RESEARCH

Sectoral carbon budgets as an evaluation framework for the built environment

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Abstract
The objective of the United Nations Paris Agreement to limit global warming to well below 2°C, with efforts to reach 1.5°C, requires a strict limitation of future global greenhouse gas (GHG) emissions based on a global carbon budget. Applying equity considerations allows for the derivation of national carbon budgets. A key question then arises: How can these national budgets be allocated at the sectoral level? A new method is proposed to allocate carbon budgets at the sectoral level. First, a cost-based approach is used to indicate a necessary carbon budget for each sector. However, the aggregation of these initial sectoral carbon budgets usually exceeds the available national carbon budget. This indicates the relevance of working with sectoral carbon budgets and the required reductions to remain within the overall national carbon budget. This conceptual approach aims at, first, a cost-effective sectoral effort-sharing; second, the design of corresponding strict carbon emission reduction pathways (at both the sector and aggregate levels); and, third, the redesign of investment policies for capital stock improvements to remain within the aggregate carbon budget (involving trade-offs in investment induced emissions for operational emission reduction).

Policy relevance
Limiting global warming according to the United Nations Paris Agreement requires a strict limitation of future global GHG emissions. A new method is presented to allocate national carbon budgets to the national sectoral level. The carbon budget concept has the potential to provide a transparent and informative tool for the analysis, policy design and monitoring of GHG emission pathways, particularly for the long time horizons involved. The area of activity involving the construction and use of buildings, termed embodied and operational GHGs, requires a particularly large fraction of the national carbon budget. Compared with other sectors, these activities have the highest potential for keeping countries within their national carbon budgets as far as enabling capital stock improvements are concerned that over-proportionally reduce use emissions. The approach can link carbon budgets at the municipal, city and regional levels. It could lend itself to an initially voluntary initiative, later compulsory policy framework for substantial and cost-effective emission reductions.

Keywords: buildings; carbon budgets; climate policy; construction sector; Paris Agreement; policy stringency; sectoral carbon; retrofit

1. Introduction
The United Nations Paris Agreement target of staying well below 2°C of warming with efforts to keep 1.5°C severely limits the remaining global carbon budget (GCB). The geophysical and earth science literature informs about the maximum future greenhouse gas (GHG) emissions that can still be released into the atmosphere without exceeding the Paris Agreement target, and at a specified likelihood. This total amount is denoted as a (likelihood and temperature target-
related) GCB. Total GHG emissions have to remain within this budget. At the international level, the allocation of this global budget across countries can be addressed through burden-sharing mechanisms based on three equity principles (responsibility, capability and equality) and their various combinations (Clarke et al. 2014; Robiou du Pont et al. 2017; Van den Berg et al. 2019). Employing these principles, it has been shown how issues of fairness can quantitatively condition this international allocation. Minimal fairness requirements include securing basic needs, attributing historical responsibility for past emissions, accounting for benefits from past emissions and not exceeding countries’ societally feasible emission reduction rate (Williges et al. 2020; Lucas et al. 2020). The findings of this literature are briefly summarised including approaches of (immediate or future convergence) equal per capita (EPC) allocations. The key question being addressed is how sectoral carbon budgets within a country can be derived.

What can be the benefit and use of such sectoral budgets? Considering that global warming is governed by the concentration of GHGs, the very long lifetime of GHGs (especially of CO₂) renders a budget concept particularly appropriate. Buildings are also characterised by comparatively long lifetimes and thus their respective quality is crucial for emission intensity over quite a long time period. GHG mitigation policy in the area of buildings can particularly benefit from a carbon budget approach. This concerns quantification of the sectoral budget available, using the budget as a management tool, and also for monitoring purposes. The derivation of a sectoral budget from the national one needs to consider the timing of a fossil infrastructure phase-out approach as this has a prominent role in such a derivation, especially if cost-effective and significant emission reduction is a concern.

In developing the budget, the choice of the GHG emission accounting approach is crucial. The approaches available in the literature are discussed for their applicability for evaluating climate policy as it relates to activities involving the construction and use of buildings. The area of activity involving the construction and use of buildings is defined to contain (1) the activities of the economic production sector ‘construction’ including upstream supply chains, which serves final demand (i.e. household and public consumption, and firm investment) of this sector’s products; (2) the use of buildings (heating and cooling, other energy, maintenance, repair); but also (3) intermediate demand of use of building by firms and the government. Our concept of ‘buildings’ thus includes those of all types of use, residential, commercial and office buildings, and under private (household, firm) or public ownership, and all types of emissions (including heating, cooling or construction).

The construction and operation of buildings accounts for the largest share of national carbon budgets but is also the most promising one to address when seeking to remain within the national overall budget by means of improving the quality of capital stocks. Given the very long lifetimes of buildings, their performance significantly affects the amount of aggregate emissions from their use, i.e. throughout their respective (remaining) lifetime. Thus, it is necessary to take into account both the emissions that are a side effect of the continued use of the remaining buildings and those embodied in the construction of new stock (or its refurbishment). Reducing overall emissions will suggest reducing both types of emissions to net zero in the long-term, but for the transition period may suggest allowing for additional embodied emissions by the construction of higher quality buildings whose use is less emission intensive.

The merits of a consumption-based accounting approach are considered, although it has more severe practical data availability constraints than, e.g., the production-based approach implemented under the United Nations Framework Convention on Climate Change (UNFCCC). A new proposed method to establish sectoral carbon budgets is presented in terms of procedure and respective challenges. Although no implementation experience exists for sectoral carbon budgets at the national level, first experience has been gained in regional (especially municipal) carbon budget development and use but also in corresponding approaches at the firm level (e.g. SBTi 2020). Sectoral carbon budgets could build upon this experience. The field of activity concerned with the construction and use of buildings in particular offers itself to such an application, given the long lifetime of its capital stock and the high amount of GHGs caused by their construction and use. A budget approach by its very nature addresses the twofold relevance of long time horizons particularly well.

This paper builds on recent carbon emission allocation by sectoral final demand which traces respective multi-country value-added chains (Lenzen & Murray 2010; Lenzen et al. 2013; Steininger et al. 2018). Empirical data of one highly developed country—Austria—are used to illustrate the quantitative relevance of following either one of the allocation and accounting principles. For the use case Austria, sectoral carbon budgets are derived. Their merits and potential use for designing climate policy are considered.

The paper is structured as follows. Section 2 surveys the conceptual foundations, the GCB approach and GHG accounting approaches. Section 3 gives a detailed account of normative approaches to allocate the GCB across nations and reports resulting national carbon budgets. Section 4 proposes a method to derive sectoral carbon budgets, which is then empirically implemented for Austria in section 5. The final section summarises core conclusions.

2. The global carbon budget (GCB): a conceptual overview
2.1 The remaining GCB

The geophysical and earth science literature has shown that containing global warming within specific temperature levels and at specified likelihoods is connected to a maximum amount of accumulated global GHG emissions. These are GHG emissions aggregated globally and across ‘all the future’. In other words, the integral of future global GHG emissions needs to be limited if certain levels of global warming are not to be exceeded (at chosen levels of likelihood).
More specifically, limiting global warming in line with the 1.5–2°C objective of the Paris Agreement (UNFCCC 2015) requires a strict limitation of future global GHG emissions (Rogelj et al. 2019). This is based on the relevant recent literature (Rockström et al. 2017; Rogelj et al. 2018, 2019; Xu and Ramanathan 2017) and a respective quantification of the GCB in line with the targets of the Paris Agreement and for different levels of ambition (Williges et al. 2020). Williges et al. (2020) enumerated a specific global limit for the cumulative total budget of anthropogenic CO₂ emissions for the period 2017–50 (34 years), hereinafter referred to as the specific GCB.

Three specific GCB options can be distinguished that aim for the target of 1.5–2°C. These have different levels of ambition, consistent with the recent literature:

- a baseline option aiming at well below 2°C, with a GCB allocation of 700 Gt CO₂ over 2017–50
- a drastic option aiming at 1.5°C with a GCB limited to 500 Gt CO₂, and
- a marginal and therefore risky option aiming to stay below 2°C with a GCB of 1100 Gt CO₂.

These three options are here specified only in terms of their CO₂ emissions, but each corresponds to a comprehensive emission scenario that also includes emissions of non-CO₂ GHGs. All options assume that only a limited budget of about 100 Gt CO₂ will be available for the period after 2050, i.e., humanity will reach net zero emissions towards the middle of the century.

In the following sections, the ‘well below 2 degrees’ GCB option (i.e., the baseline option indicated above, amounting to 700 Gt CO₂ for the period 2017–50) is used for empirical analysis. The national budget allocations can, however, equally be derived for the alternative GCB options (Williges et al. 2020).

2.2 Emission accounting principles

It is helpful first to consider what the allocation of a GCB would imply, i.e., which future activities and how much of them any such budget would permit. However, this depends upon how emissions are associated with individual activities.

As production occurs within supply chains, increasingly extending over several sectors and even countries, there are different options available in which emissions originating from one and the same activity may be attributed to different agents along the supply chain and thus to different sectors and countries. These different options are classified as GHG emissions accounting principles (Peters & Hertwich 2008; Marques et al. 2012; Davis et al. 2011). None of these accounting principles is solely the ‘true’ one; each has its advantages as well as specific shortcomings. The literature distinguishes four principles, which are briefly mentioned below. For a more detailed discussion and the difference in national emissions across the globe when applying each of them, see Steininger et al. (2016).

The accounting principle implemented in the UNFCCC is production-based accounting, where emissions are allocated to an agent (respectively, sector and country) that physically emits GHGs during the production process (e.g., the steel producer). Production-based accounting is the least ambiguous (e.g., the emission coefficient for each type of fossil fuel is known and thus CO₂ emissions can be calculated with a very high level of reliability). However, agents do influence emissions beyond those that arise through this direct production basis, e.g., producers decide not only on their direct emissions but also on the intermediate inputs they use (i.e., on how emission intensive these are).

