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# Absolute sustainable $CO_2$-limits for buildings should reflect their function. A case study of four building typologies

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ABSTRACT

Absolute sustainability gains increasing attention in the building industry. Absolute climate limits is often expressed in kg $CO_2$-eq/$m^2$/yr. This type of threshold has one main problem; it is specified per area, which rewards larger buildings regardless of the need that they fulfill. This way of setting climate limits may thus lead to increased future impacts from buildings. The purpose of this study is developing principles for differentiated $CO_2$-limits for buildings, that reflect the importance of the function that the building delivers to its users. We use the Fulfillment of Human Needs sharing principle building on a sufficientarian ethical norm. The method was demonstrated on four buildings; residential, university, hospital and kindergarten, and guidance is given on how to apply the method for any building typology. This study should be seen as demonstration of a concept for determining different $CO_2$-limits for different building typologies.

## 1. Introduction

Over the last decade Greenhouse gas emissions (GHG) have reached the highest levels in human history (IPCC, 2022). If humanity does not succeed in limiting global warming to 1.5 °C or 2 °C there is a high risk of destabilizing the climate stability of the Holocene epoch which has been essential to maintain the conditions on Earth livable for humanity to thrive (Steffen et al., 2015). Exceeding the global warming threshold of 2 °C is predicted to entail comprehensive consequences for humanity and wildlife, thus, urgent action for emission reductions across all sectors is needed (IPCC, 2022). Since the building industry is responsible of 36% of the European GHG emissions (European Commission, 2020) and the projected urbanisation trend towards 2050 (cities are expected to house additional 2.5 billion people in 2050) will require a significant increase of the build area compared to today (United Nations, 2018), there has been a strong urge both in academia, politics and the building industry to set climate impact limits for buildings. We use the term climate impact limits throughout this paper, since it is not a climate target that should be reached but rather a boundary that cannot be exceeded. Recently, absolute sustainability has gained attention in the building industry enabled by a wish to setting climate impact limits (Reduction Roadmap, 2022; Bolig og planstyrelsen, 2022a). Absolute sustainability is operationalised on product level through absolute environmental sustainability assessments (AESAs) (Ryberg et al., 2018). An AESA consists of a life cycle assessment (LCA) of a product where the calculated environmental life cycle impacts are compared to the share of the safe operating space (SoSOS) that is assigned to the product. The SoSOS is determined by downscaling the global safe operating space to product level through different sharing principles. The global safe operating space, the starting point for downscaling, can be determined with different methods, as described by Vea and colleagues (Vea et al., 2020).

The choice of sharing principle is decisive for the result of an AESA, and it is therefore of imperative importance to report it in a transparent manner (Ryberg et al., 2016). There is currently no consensus on the sharing principle or downscaling method to use. The sharing principles most commonly used are based on egalitarian (equal per capita, EPC), utilitarianism (gross value added, GVA) and inegalitarianism or acquired rights (grandfathering, GF) principles (Bjørn et al., 2020). The relevance of these principles in an absolute sustainability context has

*Abbreviations:* Fulfilment of Human Needs, (FHN); Share of safe operating space, (SoSOS); Absolute environmental sustainability assessment, (AESA).

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been questioned: GVA is criticised because the economic value rarely reflects the actual importance of products to humans (Jebb et al., 2018; Land et al., 2017). Grandfathering holds that the distribution of safe operating space should be based on historical and distribution of environmental impact, but this favours the status quo, which is fundamentally contradictory with the need for fundamental changes in a green transformation (Land et al., 2017). Many studies state that the distributive justice theory sufficientarianism is aligned with the values and understanding of absolute sustainability. Nevertheless, a sharing principle based on sufficientarianism has not been supported by any operational method, and hence GVA and GF have been preferred approaches in spite of the criticism, because data were available for these principles and they were operational (Bjørn et al., 2020; Hjalsted et al., 2020). In a recent publication (Heide et al., 2023) Heide and colleagues have developed a sharing principle and method based on the sufficientarian distributive justice theory reflecting the importance of the needs that products fulfil for the users. The principle is called Fulfilment of Human Needs (FHN), and it is further adapted and tested on buildings in this study.

In Denmark both absolute and relative $CO_2$-limits for buildings have been suggested in several studies (Reduction Roadmap, 2022; Andersen et al., 2020), in the national DGNB certification with accompanying Reduction Roadmap and in the national building regulation (BR) (Bolig og planstyrelsen, 2022a; Green Building Council Denmark, 2022).

In 2023 the Danish BR was updated with an LCA-based limit for $CO_2$-emissions for all buildings larger than 1000 $m^2$. The limit is 12 $CO_2$-eq/$m^2$/yr for all building typologies.

There are three main problems when setting a climate impact limit for buildings with the methods used to far: 1) The limit is defined based on area as kg $CO_2$-eq/$m^2$/year which removes the incentives to build smaller to reduce the total footprint of the building and instead encourages to build larger which gains allowance to emit more, 2) it does not distinguish between building typologies, despite the different services that buildings provide to the users and the society and 3) the potential to reduce the environmental impact for the building typologies are not considered. Some functions are more essential to human wellbeing than others, and for some building typologies it is easier to reduce the impact than others because of differences in technical requirements. It would therefore be meaningful to differentiate the SoSOS for different building typologies and define the SoSOS based on the function and not contingent on the area.

