Life cycle GHG emissions of the Austrian building stock

A combined bottom-up and top-down approach

Truger, B.; Nabernegg, S.; Lackner, T.; Röck, M.; Alaux, N.; Hoxha, E.; Saade, M. Ruschi Mendes; Passer, A.

Published in:
IOP Conference Series: Earth and Environmental Science

DOI (link to publication from Publisher):
10.1088/1755-1315/1078/1/012024

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

PAPER • OPEN ACCESS

Life cycle GHG emissions of the Austrian building stock: A combined bottom-up and top-down approach

To cite this article: B Truger *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1078** 012024

IOP Conf. Series: Earth and Environmental Science 1078 (2022) 012024 doi:10.1088/1755-1315/1078/1/012024

Life cycle GHG emissions of the Austrian building stock: A combined bottom-up and top-down approach

B Truger[1]*, S Nabernegg[2], T Lackner[2], M Röck[1,3], N Alaux[1], E Hoxha[1,4], M Ruschi Mendes Saade[1], A Passer[1]*

[1] Graz University of Technology, Institute of Structural Design, Working Group Sustainable Construction, Technikerstraße 4, 8010 Graz, Austria

[2] University of Graz, Wegener Center for Climate and Global Change, Brandhofgasse 5/I, 8010 Graz, Austria

[3] KU Leuven, Design and Engineering of Construction and Architecture, Leuven (Arenberg), Belgium

[4] Aalborg University, Department of the Built Environment, A. C. Meyers Vaenge 15, 2450 Copenhagen SW, Denmark.

*barbara.truger@tugraz; alexander.passer@tugraz.at

Abstract. Construction and operation of buildings are responsible for 37% of global greenhouse gas (GHG) emissions. In contrast, the Austria's National Inventory Report attributes a mere 10% of national emissions to buildings – including only direct operational emissions of residential and service sector buildings. This narrow definition of the buildings sector neglects important environmental hotspots attributable to building-related life cycle emissions and calls for a comprehensive analysis of GHG emissions of Austrian buildings. In this study, we assess annual building related GHG emissions for the Austrian building stock from a full life cycle perspective (i.e. including operational and embodied emissions). For embodied emissions, we model emissions using both a process-based and an input-output based life cycle assessment (LCA) approach. Building LCA case studies and statistical building stock data are used to estimate embodied emissions from a bottom-up perspective, which are complemented by estimated emissions from the input-output based LCA approach. Our work illustrates the importance of adopting a life-cycle perspective on building-related emissions to inform the different stakeholders and advance climate action in the built environment. While both the chosen system boundaries and methods significantly determine the results, we argue that emission reduction measures should be based on a comprehensive system boundary of building-related emissions to contribute towards the achievement of a climate-neutral built environment and the stringent climate targets. By adding indirect emissions and non-residential buildings to the officially reported building emissions, the operational emissions alone increase by a factor of 2.4. As expected, the process-based LCA yields lower embodied emissions than the input-output based approach. Depending on the method, they can be responsible for up to 40% of total buildings related emissions. Summing up, total buildings related emissions rise by a factor of 3 to 4 when extending the system boundaries to comprise the whole area of action buildings, and go from 7 Mt CO_2-eq/a (direct operational emissions, 10% of national emissions), to 22-31 Mt CO_2-eq/a for the case of Austria.

Keywords: building related emissions, life cycle assessment, input-output based LCA, process-based LCA, building stock

