Grey emission targets for municipalities based on material cadastres

Georg Schiller¹, Karin Gruhler¹, Ulrike Grießbach¹, Jörg Hennersdorf¹ and Ines Lehmann¹

¹Leibniz Institute of Ecological Urban and Regional Development (IOER), Weberplatz 1, 01217 Dresden, Germany

Corresponding author: g.schiller@ioer.de

Abstract. The building stock contributes significantly to greenhouse gas (GHG) emissions. Considerable progress has been made in the energy-efficient operation of buildings, thus the importance of grey emissions is increasing and will become a future field of action for municipalities as well. So far, there is poor knowledge regarding quantities, fields of actions and impacts. This paper is addressing this gap by applying a bottom-up material flow analysis (MFA) approach on the domestic building stock of Hamburg, and by calculating material-induced grey emissions of alternative building stock compositions as well as impacts of technical and social innovations. Overall, the stock induced grey emissions amount to 41.9 million metric tons of CO₂ equivalent. Impact with regard to technical innovations concerning GHG reduction is rather limited. In contrast, impact achieved by ambitious social innovation is quite significant. This means that technical innovations must be considered in a more radical way and merged with social innovations.

1. Introduction
The building stock contributes significantly to the emission of greenhouse gases. Considerable progress has been made in the energy-efficient operation of buildings. In the past decades, energy standards have been continuously raised. Low-energy houses are now standard for new buildings. This has led to a significant reduction in energy consumption and, in turn, climate-relevant emissions, at least in the new construction segment. In relation to this, the importance of grey emissions from building activities is increasing. Grey emissions are CO₂ emissions corresponding to the amount of grey energy here of a building. In the G7 countries, the emissions resulting from the material cycle currently amount to 17% of the total GHG emissions in existing buildings [1]. This proportion will continue to rise in the coming years. With regard to new buildings, the increasing importance of emissions resulting from the material cycle is much more evident. In a well-insulated new building (KfW 55 according to German building code), the grey energies and, under simplified assumptions, the grey emissions are about the same as the emissions resulting from operational energy over a period of 50 years [2].

In view of these dimensions, it is understandable that climate protection initiatives relating to the built environment are increasingly addressing this issue. However, there is still a great deal of uncertainty regarding the meaningful representation of grey emissions in existing building stocks and the determination of the resulting reduction potentials. In contrast to the consideration of the materials
used in the building stock, which can potentially be reused as secondary materials, grey energy and emissions in the building stock are a purely theoretical calculation. The energies are "lost", the emissions have taken place in the past - both can no longer be influenced and are not traceable. Hence, the questions are rather, a) how the building stock will be built in the future, and b) to what extent technical innovations can contribute to recycling building materials in a way as to reduce grey emissions. Furthermore, it needs to be considered how much new construction is needed and to what extent new construction can be avoided by more intensive or longer use of the existing building stock. The latter will be summarised under the term social innovations.

So, this paper discusses, at municipal level, to which extent grey emissions can be influenced in the development of the building stock and which basic approaches may have which effects. This is based on highly simplified theoretical considerations. Starting from the existing building stock, the fictitious situation of a rebuild of the entire building stock of a municipality with today’s construction standards is simulated. Assumptions are made about construction methods in which energy and emission-intensive materials are replaced by materials that require less energy to produce, but offer the same technical performance. Secondly, the substitution of building materials from natural raw materials by materials from secondary raw materials are considered. Thirdly, the savings potential will be analysed that can result from social innovations stemming, for example, from an extension of the service life of buildings and their more intensive use, based on blanket assumptions in line with the above-mentioned study of [1]. This paper thus addresses the UN SDGs 11 (sustainable cities and communities) and 13 (climate action), as well as the BEYOND2020 conference topics 3 (climate mitigation and adaptation) and 14 (urban transition).