The principle allocating all emissions to the final end user (household consumption, government consumption, firm investment) is called consumption-based accounting. Under this principle all emissions generated anywhere in the production chain (i.e., in whichever sector or country across the world) of the product are allocated to the end user. In consumption accounting, the emissions from, e.g., the construction sector include both the fuel emissions from equipment use on the construction site (as under production-based accounting) but also those generated during the production of all intermediate inputs, such as construction materials and products used (e.g., cement, steel).

Beyond those two accounting principles (which are more commonly applied and discussed), there are the extraction- and income-based principles. The former allocates all emissions to the extracting agent because this agent, being at the very beginning of the production chain, enables the emission anywhere later in the production chain by a different agent, sector or in a different country. The income-based principle considers all emissions arising in a production chain and allocates them to all agents involved proportionally to the share of value added they generate, using this weighing to indicate the influence of respective agents to determine emission intensity.

3. Equity principles and GHG allocation amongst nations

Having established an estimate for the remaining GCB compatible with a high likelihood of avoiding ‘dangerous climate change’, the next step is to analyse how countries can share the burdens of staying within the limits of this budget. This is assessed based on equity principles reflecting basic fairness considerations.

As a rough shorthand, the term ‘distributing emissions’ is used here to mean the distribution of (tradable) emission rights and not emissions themselves. At stake are the benefits that the use of emission rights makes possible and the fair distribution of these benefits via the allocation of emission rights. Emission rights are beneficial because they allow for emission-generating activities that typically are—but for their emissions—beneficial for people. Most human activities have emissions as their side-products, including those central for human welfare such as producing industrial commodities or farming. By distributing emission rights, the allocation of the GCB aims at a fair distribution of benefits from emission-generating activities among countries.
3.1 Allocation mechanisms

In the literature various burden-sharing mechanisms have been developed to create GCB allocations across countries. These can be categorised based on three equity principles (responsibility, capability and equality) and their various combinations (Clarke et al. 2014). While numerous varying interpretations of these principles have been applied for the GCB allocation (e.g. Pan et al. 2015), the majority focus on equality (allocation based on EPC emissions) and staged approaches (differentiated commitments and equal percentage targets or grandfathering; Höhne, den Elzen & Escalante 2014). To get an informed overview, hereafter, and following Williges et al. (2020), these two major approaches are exemplified by contraction and convergence (CAC) and EPC. Table A1 in Appendix A lists how these two approaches (and their various adaptations, as introduced below) correspond to and cover the range of the different concepts used in the literature.

According to CAC every country begins with its current average per person emissions and converges on a globally common future level of per person emissions by a future point in time. This makes it possible for all countries collectively to remain within the limits of the GCB. CAC does not take into account historical emissions. If CAC is meant to begin from today it implies a strong form of grandfathering: the higher the current levels of emissions, the higher the share of the GCB. CAC takes these unequal levels as the baselines for the allocation of the GCB to the individual countries. As a result, highly industrialised countries will have more emission rights during the transition phase to a low-carbon society. These countries will have more options for implementing the transformation and less associated costs. While highly industrialised countries do not explicitly argue for grandfathering, their nationally determined contributions (NDCs) under the Paris Agreement can be shown to be based on that notion in effect (Williges et al. 2020).

According to the second main approach—EPC—the GCB is split in such a way that all countries are allocated an equal amount of emissions per person for the time horizon up to 2050. EPC does not imply grandfathering, nor does it take the current levels of emissions for granted or take currently reached levels as relevant for the allocation of the GCB. EPC reflects the idea of an equal distribution of the remaining permissible emissions among persons and from now on. However, both simple understandings of EPC and CAC disregard the past. Both do not account for historical emissions and the consequences of emissions that were caused previously.

3.2 Qualifying simple allocation mechanisms for fairness

It is possible to qualify the two above mechanisms to take into account equity principles reflecting basic fairness concerns. This section builds on a previous explication of climate justice (in Meyer 2013, Meyer & Sanklecha 2014, 2017; Meyer & Pölzler 2020) and the analysis of the Fifth IPCC Assessment Report (Kolstad et al. 2014). Consideration is given to how the EPC and CAC approaches can reflect three basic fairness concerns: securing basic human needs, attributing responsibility for historical emissions and accounting for benefits from past emissions. In addition, a justification for what might be considered a limited form of grandfathering is addressed, i.e. the avoidance of exceeding feasible reduction rates. In their unqualified simple understandings, as introduced above, neither CAC nor EPC take into account these concerns.

The fairness concern of securing basic needs reflects the equity principle that all people have an equal claim to reach at least a sufficient level of well-being. Plausibly, this level is defined in terms of fulfilling people’s basic needs. Normatively speaking, allocating the GCB requires securing present and future generations’ ability to reach this sufficiency level. Hence, the justice duty to secure people’s ability to reach this level has high priority. Only when this duty is fulfilled can other principles of justice or ethics come into play. For the purpose of GCB allocation, Williges et al. (2020) proposed to operationalise this needs-based sufficiency principle in the following way. First, by comparing emissions in the past with indicators of well-being it is possible to identify a (historically and up to the present valid) relationship between increasing emissions and increasing levels of well-being. The human development index (HDI) is used as a proxy for well-being (UNDP 2019). One can identify average levels of emissions for levels of HDI and submit that a certain level of HDI is required for a high likelihood of people being able to fulfil their basic needs. If a country’s average level of per person emissions is below the required HDI level, these countries are allocated an initially higher amount of emissions to meet the HDI level. The EPC and CAC allocations are then carried out as normal.

When it comes to past and historical emissions, two fairness concerns seem valid. First, suppose that the allocation of the GCB is based on distributing the remaining permissible emission rights to provide equality of emission benefits for the period of the transition to low-carbon society. This should take into account that countries have already realised emission benefits in the past and also in those past years during which their governments can be thought to have (could and should have) known about the limit of the GCB compatible with avoiding ‘dangerous climate change’.

There is some dispute as to when governments were liable to know about the limited capacity of the atmosphere to absorb GHGs, their countries’ share of the use of this limited resource and that all plausible understandings of burden sharing require drastic reductions of emissions of most countries, especially of all highly industrialised countries. We consider 1995 to be the latest year to start attributing such liability, when the IPCC’s Second Assessment Report was published (Bolin et al. 1995), which further advanced the findings of the first report of 1990 (Houghton, Jenkins, & Ephraums 1990) and emphasised that the balance of evidence suggests a clearly discernible influence of humans
on the climate. Operationalising responsibility for emissions caused since 1995 is a straightforward task. The year of accounting is moved back to 1995, EPC and CAC allocations are then calculated for 1995. This attributes the actual emissions caused since 1995 to the emitting countries. As a result, post-1995 country levels exceeding the fair share of a country will reduce the amount of emission rights available to the country for the transformation period (and the other way around).

The second justifiable way of taking past emissions into account for the determination of current fair shares also relies on the idea of equalising benefits from emission-generating activities for present and future people. What can be considered non-objectionable permissible past emissions, namely those before 1995, are considered for their long-term consequences that contribute to the benefits enjoyed by people now and in the future. Past emission-generating activities yield highly unequal benefits for presently living and future people. Benefits from past emissions include the infrastructure built before those presently alive were born but still useful today. For operationalising inherited benefits from past emissions, Williges et al. (2020) proposed estimating the carbon emissions embodied in the global capital stock in 1995 and to add it to the initial carbon budget. This larger budget is then distributed to countries, minus their individual embodied emissions.

Both CAC and EPC should reflect these three basic normative concerns. The simple understandings of both CAC and EPC should be qualified by (Williges et al. 2020):

- a needs-based sufficiency threshold (hereafter, the N-qualification)
- responsibility for historical emissions by moving back the date of accounting to 1995 (hereafter, the H-qualification) and
- accounting for the inherited benefits from historical emissions (hereafter, the B-qualification).

While CAC reflects a strong form of grandfathering, EPC does not imply any grandfathering. However, some limited form of taking into account current country levels of emissions might be justified. There might be a limit to the feasible rate of emission reduction (in terms of economic, technological, institutional, sociocultural or other dimensions of transformation). If so, there should be a relevant limit to the burden faced by individual countries.

While there is no evidence so far for a clearly quantifiable threshold for a prohibitive reduction rate, the literature assumes some reasonable ranges. Stocker (2013: 281, fig. 3), who also refers to den Elzen, Meinshausen, & van Vuuren (2007), concludes that economic models indicate feasible maximum rates of emissions reduction to not exceed about 5% per year. Going a step further, Rockström et al. (2017) define a ‘carbon law’ of a required halving of global emissions every decade to 2050, corresponding to a reduction rate of about 7% per year, which they argue to be feasible at the global aggregate level under deep mitigation efforts including some disruptive innovations. Williges et al. (2020) suggest that one could also use this rate as a yardstick at the national level. Given any such reasonable burden limit, one can calculate the minimum possible cumulative budget a country would need to have and compare that limit with the budget allocation under an EPC simple approach. This is called the C-qualification as it reflects an understanding of a constraint on countries’ capacity to reduce emissions.

By taking into account the legitimate reason for respecting the highly different current levels of emissions, the C-qualified EPC can be understood to reflect what is defensible in the rationale of CAC. As the intention here is not to justify any particular maximal reduction rate, Figure A1 in Appendix A presents a sensitivity analysis. It clearly indicates that while the very imposition of a burden constraint has a significant effect on carbon budgets of higher HDI countries, the specific choice of the rate has little effect on per person emission budgets, for rates between 5% and 7%. For the budgets derived and presented for selected countries in Tables 1 and 2, and in the use case in section 5, a rate of 7% has been applied. Evidently, the less strict the maximum reduction rate chosen, the more has to be given up in one or more of the following dimensions: either the temperature target achieved will be less ambitious or one or more of the other fairness considerations will have to be given less weight in the distribution of the GCB.

The operationalisation of this feasibility constraint goes like this. If the simple EPC approach is found wanting, then countries are pre-allocated the difference between the minimum cumulative budget required for a feasible transformation and their EPC simple allocation. The allocation of the remaining budget follows this initial step, including the three qualifications N, H, and B, as explained above. As the budget implications denoted in Tables 1 and 2 illustrate, this qualification can make a stark difference for highly industrialised countries, including the United States. However, even such an approach may impose still higher reductions than is politically feasible at a national level. This can be mitigated by creating globally tradeable emission rights. This would allow high-emitting countries (which have already exceeded their budget) to buy permits from countries whose shares of GCB are greater than what they require and can make good use of.

