{di}$	D_{di}	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
SE	New																		
	Disposed																		
	Remaining																		
	Op. energy																		
DK	New																		
	Disposed																		
	Remaining																		
	Op. energy																		
FI	New																		
	Disposed																		
	Remaining																		
	Op. energy																		

Table 2: Assessment methods for renovation-life cycle assessment (LCA) using Swedish, Danish, and Finnish approaches.

Note: EoL = end-of-life; EPDs = environmental product declarations; LCIA = life cycle impact assessment; RSP = reference study period; SL = service lives.

	SWEDISH APPROACH	DANISH APPROACH	FINNISH APPROACH
RSP	Only includes upfront emissions. No need of the RSP	50 years	50 years
Transportation in construction (A4) for new materials	Use of standard values developed for the Swedish context connected to each product type to enhance representativeness (The Swedish National Board of Housing and Planning 2023)	Not part of the assessment for the building permit	Use of standard values depending on the transportation type developed using Finnish statistics and previous studies (Finnish Environment Institute 2023)
Construction (A5)	Consideration of the waste on site of the new materials. No packages. Only consideration of the production and transport, not the EoL processes. Available in the database (The Swedish National Board of Housing and Planning 2023)	Not part of the assessment at the building permit	Includes waste and energy use on the building site in accordance with EN 15804 (Finnish Environment Institute 2023)
Replacement scenario (B4) for new materials	Not included	Considered based on the SL of building elements from the build report (Haugbølle *et al.* 2021)	Considered based on the SL available in the database (Finnish Environment Institute 2023)
Replacement scenario (B4) for remaining materials	Not included	Based on the remaining SL and RSP	Based on the RSP
Energy use in operation (B6)	Not included	**Energy use based on Energy Performance Certificates**	
		GHGe intensity/kWh or /MJ from COWI (2020). Standard values, which include the energy decarbonisation scenario 2020–40, represent national district heating and electricity	GHGe intensity/kWh or /MJ from the database. Standard values, which include the energy decarbonisation scenario 2020–2120, represent national district heating, district cooling and electricity (Finnish Environment Institute 2023)
Deconstruction and demolition (C1)	Not included	Not included	Typical values based on Finnish previous studies. (Finnish Environment Institute 2023)
Transportation in EoL (C2) for new and remaining materials	Not included	Not included	The final result is calculated in terms of kg CO_2e/m^2 based on the case-specific volumes of demolition waste and with the help of CO2DATA for transportation (Finnish Environment Institute 2023)
Benefits and loads beyond the system boundaries (D) for new and remaining materials	Not included	Available in the database. Include benefits of reuse, recycling and energy recovery; and surplus renewable energy	Available in the database. Include benefits of reuse, recycling and energy recovery; long-term carbon storages; carbonation and surplus renewable energy
Background database (GHGe intensity of construction products)	Boverket database (use of conservative data). The value is based on the weighted average from existing EPDs (The Swedish National Board of Housing and Planning 2023). It is also possible to use EPDs for specific products	GEN_DK: an extract of generic data from the Ökobau 2021 LCIA database combined with Danish average EPDs from industry associations (Danish Housing and Planning Authority 2023). It is also possible to use EPDs for specific products	National GHGe database for construction (use of conservative data). The value is based on the weighted average from existing EPDs (Finnish Environment Institute 2023). It is also possible to use EPDs for specific products

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Table 3: Properties of the renovation case building.

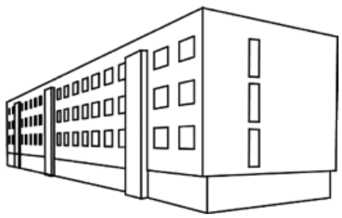
RENDERING OF THE BUILDING AFTER RENOVATION	BUILDING PROPERTIES		COMMENTS
	Gross floor area	41,255 m^2	Gross area is measured from the outside of the external walls and includes the basement
	Heated floor area	32,234 m^2	Heated floor is measured from the outside of the external walls
	Floors	4 (including ground floor)	Ground floor is mostly unheated, floors 1–3 are heated
	Basement	1,414 m^2	
	Heating system	District heating	

Table 4: Description of the renovation actions.

