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SYNTHESIS

Carbon budgets for buildings: harmonising temporal, spatial and sectoral dimensions

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Abstract

Target values for creating carbon budgets for buildings are important for developing climate-neutral building stocks. A lack of clarity currently exists for defining carbon budgets for buildings and what constitutes a unit of assessment—particularly the distinction between production- and consumption-based accounting. These different perspectives on the system and the function that is assessed hinder a clear and commonly agreed definition of 'carbon budgets' for building construction and operation. This paper explores the processes for establishing a carbon budget for residential and non-residential buildings. A detailed review of current approaches to budget allocation is presented. The temporal and spatial scales of evaluation are considered as well as the distribution rules for sharing the budget between parties or activities. This analysis highlights the crucial need to define the temporal scale, the roles of buildings as physical artefacts and their economic activities. A framework is proposed to accommodate these different perspectives and spatio-temporal scales towards harmonised and comparable cross-sectoral budget definitions.

Policy relevance

The potential to develop, implement and monitor greenhouse gas-related policies and strategies for buildings will depend on the provision of clear targets. Based on global limits, a carbon budget can establish system boundaries and scalable targets. An operational framework is presented that clarifies greenhouse gas targets for buildings in the different parts of the world that is adaptable to the context and circumstances of a particular place. A carbon budget can enable national regulators to set feasible and legally binding requirements. This will assist the many different stakeholders responsible for decisions on buildings to coordinate and incorporate their specific responsibility at one specific level or scale of activity to ensure overall compliance. Therefore, determining a task specific carbon budget requires an appropriate management of the global carbon budget to ensure that specific budgets overlap, but that the sum of them is equal to the available global budget without double-counting.

Keywords: building stock; buildings; built environment; carbon budget; climate policy; greenhouse gases (GHGs); mitigation

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1. Introduction

The climate crisis is prompting an intensive examination into the reduction of anthropogenic greenhouse gas (GHG) emissions. The relevance and pressing nature of this topic is highlighted by the integration of climate change mitigation measures into the globally recognised Sustainable Development Goals (SDGs) (UN 2015), through SDG 13: 'Take urgent action to combat climate change and its impacts'. The alarming reports of the Intergovernmental Panel on Climate Change (IPCC) (2018a: 32) and the commitments to national GHG emission-reduction measures within the framework of the United Nations Climate Change Conference of the Parties (COP) (UN 2019) have brought this topic to the top of the political agenda.

In the meantime, urbanisation is expected to add 2.5 billion people to the global urban population by 2050 (Swilling *et al.* 2018). Together with the pressure to overcome the already sizable housing deficit and lack of decent built environment, this urbanisation peak will increase the construction material requirements and GHG emissions associated to their production (Göswein *et al.* 2018). Recent studies show the small amount of progress achieved in reducing GHG emissions associated with construction of new buildings (Röck *et al.* 2020). Furthermore, in countries where most of the building stock has been built, fast and deep energy retrofit is needed of the residential building stock. The IPCC states retrofit rate of the residential building stock should increase from today's 1–2% per year up to 5% per year (in Organisation for Economic Co-operation and Development (OECD) countries) (IPCC 2018b). This renovation activity also contributes to GHG emissions through the production of insulation materials (Heeren & Hellweg 2018). Recent studies by the International Energy Agency (IEA) estimate that cement and steel used for construction and renovation of buildings would be responsible for an average of 2.3 Gt CO_2e (CO_2-equivalent) emissions annually up to 2060. An ambitious policy on material reduction demand could curb these emissions by more than 50% (IEA 2019). A current estimate of embodied GHG-emissions from buildings is 10 Gt CO_2e/yr. This amount could be reduced to only 2 Gt with decisive actions or reach 16 Gt CO_2e/yr if current trend is continued (Global Alliance for Buildings and Construction 2016). Buildings could even act as a carbon sink if insulation materials (Pittau *et al.* 2019) or structural materials (Churkina *et al.* 2020) are not based on fossil fuels but switched to bio-based materials.

Buildings are clearly identified by policy-makers as a key point to reduce GHG emissions (Anderson, Wulfhorst, & Lang 2015). However, the different stakeholders such as portfolio managers, national political leaders, heads of industry, civil and building engineers, and designers do not include the same activities under the topic called 'buildings'. Sometimes only the emissions related with the use of buildings are included (*e.g.* C40cities strategies; De Blasio 2017). Sometimes emissions related to cement and steel production are targeted (*e.g.* European Trading Scheme—ETS), but this will include building construction along with other activities such as infrastructure or automobile production.[1] Sometimes, the production of goods related to construction and operation of buildings within the country are included but not the imports are excluded, *e.g.* UK carbon roadmap (Miliband 2008). Sometimes the level of action is at the city level and budget is constrained by the population living inside administrative boundaries (Mirabella & Allacker 2020). This creates confusion as it is difficult to grasp the boundaries of what is considered. The prevailing confusion becomes an obstacle, because actors do not have a complete picture of the field of action corresponding to their perspective and their tasks. Therefore, a clear system of objectives, actors, fields of action and possibilities of influence is needed. The goal of reducing GHG emissions assigned to the built environment must be translated in such a way that each group of actors can develop strategies for their specific area of work and responsibility in order to measure the success of their activities.

The objective of this paper is to define an operational framework to clarify the targets for climate mitigation in the built environment in the different parts of the world. This operational framework needs to be transparent, by reporting hypotheses and assumptions made. It also needs to be consistent across scales and stakeholder's task in order to avoid double counting or gaps in carbon accounting. It responds to a practical need for policy-makers, regulators and administrators, designers and clients to have a clear target value for GHG emissions per m^2 or per m^2.yr. Such a design target might be different depending on the local climate and social needs.

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2. The carbon budget approach

The focus of this paper is on the definition, allocation and interpretation of a carbon budget approach. The advantage of this approach is that many actors in the construction sector already adhere to other defined budgets that must not be exceeded. A carbon budget can be adapted to the respective object under consideration and its system boundaries by choosing suitable reference values. It is thus an important instrument for reducing undesirable effects on the global climate.

The carbon budget refers to the maximum cumulative amount of anthropogenic GHGs which can be released in the atmosphere in order to keep the global Earth temperature within a given limit (IPCC 2018b). Transgressing this budget raises the risk of disturbing the climate system beyond an irreversible tipping point (Steffen *et al.* 2018). Climate change caused by GHG emissions is perhaps the most pressing environmental issue.

2.1. A global carbon budget

The IPCC has investigated different scenarios for global warming and related 'emission reduction pathways' (IPCC 2014). Based on this scientific evidence, policy-makers have agreed to use 2°C target as important objective for international climate policy (UNFCCC 2016), even though a 1.5°C target is now under consideration (IPCC 2018a: 32).

However, higher GHG concentration levels than those consistent with long-term temperature targets may be possible if negative emissions technologies reabsorb this concentration excess before 2100 (van Vuuren *et al.* 2013). Such (limited) overshoot scenarios can be attractive as they require less short-term reductions and seem to have only limited additional risks except that it shifts the efforts towards the next generation to implement these uncertain and costly carbon capture and storage technologies (Van Vuuren *et al.* 2017). A synthesis of these different carbon budgets depending on the target, 2 or 1.5°C and the potential use of negative emissions by the end of the century is presented in **Table 1**.

2.2. Allocation issues: per countries and capita

Once a global GHG budget has been defined, it can be allocated to specific actors: a national government, a city government or even a single person; or their respective area of activities. This step requires the carbon budget concept to be used as a tool in guiding practical decisions and actions of specific stakeholders.

The disaggregation of the global budget into ones for particular stakeholders (or area of activities) involves two dimensions: specification of the level of disaggregation (country to person) and of the accounting principle that determines how much of it is used up by particular activities. A common first *level of disaggregation* is by countries, within which the budget could be broken down further by, *e.g.*, economic sectors, areas of need or per capita.

