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A preliminary research on the benchmark of building resource consumption and sustainable strategies in Chinese eastern cities – Qingdao as a case study

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ABSTRACT
With China's urbanization process, a number of medium-sized cities in the south eastern coastal areas have also entered a period of rapid development. Fast-growing cities are facing many challenges, such as housing demand and resource depletion in connection with the rapid population growth. Building industry, which contributes to a large amount of resource use, plays an important role in climate change. Along with the updating of energy saving standards, the thermal condition of building envelopes has also been dramatically improved. Therefore, energy consumption for space heating and cooling has been significantly reduced in recent years. However, there is still a lack of research concerning the embodied energy mainly caused by material use. A benchmark of life-cycle resource use in the building sector is urgently required in practice in order to achieve a more sustainable development in China. This research took the city Qingdao as a case study and examined lifecycle resource use of typical office and residential buildings with different structures and thermal conditions. The method and result could be considered as a reference for a more complete research on a building lifecycle resource use in the future. In the end of this paper, a neighborhood in Qingdao was taken as a case study to show the application of resource use benchmark in the future.

Keywords: Resource use benchmark, environmental impact, Chinese eastern cities, embodied energy, life-cycle analysis, sustainable strategies

1. INTRODUCTION

With ongoing urbanization, the urban population has been growing fast in recent decades. According to the report from UN Department of Economic and Social Affairs, by 2050, the global urban population will increase by 2.5 billion, of which China will add 255 million. [1] A number of medium-sized Chinese cities have also entered a period of rapid development, especially cities in the eastern coastal areas, such as Qingdao. Fast-growing cities are facing many challenges. The increasing housing demand is one of them. Since the building sector contributes to a large amount of resource use, it plays an important role in climate change. Along with the getting stricter energy saving standards [2,9], energy consumption in building operation such as space heating and cooling has been significantly reduced in recent years. However, the embodied energy that is mainly caused by material use was relatively less improved.

Therefore, an entire lifecycle concept in the investigation of building resource consumption and its environmental impact is needed. There were some valuable previous researches in this field [3-7]. However, due to the difference of calculation boundary and method, their results vary a lot and are usually hard to be compared or integrated (Fig 1). In order to better understand the building resource use and consequently guide the construction practice onto a climate-protective path, there is an urgent need for a comprehensive building resource use benchmark in Chinese building industry. Since the year 2019, the standard for building carbon emission calculation [8] has been promulgated and implemented in China.

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It offers the opportunity to comprehensively examine the carbon emissions of Chinese buildings by using a unified method. The research demonstrated in this paper will follow this standard and took the city Qingdao as a case study to examine lifecycle resource use of typical office and residential buildings with different structures and thermal conditions. Furthermore, a neighborhood in Qingdao will be taken as an example to show the application of resource use benchmark in an urban district. In the end, sustainable strategies such as material recycling and renewable energy application will be discussed.

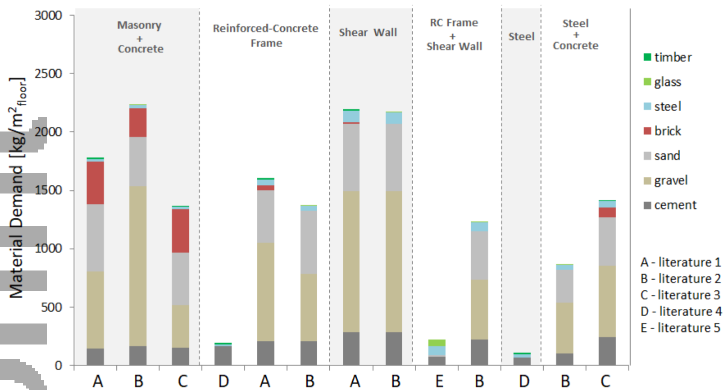


Fig 1 Construction material consumption varies among literatures.

2. METHODOLOGY

2.1 Structure of research

As shown in Fig 2, this research consists of two parts. The first part focuses on building level and defines prototypes according to three criteria, which are building function, building structure and thermal condition. The material use of the main structure and the energy demand of building service systems are examined through calculation and simulation. Then, the environmental impact that was caused by resource use is calculated by using the carbon emission factor of materials and fuels. In the second part of this research, the discussion is enlarged from buildings into the urban district level. Through the classification of buildings, the selected urban area is transformed into a mixture of typical buildings. The building resource use and the corresponding carbon emission in the examined district are calculated based on the results of the first part (building level). The sustainable strategies such as material recycling and renewable energy application are also discussed with their potential in resource saving on both building and district level.