		DESCRIPTION	NEW MATERIALS ADDED IN THE RENOVATION
Roof	Roofing	New roofing on staircase towers and balcony towers	Roofing felt (two layers)
	Attic	Insulation in attic	300 mm mineral wool
	Eaves	Replacement of eaves	Construction wood Plywood
Balconies	Balconies	Expansion of balconies and enclosing them in glass (not heated).	Fibre-reinforced concrete and plaster for the balcony extension Light walls with zinc, steel, fibre cement board and paint Mineral wool under the lower balconies Safety glass for closing off the balcony
External walls	Staircase towers	Replacing outer walls (light walls)	Steel Fibre cement board 195 mm mineral wool Vapour barrier 50 mm mineral wool Gypsum (three layers) Paint
	External walls	Insulation of the external walls	100–160 mm mineral wool (for the facade) Plaster
Slabs	Flooring	New floors in the apartments and weather porch	Wooden floors with mineral wool Slate flooring and mortar
	Ceilings	Insulation in the ceiling of the unheated area on the ground floor. New ceilings in the staircase	Mineral wool Steel Fibre cement boards Paint Mineral wool acoustic ceilings
Windows	Windows and doors	Most windows and external doors are replaced	Thermal windows (three layers) Wood/aluminium window frame Slate window ledges Aluminium curtain wall for the staircase tower

Table 5: Calculated energy demand from heating, ventilation and hot water of the building before and after renovation per heated floor area.

	BEFORE (kWh/m^2/year)	AFTER (kWh/m^2/year)
Heating (district heating)	135.8	86.4
Electricity use	0.7	0.7

	SWEDISH APPROACH	DANISH APPROACH	FINNISH APPROACH
Product stage (A1–A3) for new materials	Inventory data are based on accessible data for the case. They include the building envelope, load-bearing structural parts, interior walls and internal surface layers		
Transportation in construction (A4 and C1) for new materials	–	Not included	Distance and transportation type based on background data (Häkkinen 2021)
Construction (A5)	Use of waste factor for each building product from the national database (The Swedish National Board of Housing and Planning 2023)	Not included	Construction site emissions based on the renovation case in the background data (Finnish Environment Institute 2021)
Replacement scenario (B4) for the remaining materials	Not included	If the material provides a structural function, then service life = reference study period, otherwise same service life as the new material	
Energy use in operation (B6)	Not included	Energy use based on the energy demand calculation for the Danish context (Danish Building Regulations 2023)	
Deconstruction and demolition (C1)	Not included	Not included	Standard value for the demolition of residential buildings from the national database is used
Waste processing and disposal (C3–C4) for new and remaining materials	Not included	Does not include end of life of the existing building services, as these inventory data were not available	
Benefits and loads beyond the system boundaries (D) for new and remaining materials	Not included	–	Include the recycling of steel and long-term biogenic or technical carbon storage

Table 6: Detailing of the modeling used in the GHGe assessment of the renovation case.

Note: For quantities of materials, see the supplemental data online.

Finally, the alternative scenario to renovation not only includes building new but also the demolition of the existing building. Therefore, the GHGe from demolition of the case building calculated following the national approaches are added to the reference value for Finland and Denmark (Table 7). It is not included for Swedish values, as the system boundaries in the Swedish approach do not include existing materials. The Danish and Finnish renovation approaches already include the end-of-life (EoL) of all the building elements of the already existing building as part of the system boundaries of the renovation case (spread across the life cycle) (Table 4). Consequently, it is necessary to include demolition of the existing building in the 'demolition and new-build' scenario to ensure comparability.