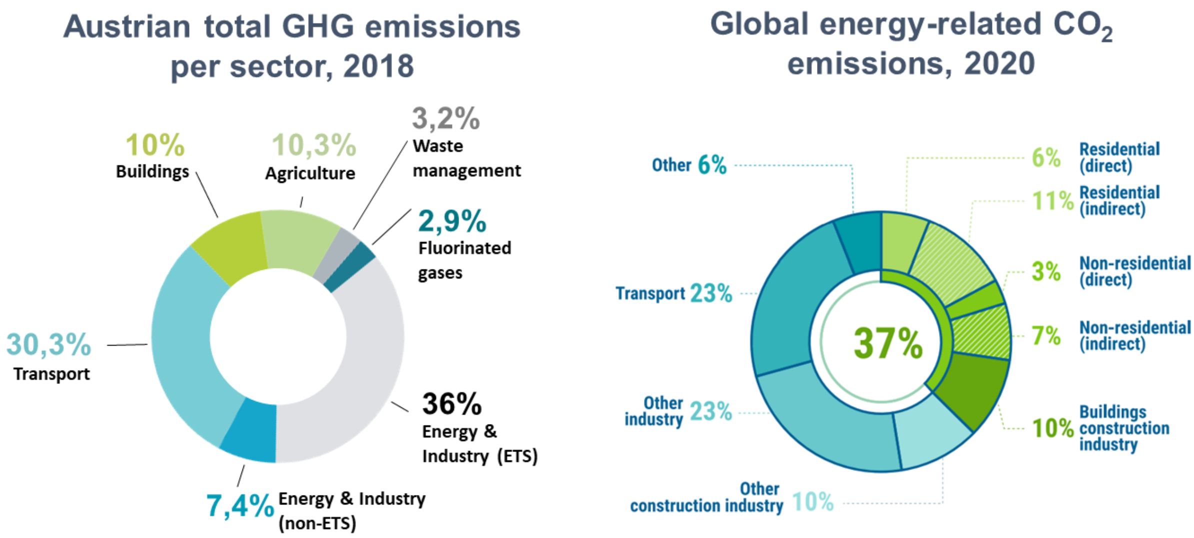
1. Introduction

The construction and operation of buildings is responsible for 37% of global energy-related CO_2 emissions [1]. The European Green Deal attributes 40% of energy consumption to buildings, and calls for a renovation wave across Europe. Moreover, the European Commission states that "*To achieve the 55% emission reduction target, by 2030 the EU should reduce buildings' greenhouse gas emissions by 60%, their final energy consumption by 14% and energy consumption for heating and cooling by 18%*"[1][2].

In order to set – and fulfill – targets for buildings related emissions, it is essential to define the activities included in the target, as well as calculate the current level of emissions which is to be reduced. The buildings related emissions assessed in [1] include direct and indirect emissions arising from the pre-use and the use-phase of residential and non-residential buildings (right side of Figure 1). In contrast, the national climate protection law in Austria, which constitutes the basis for emission reporting under the UNFCCC framework, attributes only operational emissions of residential and service sector buildings induced directly at the edifice to the buildings sector, amounting to 10% of total national GHG emissions (left side of Figure 1). Applying this definition to the global level, Figure 1 (right side) shows that it only covers 24% of total building-related emissions (i.e. (6+3)/37). This narrow definition of the buildings sector is useful in the context of production-based emission accounting within the UNFCCC framework but does not give a comprehensive estimate of life cycle emissions attributable to the national building stock, which eventually should be addressed to achieve a climate-neutral built environment. Life-cycle emissions additionally comprise emissions from electricity and district heat consumption during the use phase and embodied emissions induced during the production or renovation phase of buildings. Against this background, we claim that the definition of building-related emissions followed by [1] at the global level is particularly useful to derive emissions of what we will subsequently call the "field of action" of buildings at the level of a single country. While this definition goes beyond the principal of territorial emission accounting, it constitutes a comprehensive system boundary based on which environmental hotspots of the national building stock can be identified from a life cycle perspective rather than from the use-phase only. This view becomes even more important with increasing renovation, energy efficiency standards and increased renewables in the energy mix which successfully reduce operational emissions but tend to increase embodied emissions occurring domestically and abroad through imports of building-related construction materials.

We therefore aim to assess Austria's building related emissions including all relevant emission sources of the field of action. We use a process-based life cycle assessment (LCA) to estimate annual emissions related to buildings in Austria and cross-check the results with an input-output LCA estimate. The paper is structured as follows. Section two first outlines the detailed system boundary "field of action" buildings, which we apply to estimate annual GHG emissions of the national building stock for the case of Austria (section 2.1). Section 2.2 describes the methodological approach to estimate annual operational emissions. Section 2.3 describes the combined process-based and input-output based life cycle assessment (LCA) approach to estimate annual embodied emissions related to the national building stock. Section 3 summarizes and discusses our main results. Finally, section 4 concludes.

[1] Compared to 2015 levels.



Source:
Umweltbundesamt 2020 Klimaschutzbericht 2020, REP-0738, Wien.

Source: UNEP (2021)
https://globalabc.org/our-work/tracking-progress-global-status-report

Figure 1. Austrian (left) and global (right) buildings emissions, based on different system boundaries.

2. Methodology and data

The Austrian building stock causes emissions through different activities. Existing buildings contribute to GHG emissions by their operation, i.e. their heating, cooling and electricity demand. Additionally, embodied emissions are caused by the construction, refurbishment and demolition of buildings. To assess these emissions, we use different methods and databases. The estimation of operational emissions is based on the Austria's Useful Energy Analysis (UEA) and emission factors for the different energy production technologies. For the embodied emissions, we apply two methods, a process based LCA and an input-output based LCA, as also shown in [3].

2.1. "Field of action" buildings

Based on the considerations in the introduction and [1], we suggest the following comprehensive system boundary of annual building-related GHG emissions on a country level (comp. Figure 2), comprising the whole "field of action" for buildings. First, we include emissions from residential and non-residential (i.e., service and industry sector) buildings which together form the total building stock in a country. Second, we account for different emission scopes, including operational and embodied emissions. We define operational emissions to be emissions arising through space heating and cooling, including hot water supply as well as emissions from building's maintenance and real estate service activities. Space heating and cooling emissions can be further distinguished between direct and indirect operational emissions. Direct emissions refer to all emissions whose sources are located physically in the building (e.g., fossil fuel consuming equipment for water and space heating). Indirect operational emissions arise from energy consumption (i.e., electricity and district heat) in the building, including also emissions in the fuel supply chain. Embodied emissions originate from production activities for construction materials and transport as well as building-related (de-)construction activities across the building life cycle. They comprise direct emissions arising at the building site itself, transport, waste and disposal activities at the end-of-life as well as emissions embodied in deployed building materials. Thus, embodied emissions also consider indirect emissions arising in regional and global supply chains of the building-related construction industry (comp. also [4–6]).

