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Historical Evolution and Scenarios Up to 2050 of Heating Energy Consumption and CO_2 Emissions of Residential Buildings in Vienna

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Abstract

Today, the building sector poses a major problem concerning fossil fuel energy consumption and the corresponding emissions of local pollutants and global greenhouse gases (GHG). In addition, an increasing number of people are living in urban areas, and it is becoming challenging to provide the necessary living space and energy for heating in fast-growing cities. Currently, urban areas host approximately 50 % of the global population and generate 70 % of GHG. The core objective of this study is to analyze the historical development and to derive scenarios for the possible future development of the overall CO_2 emissions in residential buildings in Vienna up to the year 2050, considering all relevant emissions from final energy, as well as the embedded emissions from the construction of new buildings, retrofitting, and rooftop apartment extensions. This study indicates the following key points: (i) The renovation of buildings by improving the thermal quality is the most favorable scenario strategy and produces the least CO_2 emissions. (ii) The transition to the sustainable heating of buildings requires at least a temporary "investment" in embedded CO_2 emission, e.g., in retrofitting and insulation of buildings to harvest reductions in CO_2 emissions in the long run, from a smaller amount of energy used for heating. The major conclusions of this study are as follows: (i) To implement the most favorable renovation scenario, strong policy measures are required, such as standards for new buildings and for building retrofitting, as well as subsidies to ensure an accelerated refurbishment rate of the old low thermal building stock. (ii) It is important to reduce the CO_2 emission of the final energy carriers, especially of district heating, by increasing the usage of renewable energy carriers such as biomass, solar, and geothermal.

Keywords

CO_2 emissions; residential buildings; heating; scenarios; CO_2 factors

1. Introduction

The building sector is the second-largest major contributor to emissions after transport, causing approximately 20 % of the overall global greenhouse gas (GHG) emissions in the city of Vienna, Austria [1]. In 2020, Vienna had approximately 1.93 million inhabitants. In addition, the city is expected to have approximately 20 % more population by 2050 than it had in 2020 [2]. This leads to the demand for more living space, which increasingly consumes energy, particularly for heating [3]. The building sector, in general, poses a major problem with respect to the consumption of fossil fuel energy and the corresponding emissions of local pollutants and GHG emissions. To mitigate the GHG emissions and transform cities towards a low-carbon future, different measures, strategies, and technologies in urban buildings for retrofitting the existing building stock, as well as newly built dwellings, are being promoted by policymakers.

The core objective of this work is to study the history of the overall CO_2 emissions in residential buildings in Vienna and develop scenarios up to the year 2050, considering the emissions from the final energy as well as embedded emissions from the construction of new buildings, retrofitting, and rooftop apartment extensions.

In this study, three scenarios derived from Lederer et al. [4] have been investigated. The first is the business as usual scenario, where current policies are retained, and no new political interferences occur. The scenario is based on the evolution (number, size, building category, and attic expansion) of residential buildings from 1991 to 2050. The second scenario is the demolishing old buildings scenario, where the focus is on demolishing buildings that have poor thermal insulation and constructing new buildings. The third scenario is the renovation scenario, where policymakers promote an ambitious investment in the insulation of buildings and more efficient windows. In this scenario, none of the residential buildings constructed before 1946 will be demolished.

The major new contribution of this study is that it takes the GHG emissions from the final energy from the heating apartments and the embedded emissions from building construction, material, and retrofitting into consideration. In addition, changes in the building stock can also be observed.

The scenarios considered in this study have been chosen because they are considered the most realistic scenarios, and there are no other known scenarios at this time. As will be described in the following paragraph, the importance of retrofitting has already been presented in other articles (Lederer et al. [4], Luo et al. [5], and Zhou et al. [6]). This article summarizes its contribution to the area.

Previous studies have already dealt with similar topics, from which valuable findings have been derived. Lederer et al. [7] analyzed the role of material intensities (MI) in research on the material stock in buildings. By knowing the MI in tons material/net floor area (NFA, in m^2) for the different types of buildings investigated and the number of overall area (m^2) heated, as well as the specific CO_2 factors of the different building materials, the embedded CO_2 emissions were calculated. Different scenarios have also been developed by Lederer et al. [4] with respect to the consumption of raw materials for the construction of buildings. One of their main results is that by avoiding the demolition of old buildings, but with an extensive renovation (higher thermal insulation standard and attic extension), the raw material consumption can be reduced by 35 % compared to the BAU scenario. Zhong et al. [8] investigated the material-related GHG emissions from residential and commercial buildings and their reduction potentials. Future trends depend on the socio-economic developments and material use and supply strategies. A baseline scenario shows that in low- and middle-income regions, emissions will increase from 22 % globally in 2020 to 51 % in 2060. In contrast, regions with higher incomes show a decrease. Almeida et al. [9] focused their study on existing buildings and the improvement of their energy efficiency. In this context, they emphasized the importance of balanced use of measures to promote the use of renewable energies and energy efficiency measures. Liu et al. [10] evaluated and quantified various energy efficiency measures in the building sector to improve their effectiveness. A system dynamics model was used to predict the effect of the different policy measures on direct and indirect energy consumption and the resulting CO_2 emissions of urban buildings. They showed that the primary energy consumption of retrofitted buildings accounts for a large share of the total urban energy consumption. Ji et al. [11] analyzed the evolution of GHG emissions from residential buildings. They found that new buildings have lower emission intensity than older buildings, and policy interventions contribute to a reduction in GHG emissions from heating energy consumption. The increasing number of residential buildings accounts for the increase in emissions. External factors such as weather (cold winters, hot summers) also contribute to increased emissions, and policy interventions are often ineffective. Huo et al. [12] simulated the interaction mechanisms between the impact factors and the future development paths of carbon emissions from urban residential areas. Their main findings in the end-use were that heating/cooling (depending on the climate) has the largest energy saving effect as well as emission reduction effect. Nägeli et al. [13] conducted an investigation on which political measures can be used to reduce GHG emissions in the building sector. They found that ambitious targets can only be achieved by an almost complete phase-out of fossil fuel heating systems. A CO_2 limit for new and existing buildings is required to achieve this. Geng et al. [14] analyzed the CO_2 emissions from urban buildings from a life-cycle perspective. Embedded emissions from materials used in new buildings, from the operation of existing buildings, and buildings being demolished were examined. Most emissions were caused during operation. Seo et al. [15] estimated the CO_2 emissions generated during the entire life cycle of various residential buildings. The authors also concluded that most CO_2 emissions were generated during building operations. Luo et al. [5] conducted a life-cycle analysis to investigate the impact of renovating old residential areas on carbon emissions by considering the materialization, demolition, and operation phases in their study. They concluded that the renovation of old residential buildings leads to reduced emissions in the use phase. For the other phases, reduction potentials through renovations are often overestimated if embedded emissions are not considered. Renovation measures that are particularly effective are solar photovoltaic addition, greening addition, and waste recycling. The GHG emissions produced during the construction phase of the buildings were investigated by Hong et al. [16]. The results of their investigation showed that 97 % of the emissions are due to direct and indirect emissions such as on-site electricity consumption or production of building materials. Tirth et al. [17] analyzed the GHG emissions generated during the construction of residential buildings. Emissions from human activities during construction, such as cooking and water consumption, were also included. The results of this study showed that the production of building materials (mainly steel, concrete, bricks, and cement) is responsible for 74 % of the total emissions. Huang et al. [18] studied embedded emissions from the construction of different building types in urban areas. He concluded that the more compact a city is built and the higher the buildings, the higher the energy storage and CO_2 emissions. The extension of the service life of buildings and its impact on the energy balance was analyzed by Zhou et al. [6]. They found that grey energy (embodied energy) can be reduced significantly when buildings are maintained. However, old, less efficient buildings are generally kept in the same condition, which, in turn, inhibits the construction of new, efficient buildings. The results of this study showed that approximately 92 % of the total CO_2 emissions of buildings occur during operation. Goldstein et al. [19] examined the energy consumption of private households and pointed out measures to reduce emissions. Their study considered various building characteristics (age, type of house, and heating fuel) as well as the influence of climate, wealth, and energy infrastructure. It was found that emissions in particularly affluent neighborhoods were up to 15 times higher than in the surrounding neighborhoods. In addition to energy retrofits, decarbonization of the electricity grid, use of decentralized low-carbon energy sources, and reduction of living space are important.

This paper is structured as follows: Section 2 provides background information on the historical evolution of residential dwellings and heating in Vienna. Section 3 describes the methods used for scenario development. The major results of the scenarios are presented in Section 4. Section 5 discusses the main findings of this study, and Section 6 presents the major conclusions from this study.

2. Historical Evolution of Residential Dwellings and Heating Energy Carriers

2.1 Residential Dwellings by Heating Energy Carrier and Area

In this section, the major 'service' parameters corresponding to residential dwellings in Vienna have been described. They are: (i) the number of dwellings, (ii) the total area heated, and (iii) the specific indicators.

Even today, a large number of apartments in Vienna are still heated by energy carriers, such as oil, gas, and coal, that are harmful to the environment. The evolution of the number of dwellings in Vienna over the period from 1990 to 2020, in terms of the fuel used for heating them, is shown in Figure 1. In 1990, 54 % of dwellings were heated with natural gas, whereas in 2020, this percentage was 47 % (0.43 million). Only 31 % of households were heated by district heating in 1990, but by 2020, this figure had risen to almost 43 % (0.4 million). Other forms of heating in Vienna are sorted in descending order: electricity, oil, other fuel, and wood. However, most of the dwellings in Vienna are heated by natural gas.

