Carbon Footprint Limits for Common Building Types – methodology update revision

Ministry of Environment, Finland

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Summary

This report analyses the carbon footprint of new Finnish buildings in accordance with the government's latest assessment methodology, published in 2021, and data from the national emissions database CO2data.fi. The aim is to set out recommendations for carbon footprint limits for nine different building use classes that will be affected by the new Building regulation and the associated climate declaration requirements. This analysis supersedes a previous study from the year 2021. Since then, the methodology has changed, and the availability and quality of data increased, thus an update was deemed necessary.

For this study, new building carbon footprints have been calculated using statistical data of Finnish building carbon footprint assessments from years 2020-2024 on the One Click LCA platform. The data was amended with averages where modules or values were missing. The statistical energy use of Finnish building stock from 2021–2023 has been analysed as part of whole life cycle carbon footprint of the buildings. To simulate a situation where only CO2data.fi was used, the data for selected key materials was adjusted by applying CO2data.fi carbon emission factors, even when Environmental Product Declarations (EPD) had been used on projects. To validate the results, reference buildings were created using One Click LCA's Carbon Designer 3D's Finnish reference building model using CO2data.fi data. The models were also used for sensitivity scenarios considering the decarbonization potential, as well as possible solutions that result in an increased carbon footprint compared to the baseline.

The resulting average Finnish building carbon footprint was between 14 and 23 kg $CO_2e/m^2/a$, for all building types, except hospitals, that had a higher footprint at 27 kg $CO_2e/m^2/a$. One Click LCA's reference building model resulted to carbon footprints 14 to 21 kg $CO_2e/m^2/a$, for all but hospitals, that were at 22 kg $CO_2e/m^2/a$. The slightly lower carbon footprint of the reference buildings is explained by their relative simplicity, and the resulting materials efficiency. Scenarios for assumed lower and higher performance were assessed for the modelled reference buildings to quantify the carbon increase/reduction potential from structural solutions and alternate energy performance. The decarbonisation measures gave a reduction potential of 1–31%. With a combined energy and material measure, carbon savings of 18–37% were obtained. The increase resulting from additional requirements, such as improved fire safety and less efficient energy profile, was between 8 and 19%.

The results of this study are summarised and recommendations on limit values are given at the end of the report. In the main body of the report, the carbon figures are presented as kg CO_2e/m^2 (before division with the assessment period of 50 y). This allows using integers for the whole report. For the limit value recommendation at the end of the report, the limit values are given in kg $CO_2e/m^2/a$ as per the method.

Tiivistelmä

Tämän raportin tavoitteena on asettaa suositukset uusien suomalaisten rakennusten hiilijalanjäljelle. Suositukset on laadittu laajan aineiston perusteella viimeisimmän vähähiilisyyden arviointimenetelmän ja kansallisen päästötietokannan CO2data.fi mukaisesti ottamalla huomioon myös vaikuttavia keinoja hiilijalanjäljen pienentämiseksi. Edellinen raportti julkaistiin 2021, ja tämän jälkeen metodologia on muuttunut, ja tiedon määrä ja laatu kasvanut merkittävästi, joten raja-arvosuositukset on syytä päivittää.

Tutkimuksen pohjana käytetään tilastollista dataa suomalaisten rakennusten hiilijalanjäljestä vuosilta 2020-2024 sekä suomalaisten rakennusten energiankäytöstä vuosilta 2021-2023. Raakadataa on muokattu keskiarvoilla puuttuvien lukujen ja moduulien kohdalla. Data on myös muokattu soveltuvin osin CO2data.fi-tietopisteiden kanssa yhteensopivaksi valitsemalla avainmateriaaleja ja laskemalla materiaalien sekä koko rakennuksen ilmastonlämpenemisvaikutus käyttäen CO2data.fi hiilikertoimia. Datan validoimikseksi ja rakennusten herkkyysanalyysiä varten on myös tehty One Click LCA:n Carbon Designer 3D-työkalun avulla mallinnettuja referenssirakennuksia, jotka hyödyntävät suomalaisille rakennuksille tyypillisiä rakenteita ja CO2data.fi-tietopisteitä.

Keskimääräinen suomalaisten rakennusten koko elinkaaren hiilijalanjälki oli 14–23 kg $CO_2e/m^2/a$ kaikille tarkasteltaville rakennustyypeille, paitsi sairaaloille, joiden hiilijalanjälki oli 27 kg $CO_2e/m^2/a$. One Click LCA:n referenssirakennusmallien hiilijalanjäljet olivat 14–21 kg $CO_2e/m^2/a$, sairaaloille 22 kg $CO_2e/m^2/a$. Referenssirakennusten hieman alempi hiilijalanjälki on seurausta mallien suhteellisesta yksinkertaisuudesta ja siitä johtuvasta materiaalitehokkuudesta. Mallinnetuille rakennuksille toteutettiin herkkyystarkastelua olettamalla rakenteellisia yksityiskohtia tai energiatehokkuuteen vaikuttavia tekijöitä, jotka joko pienensivät tai kasvattivat elinkaaren hiilijalanjälkeä. Näiden skenaarioiden perusteella hiilijalanjälki madaltui 1–31%. Suurimmat säästöt, 18–37%, saatiin materiaaliratkaisun ja energiatoimien yhteisvaikutuksella. Mallien, joille oletettiin lisävaatimuksia kuten korkeampi paloturvallisuus, hiilijalanjälki oli 8–19% suurempi kuin perusskenaarion.

Tämän tutkimuksen tulosten yhteenveto ja suositukset raja-arvoista annetaan raportin lopussa. Runkotekstissä lukuarvot on esitetty muodossa kg CO_2e/m^2 (ilman jakoa 50 vuoden laskentajaksolle) laskentatarkkuuden säilyttämiseksi. Raja-arvosuositukset annetaan lopulta muodossa kg $CO_2e/m^2/a$ rakennuksen vähähiilisyyden arvioinnin menetelmäohjeen (2021) mukaisesti.

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1 Introduction

The new building act will enter into force in January 2025. The measures to mitigate emissions originating from the built environment, most importantly the decree on climate declaration, has now been incorporated into the legislation (38 §). This decree will be included in the National Building Code of Finland and will be applied to the majority of new buildings. A whole life carbon footprint calculation must be provided, and the values need to be below the limits. This is in line with the new European Union Energy Efficiency of Buildings Directive that entered into force in May 2024.

A methodology for calculation of carbon footprint of buildings was made available already in 2017 and has been updated in 2019 and again in 2021. The latest update was given in a government proposal for altering the building act. The proposal suggests that limit values will apply to building use classes within the climate declaration requirement, only to new buildings, and only to the building itself (excluding the site). Certain factors related to the use class, location or technical requirements are also suggested to allow for flexibility from the suggested limit values.

This report describes the whole life carbon footprints of nine different building types representing the different use classes as per the decree on energy efficiency of a new building (1010/2017), further defined by the government proposal: rowhouses, multi-storey residential buildings, office and healthcare buildings, commercial buildings including libraries and congress buildings, accommodation buildings such as hotels and care homes, educational buildings, sports halls, hospitals, and other buildings with a net heated area (NHA) above 1000 m^2, including swimming halls and ice halls. The data for statistical embodied carbon footprint analysis is taken from the Carbon Heroes Benchmark program, describing actual Finnish projects. Energy use is based on statistical averages of Finnish building stock. Furthermore, reference buildings have been modelled using the Carbon Designer 3D tool to validate the statistical data and to facilitate creation of sensitivity scenarios, and to identify carbon reduction strategies and limit value flexibility. The results have been calculated with One Click LCA's Building low-carbon assessment tool, which is aligned with the draft version of the Method for whole life carbon assessment of buildings 2021, and using the data available at the time of writing. The latest method update to the decree on climate declaration and building part catalogue was released in June 2024, and the scope of assessment has been updated accordingly.

2 Statistical analysis of new building materials carbon footprint

2.1 Source of the new building materials carbon footprint data

The statistical data is from One Click LCA's Carbon Heroes Benchmark Program, using anonymous data derived from actual projects. The projects used for calculations are all located in Finland and dated between 2020-2024. The life cycle stages included in the data are A1-A3, A4, B4 and C1-C4. These data are created using a consistent background calculation mechanism, which standardizes life-cycle phases and assumptions. While the methodology for benchmarking is consistent, the projects do not have consistent scopes and potential underrepresentation of reported life cycle stages and building elements exists. The data was cleaned in several steps, where all projects not considered to be actual buildings (e.g. test and training projects), and projects with insufficient data from several queries were removed. Outliers were removed by accepting the 1-99th percentile of the remaining sample.

The sample sizes per building type are documented in Table 1. The division to building types follows the classification in the Ministry of Environment's Decree on building energy efficiency. As an exception to the classification, healthcare centres were counted as hospitals instead of office buildings due to difficulties in separating the two from raw data. Also, swimming and ice halls in class 9 were separated into their own group.

Table 1. Samples for statistical analysis.

Class (1010/2017)	Building type	Sample size	Buildings included
1d	Rowhouse	209	Attached and row houses
2	Residential	1201	Apartment buildings
3	Office	117	Office buildings
4	Commercial	60	Retail, wholesale, cultural, historical buildings
5	Accommodation	72	Hotels and similar, social welfare buildings
6	Educational	286	Day care centres, schools, other educational buildings
7	Sports hall	12	Sports halls
8	Hospital	24	Hospitals and healthcare centres
9	Other building	127	Warehouses, industrial production, logistics buildings
9	Other building (Other+)	12	Swimming halls, ice halls

2.2 Adjusting carbon footprint results to CO2data.fi carbon factors

This section presents the results calculated from the Carbon Heroes Benchmark Program and focuses solely on the embodied carbon of materials. All data excludes external areas and foundations.

The national database CO2data.fi datapoints include a conservative factor of 20% accounting for the heterogeneity of products and to avoid underestimation of building carbon footprint. According to the proposal to change the Building act, the assessment should be delivered in the as-built stage of the project. At this stage the products are known, but if a product does not have an EPD, it is expected that a generic material with a conservative value from the database is used. To investigate the impact of using CO2data.fi carbon factors for different life cycle stages, the data was manipulated by identifying key materials and recalculating their GWP using either the conservative emission factor, or the typical value, which represents a generic value derived from EPDs. Certain high impact materials (precast slabs, different concrete grades, structural and reinforcement steel, wooden windows, bricks and insulation materials) were recalculated by multiplying mass with the typical factor. An additional 14 materials (including building technology, mortar, doors, wooden materials) were calculated with the conservative factors. While the Carbon Heroes data contains sum values for different life cycle stages, material GWPs are given only for the whole life cycle. Some adjustment of the data was thus required to separately investigate the effect of conservative factors on life cycle stages. CO2data.fi adjusted A1-A3 (product phase) was calculated by multiplying material mass with the CO2data.fi emission factor. To account for replacements and end of life (B4 and C1-C4), the materials were modelled in One Click LCA. Then, using the original GWP from unmodified Carbon Heroes data and multiplying it with the obtained "CO2data.fi adjusted" emission factor (kg CO_2e/kg) corrected with the emission factor from the unmodified data, the whole life cycle GWPs of the key materials were obtained.

The data for A1-A3 (product phase) can be considered representative in terms of quantities, but all other life cycle stages are not as comprehensively covered. Therefore, additions were made to raw data to allow for comparison: stage A4 (transport) and C1-C4 (end of life) stage values were replaced with averages where a value was missing. Stage A5 (construction process) is not present in the Carbon Heroes data, so a scenario was applied by modelling the construction site operations in One Click LCA software using the datapoint for "site operations, Nordics", which was adapted to the Finnish grid electricity, resulting in 20.01 kg CO_2e/m^2. For the total CO2data.fi adjusted whole life cycle value, A4 was replaced with the datapoint "Transport of building materials, m^2" (20.04 kg CO_2e/m^2) and A5 with the building type specific value. Because several of the key materials (concrete, reinforcement steel, etc.) do not have a replacement stage B4, the impacts for that stage were calculated by using the percentage share of B4 from A1-A3 of unmodified data, and applying that share to the new, CO2data.fi adjusted data.