In the following section the methodology used and the assumptions made are described. Afterwards, the results of the model calculations made with regard to the city of Hamburg are presented and discussed in terms of their possible implementation at the level of municipal policy-making dealing with resource management and climate protection as pertaining to existing building stocks. The analysis focuses on the housing sector. Similar considerations are possible for the non-domestic sector, too. For Germany, for example, material-related principles from [3] are available. The following methods can be adapted to the non-domestic sector with appropriate adjustments.

2. Method

The considerations and model calculations presented in this paper are based on the bottom-up material flow analysis (MFA) method. This approach follows the principle of an indicator-based extrapolation of materials in the building stock: materials in the building stock = quantity of buildings measured by a suitable reference value × specific material composition of the buildings in relation to the reference value [4]. This principle can basically be applied to the building stock as well as to its change due to new construction and demolition. In the calculations presented, we use the gross volume as a reference value. Compared to other conceivable variables such as m² of usable floor space, number of apartments or number of buildings, the gross volume shows the strongest correlation to the material stock of a building [5]. Another principle of the bottom-up method is the use of building types. These can differ, e.g. according to the type of use (in the housing sector multi-family houses - MHF and single family houses - SFH) as well as according to construction methods (e.g. reinforced concrete-, masonry-, wooden construction).

Usual construction methods are subject to a time dependency. At the beginning of the last century, masonry constructions with a comparatively high proportion of wood (wooden beam ceilings) were common in multi-family house construction, while in the second half of the 20th century reinforced concrete constructions became increasingly important. Towards the end of the 20th century, the focus shifted back to masonry constructions - in detail, however, the construction methods of individual building elements differ significantly from those of the Wilhelminian era. Reinforced concrete (e.g. in ceilings), sand-lime brick and also plastics are more important, while the amount of wood is decreasing. This is also reflected, to a different extent, in single-family homes. In addition, there are
influences of the spatial structures within the buildings (room heights and room layouts), which have an influence on the specific material composition of the buildings.

The material indicators used in this study are based on comprehensive analyses of representatives of the German residential building stock provided by [5]. On the basis of expert estimates, the authors define synthetic building types which represent a characteristic mix of construction methods from specific eras.

By linking MFA to Life Cycle Assessment tools, material-related material composition indicators (MCI) can be converted to emission-related MCI. These express the amount of CO₂ equivalent emitted during the production of one unit of the reference unit of a specific building type (described below in figure 1 as kg CO₂ equivalent per m³ gross volume).

![Figure 1. MCI of synthetic types of domestic buildings in Germany’s building stock expressed by kg CO₂ equivalent per m³ gross volume, calculated by using MCI given by [5] and the LCA-tool [6].](image)

The assumed amount of the grey emissions caused by the construction of the current building stock is to serve as a starting point and benchmark in this discussion, which will be compared with the emissions of a future development of the stock. A prerequisite for this is to know the current residential building stock.

The determination of the size of the building stock is carried out by applying the concept of a regional material cadastre. This is based on a determination of the building stock using a combination of data from official building statistics and geodata from surveying offices. This procedure, which will be described here only briefly, is used to provide planning-relevant information in the context of the circular economy in such a way that it can be directly incorporated into the corresponding planning processes. The development of the concept is supported and financed by the German Federal Environment Agency [7]. Corresponding publications are in preparation.

German building statistics provide information on the number of domestic buildings, the usable floor space and the age structure of the domestic building stock. Geo-data terrain models (LOD1) provide information on the construction volume at the level of individual buildings or building blocks. A combination of the two data sources allows the determination of construction volumes in the residential building stock, differentiated by type of use (MFH and SFH) within communities - in the case of large cities usually also within districts, indicating an average construction age of these stocks.
Options for changing the amount of grey emissions can only relate to future construction activity. This can be discussed either in the light of current experience and practice in construction, by taking up good but established examples in construction practice, or secondly, by discussing new innovative solutions, regardless of whether these solutions have already been tried and tested in practice. In this paper the former approach is followed.