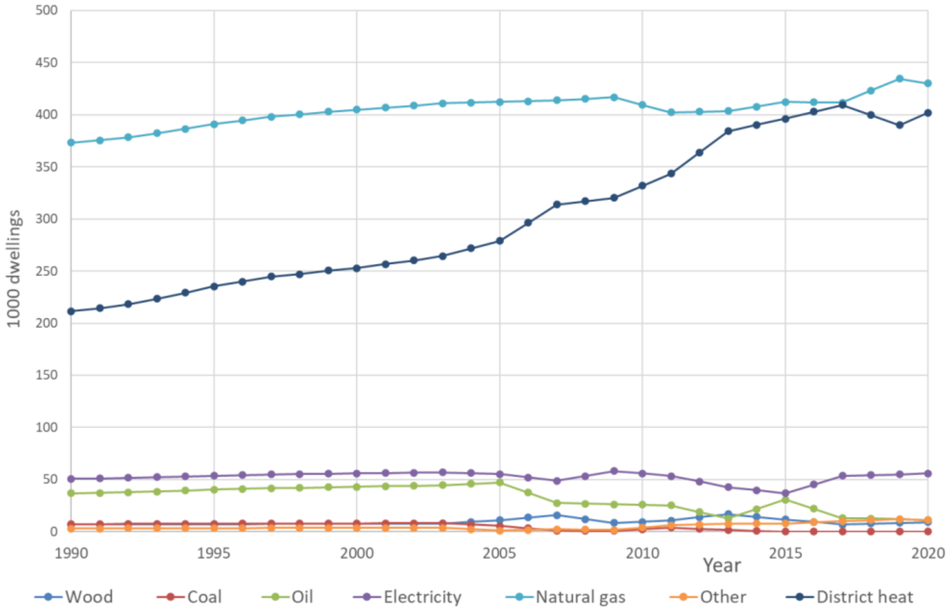

Figure 1 Historical evolution of the number of dwellings in Vienna heated by different energy carriers from 1990 to 2020.

In addition to Figure 1, the floor space of the dwellings (in m^2) in Vienna from 1990 to 2020 in terms of their construction period and retrofitting is shown in Figure 2. Among them, 42 % of the dwelling stock was unrenovated dwellings constructed between 1946 and 1980, and 1990. This share had already decreased to 22 % by 2020. Nevertheless, around 35 million m² of the effective floor area (half of the total effective floor area) in Vienna in 2020 still consisted of unrenovated apartments in old buildings constructed between 1800 and 1980.

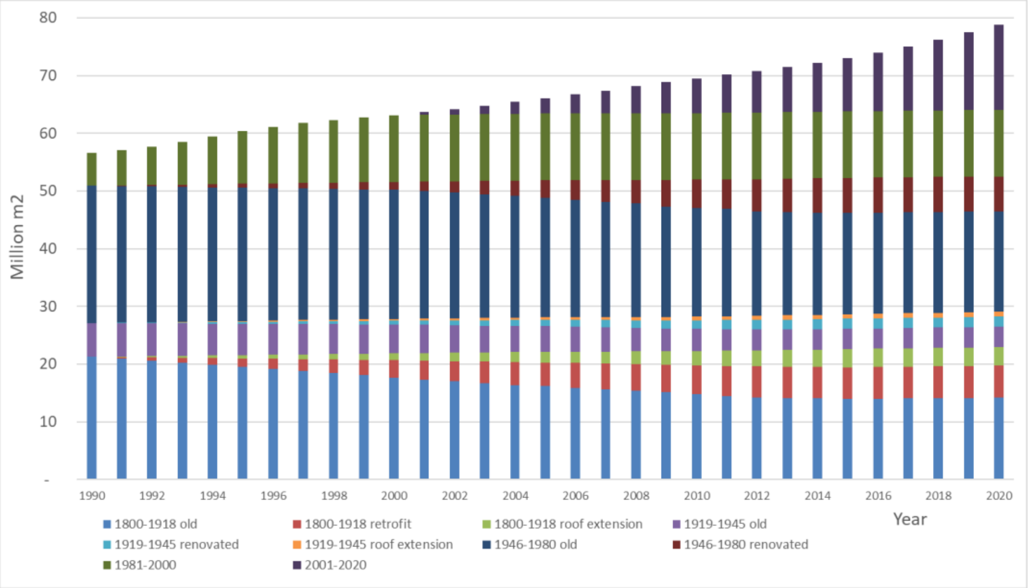

Figure 2 Evolution of the floor space area of apartments in various buildings in Vienna based on their construction period and category from 1990 to 2020.

The evolution of the different indicators of energy and CO_2 emission owing to heating in the residential dwellings in Vienna from 1990 to 2020 is illustrated in Figure 3. The energy demand per floor area (in GWh/m^2) has decreased only slowly over time; Whereas the indicator in 1990 was 0.13 GWh/m², it was 0.11 GWh/m² in 2020. In comparison, CO_2 emissions per floor area (in kg CO_2/m^2) have been decreasing faster. In 1990, this indicator amounted to 0.035 kg CO_2/m², whereas by 2020, it had dropped to 0.025 kg CO_2/m². The CO_2 emissions per energy consumed (in kWh) have declined more slowly. In 2020, the CO_2 indicator still amounted to 0.24 kg CO_2/m².

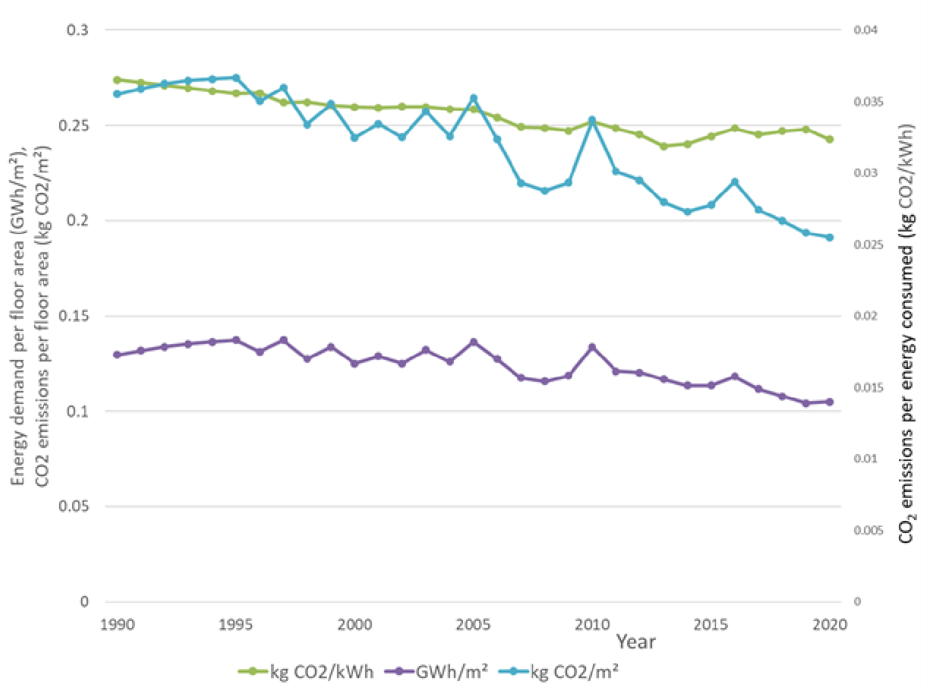

Figure 3 Evolution of the energy and CO_2 indicators of heating in residential dwellings in Vienna from 1990 to 2020.

The historical evolution of the final energy consumption of residential dwellings in Vienna in terms of different energy carriers over the period from 1990 to 2020 is depicted in Figure 4. The largest share of the final energy in 2020 was natural gas, with 56 % (4170 GWh), followed by district heating (32 %). Other energy sources (in descending order) were electricity, wood, oil, other sources, and coal. In 1990, the total final energy was 6,000 GWh, which increased to 7,500 GWh in 2020.

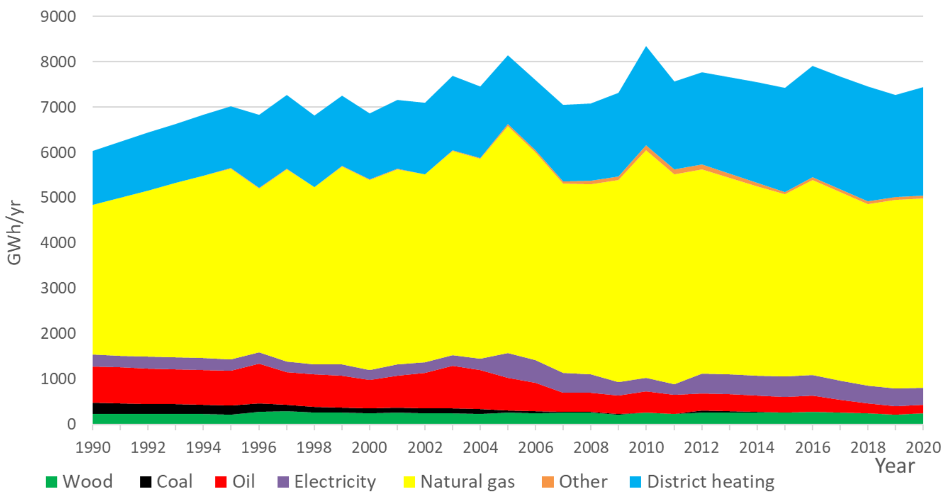

Figure 4 Historical evolution of the final energy consumed for heating residential dwellings in Vienna from 1990 to 2020 in terms of different energy carriers.

2.2 Variation in the Service, Energy, and CO_2 Emission Indices of the Residential Dwellings in Vienna

The core question discussed in this section is: What has historically happened in residential buildings in Vienna with respect to the development of heating energy carriers over the period 1990–2020?

