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Czech Building Stock: Renovation Wave Scenarios and Potential for CO_2 Savings until 2050

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Abstract: One of the major anthropogenic sources of greenhouse gases is the operation of building stock. Improving its energy efficiency has the potential to significantly contribute to achieving climate change mitigation targets. The purpose of this study was to roughly estimate such potential for the operation of the national building stock of Czechia to steer the national debate on the development of related national plans. The estimation is based on a simplified energy model of the Czech building stock that consists of sub-models of residential and nonresidential building stocks, for which their future energy consumptions, shares of energy carriers and sources, and emission factors were modeled in four scenarios. Uncertainties from the approximation of the emission factors were investigated in a sensitivity analysis. The results showed that the operation of the Czech building stock in 2016 totaled 36.9 Mt CO_2, which represented 34.6% of the total national carbon dioxide emissions. The four building stock scenarios could produce reductions in the carbon dioxide emissions of between 28% and 93% by 2050, when also considering on-side production from photovoltaics. The implementation of the most ambitious scenario would represent a drop in national CO_2 yearly emissions by 43.2% by 2050 (compared to 2016).

Keywords: national building stock; climate change mitigation; carbon dioxide; scenarios modelling; Paris Agreement; EU Green Deal; energy efficiency

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1. Introduction

1.1. Buildings and Climate Change

In the context of climate change mitigation, the world's nations are drafting and discussing their plans to achieve their national greenhouse gas reduction commitments [1–4]. The mitigation of climate change is featured in the strategic plans of the European Commission [5] and its member states. Czechia supports the EU target of complete carbon neutrality by 2050 and has committed to a reduction in national CO_2 emissions of 80–95% by 2050 compared with the base year 1990 [6]; however, a detailed national plan that describes practical measures in each segment of the national economy is not yet ready.

One of the major anthropogenic sources of greenhouse gases is the operation of buildings [7], so improving the energy efficiency of the building stock has the potential to significantly contribute to achieving the national climate change mitigation targets [8]. The efforts to exploit this potential span across scales, from the global perspective through the national building stock, building stocks of regions and cities, to the scale of a single building [9].

1.2. Background

At the scale of a single building, a growing body of literature is focused on the theory of reducing buildings' greenhouse gas (GHG) emissions. Some studies attempted to align the design of buildings with the intermediate goals of the Paris Agreement [10,11], and many papers report advances in zero-GHG buildings, including climate-neutral [12], carbon-neutral [13], and zero-emission [14–16] buildings. The various definitions and approaches were discussed at the 71st LCA Forum in 2019 [17] and recently summarized by Satola et al. [18], who analyzed the definitions and their respective emission performance targets. In the Nordic countries, GHG limits are already being introduced into building standards [19].

At the city level, efforts are concentrated on municipality-owned building stocks and policies for privately owned buildings in cities. There is an ongoing debate on how to set the balance of responsibilities among the actors [20]. Many climate-related activities are ongoing at the municipal level; in Europe, the most visible seems to be the Covenant of Mayors for Climate and Energy [21].

At the national building stock level, researchers have investigated the general potential for GHG reductions and explored various paths to align the GHG emission performance with the climatic goals of the Paris Agreement. Xing et al. [22] investigated the potential contribution of the Chinese residential sector to the nation's climatic contributions under various levels of carbon tax. The study took 2010 as the base year and modeled CO_2 emissions for 2020 and for 2030 in three scenarios of development. They found a potential to achieve CO_2 emission intensity reductions of 60–65% in the range of hypothetical situations corresponding to carbon emissions pricing between USD 44 and 58/t CO_2.

Yu et al. [23] modeled the building stock in India accounting for the evolution of the buildings sector, including changes in GDP, population, urbanization, floorspace expansion, growth in energy service demand, and choice among technologies and fuels for individual energy services. They found that implementing a wide range of energy efficiency policies can reduce the total Indian energy use by 22% and lower total Indian carbon dioxide emissions by 9% by 2050. Jeong [24] investigated four scenarios of development of the South Korean residential building sector between 2007 and 2030. They found that despite the expected strong demand for new residential developments, in one of the modeled scenarios, there was a potential for 12.9% CO_2 emissions reduction (compared with a 10.7% increase in the business-as-usual scenario). In Germany in 2013, Bürger [25] analyzed the GHG emissions of the national residential building stock in the context of the use of the development of building standards, heat supply technologies, and renewable energy potential. They analyzed three long-term scenarios of the German building stock development to 2050 and compared them with the emission budget then available for Germany. Based on the results, the authors urged for a swift implementation of additional strong climate protection measures. The work was further developed and described in Klimaneutraler Gebäudebestand 2050 [26,27], which simulated GHG emission reduction scenarios of −35%, −50%, and −65% by 2050.

Frischknecht et al. [28] conducted a complex analysis of the carbon footprint of the Swiss real estate sector. The findings showed that the use stage of buildings represents only two-thirds of the total GHG emissions in the sector, whereas an additional 30% is caused by the buildings' supply chains, stating that the relative significance of the embodied GHG is rising (which was also by an investigation of building case studies by Röck et al. [29]).

Kranzl et al. [30] analyzed GHG emission reduction scenarios from the policy-driven bottom-up model recently in place for European countries in eight EU and national projects (including data for Czechia), compared them amongst each other using various indicators, and analyzed whether the scenarios would lead to an achievement of GHG emission reductions in the range of 85–95% by 2050. The results showed that scenarios labelled as ambitious for several EU member states achieve GHG reductions of 56–96% by 2050. However, just 27% of these ambitious scenarios achieve reductions above 85%.

In Czechia, we [31] previously investigated five scenarios of the development of the Czech national building stock by modeling cumulative CO_2 emissions in the periods 2015–2030, 2031–2050, and 2051–2075, and compared them with the UN Emissions Gap Report [32]. It was based on previously developed models of energy consumption of the Czech residential and nonresidential building stocks, which also considered the future changes in climatic conditions due to climate change in two scenarios. Its most progressive scenario forecasted a reduction in the CO_2 emissions of 66% by 2075. None of the modeled scenarios was found to comply with the Paris Agreement.

Another publication that recently discussed the GHGs of the Czech buildings is the report Pathways to Decarbonize the Czech Republic [33]. It presents the cost-optimum decarbonization path for the state, including buildings, with a reduction in GHG emissions of 31% by 2030 and 97% by 2050.

1.3. Study Objectives

The study presented in this paper is a contribution to the ongoing national debate specifically focused on the national policies planned for regulating the energy efficiency of the Czech building stock (CBS). It was performed in collaboration with the Czech nongovernmental organization Chance for Buildings (CfB) and the University Centre for Energy Efficient Buildings of the Czech Technical University in Prague (UCEEB). CfB is an alliance of leading trade associations that supports energy-efficient and environmentally sustainable construction and renovation of buildings. It gathers the Czech Green Building Council, Passive House Centre, Mineral Insulation Manufacturers Association, EPS Association, and the Energy Service Providers Association. It represents over 300 companies across the entire value chain of building construction and renovation [34]. UCEEB is a multidisciplinary applied research center focused on promoting sustainable technical solutions in the built environment [35].

The objective of this work was to follow-up on our previous work and to quantify the approximate potential for CO_2 emission savings from the operation of the CBS according to the actual individual retrofitting scenarios prepared by CfB in accordance with the requirements of the long-term renovation strategy under Article 2a of the Energy Performance of Buildings Directive (EU) 2018/844, and evaluate the possible contribution of energy saving measures in the building stock to the national emission commitments considering the updated emission factors for electricity, heat from district heating systems, and future gas mix in gas pipelines.

2. Materials and Methods

The methods used in this study to model, calculate, and evaluate the potential for savings in the operational CO_2 emissions of the CBS included the following:

- Defining scenarios for the development of the CBS including starting state, especially in terms of area, quality, and expected rate of retrofitting, and increase in the number of new constructions;
- Processing of data on energy consumption in buildings for the period up to 2050 (details on the data modeling are provided in Section 2.1.2);
- Defining scenarios of shares of energy sources in future energy consumption for heating, hot water, and lighting in buildings, in line with the consumption stated in energy certificates;
- Adding estimates of energy consumption for appliances and cooking in the residential sector;
- Identifying the CO_2 emission factors for individual fuels and energy carriers;
- Calculating operational CO_2 emissions of CBS for individual building retrofitting scenarios;
- Defining scenarios for the development of photovoltaic installations and variant modeling of CO_2 emissions;
- Conducting a sensitivity analysis considering the future decrease in emission factors of electricity from the national grid, heat from district heating systems, and gas from the distribution network;

- Calculating the share of the CBS on the national operational CO_2 emissions and its theoretical share in 2050;
- Evaluating results with regard to the national climate commitments.

