Life cycle assessment of buildings and city quarters analysing the influence of different climatic conditions

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Abstract

In this study, a method for evaluating the energy demand and greenhouse gas emissions during the three life cycle stages production, use and end-of-life of a building or city quarter is presented and applied to different case studies.

The main result is that from the life cycle energetic point of view, refurbishment to a high building standard is better than demolition and reconstruction to a similar standard under the condition that the structural condition of the building allows it.

The analysis includes different climatic conditions and their high influence on the life cycle energy demand and greenhouse gas emissions.

Introduction

Urban areas consume approximately 70% of global energy and in light of a growing population and increasing densification of urban areas, this share is expected to further increase in the future (Sharifi and Yamagata 2016). Buildings account for 40% of the total energy consumption and 36% of CO_2 emissions in Europe (Dascalaki, et al. 2016).

Standards for energy efficient buildings are continuously tightening due to stronger regulations for example in Germany and California (USA) (BMUB 2013) (California Energy Commission 2015). With these new standards for efficient buildings, the energy demand and resulting emissions during the use stage are decreasing. At the same time, the energy needed during the construction stage is increasing because of the higher material input. Consequently, the energy ratio is gradually shifting from the use stage to the production stage (Cabeza, et al. 2014) (Verbeeck and Hens 2010).

Buildings should therefore be evaluated with regard to their whole life cycle, which includes the construction and end-of-life stages, and not only based on the energy demand during the use stage. This is especially important when discussing refurbishment versus demolition and new construction.

Most life cycle assessment (LCA) studies so far only consider individual buildings and case studies (Blengini, 2009). There are many design tools to analyse and simulate the energy demand of individual buildings but they are too detailed and too complicated to transfer them to the level of city quarters (Steskens, et al. 2015). Moreover, a literature review revealed that life cycle assessment has not been conducted using CityGML data before (Anderson, Wulfhorst and Lang 2015).

In this work the life cycle analysis has been integrated in the simulation platform for urban energy demand SimStadt (Monsalvete, Robinson and Eicker 2015). The platform was developed to simulate the energy needed during the use stage of a building or city quarter using CityGML-files and was extended by this work to calculate the values for embodied energy and greenhouse gases as well as the energy needed and greenhouse gases emitted during the disposal of the materials used in a building. It is designed to analyse not only one building, but to evaluate whole city quarters, cities and even regions.

To implement the strategy in the most efficient way, an individual roadmap for a specific city quarter is needed, depending on the structure (building type, size, age et cetera) of the buildings in the city quarter. In this work, a method for developing such a roadmap is presented. The results then show the reduction of the primary energy demand and greenhouse gas emissions over a certain amount of time.

Methodology

Single buildings

To calculate the material specific values for embodied energy and greenhouse gases as well as the energy needed and greenhouse gases emitted during disposal, the software for life cycle assessment Umberto (ifu Institut 2016) with the ecoinvent 3.2 database (ecoinvent 2016) is used to set up models for the different building materials.

The chosen approach for the calculation of the mentioned values is cradle-to-grave, which means that all stages of the life cycle of the building materials are taken into account. Material and energetic flows are crossing the system boundary on the input side; emissions to air, water and soil are crossing the system boundary on the output side, as can be seen in Figure 1.

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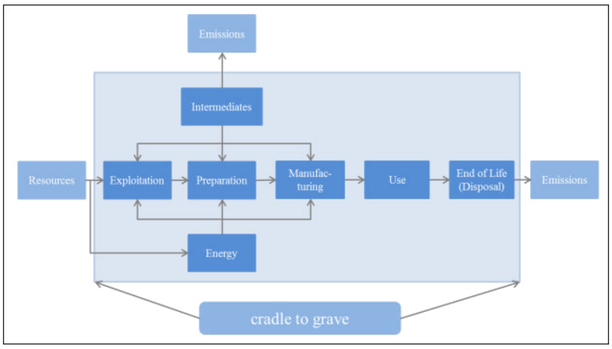

Figure 1: System boundaries and approach of the model

The different material and energetic flows are assigned to the following life cycle stages in Figure 2.