The variation in the population, floor space (m^2), energy, and CO_2 emission indices of residential dwellings in Vienna from 1990 to 2020 are shown in Figure 5. For a detailed comparison, all values for 1990 were set to zero. Overall, all indices show an increasing trend from 1990 to 2020. The highest steady increase can be seen in the heated m^2, the number of dwellings, and population. On the other hand, m^2/dwelling exhibits a slow increase, whereas energy consumption and total CO_2 emissions are observed to fluctuate but increase from 1990 to 2020.

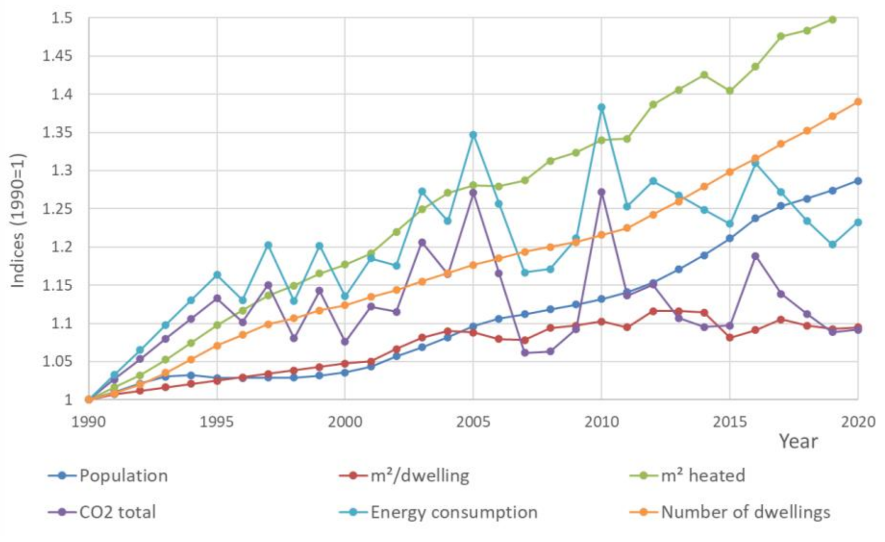

Figure 5 Variation of the population, the floor space (m^2), number of dwellings, energy, and CO_2 emission indices corresponding to the residential dwellings in Vienna from 1990 to 2020 (1990 = 1).

The variation in the CO_2 emission from the different energy carriers for heating from 2005 to 2020 is illustrated in Figure 6. Coal caused the maximum emissions with approximately 0.38 kg CO_2/kWh, followed by oil with 0.31 kg CO_2/kWh in 2020. CO_2 emissions from electricity have decreased slightly since 1995 to 0.29 kg CO_2/kWh in 2020. A similar trend is observed for district heating, with a reduction to 0.25 kg CO_2/kWh in 2020. Gas caused a CO_2 emission of 0.28 CO_2/kWh in 2020. By far, the lowest emissions are from solar energy and wood.

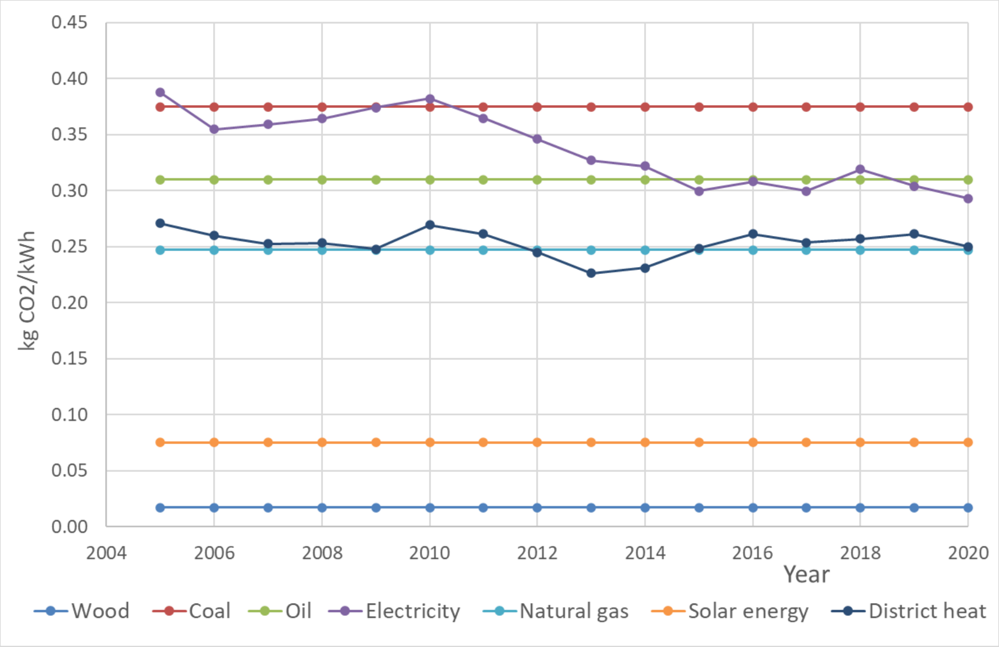

Figure 6 CO_2 emission factors corresponding to different energy carriers used for heating.

2.3 Residential Dwellings and Their Political Framework in Vienna

Since policy recommendations are also included in this work, the Smart City Wien framework, which has set specific targets for sustainable development until the year 2050, is discussed here. The revised Smart City Strategy Vienna was adopted in February 2022 [20]. The main objective of the strategy is to reduce the consumption of resources and reduce CO_2 emissions in the city of Vienna.

Concerning the development of buildings, the following goals were set, among others:

- By 2040, fossil heating, cooling, and hot water supply will phase out.
- Final energy consumption for heating, cooling, and hot water should be reduced by 20 % by 2030 and by 30 % by 2040 compared to the average values from 2005 to 2010.
- CO_2 emissions in the building sector should be reduced by 55 % by 2030 and to 0 % by 2040, compared to the average values from 2005 to 2010.
- Recyclable planning and construction for maximum resource conservation will be the standard for new construction and renovation from 2030.
- In 2040, the reusability of at least 70 % of the construction elements, products, and materials of demolition buildings and major conversions must be ensured.

A key aspect in this context is also the thermal retrofitting of buildings [21], which is promoted by the so-called *The wosan* program [22], in which structural measures such as the thermal insulation of the outer facade and renewal of windows and external doors are supported. In addition, technical measures such as the conversion to sustainable heating and hot water systems or attic conversions are also supported.

3. Method of Approach

3.1 Equations

This section describes the method of approach applied in this study for the various calculating scenarios.

The total net floor area in the scenarios is calculated as follows:

$$NFA_t = NFA_{t-1} * \frac{POP_t}{POP_{t-1}} \quad (\text{in m}^2) \tag{1}$$

where

NFA_t Net floor area in the year *t* (in m²)

POP_t Population in the year *t*

The total final energy demand in the scenarios is calculated as follows:

$$E_t = \sum E_{ijt} = NFA_{jt} * \eta_{jt} * Shd_{it} \quad (\text{in GWh}) \tag{2}$$

where

E_t Total final energy demand in the year *t*

E_ijt Energy consumption of the *j*th energy carrier in the *i*th construction period in the year *t* (in GWh)

NFA_{jt} Net floor area heated by the *j*th heating system in the year *t* (in m²)

η_{jt} Efficiency of the *j*th heating system in the year *t* (in GWh)

Shd_{it} Specific heating demand by the construction period and *i*th category in the year *t* (in kWh/m²)

$j \in$ {Wood, coal/coke briquettes, fuel oil/furnace oil/liquid gas, electric current, natural gas, other fuel, district heating}

$i \in$ {< 1919 old, < 1919 renovated, < 1919 roof extension, 1919–1945 old, 1919–1945 renovated, 1919–1945 roof extension, 1945–1976 old, 1945–1976 renovated, 1977–1996, 1997–2015}

The total CO_2 emissions for residential buildings are calculated as follows:

$$CO_{2Tot_t} = CO_{2Fin_t} + CO_{2Emb_t} \quad (\text{in Mill tons CO}_2) \tag{3}$$

where

CO_{2Tot_t} Total CO_2 emissions in the year *t* (in Mill tons CO_2)

CO_{2Fin_t} Total CO_2 emissions of the final energy in the year *t* (in Mill tons CO_2)

CO_{2Emb_t} Total embedded CO_2 emissions in the year *t* (in Mill tons CO_2)

The embedded CO_2 emissions of the residential buildings are calculated as follows:

$$CO_{2Emb_t} = \sum_{j=1}^{n} f_{CO_{2k_t}} * MAT_{ki_t} \quad (\text{in Mill tons CO}_2) \tag{4}$$

where

CO_{2Emb_t} Embedded CO_2 emission in the year *t* (in Mill tons CO_2)

$f_{CO_{2k_t}}$ Overall CO_2 emission factor of the *k*th material in the year *t* (in kg CO_2/kg)

MAT_{ki_t} Material input of the *k*th material by the *i*th construction period in the year *t* (in ton)

The CO_2 emissions of the final energy of the residential buildings are calculated as follows:

$$CO_{2Fin_t} = \sum_{j=1}^{n} f_{CO_{2j_t}} * E_{ijk_t} \quad (\text{in Mill tons CO}_2) \tag{5}$$

where

CO_{2Fin_t} Final CO_2 emission in the year *t* (in Mill tons CO_2)

$f_{CO_{2j_t}}$ Overall CO_2 emission factor of the *j*th energy carrier in the year *t* (in kg CO_2/kWh)

E_{ijk_t} Energy demand of the *j*th energy carrier by the *i*th construction period in the year *t* (in GWh)

The total material input for the construction and retrofitting of residential buildings is calculated as follows:

$$MI_{tot\ ik_t} = MI_{ik_t} * (NFA_{new_{it}} + NFA_{ret_{it}} + NFA_{roof_{it}}) \quad (\text{in kg}) \tag{6}$$

where

$MI_{tot\ ik_t}$ Total material input by type of the *k*th material in the *i*th construction period in the year *t* (in kg/m²)

MI_{ik_t} Material input by type of the *k*th material in the *i*th construction period in the year *t* (in kg/m²)

$NFA_{new_{it}}$ Net floor area of new buildings by the *i*th construction period in the year *t* (in m²)

$NFA_{ret_{it}}$ Net floor area of retrofit buildings by the *i*th construction period in the year *t* (in m²)

$NFA_{roof_{it}}$ Net floor area of buildings with rooftop extensions by the *i*th construction period in the year *t* (in m²)

The total material intensity of new, retrofitted, and rooftop construction work for different construction periods is shown in Figure 7. The materials used are concrete, bricks, mortar/plaster, wood, iron/steel, glass, mineral wool, and polystyrene. Most materials are embedded in non-retrofitted (476 kg/m³) and retrofitted (475 kg/m³) buildings from 1946 to 1980, followed by new buildings constructed between 1981 and 2015.