Tables 1a (MFH) and 1b (SFH) describe alternative construction methods of types of new buildings as they are considered typical by experts [5]. The table row "estimated composition status quo" indicates the weighting that the experts consider these individual buildings to be part of the synthetic building type of the corresponding age group. A synthetic building is a theoretical building composed of the typical buildings for an age group and their different construction methods. The weighting of those typical buildings reflects the share each of them has in the synthetic building according to the frequency of their occurrence [5]. The first row of the table describes the general construction method of the building types. The following rows provide a differentiated description of the construction method of the individual building elements. It becomes clear that, according to the source used, the construction method known as reinforced concrete is currently of no significant importance, but rather different types of masonry construction and, to a small extent, timber construction. Nevertheless, it is clear that reinforced concrete plays a dominant role in certain construction elements, especially in ceilings and cellars.

Table 1a. Assumptions on changes in building construction of synthetic MFH-building types.

|                  | Brickwork                                      | Limestone masonry                      | Aerated concrete masonry | Timber construction |
|------------------|------------------------------------------------|----------------------------------------|--------------------------|---------------------|
| **MFH – new construction** |                                                 |                                        |                          |                     |
| **Exterior walls** | Bricks (solid brick to light vertically perforated brick) with thermal insulation (polystyrene) | Sand-lime brick with thermal insulation (polystyrene) | Aerated concrete blocks (partly with insulated curtain wall) | Wooden constructions with thermal insulation (mineral wool) |
| **Interior walls** | Bricks (solid brick to light vertically perforated brick) | Sand-lime bricks | Aerated concrete blocks | Wooden constructions with insulation (mineral wool) |
| **Ceilings** | Reinforced concrete ceilings with insulation (polystyrene) | Reinforced concrete ceilings with insulation (polystyrene) | Reinforced concrete ceilings with insulation (polystyrene) | Reinforced concrete ceilings with insulation (polystyrene) |
| **Roof** | Wooden structures with insulation (mineral wool) (partly reinforced concrete binder), roofing (tiles) | Wooden constructions with insulation (mineral wool), roofing (tiles, metal, bitumen) | Reinforced concrete binder with insulation (mineral wool), roofing (tiles) | Wooden structures with insulation (mineral wool), roofing (tiles) |
| **Cellar** | Reinforced concrete with insulation (polystyrene), reinforced concrete base | Reinforced concrete with insulation (polystyrene), reinforced concrete base | Reinforced concrete with insulation (polystyrene), reinforced concrete base plate | Reinforced concrete with insulation (polystyrene), reinforced concrete base |
| **Estimated composition (status quo) [%]** | 20 | 65 | 13 | 2 |
| **Estimated composition (low-carbon) [%]** | 17 | 57 | 11 | 15 |

Table 1b. Assumptions on changes in building construction of synthetic SFH-building types.

|                  | Brickwork                                      | Limestone masonry                      | Aerated concrete masonry | Timber construction |
|------------------|------------------------------------------------|----------------------------------------|--------------------------|---------------------|
| **SFH – new construction** |                                                 |                                        |                          |                     |
| **Exterior walls** | Bricks (solid brick to light vertically perforated brick) with thermal insulation (polystyrene) | Sand-lime brick with thermal insulation (polystyrene) | Aerated concrete blocks | Wooden constructions with thermal insulation (mineral wool) |
| **Interior walls** | Bricks (solid brick to light vertically perforated brick) | Sand-lime bricks | Aerated concrete blocks, bricks | Wooden constructions with insulation (mineral wool) |
| **Ceilings** | Reinforced concrete ceilings with insulation (polystyrene) | Reinforced concrete ceilings with insulation (polystyrene) | Reinforced concrete ceilings with insulation (polystyrene) | Wood-beamed ceilings, above the cellar: reinforced concrete ceilings |
### Roof