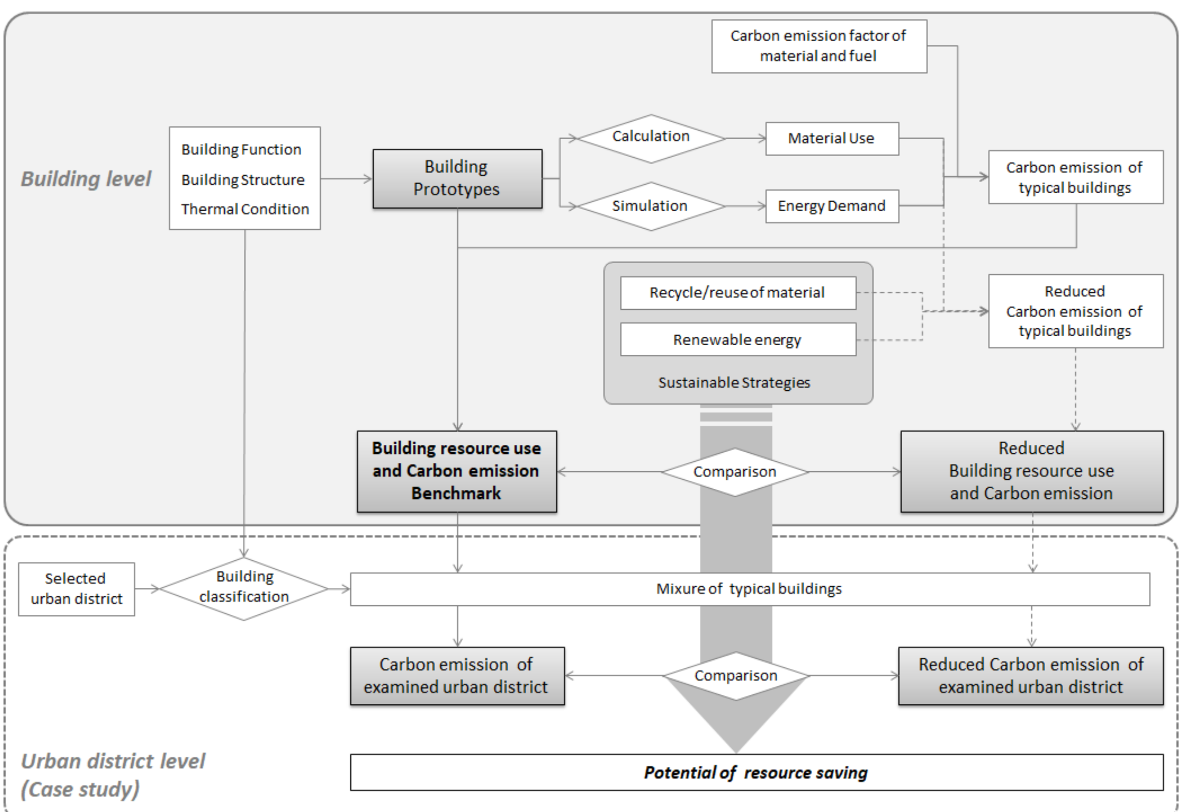
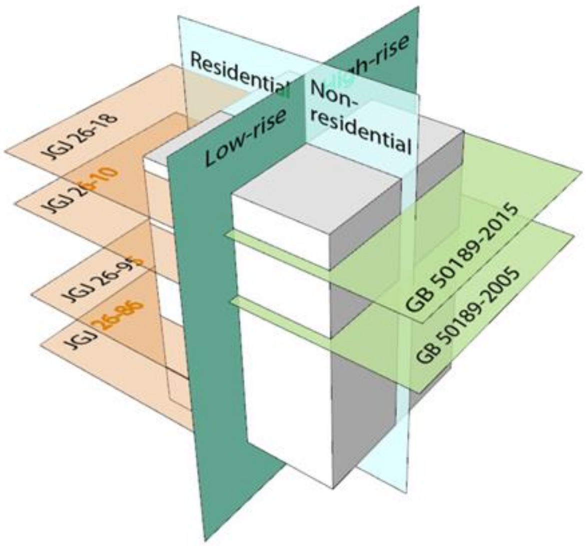


Fig 2 Structure of research.