In the literature, allocation mechanisms are discussed mainly for disaggregation at the country level (Alcaraz *et al.* 2019). The smaller the budget assigned to a country in relation to current emissions, the more mitigation effort is implied for that country. The allocation of budgets thus often is framed under the perspective of effort-sharing. Allocation mechanisms have been categorised based on the three equity principles of responsibility, capability and equality, and on their various combinations, as specified in IPCC AR5 (Clarke *et al.* 2014):

- *Responsibility:* Refers to whether historical emissions are considered. If so, their over-proportional occurrence reduces the share of a country in the global budget that is still remaining as of today.
- *Capability:* Draws on the UNFCCC principle that countries should act 'in accordance with their common but differentiated responsibilities and respective capabilities and their social and economic conditions' (UN 1992, Article 3). In budget allocation this implies a larger budget share for countries ranking lower in indicators such as gross domestic product (GDP) or the human development index (HDI).
- *Equality:* Often means 'allocations based on immediate or converging per capita emissions' (Clarke *et al.* 2014: 458). Immediate equality in per capita terms apportions the remaining global budget to countries based on their population. Equality that converges at a future point in time (possibly as late as 2050) involves a type of 'grandfathering' which acknowledges that current high emitters need time to make a transition. However, this attributes legitimacy to the status quo of highly unequal levels of emissions and even justifies their further persistence. This approach ensures highly industrialised countries have far more emission rights in the transition period, but no justification is provided for *preserving* this inequality beyond the fact that countries happen to have reached highly unequal levels (Williges *et al.* 2020).

Table 1: Total remaining global carbon budget expressed in Gt CO_2e: It includes all greenhouse gas (GHG) emissions.

	Without negative emissions			**With negative emissions**		
	T1.5C	**WB2C**	**LB2C**	**T1.5C**	**WB2C**	**LB2C**
2020–50 (Gt CO_2e)	500	700	1100	1700	1900	2300
2050–2100 (Gt CO_2e)	Net zero	Net zero	Net zero	–1200	–1200	–1200

Note: A scenario likely below 2°C (LB2C) is in line with the IPCC's 5th Assessment Report, as cited in Rogelj *et al.* (2016) with 50% below 2°C. A well below 2°C scenario (WB2C) is based on Rockström *et al.* (2017) with more than 66% below 2°C. Finally, a target of 1.5°C (T1.5C) is defined according to Millar *et al.* (2017) with 50% below 1.5°C.

Source: Adapted from Williges *et al.* (2020).

These three equity principles have also been applied in various combinations, as specified in **Table 2**.

The issue of national budgets is not pursued further in this paper. However, it is assumed that a national carbon budget defined in accordance with the approaches listed in **Table 2** is the starting point for a further subdivision into sectors, fields of action and areas of need.

2.3. Defining specific budgets according to the object of assessment

2.3.1. Mediating production and consumption models

The implementation of carbon budgets should be applicable on multiple levels, across activities. **Figure 1** illustrates a supply–demand concept. From a built environment perspective (buildings and infrastructure), the supply or production side can be represented, for instance, by the different industry sectors, which provide goods and services as an input. On the demand or consumption side one can find people and their different areas of need.

A production-based accounting approach would consider only direct emissions at the construction site (*i.e.* the *in situ* emissions from construction vehicles and equipment using fossil fuels). It is useful for the producers, yet tends to ignore the influence that the agents of final demand have on emissions during earlier steps in the production value chain. Alternatively, the emissions that had occurred in the production of upstream processes including emissions

Table 2: Categorisation of budget allocation approaches.

IPCC category	Description
Responsibility	Use of historical emissions to derive future reduction goals
Capability	Approaches relating goals to gross domestic product (GDP) or human the development index (HDI), other basic-needs-fulfilling approaches
Equality	Allocation based on immediate or converging emissions per person
Responsibility, capability and need	Includes approaches placing an emphasis on historical responsibility, balanced with capability and the need for sustainable development
Equal cumulative per capita	Combines equality with responsibility (cumulative accounting for historical emissions)
Staged approaches	Differentiated commitments, various stages, sectoral approaches or grandfathering approaches

Sources: Based on Höhne, den Elzen, & Escalante (2014) and Williges *et al.* (2020).

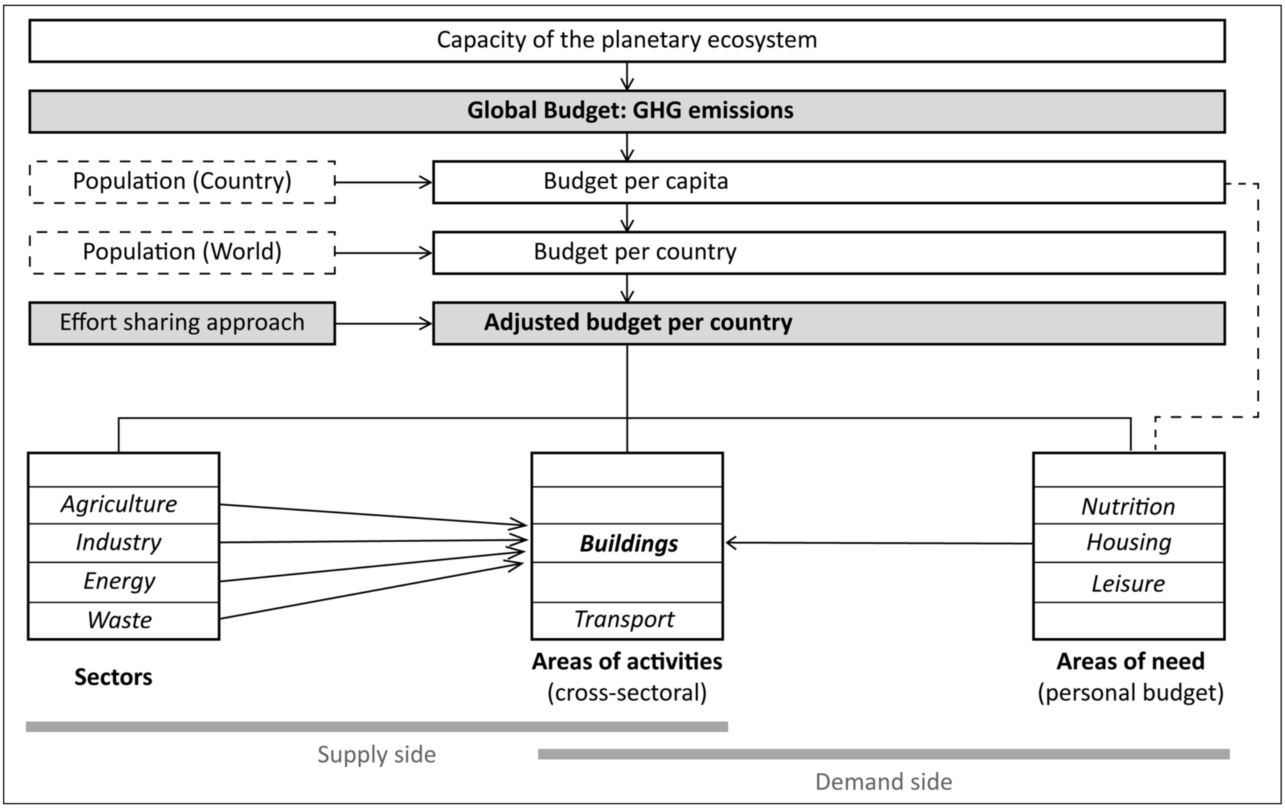

Figure 1: Different points of view for defining budgets across activities. The industry sector includes the construction product industry, construction industry and real estate industry. The agriculture sector includes by-products used as bio-based building materials.

from the production of materials or infrastructure required to provide the final product can be considered. This latter approach follows a consumption-based accounting principle. However, including this consumption-based accounting approach might not fully address the relevance of production decisions for products that are 'exported' to other agents for their final demand. Ultimately both accounting principles should be acknowledged (Steininger *et al.* 2016), such that agents' decisions are based on an indicator system suitable for their needs that avoids pathways with unintended counterproductive implications for the global GHG concentration.

2.3.2. Sectoral approach

The definition of economic sectors can follow different approaches, *e.g.* the classical three-sector model of primary, secondary and tertiary sectors, or an owner-based approach distinguishing public and private sectors, amongst others. Several international and national standards have been established for the classification of economic sectors for statistical purposes, such as, *e.g.* the International Standard Industrial Classification of All Economic Activities (ISIC) for worldwide use developed by the United Nations Statistics Division (UNSD) (2008), or the Statistical Classification of Economic Activities (NACE) classification of economic activities for the European Union (Eurostat 2008) as well as a multitude of national classifications that, more or less, align with these international systems. In practice, several definitions and conventions are used depending on the context these are defined in. For instance, the IPCC's *1.5°C Special Report* applies a sectoral perspective based on 'energy end-use sectors' focusing on society's main sectors, and includes buildings, industry, transport, energy, and agriculture, forestry and other land use (AFOLU) (IPCC 2018b). The current authors prefer an approach which, from a macro-economic point of view, divides the national economy into basic sectors such as agriculture, industry, energy and waste management. The industry sector is further subdivided and includes the construction product industry, construction industry and real estate industry.

