Basics and recommendations on influence of future electricity supplies on LCA-based building assessments

A Contribution to IEA EBC Annex 72

February 2023

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Imprint:

Published by 2023 Verlag der Technischen Universität Graz, www.tugraz-verlag.at

Editors: Rolf Frischknecht, Thomas Lützkendorf, Alexander Passer, Harpa Birgisdottir, Chang-U Chae, Shivakumar Palaniappan, Maria Balouktsi, Freja Nygaard Rasmussen, Martin Röck, Tajda Obrecht, Endrit Hoxha, Marcella Ruschi Mendes Saade

DOI: 10.3217/978-3-85125-953-7-02

Cover picture: Free image from Markus Distelrath on Pixabay

The official reports from IEA EBC Annex72 are available at following website:
https://annex72.iea-ebc.org/publications

Funding
The work within Annex 72 has been supported by the IEA research cooperation on behalf of the Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology via the Austrian Research Promotion Agency (FFG, grant #864142), by the Brazilian National Council for Scientific and Technological Development (CNPq, (grants #306048/2018-3 and #313409/2021-8), by the federal and provincial government of Quebec and Canada coordinated by Mitacs Acceleration (project number IT16943), by the Swiss Federal Office of Energy (grant numbers SI/501549-01 and SI/501632-01), by the Czech Ministry of Education, Youth and Sports (project INTEREXCELLENCE No. LTT19022), by the Danish Energy Agency under the Energy Technology Development and Demonstration Programme (grant 64012-0133 and 64020-2119), by the European Commission (Grant agreement ID: 864374, project ATELIER), by the Agence de l'Environnement et de la Maîtrise de l'Energie (ADEME) in France (grant number 1704C0022), by the Federal Ministry of Education and Research (BMBF) and the Federal Ministry for Economic Affairs and Climate Action (BMWK, the former Federal Ministry for Economic Affairs and Energy (BMWi)) in Germany, coordinated by the project management agency PTJ (project numbers 03SBE116C and 03ET1550A), by the University of Palermo - Department of Engineering, Italy, by the Research Centre for Zero Emission Neighbourhoods in Smart Cities (FME ZEN) funded by the Norwegian Research Council (project no. 257660), by the Junta de Andalucía (contract numbers 2019/TEP-130 and 2021/TEP-130) and the Universidad de Sevilla (contract numbers PP2019-12698 and PP2018-10115) in Spain, by the Swedish Energy Agency (grant number 46881-1), and by national grants and projects from Australia, Belgium, China, Finland, Hungary, India, The Netherlands, New Zealand, Portugal, Slovenia, South Korea, United Kingdom, and the United States of America.

Preface

This publication is an informal background report. It was developed as part of the international research activities within the context of IEA EBC Annex 72. Its contents complement the report "Context-specific assessment methods for life cycle-related environmental impacts caused by buildings" by Lützkendorf, Balouktsi and Frischknecht et al. (2023). The sole responsibility for the content lies with the author(s).

Together with this report, the following background reports have been published on the subject of "Assessing Life Cycle Related Environmental Impacts Caused by Buildings" (by Subtask 1 of IEA EBC Annex 72) and can be found in the official Annex 27 website (https://annex72.iea-ebc.org/):

- Survey on the use of national LCA-based assessment methods for buildings in selected countries (Balouktsi et al. 2023);
- Level of knowledge & application of LCA in design practice: results and recommendations based on surveys (Lützkendorf, Balouktsi, Röck, et al. 2023);
- Basics and recommendations on modelling of processes for transport, construction and deconstruction in building LCA (Soust-Verdaguer et al., 2023);
- Basics and recommendations on influence of service life of building components on replacement rates and LCA-based assessment results (Lasvaux et al., 2023);
- Basics and recommendations electricity mix models and their application in buildings LCA (Peuportier et al., 2023);
- Basics and recommendations on assessment of biomass-based products in building LCAs: the case of biogenic carbon (Saade et al., 2023);
- Basics and recommendations on influence of future climate change on prediction of operational energy consumption (Guarino et al., 2023);
- Basics and recommendations on discounting in LCA and consideration of external cost of GHG emissions (Szalay et al., 2023);
- Basics and recommendations in aggregation and communication of LCA-based building assessment results (Gomes et al., 2023);
- Documentation and analysis of existing LCA-based benchmarks for buildings in selected countries (Rasmussen et al., 2023);
- Rules for assessment and declaration of buildings with net-zero GHG-emissions: an international survey (Satola et al. 2023).

Summary

Mitigating greenhouse gas (GHG) emissions from buildings is important for combatting climate change because buildings are a major source of GHG emissions, which account for about 30% of global greenhouse gas emissions, and about 40% of energy-related GHG emissions. Different mitigation strategies and scenarios have been developed and implemented in the “energy” and “industry” (including the construction product industry) sectors. This allows us to explore different pathways for the development of future energy supplies, their greenhouse gas emissions, as well as the influences on future manufacturing of building components and construction products. Such scenarios are also of great importance when a transition from static to dynamic life cycle assessment (LCA) of buildings is made throughout their service lives. In particular, the consideration of these scenarios would impose consequences in the life cycle stages (as defined in *EN 15804 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products*) including module A1 (product stage - raw material supply) and A3 (product stage - manufacturing) for future new buildings, B4 (use stage - replacement) and B6 (use stage - operational energy use) for both existing and new buildings.

While in the field of energy supply, the possibilities and consequences of decarbonization strategies are being discussed and partly taken into account in the building LCAs in selected countries, corresponding discussions and implementation considering the manufacturing of building components and construction products are still in their infancy. It is necessary to make a transition by including these scenario-based dynamic considerations both on the side of operational and embodied impacts. More importantly, scenarios used to derive these considerations should have a complete global coverage, addressing consistency for both energy systems and underline assumptions between individual countries and regions.

This background report takes an example of considering future electricity supplies based on global Integrated Assessment Models, and discusses the impact of this consideration in building LCAs from both operational and embodied impact perspectives in terms of life cycle greenhouse gas emissions. These considerations are incorporated into the Swiss national building LCA database KBOB. Materials and regional electricity supplies with high emission reduction potentials are identified given different scenarios. In the end, based on this experience, recommendations are made to future national database development that can better accommodate such considerations, and the needs for future research are discussed.

Table of content

Abbreviations

Abbreviations	Meaning
CO_2 eq.	CO_2 equivalents
BIPV	Building Integrated Photovoltaics
DQR	Data Quality Requirement
EPD	Environmental Product Declaration
GHG	Greenhouse Gas Emission
IAM	Integrated Assessment Model
IEA	International Energy Agency
KBOB	Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren
kWh	kilowatt hours
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
NDC	Nationally Determined Contributions
PIK	Postdam Institute for Climate Impact Research
PV	Photovoltaics
PVC	Polyvinyl Chloride
REMIND	REgional Model of Investment and Development

1. Introduction

Life cycle assessment (LCA) has been well applied to assess the environmental performances of buildings comprehensively considering all life cycle stages, including the manufacturing of construction products, energy and water required for construction, maintenance, and replacement, the end-of-life treatment and disposal of materials as well as the operation of the building. However, uncertainties in these assessments inherently exist due to the complex supply chain upstream in product manufacturing, unpredictable service life of buildings, building components and materials, variability of electricity supplies, which are often not addressed in most of the deterministic building LCAs (Pomponi et al., 2017). Among these uncertainties, the uncertainties of electricity supplies play in particular an important role, and mainly influence building LCAs due to the energy consumption during the operation of buildings: for example, the mix of electricity supply may vary depending on the time of the consumption, the electricity system transition and potential improvement of generation technologies in the future. It also influences the manufacturing of construction components and products required for the construction as well as the retrofit of buildings, and the infrastructures for the generation of electricity.

Electricity supplies in the future are especially important for building LCA primarily because of their essential role in the transition and decarbonization of the global energy system. Electricity, among other energy supplies, is the supply that experiences the fastest decarbonization in recent decades, partly due to the deep cost reduction of renewable electricity generation, as well as the urgency of halving the greenhouse gas emissions in the next 10 years, and ultimately reaching net-zero global greenhouse gas emissions by 2050 or before in order to keep the global warming to well below 2ºC compared to pre-industrial levels.

To understand the influence of future electricity supplies and their impacts on the LCA of buildings, this work will focus on research that answers the following 3 questions (Figure 1):

1. What would be the change of future electricity carbon intensity caused by the transition of electricity system in the future (e.g. based on different energy scenarios, mix of electricity generation technologies) and technology improvement (e.g. efficiency improvement and resulted emissions reduction)?
2. How much will embodied emissions of construction materials change due to the change of carbon intensity of electricity supplies?
3. How uncertain could be the decarbonization of future electricity system, and what influence it would have on the carbon emissions of major construction material supplies in the future?

Note that this study mainly focuses on the effect of future electricity supplies on the embodied emissions of construction materials, while another dedicated subtask (Subtask 1, Activity 1.3) within IEA EBC Annex 72 has focused on the variability and uncertainty of current and future electricity supplies during the operation stage of buildings (see: Peuportier et al., 2023).

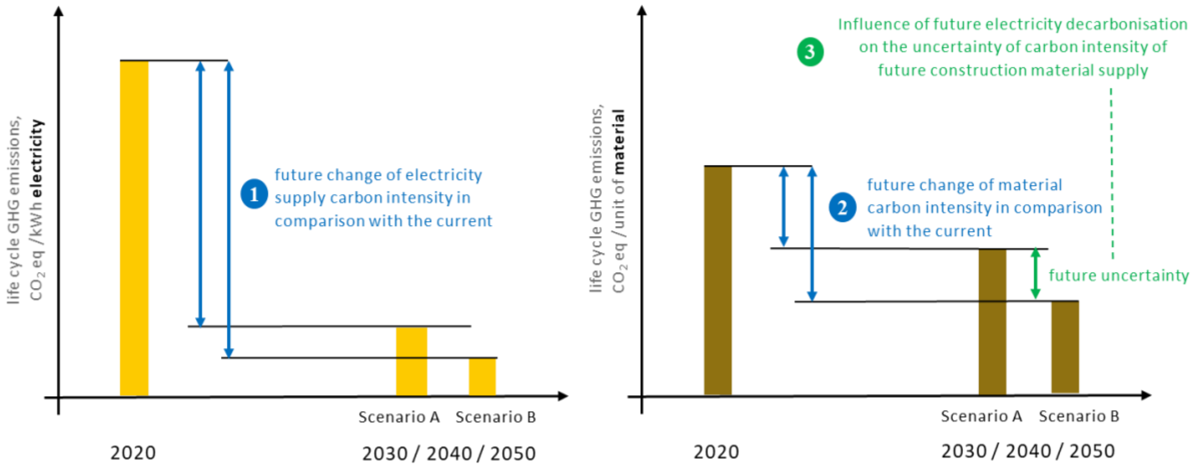


Figure 1: Illustration of the questions of interest in this analysis; "life cycle GHG emissions" are calculated from non-aggregated unit process datasets and LCA including not only the product stage (A1-A3) but also the end-of-life disposal and treatment phase (C3-C4). For electricity supply, the transmission and distribution of electricity is also included.

1.1 Scope of Work

The work will start with a literature review that gives an overview of how the uncertainty of electricity supplies have been addressed in the past literature and practices in building LCA. This will be followed by an analysis of relevant datasets in the latest KBOB (Coordination Group for Construction and Property Services; in German: Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren) database. LCI data from KBOB 2016 (KBOB, 2016) will be the basis of the analysis, because in comparison to other available databases which are a mix of LCA results from EPDs (Environmental Product Declaration) and datasets from generic LCA databases (eg. ecoinvent, Gabi), it transparently provides detailed inventory data on the unit process level which allows the scoped analysis. Next, similar to the approach applied in (Cox et al., 2018)(Mendoza Beltran, Cox, Mutel, Vuuren, et al., 2018), an IAM (Integrated Assessment Model) (Pauliuk et al., 2017) REMIND (Postdam Institute for Climate Impact Research (PIK), n.d.) is applied to construct future background database used in KBOB 2016, in order to account for the transition of electricity supply mix and power plant technology advancements in the future. The influence of these transitions will be investigated for the manufacturing of major materials used in buildings and infrastructures, with a focus on life cycle greenhouse gas emissions (GHG). Finally, based on the conclusions drawn from this work, recommendations will be provided on how the uncertainties of life cycle greenhouse gas emissions caused by future electricity supplies shall be addressed in building LCAs. This will be complemented by a recommendation on the requirement of data and tools that support such analysis in the future.