3. RESULTS

Results show how the renovation case performs compared with the reference GHGe values for new-build, and investigates differences related to the timing of emissions, and the inclusion of existing materials. These are key aspects where the results differ between demolition and new-build and renovation and are therefore important for the continued development of method and regulation.

3.1 RENOVATION VERSUS DEMOLITION AND NEW-BUILD

Following the objective of this study, this first result section introduces the results of the renovation case compared with the 'demolition and new-build' scenario defined in subsection 2.4.

All national approaches perform better for the renovation case than for new-build and demolition. However, the approaches give significantly different results for the renovation case, as well as their result compared with the reference value. This can be seen in Figure 1, which shows how the renovation case positions itself against demolition and new-build for the three national approaches.

	VALUE TYPE	STAGES	ORIGINAL REFERENCE VALUE	CASE-SPECIFIC REFERENCE VALUE (10^3 ton CO_2-eq)	REFERENCES
			(kg CO_2-eq/m^2)[a]		
Sweden	Mean (new-build)	A1–A5	368	15.2	Malmqvist *et al.* (2023)
			(kg CO_2-eq/m^2/year)[b]		
	Demolition of existing building	*C3, C4*	–	*2.4*	*From case*
Denmark	Median (new-build)	A1–A3, B4, B6, C3–C4	9.5	18.4	Zimmermann *et al.* (2021)
	Median for modules (new-build)	A1–A3	5.4	11.2	Nielsen *et al.* (2022)
		B4	0.9	1.9	
		B6	2.6	4.2	
		C3, C4	1.0	2.1	
			(kg CO_2-eq/m^2/year)[c]		
	Demolition of existing building	*C1–C4*	–	*4.1*	*From case*
Finland	Mean (new-build)	A1–A5, B4, B6, C1–C4	16	25.8	Granlund Oy (2021)
	Mean for modules (new-build)	A1–A5	7	11.3	
		B4, B6	5	8.1	
		C1–C4	4	6.4	

Table 7: Original and case specific reference values for new-build and demolition of existing building for the different life cycle stages.

Note: [a] Reference unit based on gross floor area.

[b] Reference unit based on gross floor area for material impact and heated floor area for operational energy use. Based on a 50-year reference service period.

[c] Reference unit based on heated floor area and the 50-year reference study period.

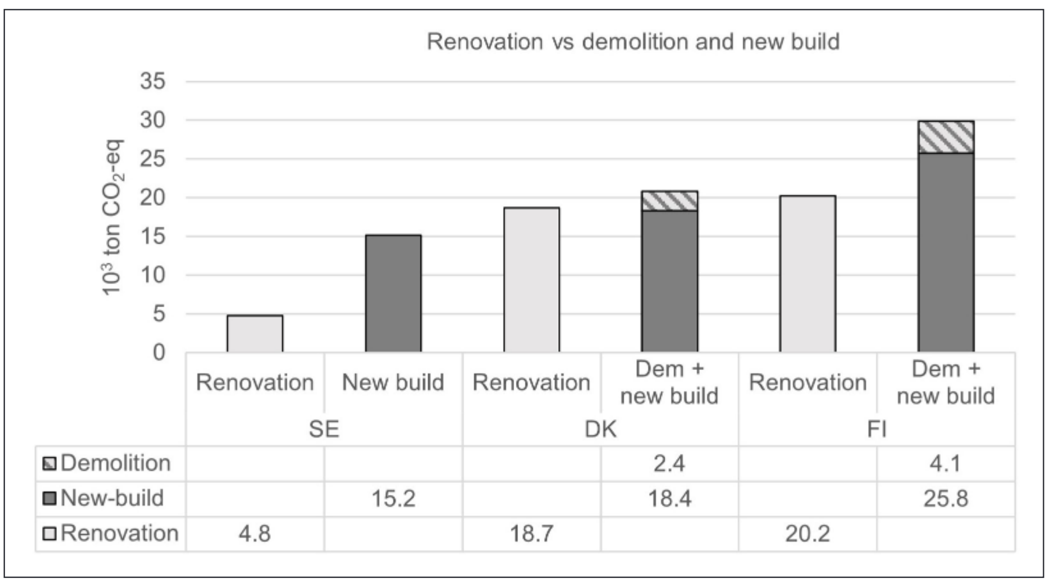


Figure 1: Results from the renovation case compared with demolition ('dem') and new-build reference values over 50 years.