A common strategy for implementing emission reductions across sectors and activities, *e.g.* in policy roadmaps, is to follow a contraction and convergence approach. This means defining emission reduction targets for individual sectors based on current (or past) levels of GHG emissions, *e.g.* a 50% reduction in GHG emissions by 2030 from a 1990 baseline.

2.3.3. Areas of activities

Based on the GHG protocol (WRI & WBCSD 2013), the GHG emissions can be defined for the national building stock or one residential building:

- *Direct emissions (scope 1)* from building operation, *e.g.* GHG emissions from burning fossil fuels for heating and cooling, lighting, hot water, *etc.*
- *Upstream emissions (scope 2)* from provision of operational energy from the respective energy sources, *e.g.* indirect emissions of district heating or electricity.
- *Indirect emissions (scope 3)* related with upstream and downstream activities, including the production and processing of building materials as well as construction, maintenance and replacement, renovation and demolition of the building at the end of its service life.

All these different perspectives—scopes 1–3—need to be considered when assessing the emissions across the full life-cycle of 'buildings' or construction assets.

An approach is proposed here to encompass the full life-cycle of 'buildings'.

The term 'sector' is used here to refer to 'economic sectors' or its parts (*e.g.* construction product industry, construction industry, real estate industry). The term 'area of activities' is used where different industrial sectors contribute to a cross-sectoral activity, such as the 'production, construction, use and end-of-life of buildings', in short, 'buildings'.

2.3.4. Areas of need

Apportioning the global (or country) budget using a consumption-perspective (Beylot *et al.* 2019; Cabernard, Pfister, & Hellweg 2019) brings the issue of appropriate needs into focus (*e.g.* mobility, housing/shelter, nutrition; Creutzig *et al.* 2018). People's needs and practices are what creates demand, which induces economic activity and causes the associated environmental burdens (**Figure 1**). However, the imposition of carbon mitigation efforts equally across all areas of needs is socially unjust as certain needs are more fundamental (*e.g.* sufficient nutrition) than others (*e.g.* air travel) (Otto *et al.* 2019).

An important distinction must be made between essential (or basic) and advanced (or luxury) needs (O'Neill *et al.* 2018; Rao & Min 2018; Raworth 2017). For example in the area of housing, the essential need may be defined as a certain floor space per inhabitant with a decent comfort level (Rao & Min 2018). Fulfilling the basic needs for a prospective world population (approximately 10 billion in 2050) with the technology available during the transition period, will consume a certain fraction of the remaining carbon budget and can be seen as the emissions necessary to ensure the social foundation (Rao & Baer 2012). Giving priority to achieve a decent life for all—in line with the internationally agreed SDGs (UN 2015)—necessitates and justifies to increase the allocation of the remaining carbon budget to areas of basic needs (**Figure 1**). Whatever is left may then be shared among advanced needs. In the example of housing, every additional m^2 or increased comfort receives a smaller carbon budget, *i.e.* assigned an increased mitigation effort.

3. Multiple perspectives on buildings and building-related activities

It is possible to identify three largely different objects of assessment as described in **Figure 1**: the economic sectors, the area of activities 'buildings' and the area of need 'housing'. Residential buildings are a subgroup of buildings here. If constructed assets or infrastructure are included, the area of activities then become 'creation and operation of construction works' in a wider sense.

Once a clear definition of the object of assessment is given, the principles described in the previous section for dimensioning and allocating budgets can be applied to buildings as area of activities.

The economic sectors contributing to the construction, maintenance and operation of buildings are related to macroeconomic sectors such as:

- *Industry:* the production of building materials (construction product industry including upstream processes), the construction of buildings and infrastructure (construction industry), and the management of buildings and building stocks (real estate industry and facilities management).
- *Energy and water supply:* all services related to the operation of buildings and associated construction and maintenance of these infrastructure and upstream processes.
- *Waste management:* the solid and liquid waste generated during the construction of the buildings and their use.

The area of activity 'buildings' focus on the production, construction and use of the physical objects, including end of life processes (reuse, recycling and/or disposal). This area of activity focuses on different spatial boundaries, from national level to the single-building scale. In relation to such physical objects the term 'building stock' is also used.

The area of needs 'housing' relates to the area of activity 'residential buildings' which is on the demand side (Jenny, Grütter, & Ott 2014; Rao & Min 2018).

In this paper, a diversity of the objects of assessment is accepted due to the diversity of stakeholders associated with building's activities. Each stakeholder has a specific interest because each of them is responsible for the management of one specific task at one specific level/scale of activity. Therefore, determining a task specific carbon budget requires an appropriate management of the global carbon budget to ensure that specific budgets overlap but that the sum of them is equal to the available global budget without double counting.

Table 3 shows the link between the list of stakeholders involved in buildings' activities and the previously described object of assessment. The general distribution of interest for the different stakeholders is defined based on expert advice[2] and is not a result of surveys (Lin *et al.* 2017) or semi-structured interviews (Li *et al.* 2018). But there is a general agreement between the common viewpoint in this paper and other studies on the powers, interests and responsibilities of stakeholders along the value chain of building construction and use (Li *et al.* 2018; Lin *et al.* 2017; Tengan & Aigbavboa 2017; Yang, Zou, & Wang 2016).

It is clear that national and regional governments have a significant power to set rules and targets. Sustainability assessment and certification bodies, which mainly operate at the building scale and sometimes at district level (Cole 2005; Pati, Park, & Augenbroe 2006) have an influence that cannot be neglected. Actually, even if the proportion of certified buildings and neighbourhoods is low in relation to all construction activities, these organisations have been and are still pioneers in the introduction of GHG emissions target values. For instance, in Germany, sustainability assessment systems like BNB and DGNB evaluates GHG emissions during the life-cycle and set limit and target values for buildings since more than 10 years (BMUB 2014).

Households and architects mostly focus on one single building and as individual actors, their influence is hardly measurable. However, as a complete group of actors, they are the key target group for the specification of carbon budget for embodied and operational part of individual buildings as they are the one who will ultimately implement such specifications. The overall concept of a carbon budget approach is not considered at the individual level. Instead, it is either through professional organisation of architects and engineers or real estate companies which can establish rules of good practice and standards (*e.g.* SIA 2040:2017; SIA 2017) or through financials constraints and incentives which can drive individual owner's choices.

In that sense, institutional investors, property and housing companies, property funds, banks and insurance companies can decide to green their investment portfolio in relation to the carbon footprint of the buildings they own (in their role as investor and portfolio manager) or finance (in their role as financer or insurer) (TEG 2019). Financial organisations can drastically transform the construction market if clear carbon data and budgets exist for specific objects. Responsible banking could finance carbon budget compatible activities (for material producers, for real estate companies or for individual owners) in the same way as insurance companies have integrated climate change risks into their portfolio management (Dlugolecki 2000). Weber & Kholdova (2017: 6) state:

> the financial industry should develop indicators that can be used internally to measure and evaluate climate change-related performance. […] Methods such as carbon footprinting, avoided emissions and green–brown metrics—though still in their infancy—are helpful for managing carbon-related risks and allocating climate change responsibilities.

Table 3: Mapping for type of budget versus kind of actor.

	Type of actor	**National government regulator/ assessor**	**National government administrator**	**Regional government regulator/ assessor**	**Regional government administrator**	**Building owner (all types)**	**Building operator (all types)**	**Industry: production (energy and products)**	**Building association (architecture and engineering; construction products association)**	**Architect**	**Bank**	**Sustainability certification body**	**Household**
Object of assessment													
A	**Economic sector**												
A1	Construction product industry	×						×	×		×		
A2	Energy sector (energy provider)		×					×			×		
A3	Waste management sector	×		×									
A3	Real estate sector					×					×		
B1	**Area of activity: operation**												
B11	National building stock		×					×	×				
B12	City/district				×								
B13	Building portfolio						×				×		
B14	Single building	×		×		×				×		×	×

(Contd.)