The objective of this paper is to provide a method for differentiating the absolute sustainable $CO_2$-limits for buildings depending on how important the building typology is for the users and test it on four different case studies; a residential building, a university, a hospital, and a kindergarten. This study initiates the discussion and develops more nuanced $CO_2$-limits for buildings.

## 2. Material and methods

AESAs operationalise absolute sustainability for decision making e.g. for building design (Ryberg et al., 2018). They consist of three elements; 1) Full LCA of the building in question, 2) Determination of the SoSOS for the building typology, involving two sub-elements; determination of the global safe operating space and choice of sharing principles for downscaling the global safe operating space to the level of the building, and 3) Comparison of the actual impact of the building to its associated SoSOS.

### 2.1. LCA and case studies

We selected four case studies each representing a common building typology in Denmark. The LCAs for the case studies were conducted following ISO 14044, and they were modelled in SimaPro using the ecoinvent 3 database (Wernet et al., 2016; SimaPro, 2023). An exception is case study 4 where the building materials were modelled in the LCAbyg software with data from the Ökobaudat database (ÖKOBAUDATÖKOBAUDAT, 2021). We considered a 50 year time period to align our results with the Danish BR where this is the reference duration. The reference service life (RSL) of the different components was used to determine the amount of replacements for each material type e.g. windows have a RSL of 30 years thus we included twice the amount of windows in the inventory. Due to confidential data we do not show the inventory for the cases but details about the results of the LCAs are shown in Appendix A-D.

The energy use during the 50 years is modelled dynamically using different forecasts for the energy sources to produce electricity and district heating. For most of the case studies the exact energy use was unknown, so best and worst case scenarios were constructed combining a low to high energy use estimate. For the future development in the energy systems two energy forecasts "Frozen policy" and "Systemic change" were modelled. The Frozen policy considers accepted agreements in Danish parliament up until 2022 and is presented by the Danish Energy Agency (Energistyrelsen, 2022). Systemic change is based on projections from Ember (2022), which bases its System change pathway on complying with the Paris agreement. The Systemic change projection constitutes the most optimistic energy scenario and has been combined with the low energy use scenario to arrive a lower bond on the $CO_2$-emissions from the building, while the Frozen policy has been combined with the medium and high energy use scenarios to determine an upper bond. Ranges for import and export from the neighboring countries were taken from Energinet (2023) to simulate the actual energy mix. All four cases use district heating for heating the buildings. For all cases, except the university in case 2, we used a forecast of the average Danish district heating (DTU management, 2018) with a "Frozen policy" scenario as the most conservative and "Carbon Budget Paris" (CBP) (equal to systemic change) as the most optimistic scenario regarding complying with the Paris agreement. For the university building the specific heating sources from the actual district heating production to the building were known and used in the study. The specific energy data can be seen in Appendix A-D.

#### 2.1.1. Descriptions of the four case studies

Case 1 is a residential building for 404 residents of 9792 $m^2$. The LCA was conducted on an initial stage of the design and the result was used to reduce the $CO_2$-footprint of the building further. The design is still under development at the time of writing, and the building is planned to be constructed in 2023. The energy use was estimated with a low, medium and high scenario. The low scenario corresponds to the energy frame from the Danish BR of 30.1 kWh/$m^2$/yr. The energy frame is a simplified calculation of the supplied energy without including the users and it represents an underestimation of the actual energy use (Petersen and Hviid, 2021). The medium was constructed by multiplying the energy frame by 2.4 to better simulate the anticipated energy use (Petersen and Hviid, 2021). The high scenario was determined by multiplying the energy amount from the medium scenario once again with 2.4. The high scenario is relevant because empirical data show that new buildings in Denmark sometimes use significantly more energy than estimated with the medium scenario (Petersen and Hviid, 2021). See details about Case study 1 in Appendix A.

Case 2 is the new Building 324 at the Technical University of Denmark. The building contains offices for researchers, classrooms for teaching, study areas for students, small tea kitchens, toilets and a super computer, which is located in the basement. The building was constructed in 2013, and the area is 4592 $m^2$. The LCA was conducted for the final design with the actual current energy consumption of 40 kWh/$m^2$/yr electricity and 107 kWh/$m^2$/yr heat. See details in Appendix B1 and B2. This case contains confidential data regarding specific materials.

Case 3 is a hospital with a capacity of 8000 admissions per year, 32 hospital beds and an area of 11639 $m^2$. This case contains confidential data about materials use and materials cannot be detailed. Hospitals are in general renovated more than other building types. A rule of thumb is that 10% of hospitals are constantly under renovation. To include the additional material use caused by renovation, we conducted a material scenario: we assumed that 10% of all indoor materials (inner walls, ceilings, floors, ventilation, plumbing and electrical installations) will be exchanged during a 10 year period, which resulted in exchanging half of the materials during the considered timeframe of 50 years. The renovation activities constitute 21% of the material impact. The hospital will be in use in 2023, therefore the energy use is estimated with a best- and worst-case scenarios. Since the operation hours at hospitals are longer than for other buildings, the energy use is larger and thus our estimate is different from the other case study typologies. The best case scenario follows the energy frame of hospitals from the Danish BR of 62.1 kWh/$m^2$/yr electricity and 46.6 kWh/$m^2$/yr heat. The hospital is projected to produce 14.2 kWh/$m^2$/yr electricity with photovoltaic panels which we subtracted from the electricity use. In the worst-case energy scenario, we multiplied the heat use from the energy frame by 2.4. The energy estimate was compared to the energy use of other hospitals as a control. See details in Appendix C.