The 26 chosen key materials contribute to 55–75% of the total GWP for all building types. The highest contributing material in all cases is concrete (including precast and ready-mix), which accounts to 36%, on average, of the A1-A3 GWP. Other high contributors include steel products, bricks and windows.

2.3 Whole life embodied carbon (A-C) with CO2data.fi carbon factors

Table 2 shows the A-C embodied impacts from the original data with possible data gaps for life cycle modules, without denomination per year. Table 3 shows the A-C embodied impacts adjusted to CO2data.fi emission factors using the key materials as explained in section 2.2. The area always refers to net heated area. Foundations and exterior areas have been removed from all values. The source data is somewhat skewed, prompting the use of median as a value for reference. The tables also show the 95% confidence interval of the statistical sample, and the confidence interval of median. The range of medians is 570–930 kg CO_2e/m^2, with the low for rowhouses and high for sports halls.

Table 2. Original embodied carbon data for A-C, kg CO_2e/m^2

Building type	Class	Median	Average	95% Conf.t.	Interval
Rowhouse	1d	399	424	13	386-412
Residential	2	445	461	6	439-451
Office	3	460	469	27	434-487
Commercial	4	532	567	50	482-582
Accommodation	5	484	497	36	448-521
Educational	6	459	478	18	441-476
Sports hall	7	471	548	131	340-602
Hospital	8	483	512	66	417-548
Other building	9	544	557	44	500-587
Swimming + ice hall	9+	410	435	90	320-500

Table 3. CO2data.fi adjusted embodied carbon emissions for A-C, kg $CO_2e/m2$

Building type	Class	Median	Average	95% Conf.t.	Interval (md)
Rowhouse	1d	567	558	11	555-578
Residential	2	635	634	4	630-639
Office	3	834	833	21	813-855
Commercial	4	857	883	39	818-897
Accommodation	5	927	926	31	896-959
Educational	6	877	875	12	854-889
Sports hall	7	840	821	79	761-919
Hospital	8	876	880	53	823-928
Other building	9	686	704	26	660-713
Swimming + ice hall	9+	763	767	29	734-793

2.4 Product phase (A1-A3) carbon footprint with CO2data.fi carbon factors

The range of medians is 310–570 kg CO_2e/m^2 for rowhouses and accommodation buildings, respectively. The original unmodified data is presented in Appendix 1, table A1.1.

Table 4. Statistical carbon emissions with CO2data.fi carbon factors for A1-A3, kg CO_2e/m^2

Building type	Class	Median	Average	95% Conf.t.	Interval
Rowhouse	1d	311	315	11	300-322
Residential	2	356	354	4	352-360
Office	3	517	512	17	500-535
Commercial	4	570	581	39	531-609
Accommodation	5	561	557	26	536-587
Educational	6	562	559	11	551-573
Sports hall	7	502	472	62	440-564
Hospital	8	554	565	35	519-589
Other building	9	450	465	24	426-474
Swimming + ice hall	9+	514	500	48	466-561

2.5 Material replacement phase (B4) with CO2data.fi carbon factors

The range for values in module B4 is 100–220 kg CO_2e/m^2 for other buildings and accommodation, respectively. The replacement considers only the manufacturing impacts of the replaced materials, not their transport or waste handling.

Table 5. CO2data.fi adjusted embodied carbon emissions for B4, kg CO_2e/m^2

Building type	Class	Median	Average	95% Conf.t.	Interval
Rowhouse	1d	116	118	5	110-121
Residential	2	122	132	3	120-125
Office	3	188	192	16	172-204
Commercial	4	154	154	17	137-172
Accommodation	5	221	226	20	200-241
Educational	6	196	203	9	187-205
Sports hall	7	160	174	54	106-215
Hospital	8	207	205	26	181-233
Other building	9	105	108	11	94-116
Swimming + ice hall	9+	143	176	61	82-204

2.6 Key differences in the statistical and CO2data.fi-adjusted results

Compared to unmodified median values from the Carbon Heroes data in Table 2, the CO2data.fi adjusted total life cycle GWP values in Table 3 are substantially higher. The whole life cycle (A-C) material carbon footprints increase 42–91%. Several factors contribute:

- Carbon footprint values for the 26 key materials have been recalculated, 12 materials with typical values and the rest with the conservative CO2data.fi values. The calculation was based on mass.

If a project has used highly optimised materials, the difference between original value and the adjusted value will be larger.

- Concrete represents over a third of the whole life cycle GWP. The default CO2data.fi data for concrete (GWP.REF) has a rather high carbon impact, as there are no alternative binders used in the cement.
- Also, steel datasets in CO2data.fi have high impacts. The applicable dataset in CO2data.fi for structural steel has 20 % recycled content, which may underrepresent actual recycled material share, and does not reflect today's market situation accurately.
- Share of building technology from total GWP increased noticeably, from 8-13% of the raw data to 20-30% after CO2data.fi adjustments. In modules A1-A3, the average GWP of building technology is between 35 and 57 kg CO2e/m2 in the unmodified data, and 42 to 125 kg CO2e/m2 in the CO2data.fi adjusted data. This is a percentage increase of 21-165%. To clarify, the scale of the increase does not prove that conservative values are too high, but it may also be contributed by a degree of underreporting in the real projects taken into account in the Carbon Heroes data.
- CO2data.fi adjusted A-C includes modules A4 and A5 missing from the raw data.

3 Statistical analysis of new building energy consumption

The energy consumption data comes from the Energy Certificate register maintained by the Housing Finance and Development Centre of Finland, ARA. All the energy data is calculated with the regulatory energy performance assessment method. Accepted data was from 2021-2023, except for hospitals where also data from year 2020 was accepted due to small sample. The outliers were removed by accepting the 1-99th percentile of the sample. Only new buildings were included, leaving 11694 energy certificates for analysis. Energy class B is the most common in the sample and close to average value in most cases. The number of C or D class buildings is negligible in most cases. The carbon emissions from operational energy consumption are based on the SYKE carbon factors for years 2026-2075 (average). Since this dataset can be considered very high quality only averages are shown in Table 6.

Table 6. Statistical average energy use (kWh/m^2) per building type: average (all classes), A class, B class

Building class	Energy class	Sample size	Electri-city	District heat	Bio-fuels	Fossil fuels	District cool	Sum of energy use (kWh/m2/a)	Emissions kg CO2e/m2
Rowhouse	Average	3515	56.3	47.2	0.5	0.0	0.0	104	155
	A	766	58.1	11.6	0.0	0.0	0.0	70	104
	B	2724	55.4	57.4	0.6	0.0	0.0	113	168
Residential	Average	4125	45.5	49.7	0.0	0.0	0.2	95	142
	A	1565	44.5	38.4	0.0	0.0	0.2	83	123
	B	2561	46.1	56.7	0.0	0.0	0.2	103	153
Office	Average	628	64.8	26.9	0.6	0.0	1.4	94	138
	A	101	52.7	22.1	0.0	0.0	3.4	78	113
	B	522	66.5	27.9	0.7	0.0	1.0	96	142
Commercial	Average	545	83.6	27.1	0.1	0.1	0.5	111	166
	A	99	58.1	21.1	0.0	0.0	2.2	81	118
	B	440	88.4	28.8	0.1	0.1	0.1	117	175
Accommodation	Average	546	88.2	82.6	0.5	0.0	0.2	171	255
	A	17	66.0	15.6	1.7	0.0	0.3	83	123
	B	521	87.9	85.9	0.5	0.0	0.2	174	259
Education	Average	840	90.0	31.0	0.5	0.1	0.8	123	152
	A	556	55.0	28.0	1.4	0.0	0.0	84	135
	B	276	90.0	31.0	0.4	0.1	0.8	123	178
Sports hall	Average	196	52.6	52.3	2.63	0.0	0.2	107	159
	A	85	50.5	41.0	0.6	0.0	0.4	93	137
	B	110	54.1	61.0	3.5	0.0	0.0	119	176
Hospital	Average	42	159.3	157.4	0.0	0.0	5.8	322	473
	A	0	*Na*	*Na*	*Na*	*Na*	*Na*	*Na*	na
	B	41	159.3	157.4	0.0	0.0	5.8	322	473
Other	Average	4253	100.4	19.3	3.4	1.0	0.0	124	197
	A	1041	56.5	10.8	0.4	0.0	0.0	68	101
	B	1522	81.6	19.3	3.6	0.2	0.0	105	158

Swimming + ice halls	Average	22	112	105.8	0	0	0.6	219	324
	A	3	14.5	100.0	0	0	0.0	115	171
	B	6	72.4	60.1	0	0	2.3	135	198

4 The carbon footprint difference from primary data sources and reaching class A energy performance

4.1 CO2data.fi defaults and average adjusted A4, A5 and C1-C4

Life-cycle stages and scopes modelled with CO2data.fi default values, such as the stage A5 (construction process) and default building technology values, were identified. To investigate their impact on the building carbon footprint, scenarios were applied where the CO2data.fi defaults were replaced with those generated by the One Click LCA software. Such comparative values were created for the scenarios for A4 (transport) and A5 (construction process).

The A4 (transport) impacts decrease about 50–70%, when One Click LCA data is used. CO2data.fi has several datapoints for transportation impacts, but for simplicity the generic “transportation of building materials (m2)” datapoint was used. One Click LCA uses the same background information, but the emissions are scaled to material masses. The A5 (construction process) impacts decrease 55–62% when using the One Click LCA scenarios. From the perspective of the whole life cycle of a building, a reduction of 4-5% in the carbon footprint can be achieved using project specific data for these life cycle stages.

4.2 Achieving class A energy performance

Moving a building type from average energy use to energy class A reduces the operational impacts from energy by 11 to 114%, with the highest savings found in swimming and ice halls. Note, that the only factor is the energy use, and no additional material assumptions were applied (e.g. increase in insulation thickness). There is no A energy class data for hospitals. From perspective of a whole life cycle of a building, moving to class A energy performance leads to a reduction of 2-14% from baseline.

Table 7. Carbon emissions from statistical average energy use and A energy class energy use per building type, kg CO_2e/m^2. See table 1 for building class codes. 9+ refers to swimming and ice halls.

Scenario	**1d**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**9+**
B6 (Statistical average)	155	142	138	166	255	152	159	473	197	324
B6 (A energy class average)	104	123	113	118	123	135	137	*Na*[1]	101	171
Difference to baseline, whole life cycle, %	-7.5	-2.6	-2.7	-4.7	-11.5	-1.7	-2.4	*Na*[1]	-11.3	-14.2

[1] *No data for hospitals*

5 Carbon footprint of modelled reference buildings

5.1 Reference building calculation methodology

The calculations were performed using One Click LCA's Carbon Designer 3D using the "Finnish reference building v. 2022.1 (CO2data.fi/SYKE)", from which the designs were transferred to the main application for further tuning using the Low carbon assessment 2021 tool fully compliant with the government method.

Prior to calculation, the following parameters were set:

- Materials service life: Product specific.
- Assessment period: 50 years.
- End-of-life calculation method: Market scenarios.
- End-of-life energy recovery scenario: District heat Finland, 2022-2072 (50 y).

The datapoints are mainly those originating from the CO2data.fi database. If an appropriate datapoint was unavailable, the next option was to use One Click LCA generic datapoint for Finland. If a more suitable option was found from a local (Nordic) producer, this was used instead. The scope of the calculation followed the YM method, but site elements and building carbon handprint were omitted from the analysis as they are not relevant in the context of carbon footprint limit values. A closer look into all the applied assumptions is provided in Appendix 2, and the applied sensitivity scenarios are summarised in Appendix 3.