The Swedish approach on the renovation case has the lowest GHGe of the three national approaches. The Swedish approach also gives the best relative performance of the renovation case compared with the reference values for new-build, with 68% lower GHGe from the renovation. The Finnish approach has the overall highest GHGe, and the renovation case results are 32% below the reference values for new-build and demolition. The Danish approach gives slightly lower GHGe than the Finnish approach, but the renovation case results are just 10% below the reference value for new-build and demolition. For the Danish case, the reference values for new-build alone (without demolition) is lower than the GHGe from the renovation case. To understand how the methods affect the differences in the results, the next section will consider the GHGe calculations over a time scale.

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3.2 TIMING OF EMISSIONS

When considering the temporal perspective of GHGe, it becomes easier to understand the differences in the results of the national approaches and their performance compared with new-build. Figure 2a shows the GHGe over time for the renovation case and the reference value for each approach. Figure 2b shows the contribution from building products (embodied impacts) and operational energy use (operational impacts) from upfront and future GHGe compared with the reference value for each approach.

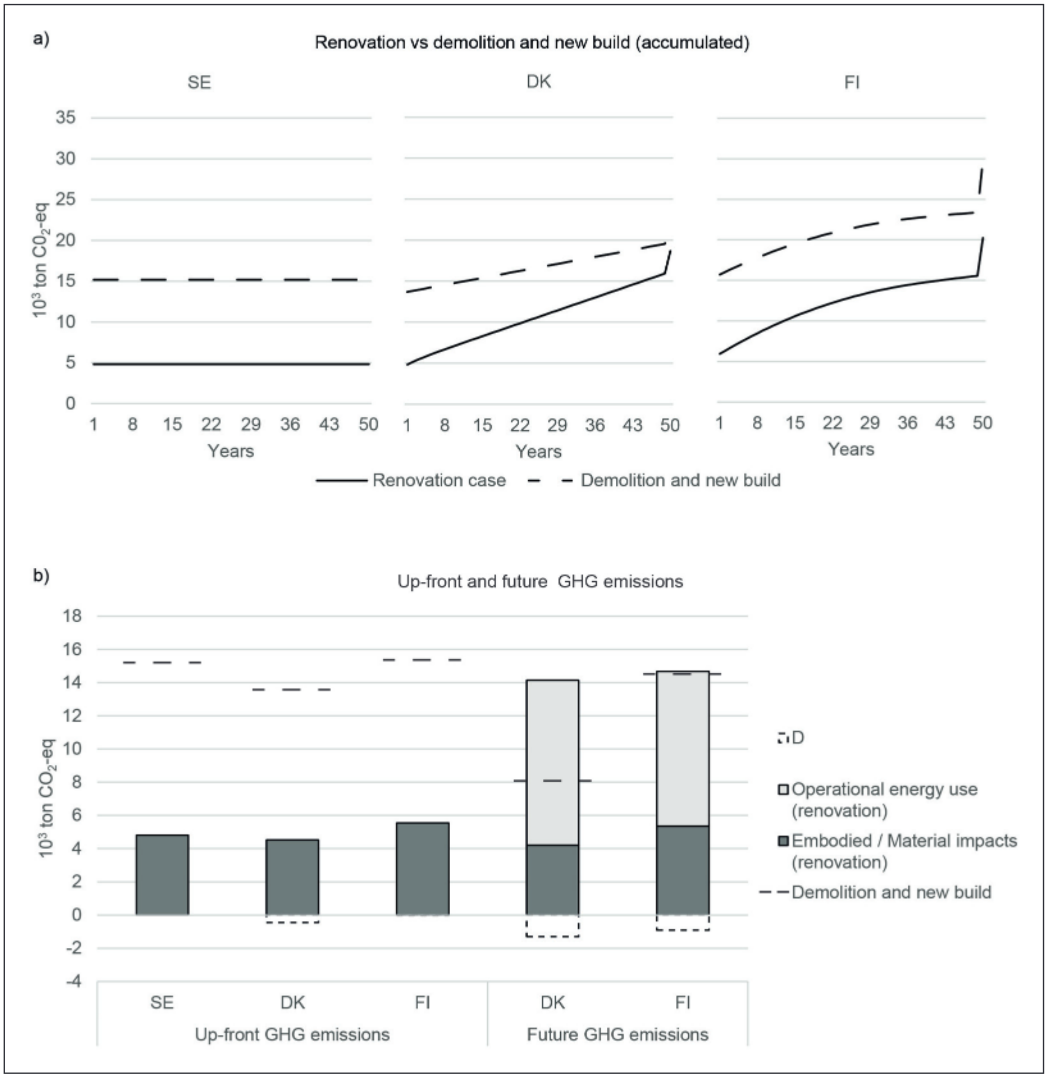

Figure 2: Temporal differences between renovation and new-build for embodied and operational impacts.

Note: (a) Greenhouse gas emissions (GHGe) from the case accumulated over time compared with demolition and new-build; and (b) what contributes to the impacts over time. Loads and benefits beyond the system boundaries (stage D) are shown as negative at the time they occur.