Case 4 is a kindergarten for 176 children and 31 employees. The heated area is 1359 $m^2$. The kindergarten is partly built with materials from an old school demolished at the same location. The kindergarten has the Nordic Swan ecolabel and complies with the Voluntary Sustainability Class in Denmark (Social- og Boligstyrelsen). The energy use has been estimated with the same method as in Case study 1 (resulting in a high, medium and low energy scenario). Details about Case study 4 can be seen in Appendix D.

### 2.2. Defining a share of the safe operating space

To define the SoSOS for a building, the first step is to determine the global safe operating space. To illustrate the influence of this value we have selected two approaches to determining it: 1) the steady state, carrying capacity based, method with a threshold of 2 °C temperature increase (Bjørn and Hauschild, 2015), and 2) the IPCC SSP1-1.9 which complies with the 1.5 °C objective of the Paris Agreement (IPCC, 2021).

The steady state method by Bjørn and Hauschild (2015) is based on the carrying capacity defined as “the maximum sustained environmental intervention a natural system can withstand without experiencing negative changes in structure or functioning that are difficult or impossible to revert”. This has been interpreted as a threshold of a 2 °C temperature increase. The steady state approach calculates means that the global safe operating space is the same every year, and thus not time dependent. This approach assigns a SoSOS corresponding to the steady state, where the global $CO_2$-emissions reaches a level that comply with the carrying capacity on a yearly basis.

The IPCC SSP1-1.9 has a dynamic approach allowing humanity to emit more $CO_2$-eq now but reduce the emissions over time (IPCC, 2018). The future emissions pathway requires a negative contribution to emissions from 2075, meaning that more $CO_2$-eq has to be removed from the atmosphere than emitted every year. This approach thus relies on development of new technology.

Fig. 1 illustrates the difference between the dynamic approach with the SSP1-1.9 and the steady state approach (Bjørn and Hauschild, 2015). We used the EPC principle to assign a share of the global safe operating space to each individual. The global population is projected with the medium variant from United Nation population prospects (UN Department of Economic and, 2022).

### 2.3. Sharing principle

The next step is to select an upscaling principle to scale the individual safe operating space to the buildings. When conducting an AESA it is important that the scope of the LCA and the SoSOS match, ensuring the assigned share of the building covers the same elements as the LCA. The scope of the assigned share for a building typically differs from the common way of scoping an LCA for a building. Usually, the outdoor spaces and underground installations for rainwater handling would not be included in the LCA when comparing two buildings with the same FU, but when conducting an AESA the assigned share typically covers the whole site and other activities. If the cost of the building is used when determining the SoSOS, then the content of the LCA should cover the same elements as the cost.

This study tests and uses a newly developed sharing principle “Fulfilment of Human Needs” (FHN), which is based on sufficientarianism, entailing that we make sure that everyone has enough (Heide et al., 2023).

The FHN sharing principle is based upon the average consumption pattern in countries classified as “most sustainable”. The most sustainable countries are identified using three sustainability criteria: a human development index (HDI) > 0.7, ecological footprint <3 gha/capita/yr, and climate change impact <5 ton $CO_2$-eq/capita/yr. The average of the consumption patterns for the 11 most sustainable countries (Algeria, Armenia, Costa Rica, Dominican Republic, Fiji, Jordan, Philippines, Samoa, Sri Lanka and Tunisia) are used to assess the relative importance of needs (and sectors) to the people. Table 1 shows the shares that are assigned to each sector based on the sustainable consumption (SC) principle.

The four case studies are paired with the consumption category to which they economically belong, and a share of SoSOS of this consumption category is assigned to the building in the case. Section 3.1 and 3.2 demonstrates how this is done for each of the four cases.

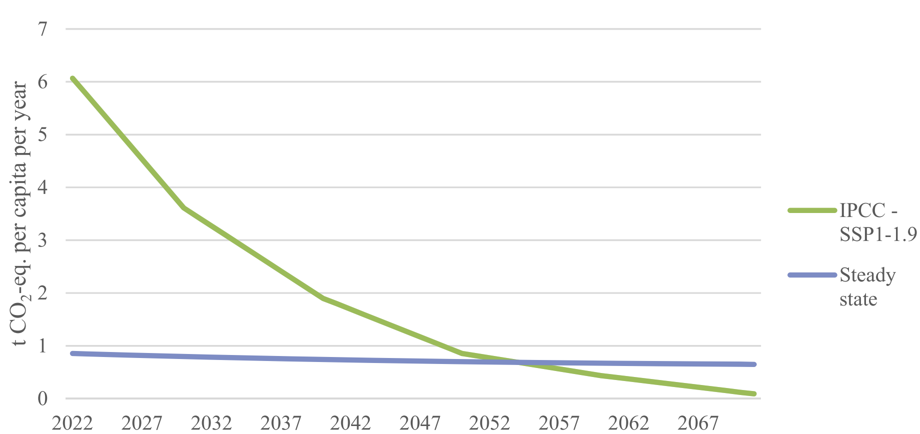


**Fig. 1.** The yearly global individual safe operating space for climate for 50 years, according to equal per capita sharing. The green line representing SSP1-1.9 complies with the maximum global warming target of 1.5 °C. The steady state complies with a 2 °C temperature increase. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