2.1. Definition of the Czech Building Stock Development Scenarios and Summarizing the Corresponding Energy Consumption

This study was based on four construction-technical scenarios for the retrofitting of the CBS. For each of them, partial scenarios were modeled, differing in the structure of energy sources in buildings.

The following sections describe the origin of the base data of the composition of the CBS; the modeling of the final energy consumption of the CBS; four scenarios of the depth and pace of energy retrofitting; the projection of the shares of energy carriers on the final energy consumption in the four scenarios; and the forecast of the development of the building-attached and building-integrated photovoltaics (BIPV).

2.1.1. Origin of the Base Data on Composition of the CBS

The data on the composition of the CBS were obtained from several previous reports published by Chance for Buildings, especially Investigation of the Czech Residential Building Stock and Potential for Savings [36], Investigation of the Czech Non-Residential Building Stock and Potential for Savings [37], Strategy for Retrofitting of Buildings [38], its 2016 update [39], and Long-Term Renovation Strategy of the Czech Building Stock—update May 2020 [40]. The data for these reports originated from various datasets provided by the Czech Statistical Office, especially data from the national 2011 census, the statistical survey on buildings called ENERGO 2015, and a statistical survey on buildings called Budovy 1–99 from 2018. The basic data on the composition of the CBS are similar to those used in the previous study [31].

2.1.2. Modeling of the Final Energy Consumption of the CBS

The base energy model of the CBS was created in 2016; hence, 2016 was the base year for which the statistical data were collected. The energy model is composed of sub-models of the residential and nonresidential building stocks. It was used to provide forecasts of yearly total final energy consumptions of Czech residential and nonresidential buildings between 2016 and 2075; in this study, we used datasets toward 2050.

For the energy simulations of existing residential building stock [36] (see Appendix A for more details), we used a stochastic energy model that calculated the energy demand for the heating of a set of 1000 simulated buildings, which was created from data samples of buildings divided into 78 categories by typology, size, and age based on the statistical data. The calculations in a custom-made tool (MS Excel sheets and macros) followed the rules given by EN ISO 13790 and applied the boundary conditions used normally when calculating energy performance certificates according to national rules. Statistical data provided the input for the estimation of the proportion of residential building stock that had already undergone energy retrofitting, estimated as 35% in 2016. The report presents the calibration of the energy model according to the available statistical data on the final energy consumption of building stock made by comparison of the calculated (52,896 GWh/year) to statistical data provided by the Ministry of Industry and Trade of the Czech Republic (47,798 GWh/year). The calibration of the model to the statistical data was made by decreasing the considered indoor air temperature. An English summary of the report is provided in Appendix A below.

The energy modeling of existing nonresidential building stock [37] (English summary of the report is provided in Appendix B below) was based on a sample of 100 nonresidential buildings with detailed energy simulations and an additional sample of 20 existing buildings with detailed data on real energy consumption. The building typologies included in the study were office buildings, administrative buildings, commercial buildings, educational buildings, cultural buildings, hotels, restaurants, medical facilities, sports facilities, storage buildings, and those with mixed use. A list of them and sample photos are presented in the report [37], where Section 2.1 describes the geometrical characteristics of the sample. Section 2.3 describes the outcomes of the energy modeling, which was processed in line with the national Decree 78/2013 Coll. used for the calculation of the energy performance certificates of buildings (the baseline scenario is provided in the charts and tables labelled as SS and visualized in black). The resulting data on energy demand and final energy consumption are provided from page 13 onward. The calibration of the energy model was made by comparison of the simulated energy consumptions with the real energy consumptions of twenty existing buildings. Based on these comparisons, we derived a correction formula for their extrapolation on the whole nonresidential building stock. It was based on a sensitivity analysis that identified the key parameters: surface area/volume ratio, ratio between the mean U-value and the reference U-value used in the declaratory energy performance calculation method, mean indoor temperature and the overall efficiency of the heating system.

The simulated energy consumptions were extrapolated to the whole Czech nonresidential building stock using national statistical data on the proportions of each type of building in the whole building stock.

The energy model considers various depths of energy retrofitting measures; their combination is described further in the sections dedicated to scenarios.

Residential buildings statistically retrofitted to a low-energy standard and without retrofitting were simulated using construction interventions leading to the reduction in energy demand for heating and the improved efficiency of heating due to the replacement of heat sources. The potential savings from the preparation of domestic hot water and lighting were simulated separately.

The modeled nonresidential buildings that were in lower-than-current energy standards were simulated using various combinations of energy-saving interventions such as: partial improvement in thermal characteristics of building envelopes; complex retrofitting actions on building envelopes as a whole; replacements of heat sources; installations of mechanical ventilation systems with heat recovery; installation of new renewable energy systems.

2.1.3. Four Scenarios of the CBS Development by the Depth and Pace of Energy Retrofitting

For this study, we defined the four scenarios of the future development of CBS (Table 1):

- Baseline Scenario, which corresponds to the state-of-the art policy without any improvements (business as usual);
- Governmental Scenario, proposed in the Long-Term Renovation Strategy Supporting Renovations of the National Residential and Nonresidential Public and Private Building Stock published by the Czech Ministry of Industry and Trade, which is responsible for energy and construction policies [41];
- Progressive Scenario (deep retrofitting of CBS);
- Hypothetical Scenario (fast deep retrofitting of CBS).

The scenarios were defined with the help of the following variables:

- Annual retrofitting rates: the percentage of building stock that undergoes retrofitting each year (by building category; Table 2).
- Retrofitting depths: In the context of the study, shallow retrofitting means that the building envelope is upgraded to required U-values aligned with the national standard ČSN 73 0540; moderate indicates the recommended U-values are met; deep indicates the U-values prescribed for passive houses and equipment of the building with a mechanical ventilation with heat recovery. Table 1 provides further insights into the typical U-values by the depths of retrofitting. The lower part of Table 2 shows the distribution of the renovated building floor area by the retrofitting depths. Figure 1 visualizes the scenarios.

Table 1. The retrofitting depths by the considered U-values of the main building compositions and ventilation systems for nonresidential building stock energy modeling.

Type of Structure	**Retrofitting Depths**		
	Shallow	**Moderate**	**Deep**
	Thermal quality of building envelope		
	Select typical U-values of the main building compositions in W/(m^2 · K)		
External walls	0.30	light 0.25, heavy 0.20	0.15
Roofs	0.24	0.16	0.10
Floor below attic without thermal insulation	0.30	0.20	0.12
Floor structures above exteriors	0.24	0.16	0.12
Floor structures above unheated underground floors	0.60	0.40	0.25
Windows	1.50	1.20	0.90
Doors	1.70	1.20	0.90
	Ventilation		
Ventilation system	Natural ventilation or mechanical ventilation without heat recovery	Natural ventilation or mechanical ventilation without heat recovery	Mechanical ventilation system with heat recovery (efficiency $\eta_{H,hr,sys}$ = 60% according to EN 308)

Table 2. Definition of the four scenarios of the development of the Czech building stock (CBS).

Building Categories	**Retrofitting Depth**	**Scenario**			
		Baseline	**Governmental**	**Progressive**	**Hypothetical**
New construction and demolition: annual increase in floor area *					
Residential—single family houses		1.11%	1.11%	1.11%	1.11%
Residential—multifamily houses		0.46%	0.46%	0.46%	0.46%
Nonresidential		0.96%	0.96%	0.96%	0.96%
Annual retrofitting rates by category (percentage of building stock that undergoes retrofitting each year)					
Residential—single family houses		1.40%	1.40%	3.00%	3.00%
Residential—multifamily houses		0.79%	0.79%	2.00%	3.00%
Nonresidential		1.40%	2.00%	2.50%	3.00%
Distribution of the renovated building floor area by retrofitting depths and their time distribution					
Shares of retrofitting depths by building categories		Default shares, stable for whole period **	Linear increase from default until 2025, then stable	Linear increase from default until 2025, then stable	Hypothetical leap in 2020 and then stable
Residential: single-family houses	Shallow	35%	20%	5%	5%
	Moderate	38%	40%	10%	10%
	Deep	27%	40%	85%	85%
Residential: multifamily houses	Shallow	31%	20%	5%	5%
	Moderate	50%	40%	10%	10%
	Deep	19%	40%	85%	85%
Nonresidential	Shallow	27%	20%	5%	5%
	Moderate	44%	40%	10%	10%
	Deep	30%	40%	85%	85%

* Considered demolition rates: single-family houses 0.2%, multifamily houses 0.1%, nonresidential buildings 0.2%. ** Default shares of retrofitting depths from the ENEX database, which collects data from the energy certificates listed for the purpose of "Major renovation of existing building", taken from [41].