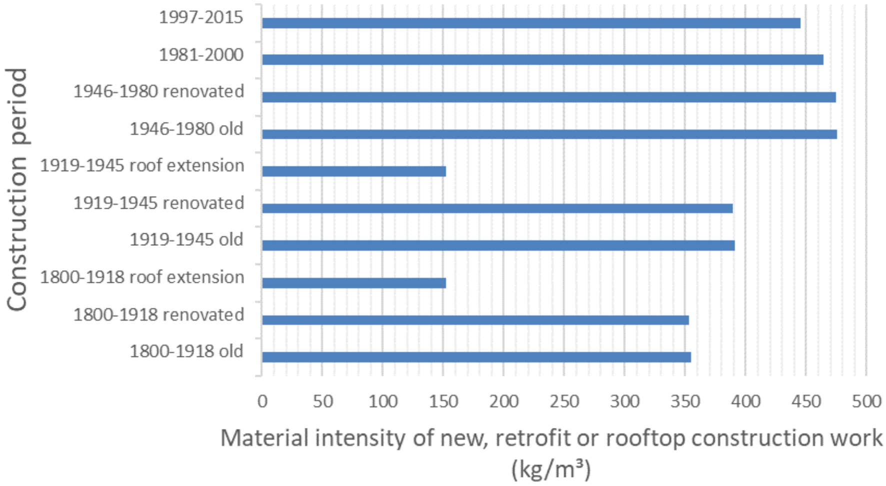

Figure 7 Total main features of materials in residential buildings [7].

The specific CO_2 emission factors of the various materials used in building construction from 1990 to 2020 can be seen in Table 1. Polystyrene causes the highest CO_2 emissions with 3.67 tons of CO_2/ton of material, followed by iron/steel with 1.52 CO_2/ton of material, and glass with 1.06 of CO_2/ton of material in 2020.

Table 1 CO_2 emission factors of different building materials ([23]).

Specific CO_2 emission factors of material (ton CO_2/ton material)				
	1990	2000	2010	2020
Concrete	0.17	0.17	0.167	0.167
Bricks	0.192	0.192	0.192	0.192
Mortar, plaster	0.948	0.948	0.939	0.939
Wood	0.028	0.028	0.028	0.027
Iron/steel	1.58	1.58	1.52	1.52
Glass	1.06	1.06	1.06	1.06
Mineral wool	0.972	0.972	0.948	0.948
Polysterene	3.61	3.61	3.67	3.67

The specific CO_2 emission factors of the final energy carriers from 1990 to 2020 are given in Table 2. The highest final CO_2 emissions (in kg CO_2/kWh) are caused by coal and coal briquettes (0.375 kg CO_2/kWh), followed by fuel oil, oil furnace, and liquid gas in 2020. The most environmentally friendly energy carriers are wood and others.

Table 2 CO_2 emission factors of different final energy carriers ([24]).

Specific CO_2 emission factors of final energy carriers (kg CO_2/kWh)				
	1990	2000	2010	2020
Wood	0.017	0.017	0.017	0.017
Coal, coke briquettes	0.375	0.375	0.375	0.375

Fuel oil, furnace oil, liquid gas	0.310	0.310	0.310	0.310
Electricity	0.388	0.388	0.382	0.293
Natural gas	0.247	0.247	0.247	0.247
Other fuel	0.075	0.075	0.075	0.075
District heating	0.271	0.271	0.269	0.250

3.2 Main Assumptions for Scenario Development

The following scenarios were defined at the city level to calculate the energy consumption and the resulting CO_2 emissions until 2050.

3.2.1 Business as Usual Scenario

The average values of the amount, size and age categories corresponding to the annually demolished buildings from 1991 to 2015 were used to forecast a possible development from 2016 to 2050 in the business as usual (BAU) scenario. This relates to the annually demolished buildings and the annually renovated buildings (retrofit by thermal insulation). Another assumption is that all residential buildings built before 1946 will have roof extensions by 2050 at the latest. This can also be derived from the trend observed from 1990 to 2015 [4].

3.2.2 Demolishing Old Buildings Scenario

The highest annual values of the number, size and age categories of the demolished buildings from 1991 to 2015 were used to perform calculations for the demolishing old buildings (DEMO) scenario. This assumption derives from the recent waste statistics, showing that in the years 2016 to 2020, the amount of demolition waste generated per year was approximately the same as the maximum value achieved from the year 1990 to 2015 [25]. As in the BAU scenario, it was assumed that all buildings constructed before 1946 will have attic extensions by 2050. However, as a higher number of these buildings are demolished compared to those in the BAU scenario, fewer buildings will have attic extensions. At the same time, fewer buildings constructed before 1980 receive thermal retrofitting since a considerable amount of public funding for housing development (*Wohnbauförderung*) is used for constructing new buildings to substitute the higher number of buildings being demolished [26]. Thus, the lowest annual value of buildings thermally retrofitted from the years 1991 to 2015 was assumed to be the average annual value in this scenario [4].

3.2.3 Renovation Scenario

In 2018, the city of Vienna enacted a new paragraph that can be used to stipulate that buildings constructed before 1946 can no longer be demolished [27]. Thus, none of the residential buildings built before 1946 will be demolished in the renovation (RENO) scenario. For residential buildings constructed after 1946, the average values for the number, size, and age categories were derived from the average values from 1991 to 2015, as in the BAU scenario. If fewer buildings were allowed to be demolished, then only fewer new buildings would have to be constructed. This would result in more financial resources available for attic extensions and particularly for thermal retrofitting of buildings than in the DEMO scenario [26]. Thus, it was assumed that all residential buildings built before 1946 will have attic conversions, and all buildings built before 1980 will be thermally retrofitted [4].

4. Results of the Scenarios

This section presents the major results of the three scenarios introduced in the previous section starting with Section 4.1 (Service: Total floor space area (m²) heated), followed by Section 4.2 (Final energy), Section 4.3 (Tons of material), Section 4.4 (Embedded CO_2 emissions) and Section 4.5 (Total CO_2 emissions).

4.1 Service: Total Floor Space Area (m²) Heated

The evolution of the total floor space area (m²) of the residential buildings heated in terms of the construction period and category over the period 2010 to 2050 is illustrated in Figure 8. In total, 70 million m² were heated in 2010. In 2050, 90 million m² will be heated. In 2010, 27 % of the heated area (19 million m²) was in old buildings from 1945–1980, followed by 20 % of the heated area (14 million m²) in very old buildings built before 1919. In 2050, 17 % of the heated area (16 million m²) will be in new buildings from 2016–2015, followed by 16 % renovated buildings from 1945–1980, and 14 % very old buildings built before 1919 but renovated.

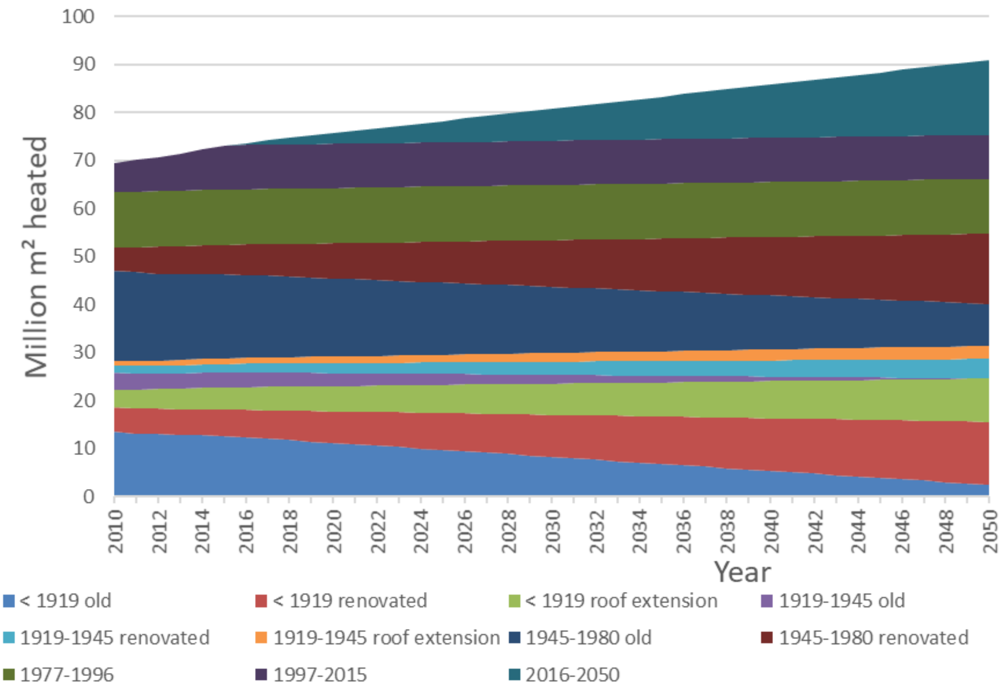

Figure 8 Evolution of the total heated area (m²) of residential buildings in Vienna by construction period and retrofit category in the BAU scenario up to the year 2050.