	Type of actor	National government regulator/ assessor	National government administrator	Regional government regulator/ assessor	Regional government administrator	Building owner (all types)	Building operator (all types)	Industry: production (energy and products)	Building association (architecture and engineering; construction products association)	Architect	Bank	Sustainability certification body	Household
B2	**Areal of activity: full life cycle**												
B21	National building stock		×				×	×	×				
B22	City/district				×	×			×				
B23	Building portfolio		×				×		×		×		
B24	Single building	×		×		×				×	×	×	
C	**Area of need**												
C1	Housing (part: operation)	×	×			×	×			×			×
C2	Housing (part: full life cycle)	×	×			×							

4. A scale specific budget approach for stakeholders

4.1. A framework spanning spatial and temporal scales

Figure 2 illustrates the overlapping interests and the need for scale specific budgets. This provides a coherent alignment across scales. In this way, one can begin to reconcile a budget for yearly emissions of an economic sector (*e.g.* the part of the construction or the energy sector required for residential activities) with a budget for one building object over its full life-cycle. A pool of buildings such as a district, a real estate portfolio or a national building stock can also be analysed and provided with specific budgets, tailored to the respective use case. This budget can consider the current state of the building stock and/or its future evolution. Finally depending on the stakeholders' interests, one would define a budget only for emissions related with operation of these objects (building/district/portfolio/national building stock) (scopes 1 and 2), or include emissions related with their production, construction, maintenance and demolition (scope 3).

Figure 3 explicitly shows the different steps for carbon budget definition. This transparency provides a comprehensible definition of the system boundaries and the hypothesis associated with a given budget. The decision choice depends on the stakeholder's viewpoint and allows for different configurations. Key aspects to consider are:

- *Global budget:* What is the global carbon budget available? This depends on the climate model taken as well as the chosen target (1.5–2°C, *etc.*).
- *Effort sharing and allocation principles*: How is this budget shared between people, countries and industrial sectors? Which rules are applied, *e.g.* contraction and convergence, equal budget per capita, *etc*?
- *Object of assessment:* What is the object of assessment: the construction industry, building operation, one specific building, one district or a complete building stock of a defined region? Which life-cycle stages are covered and how is the budget shared across them?
- *Building budget:* is the allocated budget translated to a specific building intervention? This final step establishes a correlation between the budgets defined in previous steps and translates them to a budget per m^2 building floor area. This allows engineers and architects to use this budget in the design process. Furthermore, city planners or policy-makers can use such budgets to analyse and plan interventions at building stock level, such as retrofit scenarios or science-based governance of new construction allowances.

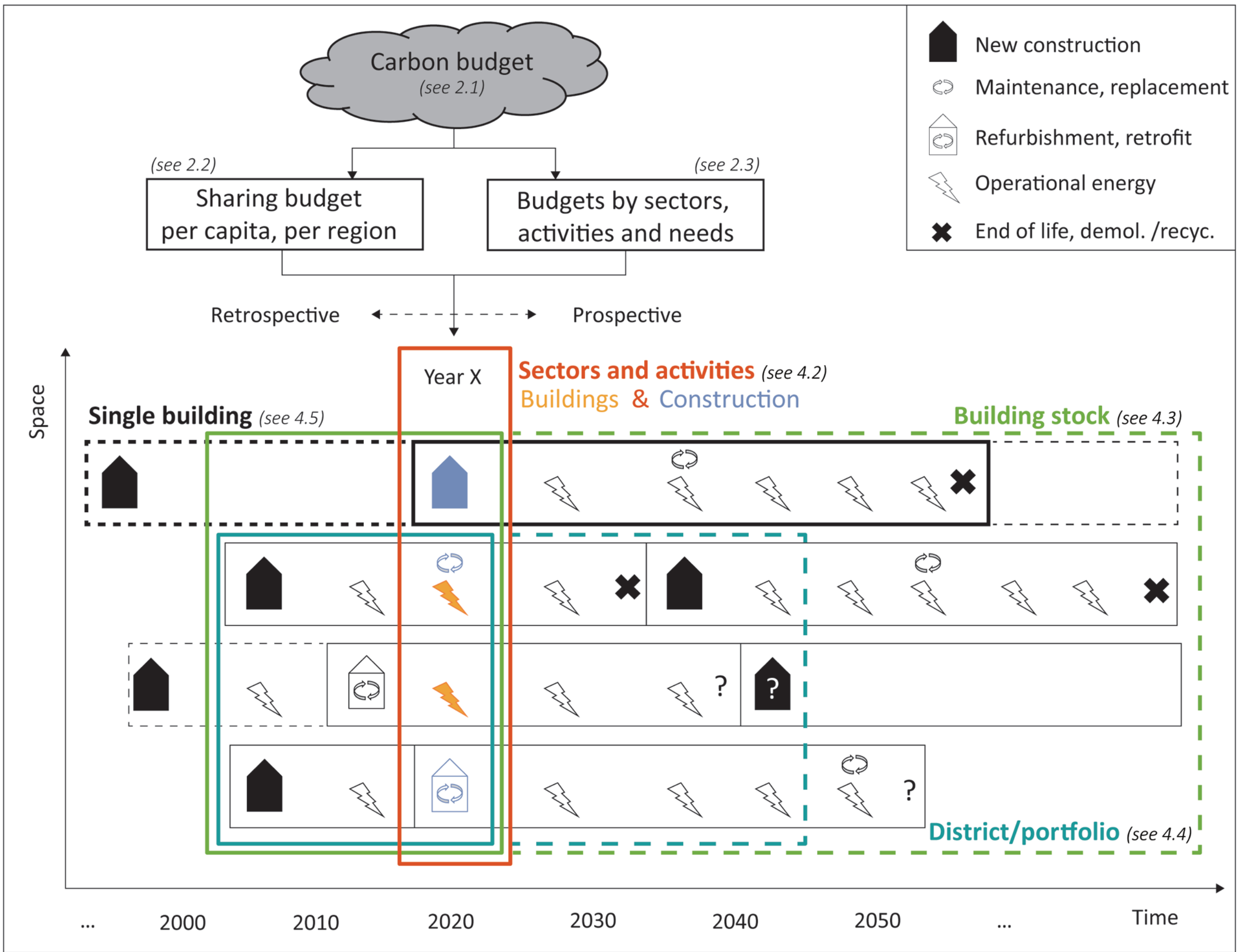

Figure 2: Four perspectives on 'buildings' and related spatial and temporal scales.

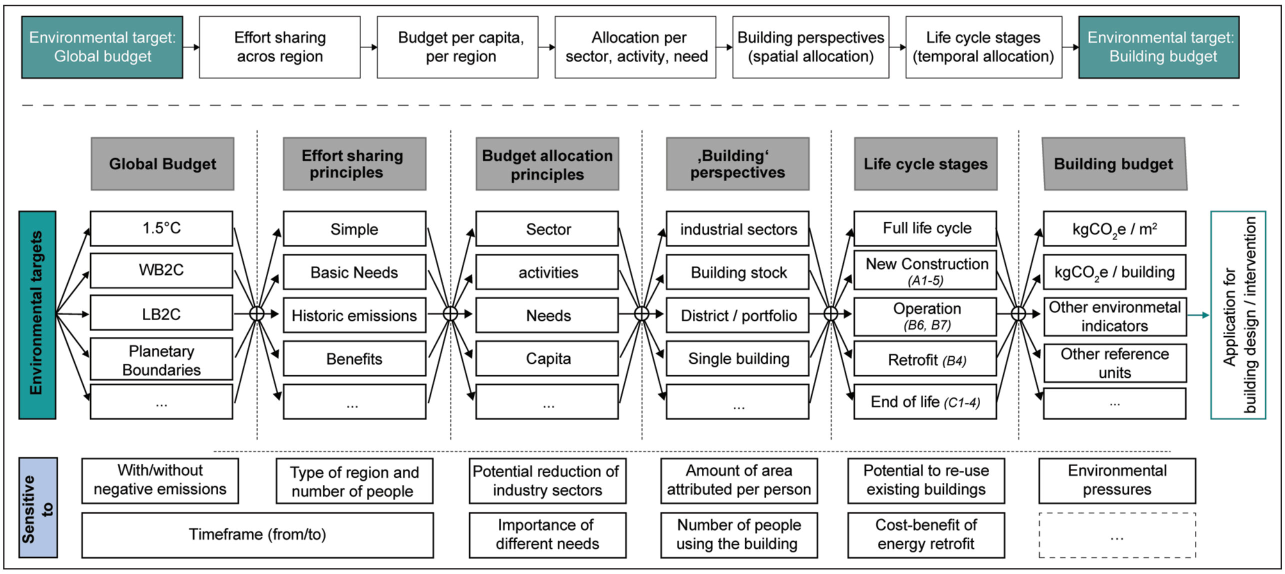

Figure 3: Decision tree for budget definition, showing the various steps and decisions to be taken and specified for definition of environmental budgets. Several aspects in this definition are sensitive to country specific characteristics (*e.g.* number of people, historic emissions, *etc.*) as well as sensitive to behavioural aspects (*e.g.* number of people using a building and area per person).