Table 1 gives the (total) carbon budget for selected countries for the period 2017–50 when adhering to either EPC or CAC and each of their respective modifications suggested on fairness grounds (the N, H and B qualifications one by one and together and, in addition, for EPC the C qualification added). Table 2 presents the very same budgets, but on a per person basis, thus allowing for both ready interpretation and cross-country comparisons.
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An EPC approach with all four qualifications (i.e. NHBC) can be considered a promising proposal for a fair allocation of the remaining GCB. The fulfillment of major and minimal fairness requirements is considered to provide a plausible basis for allocating the GCB across countries and creating a period of transformation to a low-carbon economy and society. This NHBC-qualified EPC approach can be open to further qualifications and specifications. For example, what maximum reduction rate is feasible for a country should reflect the quality of the measures countries have undertaken to curb emissions. When countries have already taken serious steps towards emission reductions but still need to drastically reduce emission intensity to reach the convergence point, the 'low-hanging fruits' are likely picked, and

### Table 1: Carbon budget allocation to selected countries for different allocation approaches, total budget in Gt CO₂ for 2017–50.

| Budget allocation approach       | Austria | China       | Germany    | India      | Russian Federation | Sweden      | UK         | United States |
|---------------------------------|---------|-------------|------------|------------|--------------------|-------------|------------|---------------|
|                                 | (Gt CO₂, total budget for 2017–50) |
| EPC simple                      | 0.832   | 131.105     | 7.861      | 125.922    | 13.726             | 0.942       | 6.242      | 30.728        |
| EPC N-qualified                 | 0.643   | 101.275     | 6.073      | 159.430    | 10.603             | 0.727       | 4.822      | 23.737        |
| EPC H-qualified                 | 0.419   | 138.563     | 1.534      | 192.227    | −1.512             | 0.954       | 2.407      | −57.870       |
| EPC B-qualified                 | 0.311   | 131.373     | 3.689      | 144.522    | 13.599             | 0.453       | 3.317      | 15.719        |
| EPC NHB-qualified               | −0.166  | 116.490     | −3.990     | 237.375    | −6.036             | 0.296       | −1.603     | −75.851       |
| EPC NHBC-qualified              | −0.251  | 122.256     | −2.196     | 207.058    | 4.535              | 0.017       | −2.542     | −25.693       |
| CAC simple                      | 1.113   | 189.613     | 13.115     | 64.177     | 30.277             | 0.913       | 8.129      | 92.989        |
| CAC N-qualified                 | 0.944   | 166.344     | 11.661     | 92.377     | 27.759             | 0.682       | 6.718      | 85.578        |
| CAC H-qualified                 | 0.931   | 47.759      | 12.429     | 126.065    | 19.457             | 1.391       | 9.666      | 52.644        |
| CAC B-qualified                 | 0.565   | 182.317     | 8.544      | 84.380     | 29.434             | 0.429       | 5.124      | 78.018        |
| CAC NHB-qualified               | 0.379   | 32.076      | 7.401      | 169.512    | 15.896             | 0.749       | 5.816      | 34.924        |

Note: Qualifications for the allocation mechanisms equal per capita (EPC) and contraction and convergence (CAC) concern basic needs (N), historical emissions (H), benefits accrued (B), contraction constraint (C) and their various combinations. Source: Williges et al. (2020).

### Table 2: Carbon budget allocation to selected countries for different allocation approaches, per person budget in tonnes of CO₂ for 2017–50.

| Budget allocation approach       | Austria | China       | Germany    | India      | Russian Federation | Sweden      | UK         | United States |
|---------------------------------|---------|-------------|------------|------------|--------------------|-------------|------------|---------------|
|                                 | (t CO₂, per person budget for 2017–50) |
| EPC simple                      | 95.095  | 95.095      | 95.095     | 95.095     | 95.095             | 95.095      | 95.095     | 95.095        |
| EPC N-qualified                 | 73.459  | 73.459      | 73.459     | 120.400    | 73.459             | 73.459      | 73.459     | 73.459        |
| EPC H-qualified                 | 47.920  | 100.505     | 18.557     | 145.168    | −10.476            | 96.362      | 36.676     | −179.093      |
| EPC B-qualified                 | 35.532  | 95.290      | 44.629     | 109.142    | 94.215             | 45.775      | 50.540     | 48.648        |
| EPC NHB-qualified               | −19.016 | 84.495      | −48.265    | 179.263    | −41.819            | 29.900      | −24.425    | −234.739      |
| EPC NHBC-qualified              | −28.729 | 88.677      | −26.561    | 156.368    | 31.415             | 1.766       | −38.727    | −79.512        |
| CAC simple                      | 127.267 | 137.534     | 158.644    | 48.465     | 209.761            | 92.181      | 123.842    | 287.778       |
| CAC N-qualified                 | 107.863 | 120.656     | 141.054    | 69.762     | 192.312            | 68.907      | 102.345    | 264.842       |
| CAC H-qualified                 | 106.382 | 34.641      | 150.352    | 95.203     | 134.799            | 140.459     | 147.261    | 162.919       |
| CAC B-qualified                 | 64.553  | 132.241     | 103.348    | 63.723     | 203.921            | 43.289      | 78.070     | 241.446       |
| CAC NHB-qualified               | 43.323  | 23.266      | 89.527     | 128.013    | 110.128            | 75.649      | 88.603     | 108.080       |

Note: Qualifications for the allocation mechanisms equal per capita (EPC) and contraction and convergence (CAC) concern basic needs (N), historical emissions (H), benefits accrued (B), contraction constraint (C) and their various combinations. Source: Williges et al. (2020).
these countries face a more difficult task of reducing emissions. Thus, it would be unreasonable to expect them to be able to reduce at the same maximum level.

This format and illustrative calculation for selected countries (Tables 1 and 2) is meant to provide a framework for developing an internationally fair allocation of the GCB compatible with minimal requirements of intergenerational justice. An analysis has been presented on how to understand the fairness considerations and how to operationalise them in ways relevant for the allocation of the GCB. If such budgets are subject to a negotiation process at the national or international levels, negotiators are likely to disagree about the weight to be given to each and every consideration that has been identified above as an element of a fair solution. What the derivation here seeks to accomplish is to show both the ethical plausibility and the quantitative relevance for the size of the allocated budgets, of adhering to these minimal requirements.

This section has identified the various equity principles that need to be considered when breaking down the GCB to national ones. Such an allocation across countries can be of interest for, or even a responsibility of national governments when determining their NDCs. But even if the nation-state does not adopt such an approach, individual production sectors, activity fields or agents at other scales (e.g. municipalities) can rely on the suggested framework to determine a plausible national carbon budget. The budget can serve as a first reference in deriving a sectoral (or activity or regional/municipal) carbon budget. By voluntarily adhering to and not exceeding the so-specified sectoral budgets, the agents aim at contributing what can be considered their fair share in achieving the Paris Agreement targets.

4. Deriving a carbon budget for buildings

Having applied the process for allocating the GCB to individual nations, as exemplified in section 3 above, these national budgets can then be assigned to individual sectors (or their aggregation to areas of activity) within countries, particularly to activities associated with buildings, i.e. those concerned with the construction and operation of buildings. A method is proposed for this in the present section, and its implementation is considered in section 5.

4.1 Allocating a national budget across sectors

To begin, consider a very simple allocation mechanism. In a first step, assume that carbon-free technology is already available. In more general terms, assume the carbon-free means to satisfy respective human needs already exist in principle. However, the currently implemented building stock still is connected to GHG emissions in two ways. First, the existing buildings generate GHG emissions when they are used. Second, this may also apply to the production processes of new (replacement) buildings, including their supply chains. The specific GHG emissions per unit supplied (e.g. space heating emissions per m²) and per new building component unit produced (e.g. per tonne of steel) will be determined by the type and quality of the capital stock in use (households, steel production) and respective patterns in consumption and production. The shift to a carbon-free economy is then a matter of phasing out the fossil capital stock to enable carbon-free use and production.

In this transformation to a net-zero carbon society, effort sharing among sectors and activities could be based on economic costs. Economy-wide transformation costs are minimised if all installed technology or infrastructure is used until the end of its respective use time (i.e. its service life or economic life), and then replaced by the carbon-free alternative. For example, a private home oil-heating system—at the end of its service life—will be replaced by a renewable-energy-based heating system, e.g. a heat pump using photovoltaic electricity. Or the blast furnace using coke for steel production at the end of its use time is replaced by renewable hydrogen technology.

How much of the available carbon budget would then need to be allocated to each economic sector (or their aggregation to activity areas) to grant enough budget to allow for exactly this—(at least comparatively) low-cost—transition? For the most simple and idealised setting where the transformation can be assumed to be linear, the following holds: as each year only one vintage of the capital stock is replaced by a capital stock that has carbon-free use, use emissions of this sector would decline linearly until the last vintage has been replaced and then ‘use’ emissions will have been eliminated altogether. Thus, a fossil supply chain phase-out approach, starting at the current emissions level and reducing emissions linearly by the end of the use time of the initially most recent vintage installed will exactly allow for this transition.

As an example, household direct emissions due to heating at the aggregate level would be eliminated after the last vintage of fossil fuel heating systems has been replaced. For the steel used in the production of the replacement heating devices, the same basic idea applies, steel production will have achieved carbon-neutrality also at the aggregate level when the last vintage of furnaces has been substituted for by one of the renewable alternatives. Therefore, the very same phase-out concept in budget allocation would allow for this transition path also for embodied emissions in heating systems (or buildings etc.).