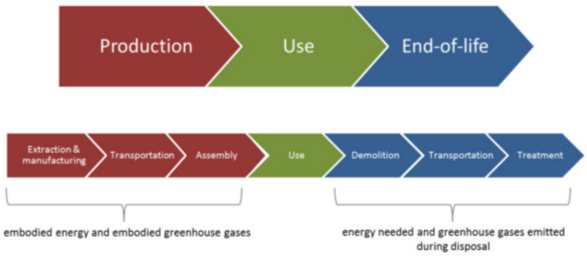

Figure 2: Life cycle stages divided into substages

The main stages production, use and end-of-life are further divided into substages to clearer show their contribution. The production stage includes the extraction of raw materials and manufacturing of products, their transportation to the construction site and their assembly to a building. The use stage only consists of the use of the building over a certain lifespan. Finally, the end-of-life stage consists of the demolition of the building, the transportation of the materials and their final treatment. For every stage, energy and emission values for each material are calculated.

Further, these calculated energy and emission values are integrated into the building physics library of SimStadt. This building physics library includes the material composition of various building types sorted by different periods of time, starting in 1859 up to newly constructed buildings as of 2016, with different energy standards for efficient buildings. Additionally, two refurbishment standards for existing buildings are defined. The library is based on a study called 'Deutsche Wohngebäudetypologie' (IWU - Institut Wohnen und Umwelt 2015). This study has an extensive range of material compositions for different building types and ages, however it can never picture the reality with 100% accuracy.

The energy and greenhouse gas values for the assembly of the buildings (see substage "assembly") are not yet included in the production stage. A surface area specific construction effort (kWh/m² and kg CO_2-eq./m²) is taken from literature, added to the embodied energy and greenhouse gases and results in the production stage (Cuéllar-Franca and Azapagic 2012) (Blengini 2007) (Xiang and Xu 2016) (Helmus, Niscancioglu and Randel 2011). In case of refurbishment with much less materials to be moved, only 10% of this value is used. Also, the values for the demolition of the building are added to the energy needed and greenhouse gases emitted during the disposal of the building materials and result in the end-of-life stage (Cuéllar-Franca and Azapagic 2012) (Srinivasan, et al. 2014).

The use stage, consisting of the space heating and domestic hot water demand, is calculated in SimStadt. In former studies, e.g. (Nouvel, et al. 2017), the influence of data quality on the calculations has been analysed by comparing the simulation results to measured energy demands in a specific case study in Germany. For example, if the number of stories is missing, which is required to estimate the heated floor area, may be retrieved based on the building height and some typical storey heights coming from the IWU study.

Since the methodology of this research is based on generic data, the software and its calculation results are applicable to a large scale to allow a comparison of different buildings and city quarters. The CityGML-file includes a 3D model and specifications such as heated floor area, building age and building use and geometrical and geographical information of each building.

SimStadt calculates the material composition of the building by using the CityGML-file including specific building information and linking it with the mentioned building physics library. At this point it is important to mention that the GML-file with the 3D model only maps the building shell (outer walls, ground floor and roof) and no internal walls or ceilings. Since the goal is the comparison of different building cases, this simplification does not affect the relative results.

SimStadt then calculates the energy and greenhouse gas values of the production, use and end-of-life stages for all buildings.

The following Figure 3 summarises the methodology for the calculation of the building specific values for embodied and disposal energy and greenhouse gases:

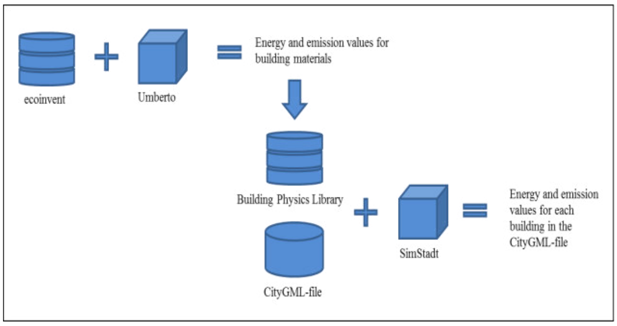

Figure 3: Graphical description of methodology

To assess the difference between several building types, a real building geometry from an urban case study was chosen for analysis. This building was then simulated with different configurations such as year of construction or level of refurbishment.

City quarters

The city quarter considered in this study is called Stöckach and is located in the east of Stuttgart, Germany. Stöckach is characteristic for the early days of the city expansion in Stuttgart and multi-family houses represent the majority of residential buildings. These buildings sometimes still have elaborated street facades and are therefore protected. Starting in the 1950's, Stöckach was further developed and residential buildings which rather fulfill functional than aesthetic requirements were built.

In this study, the focus is set on residential buildings which represent roughly 50% of the total of 1,148 buildings. The different building types in Stöckach are single family houses, multi-family houses, big multi-family houses, apartment towers and row houses. Multi-family houses and big multi-family houses represent about 64% of all residential buildings.