4.2. Budgets for economic sectors and areas of activities

This section provides some examples that have been promoted in different countries or regions to illustrate the different strategies and choices in defining environmental targets.

To deliver on the EU's commitment in the Paris Agreement and to respond to the objective of limiting global warming to 1.5°C, the European Commission (EC) communicated the target for GHG emissions reductions of 91–94% below 1990 levels by 2050 (EC 2018). The underlying in-depth analysis (EC 2018) presents multiple scenario-based pathways for reducing GHG emissions towards the aspired 'net-zero' levels by and beyond 2050. All scenarios rely on the implementation of CO_2 removal technologies.

Once this global EU budget calculated, it is possible to construct a yearly per capita budget considering current population as well as its evolution to 2050 (**Table 4**). Finally, the EC has also defined different strategies depending on the economic sectors considering the economic and technical feasibility of their decarbonation potentials. From a more technical point of view and following an efficiency and consistency strategy, greening the energy sector is the easiest, followed by the reduction in energy demand during building use (due to deep retrofit) and finally the decarbonation of building material production (included in industry sector) (Davis *et al.* 2018). There could also be a sufficiency strategy to reduce energy demand by a change in the occupants behaviour through the selection of appropriate comfort level and the optimisation of space demand. However, this approach is less promoted by the EC.

In the EU's long-term strategy for reducing GHG emissions, energy-efficiency measures, including the energy efficiency of building operation, play a central role in reaching 'net-zero GHG emissions by 2050' through the reduction of energy consumption 'by as much as half' compared with 2005 (EC 2018). To improve the energy performance of buildings, the EU has implemented the Energy Performance of Buildings Directive (EPBD) (EC 2010). EPBD targets are set per country and have thus so far focused on energy efficiency and, at least not explicitly, the reduction of GHG emission. Benchmarks are currently specified for the energy consumption per m² and the percentage share of renewable energy as well as minimum requirements regarding the thermal transmittance (*U*-value) of the building. While these requirements will have a substantial effect on the energy-related GHG emissions, they do not yet fully connect to the GHG reduction targets set by the EU.

Different approaches for definition of a carbon budget for the area of activities 'buildings' are also possible at the national level. For instance, the German Climate Protection Plan 2050 (BMUB 2016) mentions 'buildings' as an area of action. It represents the emissions related with the energy used for the operation of buildings. There is a specific objective for 2030 and it can be interpreted as a partial carbon budget for building operation emissions. For 2050 the target is a climate-neutral national building stock—when considering the operational part. There is no target or budget in place for the embodied part at the moment (**Table 5**).

The embodied emissions related to building activities are considered in the area of action 'industry', which includes construction product industry among others. Depending on the feasibility of the decarbonation process and the future demand perspective, adjustment and allocation between industries are negotiated. While some industrial activities

Table 4: Overview of European Union (EU) greenhouse gas (GHG) emissions reduction targets and related carbon budgets in total, per sector and per capita.

	Reference	Future targets	
	1990	**2030**	**2050**
EU total			
Reduction targets (%)	100	–46 to –47%[c]	–91 to –94%[c]
GHG emissions (Mt CO_2e/yr)	5650	3060–3091	343–494
Per capita			
EU population	418[d]	449[d]	441[d]
Emissions budget (CO_2e/cap.yr)	13.52	6.81–6.88	0.78–1.12
Per sector			
Power			
(%)	100%	–54 to –68%[b]	–97 to –108%
(Mt CO_2e/yr)	1869[a]	598–860	–141 to 47[c]
Industry			
(%)	100%	–34 to –40%[b]	–96 to –98%
(Mt CO_2e/yr)	1359[a]	815–897	29–53[c]
Residential and services			
(%)	100%	–37 to –53%[b]	–97 to –98%
(Mt CO_2e/yr)	731[a]	344–461	11–13[c]

Notes: [a] Values based on 1990 EU-28 GHG emissions inventory scope under UNFCCC (excluding LULUCF) (EEA 2020).
[b] Sectoral targets for 2030 based on EC (2011).
[c] 2050 based on EC (2018) (Scenarios 1.5TECH, 1.5LIFE and 1.5LIFE-LB).
[d] EU population evolution based on Eurostat (2020).

Table 5: German climate action plan.

CO_2e emissions (Mt/yr)				
Area of action	1990	2014	2030	2050
Energy	466	358	175–183	0
Buildings	209	119	70–72	0
Transport	163	160	95–98	0
Industry[a]	283	181	140–143	17
Agriculture and LULUCF	88	72	58–61	43

Notes: CO_2e emissions reduction targets are split depending on the year and the area of actions. The area of activity is called here 'area of action'. LULUCF = land use, land use change and forestry.
[a] Including waste.
Sources: Data are for 2030 (BMUB 2016) and 2050 (Benndorf *et al.* 2016).

have to reduce their emission by 100%, the construction product industries (steel, aluminium, cement, lime, glass and insulation materials) represent more than 60% of the remaining emissions in 2050 (Benndorf *et al.* 2016). It confirms the fact that these industries are the most difficult to decarbonise as emissions do not come only from the energy related processes but also from raw material-related emissions (*e.g.* limestone decarbonation in cement). Acting only on industry energy efficiency is therefore not possible for construction-related industries and a sufficiency approach is required where the objective is a reduction in material demand (IEA 2019). This material reduction must involve stakeholder beyond industry sector (Favier *et al.* 2018) and this is the reason why design targets and carbon budgets for the embodied part of buildings are needed (see section 4.5).

4.3. Budgets for national or regional building stock

Achieving regional or national GHG reduction targets, including the ones discussed above, is challenging and requires mitigating GHG emissions from both existing and new buildings of a chosen region or country (Giesekam, Tingley, & Cotton 2018; Röck *et al.* 2020). Thus, it is crucial to translate these regional or national GHG reduction targets into meaningful sub-global levels (Bjoern *et al.* 2020; Häyhä *et al.* 2016); the building stock is one of them (Balaras *et al.* 2007; Lavagna & Sala 2018).

Some researchers have already investigated about what these regional or national targets mean to building stocks in different countries (Cuéllar-Franca & Azapagic 2012; Giesekam *et al.* 2018; Lavagna & Sala 2018). However, much of the work is related to the existing buildings in a specific year (or a period) and failed to account for future changes in a building stock such as variations in construction and demolition rates, changes in building sizes, and changes in construction technologies and materials. Accounting for these aspects is critical when assigning a share of the global carbon budget to a chosen building, which can be either an existing building or a future building.

To that end, Chandrakumar *et al.* (2019, 2020b) proposed a top-down based approach for determining carbon budgets for building stocks (and individual buildings), considering the existing national building stock which should be operated in a country from now to a certain time in the future (*e.g.* 2030, 2050) as well as the new building stock that should be constructed in the same period. Their approach translates a chosen global climate target (*e.g.* 1.5 and 2.0°C) into a global carbon budget available from now until a certain time in the future and shared between countries, applying the so-called effort-sharing principle of *cumulative emissions per capita*. This effort-sharing principle is centred on achieving equality in terms of the cumulative GHG emissions of different populations across the world (van den Berg *et al.* 2019; Yu *et al.* 2011) through the contraction and convergence approach.

Subsequently, shares of the country's carbon budget are assigned to the residential as well as non-residential building and construction sectors of the chosen country, using the *grandfathering* effort-sharing principle (van den Berg *et al.* 2019). This principle implies that the carbon budget share (*i.e.* the right to emit GHGs) is determined based on the relative contribution of the sector to the country's total consumption-based GHGs in a chosen reference year (Chandrakumar *et al.* 2020a).

A carbon budget (calculated per 1 m^2 gross floor area) for embodied life-cycle stages is then determined by dividing the carbon budget available for the area of activity related with construction by the total gross floor area of the pre-existing and newly built dwellings that exist in the chosen period. Similarly, a carbon budget (calculated per 1 $m^2 \cdot yr$) for operational life-cycle stages is calculated by dividing the carbon budget for the area of activity related with building operation by the total gross floor area that operate in the same period.

Finally, carbon budgets for different buildings (can be either residential or non-residential) are determined by multiplying the calculated carbon budgets for embodied and operational life-cycle stages with the respective gross floor areas (and the service lives for operational) of the selected buildings.