2.2 Building Prototypes



	RESIDENTIAL	
	multi-family low-rise	high-rise
	M+C	RC+SW
before 1986	R-01	R-06
1986-1994	R-02	R-07
1995-2009	R-03	R-08
2010-2017	R-04	R-09
after 2018	R-05	R-10

	NON-RESIDENTIAL	
	low-rise	high-rise
	RC	RC+SW
before 2005	O-01	O-04
2005-2014	O-02	O-05
after 2015	O-03	O-06

M+C Masonry + concrete
RC+SW RC Frame + Shear wall
RC Reinforced concrete frame

Fig 3 Building classification criteria and prototypes.

This research took the city Qingdao as an example of Chinese eastern cities. As shown in Fig 3, buildings were categorized into different groups, depending on their completion year, structure type and building function. The thermal conditions of building envelopes were assumed to meet the valid building energy-saving standards of the completion year. Standard JGJ 26-86 (and its updates in 1995, 2010 and 2018 [2]) was taken as reference for residential buildings, while GB50189-2005 (and its updates in 2015 [9]) for office buildings. Regarding to building structure, "Masonry & Concrete" was selected for low-rise residential building while "Reinforced Concrete Frame" for low-rise office building. The structure type "RC Frame & Shear wall" was considered for high-rise buildings, both residential and office. Based on this, 16 building prototypes were identified (ten residential + six non-residential) (Fig 3):

- 6-floor residential building ("R 01-05"), Masonry & Concrete.
- 5-floor office building ("O 01-03"), Reinforced Concrete Frame.
- 18-floor residential building ("R 06-10"), RC Frame & shear wall.
- 24-floor office building ("O 04-06"), RC Frame & shear wall.

All these prototype buildings are assumed to have a basement with the room height of 2.2m. The floor height is set to be typically 4m in office building and 3m in residential, respectively.

3. CALCULATION AND SIMULATION

3.1 Material consumption

3.1.1 Boundary of material use calculation

In this research, the material use for the buildings' main structure, including wall, ground, floor and windows, was examined. Decoration and ancillary components are not discussed. Four prototype buildings with three different structures were modelled with the BIM modelling tool Revit (version 2020).

3.1.2 Material use of main structure

According to the "Material take-off list" outputted from Revit models, the material use of these prototype buildings are summarized as Fig 4. In this calculation, the consumption of reinforced concrete is divided into cast-in-place concrete and steel rebar by using a weight percentage. The brick wall is also divided into bricks and mortar according to the conventional masonry method.

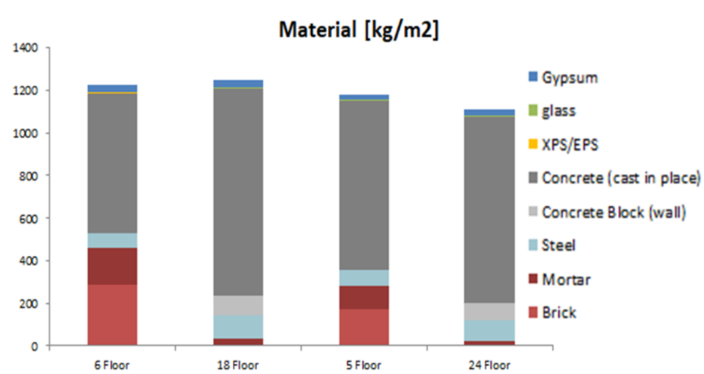


Fig 4 Material use of examined building prototypes

In order to have a comprehensive concept of the entire building life, the transport of raw materials from the factory to the building site was also considered. As suggested by the standard GBT 51366-2019 [8], medium-sized diesel trucks are assumed as the transportation medium with carbon emission factor 0.179 kg $CO_2e/(t\cdot km)$. The transporting distance is supposed to be 40km for concrete ("cast-in-place concrete" and "concrete block") and 500km for other materials, respectively.