1.2 Literature Review

Depending on the region where the buildings are located and where the construction products or components are manufactured, electricity supply and its GHG intensity could play a key role in the life cycle GHG emissions of buildings (Negishi et al., 2018). The long service life of buildings (i.e. 40 to more than 100 years) indicates the importance of taking future electricity supplies into account. However, this issue is only addressed to a limited extent in the LCA of buildings, mostly focusing on its influence on the environmental impacts of the building operation phase (Ramon & Allacker, 2021), some incorporated high resolution of the temporal electricity mix (Roux et al., 2016)(Kiss et al., 2020), while its influence on building materials production is rarely discussed. Alig et al. 2020 (Alig et al., 2020) is the only study that has addressed this issue, focusing on analyzing the future primary production of construction materials supplied in Switzerland, and their influence of two selected buildings in terms of life cycle cumulated energy demand and greenhouse gas emissions. The study has not only considered future electricity supplies, but also transportation and specific manufacturing process improvements and mitigation measures (eg. carbon capture and storage). For the future electricity supplies, the study has compiled a future scenario representing the time horizon from 2030 to 2050, with information obtained from the Swiss energy perspective 2050 published in 2012, World Energy Outlook in 2018 and Sustainable Development scenario published by the IEA in 2018.

The study in this report has a narrower scope, however, focusing on the influence of future electricity supplies only, but takes into account the future electricity supplies from an IAM at different time horizons (i.e. 2030, 2040, 2050), which ensures the consistency of energy supplies between the regions. The study focuses on investigating the influence of future electricity on the life cycle GHG emissions of buildings in from two perspectives: through the electricity supply during the operation of buildings (section 5.1), and through the electricity supply in building material and component manufacturing (section 5.2).

2. Methodology

Consistent and transparent modification of electricity production datasets in the background database is required to reflect the future development of electricity systems, thus an open-source advanced LCA analytical tool Brightway 2 (Mutel, 2017) is used to support this analysis.

To investigate the impact of the future electricity system development on building life cycle LCA and associated uncertainties, the KBOB list LCA Data 2016 is linked with a prospective background database built based on ecoinvent v3.6, in which electricity production and market (i.e. mix of supply) datasets are modified based on scenarios from the Integrated Assessment Model (IAM) REMIND (Postdam Institute for Climate Impact Research (PIK), n.d.)(Sacchi, n.d.). In order to analyze the influence of future electricity systems on the life cycle environmental impact of construction materials, future scenarios from an IAM (Mendoza Beltran, Cox, Mutel, van Vuuren, et al., 2018) are incorporated, and unit process datasets in the KBOB list data (Frischknecht, 2016) are analyzed. Due to the required systematic changes, analysis has to be performed on the unit process level rather than the static LCIA results (i.e. carbon emissions, primary energy, ecoscarcity points) originally published by KBOB (i.e. KBOB Recommendation 2009/1:2016; as “KBOB LCIA results” hereafter) (Plattform Ökobilanzdaten im Baubereich & Fachgruppe Ökobilanzdaten im Baubereich, 2016), which is what often being used in building LCAs. The relationship between the KBOB list LCA data, published KBOB LCIA results, KBOB LCA database DQR v2: 2016 and ecoinvent databases are illustrated in **Error! Reference source not found.** (on top).

Analysis in this study however cannot be performed to the original KBOB LCA database DQR v2: 2016, as the datasets in the original linked background database are not parameterized (i.e. parameters used in unit process dataset inventory derivation are provided as a feature in the dataset). Thus the background database used in the original KBOB database is migrated into ecoinvent v3.6 to allow the analysis required by this study. This migration results in exclusion of certain sector updates incorporated in KBOB LCA database DQR v2: 2016 in this analysis, which are partially different from what has been updated throughout the ecoinvent releases from version 3+.

In addition, due to the lack of unit process datasets for some material production and disposal processes, 20 (out of 256 materials in total) of such affected materials are excluded from this analysis. A list of all the construction materials in the KBOB database, and whether they are included for this analysis can be found in Appendix A.

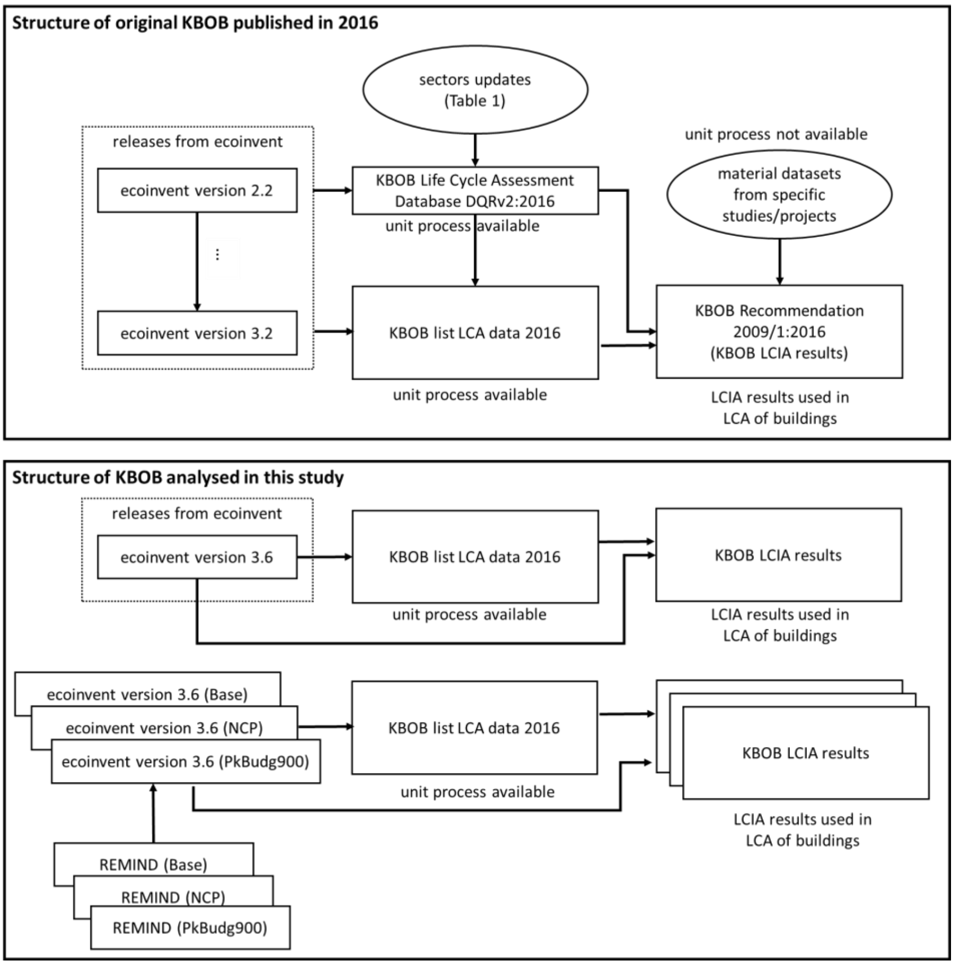


Figure 2: Structure of original KBOB LCA database DQR v2 and list LCA data published in 2016 and analyzed in this study

After linking KBOB with ecoinvent 3.6, future versions of ecoinvent are created using the open-source tool rmnd-lca version 0.0.9 (Sacchi, 2020), with 3 scenarios (CD-Links, 2017) from REMIND IAM (Aboumahboub et al., 2020) :

1. **Base,** which represents counter-factual scenario with no climate policy implemented;
2. **Nationally Determined Contributions (NDC) scenario**, in which emission reductions and other mitigation commitments of the nationally determined contributions under the Paris Agreement are implemented;
3. **PkBudget 900 scenario**, in which climate policies to limit cumulative CO2 emissions to 900 gigatons in the time horizon of 2011-2100. It corresponds to a global temperature of 1.5° increase target.

The analysis is performed in three reference years: 2030, 2040 and 2050. The future versions of ecoinvent were created by taking the assumptions of electricity mix as well as the improved electricity production efficiency and resulted decrease of direct emissions from the REMIND IAM in the future. The influence of future electricity systems on construction material is discussed in section 3.2.

3. Results and Discussion

3.1 Future Electricity Supplies During Building Operation

Since buildings are mostly supplied by distribution network, the following results are focused on the low voltage electricity supplies.

shows the GHG emissions for low-voltage electricity supplies by country in current ecoinvent v3.6. Some general regional supplies (such as global, European, rest of the world, etc.) are excluded in this figure as they overlap with the country-specific values. It shows that most of the countries in the world have a grid GHG emissions of less than 1.5 kg CO_2 eq/kWh. Although there are a few outlier countries that exhibit higher emissions (eg. Haiti, Iraq), due to the higher losses of electricity transmission and distribution or not state-of-the-art electricity generation technologies, these countries don't play a key role in the global supply chain of construction materials and their supplies of electricity to buildings are not the focus of this study.

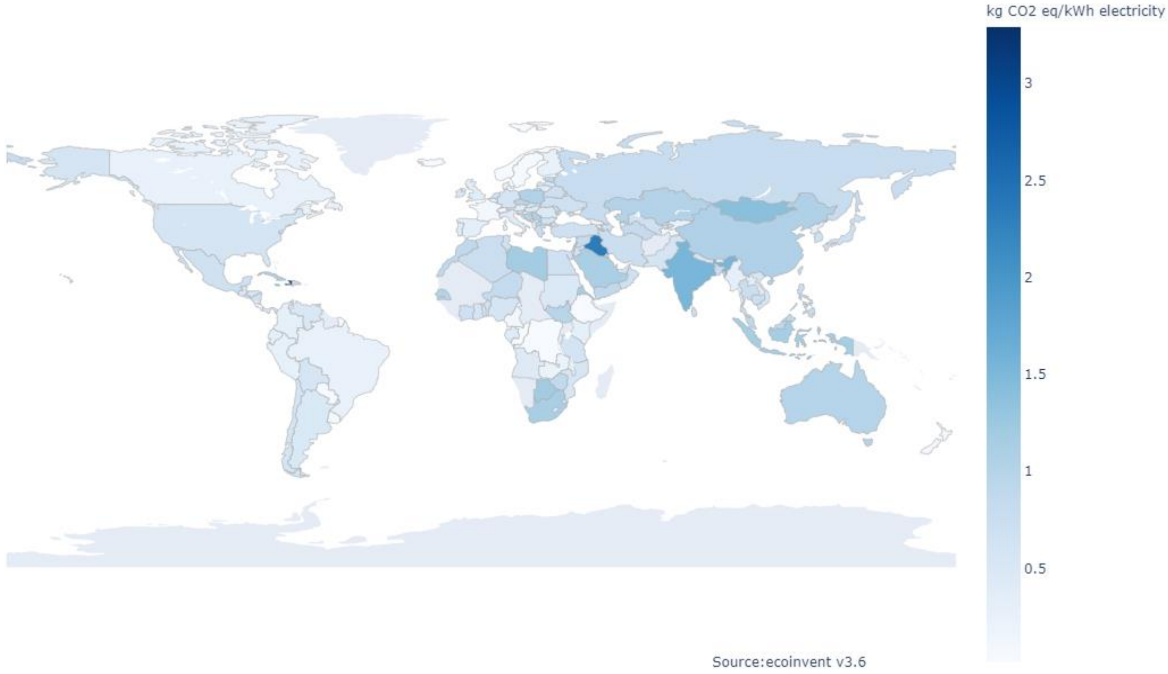


Figure 3: Life cycle GHG emissions per kWh of low-voltage electricity supply current ecoinvent v3.6, in kg CO_2 eq/kWh. An interactive version of this figure is available online at: https://plotly.com/~xiaoshir/98/ (Complete table with values for constructing this figure can be downloaded following the link for interactive plot -> data.)

Due to energy transition and technology advancement, the future electricity system will have lower GHG emissions thanks to more generation of renewable electricity and higher efficiency in production technologies. **Error! Reference source not found.** shows the life cycle GHG emissions per kWh of low-voltage electricity supply in the future versions of ecoinvent v3.6 using REMIND scenarios in 2035 and 2050. First, due to the less granularity of geographic definition in REMIND, it can be seen that the results in future background databases are mostly for regions rather than for specific countries as shown in the current ecoinvent v3.6 (

): REMIND has divided the world into 13 geographic regions (Appendix B). Second, by incorporating future scenarios, lower emissions can be observed for low-voltage electricity supply, of up to around 0.6 kg CO_2 eq per kWh world-wide in the Base scenario, and up to 0.3 and 0.05 kg CO_2 eq per kWh in the NCP and the Pkbudg900 scenario respectively. The Pkbudg900 scenario is in particular ambitious as it means most of the world has to be powered by renewable electricity, nuclear power and/or power generation with fossil fuels and carbon capture and storage technologies.[1] This also means that according to the Pkbudg900 scenario, to reach a global temperature increase of 1.5°, some countries will have to decarbonize their electricity system to a tremendous extent to up to 20 times (eg. China, 1.000 g CO2 eq/kWh in current ecoinvent v3.6, vs. 230 g CO2 eq/kWh in NDC scenario and 50 g CO2 eq/kWh in Pkbudg900 scenario by 2050), which would be influential to the life cycle GHG emissions during operation of buildings in those countries.