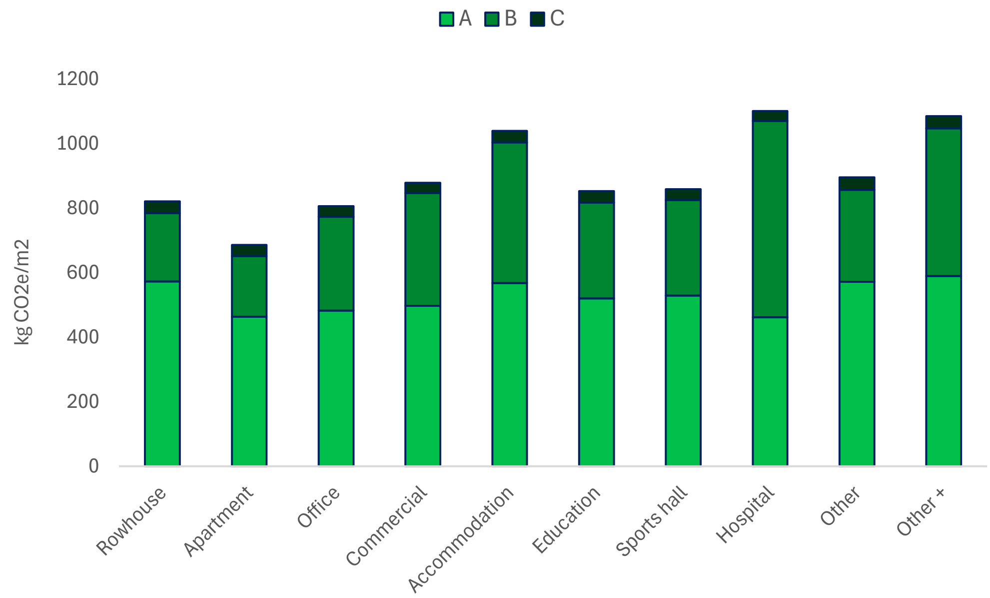
5.2 Carbon footprint results of modelled reference buildings

The modelled reference building carbon footprints per building show a similar pattern to the calculated carbon footprints, despite small differences. The reference building whole life carbon footprints before normalisation per year are presented in Table 8 and further visualised in graph 1. The values include statistical average energy use and are rounded to nearest 10. Please note that the total figures may not add up due to rounding.

Table 8. Reference building carbon footprint results before normalisation per year, kg CO2e/m2

Life cycle stage	1d	2	3	4	5	6	7	8	9	9+
A1-A3	500	380	390	410	460	430	450	370	500	390
B4	50	50	150	180	180	150	140	140	80	150
A-C	**810**	**690**	**800**	**880**	**1040**	**850**	**860**	**1100**	**900**	**1090**

As can be seen from graph 1, the embodied carbon impacts are of similar magnitude for all building types, but slightly higher for the rowhouses and class 9 other buildings, and lower for hospitals. The differences in stage B operational impacts are mainly caused by differences in energy usage and energy efficiency of this building type. The operational impacts account for about 20% of whole life carbon emissions, except in accommodation buildings and hospitals where the share is roughly 30-40%. The values are presented without accounting for biogenic carbon for simplicity. Accounting for biogenic carbon will shift some of the impacts from module A to module C, but the whole life carbon footprint remains the same.



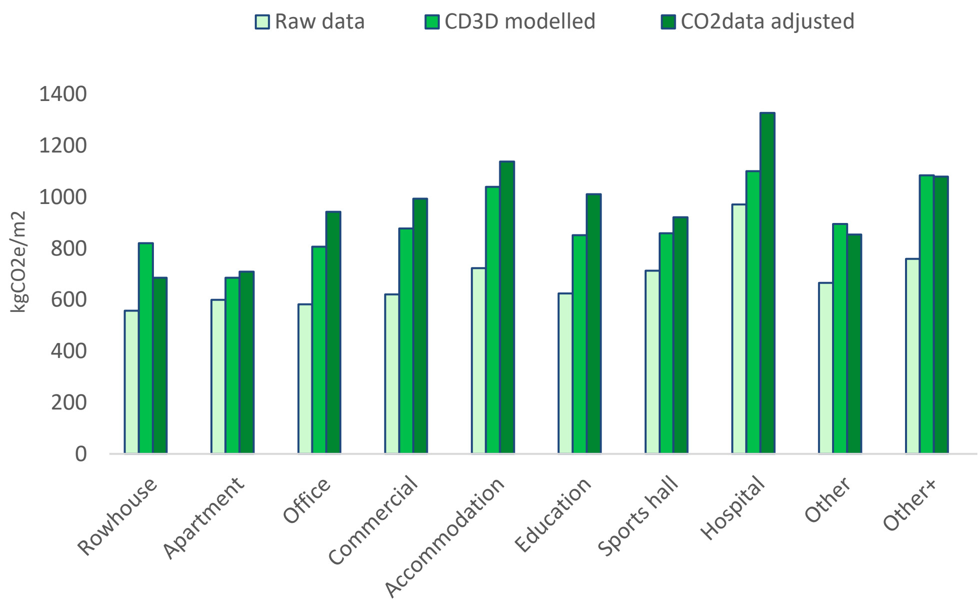
Graph 1. Reference building carbon footprints (kg CO_2e/m^2) per building type and life cycle stage (A,B,C). Values are presented without accounting for biogenic carbon.

The reference building embodied impacts originate mostly from horizontal structures: beams, floors and roofs that are heavy on concrete and reinforcing steel. These structures account for 50-60% of A1-A3 impacts for each studied building type. The next highest embodied impacts originate from building technology. The share of technology from all materials was lowest for rowhouses at 7%, and highest for commercial buildings at 33%.

Graph 2 shows the difference in whole life cycle impacts determined with different methods: the unmodified building data from Carbon Heroes, the CD3D modelled reference buildings and the CO2data.fi adjusted building data from Carbon Heroes. The CD3D reference building carbon footprints are in all cases higher than those originating from the unmodified Carbon Heroes data, but lower than the CO2data.fi adjusted values. This is expected, as the Carbon Heroes data represents real projects that can include different materials to those present in the reference buildings models, and materials may be modelled with different emission factors.

The CD3D modelled buildings and CO2data.fi adjusted data differ the most for rowhouses, where the modelled building has a higher carbon footprint. This is likely due to the carbon intensive concrete frame used in the model, which may be untypical for Finnish buildings in class 1d. On the contrast, the

CO2data.fi adjusted hospitals show a 20% higher carbon footprint than the CD3D modelled building. Here, an international reference building was used as a base due to lack of CO2data.fi reference building. It is possible that in real situations hospitals would employ several materials lacking from the reference building model. Structural steel and other metals, as well as concrete materials were identified, whereas in the model reference building the most contributing material is the building technology datapoint.



Graph 2. Comparison of unmodified Carbon Heroes data, CD3D modelled reference buildings data and CO2data.fi adjusted building data, whole life cycle carbon footprint kg CO2e/m2, with average statistical energy use included.

6 Sensitivity of carbon footprint

6.1 Increase of carbon footprint

Factors that may increase the carbon footprint, such as different energy use, special requirements and shape of the building, were investigated. The sensitivity scenarios were: 1) the building reaches the E-number limit value, 2) increased noise insulation, 3) increased fire safety measures, 4) a complex building shape, 5) heated basement, 6) tall building.

The individual scenarios resulted in an increase of 1-8% in the whole life cycle carbon footprint. The E-number limit value scenario was based on the percentual difference between the E-number average of the studied energy certificates and the building class specific E-number limit value. The difference was highest for hospitals at 8% increase. Other buildings (class 9) have no general E-number limit value and were thus omitted from the analysis.

Regarding noise insulation, only noise from traffic was considered (with the assumption of 65-70 dB noise level[1]). Vibration noise can be best handled with foundation solutions, and for air traffic the main solution is to apply a hollow core slab, and a massive enough interior ceiling panel, both of which are in this case already applied (hollow core roof slab 265 mm and panel with a mass of 11 kg/m^2). Other baseline materials solutions were also considered to have high insulation characteristics based on mass, layer thickness and insulation density. Reducing size of windows is not considered here. For external wall cladding, the render was changed to brick, which has excellent sound insulation properties[2], and full-height glazing was added to balconies (applicable to apartment buildings and offices). This led to an increase of 1-6% in the whole life cycle carbon footprint.

The fire safety scenario applied additional layers of fire-resistant gypsum plasterboard in all internal walls. Most of the added impacts, however, originated from a sprinkler system. Note, that wood-framed buildings apply sprinkler system by default. Stricter fire safety requirements resulted in an increase of 4-8%.

As for the shape of the building, the assumption was a building with an atrium, that increased the external walls and façade materials by 43%, and columns by 20%. The more complicated geometry resulted in an increase of 1 to 5%.

Consideration of the heated basement and increased height of the building led to inconclusive results. Adding materials below ground reduces the share of carbon intensive materials in the façade, leading to

[1] Kansallinen meluselvitys 2022, Kartta.hel.fi

[2] Kylliäinen M. 2011. Kivitalojen äänieristys. Suomen Rakennusmedia Oy. Helsinki 2011. 82 s.

very small change compared to baseline, while adding more upper floors reduces the area of the roof slab, which compensates for the thicker columns required. Increasing the floor area, on the other hand, also increases the divider, leading to a rather similar carbon footprint with the baseline. It is likely, that most of the additional impacts for these scenarios take place in the site, as different foundation solutions and site operations are required. Also, a tipping point beyond which the impacts of thicker columns are higher than the savings of reduced roof slab should be established, although it is expected that this will not represent a typical building height in Finland.

Table 10. Increased carbon footprint identified from applied scenarios to baseline (%).

Parameters	1d	2	3	4	5	6	7	8	9	9+
Improved fire safety	+5%	+8%	+4%	+4%	+4%	+4%	+4%	+4%	+4%	+3%
Higher noise insulation	+4%	+6%	+2%	+1%	+2%	+3%	+2%	+1%	+4%	+1%
Complex shape of building	Na	+1%	+1%	+1%	+1%	+1%	Na	+5%	Na	Na
E-number limit value	+3%	+5%	+1%	+3%	+2%	+3%	+2%	+8%	Na	Na
E-number limit, improved fire safety and noise insulation	+13%	+19%	+8%	+8%	+8%	+10%	+8%	+13%	+8%[1]	+4%[1]

[1]*No E-number limit established*

6.2 Decarbonisation potential

To closer examine the decarbonisation potential, the reference buildings were modelled with alternative scenarios: 1) COP 3 ground source heat pump to replace other heating sources; 2) A class energy instead of statistical average; 3) lower carbon concrete, i.e., GWP.70 instead of GWP.REF to replace all concrete in the structure; 4) Load-bearing CLT structure to replace concrete structure. In this scenario, also the interior walls were changed, from steel stud to wooden stud frame. For sports halls and swimming halls, the load-bearing walls were compared with a glulam column-beam structure that may be more suitable for larger spans. The decarbonisation scenarios consider changes in energy and material use. All structures and elements used in the comparison are intended to provide a comparable level of performance, and they contain all layers and materials needed to achieve this. In energy performance scenarios, only the impacts from energy were accounted for, without considering changes to materials such as added insulation. The applied scenarios are presented in closer detail in Appendix 3, Table A3.1.

The individual decarbonisation scenarios applied to modelled reference buildings resulted in decarbonisation potential of 2–31% from baseline over the whole life cycle. When combining energy and material measures, the reduction potential was maximum 15–37% from baseline (Table 11). A shift to A class energy has the highest benefits for building types with small representation in class A (accommodation buildings, hospitals), and installing a ground source heat pump is most beneficial for buildings with high district heat use (accommodation, hospitals, residential, educational, swimming halls). Based on the energy data all building types already produce some part of their heating needs with a heat pump, but the share can be further increased.

Replacing concrete with wood structures holds the biggest material-related saving for all building types. A stud frame timber structure was shown to have impacts of similar magnitude in the previous report and is a good alternative where applicable. Glulam and CLT structure resulted in a similar decarbonisation potential for sports halls and swimming halls.