The age structure of all residential buildings in Stöckach can be divided in four groups:

- Buildings with a year of construction up to 1948: 15%
- Buildings with a year of construction from 1949 to 1978: 58%
- Buildings with a year of construction from 1979 to 2001: 17%
- Buildings with a year of construction as of 2002: 10%

In the following Figure 4, a 3D city model of Stöckach can be seen.

Figure 4: 3D city model of Stöckach including all types of buildings

The traditional life cycle assessment of a building consists of its production stage, a use stage over a defined lifespan and its end-of-life stage. When analysing an entire city quarter however, the assessment can only include a part of the life cycle of this city quarter during a defined period of time. This is due to the fact that not all the buildings were constructed at the same time and might have been refurbished at a different point in their lifetime and the city quarter can therefore not be considered over a common lifespan for all buildings.

The focus is set on the evaluation of an entire city quarter starting from 2016 up to 2050. This time period is chosen because the energy efficiency goals set by the European parliament and the federal government in Germany for the building sector mostly refer to the year 2050 (European Parliament 2012) (European Parliament 2010).

The goal of the simulation is to lift all existing buildings in the considered city quarter to an advanced energy standard until 2050 by either refurbishment or demolition and reconstruction.

For the calculation of the production, use and end-of-life stages for the entire city quarter for each year from 2016 to 2050, the following assumptions are made:

- Only residential buildings are considered.
- The year 2016 is the base year for the calculations. All measures start in 2017 and are finished by the end of the year 2049. In 2050, all measures are completed.
- For the calculation of the energy and emission values of the use stages in SimStadt, different shares of heating systems are defined, according to several studies and market analyses (BDEW 2015a) (bwp 2016): gas boiler 25%, oil boiler 42%, condensing gas boiler 13%, wood pellets boiler 12%, air source heat pump 2%, geothermal heat pump 2% and electric radiator 4%. These shares remain unchanged during the entire time period as the focus is to determine the effect of the building envelope refurbishment alone.
- To calculate the primary energy demand, the appropriate current German primary energy factors are used for the calculation (BDEW 2015b).
- 12% of all buildings in the city quarter are assumed to be in such bad condition, that they cannot be refurbished but can only be torn down and reconstructed (Walberg, et al. 2011). The buildings are ranked in a descending order according to their absolute reduction in total heat demand (comparing 2016 to 2050) to determine the buildings that are to be refurbished and torn down and reconstructed.
- For the demolition and new construction, always the same building geometry is used. Based upon this fact, a possible change in land-use for reconstructed buildings is not considered in this study.
- According to a study by the German Federal Ministry for Economic Affairs and Energy (BMWi 2014), typically 5% of all buildings in the city quarter cannot be torn down or refurbished because they are protected historical buildings. These are mostly buildings with a year of construction before 1957.
- The rate of buildings which are refurbished or torn down and reconstructed each year is set on 2,123 %. This rate allows refurbishing or reconstructing all buildings in this city quarter until 2050. A similar rate is also advised by the federal government of Germany to reach energy

efficiency goals in the building sector (Bade, et al. 2014).

For this analysis, the city quarter of Stöckach is assessed with both the climatic conditions of Stuttgart, Germany and San Francisco, CA. This allows to study the influence of different ambient temperature and irradiation on the heating demand of buildings and their life cycle.

The climatic conditions of Stuttgart and San Francisco are different, but not too different to allow a reasonable comparison. The climate in San Francisco is more moderate than the climate in Stuttgart, which means warmer winters than in Stuttgart and less temperature difference between summer and winter (see Figure 5). Moreover, the average irradiance level is generally higher in San Francisco than in Stuttgart (see Figure 6).

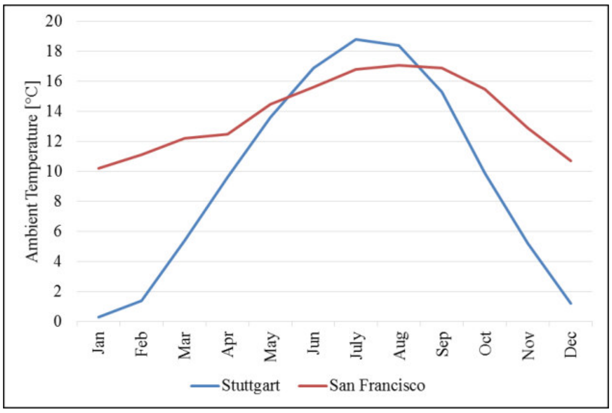

Figure 5: Mean monthly ambient temperature for Stuttgart and San Francisco (INSEL Software - doppelintegral GmbH)