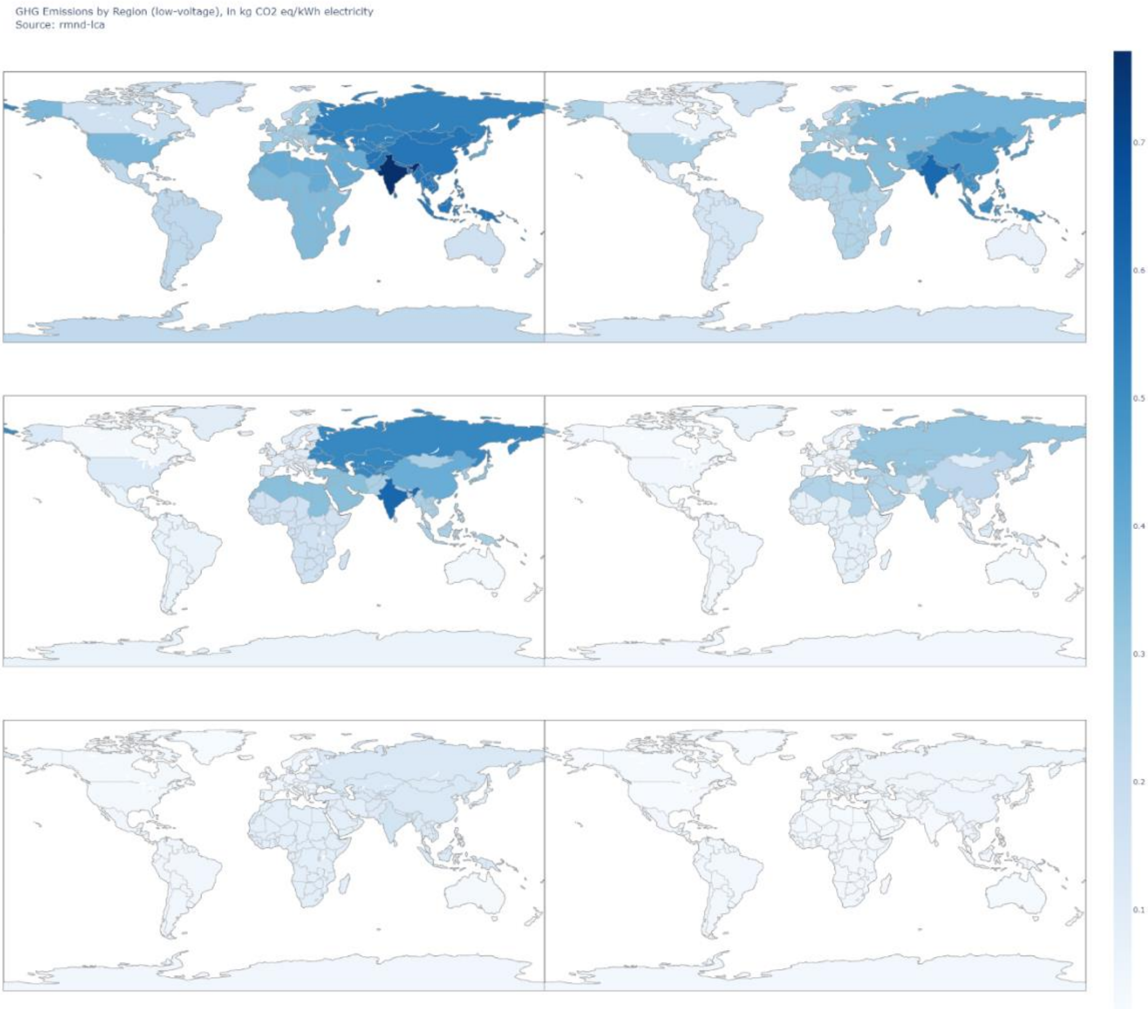
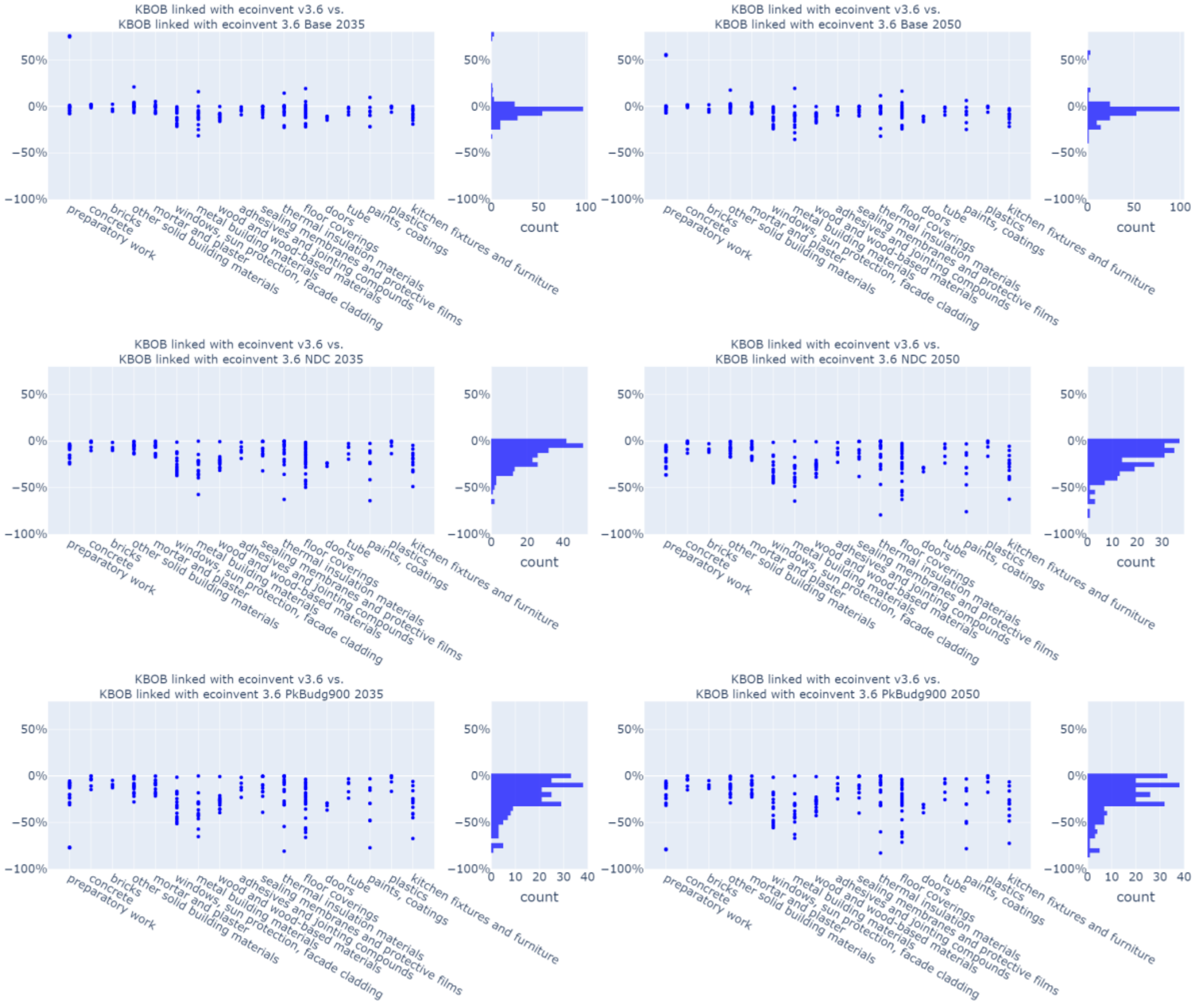


Figure 4: Life cycle GHG emissions per kWh of low-voltage electricity supply in the future, in kg CO_2 eq/kWh. Top: Base scenarios; middle: NCP scenarios; bottom: Pkbudg900 scenarios. left: reference year 2030; right: reference year 2050. An interactive version of this figure is available online at: https://chart-studio.plotly.com/~xiaoshir/152/ (Complete table with values for constructing this figure can be downloaded following the link for interactive plot -> data.)

3.2 Influence of Future Electricity System on Selected Construction Materials and Components

The percentage of life cycle GHG emissions difference is calculated for each material in the KBOB database linked with future versions of ecoinvent (future KBOB) in comparison with current KBOB database linked with ecoinvent v3.6 (current KBOB; as thereafter), as shown in



. The formula applied to calculate the difference is as follows:

$$D_m = \frac{LG_{current\ KBOB,\ m} - LG_{future\ KBOB,\ m}}{LG_{current\ KBOB,\ m}}$$

in which,
D: difference in percentage
LG: life cycle GHG emissions for unit amount of material;
m: material

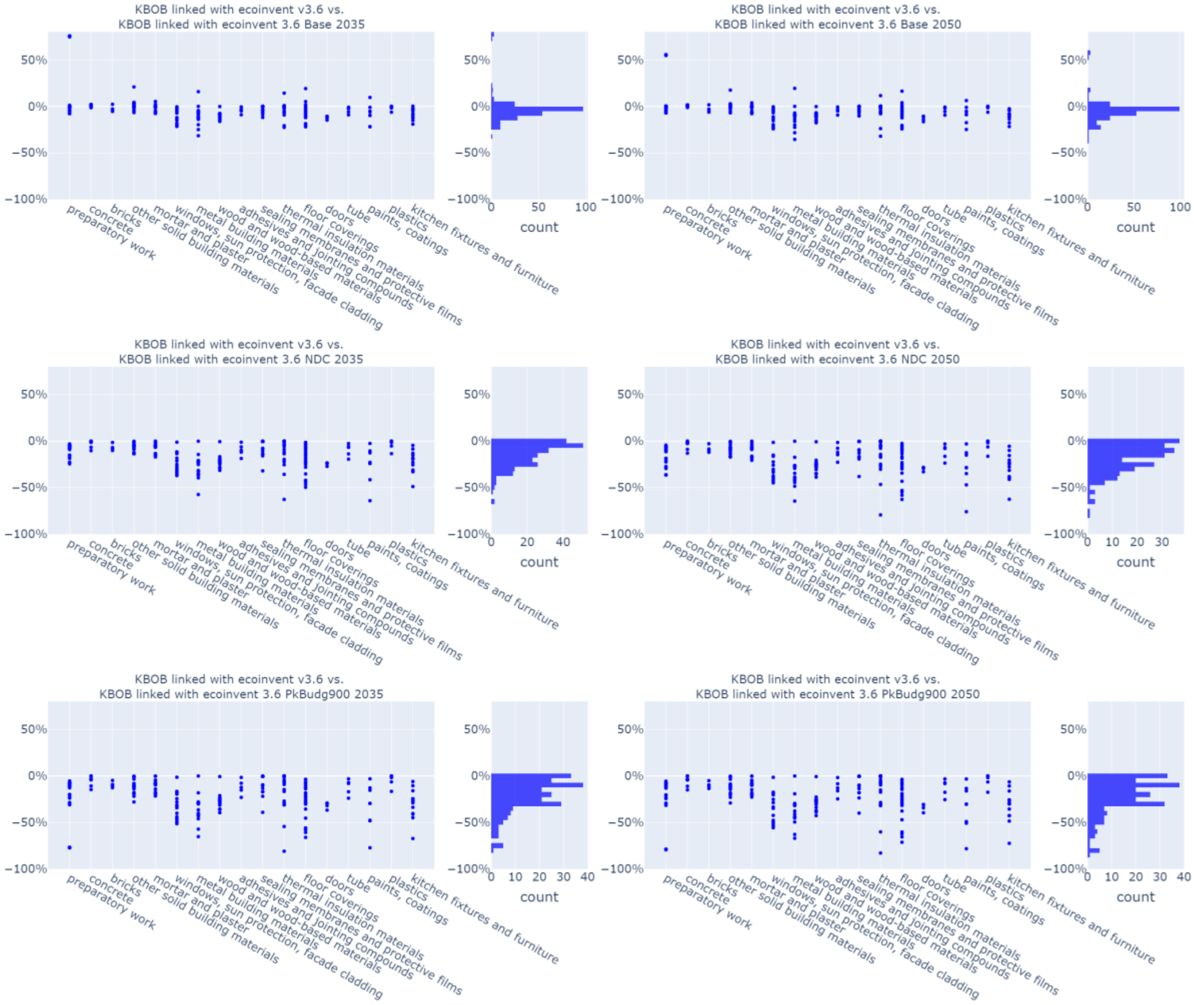


Figure 5: Percentage difference in climate change LCIA results: between KBOB linked with ecoinvent v3.6 and the ecoinvent integrated with future scenarios of IAM; each point in the figure represents the percentage difference between current and future KBOB in terms of life cycle GHG emissions, which is calculated based on the formula above; from top to bottom: Base-, NCP-, and PkBudg900- scenario; years from left to right: 2035 and 2050. An interactive version of this figure is available online at: https://plotly.com/~xiaoshir/156/, with correspondence between each scatter point and specific material. (Complete table with values for constructing this figure can be downloaded following the link for interactive plot -> data.)