This basic concept can be used to derive a carbon budget necessary for each economic sector (or area of activity) if such a transition path is followed. Relaxing the initial assumption about the carbon-free technology already being available, the budget could be increased to account for emissions that would still remain at their initial level during the development phase of this carbon-free technology, and the decline would only start once the carbon-free technology has become available, which will also differ in timing by sector.
Figure 1 illustrates stylised emission reduction paths for the activity area of construction and use of buildings, where the capital stock is not replaced in even increments but at cohorts of different size. In construction supply chains (left panel), involving embodied emissions, there may be some construction material production where the technology to shift to carbon-free production will become available only in a few years: one could think of steel production to shift to the hydrogen production starting in 2027 and being accomplished by 2040 (orange line). Cement production (yellow line) may not start to replace cement kilns before 2022, with a larger fraction of the capital stock attaining its end of lifetime for the first two years (steeper emission reduction) before the phase-out continues upon completion in 2027. The remaining construction materials imply emissions in their production to add up to the (aggregate) blue emission path, marking the necessary carbon budget as the area below. For use emissions (right panel) the phase-out of oil heating equipment may come at even replacement rates, starting immediately and progressing to 2033 (grey line), while gas heating system replacement might not start before 2022 and reach completion in 2040 (purple line), both— together with all remaining use emissions—adding up to the (green) emissions path, reaching zero in 2040.

Next, via aggregation across sectors—representing the second step of the proposed process—this (under the specified conditions) necessary budget can then be compared with the available carbon budget at the national level, with the latter determined from the GCB breakdown exercise as specified in section 3 above. If the national available budget exceeds the required one, the transition could be somewhat slower. If, however, the necessary carbon budget as derived in the first step exceeds the available one, then either a faster transition is necessary or the gap has to be closed by the acquisition of emission permits from abroad, most likely financed by a mechanism at the national but not directly sectoral level.

If a faster transition is chosen, this basically implies a replacement of supply chain production capital before the end of its use time, or a revision of the asset during its use time, such as (earlier) refurbishment of the building stock. Core indicators can inform the decisions about which projects and which sectors are most appropriate for a faster transition. The core indicators must assess the amount of net carbon budget savings and the additional economic costs.

A faster transition for buildings involving a retrofit would reduce use emissions, but additional materials and equipment might increase the embodied emissions of the building stock. Such an early transition only pays off in the physical dimension if the increase in embodied GHG emissions is exceeded by the induced ‘use’ emission reduction aggregated over the lifetime of the refurbishment investment. The resulting net emission reduction and respective additional economic costs from this project will be core indicators not only for shaping the hypothetical transition pathway but also for the antecedent decision of whether a faster transition dominates the acquisition of emission rights from abroad. Usually, each project will also shift portions of the necessary carbon budget across sectors.

In this example, if a production-based carbon accounting is followed, the necessary carbon budget for the use of buildings (heating emissions) will be lowered, while that of the construction of buildings (embodied emissions in building stock) would be increased. Naturally, the amount of the latter increase needs to be smaller than the heating emissions carbon budget reduction. Many such projects will also involve a change in budgets in various sectors. Instruments or projects addressing combined aspects of spatial planning and housing construction/refurbishment/energy planning will as a result influence (production-based) carbon budgets not only of the construction and the use of buildings (heating and electricity) but also of the transport sector.

These specified necessary carbon budgets (or future emissions) correspond with a quantity that has been calculated at the aggregated global level in a different strand of literature: the emissions a society has committed to by the existing fossil fuel infrastructure (Davis et al. 2011). Smith et al. (2019) show that globally keeping all present-day (i.e. 2018 level) fossil fuel infrastructure in operation until the end of its respective lifetime (differentiated in detail by sector) would
result in carbon emissions that would still keep the world within 1.5°C of warming in 64% of an ensemble of scenarios assessed. They cover the fossil fuel infrastructure of energy generation, transport (vehicles) and industry, but also of residential, service and other aggregated sectors. Thus, for achieving the 1.5°C target at this level of ambition (likely target achievement in the IPCC terminology) the necessary budget at the aggregated global level for operating all fossil fuel infrastructure until the end of its respective lifetime would not exceed the available one. But this will be different at the national level. Depending on which considerations are acknowledged (basic needs, historic emissions, inherited benefits, legitimate grandfathering) in allocating the global budget to individual nations, the national budgets for some countries may turn out significantly smaller as to allow for such a present-day fossil fuel infrastructure operation until the end of respective lifetimes.

4.2 A carbon budget approach for buildings

The conceptual approach developed above for the allocation of any specified national carbon budget across sectors (or areas of activity) can first, and most readily, be applied for the production-based GHG emission accounting approach. Using such an approach, the sectoral necessary carbon budgets are derived in two steps. First, data on current emissions from each sector can be collected. The production-based approach here offers the most unambiguous option among all accounting approaches. Second, a required sector carbon budget can be derived by applying the linear decline of these emissions over a period determined directly by the lifetime of the respective sector’s capital stock. For the budget of an area of activity, the respective sectoral budgets can be aggregated. The area of activity concerned with the construction and use of buildings spreads across several sectors and is built upon in the use case evaluation in section 5.

However, production-accounting based emissions are not comprehensive. Other accounting systems can more comprehensively cover the emissions actually induced by specific sector activities. In a sectoral and international interdependent economy, the system boundaries need to be set accordingly, i.e. cross-sectorally and globally. The one accounting system that best acknowledges all emissions induced by any sector’s final demand, i.e. emissions of whichever sector or country they arise in, is consumption-based accounting.

Applying consumption-based accounting does supply a sectoral emissions level as well, though they are connected to a higher level of ambiguity, because their identification usually relies on a set of assumptions (foremost, average sectoral emission intensities for attributing emissions embodied in intermediate inputs). But in principle the very same GHG capital stock phase-out approach can be applied (as developed in section 4.1 and already discussed above for the production-based accounting approach). A consumption-based approach does offer additional information highly relevant in the present context. As all emissions are attributed exclusively and comprehensively by type (sector) of final demand, it is possible to derive what fraction of a sector’s consumption-based emissions arise from this sector’s goods being used in (private or government) consumption, and what fraction from this sector’s goods are used as investment goods. The larger the latter fraction, the more the following trade-off might be a relevant option: a trade-off between raising (one-time) emissions to increase the output of investment goods in order to decrease (multi-period) emissions over the use time of these very investments.

The authors recommend using a consumption-based GHG emission accounting approach, as this approach makes all the emissions connected to one area of activity, here the construction and use of buildings (including their up- and downstream supply chains), visible and thus allows for a coherent and transparent discussion with comprehensive information for all agents involved. The first step is deriving a necessary emission budget for each sector by applying a capital stock phase-out approach with the emission decline period given by the investment capital-use time of the respective sector. If this derived carbon budget exceeds the available one, the trade-offs in early investments (one-time emissions) to reduce (multi-period) use and production time emissions need to be considered. If an emissions accounting is applied that does not follow the consumption-based approach, these trade-offs also imply sectoral carbon budgets being reallocated accordingly until their aggregate value is in line with the available national carbon budget.

4.3 Scalability

The same conceptual approach in creating the sectoral budget can be applied further to sectoral budgets for regions, cities, or—with a different intention and use—to individual projects.

The availability of sectoral emission data for individual cities largely varies across cities. Recently, however, increasing effort is devoted to derive both production- and consumption-based emission data at the city level. Wherever these data are accessible respective sectoral GHG budgets for the city level can be derived.

Beyond these levels of disaggregation at the geographical scale, the GHG budget approach may also be of relevance in project permission decisions and administrative processes. One type of use is the determination of a specific project’s impacts on the available carbon budget—across the lifetime of the respective project. For example, a city council may be interested in knowing how a specific change in its spatial planning policy (or in its retrofit incentives, public transport supply, etc.) will change the city’s future emission pathway. Aggregated over the lifetime or impact time of the policies or projects, this can inform decisions about whether the city remains within its regional GHG budget. The quality at which such a project impact can be quantified of course depends on the emission data and its disaggregation availability at the respective geographical scale of detail.
A series of municipal and regional governments have commissioned the identification of city or regional carbon budgets and have started to revise their governance practices and decision processes to use GHG budget implications and adherence as one of their decision criteria. For example, Anderson et al. (2018) applied their method of not only allocating a GCB to industrialised countries but also to dividing it between municipalities and regional governments to more than 15 regions and municipalities in Sweden, starting with Järfälla and including, e.g., the Stockholm region. They started with a pure production-based emission accounting approach and are expanding the system boundaries of emissions covered to include more and more elements, moving ever closer to consumption-based accounting.

In many countries without a formal legal obligation for municipalities to achieve specific and quantified GHG emission targets, this research group found municipalities more open than higher governance levels to use GHG budgets for deriving quantitative targets and to announce their intention to design municipal policy to remain within these budgets (Pichler & Steininger 2019).

5. Empirical implementation: the use case of Austria

Applying the concepts outlined in the previous sections to the case of Austria, the following procedure is used. First, the national carbon budget is derived, based on the different equity principles discussed. Second, recent sectoral emission levels, following a production-based emission accounting are used together with historic capital stock use times for each of the sectors (based on existing literature) for the application of the phase-out approach to derive necessary sectoral carbon budgets. Third, the sum of all sectoral necessary carbon budgets can be compared with the national available carbon budget as derived in the first step. If the necessary carbon budget exceeds the available one, the gap has to be closed. If the nation decides not to close the gap, at least not fully, by the acquisition of emission rights from abroad, some or all sectors have to remain within a narrower budget than the necessary one derived in the second step. To indicate the required level of increase in ambition for each sector, reference sectoral carbon budgets are given. These are derived by allocating a share from the national carbon budget to the sector, proportional to the recent sectoral share of the total national emissions.

Two variants of the national budget are used to derive such a reference budget, the EPC simple (as the main variant) and the CAC simple as the variant that grants the industrialised high-emitting countries the largest carbon budgets. Finally, the same stepwise approach is carried out to derive sectoral emission budgets adhering to a consumption-based accounting approach using accordingly adjusted capital stock use times. Again, sectoral reference carbon budgets are calculated as shares of the national carbon budget under EPC simple and CAC simple criteria, proportional to current sectoral emission levels.

Figure 2 shows the national carbon budgets available for Austria under different allocation principles and compares them with the necessary carbon budget for a consumption-based accounting approach aggregated across all sectors.