|                        | Wooden constructions with insulation (mineral wool), roofing (tiles, concrete roof tiles) | Wooden structures, (partly reinforced concrete binder) with insulation (mineral wool), roofing (concrete roof tiles, bitumen) | wooden constructions with insulation (mineral wool), roofing (tiles, concrete roof tiles) | Wooden structures with insulation (mineral wool), roofing (tiles) |
|------------------------|------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|-------------------------------------------------------------------|
| **Cellar**             | Bricks with insulation (polystyrene), reinforced concrete base plate                      | Reinforced concrete, sand-lime bricks with insulation (polystyrene), reinforced concrete base     | Concrete blocks with insulation, concrete strip foundation, reinforced concrete base plate | Bricks with insulation (polystyrene), concrete strip foundation, reinforced concrete base plate |
| **Estimated composition status quo** | 25                                                                                     | 53                                                                                              | 10                                                                              | 12                                                                |
| **Estimated composition low-carbon** | 20                                                                                     | 42                                                                                              | 8                                                                               | 30                                                                |

The assumptions regarding a new low-carbon building refer to a shift in the status-quo weighting to a "low carbon weighting", on the basis of which these synthetic "low carbon" new buildings are currently defined (cf. "estimated composition low carbon"). This is based on the following basic assumptions:

- significant increase in the amount of buildings made from timber – here a doubling of timber construction in the SFH sector and an increase in timber construction in the MFH sector to the amount in the SFH sector today are assumed;
- corresponding reduction of the proportion of buildings in masonry construction method in equal shares (-18% for SFH and -13% for MFH).

Another field of conceivable technical innovations concerns the substitution of primary building materials by secondary building materials obtained from recycling. In the context of this paper, this will be considered in accordance with studies by [8]. In consulting with representatives of the building materials industry it was determined that, based on what was considered by them to be ambitious assumptions, an increase in RC aggregate content in building construction from the current average of 0.4% to up to 12% (in 2050) can be anticipated. However, energy and emission savings are well below the substitution potential of natural raw materials. This is due to the additional process energy that has to be used in the production of secondary raw materials. Based on [9] and [10] it is assumed that emission reduction potentials are around 22% of the reduction potentials of natural aggregates. In general, a 3% reduction in grey energies is assumed if concrete is made from 20% RC aggregates.

In addition to technical innovations, "innovations" that relate to the use of existing buildings and lead to less new construction are looked at - by extending the service lives of existing buildings or using buildings more intensively, i.e. less m² per person. This is done on a purely informative basis, based on general statements made in the study of [1] which assume an enormous reduction potential in this area, in the order of 70% of the grey emissions caused today. They refer to studies of conceivable developments in G7 countries.

### 3. Results

According to the method described above, the grey emissions emitted in the past during the construction of the domestic building stock of the city of Hamburg add up to 41.9 million metric tons CO₂ equivalent. This corresponds to values of 118 kg CO₂ equivalent/m² gross volume. Using the GIS data this can be mapped on a small scale, for example at the level of city districts (figure 2).
Figure 2. CO₂ emissions of residential buildings in kg CO₂ equivalent differentiated by city districts.

A comparison of the corresponding values between the districts shows that the differences are small. They fluctuate by approximately +/- 1 percent around the average for the city as a whole. This is remarkable in that both the settlement structures and the age structure of the buildings differ significantly between the districts (figure 3).

Figure 3. Domestic building structure in the city districts (left) and CO₂ emissions of residential buildings in kg CO₂ equivalent/m² differentiated by city districts.

The value "stock 2017" (figure 4) was calculated using the MCI figures given in figure 1 and data collected on the gross volume of the housing stock in Hamburg, differentiated accordingly. It describes how many material-induced CO₂ emissions were involved in building the stock as it is, with the according building age classes (taking the energy mix of today into account). This is contrasted with a purely theoretical "new status quo" value, which expresses what grey emissions would have been generated if Hamburg's housing stock had been constructed using only current standard construction methods, as described in tables 1a and 1b, and neglecting the different building age classes and their respective material compositions. It becomes clear that with the construction methods...
currently in use, assuming a constant energy mix and neglecting efficiency gains in the production of building materials, we would emit approx. 7% more grey emissions than we did in the past when we built up the existing building stock.

Figure 4. Simulation of grey energies of alternative building compositions and building uses in relation to Hamburg's housing stock in the reference year 2017.