As expected, most materials show reduced GHG emissions in both 2035 and 2050 regardless of the scenarios, because the electricity supplies in most of countries have lower GHG emissions (**Error! Reference source not found.**) than the current supplies in ecoinvent v3.6 (
). In Base scenarios, the range of difference for most of the materials fall into a range of -20% to 5%, while with the NCP and Pkbudg900 scenarios, few materials could achieve much higher GHG reductions of up to around 80%. Four data points under the category of preparation work (in German: "Vorbereitungsarbeiten", very close to each other on top) in the Base scenarios show more than 50% higher emissions than in the current KBOB database (i.e. linked with ecoinvent v3.6). Similarly, in the Pkbudg900scenario, when the GHG emissions of Swiss electricity supply is reduced to about 21-23 g CO_2 eq/kWh in 2035 and 2050 (low-voltage), the emissions of these processes could be greatly reduced by about 80% accordingly.

Besides the dewatering process in the preparation work, other processes and materials also exhibit different extent of sensitivity to the future transition of electricity system. Materials from six sectors exhibit greater reduction in GHG emissions of more than 50% in the NDC scenario in 2050 as well as the Pkbudg900 in both 2035 and 2050: namely windows, sun protection, facade cladding (in German: “Fenster”, “Sonnenschutz”, “Fassadenverkleidungen”), metal construction materials (in German “Metalbaustoffe”), thermal insulation materials (in German “Wärmedämmstoffe”), floor coverings (in German “Bodenbeläge”), paints and coatings (un German “Antrichstoffe”, “Beschichtungen”) and kitchen fittings and furniture (in German “Kücheneinbauten und –möbel”). In the category of floor coverings, kitchen fittings and furniture, the high emission reduction potential are all related to natural stone materials. This is rather expected, as electricity is a major GHG emission contributor in natural stone cutting process. In paints and coatings, the great GHG emission reduction potential is led by one process named “enamelling”, which is electricity-intensive (14 kWh/m^2) to manufacture.

Since not all the materials/element/process as shown above will be needed in buildings with significant amount, the following section will zoom into a selection of specific materials, which are split into two groups: major materials for future new construction and renovation of buildings respectively (**Error! Reference source not found.**).

Table 1: List of major materials/components for future new construction and renovation.

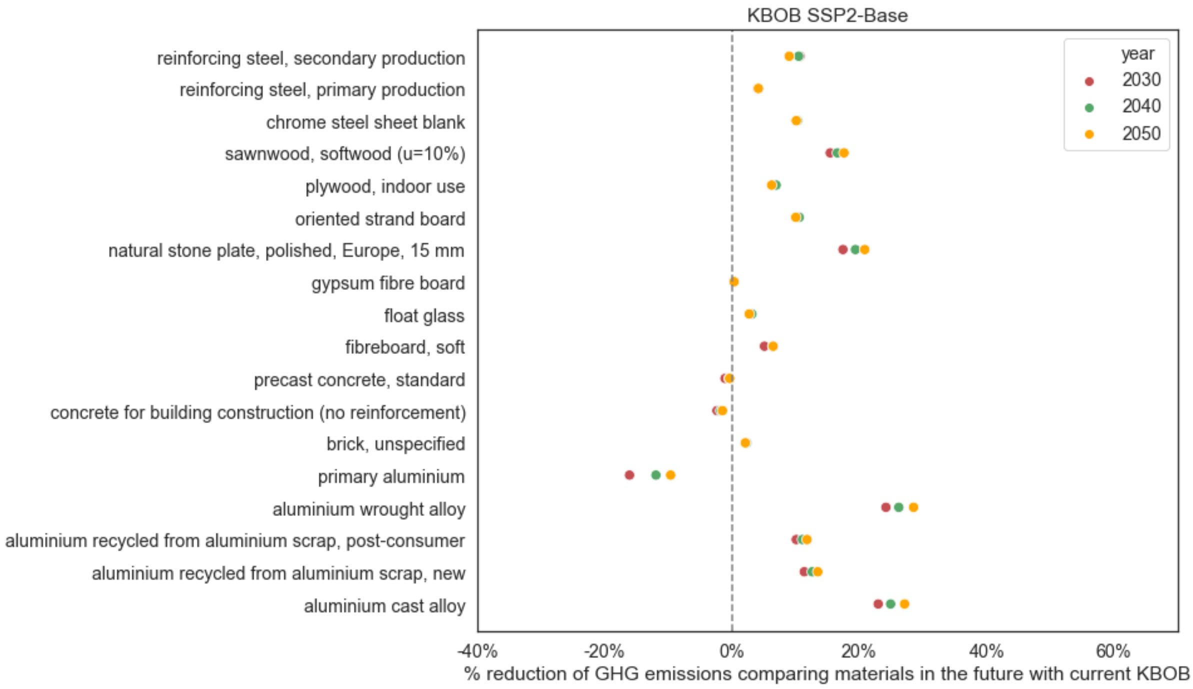
Future new construction	**Future renovation and replacement of building components**
1. Cement and Concrete	1. Windows with frames made from:
2. Steel, reinforcing	– wood
3. Steel, stainless	– PVC
4. Brick	– wood-aluminium
5. Aluminium	– aluminium
6. Float glass	2. Insulation materials:
7. Softwood, solid	– rock wool
8. Plywood, softwood	– foam glass
9. Oriented strand board (OSB) panel	3. PV systems
10. Fibreboard, soft	4. Cement mortar
11. Natural stones	

* glass wool and gypsum fibreboard had to be excluded despite being a major insulation material, because they are represented by aggregated datasets (i.e. dataset consisting of cumulated elementary flows, directly exchanged with the environment) in KBOB, whose LCIA score cannot be affected by the change of electricity system in the background database as performed in this analysis.

The percentage reductions of life cycle GHG emissions for major materials/components in new construction are shown in **Error! Reference source not found.**, while the absolute life cycle GHG emissions for each listed item in both current KBOB linked with ecoinvent v3.6 and future ecoinvent versions will be included in Appendix C.

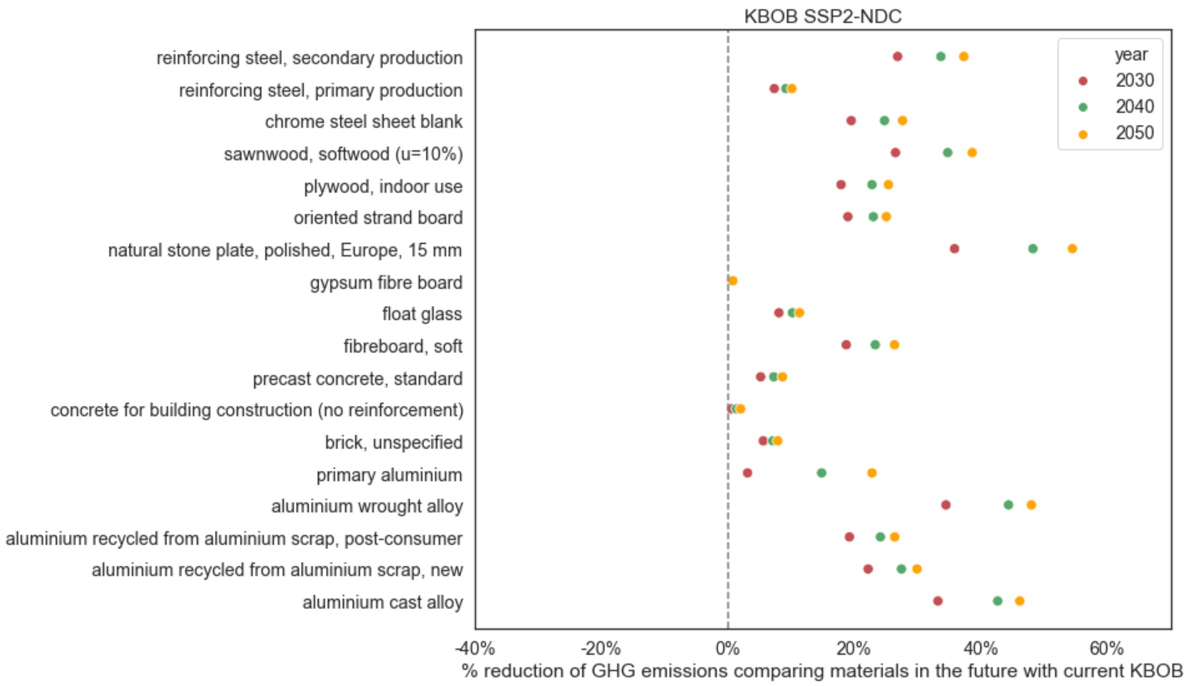
Overall, in the Base scenario, increased emissions in the future have been observed for primary aluminium, and slightly for concretes. This is caused by the phase out of nuclear power in selected countries and the continuously increased share of fossil fuels in the power generation sector in the rest part of world. Since the future electricity mix from the IAM model is region-specific and not sector-specific (eg. specific to aluminium industry), so the electricity supply for primary aluminium production is only determined by the region, which is a limitation of the method. In the most climate-ambitious scenario (PdBudg900), the percentage of emissions reduction in 2040 is very close to 2050, which shows that if the world would follow an ambitious path towards power decarbonization, the resulted emission reductions can be mostly achieved by 2030 for most of materials, indicating the vital role of progress in the next 10 years.

a)



KBOB SSP2-Base
year
2030
2040
2050
reinforcing steel, secondary production
reinforcing steel, primary production
chrome steel sheet blank
sawnwood, softwood (u=10%)
plywood, indoor use
oriented strand board
natural stone plate, polished, Europe, 15 mm
gypsum fibre board
float glass
fibreboard, soft
precast concrete, standard
concrete for building construction (no reinforcement)
brick, unspecified
primary aluminium
aluminium wrought alloy
aluminium recycled from aluminium scrap, post-consumer
aluminium recycled from aluminium scrap, new
aluminium cast alloy
-40%
-20%
0%
20%
40%
60%
% reduction of GHG emissions comparing materials in the future with current KBOB

b)



KBOB SSP2-NDC
year
2030
2040
2050
reinforcing steel, secondary production
reinforcing steel, primary production
chrome steel sheet blank
sawnwood, softwood (u=10%)
plywood, indoor use
oriented strand board
natural stone plate, polished, Europe, 15 mm
gypsum fibre board
float glass
fibreboard, soft
precast concrete, standard
concrete for building construction (no reinforcement)
brick, unspecified
primary aluminium
aluminium wrought alloy
aluminium recycled from aluminium scrap, post-consumer
aluminium recycled from aluminium scrap, new
aluminium cast alloy
-40%
-20%
0%
20%
40%
60%
% reduction of GHG emissions comparing materials in the future with current KBOB

c)

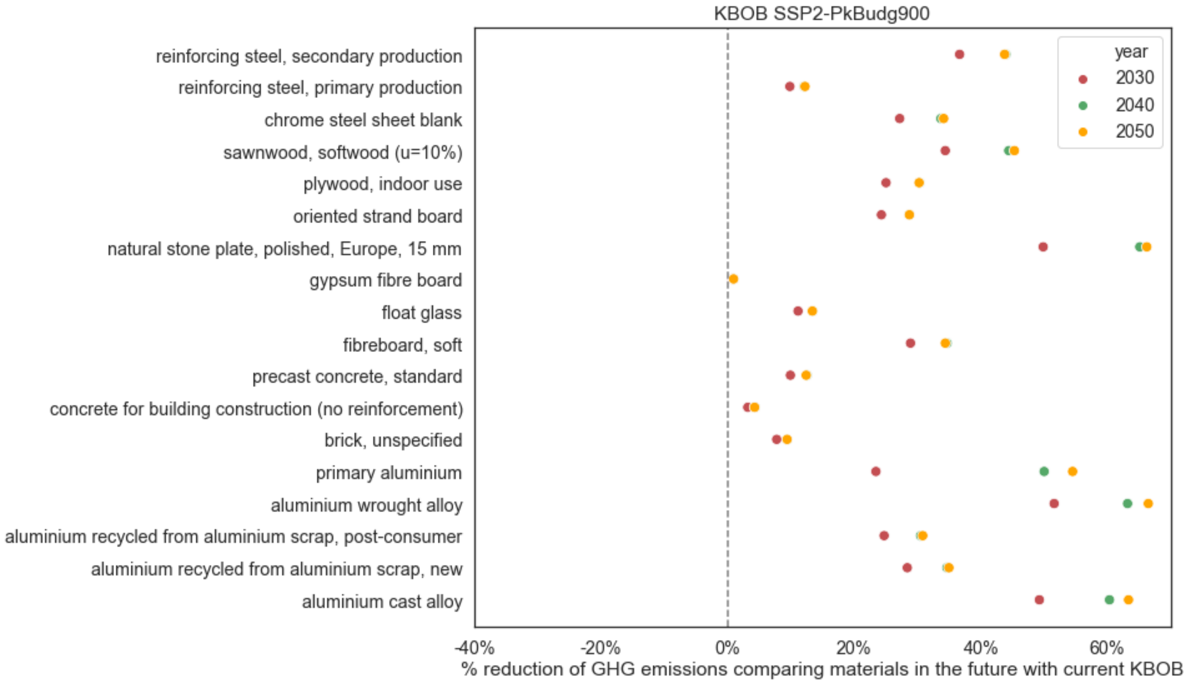


Figure 6: Percentage reduction of life cycle GHG emissions for major materials in new construction in different scenarios

In the scenario of PdBudg900, the highest future emission reduction potentials of up to more than 60% have been observed in natural stone and aluminium alloys (i.e. wrought- and cast- alloy). This is followed by sawnwood, secondary reinforcing steel and primary aluminium, which exhibit up to 40% to 60% of future emission reduction potential.