The proposed approach was recently applied by McLaren *et al.* (2020) to calculate 1.5°C consistent carbon budgets for three common types of residential dwellings in New Zealand, *e.g.* newly built single-family detached house, medium-density house and apartment. According to McLaren *et al.*, the 1.5°C consistent carbon budgets for embodied and operational life-cycle stages are 86 and 61 $kgCO_2$ e/$m^2 \cdot yr$, respectively. Furthermore, the 1.5°C consistent carbon budgets for the whole life-cycle of a typically sized[3] New Zealand newly built single-family detached house, medium-density house and apartment (over a service life of 90 years) are 35, 20 and 17 t CO_2e, respectively.[4] Alternatively, when the 2°C global climate target is chosen, the carbon budgets for the three residential dwellings increased to 50, 29 and 24 t CO_2e, respectively, which is a factor 1.4 increase compared with the 1.5°C consistent carbon budgets.

4.4. Budget for a district

Usual carbon targets are allocated at building scale (SIA 2040:2017; SIA 2017) based on the type of activities (*e.g.* housing, offices) and the intensity of use (number of occupants). This approach allocates a similar carbon budget per m^2 to a building type, without considering the specificity of each project (*e.g.* solar exposure, urban rules). A consideration of a budget at the district scale, which can then be distributed between the buildings depending on their potentials (*e.g.* solar exposure) and their constraints (*e.g.* shape), can better distribute efforts between buildings. To implement this strategy, a method has been developed in Fribourg (Switzerland) and consists of five steps:

(1) The district is divided into zones with similar context (*e.g.* maximum building height, solar exposure), so that buildings within these zones will have similar targets.
(2) For each of these zones, a series of building-level possibilities are generated by defining hypotheses of project-specific parameters and varying design options. The GHG impact of each project alternative is evaluated, thus generating a knowledge database of thousands of options and their corresponding life-cycle impacts.
(3) The average GHG impact of all project design possibilities within one zone is calculated, followed by the calculation of the available GHG impact in accordance with the building area and usage, as defined by SIA2040 norm. Contextual targets are then calculated by attributing the share of the total site impact proportionally to the average impact of each zone (Nault *et al.* 2020).

(4) The method can also be further applied from the building scale towards carbon budget for its systems and components (Jusselme *et al.* 2019) such as the windows and the heating system.
(5) The technical feasibility of reaching a specific contextualised target is thus evaluated and compared with the one of a uniform target. This technical feasibility is an index of performance calculated as the ratio between the number of design options that have a GHG impact lower than the GHG target, and the overall number of design options of the knowledge database.

In **Table 6**, the method is applied to a case study 'Blue Factory' site in Fribourg (Switzerland), which includes eight plots for new buildings (plots A1–D) mixing housing and offices. Results indicate that for the same overall GHG impact at the district level (20 CO_2e/m².yr), small changes in the target distribution at the zone level leads to a significant increase of the technical feasibility. In zone A1, for instance, increasing by 1.8 kgCO_2e/m².yr the GHG target (+9% compared with the uniform target) leads to increase by 29% the feasibility index. To balance the increase of GHG targets, zones C3 and D will have to reach slightly higher performance levels which do not affect significantly their respective feasibility indices (–6.6% and –5.5%). Hence, the allocation of a district-level carbon budget in contextual sub-targets influences significantly the technical feasibility of building-level projects and could offer more flexibility or efficiency in the building design and construction.

4.5. Budgets for a single building

4.5.1. Per capita budget for single building

The application of a per capita budget has been popularised by the Swiss 2000-Watt Society (Zimmermann, Althaus, & Haas 2005). It was first introduced by ETH Zürich in 1998 and envisioned the average First World citizen reducing the overall primary annual energy consumption to 2000 W (which is 48 kWh/day) and 1 tonne CO_2 per capita and per year by 2150 with intermediate target of 2 t CO_2 in 2050. This vision was then adapted considering the urgency of climate action in order to achieve the budget of 1 t CO_2e per capita and year already in 2050 (Hollberg, Lützkendorf, & Habert 2019). However, the 1 t per capita value does not come from a global budget but the assumption that this level is a sustainable emission level, considering current population level and applying a contraction and convergence logic.

A different approach for residential buildings in Czechia focuses on setting an intermediate GHG benchmark for 2030 aligned with the Paris Agreement (Pálenský & Lupíšek 2019). This target is derived from a global yearly allowance for GHG emission in 2030 defined in the *Emissions Gap Report 2018* (Olhoff & Christensen 2018). These annual allowed emissions are then equally distributed per global capita (using a forecasted global population of 8.55 billion in 2030), resulting in 4.68 and 2.81 t CO_2e/year per capita if 2 or 1.5°C targets are chosen.

Once a budget per capita is defined, the next step is to estimate the proportion of the personal GHG allowance to be allocated for individual housing. In Czechia as well as in Switzerland, the estimated share of the current building emission is used as a proxy. However, the definition of 'building emissions' does not cover the same buildings. In

Table 6: Results in terms of uniform and contextual distribution of the greenhouse gas (GHG) targets and relating changes in technical feasibility per zone.

Zone		**A1**	**A2**	**A3**	**B**	**C1**	**C2**	**C3**	**D**	**Total district**
Uniform target	Uniform GWS target (kgCO_2e/m².yr)	20	20	20	20	20	20	20	20	20
	Number of design options below the target	7297	8355	7948	8740	913	883	1172	1192	–
	Feasibility (%)	55.4	63.4	59.6	66.5	67.5	65.3	86.6	88.1	–
Contextual target	Contextual GWS target (kgCO_2e/m².yr)	21.8	21.4	21.6	21.4	21.3	22.2	19.1	18.9	20
	Number of design options below the target	11,137	11,210	11,283	10,448	1088	1114	1083	1117	–
	Feasibility (%)	84.5	85.1	84.6	79.5	80.4	82.3	80	82.6	–
Changes in feasibility (%)		29.1	21.7	25	13	12.9	17	–6.6	–5.5	–
Built area per zone (m²)		3000	6000	4000	10,000	4000	12,000	30,000	35,000	104,000

Note: GWS = global warming score.

Czechia, 23.35% represents an estimated share of the residential building stock to the overall 2014 national CO_2 emissions (Lupíšek 2016).

In Switzerland, emissions cover the six building categories which comprise 80% of the Swiss building stock: residential, administration, school, specialised store, food store and restaurant. The Swiss guide values include building construction, operation and also mobility directly related to the building over the whole life-cycle of a building. The current share of emission was determined for each building category based on the Swiss statistics 2010. Further details are provided in the SIA 2040:2017 (SAI 2017) standard.

Finally, it is possible to reach a budget per building or per m^2 by multiplying the personal building allowance defined previously by the planned number of building occupants, as in Czechia (Lupíšek 2019) or the energy reference area (A_E) per capita, as in Switzerland (SIA 2015). Details are presented in **Table 7**.[5]

Table 8 illustrates the importance and potential for sufficiency strategies to reduce the floor area per resident. As the budget is defined per capita, if there is a smaller area (m^2) per capita, then the GHG budget per area (m^2) would increase (see also Pfäffli *et al.* 2012).

Similar work has been conducted in Denmark. Brejnrod *et al.* (2017) defined climate targets for a single-family house in Denmark (for 2010) at 110 kg CO_2e/cap.yr. They calculated the carbon budget available for a global citizen in 2010 (985 kg CO_2e/cap.yr for 2°C) and assigned a share of it to a Danish single-family house using the sharing principle of final consumption expenditure (*i.e.* the relative share of household expenditure for housing). There is a special relation to the areas of need approach with a carbon budget for individuals and households for 'housing'. Hoxha *et al.* (2020) applied almost the same approach to Kaya's equation for the calculation targets for Austrian context (Nakićenović & John 1991). Using a hybrid top-down, bottom-up approach, they found that the target for the GHGs are of the range of 5.8 kg CO_2e/m^2.yr, comprising 4 kg CO_2e/m^2.yr and 1.8 kg CO_2e/m^2.yr for embodied and operational impacts, respectively.

Similar efforts have also been done to propose climate targets for commercial buildings (Hoxha *et al.* 2016; Russell-Smith *et al.* 2015). For example, Russell-Smith *et al.* (2015) estimated a target of 2.29 t CO_2e/m^2 for the whole life-cycle of a commercial building in the US, considering a 50-year lifetime. The target was based on the GHG emissions projections in the *IPCC Fourth Assessment Report*, which recommended a 70–80% GHG emissions reduction below 1990 levels by 2050 in order for buildings to operate within the 2°C target.