If we set this value at 100% and instead shift the building mix towards "low carbon" in favour of a greater proportion of timber construction methods and at the expense of reinforced concrete components in particular (see table 1a/b), the value will fall by 2%, but will still be above the "stock 2017" value. We are therefore still a long way from the low-emission construction methods that were common at the beginning of the last century.

Even with the additional assumption of a significant increase in the use of concrete recycling to approx. 20%, the resulting emissions remain barely below the value of the "stock 2017". Only through the radical but admittedly little reflected assumptions regarding so-called "social innovations" and thus avoidance of new construction, which are assumed based on the publication of the International Resource Panel, the emissions would be drastically reduced to less than one third of the current value.

4. Discussion and Conclusion

The objective of the introduced model calculations is to contribute to the quantitative evidence of the "grey energy" field of action in the context of the development of the building stock. This paper wants to contribute to a better understanding of which basic approaches are of which relevance in the context of municipal-level CO2 reduction policies. In a highly simplified form, variants are assumed which are based on alternative compositions of the building stock of the analysed municipal example. The results presented clearly show how limited the effects of the technical innovations considered are in terms of their potential to reduce grey emissions. At best, the measures contribute to avoiding an increase in grey emissions.

This is partly due to the not very courageous assumptions. In the "increasing wooden construction" variation, only a shift between already introduced construction methods is taken into account. Radical interventions in the construction method, which are already being discussed as niche solutions today, are not taken into consideration. However, if one is serious about a sustainable transformation and a significant reduction of climate-relevant emissions, even in the increasingly important area of
material-induced emissions, such solutions must be included in the discussion of ambitious target definitions.

The same applies with regard to the reduction potential "RC based", which is guided by the assessments compiled in collaboration with representatives of the building materials industry. Limitations should be accepted in this type of potential exploration, at most in terms of the availability of secondary materials. This requires consideration of the quantities of secondary raw materials resulting from demolition activities and a combination of those with potentials for reuse in new construction. Continuous MFA approaches, as presented by [11], offer the appropriate methodological approach.

However, in presenting reduction potentials as a result of social innovations, the estimates presented here take the opposite approach. In line with the deliberations of the International Resource Panel, highly ambitious assumptions are made which presume that, in particular by significantly reducing the consumption of living space and making much more intensive use of existing living space, 70% of new construction can be dispensed with. With reference to the situation in Germany, this would mean, for example, a reduction in living space per capita by at least 1/3 - from the current 45 m² to 30 m²/capita - while at the same time extending the average life of buildings of 70 years by over 30 years or one generation. How this can be presented and implemented in detail for a municipality needs to be specified - also against the background of demographic developments and taking into account innovative trends in building development that support these developments (e.g. tiny houses) as well as innovative use (e.g. shared space).

Regardless of this, however, the first question to be asked is how valid the calculations are. This is to be questioned on very different levels.

This concerns, for example, the plausibility of the MCI used to express grey emissions per reference unit of building types. On average, the indicators used here for new buildings (status quo) are 121 (SFH) and 131 (MFH) in relation to the unit kg CO₂ equivalent per m². These relate to the shell construction of the buildings (considered building elements see table 1a, 1b). The ratio of gross volume to usable areas can be roughly estimated to be 0.2 according to [12]. Applying this factor results in a value of approx. 660 kg grey emissions/m² floor space for the MFH type in relation to the entire service life of the building. A recent study commissioned by the German Federal Institute for Research on Building, Urban Affairs and Spatial Development [4] reports grey emissions of 8 kg/m² floor space and year for domestic buildings according to current standards - in relation to the building shell. This is done with regard to a period of 50 years. If the value used in this paper is related to the same period, this results in 13 kg emissions/m² and year. The values are thus well within a comparable range. The deviations can be explained, among other things, by deviating construction methods, but above all by deviating LCA tools and reference years used in the calculations (see energy mix discussion below). In this respect, the plausibility of the indicators used is given.