If all three fairness modifications (basic needs, historic emissions and inherited benefits) are applied when following the EPC allocation, then Austria is found to have already exploited its carbon budget, indicated by a negative number for the remainder of the first half of this century. The value is an even larger negative, when also the burden constraint

![Figure 2](image-url)
is globally applied. Conversely, neither case results in a negative remaining budget when following a CAC approach for national carbon budget allocation.

### 5.1 Sectoral budgets using production-based accounting

Table 3 shows sectoral carbon budgets according to the described procedure. The representative capital stock use times were taken from literature evaluating historic lifetimes of fossil fuel infrastructure for those sectors where such data are available (Davis & Socolow 2014; Smith et al. 2019). For the remaining sectors representative capital stock use times were calculated from the EU KLEMS (2018) database, which provides different types of capital stocks and respective assumed depreciation rates on a sectoral level. Technical details and specific sources are provided in Appendix A.

Those sectors accounting entirely to activities concerned with the construction and use of buildings are indicated by “**” next to the sector label in Table 3. Their necessary allocated budget totals 213 Mt CO₂, representing 14% of the total national necessary carbon budget. Further activities of construction and use of buildings are accounted for in other sectors, which not only cover such activities but also include further activities. Those sectors include the Electricity and extraction sectors (for building-related energy, such as lighting and district heating), the Service sector (for real estate activities) and the Government service sector (for public building use). These sectors are indicated by “*” in Table 3. The necessary sectoral carbon budgets for these sectors sums up to further 367 Mt CO₂ (24% of the nationwide necessary budget), of which, however, only a fraction, not specifically determined in the present analysis, can be related to construction and use of buildings.

The determination of these necessary sectoral budgets relies on sectoral capital stock use times. If such a framework were to be implemented for allocating legally binding carbon budgets by a nation-state or city one would expect representatives of each sector to seek to manipulate these use time figures to secure a higher sectoral budget. The implementation of an adequate procedure distinguished by high legitimacy would be required to resolve any ensuing disputes between competing sectors (e.g. timber versus steel versus concrete). One way could be the establishment of an evidence-based decision process, relying, e.g., on a combination of historic lifetime analyses, independent expert panel evaluations and industry hearings. While such elements can substantially enhance legitimacy, any actual sectoral allocation will ultimately involve value judgement in most cases, and thus is subject to political societal decision.¹

Davis et al. (2011) and Smith et al. (2019) point out that there is comparatively robust historic evidence on lifetimes in energy generation (even differentiated across fuel type) and the vehicle fleet in transport (again differentiated by mode), but that evidence is scarce for industrial, residential and commercial infrastructure lifetimes. While there are data on industry, they are as of yet available only in very selected cases. For instance, Smith et al. (2019: 7) point out that:

> estimates of the existing lifetime of industrial infrastructure are not abundant, and we are therefore limited to using one estimate from the expected lifetimes of cement kilns.

For that reason, Table 3 supplies two reference allocations of the national carbon budget to individual sectors that do not rely on any capital stock use times. These reference budget allocations start from a given national carbon budget; here the EPC simple allocation approach is used as the main reference variant, along with the CAC simple approach, as it supplies the maximum budget for an industrialised high emitter. These budgets are then allocated proportionally to current sector emissions.

As the globally allocated national budgets are best interpreted to serve a consumption-based accounting perspective, these need to be downscaled for national budgets serving production-based emissions. To do so, it is suggested to use the factor of current production-based to consumption-based carbon emissions in the respective country (for Austria the factor is 0.75). The resulting available carbon budget for a production-based accounting approach for Austria (Table 3, row ‘Total’) is 627.1 Mt CO₂ (838.8 Mt CO₂) under the EPC (respectively, CAC) global budget allocation mechanism. Thus, at the national overall level emissions have to be reduced by 59% of the necessary budget (for EPC, 45% if the CAC national budget is applied). If simple grandfathering is applied in the sectoral allocation of this reduction, each sector has to reduce its emissions by 59% of the earlier defined necessary ones. Sectoral carbon budgets are given in columns (5) and (6) for a national EPC-derived (respectively, CAC-derived) carbon budget. Sectoral shares of this overall national budget available under simple grandfathering are given in column (7). However, if sectorally differentiated capital stock use times are acknowledged in the sectoral carbon budget allocation, those sectors that employ particularly long-lived capital are granted a larger sectoral budget than otherwise, e.g. the sector mineral products is granted a share of 10.2% of the national budget (column (4)) rather than only 7.9% (column (7)). For the sector mineral products this implies a budget larger by 29% than when sectoral capital-use times are not considered (column (9)). Whereas those sectors with comparatively short-lived capital stocks are granted only a smaller share in the national budget, e.g. electronic equipment is granted a share of only 0.3% rather than 0.5% (column (4) versus column (7)), implying a sectoral budget in this case smaller by 38% than otherwise (column (9)).

For the specific sectors of concern in the present analysis, the sectoral budgets given in Table 3 indicate that if any of the two reference budgets at the national level are to be met by the sum of all sectors, available sectoral carbon budgets
Table 3: Sectoral emission levels, accordingly derived first-step necessary carbon budgets and sectoral carbon budgets under simple allocation, following a production-based accounting approach.

| Sector                      | Emission level (2011) (Mt CO$_2$) | Representative capital stock use time (years) | Necessary sectoral carbon budget (Mt CO$_2$, up to 2050) | Sectoral share of the total necessary budget (%) | Sectoral carbon budgets under EPC simple (Mt CO$_2$, up to 2050) | Sectoral carbon budgets under CAC simple (Mt CO$_2$, up to 2050) | Sectoral share of the total budget under EPC simple and CAC simple (%) | Sectoral carbon budget under EPC simple, acknowledging the sectoral capital stock use time (Mt CO$_2$, up to 2050) | Change in the sectoral budget due to capital stock use time consideration (%) |
|-----------------------------|-----------------------------------|-----------------------------------------------|--------------------------------------------------------|-----------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|-------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Agriculture                 | 1.39                              | 23                                            | 28.5                                                   | 1.9%                                         | 12.8                                                          | 17.2                                                          | 2.0%                                                                                           | 11.7                                                                 | –9%                                                                                                           |
| Extraction, coal, oil, gas  | 2.50                              | 27                                            | 56.3                                                   | 3.7%                                         | 23.0                                                          | 30.8                                                          | 3.7%                                                                                           | 23.1                                                                 | 0%                                                                                                             |
| Food products               | 1.13                              | 14                                            | 18.1                                                   | 1.2%                                         | 10.4                                                          | 14.0                                                          | 1.7%                                                                                           | 7.4                                                                 | –29%                                                                |
| Textiles                    | 0.07                              | 15                                            | 1.2                                                    | 0.1%                                         | 0.7                                                           | 0.9                                                           | 0.1%                                                                                           | 0.5                                                                 | –27%                                                                |
| Wood products               | 0.32                              | 13                                            | 5.0                                                    | 0.3%                                         | 3.0                                                           | 4.0                                                           | 0.5%                                                                                           | 2.1                                                                 | –31%                                                                |
| Paper products, publishing  | 0.97                              | 28                                            | 22.2                                                   | 1.5%                                         | 8.9                                                           | 11.9                                                          | 1.4%                                                                                           | 9.1                                                                 | 2%                                                                                                              |
| Petroleum, coal products    | 2.77                              | 29                                            | 65.1                                                   | 4.3%                                         | 25.5                                                          | 34.1                                                          | 4.1%                                                                                           | 26.7                                                                 | 5%                                                                                                              |
| Chemical, rubber, plastic products | 2.45                         | 36                                            | 66.3                                                   | 4.3%                                         | 22.6                                                          | 30.3                                                          | 3.6%                                                                                           | 27.2                                                                 | 20%                                                                                                             |
| Mineral products            | 5.37                              | 40                                            | 155.8                                                  | 10.2%                                        | 49.5                                                          | 66.2                                                          | 7.9%                                                                                           | 63.9                                                                 | 29%                                                                                                             |
| Ferrous metals              | 8.07                              | 31                                            | 197.6                                                  | 12.9%                                        | 74.3                                                          | 99.4                                                          | 11.9%                                                                                          | 81.1                                                                 | 9%                                                                                                              |
| Metals n.e.c.               | 4.56                              | 31                                            | 111.7                                                  | 7.3%                                         | 42.0                                                          | 56.2                                                          | 6.7%                                                                                           | 45.8                                                                 | 9%                                                                                                              |
| Motor vehicles and parts    | 0.05                              | 11                                            | 0.7                                                    | 0.0%                                         | 0.5                                                           | 0.6                                                           | 0.1%                                                                                           | 0.3                                                                 | –35%                                                                |
| Machinery and equipment     | 0.19                              | 11                                            | 2.8                                                    | 0.2%                                         | 1.8                                                           | 2.4                                                           | 0.3%                                                                                           | 1.1                                                                 | –35%                                                                |
| Electronic equipment        | 0.34                              | 10                                            | 4.8                                                    | 0.3%                                         | 3.1                                                           | 4.2                                                           | 0.5%                                                                                           | 2.0                                                                 | –38%                                                                |
| Electricity                 | 10.46                             | 34                                            | 271.9                                                  | 17.8%                                        | 96.3                                                          | 128.9                                                          | 15.4%                                                                                          | 111.5                                                                 | 16%                                                                                                             |
| Construction                | 2.62                              | 19                                            | 48.5                                                   | 3.2%                                         | 24.1                                                          | 32.3                                                          | 3.9%                                                                                           | 19.9                                                                 | –18%                                                                |