**Table 1**
Average government and household spending in 11 countries that meet the sustainability criteria of HDI >0.7, ecological footprint <3 gha/capita/yr, and climate change impact <5 ton $CO_2$-eq/capita/yr. The average consumption in bold is referred to as the sustainable consumption (SC), The range in each consumption category across the 11 countries is given in brackets (Table from Heide et al. (2023)).

| | Consumption categories (Sectors) | Average sustainable consumption (%) SC |
|---|---|---|
| Government | General public services | **6.9%** (2.5–12%) |
| | Defence | **2.4%** (0–10%) |
| | Public order and safety | **2.5%** (0.5–5%) |
| | Economic affairs | **5.8%** (2–11%) |
| | Environmental protection | **0.4%** (0–2%) |
| | Housing and community amenities | **1.8%** (0.1–6%) |
| | Health | **6.1%** (3–14%) |
| | Recreation, culture and religion | **3.4%** (0.2–12%) |
| | Education | **6.9%** (2–14%) |
| | Social protection | **4.1%** (1–8%) |
| Household | Food and non-alcoholic beverages | **22.5%** (14–38%) |
| | Alcoholic beverages, tobacco and narcotics | **1.8%** (0.4–5%) |
| | Clothing and footwear | **2.2%** (0.6–5%) |
| | Housing, water, electricity, gas and other fuels | **8.8%** (3–12%) |
| | Furnishings, household equipment and routine maintenance of the house | **3.0%** (0.9–6%) |
| | Transport | **8.1%** (4–10%) |
| | Communication | **2.0%** (0.04–4%) |
| | Restaurants and hotels | **2.9%** (0.5–9%) |
| | Miscellaneous goods and services | **8.4%** (0.01–19%) |

### 2.4. Sustainability ratio

The sustainability ratio is used to determine on the absolute sustainability of the building. It is determined by dividing the actual impact (the result of the LCA) by the SoSOS. If the actual impact is larger than the SoSOS (sustainability ratio is higher than 1), the product is not sustainable. If the sustainability ratio is lower than or equal to 1 the product can be considered absolute sustainable. We recommend testing different safe operating space estimations and sharing principles to understand the uncertainties in AESAs that can be large, especially for buildings due to their long service lives. Claiming absolute sustainability for a product with a sustainability ratio lower than 1 should thus be done with caution, and the result should always be followed by a statement of the assumptions, prerequisites and sharing principles which form the basis of the assessment.

## 3. Assigning and calculating the SoSOS

Section 3.1 introduces how to assign a SoSOS to any building type with the FHN principle and summarizes prerequisites in Section 3.1.1. Section 3.2 presents the equations for the calculations of SoSOS for the four case studies.

### 3.1. Assigning the SoSOS

To determine the SoSOS for a building we recommend using the five step guideline shown as a flow chart in Fig. 2.

The guide uses the FHN sharing principle to determine a SoSOS for a building and proceeds through the following steps:

1) Downscale the global safe operating space to the level of an individual. We suggest equal per capita distribution, due to the limited/shrinking safe operating space, and considering that everybody should be able to fulfil their basic needs (Heide et al., 2023). However, other distributive justice theories can be used (e.g. historical debt). Step one should always be done with a dynamic approach to represent the change in population size over time.
2) In most cases it is relevant calculate a national SoSOS by multiplying by the country's population. However, in some cases we can use the number of primary users of the building (e.g. residential building) because the whole population needs the service delivered by the building typology and thus it can be measured directly per person.
3) Determine the relevant consumption category in Table 1 according to the function of the building choose the SC percentage for that consumption category. In some situations, a building belongs to more than one category, because it is financed both by the government and households or because the building has multiple functions that belong to different consumption categories.
4) Determine the share of the building from the consumption category's share, using the local percentage share associated with the building's function of the economic spending within that consumption category.
5) Estimate how much the specific building delivers out of the total national service needed. The current national statistics are used to determine the total service or amount needed from each function. Furthermore, the capacity of the building (e.g. number of residents/users) should be prioritised as measure of the function. If the capacity cannot be defined in any other way, the cost can be used as the last option. Egalitarianism is used in this final step implying that each person who is qualified for the function offered by the building typology gets an equal share.