4.5.2. Example illustrating different sharing principles

Andersen *et al.* (2020) investigated absolute environmental sustainability using two approaches: the carrying capacity and the planetary boundaries. Planetary boundaries is a more precautionary approach and sets a lower environmental boundary than the carrying capacity. As sharing principles is a matter of *who* has the right to impact *how much*, six different sharing principles were applied to allocate the carrying capacity and planetary boundaries to a single-family dwelling (Andersen *et al.* 2020). The sharing principles include approaches such as equal per capita, final consumption expenditure, energy consumption and CO_2e emissions. The sharing principles only represent the dwelling share and not the share per m^2. However, the results have been converted here for comparison with other studies. **Table 9** shows how the carbon budget is highly dependent on the sharing principle chosen, varying from 0.67 to 8.84 kg CO_2e/m^2.yr, when the carrying capacity approach is used.

These different results highlight the diversity of approach and the difficulty to define one exact value. When the different proposition for a single building are compared, one can observe a factor 10 between budgets. This is due to all the different assumption possibilities all along the budget definition workflow. Considering the climate emergency and the severe consequences of passing earth climate tipping point will have (Steffen *et al.* 2018), it is very problematic to observe such large differences between countries, which have a relatively comparable level of development. Furthermore, none of the presented budget consider the dynamic of emissions nor the need to first allocate a share of the global budget to essential needs for emerging countries and assess afterward the remaining budget for other area of less urgent needs. They rather adopt a contraction convergence or grandfathering approach, which is unfair (Caney 2009). These two aspects are briefly discussed in the next session.

5. Environmental targets beyond '2050'

5.1. Time conflicts for operation and embodied carbon budgets

Buildings are long-lasting artefacts. The buildings created today are expected to operate far beyond 2050 when buildings will need to be net-zero emissions.

Current net-zero emissions buildings and standards fail to consider the dynamic of emissions. First, they usually focus on compensating operation energy on a yearly basis, but a yearly calculation hides the hourly dynamic and fails to point out the difficulty of daily (Barone *et al.* 2019) and seasonal storage (Kaufmann & Winnefeld 2019; Rostampour *et al.* 2019). The second failure is to consider embodied emissions on a yearly basis. Embodied emissions from construction occur mainly in the first year of the building life time and (approximately 30 years later) when deep renovation are done (**Figure 4**), while operational emissions occur every year at roughly the same rate. The current standard (SIA 2040:2017; SIA 2017) that distributes emissions all along the life time of the building underestimates the peak of emissions which will happen before 2050 exactly when emissions need to be reduced.

Table 7: Calculation details for single-building budget calculation in different countries.

	Switzerland	Switzerland adapted	Denmark	Austria	Czechia
Global budget					
Target (Paris Agreement, 2°C, 1.5°C, etc.)			1.5°C (2030)		2 and 1.5°C (2030)
With or without negative emissions			Without negative emissions		Without negative emissions
Budget per country			6.79 Gt CO_2e/yr		24 to 40 Gt CO_2e/yr
Effort-sharing principles					
Historic emissions or not	No historic emissions				
Future or current population	Current Swiss population	Current Swiss population	Current global population	Trend for future population and buildings	Czech population (2030)
Effort-sharing definition (equality, capability)	Equal per capita	Equal per capita	Equal per capita, final consumption expenditure, time spent, energy consumption, CO_2 emissions	Equal per capita	Equal per capita
Budget per capita			2.5 t (2030)		4.68 t (2°C)
(t CO_2e/cap.yr)	2 t (2050)	1 t (2050)	1.4 t (2040)	1 t (2050)	2.81 t (1.5°C)
Allocation principles					
Share of emission per sector	Current share for sectors: 33% for construction and buildings. Feasibility study to split between embodied and operation budget			Current share for sectors: 36% for construction and buildings. Feasibility study to split between embodied and operation budget	Current share of sectors: 23% for residential buildings
Share of m² per capita (m²/capita)	60 m² HFA/45 m² living space	60 m² HFA/45 m² living space	39.4 m² Gross floor area	67 m² HFA	1045 m² for 26 occupants (40.2 m²/capita)
Inhabitants per buildings			2.54		26
Type of activities included	Embodied (construction, maintenance and EoL), operational (electricity and heating)	Embodied (construction, maintenance and EoL), operational (electricity and heating)	Embodied (construction and replacement), operational (water, electricity and heating)	Embodied (construction, maintenance and EoL), operational (electricity and heating)	Embodied (construction, maintenance and EoL), operational (heating)
Related LCA life-cycle stages	A1–A3, B4, B6, C3–C4	A1–A3, B4, B6, C3–C4	A1–A5, B4, B6, B7, C3–C4	A1–A3, B4, B6, C3–C4	A1–A3, B4, B6, C3–C4

(Contd.)

	Switzerland	**Switzerland adapted**	**Denmark**	**Austria**	**Czechia**
Reference study period (yr)	60	60	120	50	
m^2 definition	HFA	HFA	Gross floor area	HFA	Net floor area
Building's budget					
Budget per m^2 (kg $CO_2e/m^2.yr$)					
Operational budget	3	1.5	0.19–2.5[a]	1.8	
Embodied budget	9	4.5	0.48–6.4[a]	4	
Life-cycle budget (op + emb)	12	6	0.67–8.8[a]	5.8	16.5–26.8
Budget per building (kg CO_2e/yr)					
Operational budget			28.3–371[a]		
Embodied budget			72.1–955[a]		
Life-cycle budget (op + emb)			101.4–1326[a]		17,200–28,300
Reference	Zimmermann *et al.* (2005)	Hollberg *et al.* (2019)	Brejnrod *et al.* (2017)	Hoxha *et al.* (2020)	Pálenský & Lupíšek (2019)

Notes: [a] Variations in budget between the six sharing principles included in the calculations of Andersen *et al.* (2020).
EoL = end of life; HFA = heated floor area.

Table 8: Relation between energy reference area (A_E) and living space per resident and the target values for the budget per capita and year based on the global target of 1 t CO_2e/cap.yr).

Living space (m²)	60	52.5	45	37.5	30
A_E per capita (m²)	80	70	60	50	40
Embodied GHG (kg CO_2e/m².yr)	3.4	3.89	4.5	5.4	6.8
Operational GHG (kg CO_2e/m².yr)	1.1	1.26	1.5	1.8	2.2
Total GHG per m² (kg CO_2e/m².yr)	4.5	5.14	6	7.2	9
Total GHG per capita (kg CO_2e/yr)	360	360	360	360	360

Table 9: Annual carbon budget per m² building (kg CO_2e/m².yr) based on the carrying capacity approach for six different sharing principles (SP).

	SP 1	SP 2	SP 3	SP 4	SP 5	SP 6
Operational budget (kg CO_2e/m².yr)	0.19	0.47	0.3	2.47	1.04	1.17
Embodied budget (kg CO_2e/m².yr)	0.48	1.22	0.77	6.36	2.68	3
Life-cycle budget (kg CO_2e/m².yr)	0.67	1.69	1.07	8.84	3.72	4.16

Note: Derived from results of a household living in a dwelling of 150 m² (Andersen *et al.* 2020). Sharing principle 1 (egalitarian + time shared + final consumption expenditure); Sharing principle 2 (egalitarian + final consumption expenditure); Sharing principle 3 (egalitarian + grandfathering); Sharing principle 4 (grandfathering + energy); Sharing principle 5 (grandfathering + final consumption expenditure); and Sharing principle 6 (final consumption expenditure).