Comparing recycled steel (i.e. secondary reinforcing steel) and aluminium with their primary production, it shows that secondary reinforcing steel has much higher future emission reduction potential (i.e. in terms of percentage of emission reduction) than its primary material, whereas the GHG reduction potential for recycled aluminium is slightly lower than that of primary aluminium (**Error! Reference source not found.**). This is due to the contribution of electricity consumption in overall life cycle GHG emissions (11%) for primary steel being much lower than its contribution in the life cycle GHG emissions of secondary steel, secondary aluminium (27%-31%) and primary aluminium (44%). This also shows that a higher amount of life cycle electricity consumption alone does not indicate higher emissions reduction potential in the future, but the contribution of electricity consumption in the life cycle GHG emissions also matter.

It is also interesting that the percentage of emission reduction potential for primary aluminium is lower than that of aluminium alloys, although it has higher cumulative electricity consumption than aluminium alloys on a kilogram basis (Similarly, the percentage reduction of life cycle GHG emissions for major materials/components in retrofitted buildings are shown in **Error! Reference source not found.**. Solar PV systems exhibit the highest GHG emissions reduction potential, of up to more than 60%, led by mono-silicon PV system among the selected PV technologies. This is due to the electricity-intensive manufacturing processes upstream, such as the purification of metallurgical grade silicon to solar-grade silicon. However, due to the fast increase of manufacturing and installed capacity of solar PV systems worldwide, the upstream supply chain processes have been constantly improving (e.g., less electricity consumption in solar-grade silicon production, less material waste as a result of improved wafer sawing process and greater cell size), which is partly not considered in the dataset used for this analysis (e.g. the state-of-art electricity consumption manufacturing solar-grade silicon from metallurgical grade silicon by key players in China is about 70 kWh/kg of solar-grade silicon production (China Photovoltaic Industry Association, 2020), whereas the dataset used in this analysis assumes 110 kWh/kg). Thus, the actual emission reduction potential of solar PV systems in the future is believed to be lower than projected in this analysis, given that only the influence of the future electricity system is considered.

Table 3: Cumulative electricity consumption by material/component

Sector	Construction material-English	Unit	electricity supply
Aluminium	aluminium cast alloy	kg	4.78
	aluminium recycled from aluminium scrap, new	kg	0.46
	aluminium recycled from aluminium scrap, post-consumer	kg	0.57
	aluminium wrought alloy	kg	11.86
	primary aluminium	kg	17.34
Brick	brick, unspecified	kg	0.06
Concrete	concrete for building construction (no reinforcement)	kg	0.02
	precast concrete, standard	kg	0.09
Fibreboard, soft	fibreboard, soft	kg	0.67
Float glass	float glass	kg	0.39
Gypsum panel	gypsum fibre board	kg	0.01
Natural stones	natural stone plate, polished, Europe, 15 mm	m2	37.52
Oriented strand board (C	oriented strand board	kg	0.40
Plywood, softwood	plywood, indoor use	kg	0.72
Softwood, solid	sawnwood, softwood (u=10%)	kg	0.18
Stainless steel	chrome steel sheet blank	kg	1.98
Steel, reinforcing	reinforcing steel, primary production	kg	0.55
	reinforcing steel, secondary production	kg	0.76

This is because the 66% of the life cycle electricity supply for aluminium alloys are from China, where a great GHG emission reduction potential is expected for the electricity grid supply, whereas for primary aluminium, the percentage of electricity supply from Iceland and Norway remains dominant, where the potential of future grid emission reduction is relatively low. Recycled aluminium, stainless steel, plywood and fibreboard are materials among the third highest level of emission reduction potential, of up to 20% to 40%.

Table 2: Comparison between primary and secondary aluminium and steel

	Life cycle electricity consumption (kWh/kg)	% GHG reduction potential by 2050 (PkBudg900 2050)	Absolute GHG emissions (kg CO2 eq/kg), KBOB linked with ecoinvent v3.6	Absolute GHG emissions (kg CO2 eq/kg), KBOB linked with ecoinvent v3.6 modified with SSP2 PkBudg900 2050
Aluminium, primary	16.6	41%	7.3	4.3

Aluminium, recycled from scrap*	0.5-0.6	31%-35%	0.6-0.9	0.4-0.6
Reinforcement steel, primary	0.6	12%	2.2	1.9
Reinforcement steel, recycled	0.8	44%	0.71	0.4

* range reflecting value ranges considering aluminium recycled from both post-consumer and new scrap.

As expected, concrete is the material with the least emission reduction potential, since only the decarbonized electricity system in the future is incorporated in this analysis, whereas the majority of emissions in concrete is contributed by process emissions and combustion of fuels from clinker production (Habert et al., 2020), regardless of the type of cement used and different mixtures in concrete production. Precast concretes have slightly higher reduction potential due to four times higher life cycle electricity consumption than standard (Similarly, the percentage reduction of life cycle GHG emissions for major materials/components in retrofitted buildings are shown in **Error! Reference source not found.**. Solar PV systems exhibit the highest GHG emissions reduction potential, of up to more than 60%, led by mono-silicon PV system among the selected PV technologies. This is due to the electricity-intensive manufacturing processes upstream, such as the purification of metallurgical grade silicon to solar-grade silicon. However, due to the fast increase of manufacturing and installed capacity of solar PV systems worldwide, the upstream supply chain processes have been constantly improving (e.g., less electricity consumption in solar-grade silicon production, less material waste as a result of improved wafer sawing process and greater cell size), which is partly not considered in the dataset used for this analysis (e.g. the state-of-art electricity consumption manufacturing solar-grade silicon from metallurgical grade silicon by key players in China is about 70 kWh/kg of solar-grade silicon production (China Photovoltaic Industry Association, 2020), whereas the dataset used in this analysis assumes 110 kWh/kg). Thus, the actual emission reduction potential of solar PV systems in the future is believed to be lower than projected in this analysis, given that only the influence of the future electricity system is considered.

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Despite 45 kWh of electricity consumption is required per cubic meter of precast concrete, its emissions reduction potential (in percentage of current emissions) is relatively low in comparison with other materials, as the main contributor to its life cycle GHG emissions is not electricity consumption (partially also due to the electricity supply from Switzerland, where the carbon intensity of grid supply is low, thanks to great share of hydropower and nuclear power), but rather the consumption of cement and reinforcing steel.

Similarly, the percentage reduction of life cycle GHG emissions for major materials/components in retrofitted buildings are shown in **Error! Reference source not found.**. Solar PV systems exhibit the highest GHG emissions reduction potential, of up to more than 60%, led by mono-silicon PV system among the selected PV technologies. This is due to the electricity-intensive manufacturing processes upstream, such as the purification of metallurgical grade silicon to solar-grade silicon. However, due to the fast increase of manufacturing and installed capacity of solar PV systems worldwide, the upstream supply chain processes have been constantly improving (e.g., less electricity consumption in solar-grade silicon production, less material waste as a result of improved wafer sawing process and greater cell size), which is partly not considered in the dataset used for this analysis (e.g. the state-of-art electricity consumption manufacturing solar-grade silicon from metallurgical grade silicon by key players in China is about 70 kWh/kg of solar-grade silicon production (China Photovoltaic Industry Association, 2020), whereas the dataset used in this analysis assumes 110 kWh/kg). Thus, the actual emission reduction potential of solar PV systems in the future is believed to be lower than projected in this analysis, given that only the influence of the future electricity system is considered.

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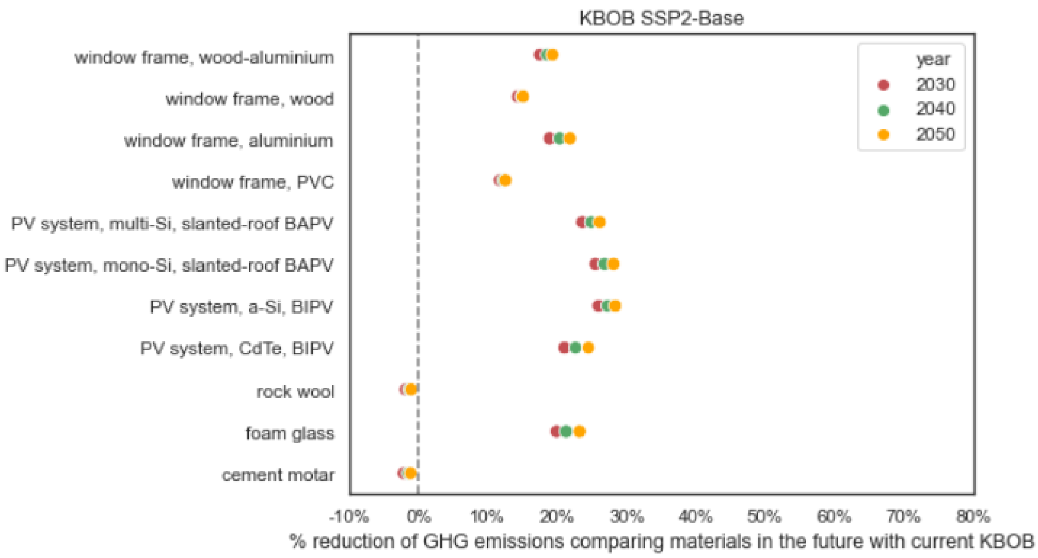
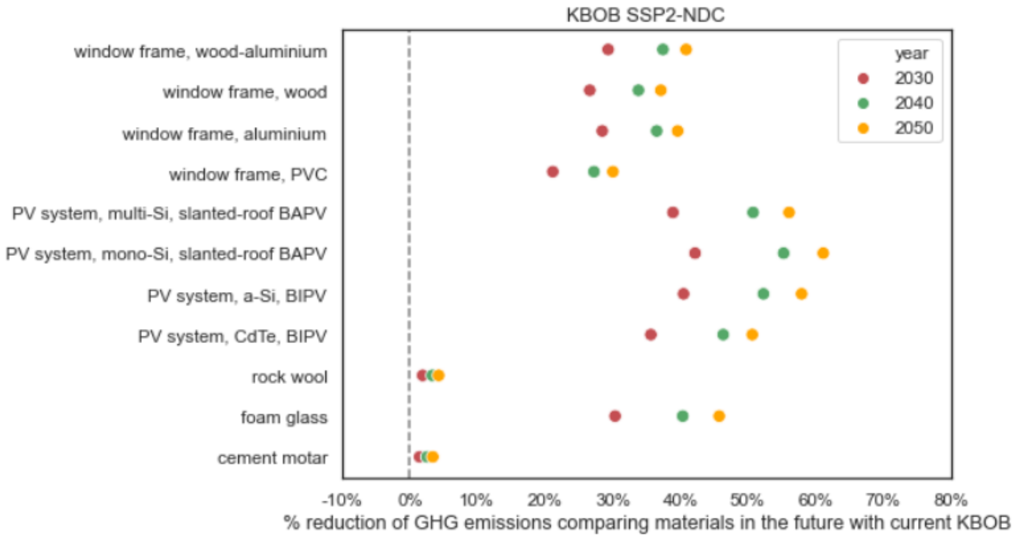
Steel, reinforcing	reinforcing steel, primary production	kg	0.55
	reinforcing steel, secondary production	kg	0.76

Insulation material foam glass is also shown to have high emission reduction potential of up to more than 60%, due to its high electricity consumption of 1.5 kWh/kg in comparison with only 0.2 kWh/kg of electricity consumption in rock wool production. This is closely followed by different types of window frames, especially the one with the consumption of aluminium, due to reasons explained above for aluminium cast alloy.

a)



b)



c)