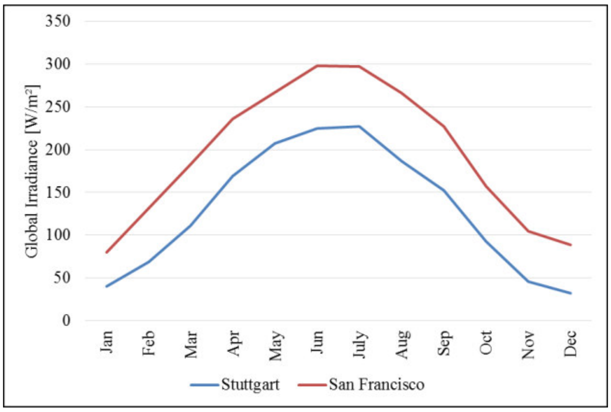

Figure 6: Mean monthly global irradiance for Stuttgart and San Francisco (INSEL Software - doppelintegral GmbH)

Calculation and results

Case study for single buildings

To verify the developed methodology, a multi-family building from 1975 in a Stuttgart city quarter was analysed under German climatic conditions. The calculations were performed for both the primary energy and greenhouse gas emissions; since the results are similar for both calculations, only the results for the primary energy are shown here.

Without refurbishment, the use dominates the overall primary energy consumption and greenhouse gas emissions, the embodied energy accounts for 5.1% (see Table 1). The same building refurbished to a medium standard has a 40% lower total energy demand, the refurbishment to an advanced standard reduces the total energy demand to 50% but increases the production energy input by 11% from 909 to 1017 MWh. When comparing only the additional production energy needed for the refurbishment materials (MedRef_OnlyRef) to the total production energy (MedRef_all), the production contribution drops from 13.8 to 7.7%. As an interesting result from the analysis it could be shown that refurbishing existing buildings to the highest standard (advanced refurbishment) is more energy efficient than demolition and new construction, when comparing the whole life cycle. Medium refurbishment scenarios on the other hand lead to a higher demand than demolition and new construction.

Table 1: Comparison of primary energy during the whole life cycle of a multi-family building in MWh

	Production	Use	End-of-life	TOTAL
	576	10,571	104	11,251
1975	5.1%	94.0%	0.9%	100.0%
	909	5,568	110	6,587
1975_MedRef_all	13.8%	84.5%	1.7%	100.0%
	471	5,568	110	6,149
1975_MedRef_OnlyRef	7.7%	90.5%	1.8%	100.0%
	1,017	4,513	111	5,641
1975_AdvRef_all	18.0%	80.0%	2.0%	100.0%
	580	4,513	111	5,204
1975_AdvRef_OnlyRef	11.1%	86.8%	2.1%	100.0%
	741	5,054	117	5,912
2016_NewConstruction	12.5%	85.5%	2.0%	100.0%

With the use of extra insulation material the question of energetic amortisation needs to be addressed. The periods for the energetic amortisation for the refurbishments are quite short and similar. The input of the additional building materials for an advanced and medium refurbishment takes approximately 4.5 years to break even. Comparing the whole life cycle, the energy values of the newly constructed building are situated between the building cases with medium and advanced refurbishment.

This leads to the challenge of evaluating the difference between refurbishing existing buildings or their demolition and reconstruction. The period for the energetic amortisation of the demolition of the original building from 1975 plus the following construction of a new building with an advanced energy standard is approximately 7.5 years. Consequently, from the energetic point of view in this case it is better to refurbish an existing building than to demolish it and reconstruct with a better standard.

Considering the savings of energy during the whole life cycle, an advanced refurbishment is more worthwhile than a medium refurbishment or a demolition and new construction of a building with an advanced energy standard.

Case study for city quarters

The methodology was then applied to a whole city quarter, simulated with two different climatic conditions. The first simulation uses the original climate data from Stuttgart, Germany and the second simulation is performed with climate data from San Francisco, CA.

As a result of the warmer winters in San Francisco, the share of domestic hot water (DHW) is higher than the share of space heating in the entire use stage. For example in the year 2016, the primary energy demand for domestic hot water in San Francisco is 13% higher than the primary energy demand of space heating in this year. On the other hand, the primary energy demand for space heating in Stuttgart in 2016 is 86% higher than the primary energy demand for domestic hot water. In the assessment, only the building shell is considered for analysis. Therefore, the primary energy demand and greenhouse gases caused by domestic hot water demand is not affected by the refurbishment or reconstruction of the buildings and is therefore left out of the analysis.