As just mentioned, the energy mix on which the calculations are based plays an important role. This is developing dynamically - the share of renewable energies has been rising steadily and will continue to rise - with a weakening effect on grey emissions. In addition, there are efficiency gains in the production processes. De facto, this means that past emissions for the production of stocks were significantly higher than those presented in this paper. However, it seems advisable to agree on a uniform energy mix for comparison purposes.

A considerable source of uncertainty may lie in the definition of the initial conditions and system boundaries that are used for the determination of construction material-specific emission values. Deviations result from the use of alternative LCA tools alone, each of which draws on specific "own" data sources - as already mentioned above. In relation to individual building materials, the deviations can be enormous, depending on how the system limits are set and the products defined. In the case of concrete, for example, the question arises as to whether, in addition to the emissions resulting from the energy consumption, emissions released during calcination processes are also taken into account, which are of a similar magnitude as the energy induced emissions. In most cases this is insufficiently documented in the programmes. With the data used here, we assume that both energy and process
induced emissions are taken into account. Considerable bandwidths can also be observed for wood. For example, glued laminated timber, which is often used in timber construction today, causes twice as much grey emissions as sawn timber boards and beams (roughly calculated on the basis of [6]). In the present study, it is assumed that most of the timber used in wooden construction are sawn timber boards and beams.

The determination of building volumes on the basis of GIS data also results in uncertainties. Geodata only recognise the volume above ground and also inaccurately represent the volume of roofs. This leads to the fact that geodata-based calculations underestimate the real construction volume by about 20% in the case of MFH and by about 30% in the case of SFH. The above mentioned results of the emission calculations must therefore, accordingly, be revised upwards.

A final point to be addressed concerns the underlying modelling concept and its applicability when it comes to planning questions of practitioners. This is an essential prerequisite if the results are to have an impact.

Discussions with representatives from the authorities of the municipality under consideration show that the considerations presented here offer a possible entry into the discussion, but that they are still too high in terms of abstraction and too reserved regarding the radicality of the assumptions. The former mainly concerns the theoretical consideration of different compositions of stocks - this is far away from real stock developments, which take place continuously. Scenario considerations that do justice to this continuity are called for. This is to be supported by assumptions from which direct references to political action can be derived, for example, stock orientation through drastic reduction of demolition rates and corresponding reduction of new construction or strengthening of low-emission construction through innovative construction methods. In addition, the development of the past itself must also be taken into account; studies by [2] indicate that the resulting grey emissions are of the order of 20% of the emissions resulting from the building shell. In addition, the development of the existing building stock itself must also be taken into account; studies by [13] indicate that grey emissions resulting from the maintenance of the existing building stock are of the order of 20% of the emissions resulting from the building shell.

The final conclusions are: As a result of the progress made with regard to energy in building operation, material-induced grey energies are gaining in importance and are emerging as future fields of action for municipal climate protection activities. So far, there is great uncertainty regarding the extent to which grey energies can be influenced and what options for action are available to municipalities. This implies a need for orientation knowledge. Knowledge of the material stock in the building stock and its changes offer a suitable starting point for this. In addition to the many questions of the robustness of model calculations and an appropriate level of detail in the considerations, other points are of central importance in order to achieve impacts in terms of emission reduction. The interrelationships are to be presented in such ways that, on the one hand, the essential influencing parameters are adequately considered and, on the other hand, the logic of action of the actors is addressed. If far-reaching effects are to be achieved, the goals must also be formulated in an ambitious and comprehensive manner - not taking into account currently conceivable developments, but far beyond them - taking into account technical as well as social innovations and understanding the relations between them.