(Contd.)
| Sector                          | Emission level (2011) (Mt CO₂) | Representative capital stock use time (years) | Necessary sectoral carbon budget (Mt CO₂, up to 2050) | Sectoral share of the total necessary budget (%) | Sectoral carbon budgets under EPC simple (Mt CO₂, up to 2050) | Sectoral carbon budgets under CAC simple (Mt CO₂, up to 2050) | Sectoral share of the total budget under EPC simple and CAC simple (%) | Sector carbon budget under EPC simple, acknowledging the sectoral capital stock use time (Mt CO₂, up to 2050) | Change in the sectoral budget due to capital stock use time consideration (%) |
|--------------------------------|--------------------------------|-----------------------------------------------|----------------------------------------------------------|-------------------------------------------------|-----------------------------------------------------------|-----------------------------------------------------------|---------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| Trade                          | 1.06                          | 13                                            | 16.4                                                     | 1.1%                                           | 9.8                                                       | 13.1                                                      | 1.6%                                                         | 6.7                                                                                                                               | −31%                                                                                                                                  |
| Services                       | 0.89                          | 12                                            | 13.4                                                     | 0.9%                                           | 8.2                                                       | 11.0                                                      | 1.3%                                                         | 5.5                                                                                                                               | −33%                                                                                                                                  |
| Services                       | 1.25                          | 24                                            | 26.2                                                     | 1.7%                                           | 11.5                                                      | 15.4                                                      | 1.8%                                                         | 10.8                                                                                                                              | −7%                                                                                                                                   |
| Public transport               | 6.38                          | 26                                            | 140.4                                                    | 9.2%                                           | 58.8                                                      | 78.6                                                      | 9.4%                                                         | 57.6                                                                                                                              | −2%                                                                                                                                   |
| Private household: heating and hot water | 8.68                          | 20                                            | 164.9                                                    | 10.8%                                          | 80.0                                                      | 107.0                                                     | 12.8%                                                        | 67.7                                                                                                                              | −15%                                                                                                                                  |
| Private household: Transport   | 6.52                          | 16                                            | 110.8                                                    | 7.3%                                           | 60.1                                                      | 80.4                                                      | 9.6%                                                         | 45.5                                                                                                                              | −24%                                                                                                                                  |
| **Total**                      | **68.05**                     | **1,528.6**                                   | **100%**                                                 | **627.1**                                      | **838.8**                                                 | **100%**                                                  | **627.1**                                                    | **0%**                                                                                                                             | **0%**                                                                                                                                |
| Emissions (respective budget) per capita (tonnes CO₂) | 8.11                          | 182.2                                        | 74.7                                                     | **100%**                                       | **100%**                                                  | **100%**                                                  | **100%**                                                     | **100%**                                                               | **100%**                                                                                                                            |

Note: ** Solely covering and * partially covering (district heating in extraction (gas); lighting etc. in electricity; real estate activities in services; use of public buildings in government services) activities involved in the construction and use of buildings.**

Source: See Table A2 in Appendix A.
are 33–52% lower than necessary carbon budgets for the construction sector and private household heating and hot water provision. For both sectors the consideration of capital stock use times reduces the sectoral carbon budget (by 18% and 15%, respectively), indicating slightly shorter capital-use times, especially when compared with emission-intensive industry sectors of mineral products or chemicals. For sectors partially related to construction and use of buildings, available sectoral carbon budgets are even 18–65% lower than the necessary carbon budgets (with some of them, but not all, having even shorter capital stock use times).

The necessary sectoral aggregated carbon budget for Austria of 1529 Mt CO$_2$ exceeds the available budget according to any method of determining the latter (Table 3, row ‘Total’). When the available budget is determined under the simple (i.e. unmodified) CAC approach, the exceedance of the necessary budget is smallest. For all other approaches in determining the available budget (i.e. those not shown in Table 3), the adjustments have to be even larger. This implies that for any national budget allocation stricter emission reductions than the economically cheapest ones have to be undertaken, and sectoral carbon budgets possibly reallocated accordingly, or a larger amount of emission permits has to be acquired from abroad. In the former case, capital stocks may have to be either replaced before the end of their lifetime or improved in their quality. For quality improvement strategies, higher budgets might be advisable for sectors that supply investment goods, if the latter can contribute to emission reduction over the lifetime of the respective investments due to the quality improvement they achieve. Refurbishment may increase the embodied emissions in the construction sector but reduce operational emissions during the lifetime of the refurbished building stock.

A related strand of the literature indicates that Austria is not alone in its necessary budget’s exceedance of its available one. While this literature does not address the infrastructure-derived first step ‘necessary budget’, it has compared the GHG budget necessary for the emissions pathway when current developed countries’ NDCs are implemented with one derived under equity considerations. Considering the GCB and its allocation according to ‘common but differentiated responsibilities and respective capabilities’ as implied by the modifications of simple principles discussed in section 3, Anderson, Broderick, & Stoddard (2020) identify the demand for a significant scaling up of industrialised countries’ mitigation efforts. They show that when not relying on large scale negative emissions technologies (considered as highly speculative), for developed countries the necessary rates of mitigation increase markedly, and that this even holds for countries considered at the forefront of developing ‘progressive’ climate change legislation, such as the UK and Sweden. For these two countries the carbon budgets underpinning mitigation policy are halved, with the immediate mitigation rate being increased to over 10% per annum, and full decarbonisation of the energy system having to occur already by 2035–40. Starting from first-step necessary sectoral budgets, their alignment to remain within the available budget at the aggregated level can inform the design of the necessary scaling up of mitigation efforts and will involve steps including the following:

- a simple strategy of proportional alignment
- a more elaborate strategy of reallocating budgets to allow for (earlier) improvements in sectoral capital stock quality and
- a dynamic strategy of identification of sectors where low-carbon transitions or even negative emissions can be fostered for fastest and/or cheapest realisation.

### 5.2 Sectoral budgets using consumption-based accounting

Alternatively, consumption-based emission accounting can be the principle of emission allocation to respective sectors. Thus, sectoral carbon budgets for the same sectoral structure in Austria (including the construction sector and private household heating and hot water provision) are derived next, when following consumption-based accounting. Sectoral capital stock lifetimes are again used, but now those use times need to be considered along the whole production chain (i.e. the whole sectoral intermediate input production structure). For the current consumption-based emissions an environmentally extended multiregional input–output (EE-MRIO) method employing GTAP9 data (Aguiar, Narayanan, & McDougall 2016) is used to derive the Austrian emission levels on a sectoral level (cf. Steininger et al. 2018, Nabernegg et al. 2019). The estimated use times for sectoral capital stocks under the production-based accounting approach (Table 3) are transferred to the sectoral shares of upstream embodied emissions. For example, the emissions share of cement production or steel production is transferred to the construction sector (at respective input shares) and the corresponding sectoral capital stock use times (see Figure A2 in Appendix A). The consumption-based capital stock-use times thus take into account the emission shares that arise from each sector along the production chain as weighting factor for the respective capital stock-use time.

The resulting necessary sectoral carbon budgets for construction and private household heating and hot water provision amount to 473 Mt CO$_2$, representing 23% of the total national necessary carbon budget (Table 4). For sectors partially including activities from buildings and their supply chains, sectoral carbon budgets of an additional 494 Mt CO$_2$, or 24% of the total national necessary carbon budget are allocated. As in the previous section, available sectoral carbon budgets from global allocation procedures for EPC simple and CAC simple criteria are also provided in Table 4.
Table 4: Sectoral emission levels, accordingly derived first-step necessary carbon budgets and sectoral carbon budgets under simple allocation, following a consumption-based accounting approach.

| Sector                          | Emission level (2011) (Mt CO₂) | Representative capital stock use time (years) | Necessary sectoral carbon budget (Mt CO₂, up to 2050) | Sectoral share of the total necessary budget (%) | Sectoral carbon budgets under EPC simple (Mt CO₂, up to 2050) | Sectoral carbon budgets under CAC simple (Mt CO₂, up to 2050) | Sectoral share of the total budget under EPC simple and CAC simple (%) | Sectoral carbon budget under EPC simple acknowledging sectoral capital stock use time (Mt CO₂, up to 2050) | Change in the sectoral budget due to capital stock use time consideration (%) |
|--------------------------------|--------------------------------|-----------------------------------------------|------------------------------------------------------|-----------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|-----------------------------------------------------------------------------|------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Agriculture                    | 0.76                           | 26                                            | 16.9                                                 | 0.8%                                          | 7.0                                                           | 9.4                                                           | 0.8%                                                                         | 6.8                                                                     | −3%                                                                                |
| Extraction, coal, oil, gas     | 0.64                           | 29                                            | 14.8                                                 | 0.7%                                          | 5.9                                                           | 7.8                                                           | 0.7%                                                                         | 6.0                                                                     | 1%                                                                                 |
| Food products                  | 3.98                           | 26                                            | 88.5                                                 | 4.3%                                          | 36.7                                                          | 49.1                                                          | 4.4%                                                                         | 35.6                                                                    | −3%                                                                                |
| Textiles                       | 2.63                           | 30                                            | 62.9                                                 | 3.0%                                          | 24.2                                                          | 32.4                                                          | 2.9%                                                                         | 25.3                                                                    | 4%                                                                                 |
| Wood products                  | 0.21                           | 29                                            | 5.0                                                  | 0.2%                                          | 2.0                                                           | 2.6                                                           | 0.2%                                                                         | 2.0                                                                     | 2%                                                                                 |
| Paper products, publishing     | 0.84                           | 30                                            | 20.4                                                 | 1.0%                                          | 7.7                                                           | 10.4                                                          | 0.9%                                                                         | 8.2                                                                     | 6%                                                                                 |
| Petroleum, coal products       | 2.72                           | 29                                            | 63.7                                                 | 3.1%                                          | 25.0                                                          | 33.5                                                          | 3.0%                                                                         | 25.6                                                                    | 2%                                                                                 |
| Chemical, rubber, plastic products | 2.17                         | 33                                            | 55.3                                                 | 2.7%                                          | 20.0                                                          | 26.8                                                          | 2.4%                                                                         | 22.3                                                                    | 11%                                                                                |
| Mineral products               | 0.66                           | 37                                            | 18.3                                                 | 0.9%                                          | 6.1                                                           | 8.1                                                           | 0.7%                                                                         | 7.3                                                                     | 21%                                                                                |
| Ferrous metals                 | 0.02                           | 31                                            | 0.4                                                  | 0.0%                                          | 0.2                                                           | 0.2                                                           | 0.0%                                                                         | 0.2                                                                     | 8%                                                                                 |
| Metals n.e.c.                  | 1.43                           | 31                                            | 35.4                                                 | 1.7%                                          | 13.2                                                          | 17.7                                                          | 1.6%                                                                         | 14.2                                                                    | 8%                                                                                 |
| Motor vehicles and parts       | 3.83                           | 30                                            | 92.8                                                 | 4.5%                                          | 35.3                                                          | 47.3                                                          | 4.2%                                                                         | 37.3                                                                    | 6%                                                                                 |
| Machinery and equipment        | 4.36                           | 31                                            | 106.5                                                | 5.1%                                          | 40.2                                                          | 53.8                                                          | 4.8%                                                                         | 42.8                                                                    | 7%                                                                                 |
| Electronic equipment           | 3.98                           | 27                                            | 90.3                                                 | 4.4%                                          | 36.7                                                          | 49.1                                                          | 4.4%                                                                         | 36.3                                                                    | −1%                                                                                |
| Electricity                    | 5.64                           | 34                                            | 145.3                                                | 7.0%                                          | 52.0                                                          | 69.5                                                          | 6.2%                                                                         | 58.4                                                                    | 12%                                                                                |
| Construction                   | 12.68                          | 31                                            | 308.2                                                | 14.9%                                         | 116.9                                                         | 156.4                                                         | 14.0%                                                                        | 123.9                                                                   | 6%                                                                                 |

* Change in the sectoral budget due to capital stock use time consideration is calculated based on the difference between the budget with and without consideration of capital stock use time.