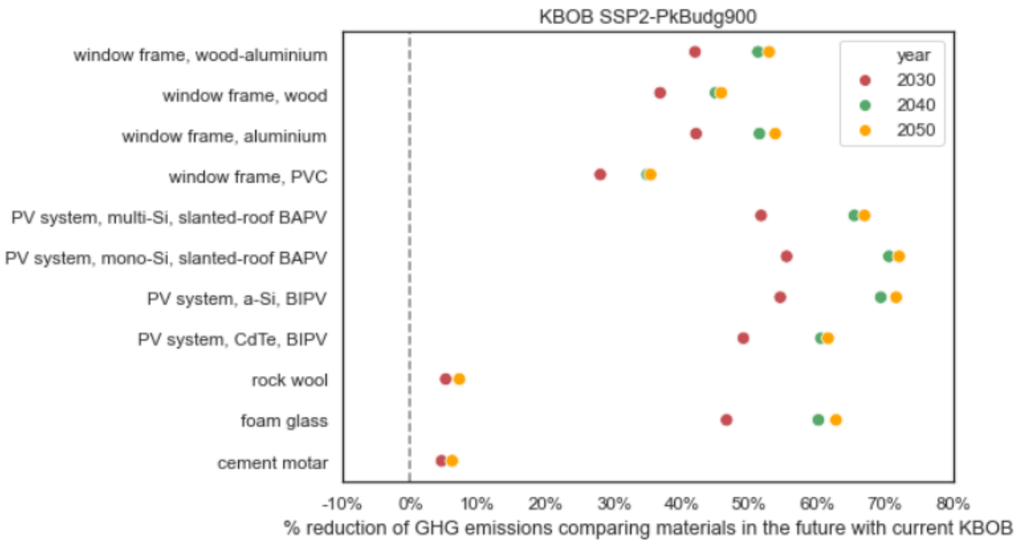
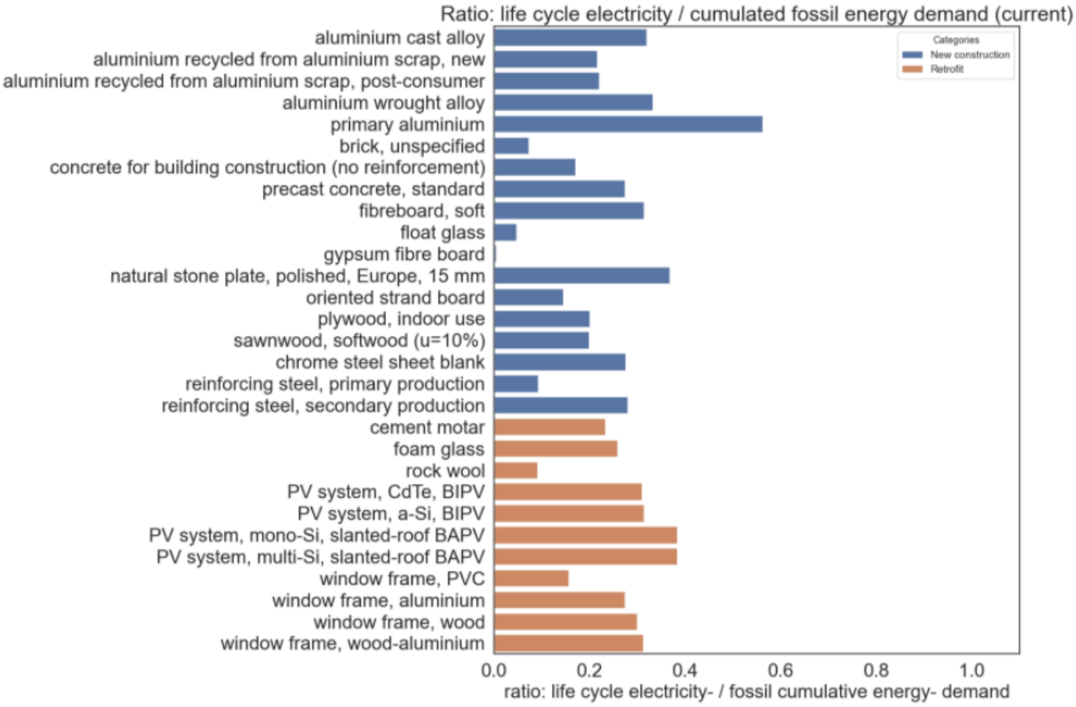


Figure 7: Percentage reduction of life cycle GHG emissions for major materials for retrofitted buildings

Although most of the materials/components selected have the reference unit of kilogram, some materials have different reference units, such as square meter (e.g. natural stones, windows) and unit of system of a certain size (e.g. PV systems at the power capacity of 3 kWp). To investigate whether there is an indicator that can reflect the sensitivities of life cycle GHG emissions to future electricity system decarbonization across different materials/components, even if the future background database is not in place, the amount of cumulative electricity consumption is normalized by the amount of cumulative fossil energy demand (**Error! Reference source not found.**). Although for PV systems and natural stone, the higher values for this indicator reflect the high emission reduction potential, it is found that this indicator alone in the current database (**Error! Reference source not found.**a) does not always indicate the sensitivity of embodied emissions of materials/components to future electricity system decarbonization (e.g. primary aluminium vs. aluminium alloys), because it does not reflect the geographical distribution of the upstream processes including their electricity supplies, thus their future emission reduction potentials cannot be estimated. This can be partly compensated by estimating this indicator in the future scenario (**Error! Reference source not found.**b), for which a great increase in its value hints a great reduction of fossil fuel consumption upstream in the future, but it still does not reflect if the consumption of electricity dominates the overall life cycle GHG emissions or not in comparison with other contributions, which is also key for a great percentage reduction of GHG emissions. In conclusion, the sensitivity of materials/components' embodied emissions to future electricity system decarbonization is determined not only by the amount of cumulative electricity consumption, but also the contribution of electricity consumption in its current life cycle GHG emissions, as well as the main countries of electricity supplies upstream where the majority of electricity is consumed and its future potential for decarbonization.

a)



b)

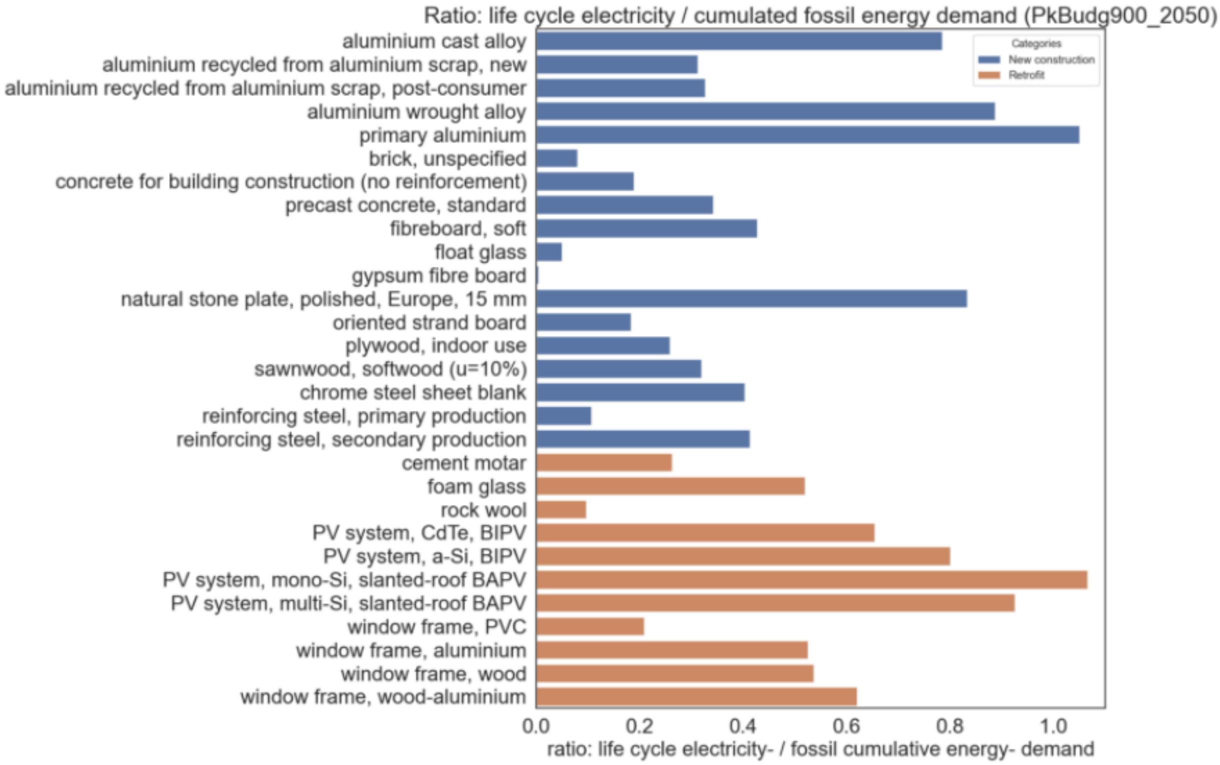


Figure 8: Ratio of life cycle electricity (in the processes from which life cycle GHG emissions are calculated based on explanation in Figure 1) and fossil cumulative energy demand, in kWh/kWh oil-eq: a) KBOB linked with ecoinvent v3.6 (current); b) KBOB linked with future ecoinvent v3.6 modified using scenario PdBudg900 in 2050. The value

of ratio increases in b) in comparison with a), due to decreased fossil energy demand in the supply chain of the materials upstream, as a result of decarbonized power system in the future

4. Conclusions and Outlook

The main results produced from this analysis is the life cycle GHG emissions per kWh of electricity supply (**Error! Reference source not found.**) and per unit amount of material or component, considering different future scenarios and time horizons. The table below includes selected results of life cycle GHG emissions of material or component, for base scenario from 2030 to 2050 at a 10-year interval, while the complete results for all scenarios for the same time horizons can be found in Appendix C.

Table 4: Life cycle GHG emissions (in kg CO_2 eq) per unit amount of material/component in KBOB, linked with ecoinvent v3.6, and with ecoinvent v3.6 incorporating global electricity system decarbonization from selected scenarios

New Construction /Retrofit	Index	Material/ Components	Material/Components displayed name in Figures	Unit	Life cycle GHG emissions per unit amount of material/component			
					KBOB linked with ecoinvent v3.6	KBOB SSP2-Base_2030	KBOB SSP2-Base_2040	KBOB SSP2-Base_2050
New construction	N1	Concrete	concrete for building construction (no reinforcement)	kg	9.49E-02	9.72E-02	9.66E-02	9.63E-02
	N2	Concrete	precast concrete, standard	kg	1.67E-01	1.69E-01	1.68E-01	1.67E-01
	N3	Steel, reinforcing	reinforcing steel, secondary production	kg	7.12E-01	6.36E-01	6.37E-01	6.48E-01
	N4	Steel, reinforcing	reinforcing steel, primary production	kg	2.20E+00	2.11E+00	2.11E+00	2.11E+00
	N5	Brick	brick, unspecified	kg	2.59E-01	2.53E-01	2.53E-01	2.54E-01
	N6	Aluminium	primary aluminium	kg	9.59E+00	1.11E+01	1.07E+01	1.05E+01
	N7	Aluminium	aluminium wrought alloy	kg	1.31E+01	9.91E+00	9.65E+00	9.34E+00
	N8	Aluminium	aluminium cast alloy	kg	5.41E+00	4.17E+00	4.06E+00	3.94E+00
	N9	Aluminium	aluminium recycled from aluminium scrap, new	kg	6.24E-01	5.53E-01	5.46E-01	5.40E-01
	N10	Aluminium	aluminium recycled from aluminium scrap, post-consumer	kg	9.09E-01	8.17E-01	8.09E-01	8.02E-01
	N11	Stainless steel	chrome steel sheet blank	kg	2.25E+00	2.03E+00	2.02E+00	2.02E+00
	N12	Float glass	float glass	kg	1.18E+00	1.14E+00	1.15E+00	1.15E+00
	N13	Natural stones	natural stone plate, polished, Europe, 15 mm	m2	2.86E+01	2.36E+01	2.31E+01	2.27E+01
	N14	Softwood, solid	sawnwood, softwood (u=10%)	kg	2.48E-01	2.10E-01	2.07E-01	2.05E-01
	N15	Plywood, softwood	plywood, indoor use	kg	9.32E-01	8.69E-01	8.68E-01	8.74E-01
	N16	Oriented strand board (OSB) panel	oriented strand board	kg	7.08E-01	6.34E-01	6.33E-01	6.37E-01
	N17	Fibreboard, soft	fibreboard, soft	kg	5.76E-01	5.47E-01	5.39E-01	5.39E-01
	N18	Gypsum panel	gypsum fibre board	kg	5.24E-01	5.22E-01	5.22E-01	5.22E-01

Retrofit	R1	Windows	window frame, aluminium	m2	6.00E+02	4.87E+02	4.78E+02	4.69E+02
	R2	Windows	window frame, wood	m2	1.74E+02	1.49E+02	1.48E+02	1.48E+02
	R3	Windows	window frame, wood-aluminium	m2	3.27E+02	2.70E+02	2.67E+02	2.64E+02
	R4	Windows	window frame, PVC	m2	3.31E+02	2.92E+02	2.91E+02	2.90E+02
	R5	Insulation material	foam glass	kg	1.78E+00	1.43E+00	1.40E+00	1.37E+00
	R6	Insulation material	rock wool	kg	1.09E+00	1.11E+00	1.10E+00	1.10E+00
	R7	Cement motar	cement motar	kg	2.09E-01	2.13E-01	2.12E-01	2.11E-01
	R8	PV system	PV system, multi-Si, slanted-roof BAPV	unit	6.54E+03	4.99E+03	4.91E+03	4.83E+03
	R9	PV system	PV system, mono-Si, slanted-roof BAPV	unit	7.60E+03	5.66E+03	5.56E+03	5.46E+03
	R10	PV system	PV system, a-Si, BIPV	unit	4.83E+03	3.58E+03	3.51E+03	3.46E+03
	R11	PV system	PV system, CdTe, BIPV	unit	4.28E+03	3.38E+03	3.31E+03	3.23E+03

4.1 Conclusions and Recommendations

It shows that incorporating future electricity supplies in the background database for construction material database can be crucial for materials with electricity-intensive manufacturing process upstream in the supply chain and which are used in building elements that need replacement during the service life of buildings. Depending on the material, its upstream processes and the selected future scenarios, the changes of life cycle GHG emission from -80% to +20% in comparison with the materials as in current KBOB database can be achieved, which is significant.. The life cycle GHG emissions of construction materials that are sensitive to future electricity supplies are concentrated in aluminium- (up to -60% emissions reduction), natural stones-related materials (up to -60%~-71% emissions reduction), as well as certain insulation (eg. aerogel vilies, up to -83% emissions reduction) and coating materials (eg. enamelling, up to -78% emissions reduction). The percentage of life cycle GHG emission variations for electricity supply itself in the future is much higher, which indicates prominent influence on the operation phase of buildings.