Figure 2 shows that for all countries, the renovation case has significantly smaller GHGe the first year (upfront emissions) in comparison with the reference value. Upfront emissions do not vary significantly across the national approaches. The reason upfront emissions are lower for renovation is due to less disposal of existing building components and hence less needed production of new materials. The Danish and Finnish approaches include the use stage (years 1–49). Here, the renovation case performs worse than the scenario based on reference values. Though the renovation case includes many energy-retrofitting actions, Figure 2b shows that the GHGe from energy for this case is still higher for the renovation case than for new-build, especially for the

Danish approach. Year 50 in Figure 2a shows that EoL emissions for the renovation case are similar to reference values for new-build for both Denmark and Finland. This could be expected as both the reference values and the renovation case consider the EoL of the whole building following the assessment method for the national approaches. Figure 2b shows that the main contributor to future emissions (years 1–50) for the renovation case is the operational energy use of the building. Thus, the contribution of future emissions—in particular from the operational energy use—is the reason the performance of the renovation case performs worse for the Danish and Finnish approaches compared with the Swedish approach in Figure 1.

3.3 UPFRONT EMISSIONS

Though the results appear similar for upfront emissions across the national approaches in Figure 2, the results detailed according to the contribution of life cycle stages of different material types (new versus disposed) of upfront emissions are different. Figure 3 shows the upfront emissions of the renovation case for the three approaches. The upfront emissions consist of emissions from the 'new materials' installed in the building, and the emissions due to the EoL processes of disposed materials. These are considered in modules C3 and C4 in the Danish approach and in A5 in the Finnish approach (Figure 3) as long as the materials have the status of 'waste' (CEN 2019).