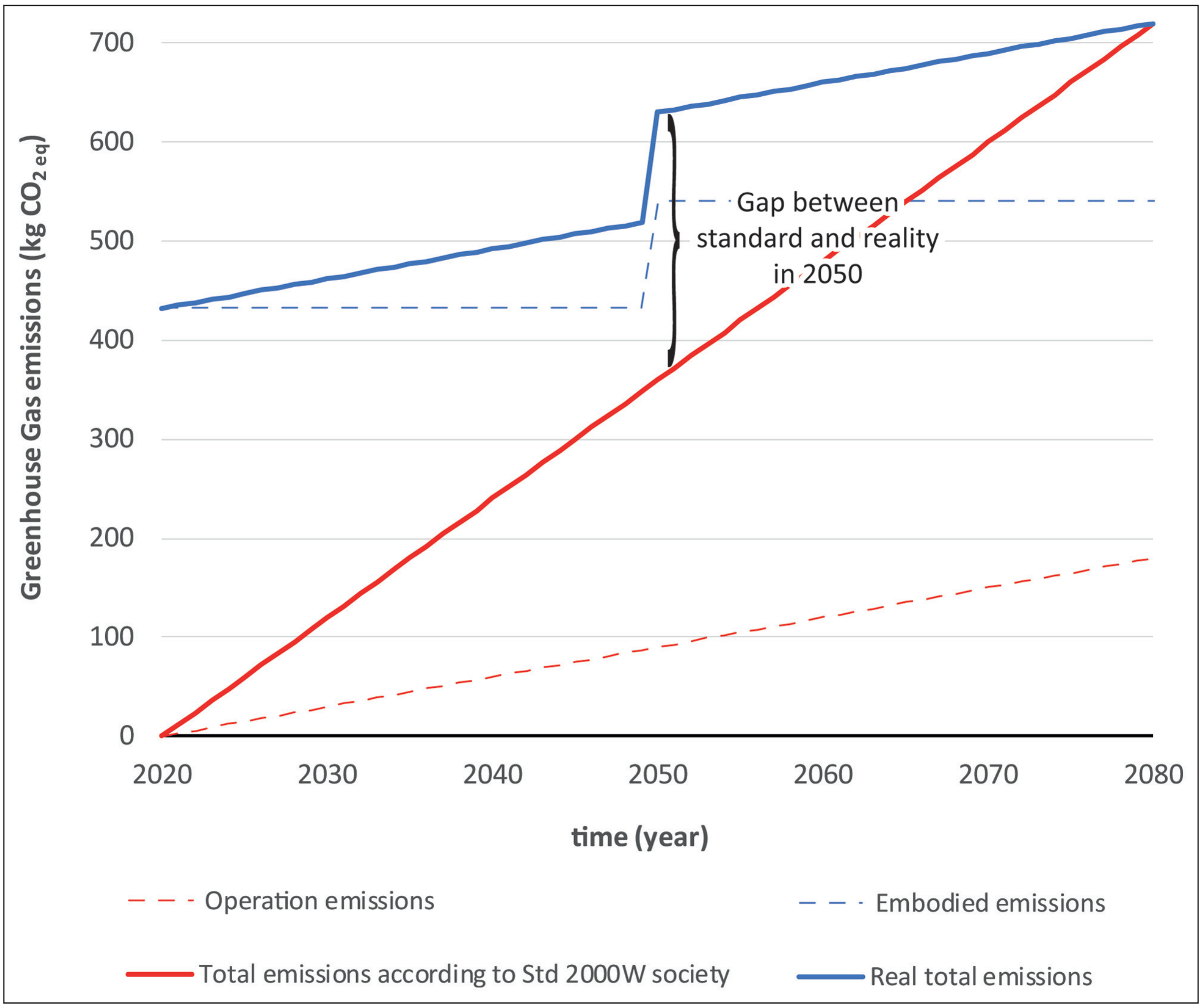

Figure 4: Comparison between operation emissions and embodied emissions for a standard new building according to the 2000 Watt Society standard.

As a consequence, operational emissions can be accounted over the full life-cycle of a building, but should be net zero on an hourly basis in order to be compatible with energy standards post-2050 and construction emissions cannot be allocated and spread over the full life-cycle. Embodied emissions should be counted within the remaining budget at the point in time that they are emitted.

5.2. Carbon investments for enabling a transition

GHG emissions will be needed to build low carbon energy production plants (*e.g.* solar panels, wind turbines) and it is important to avoid lock-in effects by exceeding the available carbon budget through the construction of such infrastructure (Corvellec *et al.* 2013; Shakou *et al.* 2019). The contribution to indirect emissions of infrastructure is generally higher than buildings due to a larger share per m^2 of carbon intensive materials, mainly cement, steel and aluminium (Müller *et al.* 2013). Müller *et al.* (2013) estimate that a budget of 350 Gt of carbon is needed to develop the infrastructure networks in the Global South. This represents already half the total available global budget for all human activities if the 2°C target without negative emissions is considered (**Table 1**). Additional emissions are also to be expected from developed countries where a large share of the existing infrastructure heritage needs to be rehabilitated in the next decades (Hajiesmaeili *et al.* 2019; Vogel *et al.* 2009).

In Europe, the renovation of the building stock has been identified as the main keystone to achieve climate neutrality by 2050. To meet this target, the energy efficiency of existing buildings should be increased by 75% by 2030 and the renovation rate increased to 3%, at least (Sesana, Rivallain, & Salvalai 2020). Thus, a large amount of construction materials, especially thermal insulation, will also be needed to improve the energy efficiency of the building stock (Heeren & Hellweg 2018). If conventional fossil-based materials are used, their embodied carbon risks to consume the remaining carbon budget for EU. However, if the demand of extra insulation were covered by bio-based solutions, especially from fast-growing species (*e.g.* straw, hemp), buildings could act as carbon sinks, providing an extra budget to be spent for the required energy transition and transformation of infrastructure (Pittau *et al.* 2019).

It is fundamental to reconsider all infrastructure projects in the light of their embodied emission level. Low-carbon solutions should be privileged (Hajiesmaeili *et al.* 2019; Pittau *et al.* 2019) and a drastic reduction of the energy demand is required to minimise the need for new infrastructure (Rovers 2019).

5.3. Beyond carbon

Finally, the focus on GHG emissions bears the risk of burden shifting. Beyond the climate crisis, there are many other urgent environmental concerns (*e.g.* biodiversity loss, water scarcity) (IPBES 2019; Rockström *et al.* 2009). A shift towards low-carbon materials and processes (*e.g.* from fossil to renewable energy) may reduce GHG emissions, but increase the pressure on other environmental issues. For renewable energy, the pressure increases particularly on biodiversity, land and water (Desing *et al.* 2019). Specific resources might become critical for a transition towards low carbon economy (de Koning *et al.* 2018; Nansai *et al.* 2014). Reaching the climate target is therefore not sufficient to reach environmental sustainability.

6. Conclusions

The development of a multi-scale carbon budget for buildings is a key policy instrument because it will help the different stakeholders involved all along the value chain of buildings construction and management as well as national regulators to clearly identify their specific targets.

In order to be able to define such cross-sectorial and multi-scale carbon budget, much care is needed in defining what constitutes the object of assessment. Buildings can have many different system boundaries depending on the stakeholder's viewpoint. Transparency along the different steps to define the operating budget is required. In particular, it is fundamental to declare what is the global target chosen, how this global budget is shared among countries and people, how this individual budget is then shared between economic sectors, area of activities and area of needs.

The examples presented in this paper show the feasibility of developing a carbon budget for buildings. However, a similar object of assessment, (with similar overall logic for the budget definition and countries with globally similar level of development) revealed a factor 10 between carbon budgets for single residential buildings. This shows the high sensitivity of hypothesis on the budget definition and the need for clarity in definition and consistency of approach. There are different solutions in place in specific countries—bottom up approach starting from technical and economic feasibility or top down approach, starting from planetary boundary, specific sharing principles or different data sources, among other reasons. Consensus on process is needed to narrow this gap.

Finally, it is clear that the remaining carbon budget should be used in priority to prepare the transition towards post carbon society. Given a clear framework and process it is necessary to develop accurate budget definition. This will enable the creation of equitable and context appropriate legally binding requirements to limit the greenhouse gas (GHG) emissions in the life-cycle of buildings.[6]

Notes

[1] Approximately 50% of the steel production is used for buildings and infrastructure. The other 50% is mainly used for automobile industry.

[2] The authors of this paper conducted an expert workshop in September 2019 in TU Graz (Passer *et al.* 2020).
[3] Gross floor areas for New Zealand's newly built single-family detached house, medium-density house and apartment are 198, 114, and 94 m^2, respectively.
[4] For a detailed description of these dwellings, see Chandrakumar *et al.* (2020b).
[5] The approaches used in the concept of 2000 Watt Society vision do not consider the potential changes of built area over the years. SIA 2040 defines GHG targets for residential buildings based on a fixed value of 60 m^2 energy reference area (A_E) per capita, where A_E is the gross floor area within the thermal building envelope (SIA 2015) and is also used as reference unit for the calculation of the operational energy demand in Switzerland. According to Pfäffli *et al.* (2012), a factor of 1.33 can be used to convert to useful floor area. This value matches the 45 m^2 of average living space reported by the Swiss Federal Office for Statistics (BFS 2016) for 2016.
[6] A recent initiative called the 'Graz Declaration for Climate Protection in the Built Environment' (SBE19 2019) provides guidance to researchers and policy-makers.

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Competing interests
The authors have no competing interests to declare.

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