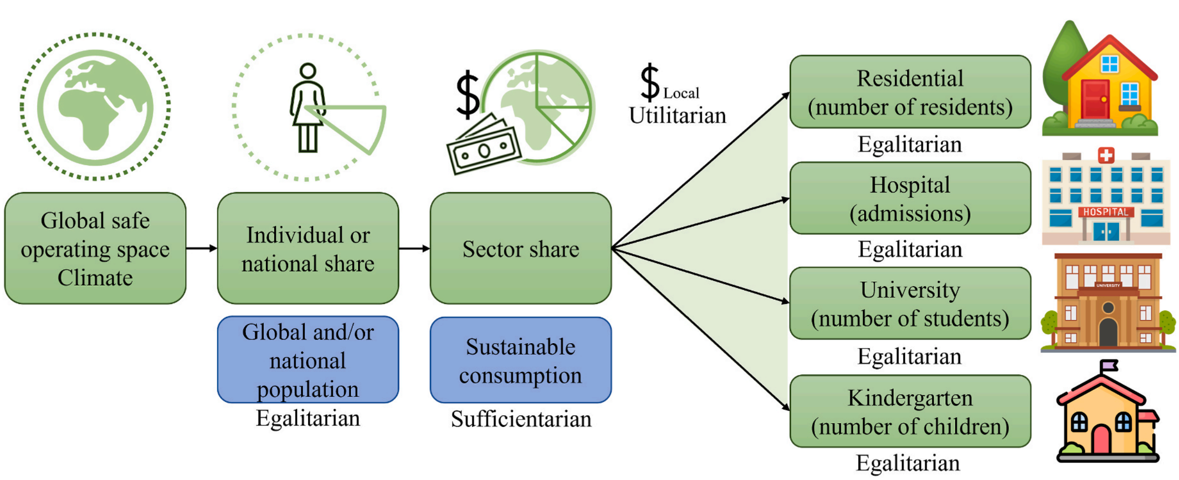


**Fig. 2.** Flow chart of how to assign a SoSOS to a building according to the FHN principle. The figure presents the ethical norms and measures applied in each step. The last applies an egalitarian approach since everyone who qualifies for the service provided by the building typology gets an equal share.

In step 4 local spending patterns were used to divide the sustainable consumption categories further down to the level of the four building typologies. The use of local spending patterns is assumed to represent local culture and priorities and entails that all "services" within a consumption category should decouple environmental impact from economic expenditure equally well. For example, the importance of the university is weighted according to the expenditure on academic education and research compared to the expenditure on other educational activities. This assumption incorporates risk of applying non-sustainable consumption from the national contexts.

In step 5 we apply an egalitarian ethical norm, assuming for residential buildings that all individuals within the share of the national context has equal *rights* of residence and thus everybody gets an equal share. The three other building typologies meet more specific needs and everybody is not qualified at all times to get a share. For the kindergarten building, the current number of children in kindergartens is used to determine the total national need for day-care spots, and every child who is qualified for a spot gets an equal share.

The capacity of a building typology can be measured in different ways; f or the hospital it could be patient days, number of admissions/operations or a combination of these. We used number of admissions as capacity measure (due to data availability), and the total "need" is thus described by the total yearly national number of hospital admissions. For the university buildings, each building consists of a mix of lecture halls, shared study areas, offices for researchers, canteens, special equipment (e.g. 3D printers, laboratories), etc. It is not obvious what would be a common descriptor of these different functions and we therefore use area to describe the capacity for a situation where the total function is delivered by several buildings with interlinked utilities, where only one building is considered in the study.

### 3.2. Calculating the SoSOS

For the four different building typologies, the SoSOS is calculated as follows:

*Residential building*

$$SoSOS_{Residential} = \sum_{t=2023}^{2073} \left( \frac{SOS_{climate}(t)}{Pop_{world}(t)} \right) \bullet Pop_{Dwelling} \bullet SC_{HousingH} \bullet \frac{FCE_{Dwelling}}{FCE_{HousingH}} \quad (1)$$

*University building*

$$SoSOS_{UniX} = \sum_{t=2013}^{2063} \left( \frac{SOS_{climate}(t)}{Pop_{world}(t)} \right) \bullet Pop_{DK}(t) \bullet SC_{EducationG} \bullet \frac{FCE_{Construction+operationUniX}}{FCE_{EducationG}} \bullet \frac{Area_{building}}{Area_{UniX}} \quad (2)$$

*Hospital*

$$SoSOS_{HospitalX} = \sum_{t=2023}^{2073} \left( \frac{SOS_{climate}(t)}{Pop_{world}(t)} \right) \bullet Pop_{DK}(t) \bullet SC_{HealthG} \bullet \frac{FCE_{HospitalsG}}{FCE_{HealthG}} \bullet \frac{Capicity_{HospitalX}}{Capacity_{HospitalsDK}} \bullet \frac{Buildingcost}{Totalcost} \quad (3)$$

*Kindergarten*

$$SoSOS_{kindergarten} = \sum_{t=2023}^{2073} \left( \frac{SOS_{climate}(t)}{Pop_{world}(t)} \right) \bullet Pop_{DK}(t) \bullet \left( SC_{SocialProtectionG} \bullet \frac{FCE_{DaycareG}}{FCE_{SocialProtectionG}} \right) + \left( SC_{MiscellaneousH} \bullet \frac{FCE_{DaycareH}}{FCE_{MiscellaneousH}} \right) \bullet \frac{Pop_{Kindergarten}}{Pop_{daycare}} \bullet \frac{Buildingcost}{Totalcost} \quad (4)$$

Where.