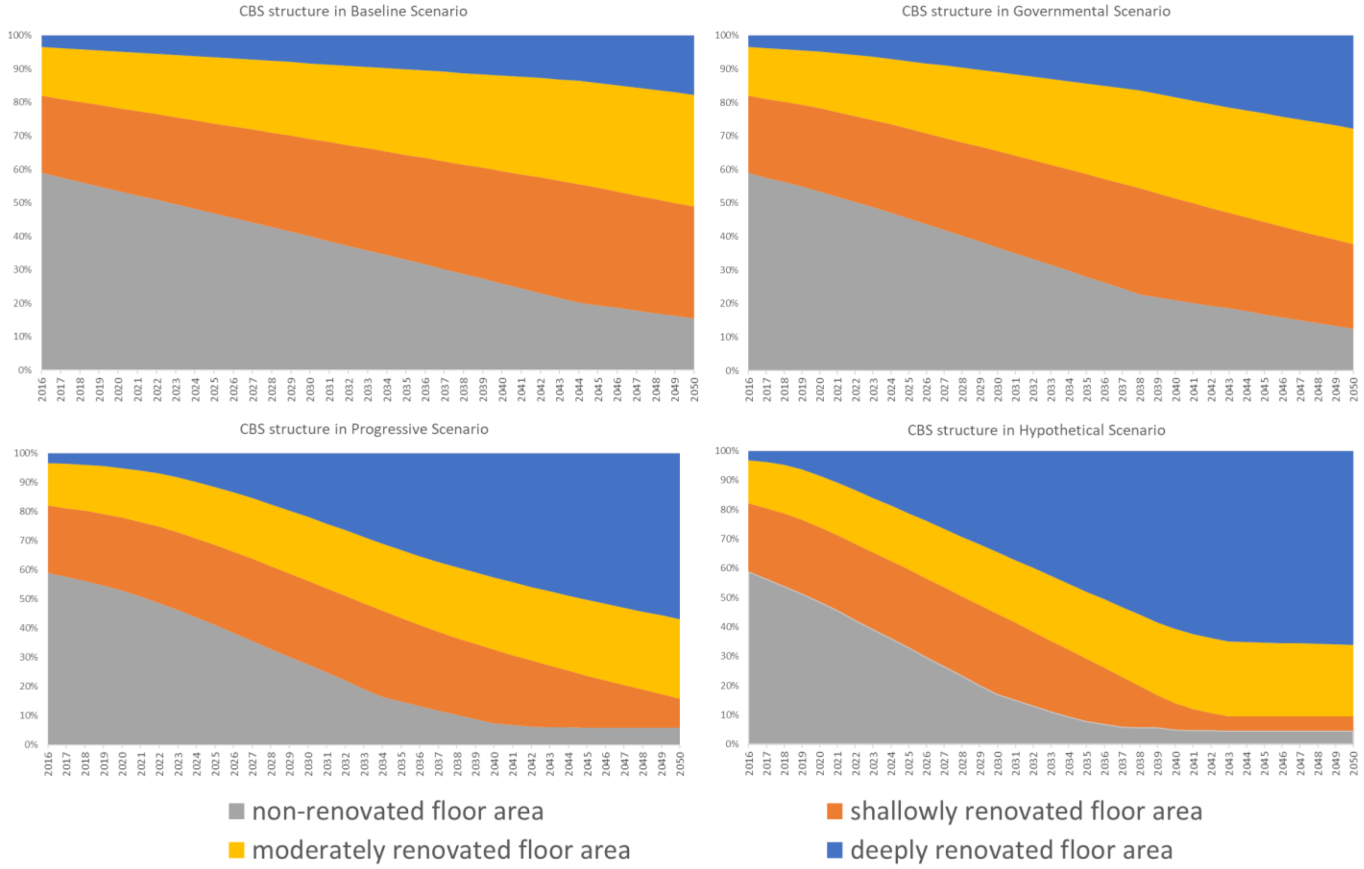

Figure 1. Modeled shares of the nonrenovated, shallowly renovated, moderately renovated, and deeply renovated buildings in the whole CBS (by buildings' floor area).

From the energy model, we obtained the yearly final energy consumption for residential and for nonresidential building stocks between 2016 and 2050. Table 3 shows the selected figures.

Table 3. A simplified overview of the final energy annual consumptions in PJ obtained from the energy model that was used for the modeling of the carbon dioxide emissions of the CBS.

Scenario	**2016**	**2030**	**2040**	**2050**
Residential building stock				
Baseline	253	234	219	204
Governmental		232	214	196
Progressive		206	154	126
Hypothetical		179	126	115
Nonresidential building stock				
Baseline	125	117	109	102
Governmental		113	102	93
Progressive		107	94	86
Hypothetical		98	85	83

As the energy model used for residential buildings excluded energy consumption for cooking and home appliances, they were added at the end in the annual amount of 15.5 PJ for home appliances (in electricity) and 15.0 PJ for cooking (equal share of electricity and natural gas). These values were constant for each modeled year.

2.1.4. Projection of the Shares of Energy Carriers on the Final Energy Consumption in the Four Scenarios

The projections of the shares of the energy carriers were defined separately for the residential and nonresidential building stock for the years 2016 and 2050, and values for the intermediate years were linearly interpolated. The base values for 2016 were defined by the analysis of sources from the Czech Statistical Office listed above. The values for 2050 were defined using national energy commitments by analyzing national policy documents published recently by the Czech Ministry of Industry and Trade, especially The National Energy and Climate Plan of the Czech Republic [6]. The definition of the share of renewables was based on the reports by the Czech Chamber of Renewable Energy Sources dealing with the renewable energy sources potential in buildings and on Czechia on Way towards Carbon Neutrality [42]. The considered shares of the energy carriers and sources are summarized in Table 4. Photovoltaics are discussed in the next section.

Table 4. Considered shares of energy carriers and sources on the final energy consumption in the four scenarios.

Scenario		Baseline	Governmental	Progressive	Hypothetical
Energy Carrier/Source	**2016**	**2050**	**2050**	**2050**	**2050**
Residential building stock					
Fuel oils	0%	0%	0%	0%	0%
Natural gas	30%	25%	26%	23%	22%
Coal	12%	10%	3%	0%	0%
Biomass (excluding pellets)	20%	25%	20%	15%	12%
Pellets	0.3%	4%	9%	14%	16%
District heating	17%	16%	16%	15%	15%
Electricity	19%	10%	11%	8%	8%
Solar thermal	0.3%	2%	4%	6%	7%
Heat pumps	1%	9%	12%	19%	21%
Nonresidential building stock					
Gas cogeneration	2%	2%	2%	2%	2%
Natural gas	27%	26%	23%	22%	22%
Coal	0.2%	0.2%	0%	0%	0%
Biomass (excl. pellets)	0%	0%	0%	0%	0%
Pellets	0.3%	4%	8%	8%	9%
District heating	29%	28%	25%	25%	25%
Electricity	42%	39%	36%	36%	35%
Solar thermal	0.2%	2%	4%	4%	4%
Heat pumps	0%	0.2%	3%	3%	3%

2.1.5. Forecast of the Development of the BIPV

Scenarios for the electricity produced from BIPV differ within the scenarios. The basic difference is the depth of the retrofitting: the deeper the retrofitting, the greater the assumption of preference for more complex projects and thus the installation of a photovoltaic system. The scenarios were paired with the scenarios from the document Potential for utilization of renewable energy sources in buildings (2018) provided by Czech Chamber of Renewable Energy Sources, which explored the technical potential for BIPV. It started from the optimum orientation and slope, which is in Czechia south facing area with 35° inclination. For BIPV installation, areas of roofs that have a reduction in the energy yield lower than 20% and walls lower than 40% compared to the optimum position were considered, and the maximum usable area on roofs for BIPV is considered as 40% and only 20% of the south facing walls' area. It was also assumed that 30% of buildings are not suitable for PV installation at all due to shading by vegetation, other buildings or because of legal restrictions or heritage protection. The considered efficiency of the PV panels was 18%. The resulting production of electricity from BIPV is shown in Table 5.

Table 5. Considered yearly amount of electricity production in GWh from building-attached and building-integrated photovoltaics. The values for the intermediate years were linearly interpolated.