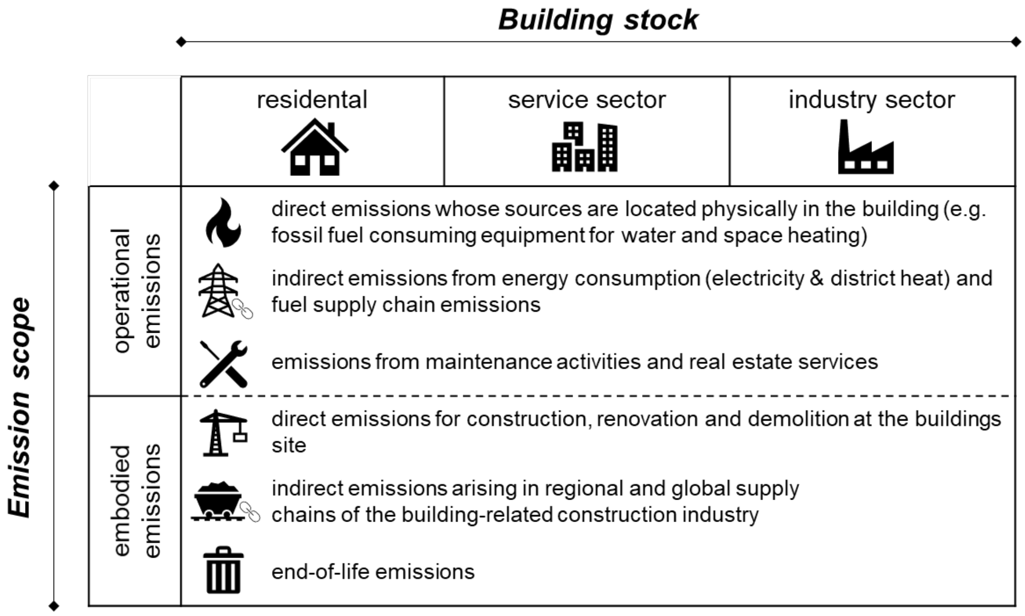


Figure 2. Proposed system boundary of the "field of action" for buildings, to be considered for emission evaluation of a national building stock.

2.2. *Operational emissions*
In national assessments, buildings related emissions and operational emissions of buildings are often seen as equivalent, even if only direct operational emissions are accounted for (see section 2.1.). To assess operational emissions on the national level, we use a more comprehensive system boundary to also include indirect operational emissions from electricity use and district heating, as well as non-residential buildings.

To calculate the operational emissions, we use both statistical data on the energy consumption as well as LCA-based emission factors. The Useful Energy Analysis (UEA) 2014 by Satistics Austria [7] provides the final energy demand for heat, warm water and lighting by energy carrier in private households as well as 16 services and industry sectors. To calculate associated GHG emissions, required emission factors are derived from the ecoinvent database [8], which includes both direct emissions of the fuels' burning and indirect emissions occurring at other life cycle stages, e.g. fuel extraction, transport and infrastructure. For energy carriers which were not sufficiently covered in the ecoinvent database for the Austrian context, e.g. district heating, we used emission factors provided by the climcalc tool[2].

Multiplying sector-specific energy consumption per carrier and the respective emission factor yields operational emissions of Austrian buildings, differentiated by economic sectors to represent non-residential buildings and private households to represent residential buildings.

2.3. *Embodied emissions*
Embodied emissions arise from the production of materials for construction and maintenance, as well as building-related activities themselves, like the construction sector. To evaluate these emissions, we use life cycle assessment, which allow to estimate environmental impacts over the entire life cycle, including raw material extraction, production, use phase and disposal [9]. As main approach we employ a process-based LCA of buildings to estimate national embodied emissions through a bottom-up perspective, supplemented by statistical data on the national building stock. To complement this

[2] https://nachhaltigeuniversitaeten.at/arbeitsgruppen/co2-neutrale-universitaeten/

assessment, we provide estimates from an Input-Output based LCA, which are based on a top-down macroeconomic point of view.

2.3.1. Process-based LCA approach. The process-based assessment of the embodied emissions of buildings is based on building LCA data from the study of [10], and building stock data from Statistics Austria [11], supplemented by data from TU Wien's Energy Economics Group.