The evolution of the total m² of the residential buildings in Vienna heated from 1990 to 2050 is shown by the upper line in Figure 9. In addition, the evolution of the area of the stock existing in 2015 in the three scenarios up to the year 2050 is also shown. It can be seen that the largest area remaining from the 2015 area is in the RENO scenario, followed by the BAU. In the DEMO scenario, the highest new construction quantity is implemented.

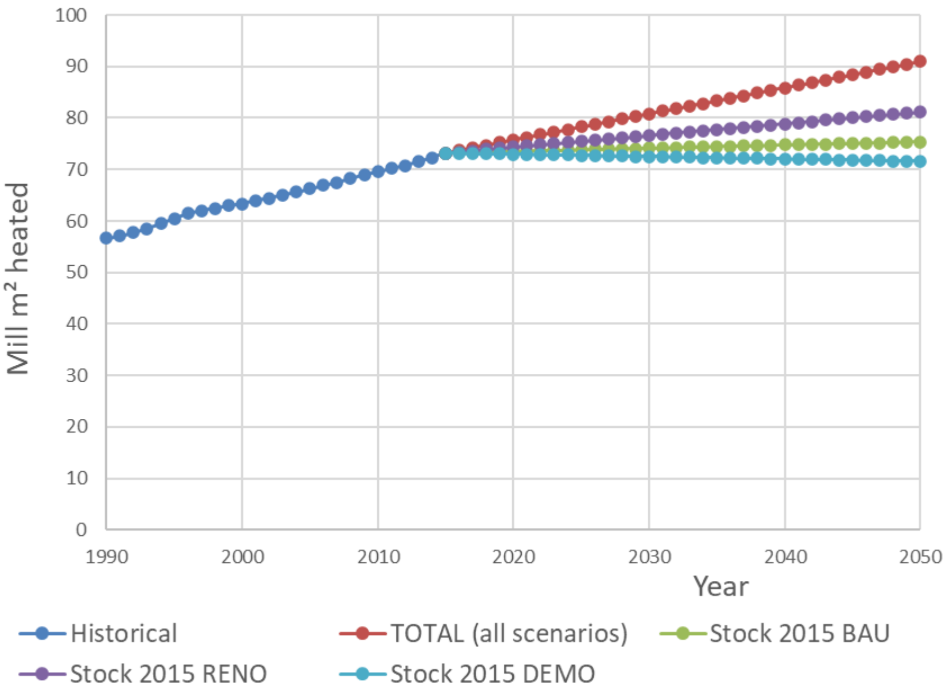

Figure 9 Evolution of total heated area (m²) of residential buildings in Vienna in total and for the stock of 2015 in the three scenarios, up to the year 2050.

The evolution of the area of the residential buildings in Vienna heated over the historical periods, namely, 'built before 1919' and '1945–1960', in the three scenarios up to the year 2050, is illustrated in Figure 10. Overall, the largest area is heated in the renovation (RENO) scenario from 2015, followed by the BAU and the DEMO scenarios. As of 2015, the largest area share in the RENO scenario is heated in buildings from 1945–1980. This is followed by the share of the area in historic buildings built before 1919. In the BAU scenario, the largest share of the heated area as of 2015 is in the buildings built between 1945–1980, followed by heated areas in the buildings built before 1919. In the third scenario, the DEMO scenario, the largest share of heated floor space is once again in buildings built between 1945–1980, followed by the buildings built before 1919.

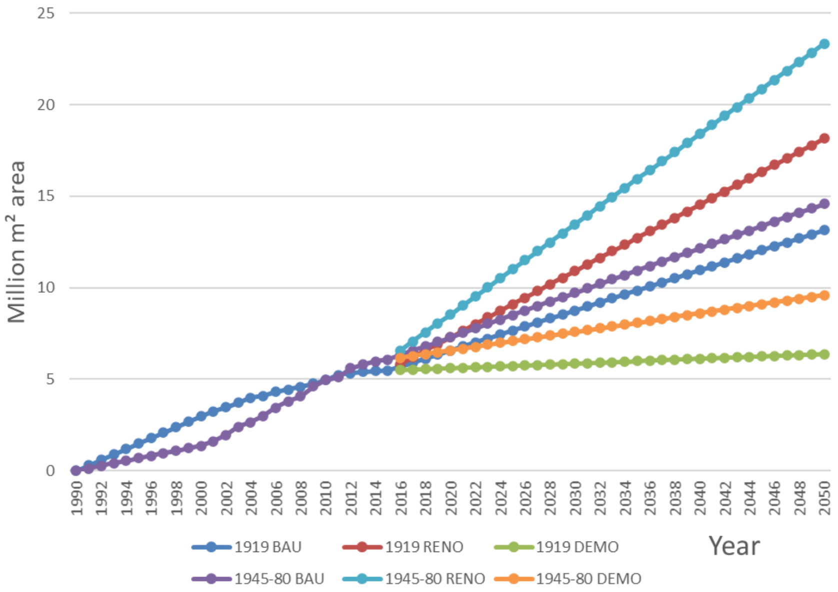

Figure 10 Comparison of the evolution of the heating area of residential buildings in Vienna constructed in two historical periods (before 1919 and between 1945–1960) with respect to the retrofit category in the three scenarios up to the year 2050.

4.2 Final Energy

The evolution of the total final energy of the residential buildings in Vienna in terms of the different energy carriers in the BAU scenario up to the year 2050 is illustrated in Figure 11. Until 2050, the final energy will steadily decrease. In 2010, a total of 8,400 GWh of final energy was consumed. In 2050, this will be only 7,830 GWh, out of which 51 % will be from natural gas (4,100 GWh), followed by 33 % from district heating (2,600 GWh). Other energy sources exhibit a descending trend in the following order: electricity, oil, wood, coal, and other fuels.

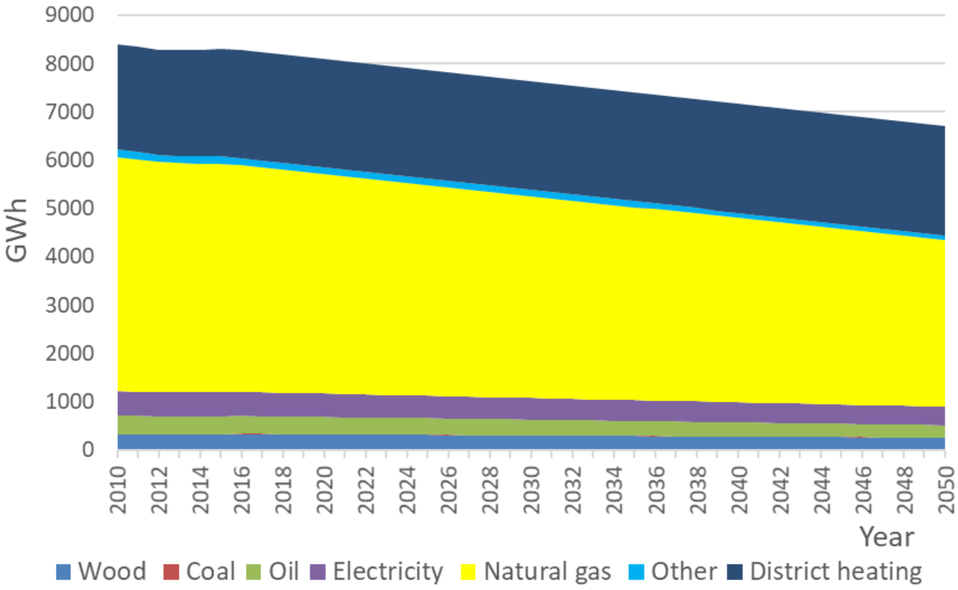

Figure 11 Total final energy of residential buildings in Vienna in terms of the different energy carriers in the BAU scenario up to the year 2050.

The total final energy of the residential buildings in Vienna in the three scenarios is depicted in Figure 12. In all three scenarios, the final energy will decrease steadily until 2050. In the RENO scenario, the final energy decrease is most rapid, from 8,000 GWh in 2020 to 5,400 GWh in 2050.

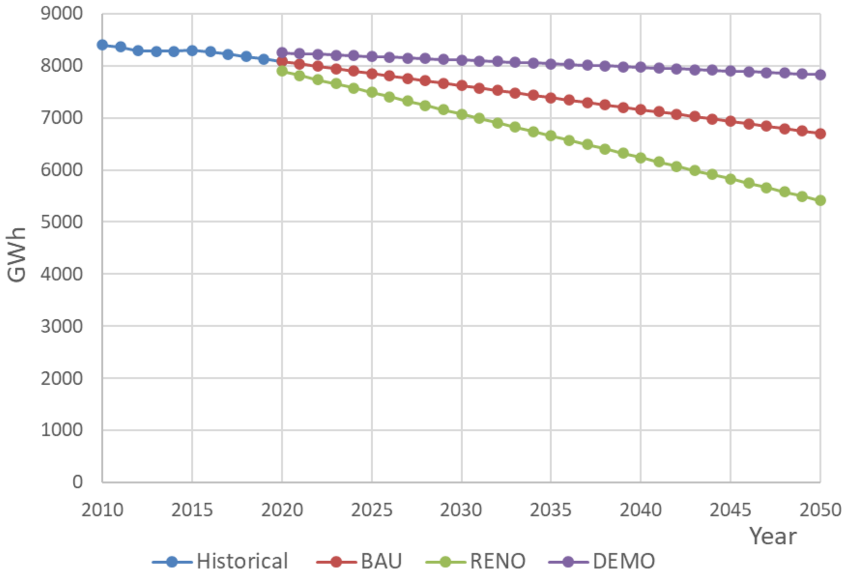

Figure 12 Total final energy of residential buildings in Vienna in the three scenarios up to the year 2050.