Sector	Scenario	2016	2030	2040	2050
Residential	Baseline and Governmental	262	2944	4710	6477
	Progressive	262	5561	8995	12,430
	Hypothetical	262	5414	9707	14,000
Nonresidential	Baseline and Governmental	140	1560	2490	3420
	Progressive	140	2940	4755	6570
	Hypothetical	140	3129	5265	7400
Whole building stock	Baseline and Governmental	402	4504	7200	9897
	Progressive	402	8501	13,750	19,000
	Hypothetical	402	8543	14,971	21,400

2.2. Calculations of CO_2 Emissions in Scenarios

The calculations procedure for the amounts of CO_2 emissions included these steps:

- Taking the input yearly datasets for total energy consumption for residential and nonresidential building stock in the four scenarios (data for 2016, 2030, 2040, and 2050 are shown in Table 3);
- Distributing the total energy consumption per energy carrier and energy source according to Table 4;
- Allocating the electricity production from BIPV for each year according to Table 5;
- Multiplying the energy consumption by the corresponding emission factor (below);
- Totaling the resulting emissions for each year in the four scenarios.

Assumptions about the Emission Factors

The CO_2 emission factors for fuels were obtained from the National Inventory Report [43,44]. For the emission factor of the electricity from the grid, no single official number was available. On the basis of an analysis of available sources [45–47] and consultations with the representatives of the Ministry of the Environment, we set the emission factor as 0.6 t CO_2/MWh.

Deciding on a single emission factor for the heat from district heating systems is difficult because the emission factors are locally specific and the used fuels also depend on the efficiency of the heat source, system losses, and, in case of cogeneration, on the allocation of the produced emissions among the produced (and sometimes wasted) heat and electricity. We considered various sources of relevant information [48–51]; for the heat from the district heating systems, we selected a value of 0.3 t CO_2/MWh.

The emissions from gas cogeneration units were roughly proxied by halving the emission factor of the combustion of natural gas. In the calculations of the emissions from heat pumps, we considered an average coefficient of performance 3.0 and electricity from the grid as the energy carrier (so the resulting emission factor was one-third the electricity emission factor).

We assumed that the electricity produced onsite from BIPV will save electricity that would otherwise have had to be produced by the centralized sources supplying power to the national electricity grid. Therefore, we multiplied the energy produced from photovoltaics by the emission factor for the grid electricity and subtracted them from the totals for each year.

For the biomass, in line with the Czech methods for energy auditing, we assumed sustainable forest stewardship and simplification leading to a zero emission factor. Similarly, a zero emission factor was applied to the heat from the solar thermal collectors (not considering the embodied impacts and neglecting the needed auxiliary energy).

The CO_2 emission factors applied in the calculation are summarized in Table 6.

Table 6. CO_2 emission factors applied in the calculations in metric tonnes of CO_2/MWh. BIPV, building-integrated photovoltaics.

Fuel or Energy Carrier	Assumed Emission Factor (t CO_2/MWh)
Coal	0.35
Fuel oils	0.26
Natural gas	0.20
Biomass	0.00
Heat from solar collectors	0.00
Electricity from the national grid	0.60
Onsite-produced electricity from BIPV	(−)0.60
Heat from district heating system	0.30
Energy from gas cogeneration (proxy)	0.10
Heat from heat pumps	0.20

Due to the uncertainties regarding emission factors and the assumptions of future reduction in some of them with the expected decarbonization of the Czech energy sector, a sensitivity analysis was performed, as described below.

2.3. Sensitivity Analysis Considering the Future Decrease in Emission Factors of Electricity from the National Grid, Heat from District Heating Systems, and Gas from Distribution Network

Due to the uncertainties regarding the emission factors for electricity, district heat, and the possible future development of the gas mix, a sensitivity analysis was performed for 2050. The sensitivity analysis was performed both without and with consideration of BIPV. Notably, we did not analyze the technical or legal potential of the emissions factors—it was performed only to show what-if scenarios.

The effects of the potential reduction in emission factors were examined separately:

For electricity from the grid, a reduction in emission factors of 67% and 33% was applied, from the initial value of 0.6 to 0.4 and 0.2 t CO_2/MWh. This considers the possible future decarbonization of the electricity grid (at the utility level). For district heating, a reduction in emission factors of 75% and 50% was used, i.e., from the initial value of 0.3 to values of 0.225 and 0.15 t CO_2/MWh. This considers the possible future exchange of coal resources for gas or biomass. For distribution gas, a reduction in the emission factor of 90% and 80% was used, i.e., from the initial value of 0.2 to 0.18 and 0.16 t CO_2/MWh. This reflects the possible future injection of biogas into the distribution system, or syngas produced with the help of low-emission electricity.

In the second step, these emission factor reductions were assigned to two variant scenarios of emission factors' reductions, as described in Table 7.

Table 7. Variant scenarios for CO_2 emission factors (EFs) applied in the sensitivity analysis for electricity, heat from district heating systems, and gas from gas distribution systems for the year 2050 in metric tonnes of CO_2/MWh.

Fuel or Energy Carrier	Emission Factors for Variant Scenarios for 2050 (t CO_2/MWh)		
	EF1 (Baseline)	EF2	EF3
Electricity from grid	0.600	0.400	0.200
Heat from district heating system	0.300	0.225	0.150
Gas from gas distribution system	0.200	0.180	0.160

2.4. Evaluating Results Regarding National Climate Commitments

To evaluate the results of the study with respect to national climate commitments, we needed to summarize the input data related to the national climate commitments. In its Climate Protection Policy, the Czech Republic has committed to reducing greenhouse gas emissions at least by 80% compared with 1990 [52]. Recently, the Czech government supported the carbon neutrality of the EU as a whole by 2050 and articulated the willingness to commit to a national reduction of 95% by 2050, but this statement has not yet been materialized into any national policy. According to *the National Energy and Climate Plan of the Czech Republic* [6], the Czech Republic produced a total of 194.35 Mt $CO_{2,eq}$ in 1990 (without considering LULUCF and waste). By 2016, these emissions had fallen to 124.02 Mt $CO_{2,eq}$. Compliance with the commitment will necessitate a reduction in annual emissions to 38.87 Mt $CO_{2,eq}$.

In this study, the complete localized emission factors for the global warming potential (GWP (t $CO_{2,eq}$)) were not available; therefore, only emissions of carbon dioxide were considered. The National Inventory Report of the Czech Republic from 2020 [43] provides an overview of the production of greenhouse gases by individual gases. For CO_2 emissions in the Czech Republic in 1990, it states a value of 164.2 Mt. If we consider the theoretically even distribution of the national commitment among the monitored greenhouse gases and sectors (applying the even contraction approach), the commitment means an 80% reduction in the CO_2 production by 2050 of a maximum of 32.8 Mt. In 2016, this production was 106.6 Mt CO_2, so by 2050, it is necessary to reduce the annual production of Czech emissions by another 73.8 Mt CO_2.

The results of this study showed that the building stock produced a total of 36.9 Mt CO_2 in 2016, which means that the operation of the building stock accounted for approximately 34.6% of total national emissions. The maximum target value needed to meet the adequate national emission commitment allocated to the building stock is 11.4 Mt CO_2 for 2050.

For 1990, emissions from the building stock could be retrospectively estimated as 67.25 Mt CO_2 (but this estimate is highly inaccurate; emissions fell sharply in the early 1990s mainly due to the downturn in heavy industry and economic restructuring).

3. Results

3.1. Results of the Calculated CO_2 Emissions by Scenario

The resulting emissions by scenarios are shown in the following tables. Table 8 shows the emissions achievable through energy-efficient retrofitting of buildings for each individual scenario, i.e., improving the quality of building envelopes, replacing resources with more efficient ones, and using efficient control systems and mechanical ventilation with heat recovery, but without the installation of photovoltaic systems. Table 9 also includes BIPV. For the sake of simplicity, the tables do not show values for each year between 2016 (which was the base year of the energy model) and 2050, but only for 2016, 2030, 2040, and 2050.

Table 8. Resulting CO_2 emissions from the operation of the Czech building stock for individual scenarios without considering BIPV. The values are given in Mt CO_2/year.

Segment	Scenario	Year			
		2016	2030	2040	2050
Residential	Baseline	23.2	20.3	18.2	16.2
	Governmental		19.7	17.2	14.9
	Progressive		17.5	13.0	10.4
	Hypothetical		15.8	11.4	9.9
Nonresidential	Baseline	13.7	12.5	11.5	10.5
	Governmental		11.7	10.1	8.9
	Progressive		11.1	9.3	8.1
	Hypothetical		10.1	8.3	7.7
Whole building stock	Baseline	36.9	32.8	29.6	26.7
	Governmental		31.4	27.3	23.8
	Progressive		28.5	22.3	18.5
	Hypothetical		26.0	19.8	17.7

Table 9. Resulting CO_2 emissions from the operation of the Czech building stock for individual scenarios considering onsite electricity production from BIPV. The values are given in Mt CO_2/year.