3.2 Energy consumption

3.2.1 Boundary condition of thermal simulation

The energy consumption for heating, cooling and lighting of each building prototype were examined by using thermal simulation. The city Qingdao locates in the "Cold climate zone" in China [11]. The corresponding energy saving standard JGJ 26 [2] and GB 50189 [9] were taken as the reference for the thermal condition of the building envelopes in residential and office buildings, respectively. The heating setpoint temperature during heating period (01.Nov – 31.Mar) is 18 degrees in residential buildings and 20 degrees in office buildings. The cooling setpoint temperature is 26 degrees during cooling period (01.Apr – 31.Oct). In total 16 building energy models ("R01-R10", "O01-O06") were built by using thermal simulation software DesignBuilder (version 6.1.0).

3.2.2 Building energy consumption

According to the simulation results as shown in Fig 5, the heating demand is dominant in both residential and office buildings. With the continuous improvement of energy saving standards, energy demand has been steadily reduced, especially in residential buildings. The final energy consumption is largely influenced by building service system. In the cold climate zone in China, most cities locate in district heating regions, such as Qingdao. The space heating is supplied by district heating systems (distribution efficiency = 90%), where the heat source is generated 50% by co-generated heat and power system (CHP), 33% by centralized coal boiler, 12% by centralized gas boiler, and 7% by others. In this research, the final energy demand of the building prototypes was calculated in two scenarios (Fig 5), which are „scenario 1 – Coal boiler district heating" and "scenario 2 – CHP district heating", respectively. In both scenarios, the cooling demand is covered by air-conditioner (COP=4), which is the most popular equipment for space cooling in China.

Comparing to „scenario 1 – Coal boiler district heating", the energy consumption for space heating in "scenario 2 – CHP district heating" is significantly higher. However, the co-generated electricity by CHP offers a large amount of CO_2 credit and works as a compensation.

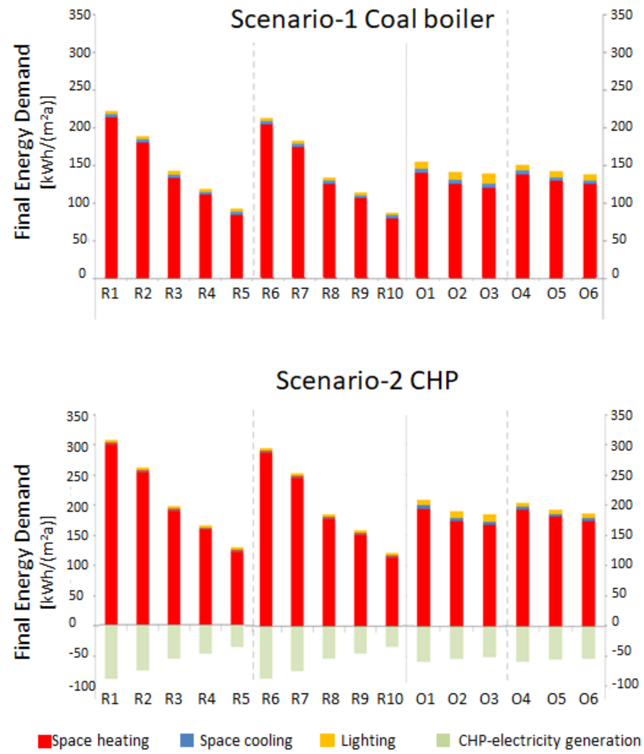


Fig 5 Energy consumption of building prototypes.

4. RESULTS AND DISCUSSION

4.1 *Lifecycle resource use of typical buildings*

In previous chapters, material uses in construction phase and energy consumption in operation phase were