The evolution of the CO_2 emission from different final energy carriers used for heating residential buildings in Vienna up to the year 2050 is illustrated in Figure 13. The CO_2 emission from coal, oil, natural gas, wood, and other fuels remains unchanged over the period from 1990 to 2050. The highest CO_2 emissions per kWh are still emitted by coal, followed by oil, electricity, district heating, and natural gas. Electricity emissions exhibit a significant decrease from 0.4 kg CO_2/kWh to 0.3 kg CO_2/kWh. The balance of district heating also shows improvement, with 0.3 kg CO_2/kWh emitted in 2005. In 2050, only 0.2 kg CO_2/kWh corresponds to the value of CO_2 emission from natural gas.

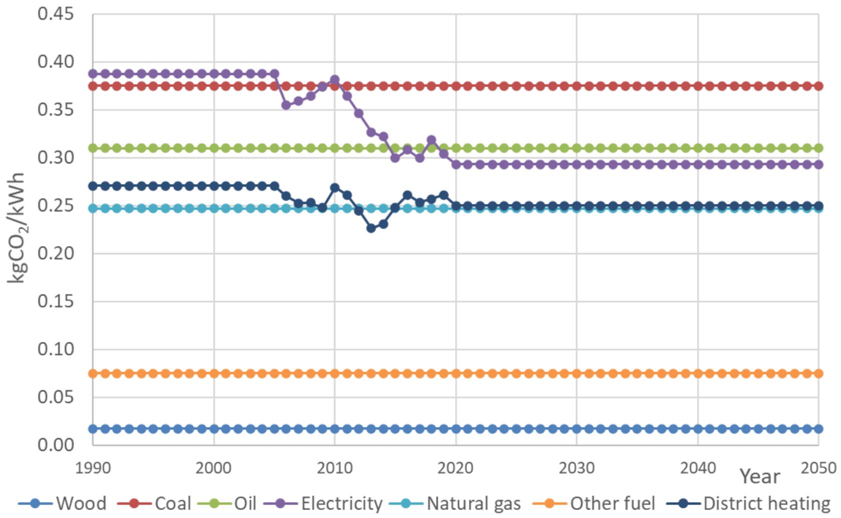

Figure 13 CO_2 emissions factors of different final energy carriers used for heating residential buildings in Vienna up to the year 2050.

The total CO_2 emissions from the final energy emitted by different energy carriers used in the residential buildings in Vienna in the BAU scenario from 1990 to 2050 are presented in Figure 14. The largest share per year has always been emitted by natural gas, followed by emissions produced by district heating and electricity. Over time, the total final emissions in the BAU scenario will decrease from 2.4 million tons in 1990 to 1.6 million tons in 2050.

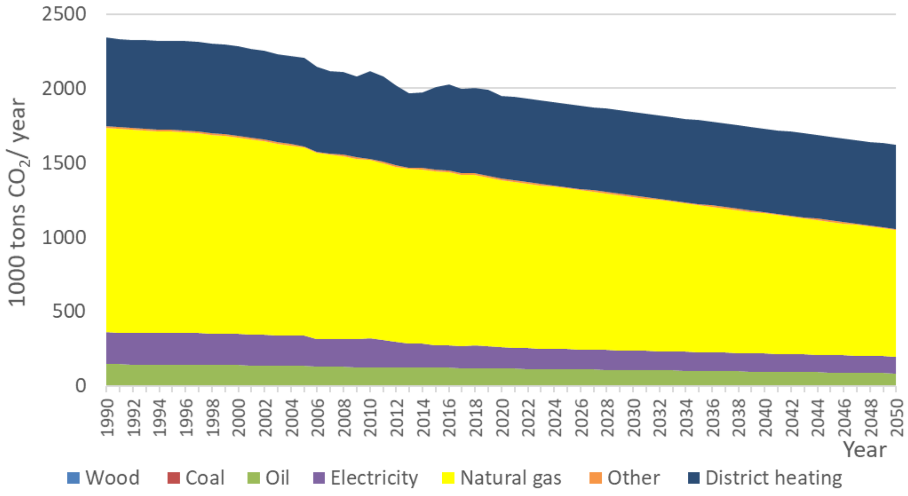

Figure 14 Total CO_2 emissions from final energy emitted by energy carrier used for heating residential buildings in Vienna in the BAU scenario up to the year 2050.

The evolution of the total CO_2 emissions from the final energy of residential buildings in Vienna in the three scenarios up to the year 2050 is illustrated in Figure 15. As can be seen from the figure, there is a clear overall advantage for the reduction of energy demand in the RENO scenario, which is approximately 20 % less than in the BAU scenario. The worst one, with almost no energy reduction compared to 2015, is the DEMO scenario.

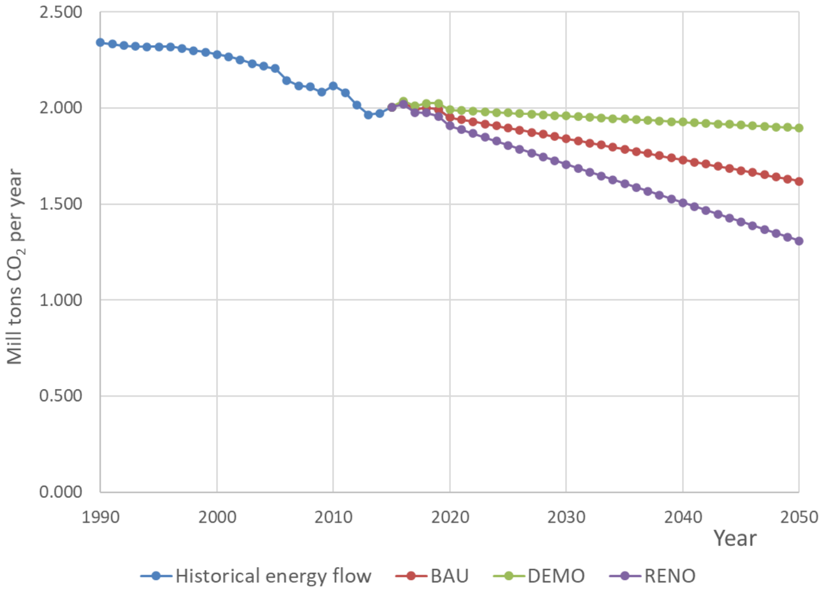

Figure 15 Total CO_2 emissions from final energy of residential buildings in Vienna in the three scenarios up to the year 2050.

4.3 Tons of Material

The total tons of different types of materials used for the construction and retrofitting of residential buildings in Vienna in the BAU scenario up to the year 2050 are depicted in Figure 16. As can be seen from the figure, the largest amount of material used is concrete. It should be noted that the quantities are the same every year from 2016 to 2050 because the measures implemented by year, e.g., construction of new buildings or buildings renovated, are the same every year. This argument applies to Figures 17 to 19.

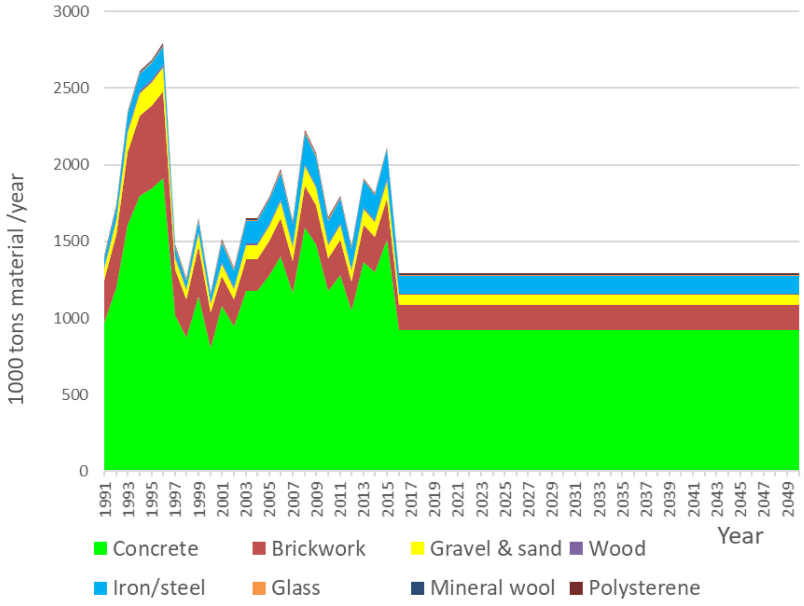

Figure 16 Total tons of different types of materials used for the construction and retrofitting of residential buildings in Vienna in the BAU scenario up to the year 2050.

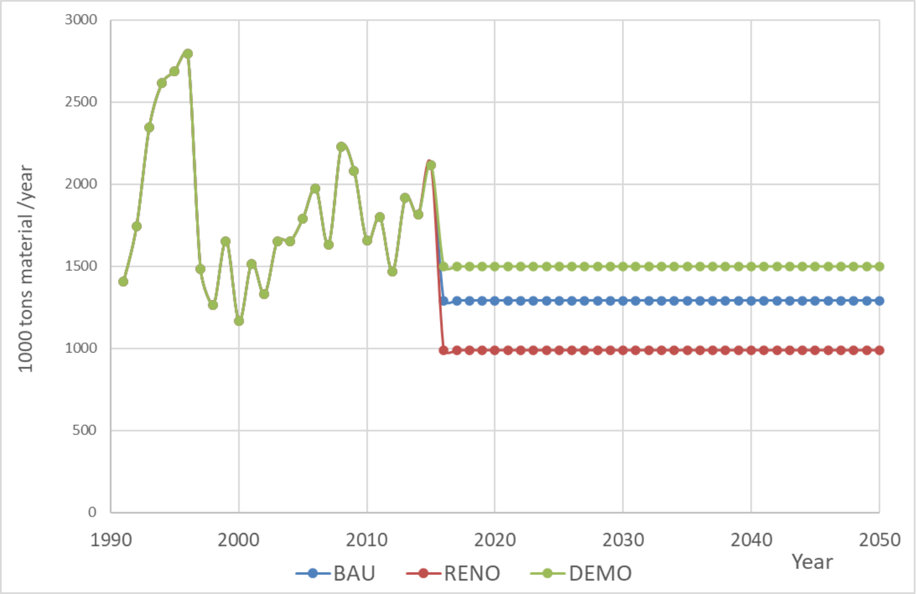

Figure 17 Comparison of the total tons of material used for the construction and retrofitting of residential buildings in Vienna in the three scenarios up to the year 2050.