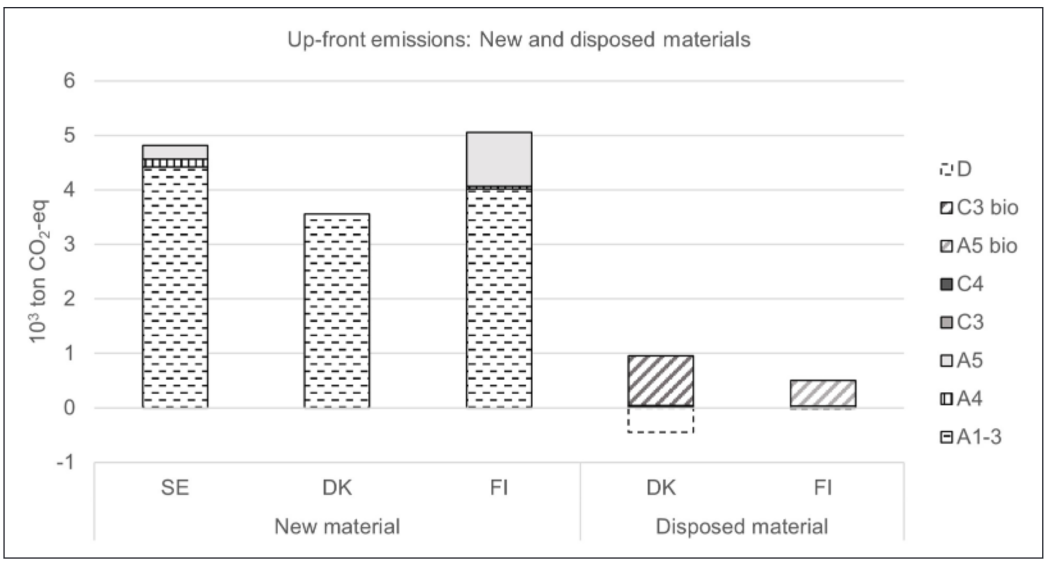

Figure 3: Upfront embodied emissions from new and disposed materials using Swedish (SE), Danish (DK) and Finnish (FI) calculation approaches.

Note: A large part of the emissions are from biogenic material ('C3 bio' and 'A5 bio'), where end-of-life (EoL) processes only include the emissions of biogenic CO_2.

Results show that the GHGe due to the production of new materials (A1–A3) are significantly lower for the Danish and Finnish approach than for the Swedish approach. This is mainly due to the differences in the databases of handling the biogenic materials. Following EN15804+A1 and A2, respectively, the Danish and Finnish databases consider the removal of CO_2 into biomass as negative emissions during the product stage (stage A) and as positive emissions during EoL processes (CEN 2019). This results in zero net CO_2 emissions across the stages. The Swedish database does not include biogenic carbon since it only considers module A, resulting in higher emissions from new materials in the product stage. However, many of the biogenic materials are replaced; the upfront biogenic carbon is therefore close to neutral, leading to similar total values for the upfront emissions between the three approaches. Indeed, the EoL processes of the disposed materials contribute 21% of the upfront emissions for the Danish approach and 9% for the Finnish approach. Of these impacts, 95% and 94% come from materials with the release of biogenic carbon such as wood flooring or window frames for Denmark and Finland, respectively. For the assessment of disposed materials in renovation calculations, only EoL stages are included. Therefore, only the release of biogenic carbon is considered.

Figure 3 also displays module D, which captures the potential loads and benefits deriving from the recycling, energy recovery or reuse of the disposed products outside the system boundaries—

once the product is not considered as 'waste' anymore. Module D is not aggregated with other modules in the approaches studied and in current standards (CEN 2019). The assessments of module D vary significantly between the Danish and Finnish approaches: in the Danish approach it would correspond to 9% of upfront emission, if included, and less than 0% for the Finnish. This is because at the time of this study, the Finnish database only included benefits from the recycling of metals which are part of the Finnish 'carbon handprint' approach (Häkkinen *et al.* 2021). The Danish approach follows EN15804+A1 (CEN 2012a), thus including other recycling potential as well as energy recovery, which results in larger benefits.

4. DISCUSSION

The discussion addresses the potential influence that national approaches have in terms of the promotion of renovation or new-build, as well as method considerations for adaptations of the approaches to renovation projects.

4.1 RENOVATION VERSUS NEW-BUILD

The results for the case building showed that the Swedish approach provides the largest incentive to renovate the case building rather than building new. This is followed by the Finnish and then the Danish approach, which is just 9% lower than the reference value.