** Construction sector data includes both capital stock use time and EPC simple allocation.
| Sector                        | Emission level (2011) (Mt CO₂) | Representative capital stock use time (years) | Necessary sectoral carbon budget (Mt CO₂, up to 2050) | Sectoral share of the total necessary budget (%) | Sectoral carbon budgets under EPC simple (Mt CO₂, up to 2050) | Sectoral carbon budgets under CAC simple (Mt CO₂, up to 2050) | Sectoral share of the total budget under EPC simple and CAC simple (%) | Sectoral carbon budget under EPC simple acknowledging sectoral capital stock use time (Mt CO₂, up to 2050) | Change in the sectoral budget due to capital stock use time consideration (%) |
|------------------------------|--------------------------------|---------------------------------------------|---------------------------------------------------|-----------------------------------------------|----------------------------------------------------------|----------------------------------------------------------|-----------------------------------------------------------------|-------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| Trade                        | 7.52                          | 28                                          | 173.6                                            | 8.4%                                          | 69.3                                                      | 92.7                                                      | 8.3%                                                            | 69.8                                                                             | 1%                                                                               |
| * Services                   | 5.45                          | 29                                          | 127.9                                            | 6.2%                                          | 50.3                                                      | 67.2                                                      | 6.0%                                                            | 51.4                                                                             | 2%                                                                               |
| * Government services        | 8.55                          | 30                                          | 206.0                                            | 10.0%                                         | 78.7                                                      | 105.3                                                     | 9.5%                                                            | 82.9                                                                             | 5%                                                                               |
| Public transport             | 7.01                          | 28                                          | 160.6                                            | 7.8%                                          | 64.6                                                      | 86.4                                                      | 7.8%                                                            | 64.6                                                                             | 0%                                                                               |
| ** Private household:        |                                |                                              |                                                  |                                               |                                                           |                                                           |                                                                  |                                                                                  |                                                                                  |
| Heating and hot water        | 8.68                          | 20                                          | 164.9                                            | 8.0%                                          | 80.0                                                      | 107.0                                                     | 9.6%                                                            | 66.3                                                                             | −17%                                                                             |
| Private household: Transport | 6.52                          | 16                                          | 110.8                                            | 5.4%                                          | 60.1                                                      | 80.4                                                      | 7.2%                                                            | 44.6                                                                             | −26%                                                                             |
| Total                        | 90.29                         | 2,068.7                                     | 832.0                                            | 1,113.0                                       | 832.0                                                     |                                                           |                                                                  |                                                                                  |                                                                                  |
| Emissions per capita (tonnes CO₂) | 10.76                      | 246.6                                       | 99.2                                             | 132.7                                         |                                                           |                                                           |                                                                  |                                                                                  |                                                                                  |

**Note**: ** Solely covering and * partially covering (district heating in gas; lighting etc. in electricity; real estate activities in services; use of public buildings in government services) activities involved in the construction and use of buildings.**

Source: See Table A2 in Appendix A.
These are based on the distribution of recent consumption-based emissions across sectors, such as to sum up to country totals (available budget) taken directly from the global emission allocation (Table 1).

Different than for production-based sectoral carbon budgets, in comparing necessary and reference budget distribution for consumption-based budgets, the reliance by most sectors on sectorally differentiated capital-use times (as relevant for the necessary budgets) is no longer of significant relevance for determining the respective sector’s share in the national budget (sectoral shares given in columns (4) and (7) of Table 4 deviate much less than in Table 3). The final demand sector construction in this case is even allocated a larger budget share (14.9% versus 14%, columns (4) versus (7)) when accounting for capital-use times than when not. The budget for the construction sector is larger by 6% (column (9)) than when capital-use times are not considered. However, again the overall gap is large, even for the national budgets derived under ‘simple’ approaches. For the construction sector and private household heating and hot water provision, available sectoral carbon budgets are 45–62% lower than the derived necessary carbon budgets. Available sectoral carbon budgets are even 47–64% lower than the necessary carbon budgets for those sectors partially including activities engaged in the construction and use of buildings.

For an industrial country such as Austria, the first-step necessary budget strongly exceeds all types of the available budget, if emissions occurring along the whole production chain are accounted for (i.e. the consumption-based accounting approach) (Figure 2). In order to remain within the available budget determined by any of these methods, capital stocks in at least some sectors have to be replaced significantly earlier—before the end of their lifetime.

Such earlier replacement may also involve a reallocation of sectoral carbon budgets. As discussed in section 4.1, a reduction of emissions in the use phase (e.g. a reduction of emissions due to improved heating efficiencies) is linked to higher emissions due to the production of additional investment (e.g. due to retrofit of the building stock). While the emission reductions for heating are accounted for in private household heating, the additional emissions for refurbishment (if not yet carbon free) are accounted for in the construction sector. As an indicator how relevant such cross-sectoral linkages can be for any particular sector, the sectoral investment intensity of final demand (i.e. the share of investment demand in total final demand for goods of that sector) can be considered. Figure 3 aligns the sectors vertically according to their consumption-based emission level (absolute value) and horizontally according to the investment intensity of final demand (calculated from GTAP9 data). The bubble size shows the first-step necessary sectoral carbon budget. For the construction sector especially, the high investment intensity in final demand indicates significant potential for investment to raise the justified sectoral carbon budget as a trade-off for less use emissions. Such a shift will increase the carbon budget for the sector with the largest initial sectoral carbon budget (construction) even further.

Figure 3: Necessary sectoral consumption-based carbon budgets (bubble size) by current consumption-based emissions (vertical axis) and share of investment demand in total demand for sector goods and services (horizontal axis).
It is clear that the switch in the GHG accounting method significantly changes sectoral carbon budgets. For the construction sector the first-step necessary budget accounted for only 3.2% of the total necessary budget under the production-based accounting approach. However, this share is nearly five times higher (14.9%) under the consumption-based accounting method. In both cases the share will rise due to higher investments using goods produced in construction to reduce use emissions.

Aligning sectoral budgets to remain within the aggregate national budget can be performed using the approach outlined in this paper. This can be done by starting with the first-step necessary sectoral budgets under the consumption-based approach, and then following equivalent steps as indicated in the discussion of sectoral budgets under the production-based approach.

6. Conclusions

A process was created to derive sectoral carbon budgets, first at the national level. The same approach can be applied to further disaggregate sectoral budgets sub-nationally to regions or cities. The specific method is grounded in an economic cost argument, seeking to keep costs of transformation low. To that end the concept applied considers the lifetime of sectoral capital stocks, and, in a first step, assumes their substitution by capital stocks that allow for carbon-free operation only at the end of their lifetime. This indicates a ‘first-step’ necessary budget for each sector. The case of Austria shows that the derived first-step sectoral carbon budgets at the national aggregated value exceeds the available carbon budget for all types of definitions.

For sectoral carbon budget accounting under a consumption-based approach, the analysis finds that acknowledgement of capital stock use times does not change the share in national budgets much for most sectors, including the construction sector. Thus, extended discussions on agreeing on sectoral capital stock use times seem to be not worth the effort. The reason being that under consumption-based accounting, each sector relies on the capital-use times prevalent in all its intermediate supply, moving all sectors closer to the nationwide average. The remaining challenge is consumption-based accounting itself. If this latter challenge is foregone and production-based emission accounting is applied, then capital stock use time do matter significantly in allocating sectoral carbon budgets. Conversely to consumption-based accounting, under production-based accounting for both the construction and household own heating the acknowledgement of sectorally differentiated capital-use times reduces sectoral carbon budgets.

For both accounting approaches, the excess of necessary over available budgets indicates the relevance of working with sectoral carbon budgets and their adjustments to remain—at their aggregated value—within the respective national carbon budget. The conceptual approach can be used to inform:

- how strictly carbon emission reduction pathways need to be designed (at both the sector and the aggregate level)
- to what degree the acknowledgement of cost arguments on avoiding premature decommissioning of infrastructure shape sectoral effort distribution and
- which redesign of investment policies for capital stock improvements remain within the aggregate carbon budget (engaging a trade-off in investment induced emissions for emission reduction in the use phase, and the according sectoral carbon budget reallocation).

In order to acknowledge all global emission implications of a field of activity, such as that concerned with the construction and use of buildings, the use of a consumption-based greenhouse gas (GHG) accounting approach is recommended. Thereby, a comprehensive approach in policy design is fostered, avoiding any ‘blind spots’ that could otherwise lead to carbon leakage (i.e. outsourcing of emission-intensive activities beyond national borders, and thus lacking one angle of emission reduction).

It was found that the construction sector—especially under the most comprehensive accounting of the consumption-based approach—requires a particularly large fraction of the national carbon budget. Two parameters govern this share: the sector’s current share in consumption-based emissions and the capital stock use times involved.