Using GWP.70 concrete leads to more moderate reductions, however, it is worth noting that the emission factor for this material is still rather conservative. Also, the hollow core slabs were replaced with a datapoint that only resulted in a 20% reduction in carbon impacts instead of the 30% due to a lack of GWP.70 datapoint for this element. Further optimizing concrete solutions and recipes can achieve higher carbon reductions.

Table 11. Decarbonisation potential identified from applied scenarios to baseline (%)

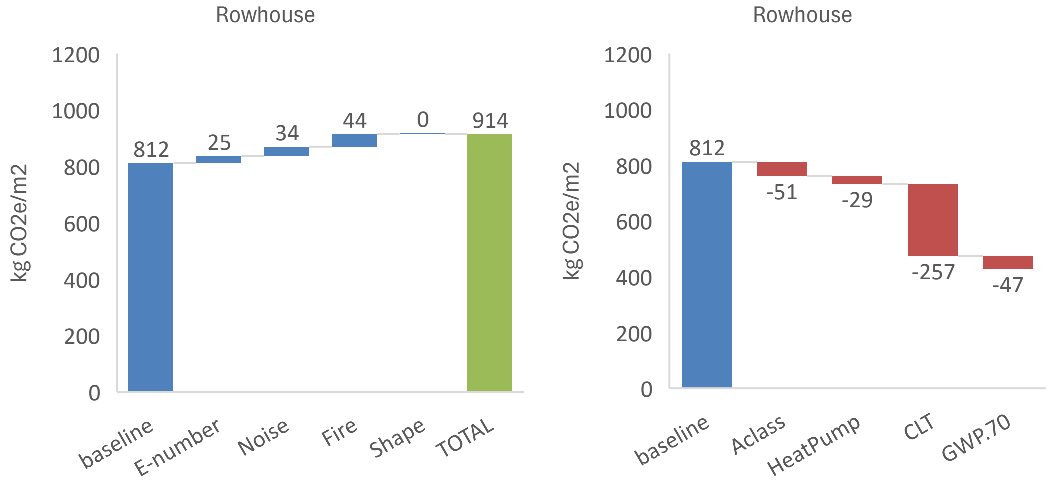
Parameters	**1d**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**9+**
A class energy performance	-6%	0%	-3%	-5%	-13%	-2%	-3%	*Na*	-11%	-14%
Ground source heat pump	-4%	-3%	-1%	-1%	-7%	-4%	-5%	-14%	-2%	-8%
CLT frame	-32%	-22%	-14%	-13%	-17%	-17%	-22%	-12%	-26%	-19%
GWP.70 concrete	-6%	-4%	-5%	-4%	-4%	-5%	-5%	-3%	-6%	-3%
Most effective measures: CLT frame & ground heat pump or A energy class[1]	-38%	-25%	-18%	-19%	-31%	-22%	-26%	-26%	-36%	-32%
Low-carbon concrete & ground heat pump or A energy class	-12%	-7%	-8%	-10%	-17%	-10%	-10%	-20%	-17%	-17%

The decarbonisation measures available to the market are not limited to the ones analysed in this report. An additional effective measure would be sourcing low carbon products for all categories, not just concrete. Additionally, material-efficient design and material use optimisation provide further potential for cost and carbon reductions.

6.3 Sensitivity scenarios for buildings

Note, that the decarbonisation scenario cannot be considered fully cumulative, but an energy measure and a material measure may be combined.

6.3.1 Rowhouses

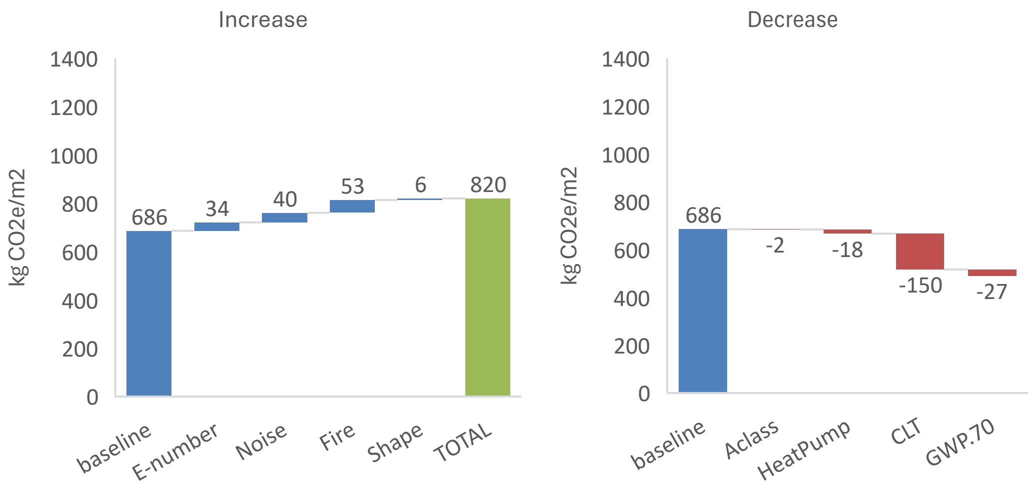


Graph 3. Impacts from applied flexibility scenarios in rowhouses (kg CO2e/m2/a).

For rowhouses, the highest increase in carbon footprint results from the increased fire safety scenario. A more complex shape was not accounted for rowhouses. Largest savings, on the other hand, are obtained with a CLT structure. The magnitude is larger than for other building types, which may be the result of a disregarded sprinkler system. For rowhouses under 2400 m^2, a sprinkler system is not required[3], and thus omitted here. For a larger area, the sprinkler system would lead to a smaller decarbonisation potential. If added to scope, the sprinkler system adds 5% (0.62 kg/m^2) to the A1-A3 impacts.

[3] Paloturvallinen puutalo: Asuin- ja toimitilarakentaminen. Puuinfo Oy, Helsinki, 2021.

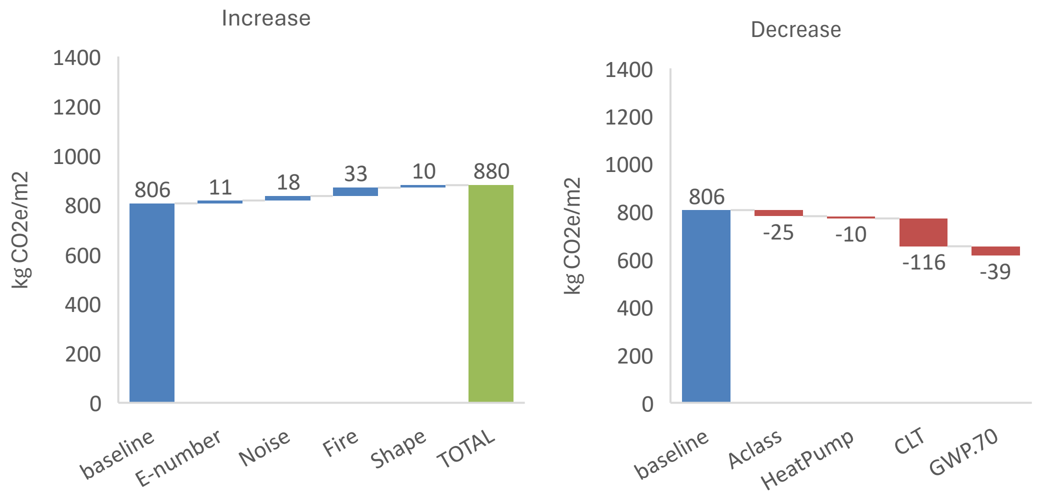
6.3.2 Residential buildings



Graph 4. Impacts from applied flexibility scenarios in residential buildings (kg CO2e/m2/a)

The greatest increase in the carbon footprint of residential buildings resulted from the increased fire safety requirements. The number of interior walls has an impact, as the applied measure was to add more gypsum plasterboards to the walls, but the addition of a sprinkler system has a larger influence on the result. The smallest impact from decarbonisation measures originated the shift to A energy class. This is due to the relatively good energy performance of new apartment buildings. The most effective means is the CLT frame design, that resulted in 22% reduction in carbon footprint. The baseline scenario is a precast concrete frame with very little wooden structures. Specifying concrete with a smaller carbon intensity would bring about more decarbonisation potential to the “green concrete” scenario.

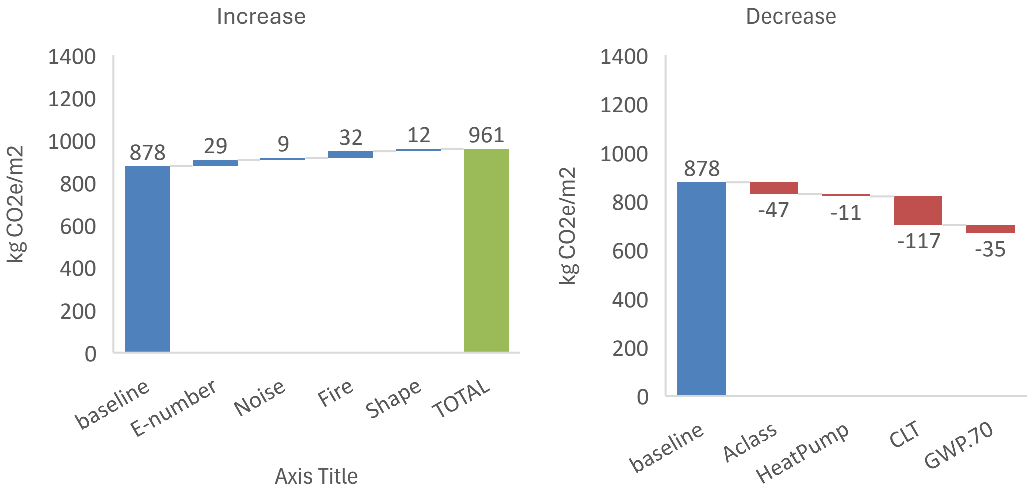
6.3.3 Office buildings



Graph 5. Impacts from applied flexibility scenarios in office buildings (kg $CO_2e/m^2/a$)

In office buildings, the increased fire safety was again the most contributing scenario, and the most effective decarbonisation scenario was the CLT frame. This building type is already rather energy efficient, with 17% of buildings in class A and the other 83% in class B.

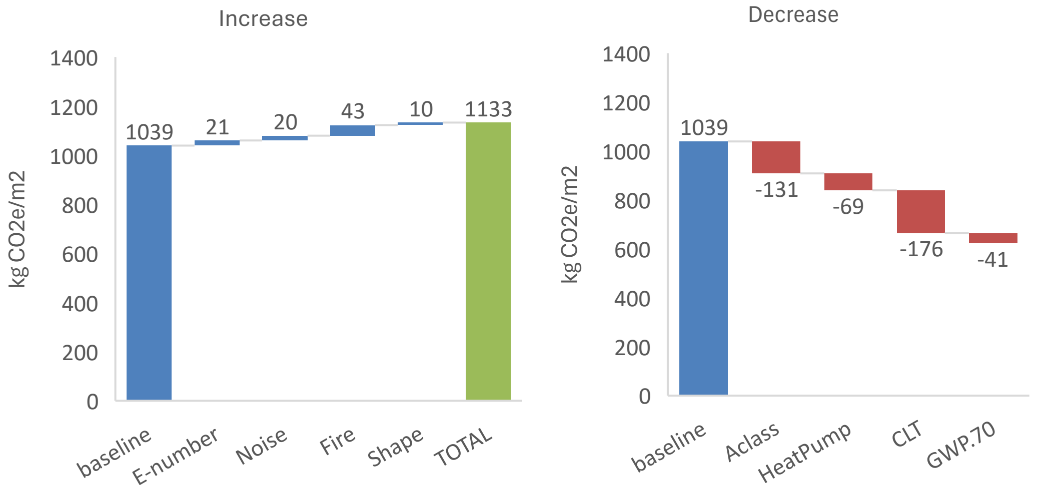
6.3.4 Commercial buildings



Graph 6. Impacts from applied flexibility scenarios in commercial buildings (kg $CO_2e/m^2/a$)

For commercial buildings the highest increase followed from the E-number limit value scenario and fire safety scenario, where both resulted in nearly 4% increase in carbon footprint. The decarbonisation potential was highest for the CLT frame, but reaching A energy class also contributes to a 6% decrease. The reference building is based on retail/wholesale building with a small number of interior walls. Installing a heat pump leads to smaller changes than in most other building types due to a modest consumption of heating energy compared to electricity.