The LCA data builds upon a meta-study of published building LCA studies conducted in the context of the IEA EBC Annex 72 as presented in [10]. The data were harmonised to a reference service life of 50 years and given per square meter gross floor area (GFA) and year (kg CO_2-eq/m^2a). Out of the global data set of LCA studies, a limited sample was defined including only studies from Austria and neighbouring countries, or studies from European countries in the same climate zone as Austria. As a result, 354 building LCA case studies, mostly residential or office buildings, were analysed in this study. These studies are characterized according to seven different building types. To estimate the embodied emissions of new buildings' construction, the case studies were first filtered to include only new construction or existing building cases (271 cases), and cases which state embodied emissions separately (194 cases). In order to ensure the comparability of the studies, they were further filtered by their scope, i.e. the life cycle stages and building elements considered in the respective study, applying the life cycle phase model of the related standard for building LCA, EN 15978. Only studies including life cycle stages of modules A (production and construction), B (use stage), and C (deconstruction) were included in the analysis (163 cases). These were further filtered to only consider studies including all most relevant building parts (i.e., structure, internal elements, building services, and foundation). The final sample includes 87 building LCA case studies. The mean value of the embodied GHG emissions per area and year was estimated per building type, and also per LCA module.

In order to assess the total embodied emissions of new construction in Austria, statistical data on new construction was analysed and filled in with data from TU Wien for better detail in building types (e.g. dividing "office buildings" into small and large office buildings). The newly constructed area per building type was then multiplied by the estimated emission value for module A, considering the entire emissions not divided by the buildings' estimated service life.

Refurbishment case studies for module B5 are assessed separately from the same basis of case studies, as well as additional literature. 64 case studies out of the original 354 case studies were used, including residential buildings and non-residential buildings, but no office buildings were in the studied sample. Refurbishment emissions for office buildings are based on [12].

The estimated emission factors for different building types and life cycle stages are applied to different building stock data. While the emission factors were originally harmonized to a reference service life of 50 years, and given in kgCO_2-eq/m^2a, the embodied emissions occur in the year of construction (or replacement/refurbishment/demolition) and are therefore used in kgCO_2-eq/m^2. Module A1-A3 is multiplied by the area of newly constructed buildings in 2014 [13]. Modul B4 (replacement) is based on the building stock built before 1990, with the assumption that 1% of the buildings go through replacement every year. The refurbishment rate for module B5 is set to 1,5% of the whole building stock [14]. For the end of life (module C), data on the demolishing of buildings from Statistics Austria was used. Multiplying the respective building stock data with the average emission factors gives an estimate of yearly embodied emissions of buildings in Austria.

2.3.2. Input-Output LCA approach and comparison. To compare the emission estimates of the process-based LCA, we complement our analysis by a cross-check, using an Input/Output (I/O) LCA.

The boundary selection of process-based LCAs necessarily implies a truncation bias, potentially leading to underestimations [15] amounting up to tens of percentage points at the building level [16].

Input-output LCA, first introduced by Leontief in the 1970s [17], exhibits a broader, top-down perspective than process-based LCA by considering the whole economy. Based on economic Input-Output matrices, I/O LCA estimates environmental impacts of final demand along international supply chains [18]. While Input-Output tables translate a transaction in one economic sector into the distribution of value added across the whole economy, the environmental impact of this transaction is assessed by extending the I/O tables by sector-specific emission intensities. This achieves full system completeness and does not lead to a truncation bias [15]. However, related uncertainties with this approach stem from the underlying assumptions that the (weighted) average values reported in the I/O tables are representative for all products and firms of a specific sector (i.e. homogeneity assumption and aggregation error) and that emissions linearly correlate with the product's market price (i.e. linearity assumption) [19,20]. Despite its limitations, the environmentally extended I/O analysis is particularly suited to assess entire sectors [20] and thus to cross-check our results obtained by the process-LCA approach.

Building on the approach of [21] and [22], we conduct an environmentally extended multi-regional I/O analysis based on the Global Trade Analysis Project (GTAP) database V10 [23] with base year 2014. We construct an emission data set for this base year by following a similar approach as in [22] and include industrial process emissions for each region, as this type of emissions appears especially relevant for building materials such as steel and cement. Based on this newly constructed emissions data base and the economic GTAP data base, we calculate consumption-based GHG emissions of the Austrian economy on a sectoral level, see also [24]. The I/O model is specified as

$$e^* = \boldsymbol{e}\,\hat{\boldsymbol{x}}^{-1}\,(\boldsymbol{I} - \boldsymbol{Z}\hat{\boldsymbol{x}}^{-1})^{-1}\hat{\boldsymbol{y}}$$

with:

e^*	Vector of emissions re-allocated on the basis of consumption-based accounting
e	Vector of sectoral emissions allocated according to a production-based principle across countries
$\hat{x}$	Diagonalized vector of sectoral outputs across nations
I	Identity matrix
Z	Matrix of intermediate inputs within and among regions
$\hat{y}$	Diagonalized vector of sectoral final demands across countries

We further decompose sectoral emissions into regional and sectoral sources by using a diagonalized vector of region-specific sectoral emission intensities $\widehat{e_r\hat{x_r}^{-1}}$, for the example of Austria as region r, instead of a matrix of sectoral emission intensities of all regions $e\,\hat{x}^{-1}$ in the above specification. More details on the MRIO specifications can be found in [21,25].