$SoSOS_X$ is the share of the safe operating space – the sustainability reference for building x
$SOS_{climate}$ (t) is the global safe operating space for climate change at time t
$Pop_{world}(t)$ is the global population at time t
$Pop_x$ is the number of people either in country x or number of people using building x
$SC_x$ is the share assigned to consumption category x [%] based on the sustainable consumption principle. G or H indicates whether it is governmental spending or household consumption.
$FCE_x$ is the final consumption expenditure on sector or function x in the local context
$Capacity_x$ is a way of measuring the utility delivered to the users of the building. $Area_x$ is the area of building x [$m^2$].

The abbreviations are put on general terms to cover all four equations.

The SoSOS of the kindergarten comprises of contributions from two consumption categories (Table 1): Miscellaneous goods and services and Social protection since both public and private spending funds the kindergartens in Denmark. All calculations of SoSOS are documented in detail in Appendix A-D.

## 4. Results

In this section we present the LCA results of the four case study building typologies and the sustainability references (SoSOS) for each of them. Table 2 shows the results in impact per building area to allow comparison with other studies, the BR and across the case studies. However, it is essential to note that the SoSOS does not depend on the area, thus a different design of the building (smaller or larger) providing the same functional unit would result in a different SoSOS per area.

To convert the results into general $CO_2$-limits for each building typology, in absolute values, we divided the SoSOS with the main function of each building instead of the area (see Table 3). The main function is used in the calculation of the SoSOS for all cases. To estimate the number of users of the university building, we calculated an average number of students/employees per area at the university overall, and multiplied the average number of users per square meter with the area of the specific building, which resulted in 139 users of the building.

The sustainability ratios can now be determined for each building by dividing the life cycle impact by the SoSOS for the building. Results are shown in Fig. 3 and the intervals indicate the sustainability ratio for the best- and worst-case energy scenario. A sustainability ratio below 1 indicates that the building is sustainable in terms of its climate change impact, i.e. that its impacts do not exceed its assigned share of the safe operating space for climate change and thus complies with the 1.5 °C and 2 °C global warming target.

## 5. Discussion

The SoSOS values in Table 2 indicate which building typologies are of greater importance to society than others in terms of fulfilling human needs, and thus they suggest which building typologies should have the most strict and most lenient $CO_2$-limitations. However, these results are case specific. Even though, the FHN-based SoSOS is presented as impact per area in Tables 2 and it does not depend on the area. Thus, the SoSOS defined in impact per area is inappropriate as general climate change impact limits in the building industry. The residential building gets a SoSOS of 6.3 kg $CO_2$-eq/$m^2$/yr and 2.5 kg $CO_2$-eq/$m^2$/yr depending on the scenario defining the SOS. The total SoSOS for the building would be the same if it were designed for the same number of residents but with a smaller area, the assigned share per area would increase. The hospital gets by far the largest share per area, and the smallest SoSOS is assigned to the residential building. This result is in accordance with the technical building requirements from the Danish BR and the special conditions

**Table 2**
The $SoSOS_{climate}$ and climate impact of the case study buildings expressed per area for the four case study buildings. The IPCC (SSP1-1.9) and steady state emissions 2.0° (SS) scenarios indicate uncertainty intervals on the SoSOS. The intervals of the life cycle results indicate the results from low to high energy scenarios. These results are case specific, the SoSOS does not depend on the area, and a different design of the building (smaller or larger) providing the same functional unit would result in a different SoSOS per area. SoSOS and LCA results that comply with the regulation of 12 kg $CO_2$-eq/$m^2$/yr are highlighted in light green, SoSOS that comply with the Danish Voluntary Sustainability Class are highlighted in darker green.

| Building | $SoSOS_{climate}$ kg $CO_2$-eq / $m^2$ / yr FHN IPCC SSP1-1.9 | $SoSOS_{climate}$ kg $CO_2$-eq/ $m^2$ / yr FHN SS | LCA results kg $CO_2$-eq/ $m^2$ / yr |
|---|---|---|---|
| Residential | 6.3 | 2.5 | 9.5-16.8 |
| University | 14.6 | 4.0 | 21.1-26.6 |
| Hospital | 71.5 | 28.8 | 21.5-27.0 |
| Kindergarten | 29.7 | 12.0 | 16.7-22.1 |


| Building | $SoSOS_{climate}$ kg $CO_2$-eq/$m^2$/yr FHN IPCC SSP1-1.9 | $SoSOS_{climate}$ kg $CO_2$-eq/$m^2$/yr FHN SS | LCA results kg $CO_2$-eq/$m^2$/yr |
|---|---|---|---|
| Residential | 6.3 | 2.5 | 9.5–16.8 |
| University | 14.6 | 4.0 | 21.1–26.6 |
| Hospital | 71.5 | 28.8 | 21.5–27.0 |
| Kindergarten | 29.7 | 12.0 | 16.7–22.1 |


**Table 3**
The $SoSOS_{climate}$ and climate impact of the case study buildings expressed per function for the four case study buildings. The IPCC (SSP1-1.9) and steady state emissions 2.0° (SS) scenarios indicate uncertainty intervals on the SoSOS. The intervals of the life cycle results indicate the results from low to high energy scenarios. The SoSOS cannot be compared across buildings.