The significantly better performance of the renovation case in the Swedish approach is mainly due to the system boundaries, which only include upfront emissions. The results illustrate that this difference in system boundaries between the three approaches can lead to different incentives in practice. The Danish and Finnish inclusions of operational GHGe incentivise an increased focus on reducing these in a renovation case. This could encourage deeper renovations in order to reduce the operational energy use to match the level of new-build. On the other hand, the Swedish approach encourages low upfront material use independently of the extent and goal of the renovations. Another, more practical aspect is the benefit of a simpler calculation approach for the practitioner. The Swedish approach has the advantage of not accounting for any existing materials, as only new materials are included in the assessment, hence greatly reducing complexity.

4.2 REFERENCE VALUES USED FOR RENOVATION CASES

4.2.1 Demolition

For this study, the renovation case was compared with a scenario where a new building is constructed and the existing building is demolished. Reference values from previous studies were used for GHGe from new construction Danish and Finnish values, the value included GHGe from the demolition of the existing building, hence the associated disposal of materials. The inclusion of the latter proved to be important for the Danish comparison in this case (Figure 1), thus making the difference between whether renovation or new construction provided the lowest results of GHGe. This highlights the importance of system boundaries to ensure comparability between renovation and new-build. For instance, it is needed to include demolition in the reference value, when using approaches such as the Danish and the Finnish, where emissions from existing materials are included in the system boundaries of renovation.

This is specifically important at a time when limit values for new-build are also often applied to larger renovation projects (Lund *et al.* 2022). Again, the inclusion of demolition also complicates and adds to the workload. These calculations must be based on the specific case which demands a full inventory of the existing building or generic values need to be created.

4.2.2 Temporal differences

The results showed clear differences in the timing of emissions between the renovation case and the new-build scenario. The timing of emissions is important due to the need for immediate reduction of GHGe to keep the global temperature increase at 1.5°C. The new-build scenario has most GHGe upfront for all three national approaches. In contrast, most GHGe from the renovation case takes place during the modelled use and EoL stages as illustrated by the Danish and Finnish approaches. When all results are aggregated over the included life cycle modules, only the Swedish approach specifically incentivises the reduction of upfront emissions.

A possible way of incorporating the temporal perspective, while still including a life cycle perspective, is to report separately life cycle modules or divided into upfront and future emissions. This disaggregated reporting is illustrated in Figure 2b, and also demanded in the current Finnish and French regulations (Ministry of the Environment 2022; Ministère de la Transition écologique 2020). This can help give an incentive to reduce upfront emissions as a separate declaration.

4.3 EXISTING MATERIALS

The temporal perspective is also relevant when including existing materials of the renovation. The Danish and Finnish approaches include GHGe from the EoL processes of the disposed of materials during the renovation process, as well as the replacement and EoL processes of the 'remaining' materials kept in the renovated building. Including these existing materials can be relevant in providing incentives for reuse and recycling of existing materials:

- *Incentive for reuse on site*

  Onsite reuse of materials postpones upfront EoL emissions to future EoL emissions at the end of the buildings' service life This is only visible if a temporal perspective is considered. The results (Figure 2b) show that the inclusion of disposed materials' EoL has a considerable impact on upfront embodied emissions. However, the results also show that these emissions were mainly from bio-based materials. Therefore, the inclusion of existing materials will mainly incentivise the reuse of biogenic materials, which is further discussed below.

- *Incentive for reuse in other projects*

  Benefits from the reuse of disposed building materials are calculated outside of the system boundaries—in module D. Hence, only the emissions due to EoL recycling processes are included, but not the potential emission saving from recycling or reusing it in another system. However, these specific benefits happen around the time of the renovation activities, and thus could be considered in the upfront emissions. Development in data availability is, however, also needed if module D is intended to be included in the declaration to give incentive to encourage better reuse and recycling. Reuse in other projects can also simply be considered by not including any EoL processes for these products as proposed in the Finnish method (Ministry of the Environment 2022). Rewarding reuse and recycling should also be allowed only if such practices are truly implemented.