Segment	Scenario	Year			
		2016	**2030**	**2040**	**2050**
Residential	Baseline	23.1	18.5	15.3	12.3
	Governmental		17.9	14.4	11.0
	Progressive		14.1	7.6	2.9
	Hypothetical		12.6	5.6	1.5
Nonresidential	Baseline	13.6	11.5	10.0	8.4
	Governmental		10.8	8.6	6.8
	Progressive		9.3	6.5	4.2
	Hypothetical		8.3	5.2	3.3
Whole building stock	Baseline	36.7	30.0	25.3	20.8
	Governmental		28.7	23.0	17.8
	Progressive		23.4	14.0	7.1
	Hypothetical		20.8	10.8	4.8

The results of the calculation show the potential for reducing the operating CO_2 emissions of the CBS until 2050 without considering photovoltaics in the range between approximately 27.6% in the Baseline Scenario and 52.0% in the Hypothetical Scenario, compared with 2016. Including BIPV enables a total reduction in CO_2 emissions ranging from 43.6% to 86.9%. The results are visualized in Figure 2.

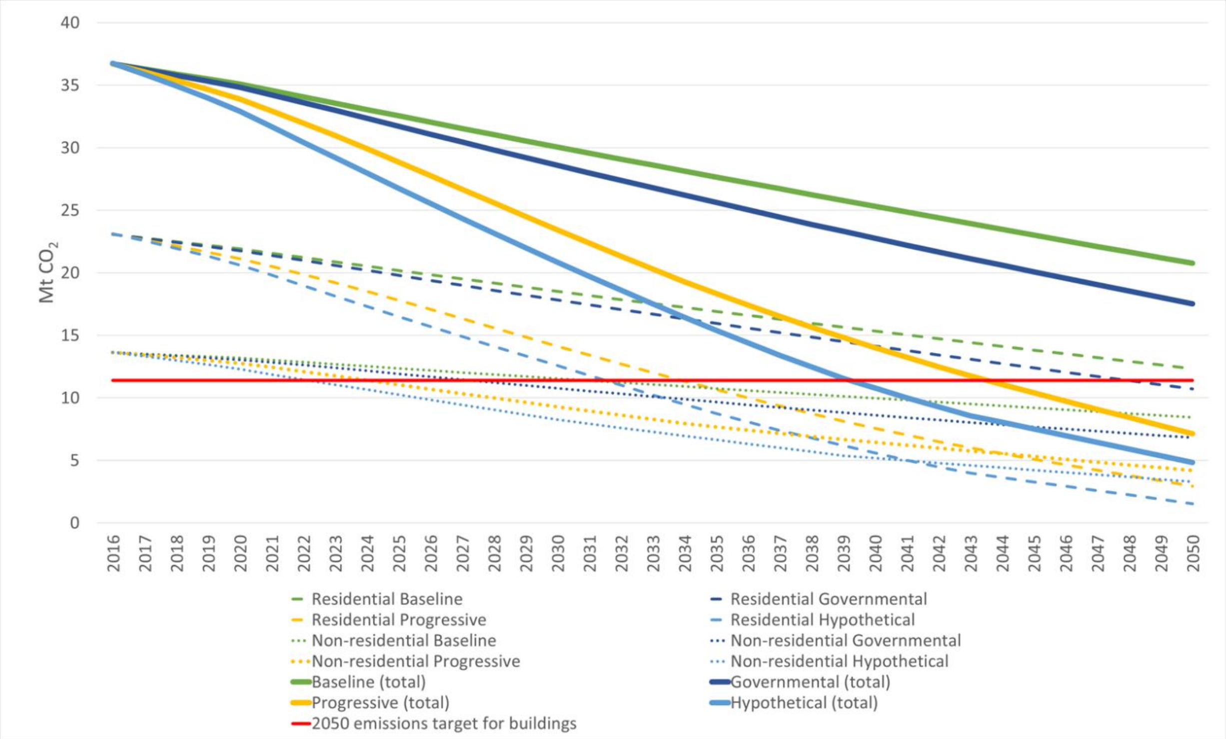

Figure 2. Modeled development of the amount of operational CO_2 emissions of the Czech building stock, including the consideration of BIPV (considered constant emission factors, in Mt CO_2). The dotted lines represent nonresidential building stock, the dashed lines represent residential building stock, and the solid lines show totals for the whole CBS. The red line represents the 2050 emission target for the whole CBS.

3.2. Results of the Sensitivity Analyses by Scenario

The following tables show the results of the sensitivity analysis of the values of operational CO_2 emissions in 2050. Tables 10–12 show the sensitivity to the emission factors of electricity from the grid, from the distribution, and from district heating, respectively.

The sensitivity to combinations of emission factors according to the combined variants EF1–EF3 is listed in Table 13.

Table 10. Sensitivity of the resulting CO_2 emissions from the operation of the CBS to the value of the electricity emission factor in 2050 for individual scenarios. Values are given in Mt CO_2/year.

Electricity		**Without BIPV**			**With BIPV**		
Electricity Emission Factor (t CO_2/MWh)		**0.6 (Baseline)**	**0.4**	**0.2**	**0.6 (Baseline)**	**0.4**	**0.2**
Residential	Baseline	16.2	13.4	10.6	12.3	10.8	9.4
	Governmental	14.9	12.0	9.2	11.0	9.5	7.9
	Progressive	10.4	8.1	5.9	2.9	3.2	3.4
	Hypothetical	9.9	7.7	5.5	1.5	2.1	2.7
Nonresidential	Baseline	10.5	8.3	6.1	8.4	6.9	5.4
	Governmental	8.9	7.0	5.1	6.8	5.6	4.4
	Progressive	8.1	6.4	4.6	4.2	3.8	3.3
	Hypothetical	7.7	6.1	4.4	3.3	3.1	2.9
Whole building stock	Baseline	26.7	21.7	16.7	20.8	17.8	14.8
	Governmental	23.8	19.0	14.2	17.8	15.1	12.3
	Progressive	18.5	14.5	10.5	7.1	6.9	6.7
	Hypothetical	17.7	13.8	9.9	4.8	5.2	5.6

Table 11. Sensitivity of the resulting CO_2 emissions from the operation of the CBS to the value of the emission factor of gas from the distribution system in 2050 for individual scenarios. Values are given in Mt CO_2/year.

Gas		**Without BIPV**			**With BIPV**		
Gas Emission Factor (t CO_2/MWh)		**0.2 (Baseline)**	**0.18**	**0.16**	**0.2 (Baseline)**	**0.18**	**0.16**
Residential	Baseline	16.2	15.9	15.6	12.3	12.0	11.7
	Governmental	14.9	14.6	14.3	11.0	10.7	10.4
	Progressive	10.4	10.2	10.0	2.9	2.7	2.5
	Hypothetical	9.9	9.8	9.6	1.5	1.4	1.2
Nonresidential	Baseline	10.5	10.3	10.2	8.4	8.3	8.1
	Governmental	8.9	8.8	8.6	6.8	6.7	6.6
	Progressive	8.1	8.0	7.9	4.2	4.1	4.0
	Hypothetical	7.7	7.6	7.5	3.3	3.2	3.1
Whole building stock	Baseline	26.7	26.2	25.8	20.8	20.3	19.8
	Governmental	23.8	23.3	22.9	17.8	17.4	17.0
	Progressive	18.5	18.2	17.9	7.1	6.8	6.5
	Hypothetical	17.7	17.4	17.1	4.8	4.6	4.3

Table 12. Sensitivity of the resulting CO_2 emissions from the operation of the CBS to the value of the emission factor of heat from the district heating systems in 2050 for individual scenarios. Values are given in Mt CO_2/year.

District Heating		**Without BIPV**			**With BIPV**		
Heat from District Heating System Emission Factor (t CO_2/MWh)		**0.300 (Baseline)**	**0.225**	**0.150**	**0.300 (Baseline)**	**0.225**	**0.150**
Residential	Baseline	16.2	15.6	14.9	12.3	11.7	11.0
	Governmental	14.9	14.3	13.6	11.0	10.4	9.8
	Progressive	10.4	10.0	9.6	2.9	2.6	2.2
	Hypothetical	9.9	9.6	9.2	1.5	1.2	0.8
Nonresidential	Baseline	10.5	9.9	9.3	8.4	7.8	7.2
	Governmental	8.9	8.4	7.9	6.8	6.3	5.9
	Progressive	8.1	7.7	7.2	4.2	3.7	3.3
	Hypothetical	7.7	7.3	6.9	3.3	2.9	2.4
Whole building stock	Baseline	26.7	25.4	24.2	20.8	19.5	18.3
	Governmental	23.8	22.7	21.6	17.8	16.7	15.6
	Progressive	18.5	17.7	16.9	7.1	6.3	5.5
	Hypothetical	17.7	16.9	16.1	4.8	4.1	3.3

Table 13. Sensitivity of the resulting CO_2 emissions from the operation of the CBS to the combination of the improved emission factors in 2050 for individual scenarios. Values are given in Mt CO_2/year.