| Building | $SoSOS_{climate}$ kg $CO_2$-eq/FU/yr FHN_IPCC | $SoSOS_{climate}$ kg $CO_2$-eq/FU/yr FHN_SS | Actual impact kg $CO_2$-eq/ FU/yr |
|---|---|---|---|
| Residential (FU = resident) | 153.4 | 61.7 | 229–407 |
| University (FU = student or employee) | 482.9 | 131.9 | 700–879 |
| Hospital (FU = admission) | 104.1 | 41.9 | 31–39 |
| Kindergarten (FU = child or employee) | 195 | 78 | 115–150 |

which justify an increased impact also defined in the regulation (Bolig og planstyrelsen, 2022b). The technical requirements for e.g. ventilation rates, number of overheated hours and amount of daylight for the residential building are thus the lowest among the four building typologies. On the other hand, a hospital is allowed an additional energy use in the Danish energy frame due to increased operational time. The requirements for ventilation rates for offices, schools and hospitals are also stricter than for residential buildings according to the BR. Use of hospital equipment is one of the special conditions defined by the BR that allows an exceedance of the 12 kg $CO_2$-eq/$m^2$/yr. However, this exceedance (which is less than 0.5 kg $CO_2$-eq/$m^2$/yr (Nielsen et al., 2022)) is not sufficient to accommodate the climate change impacts found for the hospital in this study.

To avoid assigning an unnecessarily large SoSOS to a building typology, the reduction potential should also be considered. If known methods or technologies can provide the utility to the users with a much smaller impact than the assigned SoSOS, the excess share can advantageously be assigned to other products where current methods and technologies are insufficient at providing the utility to the users within their SoSOS. The reduction potential depends on the technical requirements stated in the BR, as introduced above, but it also depends on other factors such as user behavior. For example it is easier to reduce the area per person in a residential building than in other building typologies. There are many examples of mini homes, dorms, smaller apartments and collectives where people have a much smaller area available than the average person. New technologies and online connectivity activities (developed and practiced during the Covid 19 lockdown) have broadened the possibilities for online teaching, meetings, work etc. which might reduce the demand for number of square meters in offices and in schools/universities in the future.

The SoSOS values expressed per building function in Table 3 as impacts per resident, student, admission, and child, can work as a general guide for setting $CO_2$-limits for different building typologies. However, to avoid assigning too large shares for buildings in general it is important to be aware that the sharing principle takes its starting point in sustainable consumption. It only works as intentioned if consumption of redundant products is reduced markedly in wealthy countries. The FHN sharing principle will assign larger shares to the most essential needs and smaller shares to redundant and less essential needs. Therefore, the results of this study indicate that we need to set more ambitious $CO_2$-limits for residential buildings compared to hospitals. This is also aligned with the study by BUILD (Zimmermann et al., 2020) according to which residential buildings can be built in Denmark today with 6–10 kg $CO_2$/$m^2$/yr (however, based on the energy frame which underestimates the energy use during operation of the building).

The residential case building has by far the smallest impact per area and is the only one that complies somewhat with the regulation of 12 kg $CO_2$/$m^2$/yr, as shown with green in Table 2. However, the FHN principle deems the other buildings typologies more important, and thus the residential building actually performs second worst when considering the importance of the needs the buildings provide to the users (see

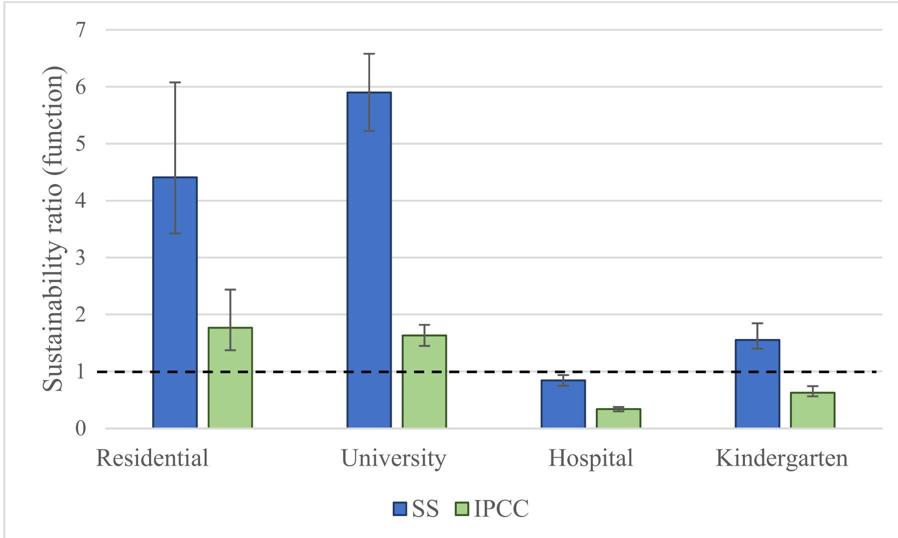


**Fig. 3.** Sustainability ratios based on normalized results per FU from Table 3. Error bars defined by the different energy scenarios (high, medium, low).

Fig. 3).