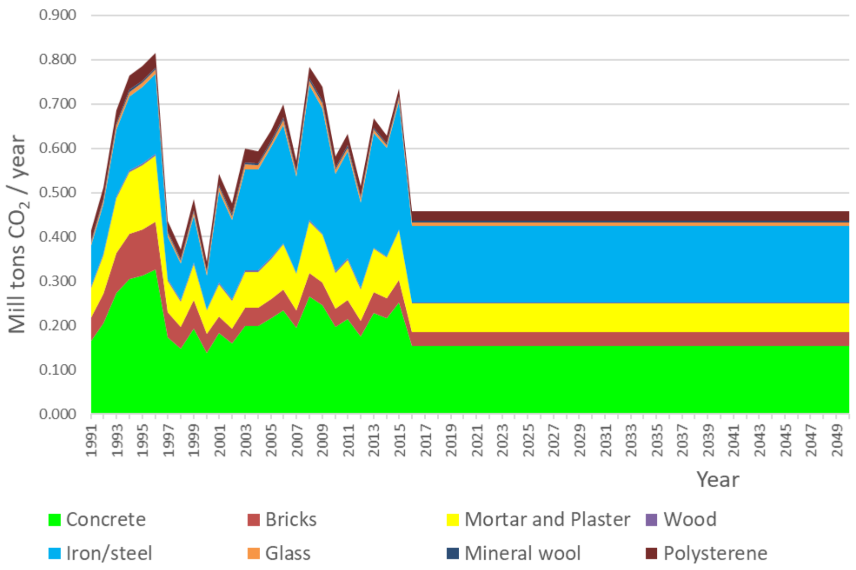

Figure 18 Total embedded CO_2 emissions from the different materials used in the residential buildings in Vienna in the BAU scenario up to the year 2050.

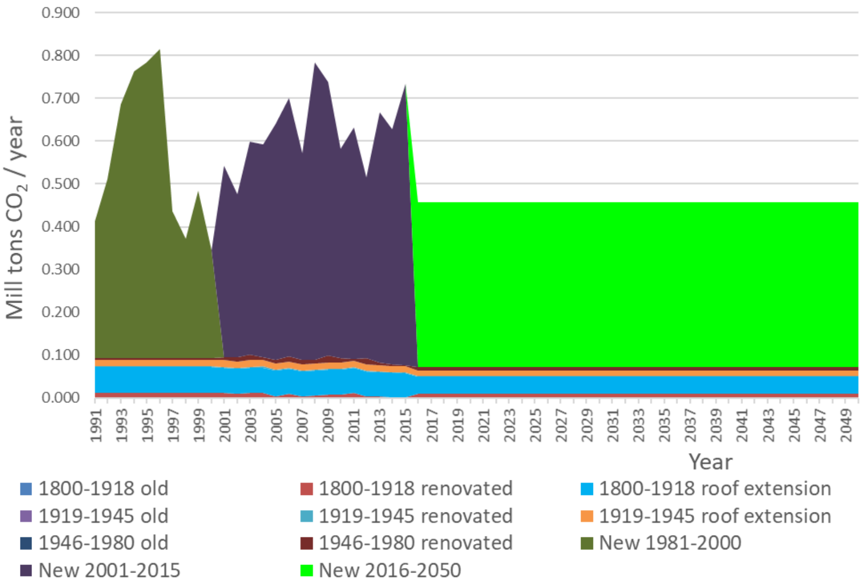

Figure 19 Total embedded CO_2 emissions from residential buildings in Vienna in the BAU scenario up to the year 2050 in terms of the construction period and retrofit category.

A comparison of the total tons of material used for the construction and retrofitting of residential buildings in Vienna in the three scenarios up to the year 2050 is presented in Figure 17. The largest quantity of material is used in the DEMO scenario, whereas the lowest quantity of material is required in the RENO scenario, approximately 25 % less than in the BAU scenario up to the year 2050.

4.4 Embedded CO_2 Emissions

The total embedded CO_2 emissions from different materials of the residential buildings in Vienna in the BAU scenario up to the year 2050 are illustrated in Figure 18. The figure shows that the largest amount of CO_2 emission is due to iron/steel. Concrete, with the largest quantity of tons of material (see Figure 16), is ranked second. All other materials play only a minor role.

The evolution of the total embedded CO_2 emissions of residential buildings in Vienna in the BAU scenario up to the year 2050 in terms of their construction period and retrofitting category is presented in Figure 19. New buildings from 1981–2000 emitted the largest share of CO_2 emissions between 1990 and 2000, followed by buildings constructed from 1800 to 1918 with roof extensions. From 2001 onwards, most CO_2 emissions were emitted from newly constructed buildings from the year 2001 to 2015. From 2016 onwards, most pollutants were once again from completely new buildings.

The total embedded CO_2 emissions from residential buildings in Vienna in the three scenarios up to the year 2050 are illustrated in Figure 20. Overall, the DEMO scenario results in the most embedded CO_2 emissions since 2015. Between 2015 and 2050, the emissions amount to 0.53 million tons of CO_2. In the BAU scenario, approximately 0.46 million tons CO_2, and in the RENO scenario, 0.4 million tons CO_2 emission is caused up to the year 2050.

Figure 20 Total embedded CO_2 emissions of residential buildings in Vienna in the three scenarios up to the year 2050.

4.5 Total CO_2 Emissions

The total CO_2 emissions of residential buildings in Vienna in the BAU scenario from 1990 to 2050 are shown in Figure 21. The largest share (38 % in 2050) is CO_2 emissions from the final energy. Overall, the total emissions exhibit a decrease from 2.4 million tons CO_2 in 1992 to 2.1 million tons in 2050.

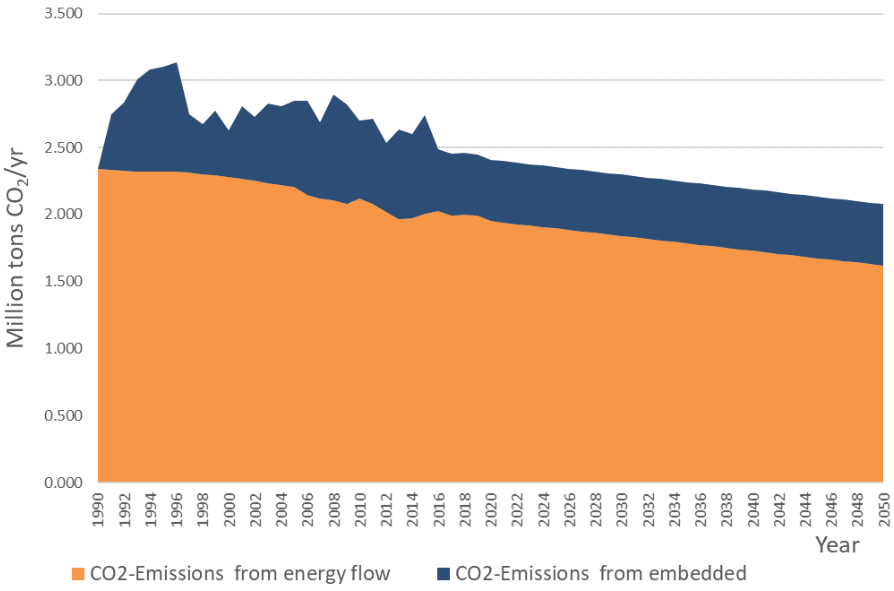

Figure 21 Total CO_2 emissions of residential buildings in Vienna in the BAU scenario up to 2050.

A comparison of the total tons of CO_2 emissions from embedded and final energy of residential buildings in Vienna in the three scenarios up to the year 2050 is presented in Figure 22. The largest amount of CO_2 emission is observed in the DEMO scenario, followed by that in the BAU scenario, and finally in the RENO scenario. The total CO_2 emissions in the BAU scenario will decrease from 2.7 mill tons CO_2 to 2 mill tons CO_2 in the year 2050. In the RENO scenario, emissions will decrease much faster than in the BAU scenario, to 1.7 mill tons CO_2 in the year 2050. In the DEMO scenario, the CO_2 emissions will decrease very slowly to 2.4 mill tons CO_2 in the year 2050.