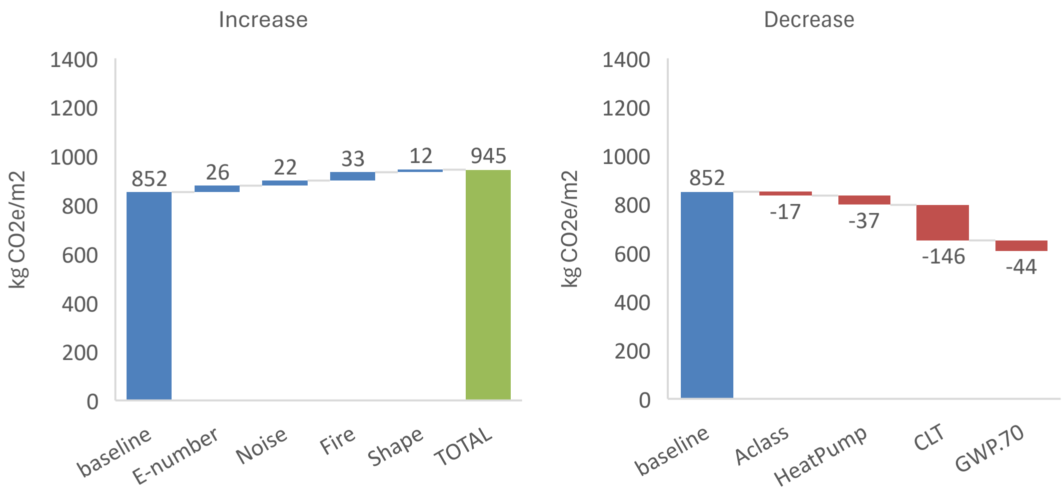
6.3.5 Accommodation buildings



Graph 7. Impacts from applied flexibility scenarios in accommodation buildings (kg $CO_2e/m^2/a$)

The largest increase is again found with the fire safety scenario. The decarbonisation scenarios show a wide array of potential improvement areas. The energy performance of accommodation buildings is on average closer to the E-number limit value than A class, so a shift to A energy class leads to a decarbonisation potential of 13%. The largest impact is still realised with a CLT frame, 17%.

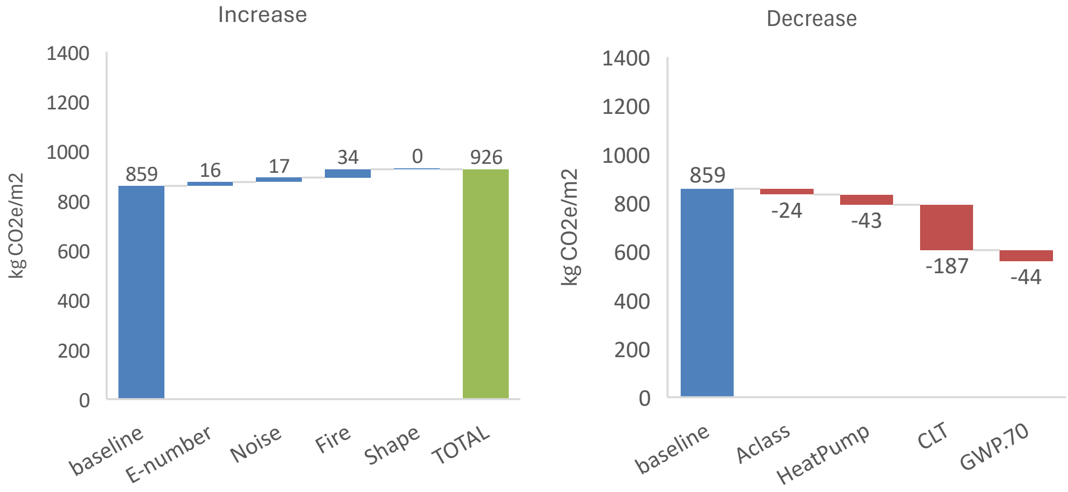
6.3.6 Educational buildings



Graph 8. Impacts from applied flexibility scenarios in educational buildings (kg $CO_2e/m^2/a$)

For educational buildings the increased carbon footprint scenarios resulted 3-4% increase. From the decarbonisation measures, the CLT frame was the most effective.

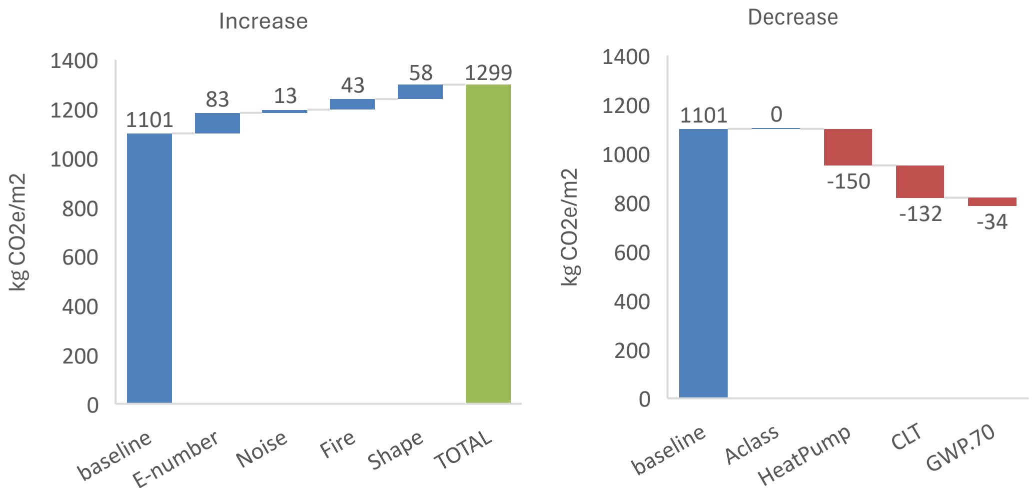
6.3.7 Sports halls



Graph 9. Impacts from applied flexibility scenarios in sports halls (kg $CO_2e/m^2/a$)

The baseline sports hall is based on international reference building model, with all the structures manually changed into CO2data.fi structures. The structure is simple, and quantity of internal elements small. The average E-value is 91, when the limit number for class A is 90, and the limit number for new buildings is 100. The range is rather small, which leads to small changes between the E-number and A class scenarios. Highest decarbonisation potential is obtained with a timber frame.

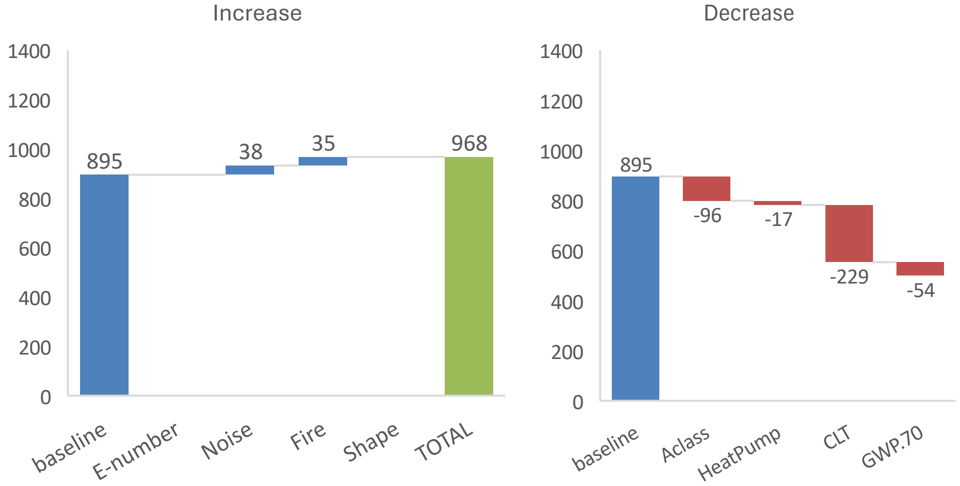
6.3.8 Hospitals



Graph 10. Impacts from applied flexibility scenarios in hospitals (kg $CO_2e/m^2/a$).

The hospitals have average energy performance, and the E-number limit value is quite high at 320 compared to the average in the sample, 272. An increase of 8% is possible in this scenario. The decarbonisation measures show that the highest potential is reached with a ground source heat pump installation. No hospitals reached class A, so improving the energy performance would likely lead to great additional decarbonisation results. Here it is to be noted that the model behind the hospital reference building may underestimate the impacts in product phase A1-A3. Material related measures could therefore lead to higher differences from the baseline that what is pictured here.

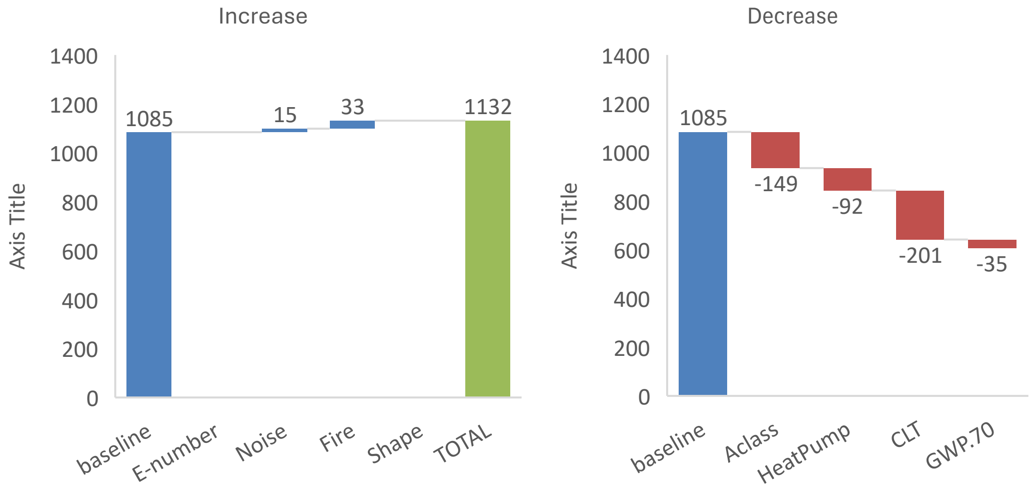
6.3.9 Other buildings



Graph 11. Reduced impacts from decarbonisation scenarios in other buildings (kg CO_2e/m^2/a)

The class “other buildings” represents a variety of building types. The baseline is based on international reference building model for warehouse. The building technology datapoint is that of logistics building. This kind of building has a simple structure with few windows, internal walls and floor finishes.

6.3.10 Swimming halls



Graph 12. Reduced impacts from decarbonisation scenarios in swimming halls (kg CO_2e/m^2/a).

Swimming and ice halls belong to class 09, “other buildings”, but due to their different energy profile and material distribution they are be handled as a separate group. The baseline was modelled with international reference building model for sports halls, with the interiors reflecting those found in a swimming hall. The building technology is different from both sports halls and other buildings, and also higher than for ice halls.

7 Discussion and recommendations

7.1 Emissions from the Finnish construction sector

The Finnish national greenhouse gas emissions were about 50 Mt CO2e in 2022 (including LULUCF). Only preliminary information exists for 2023 at the time of writing of this report. The estimated development based on current policies and measures expects the emissions to be around 28 Mt CO2e in year 2030, and 21 Mt CO2e in goal net zero year of 2035. The construction sector is responsible for about a third of these emissions and the share of buildings (materials, construction, operational emissions) is 86% of the total. This gives a theoretical carbon budget of 13 Mt in 2022, 7 Mt in 2030 and 5 Mt in 2035. According to Rakennusteollisuus, in 2021 the entire construction sector was responsible for 15 Mt CO2e, which corresponds well with the carbon budget allocated for the sector. From this, the building emissions accounted for 12 Mt. The use phase energy consumption was responsible for 60% of the total building carbon footprint, which left a bit under 5 Mt CO2e for the building embodied emissions in 2021. To stay within the carbon budget, the sector needs to cut 40-50% by 2030 and a further 25% by 2035.