Combinations		**Without BIPV**			**With BIPV**		
Emission Scenario		**EF1 (Baseline)**	**EF2**	**EF3**	**EF1 (Baseline)**	**EF2**	**EF3**
Residential	Baseline	16.2	12.5	8.7	12.3	9.9	7.4
	Governmental	14.9	11.1	7.3	11.0	8.5	6.0
	Progressive	10.4	7.5	4.7	2.9	2.6	2.2
	Hypothetical	9.9	7.2	4.4	1.5	1.6	1.6
Nonresidential	Baseline	10.5	7.5	4.6	8.4	6.2	3.9
	Governmental	8.9	6.4	3.9	6.8	5.0	3.2
	Progressive	8.1	5.8	3.5	4.2	3.2	2.2
	Hypothetical	7.7	5.6	3.4	3.3	2.6	1.9
Whole building stock	Baseline	26.7	20.0	13.3	20.8	16.0	11.3
	Governmental	23.8	17.5	11.1	17.8	13.5	9.1
	Progressive	18.5	13.4	8.2	7.1	5.8	4.4
	Hypothetical	17.7	12.7	7.8	4.8	4.2	3.5

3.3. Evaluation of Results from the Perspective of Emissions Targets

The results of the calculations showed that the modeled building stock produced a total of 36.9 Mt CO_2 in 2016, with 23.3 Mt CO_2 originating from residential buildings and 13.7 Mt CO_2 from nonresidential buildings. The total floor area of the buildings in 2016 was 599.49 million m^2, and the mean emission intensity for the entire building stock was 61.6 kg $CO_2/m^2 \cdot$year.

In the same year, 2016, the national emissions amounted to 106.6 Mt CO_2, which means that the share of the operation of the building stock in total national emissions was approximately 34.7%. The share of residential buildings in national emissions was approximately 21.9% and that of nonresidential buildings was 12.9%.

As for the accuracy of the provided results, the emission calculations of the baseline scenario were based on energy consumption data from the energy model that was calibrated to the available national statistics as described in Section 2.1.2 and on the emission factors shown in Table 6. Thus, the inputs on the energy inputs were as precise as possible; on the other hand, there is a source of uncertainties in the emission factors of the electricity from the grid and in the emission factor of the heat from district heating systems (which were both represented by just one figure).

The national commitment converted to CO_2 emissions in 2050 represents the total production of emissions as 32.8 Mt CO_2. For simplification, if we assume an even distribution of responsibility for reducing emissions across the sectors of the Czech economy, we can consider a constant share of national emissions for the building stock. This would mean that the target maximum annual CO_2 emissions of the building stock in 2050 would be 11.4 Mt CO_2. The expected floor area of buildings in 2050 was estimated at 741.02 million m^2, so the target emission intensity of the building stock to meet the national commitment was calculated as 15.4 kg $CO_2/m^2 \cdot$year, which is one-fourth compared with 2016.

The comparison of the emission values in individual scenarios listed in Tables 7 and 8 with the maximum target value needed to meet the national emission commitment of 11.4 Mt CO_2 showed that the commitment can only be met by implementing the Progressive Scenario at least for the retrofitting of buildings in combination with the development of photovoltaics.

In the Hypothetical Scenario, the target would be met as early as 2040, and in 2050, it would be close to the commitment to fully decarbonize the Czech building stock.

The Baseline scenario does not lead to a sufficient reduction: it reaches almost twice the value of the target for 2050. The Governmental Scenario then exceeds the target value by 56%.

To meet the Czech Republic's emission commitment, it is necessary to reduce the annual national production of emissions by 73.8 Mt CO_2 by 2050. If the Hypothetical Scenario considering photovoltaics is implemented, the building stock would save 31.9 Mt CO_2

per year, which would contribute a total of 43.2% to the reduction at the national level, i.e., a higher share than current emissions from buildings in total emissions.

In the Hypothetical Scenario without the development of photovoltaics, if the emission factor of electricity from the grid is reduced by 33% to 0.4 t CO_2/MWh, the emissions of the CBS will decrease by 22.0% by 2050 compared with the model with a constant emission factor. In the case of a reduction of 67% to 0.2 t CO_2/MWh, the decrease would be approximately 44.0%. A reduction in the emission factor of the heat from district heating systems by 25% or 50% would reduce the emissions by 4.5% or 9.0%, respectively. A reduction in the gas emission factor by 10% or 20% would result in a drop in the carbon dioxide emissions by 1.7% and 3.4%, respectively. In the case of a reduction in emission factors according to the EF2 combination of emission factors, the reduction in emissions would be 28.2%; EF3 would result in a 56.5% decrease in emissions.

In cases where BIPV is included and the deduction of theoretically excess electricity is compared with the electricity emission factor from the grid, the situation is less clear, because the higher the reading, the higher the electricity emission factor, and the faster the development of photovoltaics. In practice, this means that as the electricity emission factor decreases, the total emissions from buildings in 2050 will be slightly higher in the most progressive retrofitting scenario, as this scenario also envisages the rapid development of photovoltaics, the production of which is exported to the grid. However, this only provides a methodology for calculating emissions from the building sector and the specific role of electricity and photovoltaics.

In the Hypothetical Scenario until 2050, the total emissions of the building sector can be reduced by up to 90% compared to 2016 due to the integration of photovoltaics and the consideration of the EF3 combination of emission factors.

4. Discussion

4.1. Uncertainties

Due to the scale of the energy model, a number of simplifications were required in this study, which inevitably lead to uncertainties.

The main source of uncertainty is the emission factors used. In contrast with the previous study from 2016 [31] published in 2019, which was based on the emission factor of electricity from the grid, which was based on the already obsolete value of 1.17 kg/kWh specified in the then valid decree for conducting energy audits, here, we used an emission factor closer to the statistical values for the Czech energy mix of 0.6 kg/kWh, which is almost half the old value. This led to a significant correction toward a reduction in the resulting CO_2 emissions. In future work, the emission factor change during the day and over the year in various situations should be considered, and the marginal emission factor should be calculated for the specific subcategories of the national building stock, including forecasting future scenarios related to the future composition of the power sector, flexibility and smartness of the energy grid, and flexibility and smartness of the buildings (as leading examples of these studies, see Kiss et al. [53] or Clauß et al. [54]).

Another source of uncertainty is that the emission factors were not used dynamically, and some back loops were not considered. For example, a reduction in the emission factors for both gas and district heating should be reflected in the reduction in the emission factor for electricity cogeneration in heating plants.

Emission factors for renewable energy sources were considered to be zero, but in reality, this is not the case. For example, to obtain heat from solar collectors, auxiliary energy is needed, which was neglected. Similarly, a zero emission factor was used for biomass, as the condition of renewable nature was assumed to be met, which means sustainable cultivation of biomass so that no more biomass is used than can be grown. However, it is uncertain whether this condition will be met in the future. Emissions related to the extraction and processing of biomass were also neglected.

Uncertainties in emission factors were partially solved by the performed sensitivity analysis for the target year 2050, which showed how the individual scenarios behave when considering the gradual reduction in emission factors.

Other sources of uncertainty are the assumptions of the future development of the share of energy sources in buildings and thus various fuels or energy carriers. The definition of their scenarios was preceded by an expert discussion and analysis of available documents. We estimated that the effect of the deviation from the assumed share of resources in buildings is less than the effect of the inaccuracy of emission factors.

Some uncertainties arise from the nature of the input data of the time evolution of final energy consumption in buildings, which was based on a simplified energy model and assumptions about the future development of the building stock.

In addition, there are uncertainties in the marginal climatic conditions. In the previous study from 2016 [31], energy consumption was modeled in two climate scenarios, RCP4.5 and RCP8.5, to determine the impact of changes in climatic conditions in the Czech Republic on the final energy consumption in buildings. With regard to the expected increase in temperatures in both climatic scenarios, the assumption of an increase in consumption for cooling and air conditioning and a decrease in consumption for heating was added to the energy model. The resulting effect was a reduction in energy consumption in individual scenarios in 2050 by 1.7% to 2.3% for RCP4.5 and 5.5% to 6.4% for RCP8.5 compared with the baseline scenario. This reduction would also affect emissions. Due to the relatively small variance in consumption and the relative laboriousness of the modeling results in this updated study, these differences were not incorporated.