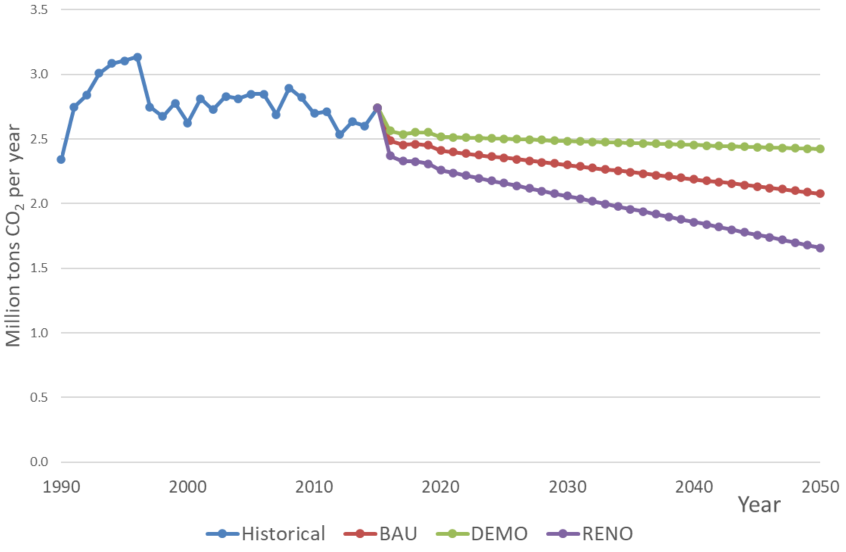

Figure 22 Total CO_2 emissions from the embedded and final energy of residential buildings in Vienna in the three scenarios up to the year 2050.

The scenarios of the evolution of the different indicators for energy consumption and CO_2 emission are illustrated in Figure 23. The different indicators exhibit the already observed trend in the previous figures. The energy consumption in MWh/m^2 decreases fastest in the RENO scenario, followed by the BAU and DEMO scenarios until the year 2050. The CO_2 emissions caused by tons CO_2/m^2 decrease to the largest extent in the RENO scenario up to the year 2050. Overall, energy consumption can be reduced faster than the emitted emissions over the period from 2015 to 2050.

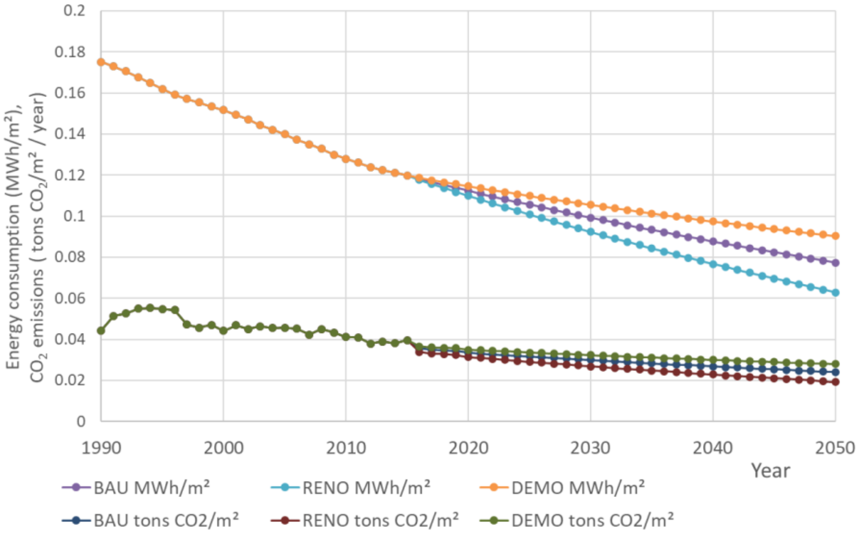

Figure 23 Scenarios of the evolution of the energy consumption and CO_2 indicators of the residential dwellings in Vienna from 1990 to 2050 in the three scenarios.

5. Discussion

5.1 Total Floor Space Area (m^2) Heated

The heated floor space area of residential buildings will increase steadily in the BAU scenario in Vienna until 2050 (Figure 8). Overall, there is a positive correlation between the heated floor space area and the average floor area per capita (Figure 5). To reduce the high final energy demand, in the long run, a political target regarding the maximum floor space area per capita could be useful. However, this is also a question of minimum standards.

A very crucial and bi-vocational issue is the future development of the available living area. On the one hand, for social reasons, it is not an objective of the urban housing policy to reduce the size of flats. On the other hand, there are at least the following three arguments against generous further new construction. First, the number of occupants per dwelling has steadily declined in recent decades. The trend is that in flats where families of four to five people used to live, after approximately 30 years, only have one or two people living in them. A dynamic urban policy that allocates rental housing flexibly could help in this case. In addition, it should be criticized that corridors, floors, and ancillary rooms in old buildings and also within flats are wastefully large and contribute nothing to the living space. This should also be improved in the course of renovations. Finally, considerable areas of flats are vacant; in 2020, this value was approximately 10 %. Therefore, some architects in Vienna are of the opinion that due to these three effects, no new flats need to be built in the next few years. However, in this work, we have assumed that the average area heated per capita will remain constant up to 2050. In the DEMO scenario, the total heated floor space area can be reduced to the largest extent up to 2050 (Figure 9).

5.2 Final Energy

Although the average heated floor space area of the residential buildings in Vienna is increasing, the final energy will decrease by 2050 in all three scenarios (Figure 11). On the one hand, this is due to the replacement of inefficient energy carriers with more efficient ones, especially district heating. On the other hand, a major driver for reducing the final energy demand is the forced renovation of old buildings. In the RENO scenario, the total final energy can be reduced to the largest extent up to the year 2050 (Figure 12). Because fewer buildings are demolished in this scenario, a lesser number of new buildings have to be constructed. This implies that more financial resources remain available for thermal insulation, especially for old buildings.

5.3 CO_2 Emissions from Final Energy

CO_2 emissions from the final energy of the residential buildings in Vienna will decrease in all three scenarios up to the year 2050 (Figure 15). Most CO_2 emissions can be avoided in the RENO scenario. As already mentioned, more financial resources can be invested in thermal insulation, which means less heating will be required. This is due to the replacement of the inefficient energy carriers with high CO_2 emissions (coal, oil, gas, as presented in Figure 6 and Table 2) with more efficient energy carriers with lower CO_2 emissions (electricity in heat pumps, district heating) up to the year 2050. Another explanation for decreasing CO_2 emissions is the reduction in the CO_2 emission from district heating until the year 2050 (Figure 13).

5.4 Tons of Material

Concrete is the most extensive material used for the construction and retrofitting of residential buildings in Vienna (Figure 16). The largest quantity of materials is used in the DEMO scenario (Figure 17), owing to the large amounts of materials required for constructing new buildings. The lowest quantities of materials are required in the ambitious RENO scenario.

5.5 Embedded CO_2 Emissions

Concrete has very high specific embedded CO_2 emissions, and thus the substantial usage of concrete in residential buildings in Vienna causes very high CO_2 emissions (Figure 18). Iron/steel causes very high CO_2 emissions despite a rather low material input (Figure 16) because their specific CO_2 emission factor is very high at 1.52 ton CO_2/ton material (Table 1). The highest total embedded CO_2 emissions are caused in the DEMO scenario, which is once again derived from the very high material input used for constructing new buildings. It should be noted that in the RENO scenario, more thermal insulation material and less CO_2-intensive concrete are used.

5.6 Total CO_2 Emissions

In every scenario, the largest share of CO_2 emissions in residential buildings in Vienna is caused by the use of final energy (Figure 21). In the DEMO scenario, the most CO_2 emissions are caused (Figure 22) by the fact that the highest amount of embedded energy is required in it, thus leading to the highest total CO_2 emissions (Figure 23).

6. Conclusion

The major result of this analysis is that the RENO scenario is clearly the most favorable. This implies improving the current residential building stock by renovation and retrofitting, improving the thermal quality of the outdoor walls and the attic, and replacing old windows with more efficient ones. It is undoubtedly the most favorable strategy and will bring about the lowest overall CO_2 emission balance. Next is the BAU scenario, with lower overall emissions than in the DEMO scenario, whereas the DEMO scenario is the worst for long-term planning. This is because it is mainly the demolition step that requires the highest quantity of materials. It has also been shown that the RENO scenario uses the least CO_2-intensive materials. The worst scenario is the DEMO scenario, where especially significant amounts of CO_2-intensive materials are spent.

Regarding the CO_2 emissions of final energy versus the embedded emissions in the RENO scenario, it is that the RENO scenario shows higher embedded CO2 emissions compared to the BAU scenario. However, the CO_2 emissions are lower in the RENO scenario overall. In other words, the transition to sustainable heating of buildings requires, at least temporarily, the "investment" in embedded CO_2 emissions, e.g., in retrofitting and insulation of buildings to harvest reductions in CO_2 emissions in the long run from less energy used for heating.

A major conclusion of this study is that policies are very important. To implement the most favorable renovation scenario, strong policy measures are required, such as standards for new buildings and for building retrofitting as well as subsidies, to ensure an accelerated refurbishment rate of the old low thermal building stock.

Another important aspect is the evolution of the CO_2 emission factors of district heating and electricity. We have assumed in this work that they will remain constant up to 2050. This is mainly due to the production of district heating in combined heat and power plants. A major conclusion from this study is that the CO_2 emission factor, especially in district heating, has to be reduced by increasingly using renewable energy carriers such as biomass, solar, and geothermal. In addition, electricity generation from wind and solar energy has to be promoted.

An outlook for future research involves more specific modeling of policies. The model used in this study allows to consider the CO_2 from the final energy as well as embedded CO_2 emissions in buildings and to provide simulations of future developments depending on the policies implemented for any city around the world. In future research, it would be of interest to analyze which specific policy measures lead to what sort of developments.

What is left for future research is the major issue of the future evolution of the size of flats and the area heated per capita. Of the highest relevance is to provide measures to reduce the size of apartments by means of city planning to make buildings more compact and meet the standards of sufficiency.

Author Contributions

Conceptualization, R.H.; methodology, R.H.; formal analysis, R.H.; investigation, R.H.; resources, J.L., R.H. and M.S.; data curation, J.L., R.H. and M.S.; writing—original draft preparation, R.H. and M.S.; writing—review and editing, R.H. and M.S.; visualization, M.S.; supervision, A.A.; project administration, A.A.; funding acquisition, A.A.

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Competing Interests

The authors have declared that no competing interests exist.

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