At the macroeconomic level, activities in the construction sector in general have the single most relevant potential to contribute to remaining within national carbon budgets for enabling capital stock improvements across sectors. The advisable consumption-based carbon budget for the construction sector may warrant an increase in the short term to allow for refurbishment and other activities to improve the quality of the building stock, provided an even stronger decrease in use emissions occurs.

The carbon budget concept has the potential to provide a transparent and informative tool for the analysis, policy design and monitoring of GHG emission pathways. The long-time horizons in both (1) GHG lifetime in the atmosphere and (2) lifetime of buildings are crucial for both adequate policy design in public governance at all levels (national, regional, municipal) and strategy development and action by business or economic sectors. A GHG budget approach addresses the long-time horizon relevant in all these dimensions. In a comprehensive governance approach the interlinkage between the GHG and financial budget will be reflected in them being developed in an interactive and mutually informative process.

A range of practical implementation issues requires further research, as well as further practical application experience and improvement. This paper contributes to this development by proposing a method to derive sectoral carbon budgets from the national one that focuses on overall societal cost minimisation. Sectors with high ambitions
for achieving the Paris Agreement targets could identify whether sectoral capital lifetimes can be agreed upon or if a simpler grandfathering approach is the more appropriate (or the only doable).

Further research could particularly contribute to this development:

- Historic evidence on capital stock lifetimes is scarce, particularly for most industrial, but also residential and commercial buildings.
- Process co-design for all steps in carbon budget application (definition, pathway comparisons, monitoring) requires further development.
- First carbon budget implementation experience exists with a municipal focus, but not yet for economic sectors.

Given the significant share that construction and use of buildings have in overall GHG emissions, there is potential to gain from a sectoral carbon budget approach, to define sectoral targets, to contribute to the design of most cost-effective sectoral climate action and to create a monitoring tool.

**Note**

1 In some sectors (e.g. electricity generation) lifetimes will be less controversial (for further details, see section 5.1), while for others only broad ranges can plausibly be argued. Buildings can probably serve as a prominent example of the latter. We are grateful to a referee for questioning how to determine the relevant ranges: even within building typologies lifetimes can diverge across substantial ranges, governed much more by local economic circumstances (e.g. land rent) or history (share of historical buildings, landmark buildings) than material or design. Does this render a carbon budget allocation discussion useless because agreement is at least difficult, possibly unlikely? We think that sectoral carbon budgets can serve as a very useful tool to structure this discussion—a discussion that cannot be avoided but might be facilitated by relying on shared concepts. Carbon budgets have several important advantages: first, they allow for an unveiling of the dimension of the decarbonisation effort to be achieved, including at the sectoral level. Second, they allow the analysis of the dynamic character of the environmental and economic dimensions. While for the environmental dimension only the integral of the emissions pathway matters, the economic dimension takes into account annual investments—and thus foregone consumption—that govern the stock development and in turn allow annual consumption. Third, carbon budgets offer a common numeraire across sectors directly linked to the issue at hand. Without doubt, practical implementation will reveal numerous issues of potential controversy—an ample field for further research. We consider it a promising path, one that could in turn contribute to addressing and resolving the underlying issues of societal discussion.

**Acknowledgements**

The authors thank Keith Williges, Alexander Passer and the team of the Paris Buildings project at TU Graz for very supportive discussion; as well as two anonymous reviewers and the editors of this special issue for detailed and very helpful comments and suggestions, which all substantially contributed to this paper.

**Competing interests**

The authors have no competing interests to declare.

**Funding**

Financial support for this study provided by the Austrian Climate and Energy Fund under its Austrian Climate Research Program (ACRP), project ‘Transition of the Procurement Process towards Paris Compatible Public Buildings’ (ParisBuildings) [project number B960256], is thankfully acknowledged. Additionally, Stefan Nabernegg was supported by the Austrian Science Fund (FWF) [research grant number W1256] (Doctoral Programme Climate Change: Uncertainties, Thresholds and Coping Strategies).

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### Appendix A

#### A.1 Effort sharing approaches

Table A1: Effort-sharing-approach categorisation and description of the allocation approaches used.

| IPCC category                        | Description                                                                 | Analogue in this work                                                                 |
|--------------------------------------|------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|
| Responsibility                       | Use of historical emissions to derive future reduction goals                 | Historical emissions qualification (Historical)                                         |
| Capability                           | Approaches relating goals to gross domestic product (GDP) or the human development index (HDI), other basic-needs-fulfilling approaches | Basic-needs qualification (N-qualified)                                                 |
| Equality                             | Allocation based on immediate or converging emissions per person             | Equal per capita approach (equal per capita (EPC) simple)                               |
| Responsibility, capability, and need | Includes approaches placing an emphasis on historical responsibility, balanced with capability and the need for sustainable development | Basic needs, historical emissions and benefits qualifications (NHB-qualified); for EPC also reasonable burden limit qualification (NHBC-qualified) |
| Equal cumulative per capita          | Combines equality with responsibility (cumulative accounting for historical emissions) | Historical emissions and benefits qualifications (HB-qualified)                         |

(Contd.)
Sectoral carbon budgets as an evaluation framework for the built environment

A.2 Data sources: sectoral emissions and capital stock use times

Table A2: Data sources for calculations reported in section 5, and in Tables 3 and 4.

| Sector                              | Emission level (2011) (Mt CO₂) | Representative capital stock use time (years) | Necessary sectoral carbon budget\(^b\) | Sectoral carbon budgets under EPC simple\(^b\) | Sectoral carbon budgets under CAC simple\(^b\) |
|-------------------------------------|--------------------------------|---------------------------------------------|--------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Agriculture                         |                                | Based on (3)                                |                                      |                                               |                                               |
| * Extraction, coal, oil, gas        |                                | Based on (3) and (4)                        |                                      |                                               |                                               |
| Food products                       |                                | Based on (3)                                |                                      |                                               |                                               |
| Textiles                            |                                | Based on (3)                                |                                      |                                               |                                               |
| Wood products                       |                                | Based on (3)                                |                                      |                                               |                                               |
| Paper products, publishing          |                                | Based on (3) and (4)                        |                                      |                                               |                                               |
| Petroleum, coal products            |                                | Based on (3) and (4)                        |                                      |                                               |                                               |
| Chemical, rubber, plastic products  |                                | Based on (3) and (4)                        |                                      |                                               |                                               |
| Mineral products                    |                                | (2)                                         |                                      |                                               |                                               |
| Ferrous metals                      |                                | Based on (3) and (4)                        |                                      |                                               |                                               |
| Metals n.e.c.                       |                                | Based on (3) and (4)                        |                                      |                                               |                                               |
| Motor vehicles and parts            |                                | Based on (3)                                |                                      |                                               |                                               |
| Machinery and equipment             |                                | Based on (3)                                |                                      |                                               |                                               |
| Electronic equipment                |                                | Based on (3)                                |                                      |                                               |                                               |
| * Electricity                       |                                | Based on (5)                                |                                      |                                               |                                               |
| ** Construction                     |                                | Based on (3)                                |                                      |                                               |                                               |
| Trade                               |                                | Based on (3)                                |                                      |                                               |                                               |
| * Services                          |                                | Based on (3)                                |                                      |                                               |                                               |
| * Government services               |                                | Based on (3)                                |                                      |                                               |                                               |
| Public transport                    |                                | (4)                                         |                                      |                                               |                                               |
| ** Private household: heating and hot water |                  | Based on (6)                                |                                      |                                               |                                               |
| Private household: transport        |                                | (4)                                         |                                      |                                               |                                               |
| Total                               |                                |                                             |                                      | (7)                                           | (7)                                           |
| Emissions per capita (tonnes CO₂)   |                                | Population data from (2): 8.39 million people in 2011 |                                      |                                               |                                               |

Notes: * = based on (1); \(^b\) = authors’ own calculations.
Sources: (1) Nabernegg et al. (2019); (2) Statistik Austria (2019); (3) EU KLEMS (2018); (4) Smith et al. (2019); (5) Davis & Socolow (2014); (6) Umweltbundesamt (2011); and (7) Williges et al. (2020).

Representative capital stock use time are obtained from empirical studies on historic lifetimes of fossil fuel infrastructure (Davis & Socolow 2014; Smith et al. 2019) if they were available on a sectoral level. If not available, use times are calculated from the EU KLEMS (2018) database, using physical capital stocks only (Computing equipment, Communications equipment, Computer software and databases, Transport equipment, Other Machinery and equipment, Total Non-residential investment, Residential structures) and respective depreciation rates for Austria on a NACE-2 sectoral level.\(^{EN1}\)

For industry sectors of Extraction, Coal, Oil, Gas, Paper products, publishing, Petroleum, coal products, Chemical, rubber, plastic products, Ferrous metals and Metals n.e.c. the overall industry average use time is taken to be 30 years according to the industry sector in Smith et al. (2019) while sectoral variation between those sectors (i.e. the spread of sectors around this average) is implemented based on the EU KLEMS (2018) database. For private household heating and hot water systems, depreciation rates from Umweltbundesamt (2011) are used.
A.3 Sensitivity analysis of varying the maximal annual emission reduction rate

Figure A1: Sensitivity analysis of varying the maximum annual rate of reduction adopted as a reasonable burden limit. For the equal per capita (EPC) NHBC-qualified allocation approach, a range of adopted reasonable burden limits were compared with a scenario with no rate restriction, here shown for the results with human development index (HDI) threshold level set to 0.55. Choosing a maximum rate between 0.05 (5%) and 0.07 (7%), versus using no rate restriction at all, has a much larger effect on average budget allocation than the choice between different plausible rates. For countries with a low HDI value, generally not expected to be required to reduce emissions at rates higher than the reasonable burden limit, the average allocation is reduced slightly, while for states above the threshold, budget allocations can increase dramatically, avoiding burdening countries with large negative emissions requirements. Source: Williges et al. (2020, figure S3 in the supplemental data online).

A.4 Upstream sectoral emissions of sector construction

Figure A2: Upstream sectoral emissions of the Austrian sector ‘Construction’.

Appendix Note

NATE = Statistical Classification of Economic Activities in the European Community.