Energy-efficient retrofitting of the building stock will be associated with the production of associated greenhouse gas emissions, which will be released as a result of the extraction of raw materials, the production of building materials and energy systems, their transport, and the construction processes for their incorporation. These embodied emissions have not yet been thoroughly considered as they have not been considered significant in relation to operational emissions. However, once operational emissions from buildings can be reduced to zero, the combined emissions from construction products and HVAC systems will become more important and will significantly impact the overall production of greenhouse gas emissions related to the building stock, as indicated by recent studies [29]. A good example of various material considerations in such analyses is presented in [55].

4.2. Discussion of the Results in the Context of Previous Studies

Although the previous study from 2016 presented the share of buildings in national CO_2 production as being 43%, this refined study reports a 34.7% share, which is closer to the European average of 36% reported by the European Commission [7].

The calculated reduction potential for the national building stocks' CO_2 production in 2050 ranges from 27.6% to 52.0% without considering the uptake of BIPV, and from 43.6% to 86.9% when factoring in the rapid uptake of BIPV. These figures are not comparable to the relatively low reduction potential reported from the Asian countries mentioned in the introduction, where the massive growth in building stock is expected. However, the resulting figures are compatible with the GHG saving potential ranges for 2050 from Germany (35–65%) [25–27] and with the figures presented [30] for Czechia (CZ-ENTRANZE for 2030: 40%; CZ-Mapping for 2030 37%; CZ-Briskee for 2030: 38%; CZ-Progressh for 2030: 26%). The report does not include Czech figures for 2050, but the figures for 2050 for the neighboring Slovakia are 72% (ZEBRA), 70% for Germany (ZEBRA), and 60% for Poland (ZEBRA).

4.3. Recommended Policy Actions

The CfB issued a report [40] that summarized the long-term strategy for the renovation of buildings, which aligns with the results of the investigations presented in this paper. The report (in its Section 11) summarizes the recommendations of the following measures to be taken to achieve the national climatic targets:

- Policy measures:
    - Inclusion of the modeled scenarios into the national energy policy;
    - Inclusion of the savings measures proposed in the study into sectorial policies.
- Economic measures:
    - Maintain all incomes from the EU Emission Trading Scheme dedicated for GHG emissions reduction in the existing subsidy scheme, New Green Savings Programme for energy retrofitting of residential buildings and support new construction meeting the passive energy standard and with additional financial instruments;
    - Maximize the use of the European Structural and Investment Funds and the European Commission's Modernisation Fund for increasing the energy efficiency of public and commercial buildings and the rollout of renewable energy systems for buildings;
    - Combine the investments with energy performance contracting (EPC) in the public sector;
    - Using the above-mentioned financial sources and EPC for governmental buildings, which shall be used as examples of best practices (following the EU Energy Efficiency Directive);
    - Provide financial support for energy-efficient social housing in the form of training social workers in do-it-yourself energy efficiency measures for low-income people.
- Legislative and administrative measures:
    - Tightening of the energy performance standards for subsidized building renovations. The actual standard was set as a cost optimum, but when a project is subsidized, the requirements can be shifted accordingly;
    - Improving the standard for nearly zero energy buildings (which is, in the actual Czech implementation, less demanding than passive housing standards) closer to the passive house standard equipped with renewable energy systems;
    - Harmonizing the boundary conditions and calculation methods for the Czech implementation of the Energy Performance Certificates;
    - Examining the possibility of tax benefits for energy-efficient buildings;
    - Ensuring coherent requirements of construction legislation and harmonized energy performance requirements in the building permission process;
    - Broadening the existing ENEX system for reporting and evaluation of energy savings.
- Education and counseling measures:
    - Strengthening support for consultancy by extending the existing partly subsidized Energy Consulting and Information Centers network and by presenting examples of good practices including their economic performance;
    - Preparation of targeted methods to support quality project preparation in the public sector, i.e., the creation of project stocks for investment in all building segments which needs to be further developed;
    - Increasing public awareness among real estate owners on the benefits of deep energy retrofits;
    - More intensive training and education on all scales.
- Research and development:
    - Supporting the research and development of new materials, technologies, and processes that can significantly reduce the costs of implementing energy-saving measures and local renewable energy systems. Opportunities for targeted support of science and research in the field of energy-efficient construction should be sought.

5. Conclusions

In this study, we quantified the potential for CO_2 emission reductions from the operation of the Czech building stock according to updated building retrofitting scenarios and evaluated the possible contribution of energy-saving measures applied to the building stock to national emissions commitments.

The calculations were based on the modeled final annual energy consumption of the CBS in four retrofitting scenarios in the years 2016–2050. The results showed that the building stock produced a total of 36.9 Mt CO_2 in 2016, with 23.2 Mt CO_2 originating from residential buildings and 13.7 Mt CO_2 from nonresidential buildings. The share of residential buildings in national emissions was approximately 21.8%, the share of nonresidential buildings was 12.8%, and the total share was 34.6%.

The results of the calculation showed the potential for reducing operating emissions without considering the photovoltaics of the CO_2 buildings of the Czech building stock until 2050, ranging from approximately 27.6% in the Baseline Scenario to 52.0% in the Hypothetical Scenario. When BIPV was included, this reduction ranges from 43.6% to 86.9%. Compared with 1990 emissions, the reduction range under various assumptions for building retrofitting and the development of photovoltaics is between 69% and 93%.

Assuming a balanced share of industry sectors in reducing greenhouse gas emissions, the national climate commitment for the building stock in 2050 was calculated as 11.4 Mt CO_2. The resulting values for the individual scenarios were compared with this target value.

The comparison of emission values in individual scenarios, listed in Tables 8 and 9, with the maximum target value needed to meet the national emission commitment of 11.4 Mt CO_2 showed that the commitment can only be met by implementing at least the Progressive Scenario for the retrofitting of buildings with the simultaneous development of photovoltaics. In the Hypothetical Scenario, the target would be met as early as 2040, and in 2050, emissions from the building stock would be close to the target of their full decarbonization. The Baseline Scenario led to almost double the values compared with the required target for 2050. The Governmental Scenario exceeded the target value by 56%.

Achieving truly zero emissions in the future must be heavily supported by reducing electricity, district heating, and gas emission factors, and/or significantly changing the share of buildings in energy sources so that high-emission sources are not used, and/or pairing buildings with carbon capture and storage technologies in the future.

To meet the Czech Republic's emission commitment, it is necessary to reduce the annual national production of emissions by 73.8 Mt CO_2 by 2050. In the case of the implementation of the Hypothetical Scenario with photovoltaics, the CBS would save 31.9 Mt CO_2 per year, which would contribute to a reduction at the national level by reducing emissions by a total of 43.2% compared with the 2016 emissions benchmark.

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Appendix A. English Summary of the Data from the Report on the Investigation of the Czech Residential Building Stock

This appendix summarizes the main information provided in the report Průzkum fondu rezidenčních budov v České republice a možnosti úspor v nich, which describes the energy modeling of the residential building stock [36]. In the text below, the page numbers in the report are referenced, which is available at http://sanceprobudovy.cz/wp-content/uploads/2018/04/pruzkum-rezidencnich-budov-v-cr.pdf (accessed on 21 March 2021).

The demand for energy for heating for the base year was calculated from simulated samples of residential buildings in the categories of single-family houses and multi-family houses (page 8). Both categories were broken down to subcategories by year of construction (before 1920; 1920–1945; 1946–1960; 1961–1980; 1981–1994; after 1994) and by the level of floors above ground. The categories were also broken down by the number of floors (single-family houses: 1; 2; and 3; multi-family houses between 1 and 11 per floor, then a category of buildings above 11 floors). For each category, a parametric sample of 1000 buildings describing various geometries and thermal properties of the building envelopes was created. The resulting energy demands for heating were recorded for each building and for the whole category and they were coupled with the statistical data on the Czech residential building stock. The resulting figures were compared with the statistical data on energy and fuels consumption, which served as a basis for the calibration of the model.

The related statistical data on the categories by number of units and floor areas are summarized on pages 11–13 (single family houses) and 14–16 (multi-family houses). The chart on page 17 shows the amounts of residential buildings by number of floors.

The considered U-values of the components of building envelopes per category by the year of construction are summarized on pages 18–20 (Figure 9 shows U-values of external walls; Figure 10 U-values of roofs; Figure 11 U-values of floors on the ground; Figure 12 U-values of windows and doors).