If the owner has a portfolio of buildings (as in the case with the university building) it could be up to the builder to decide which buildings in the portfolio are of greater value and thus get a larger proportion of the SoSOS. We did not distinguish between the different types of activities in the different areas at the university, e.g. laboratories and lecture halls, but such distinctions could be added to the equation. As long as the total SoSOS for the university is not exceeded, the builder/owner can assign larger shares to the most important buildings, at the expense of the least important buildings, which would get a correspondingly reduced share. Also for the hospital, the definition of capacity should be further considered and potentially defined by several factors to better capture the function that the hospital provides. Number of admissions was used in this study due to data limitations, but other factors could be integrated into the model, e.g. number of operations, potentially qualified further by weighting according to disability-adjusted life years (DALY) saved by the hospital treatment.

This study suggests a new way of including absolute sustainability in the building industry and its practices. An invitation to bid from an investor or builder normally specified a fixed area of the building, and this removes the degree of freedom to design a building that fulfils the function needed on an area as small as possible. By specifying $CO_2$ requirements per area, the BR allows a larger impact for larger buildings regardless of the relevance to the function provided to the users or society. The BR $CO_2$-limit is decided with a relative sustainability approach. Absolute approaches do exist (Reduction Roadmap, 2022), however, the distinction between $CO_2$-limits for different building typologies are still lacking in these methods.

We recommend using both impact/$m^2$/yr and impact/resident/yr when setting $CO_2$-limits and calculating the impact of a residential building. A challenge is that we cannot guarantee the number of residents in general, with the exception of a few building types e.g. dorms with one student per room. It is a risk that some would overestimate the number of residents. We recommend using the amount of bed spots and creating a worst- and best-case scenario regarding the number of residents.

Another challenge with this method is that it is used to set a limitation for the maximum level of emissions. In some building cases it might be possible to reduce the impact more than the assigned SoSOS. The impact could even be further reduced if the function of the building was provided without the construction of a building in the first place. For example, there are alternatives to classic kindergartens where children remain outdoors all day, and rely on access to amenities within a simple construction. This solution has a smaller impact, while still providing the function of care of children. However, it might demand additional transportation of the children.

Although a 50-year service life is the standard in the construction industry, it introduces some challenges. While buildings are designed to last much longer than 50 years (Palacios-Munoz, 2019), the industry has adopted a shorter timeframe to emphasize the upfront embedded carbon emissions. In contrast, using the dynamic approach (IPCC SSP1-1.9) to define the global safe operating space illustrated in Fig. 1, the SoSOS per year for a building diminishes as the assumed service life increases, which is counterintuitive. Despite these challenges, we selected the 50-year service life to enable comparison across various case studies.

One of the primary concerns associated with AESAs is that there is a need to sequester more carbon dioxide than what is emitted annually by the year 2075 (according to IPCC SSP1-1.9) and thus, achieve global net negative emissions annually. A central element of AESAs is to define how we share the remaining carbon budget as presented in Fig. 1. Carbon sequestration seems promising in four areas, which are: (1) the energy sector using carbon capture and utilization or storage, (2) forest growth, (3) changes in agricultural systems and soil management (IPCC, 2018), and (4) uptake in the ocean by sequestration into seaweed and algae (DeAngelo et al., 2023). This forges the importance of AESAs since reducing the impact from buildings will in turn lower the need for additional carbon dioxide sequestration within the mentioned sectors. Our study provides insights on which buildings should be assigned the largest share and which ones should emit the least to achieve the objective of staying within the safe operating space for climate.

## 6. Conclusions

This study provide s a method to differentiate absolute $CO_2$-limts for different building typologies. The differentiation is conducted based on the Fulfilment of Human Needs (FHN) sharing principle that estimates which buildings are of greatest importance according to the utility they provide to the users. A main result is that hospitals should have a larger SoSOS compared to other building typologies, since hospitals are fundamental to our society and because it is more difficult to reduce the impact hereof due to the Danish building regulation. Furthermore, fewer hospitals are built, compared to e.g. residential buildings and thus in total the relative impact from construction of hospitals is rather small on national level. Reducing the SoSOS for residential buildings on the other hand is of great significance, and it is easier to comply with more strict $CO_2$-limits both per person and area due to less stringent requirements from building regulations.

A main challenge with the FHN sharing principle is that it assumes that a sustainable lifestyle would be realized in all societies. The issue with this assumption is, if all consumption patterns are not altered to reach a sustainable level, buildings will be assigned a share that is too large and the global impact would exceed the yearly SoSOS. The method also assumes that we only build what it necessary considering human needs and do not maintain the current yearly construction levels. Thus, for the model to work as intended, a society like the Danish as a whole must change. The large SoSOS assigned to buildings with the FHN (compared to other sharing principles) can be interpreted as buildings being important. This means that the impact from other consumption goods should be reduced relatively more than emissions from buildings.

We recommend to further develop and merge this method with other methods to reach ambitious and absolute $CO_2$-limits that encompass the importance of the function the buildings provide to the users. We recommend using both $CO_2$-limits per area and per function to get a more nuanced insight into building emissions to comply with absolute sustainability thinking.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

All data are provided in Appendixes

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## Appendices.

Appendix A-D contain details about the LCA results and the SoSOS calculations for each of the four case studies. Appendix A considers the residential building, Appendix B1 and B2 considers the University building, Appendix C considers the hospital, and Appendix D considers the kindergarten.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.dibe.2023.100175.

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