7.2 Goal of the limit values

Effective measures are required to cut down emissions in all sectors, construction sector included. To establish a limit value for different building types, two different approaches are used. The goal in both approaches is to achieve a significant reduction in the emissions originating from the built environment, with a focus on new buildings. The first approach leads to a limit value compliant with the national and international commitments for mitigating the impacts of climate change within a tight schedule. This limit also aligns with the national climate and energy strategy, according to which the emissions should be cut by 60% by 2030, compared to the level of 1990. Calculating from the emissions of 2022, the emissions should be cut by 40-50% by 2030, however, it is clear that present actions are not enough to reach this, and even more ambitious measures would be justified. The assumption is that the construction sector share of the national emissions and decarbonisation burden is the same as for all the other sectors.

The second approach relies on setting a fixed percentual decrease to building carbon footprint from the year 2026, with the expectation that the building stock – new and existing – is decarbonised by the target year 2050. The assumption is that the decarbonisation burden is not the same for different sectors. However, as upfront carbon (carbon emitted before the building is taken to use) already makes a large share of the building whole life carbon footprint, the percentage decrease should be ambitious enough to cause a meaningful change. This approach can also be implemented in a manner similar to the one presented in the Buildings Performance Institute Europe's Roadmap to climate-proof buildings and construction, where the limit value is gradually tightened until 2050.

7.3 Current state of building whole life cycle carbon footprint

Table 12 shows the final statistical, CO2data.fi adjusted whole life cycle carbon footprint per building type including both energy and materials. The range is 690–1330 kg CO_2e/m^2 or 14–27 kg $CO_2e/m^2/a$ for 50 years calculation period. The number corresponds roughly to the 50th percentile in graphs 13-17 and is the basis for calculating the national target aligned limit value.

Table 12. CO2data.fi adjusted carbon emissions for whole life cycle A-C, sum of materials and energy impacts, per m^2 and per m^2/a.

	1d	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**9+**
kg $CO2e/m^2$	677	709	942	994	1139	1011	921	1328	854	1080
kg $CO2e/m^2/a$	14	14	19	20	23	20	18	27	17	22

The graphs below show the current range of whole life carbon footprint of Finnish buildings, calculated with CO2data.fi adjusted embodied impacts and average operational impacts. From the data, it is simple to determine the percentual share of buildings under certain limits. It is to be considered, that the results are based on manipulated data with the assumption that conservative factors are used for life cycle assessment. The median value is therefore a justified starting point to consider impactful limit values. The graphs are divided to similar ranges of carbon footprint to preserve visual quality. Note, that due to rounding impacts the absolute numbers in tables may differ slightly.

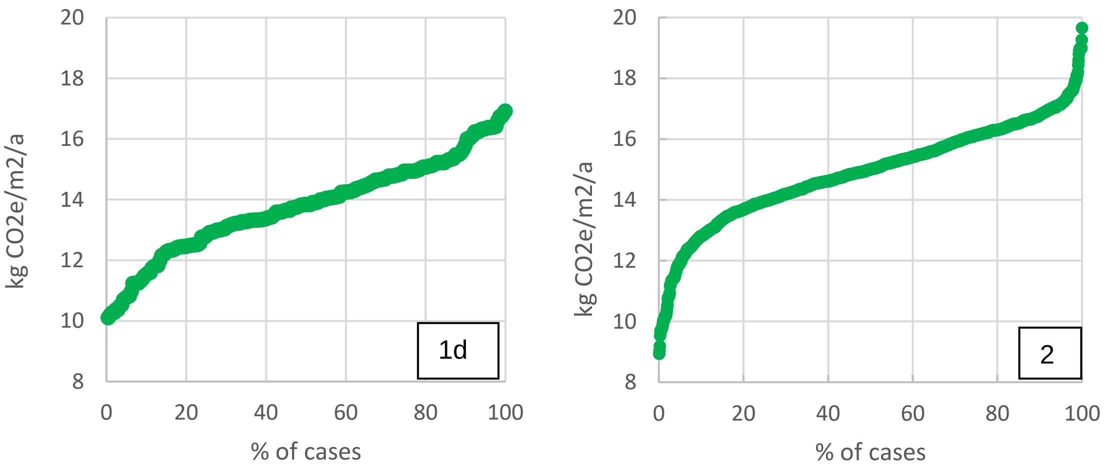


Figure 13. Whole life carbon footprint of Finnish residential buildings. 1d) rowhouses, 2) residential buildings, carbon footprint in the range of 8-20 kg $CO_2e/m^2/a$.

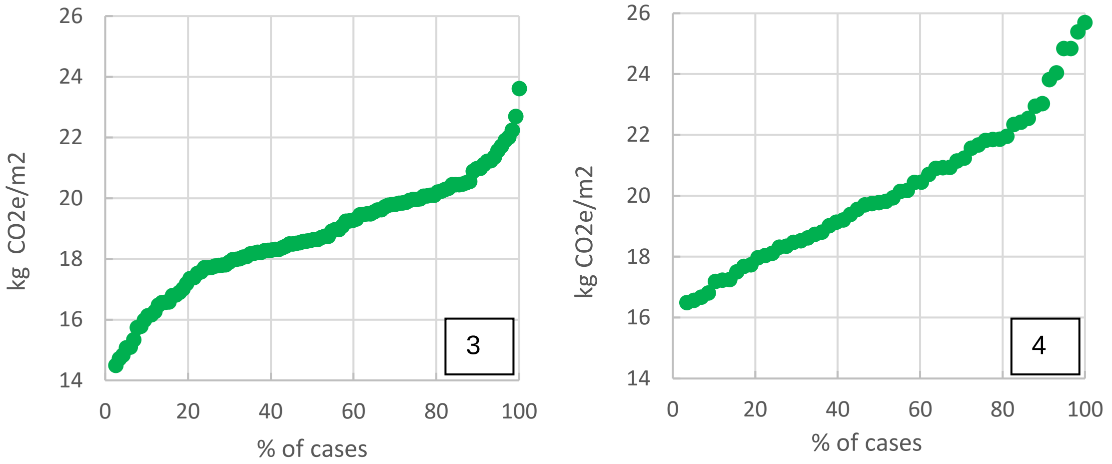


Figure 14. Whole life carbon footprint of Finnish 3) offices and 4) commercial buildings, carbon footprint in the range of 14-26 kg $CO_2e/m^2/a$.

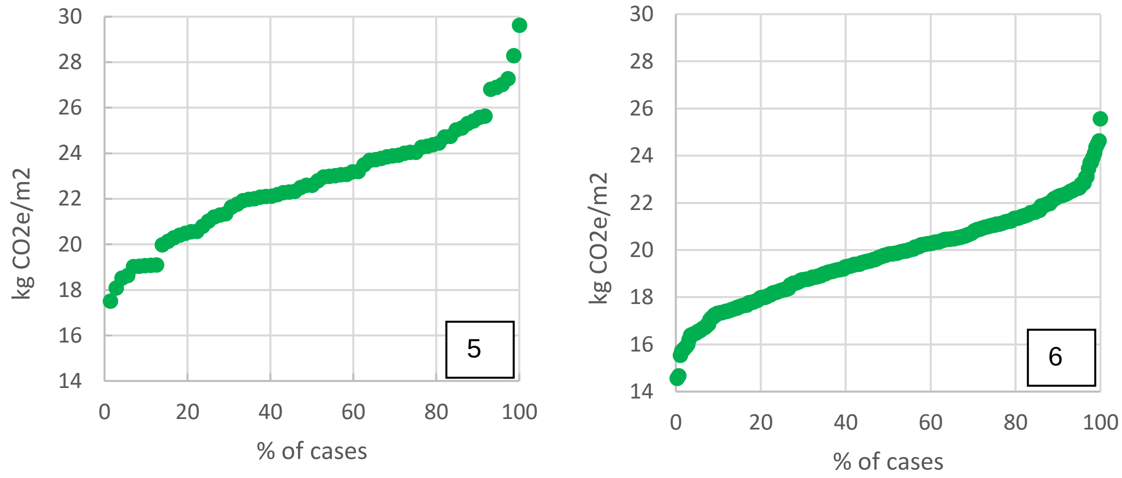


Figure 15. Whole life carbon footprint of Finnish 5) accommodation buildings and 6) educational buildings, carbon footprint in the range of 14-30 kg $CO_2e/m^2/a$.

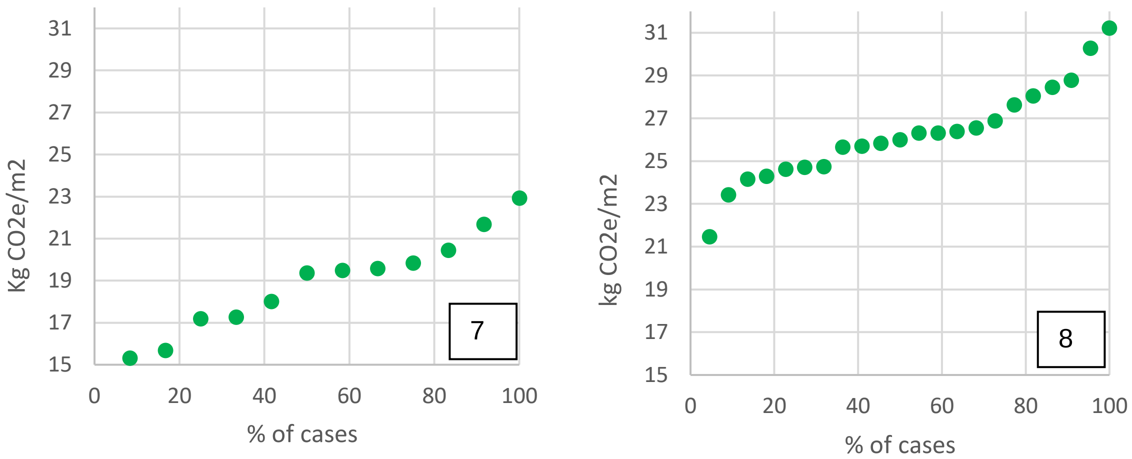


Figure 16. Whole life carbon footprint of Finnish 7) sports halls and 8) hospitals, carbon footprint in the range of 15-32 kg $CO_2e/m^2/a$.

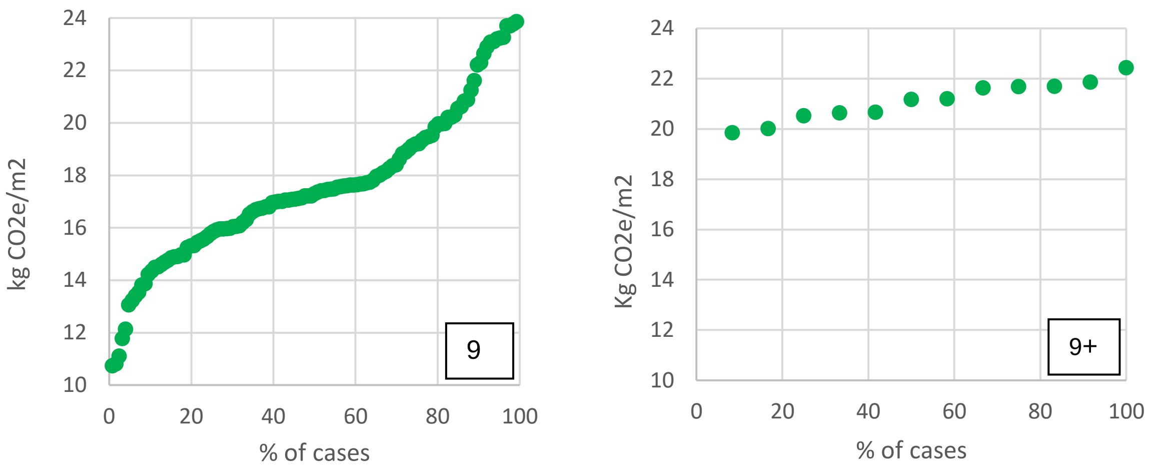


Figure 17. Whole life carbon footprint of Finnish 9) other buildings and 9+) swimming and ice halls. Carbon footprint in the range 10-24 kg $CO_2e/m^2/a$.