Table A1. Considered U-values for the components of building envelopes of single-family houses by the year of construction (in in W/m^{2}K) Reproduced from [36], Šance pro budovy: 2016.

Year of Construction	Before 1920		1921–1945		1946–1960		1961–1980		1981–1994		After 1994	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Roofs/floors below attics	0.66	1.05	0.83	1.48	0.68	1.48	0.64	1.01	0.26	0.55	0.17	0.42
External walls	0.83	1.31	1.02	1.62	1.02	1.70	0.90	1.66	0.38	0.59	0.19	0.30
Floors on ground	2.42	3.84	0.77	1.78	0.77	1.34	0.68	1.52	0.38	1.31	0.34	0.62
Windows and doors	1.80	2.85	1.80	2.85	1.80	3.44	2.03	3.21	1.50	2.90	0.83	1.54

Table A2. Considered U-values for the components of building envelopes of multi-family houses by the year of construction (in in W/m^{2}K) according to [36].

Year of Construction	Before 1920		1921–1945		1946–1960		1961–1980		1981–1994		After 1994	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Roofs/floors below attics	1.10	3.09	0.60	1.78	0.76	1.72	0.43	1.01	0.35	0.55	0.24	0.38
External walls	0.83	1.62	0.83	1.31	1.07	1.70	0.70	1.43	0.55	0.90	0.19	0.59
Floors on ground	0.49	0.77	0.77	1.22	0.76	1.22	0.69	1.09	0.62	1.31	0.30	0.53
Windows and doors	1.80	2.85	1.80	2.85	2.18	3.44	1.83	3.21	2.03	3.44	1.20	1.90

Pages 21–23 report on the geometric characteristics of the family houses and Table 13 on page 23 shows in detail used geometric characteristics for the group of single-family houses with two floors.

On pages 24–25, datasets obtained from the Ministry of Industry and Trade of the Czech Republic on the total energy consumptions for space heating, domestic hot water preparation and for lighting in 2011 are presented.

Pages 25–27 present an estimation of a share of buildings with applied thermal insulation. It is based on the study from the previous project PanelSCAN and on the estimation of the amount of installed external thermal insulation composite systems based on sales statistics by the Czech Guild for Thermal Insulation of Buildings. The resulting estimation of already insulated buildings used in the calculations is 35%.

Considered efficiencies by energy sources are shown in Table 20 on page 28, which shows calculated energy demand for heating and considered efficiency by type of fuel. The considered combined energy efficiencies for heat sources were:

- Oil and petroleum products: 81.6%;
- Natural gas: 81.6%;
- Coal and coal products: 72.0%;
- Biomass: 72.0%;
- Heat from district heating systems: 94.1%;
- Electricity: 85.5%;
- Heat from solar systems or from heat pumps: 96.0%.

Assumed consumptions of the hot water are shown in Table 24 on page 31 (in single-family houses 35–55 L per person and day, in multifamily houses 12.78–20.08 L per person and day). The considered volumes of the hot water storages and the lengths of the heat distribution piping are in Annex 3.

Table 34 on page 36 presents the calculation of the energy consumptions for lighting.

From page 38 on, the report discusses the investment costs; the economic aspect is out of the focus of this paper, so it is skipped in this description.

Appendix 1 on pages 60–64 summarizes the geometric characteristics, proportions of the building envelopes' components, mean U-values of the building envelopes and the percentage of glazed areas for all categories of the single-family houses.

Appendix 2 on pages 65–72 provides a summary of the energy simulation results. The energy consumption for the baseline year for the single-family houses is shown in Table 59 on page 66 and for the multifamily residential houses in Table 64 on page 71.

Appendix B. English Summary of the Data from the Report on the Investigation of the Czech Nonresidential Building Stock

This appendix summarizes the main information provided in the report Průzkum fondu nerezidenčních budov v České republice a možností úspor v nich, aktualizovaná verze prosinec 2016, which describes the energy modeling of the nonresidential building stock [37]. In the text below, the page numbers in the report are referenced, which is available at http://sanceprobudovy.cz/wp-content/uploads/2018/04/pruzkum-nerezidencnich-budov-v-cr.pdf (accessed on 21 March 2021).

The energy modeling of the nonresidential building stock was based on two samples of buildings. One is a sample of 100 buildings for which an energy model is available to assess the energy performance certificate. The model is created for all buildings in the same way and in accordance with Decree 78/2013, Coll., TNI 730331, and EN ISO 13790. Furthermore, the study evaluates a sample of 20 buildings for which, in addition to the energy model, real energy consumption (especially for heating) based on energy bills is also available. The text then compares the calculated values according to standard energy certificate calculation method and the real consumption of buildings. The calibration of the energy model was made by comparison of the simulated energy consumption with the real energy consumption on twenty existing buildings. Based on these comparisons, a correction formula for their extrapolation on the whole nonresidential building stock was derived. It was based on a sensitivity analysis that identified the key parameters: surface area/volume ratio, ratio between the mean U-value and the reference U-value used in the declaratory energy performance calculation method, mean indoor temperature and the overall efficiency of the heating system.

The report starts with the introduction of the sample of 100 buildings. The building typologies included in the study were office and administrative buildings, commercial buildings, educational buildings, cultural buildings, hotels, restaurants, medical facilities, sports facilities, storage buildings, and those with mixed use. Appendix 1 on pages 69–80 presents photos of all buildings for illustration. The buildings' heated floor area varied from 163 m^2 and 32,211 m^2; the mean area was 4502 m^2 and median 2313 m^2 (details on distribution chart (Figure 2), volumes (Figure 3), A/V ratios (Figure 4) and glazing ratios (Figure 5) are on pages 6–7). Section 2.2 on pages 9–11 describes the U-values and boundary conditions in the considered scenarios, which are summarized in Table 1 of this paper above.

Section 2.3 presents results of the simulations. Figure 6 shows the distribution of mean U-values of the modeled building's envelopes and Table 8 presents the energy classifications of the building envelopes by scenario. Table 9 shows the calculated energy demands for heating; for the baseline scenario, the results span between 40 and 371 kWh/m^2. The mean value of energy demand for heating is 135 kWh/m^2, which results in 233 kWh/m^2 in final energy consumption after figuring in the auxiliary energy consumption and the system efficiencies.

Section 3 works with the sample of real twenty buildings with data from energy audits and elaborates on the energy savings potential in scenarios.

Section 3.2 documents the design of the correction factor formula by using the sensitivity analyses, and the formula itself is presented on page 29.

Section 4 presents the outcomes of the application of the correction formula on the sample of 100 buildings, which shifts the span of results in the final energy consumption to the range of 40–256 kWh/m^2 and the mean value to 108 kWh/m^2. Section 4.2 describes the economic evaluation of the energy retrofitting measures (which is out of the scope of this paper).

Section 5 summarizes the background statistical data that were used for the energy modeling of the Czech nonresidential building stock. General data are presented on pages 38–46, page 47 provides granular information on educational buildings.

Section 6 deals with the procedure of the extrapolation of economic considerations to the whole nonresidential building stock.

Section 7 provides a detailed description of the modeled heat sources and their parameters. The dimensioning of the modeled heat sources was performed for the extreme external temperature −15 °C (which is more or less representative for Czechia on average) and safety surcharges of 20% were added. As shown in Table 39, the power of the heat sources varied from 20 kW to 3 MW, the average power was 330 kW for the baseline scenario. For the calculations, the heat loss calculation has been made per square meter, as shown in Table 40. Considered efficiencies of heat sources by energy type or fuel are presented in Table 43 on page 54. The prevailing heat sources and their considered efficiencies were:

- Heat from district heating systems: efficiency 98–99%;
- Natural gas: efficiency 77–98%;
- Electricity: efficiency 93–99%.

Table 60 on page 67 summarizes the energy consumption other than for heating. The largest average value of supplied energy was for the lighting (15 kWh/m^2a) and for hot water preparation (14 kWh/m^2a). For cooling, the average value of 1.3 kWh/m^2a was stated, but it should be noted that only 33% of the buildings had cooling. The average value for buildings where cooling occurred was 4 kWh/m^2a. It should also be noted that even for buildings that have energy supplied for cooling, these are usually only some parts of the buildings that are cooled. From the point of view of the methodology of the calculation of supplied energy, cooling is approached differently from heating and the supplied energy is identical to energy consumption. The specific energy demand for cooling would therefore be approximately 12 to 16 kWh/m^{2}a for buildings with cooling, taking into account a cooling factor of 3 to 4. At the same time, however, it should be noted that the calculation of cooling energy consumption using the monthly method ČSN EN ISO 13790 shows irrelevant results in many cases.

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