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References
[1] UN environment programme 2020 International Resource Panel. Resource Efficiency and Climate Change. Factsheet. https://www.resourcepanel.org/reports/resource-efficiency-and-climate-change accessed 13 March 2020
[2] Mahler B, Idler S, Nusser T and Gantner J 2019 Energieaufwand für Gebäudekonzepte im gesamten Lebenszyklus Entwurf Endbericht (Dessau-Roßlau: Umweltbundesamt) p. 175
https://www.bmu.de/fileadmin/Daten_BMU/Pools/Forschungsdatenbank/fkz_3715_41_111_energieaufwand_gebaeudekonzepte_bf.pdf accessed 25 October 2019

[3] Ortlepp R, Gruhler K, and Schiller G 2016 Material stocks in Germany’s non-domestic buildings: a new quantification method Building Research & Information 44 8 pp 840-862
http://dx.doi.org/10.1080/09613218.2016.1112096

[4] UNEP (United Nations Environment Programme) ed. 2010 International Panel for Sustainable Resource Management: Working Group on the Global Metal Flows. Metal Stocks in Society: Scientific Synthesis. (Paris: UNEP DTIE)
www.unep.org/resourcepanel/Portals/24102/PDFs/Metalstocksinsociety.pdf accessed 25 April 2016.

[5] Ortlepp R, Gruhler K and Schiller G 2018 Materials in Germany’s domestic building stock: calculation model and uncertainties Building Research & Information 46 2 pp 164-178
http://dx.doi.org/10.1080/09613218.2016.1264121

[6] IINAS International Institute for Sustainability Analysis and Strategy 2020 GEMIS download http://iinas.org/gemis download.html accessed 13 March 2020

[7] KartAL IV 2020 Mapping the anthropogenic material stock IV – development of a building passport and cadastre concept for the rationalized identification of material stocks and flows in order to optimize recycling research projekt funded by the Federal Environment Agency (UBA) https://www.ioer.de/1/projects/kartal-iv/ accessed 18 March 2020

[8] Gruhler K and Deilmann C 2016 Resource saving potentials through increase recycling in the building sector – sensitivity studies on current and future construction activity ZEBAU – Centre for Energy, Construction, Architecture and the Environment GmbH (Hamburg: Sustainable Built Environment Conference 2016 in Hamburg: Strategies, Stakeholders, Success factors, 7th-11th March 2016) Conference Proceedings pp 1010-1019, http://nbn-resolving.org/urn:nbn:de:swb:90-516995 accessed 13 March 2020

[9] Bimesmeier T, Gruhler K, Deilmann C, Reichenbach J and Steinmetzer S 2020 Sekundärstoffe aus dem Hochbau. Energie- und Materialflüsse entlang der Herstellung und des Einsatzortes von Sekundärstoffen aus dem Hochbau für den Baubereich (Fraunhofer IRB Verlag: Forschungsinitiative Zukunft Bau, Band F 3184) p. 252
https://www.baufachinformation.de/sekundaerstoffe-aus-dem-hochbau/fb/253180 accessed 13 March 2020

[10] Gruhler K, Bimesmeier T and Deilmann C. 2019 Secondary materials in the building sector – energy and material flows IOP Conference Series: Earth and Environmental Science 290 (2019) 012014, pp. 1-6 https://doi.org/10.1088/1755-1315/290/1/012014

[11] Schiller G, Gruhler K and Ortlepp R 2017 Continuous material flow analysis approach for bulk nonmetallic mineral building materials applied to the German building sector Journal of Industrial Ecology 21 3 pp. 673-688 http://dx.doi.org/10.1111/jiec_12595

[12] Gruhler K, Böhm R, Deilmann C and Schiller G 2002 Stofflich-energetische Gebäudesteckbriefe - Gebäudevergleiche und Hochrechnungen für Bebauungsstrukturen IÖR-Schriften; 38 (Dresden: IÖR) p. 307 http://www.qucosa.de/fileadmin/data/qucosa/documents/15137/38_gruhler.pdf

[13] Mahler B, Idler S and Gantner J 2019 Mögliche Optionen für eine Berücksichtigung von grauer Energie im Ordnungsrecht oder im Bereich der Förderung (Bundesinstitut für Bau-, Stadt- und Raumbeforschung) https://www.bbsr.bund.de/BBSR/DE/FP/Auftragsforschung/5EnergieKlimaBauen/2017/grau-energie/Endbericht.pdf?_blob=publicationFile&v=3 accessed 13 March 2020