Referring to the outlined system boundary of the "field of action" for buildings, we consider emissions induced by final demand of private households and the government and investment demand by firms for goods and services produced by building-related sectors. Also, we include emissions induced by intermediate demand of economic sectors for these building-related goods and services, which we calculate by applying the emission factors derived from the I/O analysis. Building-related sectors include construction (NACE sectors 41 and 43), real estate activities (NACE sector 68) and services to buildings and landscape activities (NACE sector 81). Embodied emissions estimated by the I/O approach thus include all building types (i.e., residential, service sector and industry buildings) located in Austria that are newly built, maintained or renovated in a given year. They include direct emissions that arise at the construction site itself and indirect impacts attributable to uncut international upstream supply chains of the building-related construction industry. However, end-of-life emissions beyond direct demolition works that occur outside of the building-related construction sector (e.g., transport, recycling and disposal of materials) are not captured by this estimation.

Given the different nature of process-based and I/O LCA, estimating emissions based on a (preferably) common system boundary yields diverging results. I/O LCA tends to produce significantly higher estimates than process-based LCA (comp. [26,27]). Even at the level of a single building, I/O

LCA is found to estimate emissions up to twice as high as process-based estimates [15]. While it is difficult to trace back the exact sources of the difference in results [15], the aim of using both approaches is to obtain a validated range of building-related emissions and identify environmental hotspots of the building sector from a life-cycle perspective.

3. Results and discussion

The embodied emissions of buildings per m^2 GFA according to process-based LCA are given in Figure 3, by building type. The results vary, but especially building types with more case studies (single-family houses, multi-family houses, large office buildings) give a good indication where the emissions can lie. Module A, which includes the manufacturing of the building materials as well as the construction process, has the highest share of emissions on the building level across all building types with 61%, followed by module B1-B4 with 25% and module C with 13%. A study on the emissions by life cycle stages shows similar results with 64% for module A, 22% at module B, and 14% of module C [28].

Total embodied emissions of 4.3 Mt CO_2-eq/a, derived by the process-based approach. Their decomposition shows that 66% of the embodied emissions per year are allocated to residential buildings, which also make up the largest part of the building stock and new construction activities (see Figure 4). Non-residential service buildings and industry buildings account for 22% and 12% of the emissions, respectively. From a life cycle stage point of view, 45% of yearly embodied emissions are released through new construction activities, followed by renovation activities with 40%. Maintenance and replacement, as well as demolition at the end of life have lower impacts in comparison, with 15% and 1%, respectively.

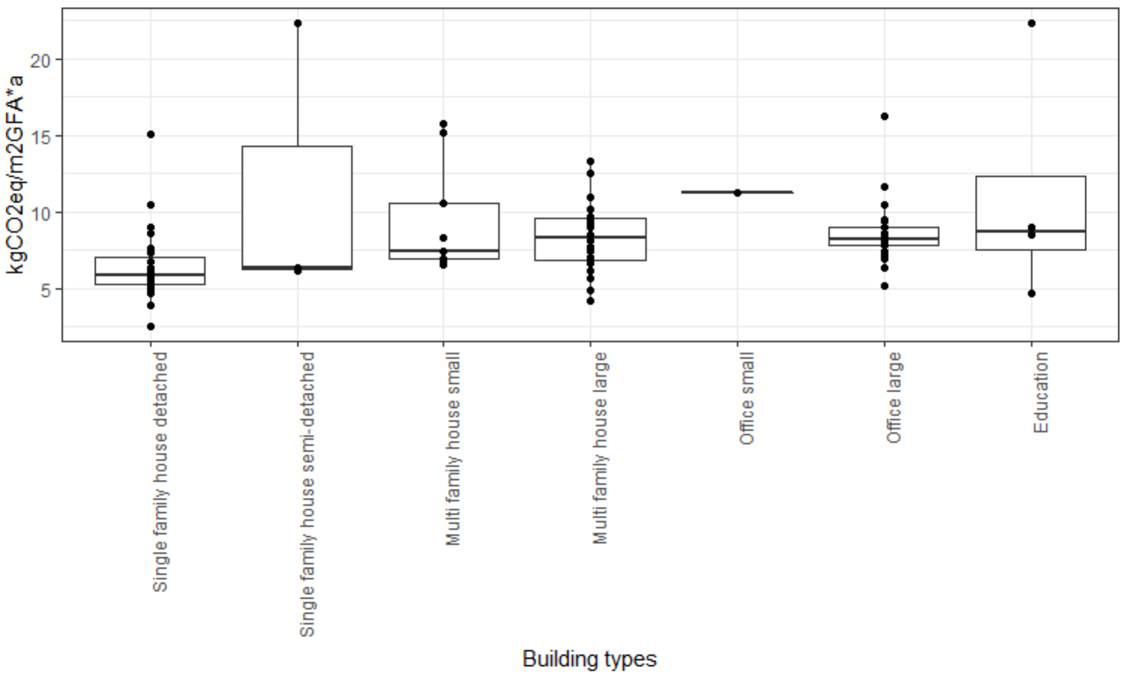


Figure 3. Embodied emissions per m2 GFA and year from the LCA case studies by building type.