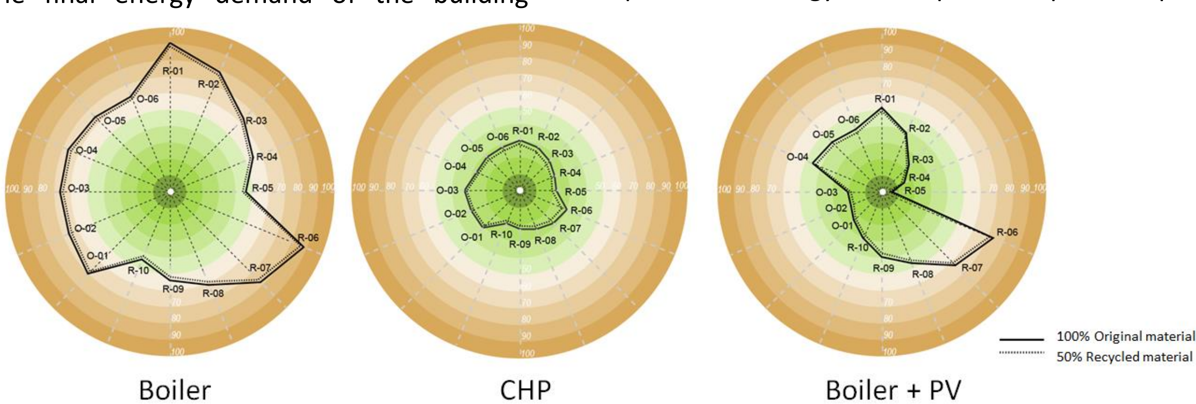


Fig 6 Lifecycle CO_2 emission benchmark

separately calculated for each building type. In China, the building life is normally considered as 50 years. Calculated with the carbon emission factor of fuels (coal: 0.34 $kgCO_2e/kWh$, electricity: 9914 $kgCO_2e/kWh$) and materials [8], the annual CO_2 emission in entire building life of each building prototype was calculated and shown as Fig 6. Because of the CO_2 credit of co-generated electricity, lifecycle CO_2 emission of buildings in "scenario 2 – CHP district heating" is 51%-67% less than that in "scenario 1 – Coal boiler district heating".

4.2 Resource use in a neighborhood – case study

In this Chapter, a neighborhood with the size around 1sqkm in Qingdao was selected for a case study to show the application of building resource use database. This neighborhood includes residential buildings from the 1980s, 1990s and newly-built projects. Therefore it was announced as typical neighborhood in the research of Dr. Deng [10]. Buildings in this neighborhood are mostly multi-floor residential buildings, which are older than ten years. There are a few new-built high-rise residential projects along the northern border. Non-residential buildings contribute to only 20% of total floor area in this neighborhood. In order to simplify this research, non-residential buildings in this case study were considered as office buildings. The layout and the classification of buildings are shown as Fig 7.

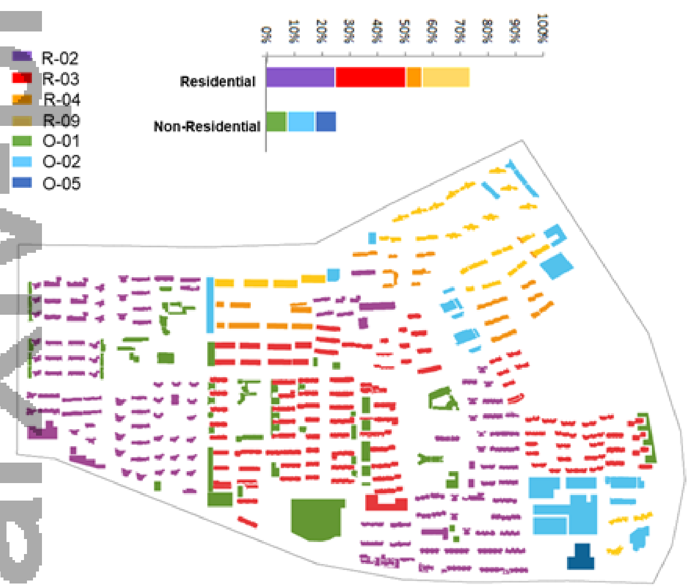


Fig 7 A neighborhood in Qingdao.

The resource use and CO_2 emission of this urban area is considered as the sum of all buildings'. Based on the previously calculated value on building level (chapter 4.1), the CO_2 emission in this neighborhood is 66 $kgCO_2e/(m^2a)$ and 27 $kgCO_2e/(m^2a)$ in "scenario 1 – Coal boiler district heating" and "scenario 2 – CHP district heating", respectively.

4.3 potential of resource saving

4.3.1 Material reuse/recycle

With the development of technology, several building materials become reusable or recyclable. However, in practice, a large amount of construction waste is directly discarded without proper treatment. In order to solve this problem and encourage the recycling/reuse of construction waste, a series of relevant standards and regulations have been issued at the national and local levels. The „Implementation plan for comprehensive utilization of bulk solid waste" announced that, by 2015, the utilization rate of construction waste in large and medium cities across the country should increase to 30%. In the year 2013, "Qingdao Municipal Construction Waste Resource Utilization Regulation" was implemented. According to this regulation, the plan of construction waste treatment is required before the demolition.