On a practical perspective, it should be considered if these incentives make up for the extra work that is also associated with mapping all the existing materials for the assessment. It is also relevant to consider whether the renovation project is responsible for the burden from the EoL of the existing materials that they have had no influence on choosing, as suggested by Hasik *et al.* (2019).

4.4 BIOGENIC MATERIALS

The inclusion of existing materials contributes to methodological challenges for biogenic materials. The results in Figure 3 show clear disadvantages in disposing biogenic materials compared with other materials. This is due to the methods used in the Danish and Finnish databases, which only consider the emissions of CO_2 from the biomass (since the uptake of biogenic CO_2 has happened at biomass growth, before the renovation and thus part of the preceding life cycle of the building). Though the same GHGe will apply to a possible demolition, the communication of results will be difficult, especially when compared with other renovation projects or new-build (without demolition). Here, buildings with a lot of biogenic material will have a disadvantage, and could be considered worse than new construction.

4.5 LIMITATIONS OF STUDY

The results in this study represent a snapshot of how methods are used at the time of writing this paper, but the methods are developing quickly, including changes in the databases used, and the definition of reference values. Thus, specific numbers reported for reference values and results in this study only have limited relevance in a long-term perspective. However, focus for the study has been the analyses of methodological challenges, which have a more persistent and general relevance.

Further, this study is based on a single renovation project to highlight the immediate challenges observed from the national approaches and the associated reference values. However, renovation projects vary significantly, also in the scale and purpose of the renovation, and may involve more technical installations, which was not a part of this assessment. Testing methods on other types of renovation cases may lead to additional methodological issues, and could thus be a topic for future research efforts.

5. CONCLUSIONS

This study explores how Danish, Finnish, and Swedish life cycle assessment (LCA)-based greenhouse gas emissions (GHGe) assessments perform for building renovations compared with new-build, and what steering effects they have. The study further investigates which method-related aspects are important to highlight for performance evaluation of renovations. This has been investigated by using a generic real case study to illustrate the three national approaches which have been developed in a similar geographical context and with a common focus on methodological coordination and knowledge-sharing.

Results show that the system boundaries (inclusion of the existing building materials in the assessment) as well as the timing of GHGe are aspects of specific relevance when comparing renovation with new-build. All approaches display lower upfront emissions for the renovation project compared with new-build. However, the inclusion of the future emissions in the Danish and Finnish approaches provided less incentive for renovation against new-build, compared with the Swedish approach, which only includes upfront emissions. This was particularly due to the difference in operational energy use between the renovation case and new construction. Furthermore, the inclusion of storage and release of biogenic carbon as well as disposed material leads to different results for the upfront emissions in the three approaches.

Accounting for existing material in climate declarations for the renovated building can incentivise reuse under the condition that upfront emissions are reported separately from future emissions. The inclusion of biogenic carbon, as advocated by the EN 15804 standard, can promote reuse, but also bears the risk of burdening renovation projects that have a high content of biogenic materials.

On a practical perspective, including the assessment of existing materials leads to significant additional workload in establishing the inventory. The tested national approaches do not currently provide an incentive for upfront reuse of disposed materials in other projects, since the potential benefits are considered to be outside the system boundaries (in 'module D'). However, the study also conveys that even if they are considered, data are currently lacking for end-of-life (EoL) and potential benefits from reusing materials.

The study demonstrates the relevance in considering the temporal perspective when comparing renovation with demolition and new-build. A suggested way of incorporating this temporal perspective is to ensure that GHGe are reported for individual life cycle modules in climate declaration regulations, or between upfront and future emissions. Such an approach is also relevant for potential development of limit values. Thus, the results can communicate on the potential temporal 'gains' from renovation while promoting the reuse of existing materials onsite. Development in methods towards more dynamic future scenarios could also highlight the importance of upfront emissions.

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COMPETING INTERESTS

The authors have no competing interests to declare.

DATA AVAILABILITY

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