Given the high variability of the electricity system in terms of time and geographical regions currently (*ElectricityMap* | *Live CO_2 Emissions of Electricity Consumption*, n.d.) and its uncertainty in the future, this analysis shows the importance of using non-aggregated unit process datasets in the background when establishing building LCA databases for designers and architects such as the KBOB recommendation 2009/1:2016. Especially for those materials with relatively electricity-intensive manufacturing process, transparent non-aggregated unit process datasets allow such analysis changing background database, which can facilitate a more up-to-date and precise understanding of life cycle GHG emissions of construction materials. On the other hand, close and up-to-date linkages material datasets have with the background databases should be better addressed in the future, so that updated, more diverse and detailed material datasets can be utilized by sectors other than building industry, for example, cement and steel consumption in large infrastructures such as power plants or general infrastructure required in industry sectors.

4.2 Limitations and Future Research

While this analysis demonstrates the possibility of incorporating future electricity supplies in assessing the life cycle GHG emissions of construction materials, it has also a few limitations that should be further investigated.

There are few limitations in the analysis arise from applying IAM in the background database. First of all, only future electricity system has been considered, while other sectors such as transport, specific industry sectors are excluded. In addition, the IAM considered in this analysis is only one of the IAM available in literature (Pauliuk et al., 2017), future research should investigate what variation of results it would bring by incorporating other IAMs in the analysis. In addition, IAM often has aggregated global regions than considering specific countries or regions smaller than countries (which can bring great varieties especially for large countries like the USA and China). The most climate-ambitious scenario (eg. PkBudget 900 scenario in this analysis) also exhibits very ambitious targets of decarbonization (**Error! Reference source not found.**), for which a path towards the future is less addressed, which might make potential GHG emission reductions analyzed in this study optimistic.

Additionally, diverse future scenarios for specific sectors (eg. heat supply, recycling) and industries should also be further investigated and incorporated in such analysis, in order to better understand the specific conditions and challenges that are faced in reality. Further analysis can be also performed looking into the upstream supply chains for critical materials in terms of their geographical distribution and dependencies, which can help to understand the supply of security for specific countries. At last, results generated from this analysis have only focused on materials alone, and they can be further applied in different types of building case studies to take into account the relative consumption amount, which could help to form priorities in the making of national policies and strategies.

5. Acknowledgement

This research has received funding from the European Union's Horizon 2020 research and innovation program for project ATELIER [grant agreement No. 864374].

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Appendix

A. List of datasets excluded due to lack of unit process datasets

Sector	Material name
Fenster, Sonnenschutz, Fassadenverkleidungen	Fassade, Pfosten-Riegel, Alu/Glas
Fenster, Sonnenschutz, Fassadenverkleidungen	Fensterrahmen Aluminium, WICLINE 75evo
Fenster, Sonnenschutz, Fassadenverkleidungen	Isolierverglasung 2-fach, VSG, Ug-Wert 1.1 W/m2K
Fenster, Sonnenschutz, Fassadenverkleidungen	Isolierverglasung 3-fach, VSG, Ug-Wert 0.6 W/m2K
Fenster, Sonnenschutz, Fassadenverkleidungen	Fassadenplatte, Kalkstein, 30 mm
Holz und Holzwerkstoffe	Massivholz Fichte / Tanne, kammergetr., Vollholzhaus holzpur
Holz und Holzwerkstoffe	Brettschichtholz, MF-gebunden, Feuchtbereich, Produktion Schweiz
Holz und Holzwerkstoffe	Brettschichtholz, UF-gebunden, Trockenbereich, Produktion Schweiz
Holz und Holzwerkstoffe	Massivholz Buche / Eiche, kammergetrocknet, gehobelt, Produktion Schweiz
Holz und Holzwerkstoffe	Massivholz Buche / Eiche, kammergetrocknet, rau, Produktion Schweiz
Holz und Holzwerkstoffe	Massivholz Buche / Eiche, luftgetrocknet, rau, Produktion Schweiz
Holz und Holzwerkstoffe	Massivholz Fichte / Tanne / Lärche, kammergetr., gehobelt, Produktion Schweiz
Holz und Holzwerkstoffe	Massivholz Fichte / Tanne / Lärche, luftgetr., gehobelt, Produktion Schweiz
Holz und Holzwerkstoffe	Massivholz Fichte / Tanne / Lärche, luftgetrocknet, rau, Produktion Schweiz
Dichtungsbahnen und Schutzfolien	Dichtungsbahn Polyolefin (FPO)
Wärmedämmstoffe	Glaswolle, Isover
Wärmedämmstoffe	Strohballenwand
Mauersteine	Kalksandstein, FBB
Andere Massivbaustoffe	Kalksteinplatte
Rohre	Polypropylen (PP), rezykliert, Rehau

B. List of countries & regions

Country	Country Code	Region Code	Alpha-3 Code
Aruba	AW	LAM	ABW
Afghanistan	AF	OAS	AFG
Angola	AO	SSA	AGO
Anguilla	AI	LAM	AIA
Aland Islands	AX	EUR	ALA
Albania	AL	NEU	ALB
Andorra	AD	NEU	AND
United Arab Emirates	AE	MEA	ARE
Argentina	AR	LAM	ARG
Armenia	AM	REF	ARM
American Samoa	AS	OAS	ASM
Antarctica	AQ	LAM	ATA
French Southern Territories	TF	OAS	ATF
Antigua and Barbuda	AG	LAM	ATG
Australia	AU	CAZ	AUS
Austria	AT	EUR	AUT
Azerbaijan	AZ	REF	AZE
Burundi	BI	SSA	BDI
Belgium	BE	EUR	BEL
Benin	BJ	SSA	BEN
Bonaire, Sint Eustatius and Saba	BQ	LAM	BES
Burkina Faso	BF	SSA	BFA
Bangladesh	BD	OAS	BGD
Bulgaria	BG	EUR	BGR
Bahrain	BH	MEA	BHR
Bahamas	BS	LAM	BHS
Bosnia and Herzegovina	BA	NEU	BIH
Saint Barthelemy	BL	LAM	BLM
Belarus	BY	REF	BLR
Belize	BZ	LAM	BLZ
Bermuda	BM	LAM	BMU
Bolivia, Plurinational State of	BO	LAM	BOL
Brazil	BR	LAM	BRA
Barbados	BB	LAM	BRB
Brunei Darussalam	BN	OAS	BRN
Bhutan	BT	OAS	BTN
Botswana	BW	SSA	BWA
Central African Republic	CF	SSA	CAF
Canada	CA	CAZ	CAN
Cocos (Keeling) Islands	CC	OAS	CCK
China	CN	CHA	CHN

Switzerland	CH	NEU	CHE
Chile	CL	LAM	CHL
Cote d Ivoire	CI	SSA	CIV
Cameroon	CM	SSA	CMR
Congo, the Democratic Republic of the	CD	SSA	COD
Congo	CG	SSA	COG
Cook Islands	CK	OAS	COK
Colombia	CO	LAM	COL
Comoros	KM	SSA	COM
Cape Verde	CV	SSA	CPV
Costa Rica	CR	LAM	CRI
Cuba	CU	LAM	CUB
Curacao	CW	LAM	CUW
Christmas Island	CX	OAS	CXR
Cayman Islands	KY	LAM	CYM
Cyprus	CY	EUR	CYP
Czech Republic	CZ	EUR	CZE
Germany	DE	EUR	DEU
Djibouti	DJ	SSA	DJI
Dominica	DM	LAM	DMA
Denmark	DK	EUR	DNK
Dominican Republic	DO	LAM	DOM
Algeria	DZ	MEA	DZA
Ecuador	EC	LAM	ECU
Egypt	EG	MEA	EGY
Eritrea	ER	SSA	ERI
Western Sahara	EH	MEA	ESH
Spain	ES	EUR	ESP
Estonia	EE	EUR	EST
Ethiopia	ET	SSA	ETH
Finland	FI	EUR	FIN
Fiji	FJ	OAS	FJI
Falkland Islands (Malvinas)	FK	LAM	FLK
France	FR	EUR	FRA
Faroe Islands	FO	EUR	FRO
Micronesia, Federated States of	FM	OAS	FSM
Gabon	GA	SSA	GAB
United Kingdom	GB	EUR	GBR
Georgia	GE	REF	GEO
Guernsey	GG	EUR	GGY
Ghana	GH	SSA	GHA
Gibraltar	GI	EUR	GIB
Guinea	GN	SSA	GIN
Guadeloupe	GP	LAM	GLP

Gambia	GM	SSA	GMB
Guinea-Bissau	GW	SSA	GNB
Equatorial Guinea	GQ	SSA	GNQ
Greece	GR	EUR	GRC
Grenada	GD	LAM	GRD
Greenland	GL	NEU	GRL
Guatemala	GT	LAM	GTM
French Guiana	GF	LAM	GUF
Guam	GU	OAS	GUM
Guyana	GY	LAM	GUY
Hong Kong	HK	CHA	HKG
Honduras	HN	LAM	HND
Croatia	HR	EUR	HRV
Haiti	HT	LAM	HTI
Hungary	HU	EUR	HUN
Indonesia	ID	OAS	IDN
Isle of Man	IM	EUR	IMN
India	IN	IND	IND
British Indian Ocean Territory	IO	OAS	IOT
Ireland	IE	EUR	IRL
Iran, Islamic Republic of	IR	MEA	IRN
Iraq	IQ	MEA	IRQ
Iceland	IS	NEU	ISL
Israel	IL	MEA	ISR
Italy	IT	EUR	ITA
Jamaica	JM	LAM	JAM
Jersey	JE	EUR	JEY
Jordan	JO	MEA	JOR
Japan	JP	JPN	JPN
Kazakhstan	KZ	REF	KAZ
Kenya	KE	SSA	KEN
Kyrgyzstan	KG	REF	KGZ
Cambodia	KH	OAS	KHM
Kiribati	KI	OAS	KIR
Saint Kitts and Nevis	KN	LAM	KNA
Korea, Republic of	KR	OAS	KOR
Kuwait	KW	MEA	KWT
Lao People's Democratic Republic	LA	OAS	LAO
Lebanon	LB	MEA	LBN
Liberia	LR	SSA	LBR
Libya	LY	MEA	LBY
Saint Lucia	LC	LAM	LCA
Liechtenstein	LI	NEU	LIE
Sri Lanka	LK	OAS	LKA

Lesotho	LS	SSA	LSO
Lithuania	LT	EUR	LTU
Luxembourg	LU	EUR	LUX
Latvia	LV	EUR	LVA
Macao	MO	CHA	MAC
Saint Martin (French part)	MF	LAM	MAF
Morocco	MA	MEA	MAR
Monaco	MC	NEU	MCO
Moldova, Republic of	MD	REF	MDA
Madagascar	MG	SSA	MDG
Maldives	MV	OAS	MDV
Mexico	MX	LAM	MEX
Marshall Islands	MH	OAS	MHL
Macedonia, the former Yugoslav Republic of	MK	NEU	MKD
Mali	ML	SSA	MLI
Malta	MT	EUR	MLT
Myanmar	MM	OAS	MMR
Montenegro	ME	NEU	MNE
Mongolia	MN	OAS	MNG
Northern Mariana Islands	MP	OAS	MNP
Mozambique	MZ	SSA	MOZ
Mauritania	MR	SSA	MRT
Montserrat	MS	LAM	MSR
Martinique	MQ	LAM	MTQ
Mauritius	MU	SSA	MUS
Malawi	MW	SSA	MWI
Malaysia	MY	OAS	MYS
Mayotte	YT	SSA	MYT
Namibia	NA	SSA	NAM
New Caledonia	NC	OAS	NCL
Niger	NE	SSA	NER
Norfolk Island	NF	OAS	NFK
Nigeria	NG	SSA	NGA
Nicaragua	NI	LAM	NIC
Niue	NU	OAS	NIU
Netherlands	NL	EUR	NLD
Norway	NO	NEU	NOR
Nepal	NP	OAS	NPL
Nauru	NR	OAS	NRU
New Zealand	NZ	CAZ	NZL
Oman	OM	MEA	OMN
Pakistan	PK	OAS	PAK
Panama	PA	LAM	PAN
Pitcairn	PN	OAS	PCN