In both assessments, the buildings are ranked according to their respective absolute improvements in total heat demand comparing 2016 to 2050. This means that buildings with the highest absolute improvement in primary energy demand are refurbished or reconstructed first.

Calculations are performed to assess both the primary energy demand and the greenhouse gas emissions for the scenarios. In the following, only the results for the greenhouse gas emissions are shown, since the characteristics are similar for both assessments.

The first analysis considers the case study with the original climatic conditions of Stuttgart, Germany.

In Figure 7 it is noticeable that the bars for each year, i.e. the annual greenhouse gas emissions, are decreasing fast in the first years which is mainly due to the high reduction of the use stage. The annual reduction slows down after approximately 15 years, because by then, the buildings with a very high heat demand have already been reconstructed or refurbished.

The production stage is higher in the first years and decreasing steadily. This is also due to the fact that the first buildings to be refurbished or reconstructed are the ones with a high total heat demand, which usually implies that these buildings have a large heated floor area and consequently a high production energy input and a high amount of greenhouse gas emissions during the production stage.

The end-of-life stages are almost not visible in the chart, since only 12% of all buildings are torn down and reconstructed, therefore the greenhouse gas emissions for demolition and disposal are very low compared to the use stage.

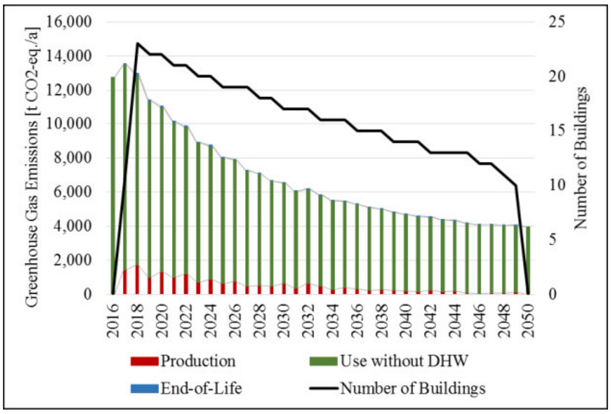

Figure 7: Greenhouse gas emissions for the Stuttgart scenario and number of buildings torn down and reconstructed or refurbished every year

The reduction of greenhouse gas emissions of the use stage in 2050 compared to 2016 is 69%. However, if the greenhouse gas emissions of the production and end-of-life stages are added to the use stages over 34 years and compared to a reference scenario (which consists of the same use stage for each year, since there are no changes to the existing buildings during the entire time period), the reduction is 54%.

The second analysis considers the same case study, i.e. the same building geometries and configurations with the same refurbishment and reconstruction measures, with the climatic conditions of San Francisco, CA.

First, it needs to be noted that the primary axis in Figure 8 is scaled differently than Figure 7, since the annual emissions are significantly lower in San Francisco than in Stuttgart.

Figure 8 shows the same measures as Figure 7, but the impact is very different and shifts the ratio between the different life cycle stages. Since the use stage is very low in the San Francisco scenario, the use and production stages have a similar contribution to the annual greenhouse gas emissions. In addition, the end-of-life stages have a higher share of the life cycle by comparison to the Stuttgart scenario, although the absolute values are the same in both scenarios.

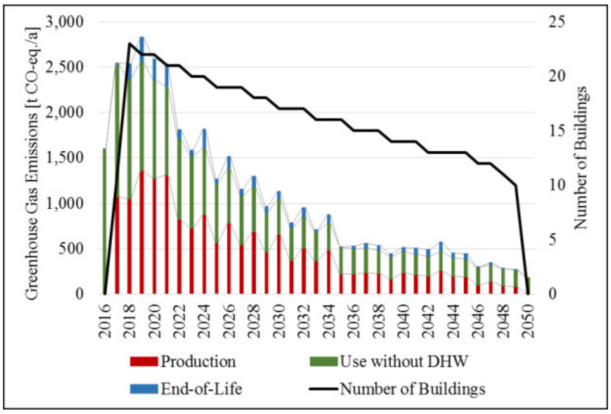

Figure 8: Greenhouse gas emissions for the San Francisco scenario and number of buildings torn down and reconstructed or refurbished every year

The reduction of greenhouse gas emissions of the use stage in 2050 compared to 2016 is 89%. However, if the greenhouse gas emissions of the production and end-of-life stages are added to the use stages over 34 years and compared to the reference scenario, the reduction is 34%.