In this case study, 50% of construction materials were supposed to be recycled materials, with a carbon emission factor considered as half of the original. On this basis, the lifecycle CO_2 emission of building prototypes were re-calculated. (Fig 6) Compared to the non-recycle scenario, the CO_2 emissions of the examined neighborhood can been reduced to 64 $kgCO_2e/(m^2a)$ and 25 $kgCO_2e/(m^2a)$ in "scenario 1 – Coal boiler district heating" and "scenario 2 – CHP district heating", respectively.

4.3.2 Renewable energy

Using on-site renewable energy to cover the energy consumption in the operation phase is another solution for reducing the greenhouse gas (GHG) emission of building sector. The roofs and façades could be used for PV/solar system, while the ground under the building could be used for ground-source heat pump. In Qingdao, the global solar radiation is approx. 1868 $kWh/(m^2a)$. With the PV-efficiency of 15%, annual PV-electricity generated on $1m^2$ building footprint is about 280 $kWh/(m^2a)$.

If the roof of the prototype buildings is covered by PV panels, the electricity requirements for space cooling and lighting could be fulfilled by the on-site generated PV-electricity. On this basis, the building lifecycle CO_2

emission of the examined neighborhood could be reduced to 31 $kgCO_2e/(m^2a)$ in "scenario 1 – Coal boiler district heating" (53% reduced), while in "scenario 2 – CHP district heating" the CO_2-neutral neighborhood could be achieved.

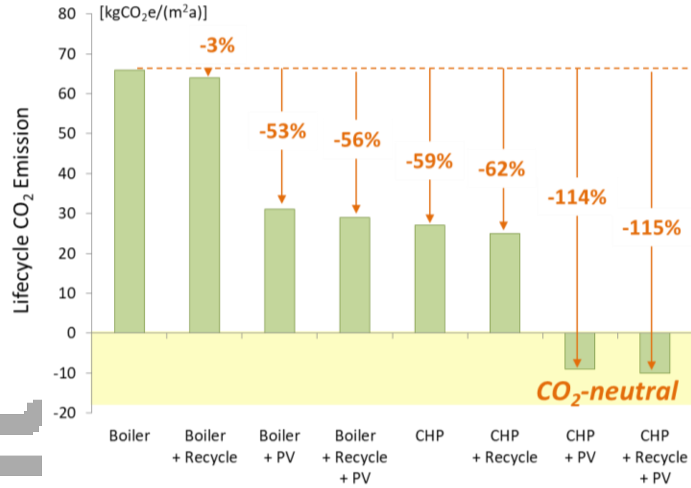


Fig 8 Reduction of lifecycle CO_2 emission by using different resource saving strategies.

Fig 8 illustrates the potential of GHG saving by different sustainable strategies. Comparing to the basic case, the lifecycle CO_2 emission of the examined neighborhood could be 3% reduced by material recycling, 53% reduced by PV-roof. Using CHP instead of coal boiler as heat source of district heating could cut half of GHG emission. The combination of various sustainable strategies could finally achieve CO_2-neutrality in the examined neighborhood.

5. CONCLUSION

This research focused on the lifecycle resource use and corresponding CO_2 emission of buildings in eastern Chinese cities. As one of the most important cities in this region, Qingdao was selected as an example. Buildings were classified into 16 types according to three criteria of building function, structure type and thermal condition. Building prototypes were modeled and investigated with their material use and energy consumption. According to this research, the lifecycle CO_2 emission of examined 16 building prototypes are between 42-91 $kgCO_2e/(m^2a)$ and 61-70 $kgCO_2e/(m^2a)$ in residential and office buildings, respectively. Furthermore, a residential neighborhood in Qingdao was selected as a case study to show the application of building resource use benchmark in the future. The potential of reducing resource use and GHG emission by the recycling of material and the application of renewable energy was also discussed with the case study. It is shown that the examined neighborhood could achieve CO_2-neutrality by a combination of CHP district heating, material recycling and PV roof.

Since the building sector is a large contributing factor to global climate change, resource use and its environmental impact is an urgent research topic. The method and results demonstrated in this paper could be considered as a reference and be helpful for the relevant researches in the future.

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