Although the LCA studies were filtered by their scope regarding building elements and life cycle stages, there can still be considerable differences in details – and hence, in the results. Especially technical and electrical equipment are often neglected in LCAs. [29] show significant differences between a simplified and a very detailed LCA for an office building case study. Thus, we propose to use a correction procedure to the LCA results with lacking detail in the calculations. [29] use an office building at a university as a case study. The detailed LCA accounts for embodied emissions that are 66% higher than the simplified version, with the largest gaps happening in life cycle stages A1-A3 (electrical and technical equipment, internal walls) and B4 (replacement of electrical and technical equipment). As the emission gap is dependent on the life cycle stage and was quantified for an office building it is not directly applicable to residential buildings as well. As multiplying simplified LCA results with low calculated emissions with a correction factor may enforce the underestimation, we propose instead to add an absolute emission amount for the relevant life cycle stages, such as technical equipment. Correcting the emission factors on the building level yields the result of 4.8 Mt CO_2-eq/a instead of 4.3 Mt CO_2-eq/a (+12%).

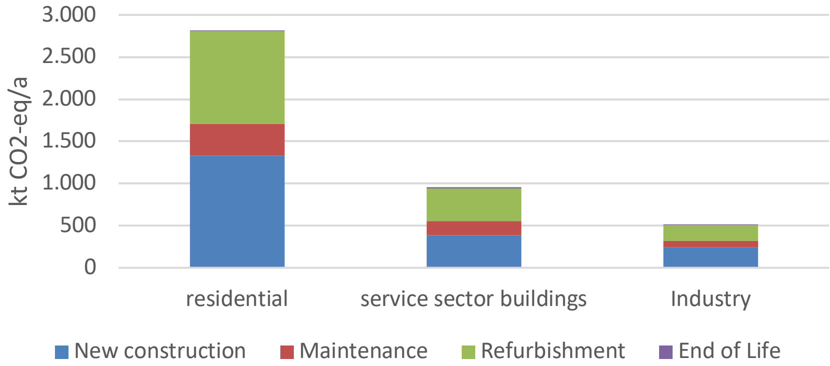


Figure 4. CO_2-eq/year by life cycle stage, process-based approach.

Finally, we can give an indication of the total annual building related emissions in Austria (see Figure 5). The direct operational emissions of residential and service sector buildings, which were stated as 10% of national emissions in Figure 1, account for 7.0 Mt CO_2-eq/a. Additionally, we consider operational emissions of industry buildings (1.2 Mt CO_2-eq), and indirect emission through the supply chain, including the use of electricity and district heat (8.9 Mt CO_2-eq). All in all, the operational emissions of the Austrian building stock were estimated to account for 17.1 Mt CO_2-eq/a.

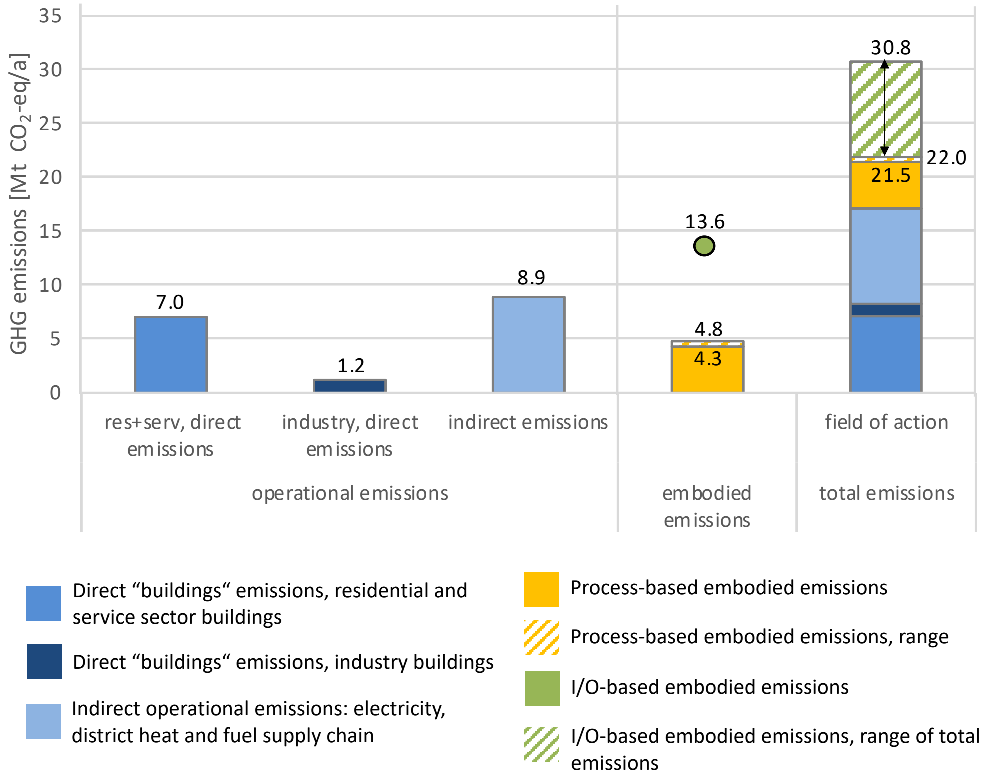


Figure 5. Composition of annual GHG emissions attributable to the Austrian field of action buildings in 2014