The embodied impacts are responsible for 60-80% of the whole life cycle impacts, when operational emissions are calculated with the average value for years 2026-2074. This corresponds to the advanced energy performance level presented for new building baseline archetypes within the EU. When only looking at the operational emission, the impacts from electricity, district heating and district cooling (calculated with SYKE energy emission factors) will reduce on average 36% by 2035 and 48% from 2026 by 2050, assuming unchanged energy consumption. Largest change is for district heat, the impacts of which are estimated to reduce by 60% by 2050. Calculating with the current embodied carbon footprint (CO2data.fi adjusted) and current average energy consumption per energy type, the whole life carbon footprint reduces by 14 to 20% just by applying energy measures between 2026 and 2035, depending on the building type. The effect is naturally largest for building use classes with high energy consumption, i.e., hospitals, accommodation buildings, swimming halls and ice halls.

Several changes will apply the energy regulation of new buildings due to the Energy Efficiency Directive (EED) and the new Energy Performance of Buildings Directive (EPBD). Among other changes, solar panels gradually become mandatory from year 2026 onward, and installation of fossil-based energy generators is to be banned. However, this will not affect the calculations presented in this study, as average emission factors based on already agreed actions were used. These factors are averages, the values corresponding to ones that will be reached in the early 2050s due to heavier decarbonisation towards the end of calculation period. Thus, in assessments conducted from 2026 onwards, the majority of the impacts are already embodied and the energy is not further studied separately from the other impacts.

7.4 Calculation of the limit values

7.4.1 National target aligned limit value

The national target aligned (strict) limit value aims to comply with national and international climate objectives. For Finland to reach the decarbonisation goals, the building sector would need to cut close to 50% by 2030, from 2022 levels. This coincides with the statement from World Green Building Council, that has called the building sector to cut embodied carbon by 40% and operational carbon by 100%. For Finland, this means halving the emissions by year 2030. Thus, a cut of 50% is suggested to today's values by 2030. This is the highest allowable level of new building carbon emissions by 2030 from the climate point of view. The authors recommend applying the following steps:

1. Start from statistical whole-life carbon footprint values (A-C), chapter 7.3.
2. Adjust the value based on changes to CO2data.fi defaults or energy regulations, if any.
3. Adjust the value downwards to achieve the initial limit values based on the use of the two most effective decarbonization measures identified in 6.2. As this only considers two of the most effective individual decarbonization measures, it is by far not the maximum decarbonization potential any project has but a rather conservative estimate. The decarbonisation measures available to market players are not limited to the ones analysed in this report. The most important such measure is material-efficient design and material use optimisation, which also save costs.
4. The limit value is tightened in four-year steps, starting from the year 2026. Based on the source data modified with certain data assumptions, 40% of current buildings (apartments) would reach this goal were suggested decarbonisation levels implemented.
5. The limit value for 2030 is predefined according to the national climate goals to reduce the emissions by 50%. Based on source data, no current buildings reach this goal, but with suggested decarbonisation measures about 5% would reach this goal (apartments), corresponding to about 375 000 m2 annually.
6. The value for 2034 is also predefined to aid reaching the national objectives in function of time. A reduction of 25% is calculated to take place every four years. Recalibrate as required.
7. A 10% margin can be added when required to account for project sensitivity, related to regulatory requirements regarding site-specific factors, zoning and/or building characteristics.

7.4.2 Controlled disruption limit value

The goal of this limit value is to not disrupt the construction sector, but it is outside this study's scope to assess the impacts of this kind of limit value to construction sector and the society. Any limit value that is higher than the national target aligned one suggested above will lead to greater disruption and to more drastic cuts in the future in order to achieve the 2050 targets.

For the controlled disruption limit value, an example level that is reached by 80% of buildings built today is given (see Figure 13). For example, Boverket proposes a level corresponding the 50-75th percentile depending on the building use type. From 2026 onwards, a % cut of required magnitude is applied in 4-year steps. The percentage is subject to political decision and can be set with increasing level of ambition towards the target year. The authors recommend setting the limit values following these steps:

1. Define the share of new buildings that will be allowed to perform below the limit values without any additional effort. It assumed for the description of this process, this share to be 80%.
2. Start from statistical whole-life carbon footprint values (A-C) reached by 80% of buildings today, chapter 7.3.
3. Consider a desired target level of building emissions for every four years. For example, implementing a 20% cut every four years would lead to the impacts per m^2 halving by year 2038 and reduced by around 75% by 2050. About 20-25% of current buildings already reach the limit value in 2030, but no additional decarbonisation actions are considered in this value.
4. The percentage decrease may be recalibrated as required based on feedback after implementation.

7.5 Impacts of limit values to national emissions

The main focus of the carbon footprint limit values in in embodied carbon, as the upfront carbon emissions originating before the building is taken into use happen today. The operational carbon of Finnish building stock is driven down with already agreed actions and upcoming regulations that gradually decarbonise the electricity grid and district heating during the following years. The limit values need to be visited frequently to account for this progress in the energy sector to ensure that embodied carbon will be driven down efficiently without projects just taking advantage of the availability of low carbon energy.

The limit values will have an impact on the national emissions, the magnitude of which depends on several assumptions. An estimate based on available data is given here. The assumptions are:

- the national emissions of Finland are at 50 Mt CO_2e (including LULUCF). The value from 2022 is used as a basis, as only preliminary data exists from year 2023. The target for 2030 is 28 Mt,
- the embodied emissions from new buildings (year of comparison 2021) are close to 5 Mt,
- the new built area per year is about 7 500 000 m^2 per year (2015-2023, finished buildings), 60% of which was residential buildings (single family houses, rowhouses and apartment buildings),
- new buildings will be built at the same rate as now until 2050.

As majority of new buildings are residential, the carbon footprint for residential buildings (11 kg $CO_2e/m^2/a$ embodied) was chosen as the average carbon footprint of all new buildings. Multiplying this with the area of new buildings per year, an estimate of current embodied carbon footprint of new buildings can be given. Applying the steps presented in chapter 7.4.1, the national target aligned limit values could cut the annual embodied emissions of the building sector by 24% between 2026 and 2030, and 43% between 2030 and 2034. Considering current emissions on a national level, this would be 2.4% annually in 2026-2030 and 8% in 2030-2034. This translates to 5.5% of the annual savings that need to be achieved by 2030 (22 Mt) and 31% of the savings that need to be achieved by 2035 (9 Mt).

Considering the controlled disruption limit value based on the 80th percentile of the sample and following the steps outlined in the previous chapter, no savings are calculated for 2026-2030, and a fifth of the sector's embodied emissions would be cut annually between 2030 and 2034. This translates to 3.6% of annual national target emissions for 2030 to 2034.

8 Conclusions and recommendations

All the conclusions and recommendations in this report are exclusively those of the authors, and do not represent the view of the Finnish government nor are they endorsed by the Finnish government.

8.1 Methodology considerations and the validity of results

The results presented in this report are based on the whole life carbon assessment methodology of the Ministry of Environment (2021). As limited assessments have been undertaken in accordance with the latest methodology version, the available data was adjusted to align with the methodology. Although effort has been made for the adjusted data to be as representative as possible, they may include errors or may deviate from purposely compliant assessments. As such, authors suggest updating results as required.

These results, or the proposed limit values are to be updated when any of the following changes occur:

1. The CO2data.fi materials undergo a major update, for example steel and concrete.
2. The CO2data.fi defaults for parts such as A5 impacts or building technology are updated.
3. Stricter energy efficiency regulations are introduced, or energy emission factors change.
4. The market starts to supply significantly lower carbon products with product level EPDs.
5. Once the limit values have been enforced for at least a period of one year, providing a consistent and comparable set of primary data from actual new construction projects.

8.2 Author’s recommendation for carbon footprint limit values

The authors recommend setting the whole-life carbon footprint (A-C) limit values based on steps defined in chapter 7.4. The national target aligned limit value is based on current median carbon footprints and several assumptions. This limit value takes into account the decarbonisation measures, but a 10% margin may also be added to account for factors such as increased fire safety and noise insulation, or a complex shape or height of building (see chapter 6). Based on the results, it is also justified to set a limit value based on building use type rather than having a generic value. The controlled disruption limit value is based on a set percentile of new buildings as of today that will be able to achieve a footprint below the limit value with no additional steps. It is set to control short term disruption in the construction industry to an acceptable level. The definition of further thresholds will depend on the desired outcomes.

It is the view of the authors that setting a predictable roadmap of decarbonization gives the industry the highest certainty and incentive to invest in developing and implementing low-carbon solutions. The two leaders with regulatory limit values set to decrease in advance are Denmark and France. Both have successfully communicated to the industry the intent to decarbonize at set intervals going forward to achieve national climate objectives.

Table 13. The recommended national target aligned limit values (kg $CO_2e/m^2/a$) for 2026, 2030 and 2034.

	1d	2	3	4	5	6	7	8	9	9+
CO2data.fi adjusted statistical carbon footprint (Ch. 7.2)	14	14	19	20	23	20	19	27	17	22
Decarbonization from the two most effective measures (Ch. 6.2)	-5	-4	-3	-4	-7	-4	-5	-7	-6	-8
Recommended limit value for 2026	9	10	16	16	16	16	14	20	11	14
Recommended limit value for 2030 (subject to recalibration)	7	7	9	10	11	10	9	13	9	11
Recommended limit value for 2034 (subject to recalibration)	5	5	7	8	9	8	7	10	6	8

Table 14. Example of a controlled disruption limit value for 2026 according to the 80th percentile.

	1d	2	3	4	5	6	7	8	9	9+
80th percentile of current buildings sets the limit value for 2026	15	16	20	22	24	21	20	28	20	22

Appendix 1 Carbon footprint of unmodified statistical buildings

The data presented here is the unmodified statistical data extracted from Carbon Heroes Benchmark.

Table A1.1. Unmodified statistical data for A1-A3, kg CO_2e/m^2

Building class	Median	Average	95% Conf.t.	Interval
Rowhouse	234	238	7	227-241
Residential	297	302	4	293-301
Office	271	277	16	255-287
Commercial	295	331	31	264-325
Accommodation	271	297	23	248-294
Educational	299	312	9	290-309
Sports hall	358	361	72	286-431
Hospital	306	323	46	260-352
Other building	328	342	26	302-354
Other+ (swim+ice)	272	270	50	223-322

Appendix 2 Detailed reference building assumptions

This section presents the assumptions used to model the reference building in Carbon Designer 3D and One Click LCA software, the results for which are presented in Chapter 5 in the main report body. The reference buildings for each building type under consideration were defined by applying structures and solutions typical for that building type. The calculations are based on One Click LCA's Carbon Designer 3D tool (CD3D). The tool allows calculations for a "Finnish reference building", a hypothetical yet typical building consisting of structural solutions for a specified building type. The version 2022.1 uses predominantly One Click LCA generic datapoints that have been created with CO2data.fi as a material data source. Constructions including CO2data.fi data were applied whenever a datapoint was available. Sports halls, Hospitals and class 9 Other buildings were modelled using the international reference building model, and the constructions were changed to CO2data.fi compliant ones. For these buildings, no further assumptions were made on dimensions, wall areas etc. The CO2data.fi construction site operation impacts (A5) and end of life impacts (C1-C4) were used. The operational energy use was that of statistical average presented in Chapter 3 with GWP corresponding to the 2026–2075 emission factors. A whole life carbon assessment was conducted for each reference building and their additional scenarios.