Peru	PE	LAM	PER
Philippines	PH	OAS	PHL
Palau	PW	OAS	PLW
Papua New Guinea	PG	OAS	PNG
Poland	PL	EUR	POL
Puerto Rico	PR	LAM	PRI
Korea, Democratic People's Republic of	KP	OAS	PRK
Portugal	PT	EUR	PRT
Paraguay	PY	LAM	PRY
Palestine, State of	PS	MEA	PSE
French Polynesia	PF	OAS	PYF
Qatar	QA	MEA	QAT
Reunion	RE	SSA	REU
Romania	RO	EUR	ROU
Russian Federation	RU	REF	RUS
Rwanda	RW	SSA	RWA
Saudi Arabia	SA	MEA	SAU
Sudan	SD	MEA	SDN
Senegal	SN	SSA	SEN
Singapore	SG	OAS	SGP
South Georgia and the South Sandwich Islands	GS	LAM	SGS
Saint Helena, Ascension and Tristan da Cunha	SH	SSA	SHN
Svalbard and Jan Mayen	SJ	NEU	SJM
Solomon Islands	SB	OAS	SLB
Sierra Leone	SL	SSA	SLE
El Salvador	SV	LAM	SLV
San Marino	SM	NEU	SMR
Somalia	SO	SSA	SOM
Serbia	RS	NEU	SRB
South Sudan	SS	SSA	SSD
Sao Tome and Principe	ST	SSA	STP
Suriname	SR	LAM	SUR
Slovakia	SK	EUR	SVK
Slovenia	SI	EUR	SVN
Sweden	SE	EUR	SWE
Swaziland	SZ	SSA	SWZ
Sint Maarten (Dutch part)	SX	LAM	SXM
Seychelles	SC	SSA	SYC
Syrian Arab Republic	SY	MEA	SYR
Turks and Caicos Islands	TC	LAM	TCA
Chad	TD	SSA	TCD
Togo	TG	SSA	TGO
Thailand	TH	OAS	THA
Tajikistan	TJ	REF	TJK

Turkmenistan	TM	REF	TKM
Timor-Leste	TL	OAS	TLS
Tonga	TO	OAS	TON
Trinidad and Tobago	TT	LAM	TTO
Tunisia	TN	MEA	TUN
Turkey	TR	MEA	TUR
Tuvalu	TV	OAS	TUV
Taiwan, Province of China	TW	CHA	TWN
Tanzania, United Republic of	TZ	SSA	TZA
Uganda	UG	SSA	UGA
Ukraine	UA	REF	UKR
United States Minor Outlying Islands	UM	OAS	UMI
Uruguay	UY	LAM	URY
United States	US	USA	USA
Uzbekistan	UZ	REF	UZB
Holy See (Vatican City State)	VA	NEU	VAT
Saint Vincent and the Grenadines	VC	LAM	VCT
Venezuela, Bolivarian Republic of	VE	LAM	VEN
Virgin Islands, British	VG	LAM	VGB
Virgin Islands, U.S.	VI	LAM	VIR
Viet Nam	VN	OAS	VNM
Vanuatu	VU	OAS	VUT
Wallis and Futuna	WF	OAS	WLF
Samoa	WS	OAS	WSM
Yemen	YE	MEA	YEM
South Africa	ZA	SSA	ZAF
Zambia	ZM	SSA	ZMB
Zimbabwe	ZW	SSA	ZWE
Kosovo	XK	EUR	XKX
Rest of the world	RoW	CAZ	#N/A
Europe	RER	EUR	#N/A
Northern America	RNA	USA	#N/A
Latin America	RLA	LAM	#N/A
Africa	RAF	SSA	#N/A
Asia	RAS	OAS	#N/A
Oceania	UN-OCEANIA	CAZ	#N/A
World	GLO	World	#N/A

Appendix C: Life cycle GHG emissions per material/component in KBOB linked with ecoinvent v3.6 and with ecoinvent v3.6 incorporating global electricity system decarbonization from different SSP scenarios

New Construction /Retrofit	Index	Material/ Components	Material/Components displayed name in figures	Unit	Life cycle GHG emissions / unit			
					KBOB linked with ecoinvent v3.6	KBOB SSP2-Base_2030	KBOB SSP2-Base_2040	KBOB SSP2-Base_2050
New construction	N1	Concrete	concrete for building construction (no reinforcement)	kg	9.49E-02	9.72E-02	9.66E-02	9.63E-02
	N2	Concrete	precast concrete, standard	kg	1.67E-01	1.69E-01	1.68E-01	1.67E-01
	N3	Steel, reinforcing	reinforcing steel, secondary production	kg	7.12E-01	6.36E-01	6.37E-01	6.48E-01
	N4	Steel, reinforcing	reinforcing steel, primary production	kg	2.20E+00	2.11E+00	2.11E+00	2.11E+00
	N5	Brick	brick, unspecified	kg	2.59E-01	2.53E-01	2.53E-01	2.54E-01
	N6	Aluminium	primary aluminium	kg	9.59E+00	1.11E+01	1.07E+01	1.05E+01
	N7	Aluminium	aluminium wrought alloy	kg	1.31E+01	9.91E+00	9.65E+00	9.34E+00
	N8	Aluminium	aluminium cast alloy	kg	5.41E+00	4.17E+00	4.06E+00	3.94E+00
	N9	Aluminium	aluminium recycled from aluminium scrap, new	kg	6.24E-01	5.53E-01	5.46E-01	5.40E-01
	N10	Aluminium	aluminium recycled from aluminium scrap, post-consumer	kg	9.09E-01	8.17E-01	8.09E-01	8.02E-01
	N11	Stainless steel	chrome steel sheet blank	kg	2.25E+00	2.03E+00	2.02E+00	2.02E+00
	N12	Float glass	float glass	kg	1.18E+00	1.14E+00	1.15E+00	1.15E+00
	N13	Natural stones	natural stone plate, polished, Europe, 15 mm	m2	2.86E+01	2.36E+01	2.31E+01	2.27E+01
	N14	Softwood, solid	sawnwood, softwood (u=10%)	kg	2.48E-01	2.10E-01	2.07E-01	2.05E-01
	N15	Plywood, softwood	plywood, indoor use	kg	9.32E-01	8.69E-01	8.68E-01	8.74E-01
	N16	Oriented strand board (OSB) panel	oriented strand board	kg	7.08E-01	6.34E-01	6.33E-01	6.37E-01
	N17	Fibreboard, soft	fibreboard, soft	kg	5.76E-01	5.47E-01	5.39E-01	5.39E-01
	N18	Gypsum panel	gypsum fibre board	kg	5.24E-01	5.22E-01	5.22E-01	5.22E-01
Retrofit	R1	Windows	window frame, aluminium	m2	6.00E+02	4.87E+02	4.78E+02	4.69E+02
	R2	Windows	window frame, wood	m2	1.74E+02	1.49E+02	1.48E+02	1.48E+02
	R3	Windows	window frame, wood-aluminium	m2	3.27E+02	2.70E+02	2.67E+02	2.64E+02
	R4	Windows	window frame, PVC	m2	3.31E+02	2.92E+02	2.91E+02	2.90E+02
	R5	Insulation material	foam glass	kg	1.78E+00	1.43E+00	1.40E+00	1.37E+00
	R6	Insulation material	rock wool	kg	1.09E+00	1.11E+00	1.10E+00	1.10E+00
	R7	Cement motar	cement motar	kg	2.09E-01	2.13E-01	2.12E-01	2.11E-01
	R8	PV system	PV system, multi-Si, slanted-roof BAPV	unit	6.54E+03	4.99E+03	4.91E+03	4.83E+03
	R9	PV system	PV system, mono-Si, slanted-roof BAPV	unit	7.60E+03	5.66E+03	5.56E+03	5.46E+03
	R10	PV system	PV system, a-Si, BIPV	unit	4.83E+03	3.58E+03	3.51E+03	3.46E+03
	R11	PV system	PV system, CdTe, BIPV	unit	4.28E+03	3.38E+03	3.31E+03	3.23E+03

New Construction /Retrofit	Index	Material/ Components	Material/Components displayed name in figures	Unit	Life cycle GHG emissions / unit					
					KBOB SSP2-NDC_2030	KBOB SSP2-NDC_2040	KBOB SSP2-NDC_2050	KBOB SSP2-PkBudg900_2030	KBOB SSP2-PkBudg900_2040	KBOB SSP2-PkBudg900_2050
New construction	N1	Concrete	concrete for building construction (no reinforcement)	kg	9.44E-02	9.36E-02	9.30E-02	9.19E-02	9.08E-02	9.09E-02
	N2	Concrete	precast concrete, standard	kg	1.58E-01	1.55E-01	1.52E-01	1.50E-01	1.46E-01	1.46E-01
	N3	Steel, reinforcing	reinforcing steel, secondary production	kg	5.21E-01	4.72E-01	4.46E-01	4.51E-01	3.99E-01	4.00E-01
	N4	Steel, reinforcing	reinforcing steel, primary production	kg	2.04E+00	2.00E+00	1.98E+00	1.99E+00	1.94E+00	1.93E+00
	N5	Brick	brick, unspecified	kg	2.44E-01	2.41E-01	2.39E-01	2.39E-01	2.35E-01	2.35E-01
	N6	Aluminium	primary aluminium	kg	9.29E+00	8.17E+00	7.41E+00	7.34E+00	4.80E+00	4.37E+00
	N7	Aluminium	aluminium wrought alloy	kg	8.57E+00	7.27E+00	6.80E+00	6.33E+00	4.82E+00	4.39E+00
	N8	Aluminium	aluminium cast alloy	kg	3.61E+00	3.10E+00	2.92E+00	2.75E+00	2.15E+00	1.99E+00
	N9	Aluminium	aluminium recycled from aluminium scrap, new	kg	4.86E-01	4.53E-01	4.38E-01	4.47E-01	4.08E-01	4.06E-01
	N10	Aluminium	aluminium recycled from aluminium scrap, post-consumer	kg	7.35E-01	6.90E-01	6.70E-01	6.85E-01	6.32E-01	6.29E-01
	N11	Stainless steel	chrome steel sheet blank	kg	1.81E+00	1.69E+00	1.63E+00	1.64E+00	1.49E+00	1.48E+00
	N12	Float glass	float glass	kg	1.09E+00	1.06E+00	1.05E+00	1.05E+00	1.02E+00	1.02E+00
	N13	Natural stones	natural stone plate, polished, Europe, 15 mm	m2	1.84E+01	1.48E+01	1.30E+01	1.44E+01	9.99E+00	9.68E+00
	N14	Softwood, solid	sawnwood, softwood (u=10%)	kg	1.83E-01	1.62E-01	1.52E-01	1.63E-01	1.38E-01	1.36E-01
	N15	Plywood, softwood	plywood, indoor use	kg	7.66E-01	7.20E-01	6.96E-01	6.99E-01	6.50E-01	6.50E-01
	N16	Oriented strand board (OSB) panel	oriented strand board	kg	5.74E-01	5.45E-01	5.31E-01	5.36E-01	5.05E-01	5.05E-01
	N17	Fibreboard, soft	fibreboard, soft	kg	4.69E-01	4.42E-01	4.25E-01	4.10E-01	3.77E-01	3.78E-01
	N18	Gypsum panel	gypsum fibre board	kg	5.21E-01	5.20E-01	5.20E-01	5.20E-01	5.19E-01	5.19E-01
Retrofit	R1	Windows	window frame, aluminium	m2	4.29E+02	3.81E+02	3.62E+02	3.47E+02	2.91E+02	2.77E+02
	R2	Windows	window frame, wood	m2	1.28E+02	1.15E+02	1.09E+02	1.10E+02	9.57E+01	9.42E+01
	R3	Windows	window frame, wood-aluminium	m2	2.31E+02	2.05E+02	1.94E+02	1.90E+02	1.59E+02	1.54E+02
	R4	Windows	window frame, PVC	m2	2.61E+02	2.41E+02	2.32E+02	2.38E+02	2.15E+02	2.14E+02
	R5	Insulation material	foam glass	kg	1.24E+00	1.06E+00	9.67E-01	9.52E-01	7.10E-01	6.64E-01
	R6	Insulation material	rock wool	kg	1.07E+00	1.05E+00	1.04E+00	1.03E+00	1.01E+00	1.01E+00
	R7	Cement motar	cement motar	kg	2.06E-01	2.03E-01	2.01E-01	1.99E-01	1.96E-01	1.96E-01
	R8	PV system	PV system, multi-Si, slanted-roof BAPV	unit	3.99E+03	3.22E+03	2.87E+03	3.15E+03	2.26E+03	2.16E+03
	R9	PV system	PV system, mono-Si, slanted-roof BAPV	unit	4.39E+03	3.40E+03	2.95E+03	3.38E+03	2.24E+03	2.12E+03
	R10	PV system	PV system, a-Si, BIPV	unit	2.88E+03	2.30E+03	2.03E+03	2.20E+03	1.48E+03	1.37E+03
	R11	PV system	PV system, CdTe, BIPV	unit	2.75E+03	2.29E+03	2.11E+03	2.18E+03	1.69E+03	1.64E+03