Figure 9 shows the cumulated greenhouse gas emissions over all life cycle stages for both assessments in Stuttgart and San Francisco from 2016 until 2050. This comparison clearly shows that the production and end-of-life stages are the same in both scenarios, but the use stage is considerably different and is very dominating in the Stuttgart scenario.

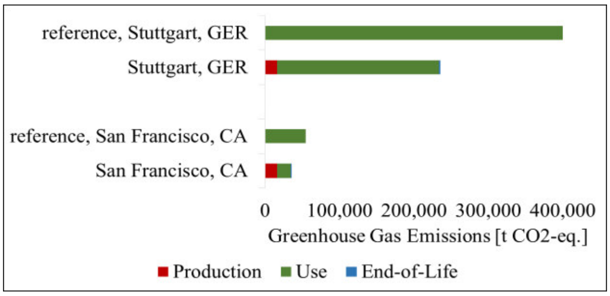

Figure 9: Cumulated greenhouse gas emissions for Stuttgart and San Francisco over all life cycle stages until 2050, compared to the reference scenario

Discussion and conclusion

A method for calculating the different life cycle stages production, use and end-of-life of a building or city quarter was developed in this work. 3D urban geometry data based on the CityGML standard was used for all simulations. The method was tested and verified on building cases with different insulation standards and a comparison between building refurbishment or building demolition and new construction was carried out.

The main result of the analysis was that the highest building refurbishment standard resulted in the best life cycle energy and emission performance when compared with less ambitious refurbishment or construction of a new building of today's standards.

Using the new methodology and simulation framework, the whole life cycle of city quarters can be analysed by calculating their values for energy and greenhouse gases.

For future studies, additional forecasts regarding the change of energy systems used in residential buildings must be included in the analysis as well as the change of the primary energy factors. For example, the future primary energy factor for electricity is estimated to decrease, caused by the rising share of renewable energies in the electricity grid. Moreover, old conventional energy systems are going to be replaced by more efficient renewable energy systems in the years ahead. Both effects could contribute amongst others to a decreasing primary energy demand in the building sector.

The scenarios analysed in this study include ambitious building standards for refurbished or newly constructed buildings. With these standards and the climatic conditions of Stuttgart, Germany, a reduction of the greenhouse gases emitted during the use stage of roughly 69% can be achieved instead of the aim of 80-95% greenhouse gas emissions reduction of the German federal government. However, if all the greenhouse gas emissions, which means the production and end-of-life stages, are added to the use stages, accumulated over 34 years and compared to the reference scenario, the cumulated reduction adds up to only 54% for the Stuttgart scenario.

The reduction of greenhouse gas emissions of the use stage for the San Francisco assessment in 2050 compared to 2016 is 89%. However, if the greenhouse gas emissions of the production and end-of-life stages are added to the use stages over 34 years and compared to the reference scenario, the reduction is 34%.

Comparing these numbers to the reductions of the Stuttgart scenario, the high influence of the climatic conditions is evident. It is clear that the achieved use stage reductions in San Francisco are considerably higher than in Stuttgart. However, the reductions of greenhouse gas emissions over the whole life cycle are a little less than in the Stuttgart scenario. This is due to the fact that the ratio of the production and end-of-life stages is higher, which contribute with the same amount in both scenarios.

Even though the measures seem to be over-ambitious for the San Francisco climate at first, if the ambitions for emission reductions in mild climates such as California are similarly high as in Germany, an akin advanced building standard is required. Moreover, since the domestic hot water demand is higher than the space heating demand in such mild climates, renewable solutions to satisfy this demand should be prioritised to reduce the primary energy demand and resulting emissions.

Economic factors do not play any role in the assessments presented in this study. If they were taken into account, the goal of saving a maximum of primary energy and reducing greenhouse gas emissions might be conflicting with the cost of the necessary improvements.

The results can be used for giving recommendations for action to policymakers, building authorities or building owners.

The current policy instruments in Germany do not motivate or force building owners to refurbish their buildings to such ambitious building standards (ENTRANZE consortium 2014). In reality many building owners orient their activities according to the minimum legal requirements, so without strengthening of these requirements, it will be difficult to accomplish the ambitious energy efficiency goals set by the European parliament and the federal government in Germany.

Designing sustainable city quarters will make an important contribution to saving energy and emitting less greenhouse gases in the context of ongoing urbanisation.

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