The embodied emissions, estimated by the process-based LCA, add further 4.3 Mt CO_2-eq. This number is significantly higher when using the I/O LCA (13.6 Mt CO_2-eq, shown in green). Since the process-based approach can underestimate the emissions, a correction factor was used to account for lacking detail in the LCA studies. With this factor, the results are closer to the I/O based results with 4.8 Mt CO_2-eq. The height of the correction factor was roughly estimated and needs further research, but shows that it can close part of the emission gap between process-based and I/O based LCA results.

The total emissions of the field of action buildings lie between 22 and 30.8 Mt CO_2-eq/a, depending on the method.

4. Conclusion

The emission estimates shown in this study indicates that the “field of action” for buildings to decrease overall GHG emissions goes beyond direct operational energy and is linked to the development in many economic sectors (e.g., industry, energy and heating sector). In this context, adopting a full life cycle perspective is crucial as it reveals important emissions “embodied” in building-related processes (e.g., material production, transport, refurbishment or end-of-life). Investigating the „field of action” for buildings at the national level allows to identify environmental hotspots in the life cycle of buildings located in a specific country, and related economic sectors whose emission reductions affect building-related emissions most.

Since the field of action buildings draws from various economic sectors, a comparison of emissions to those of other sectors or fields of action can be challenging. The intersectionality of the approach needs to be considered to avoid double counting. We therefore suggest to use the “field of action” buildings in order to raise awareness of policy makers and stakeholders regarding buildings related emissions and their sources within the building and construction sectors all over the world, rather than to include it in national emission accounting. The field of action helps stakeholders involved in the building design process to understand the complexity of buildings related emissions and the emission hotspots which should be targeted first to reduce the emissions of buildings.

When assessing GHG emissions, clear definition of scope is essential. In this study, we aimed for a comprehensive view of the field of action buildings. When considering "buildings" responsible only for direct operational emissions of residential and service buildings, as seen in Figure 1 (left part) and Figure 5 (left bar), the emissions amount to 7 Mt CO_2-eq/a. Adding indirect emissions through electricity and district heating, as well as emissions embodied in building materials and construction activities to the analysis, the total emissions are 3 to 4 times higher. This result is similar to the global estimate given in Figure 1, where direct residential emissions account for a quarter of buildings related emissions. This information can provide a valuable basis for stakeholders (from building design professionals to policy makers on a regional and national level) aiming to create a climate-neutral building stock and for the achievement of (national) climate targets.

The embodied emissions include different activities, from the production of building materials to the construction and demolition of buildings. Embodied emissions account for a significant share of 20-44% of total buildings related emissions, depending on the method used for estimation. While the inherent differences between process-based and I/O based approaches are acknowledged in the literature [15], we provide an adjustment for process-based LCAs to correct underreporting to (slightly) reduce the gap between the different approaches.

For mitigating climate change, it is important not to neglect emission sources. Our study highlights the importance of considering the whole life cycle of buildings, as well as the benefits of complementing process-based assessment with an I/O approach. To minimise building related emissions in the future, increasing energy efficiency and the use of renewable energy for operation is required but will not be enough. Moving towards a carbon-neutral building stock, all relevant emissions including in particular those emissions 'embodied' in building-related processes, have to be considered and reduced in line with dedicated climate targets.

Acknowledgement
This paper was developed in the course of the ongoing research project "Transition of the procurement process towards Paris compatible public buildings" (ParisBuildings), conducted by the Working Group on Sustainable Construction from the Graz University of Technology and the Wegener Center of the University of Graz. The project is financially supported by the Klima- und Energiefonds, ACRP11 KR18AC0K14693.

References

[1] UNEP. Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. Nairobi: 2021.
[2] European Commission. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives. Brussels: 2020.
[3] Lackner T, Nabernegg S, Truger B, Steininger KW, Passer A, Röck M. Towards a climate-neutral building stock – GHG emissions of Austrian buildings. 13. Input-Output-Workshop, 2021.
[4] Environment GA for B and C& UN. GLOBAL ROADMAP TOWARDS LOW-GHG AND RESILIENT BUILDINGS | Globalabc 2016. http://globalabc.org/resources/publications/global-roadmap-towards-low-ghg-and-resilient-buildings.
[5] Agency IE, Programme the U nations E. 2018 Global Status Report: towards a zero-emission, efficient and resilient buildings and construction sector. 2018.
[6] Onat NC, Kucukvar M. Carbon footprint of construction industry: A global review and supply chain analysis. Renew Sustain Energy Rev 2020;124:109783.