For comparability, all building types are assumed to have a similar precast concrete frame. Average building floor areas and number of floors are the same as in the 2021 report, based on Norwegian reference buildings. All baseline buildings over one floor high have one elevator as default. The assumptions are, in general, the same as with the previous study with the exception that the external paved areas have been excluded to align with the scope of the regulation. The CO2data.fi building technology values were used for all building types.

Table A2.1 Assumptions made for each building type reference building

	Attached/ Rowhouse	Residential	Office	Commercial	Accommodation	Educational	Sports	Hospital	Other	Other+
GFA	506	3216	4231	4144	2126	2668	4000	10500	1052	4000
Floors	1	4	4	2	2	2	1	4	1	2
Ref. building	FI reference building v.2022.1 (CO2data.fi/ SYKE data), Attached/ rowhouse	FI reference building v.2022.1 (CO2data.fi/ SYKE data), Apartment	FI reference building v.2022.1 (CO2data.fi/ SYKE data), Office	FI reference building v.2022.1 (CO2data.fi/ SYKE data), Retail & wholesale	FI reference building v.2022.1 (CO2data.fi/ SYKE data), hotels & similar	FI reference building v.2022.1 (CO2data.fi/ SYKE data), educational building	International reference building v2022.1, sports hall	International reference building v2022.1, hospitals & healthcare	International reference building v2022.1, warehouse	International reference building v2022.1, sports hall
Frame type	Precast concrete, column-beam	Precast concrete, column-beam	Precast concrete, column-beam	Precast concrete, column-beam	Precast concrete, column-beam	Precast concrete, column-beam	Precast concrete, column-beam	Precast concrete, column-beam	Precast concrete, column-beam	Precast concrete, column-beam
External walls + finishing	Concrete sandwich element, mineral wool, U = 0.17 W/m2K, render 10 mm	Concrete sandwich element, mineral wool, U = 0.17 W/m2K, render 10 mm	Concrete sandwich element, mineral wool, U = 0.17 W/m2K, render 10 mm	Concrete sandwich element, mineral wool, U = 0.17 W/m2K, render 10 mm	Concrete sandwich element, mineral wool, U = 0.17 W/m2K, render 10 mm	Concrete sandwich element, mineral wool, U = 0.17 W/m2K, render 10 mm	Concrete sandwich element, mineral wool, U = 0.17 W/m2K, r ender 10 mm	Concrete sandwich element, mineral wool, U = 0.17 W/m2K render 10 mm	Concrete sandwich element, mineral wool, U = 0.17 W/m2K render 10 mm	Concrete sandwich element, mineral wool, U = 0.17 W/m2K render 10 mm
Non-load-bearing walls	Steel stud internal wall assembly, incl. mineral wool insulation, 70 mm, plasterboard 13 mm on both sides	Steel stud internal wall assembly, incl. mineral wool insulation, 70 mm, plasterboard 13 mm on both sides	Steel stud internal wall assembly, incl. mineral wool insulation, 70 mm, plasterboard 25 mm on both sides	Steel stud internal wall assembly, incl. mineral wool insulation, 70 mm, plasterboard 13 mm on both sides	Steel stud internal wall assembly, incl. mineral wool insulation, 70 mm, plasterboard 13 mm on both sides	Steel stud internal wall assembly, incl. mineral wool insulation, 70 mm, plasterboard 25 mm on both sides	Concrete block internal wall assembly incl. render	Steel stud internal wall assembly, incl. mineral wool insulation, 70 mm, plasterboard 25 mm on both sides	Steel stud internal wall assembly, incl. mineral wool insulation, 70 mm, plasterboard 13 mm on both sides	Concrete block internal wall assembly incl. render
Roofing	Steel sheet roofing assembly	Steel sheet roofing assembly	Steel sheet roofing assembly	Steel sheet roofing assembly	Steel sheet roofing assembly	Steel sheet roofing assembly	Steel sheet roofing assembly	Steel sheet roofing assembly	Steel sheet roofing assembly	Steel sheet roofing assembly
Floor slabs	None	Hollow-core slab floor assembly, 370 mm slab	Hollow-core slab floor assembly, 370 mm slab	Hollow-core slab floor assembly, 370 mm slab	Hollow-core slab floor assembly, 370 mm slab	Hollow-core slab floor assembly, 370 mm slab	None	Hollow-core slab floor assembly, 370 mm slab	None	Hollow-core slab floor assembly, 370 mm slab
Floor finishes	15% Ceramic tiles + underl, 85% Laminate	20% Vinyl, 20% Ceramic tiles + underl, 60% Laminate	20% Vinyl 20% Ceramic tiles+ underl, 60% Laminate	30% Parquet, 10% Vinyl, 60% Ceramic tiles	20% Vinyl, 20% Ceramic tiles+ underl, 60% Laminate	60% Vinyl, 20% Ceramic tiles+ underl, 20% Laminate	90% vinyl, 10% ceramic tiles + underlay	80% vinyl, 20% ceramic tile	20% of floor area covered: 90% vinyl, 10% tiles. Rest concrete.	20% Vinyl 80% Ceramic tiles + underlay
Service life	Normal	Normal	short	Short	Short	Short	Short	Short	Short	Short
Stair-cases	None	1	1	1	1	1	None	2	None	None
Elevator	None	1	1	1	1	1	None	2	None	None

Table A2.2 Assumed reference building dimensions

	Rowhouse	Apartment	Office	Commercial	Accommodation	Education	Sports hall	Hospital	Other	Other+
GFA	506	3216	4231	4144	2126	2638	4000	10500	1052	4000
NHA	460	3000	4000	4000	2000	2500	3900	10000	1000	3900
Width (m)	2.8	12	14.4	8	7.2	7.2	8	14.4	6.3	8
Height (m)	69.6	63.2	64.6	70.8	73.1	104.8	98.4	160	50.5	98.4
Depth (m)	8	14	18	32.2	16	14	44.7	18	22.9	44.7
Internal floor height m	2.5	2.7	3.3	3.7	3.3	3.3	7.7	3.3	6	7.7
Int. Walls m2	857	2250	911	492	719	405	992	8734	498	992
Windows m2	101	643	846	829	425	534	800	2100	210	643

Appendix 3 Detailed reference building sensitivity scenarios

This section refers to chapter 6.1-6.3 in the main body of the report. Table A3.1 describes the assumptions used for the decarbonisation scenarios. Listed are the applicable changes and reference case construction system assumptions.

Table A3.1. Flexibility scenarios applied to reference buildings by building type

Increased footprint scenarios	**Applied changes**	**Reference case**
Increased noise insulation requirements	Brick cladding, balcony glazing (not in all building types, 8 mm for sound insulation). Default insulation is classified as soft (10-35 kg/m3 and thus works well as noise insulation).	Render finishing 10 mm, 1 m high glass railing in balconies.
Increased fire safety requirements	Increase thickness of fire-resistant gypsum plasterboard by applying an additional layer (15mm) on both sides. Add sprinkler system.	Steel stud internal wall assembly with 13 mm of fire-resistant gypsum plasterboard on both sides (25 mm for office, accommodation, educational, hospital). No added sprinkler system.
Energy performance: the building reaches E-value limit	The building has the highest allowed energy consumption and reaches the limit value. Calculated as a percentage increase in E-value. Not considered for other buildings that lack E-value limits.	Average energy consumption.
More complicated shape	The building has a rectangular shape with an atrium in the middle. The area of facades increases 43%. The number of columns increases 20%. A middle staircase is replaced by two constructions located at opposite ends of the building. Default elevators. Not considered for rowhouses, sports halls, and other buildings.	A "shoebox" shape.
Heated basement	One underground heated basement is added (rowhouses or other buildings not considered).	No basement.
A taller building	The building has more floors, affecting mainly the column dimensions and external wall dimensions. The building GFA is increased accordingly (rowhouses, sports halls and other buildings not considered).	
Decarbonisation scenarios	**Applied changes**	**Reference case**
Ground source heat pump for heating and cooling	The entire heating and cooling demand is replaced by a ground source heat pump system with COP 3. Dimensioned to 50 W/m2.	District heating and cooling, possible renewable and fossil heat production.
Achieving energy class A	Benefits from energy consumption reduction. Scenario considers only energy,	Statistical average energy consumption (in most cases

	not embodied impacts from e.g. increased use of insulation.	corresponds roughly to class B). Not accounted for hospitals.
Using concrete with a smaller carbon footprint	All ready-mix concrete replaced by CO2data.fi datapoint for "**concrete (grade), GWP.70**". Hollow core slabs replaced with corresponding slabs with 20% smaller impacts (conservative estimate)	Datapoint "Concrete (grade), GWP.REF"
CLT frame structure	Considered fire safety levels: P3 R0: Rowhouse; P3 R60 residential, office, commercial, accommodation, school, hospital	
	External wall, CLT: 1. CLT element 100 mm for rowhouse, commercial, accommodation, educational, sports hall, other building; 120mm for residential, office, hospital. 2. Vapor barrier. 3. Insulation (glasswool) 150mm. 4. Windscreen (glasswool) 50mm. Cladding: Wooden cladding 20 mm + wooden lathes, painted.	External wall concrete sandwich element with 220 mm mineral wool insulation. Cladding: Render finishing with glass fibre reinforcing mesh, 10 mm, water-borne paint for exteriors
	Internal wall, load bearing: CLT element, 100 mm, gypsum plasterboard, hard, fire resistant 875 kg/3m 18 mm, glass wool insulation 50 mm.	No load-bearing walls
	Internal wall, non-bearing: wooden stud internal wall assembly: 1. gypsum plasterboard 13 mm, wooden frame with 600 mm spacing, glass wool insulation 75 mm, gypsum plasterboard 13 mm.	Steel stud internal wall assembly, incl. mineral wool insulation, 70 mm and plasterboard 13 or 25 mm on both sides.
	Floor slab: Floor slab, CLT. 1. Levelling 50mm, 2. Reinforcement mesh fabric (glass fibre), 3. Acoustic insulation (mineral wool) 50mm, 4. CLT element 240mm, 5. Fire resistant gypsum board (K2 30, A2-s1, d0) 18mm for Residential and Office.	Hollow-core slab floor assembly, 370 mm slab
	Roof: Flat roof, timber joists, U ≤ 0.09 W/m2K. 1. Gypsum plasterboard, fire resistant, 2. supporting timber rails, 3. vapour control layer, 4. glass wool insulation panels 400 mm + 50 mm, 5. timber beams, 6. plywood underlayment.	Roof slab, for apartment building, concrete slab, U= 0.09 W/m2K
	Other elements: sprinkler system, assumption 700 m of pipes per 1000 m2	No sprinkler system

Appendix 4 Terms and abbreviations

Carbon footprint – term describing only the impact indicator GWP (global warming potential), with a unit kg CO_2e.

CO2data.fi – National emissions database of Finland.

CD3D – Carbon Designer 3D.

Embodied carbon – Carbon embodied in the materials, includes life cycle stages A1-A5, B1-B5, C1-C4, i.e., excludes only the operational carbon.

EPD – Environmental Product Declaration as per ISO 14025 and EN 15804.

LCA – Life cycle assessment as per ISO 14040 and 14044. EN 15978 set the standard for assessment of environmental performance of buildings.

Life cycle stages and modules

- A1-A3
  - Includes product stage modules A1: raw material extraction and processing, A2: raw material transport, A3: product manufacturing
- A4
  - Transport to construction site
- A5
  - Construction site activities: All energy and waste flows related to assembly and installation.
- B4
  - Use phase module describing the emissions from replacement of a material after its service life, within the assessment period of a building.
- B6
  - Use phase operational emissions from energy consumption of a building during the assessment period (electricity, heating, cooling).
- C1-C4
  - End-of-life stage including modules C1: deconstruction, C2: transport to waste processing/final disposal, C3: waste processing, C4: final disposal.