https://doi.org/10.1016/j.rser.2020.109783.
[7] Statistik Austria. Useful energy analysis 2020. http://www.statistik.at/web_en/statistics/EnergyEnvironmentInnovationMobility/energy_environment/energy/useful_energy_analysis/index.html.
[8] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 2016;21:1218–30. https://doi.org/10.1007/s11367-016-1087-8.
[9] Klöpffer W, Grahl B. Life Cycle Assessment (LCA): A Guide to Best Practice. John Wiley & Sons; 2014.
[10] Röck M, Saade MRM, Balouktsi M, Rasmussen FN, Birgisdottir H, Frischknecht R, et al. Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. Appl Energy 2020;258:114107. https://doi.org/10.1016/j.apenergy.2019.114107.
[11] Statistik Austria. STATcube – Statistische Datenbank von STATISTIK AUSTRIA. Registerzählung 2011 - GWZ: Gebäude (Q SW). 2021.
[12] Marique A-F, Rossi B. Cradle-to-grave life-cycle assessment within the built environment: Comparison between the refurbishment and the complete reconstruction of an office building in Belgium. J Environ Manage 2018;224:396–405. https://doi.org/10.1016/j.jenvman.2018.02.055.
[13] Statistik Austria. 2005 bis 2019 fertiggestellte neue Gebäude nach Gebäudeeigenschaften und Bundesländern. 2021.
[14] Amman W, Storch A, Schieder W. Definition und Messung der thermisch-energetischen Sanierngsrate in Österreich. Wien: 2020.
[15] Säynäjoki A, Heinonen J, Junnonen J-M, Junnila S. Input–output and process LCAs in the building sector: are the results compatible with each other? Carbon Manag 2017;8:155–66. https://doi.org/10.1080/17583004.2017.1309200.
[16] Lenzen M, Treloar G. Embodied energy in buildings: wood versus concrete—reply to Börjesson and Gustavsson. Energy Policy 2002;30:249–55. https://doi.org/10.1016/S0301-4215(01)00142-2.
[17] Leontief W. Environmental repercussions and the economic structure: an input-output appraoch. Routledge: 2018.
[18] Chang Y, Ries RJ, Wang Y. The embodied energy and environmental emissions of construction projects in China: An economic input–output LCA model. Energy Policy 2010;38:6597–603. https://doi.org/10.1016/j.enpol.2010.06.030.
[19] Crawford RH. Life Cycle Assessment in the Built Environment. Spon Press; 2011.
[20] Crawford RH, Bontinck P-A, Stephan A, Wiedmann T, Yu M. Hybrid life cycle inventory methods – A review. J Clean Prod 2018;172:1273–88. https://doi.org/10.1016/j.jclepro.2017.10.176.
[21] Muñoz P, Steininger KW. Austria's CO2 responsibility and the carbon content of its international trade. Ecol Econ 2010;69:2003–19. https://doi.org/10.1016/j.ecolecon.2010.05.017.
[22] Steininger KW, Munoz P, Karstensen J, Peters GP, Strohmaier R, Velázquez E. Austria's consumption-based greenhouse gas emissions: Identifying sectoral sources and destinations. Glob Environ Chang 2018;48:226–42. https://doi.org/10.1016/j.gloenvcha.2017.11.011.
[23] Aguiar A, Chepeliev M, Corong EL, McDougall R, Mensbrugghe D van der. The GTAP Data Base: Version 10. J Glob Econ Anal 2019;4:1–27. https://doi.org/10.21642/JGEA.040101AF.
[24] Nabernegg S. Emission distribution and incidence of national mitigation policies among households in Austria. Graz Econ Pap 2021;2021–12.
[25] Miller RE, Blair PD. Input-output analysis: foundations and extensions. Cambridge university press; 2009.
[26] Takano A, Winter S, Hughes M, Linkosalmi L. Comparison of life cycle assessment databases: A case study on building assessment. Build Environ 2014;79:20–30.

https://doi.org/10.1016/j.buildenv.2014.04.025.
[27] Zhu W, Feng W, Li X, Zhang Z. Analysis of the embodied carbon dioxide in the building sector: A case of China. J Clean Prod 2020;269:122438. https://doi.org/10.1016/j.jclepro.2020.122438.
[28] Moncaster AM, Rasmussen FN, Malmqvist T, Houlihan Wiberg A, Birgisdottir H. Widening understanding of low embodied impact buildings: Results and recommendations from 80 multi-national quantitative and qualitative case studies. J Clean Prod 2019;235:378–93. https://doi.org/10.1016/j.jclepro.2019.06.233.
[29] Hoxha E, Maierhofer D, Saade MR., Passer A. Influence of technical and electrical equipment in life cycle assessments of buildings: case of a laboratory and research building. Int J Life Cycle Assess 2021;26:852–63. https://doi.org/10.1007/s11367-021-01919-9.