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Including Carbon Dioxide and Sulphur Dioxide Production in the Lifetime Costs of Buildings

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Abstract

Reduction in the consumption of operational (primary) energy and emissions of harmful gases has recently become the focus of attention of the civil engineering sector. In this context, there is also emphasized the energy consumption and emission production values associated with the whole life cycle of the construction materials used, which is referred to as “bundled energy consumption” and “bundled emissions”. This paper analyses the energy performance certificates in combination with the SBToolCZ methodology. Sustainability Building Tool is a methodology designed to assess the sustainability of buildings. This methodology is used to assess the environmental impact of buildings at different stages of their life cycle, such as production, operation and demolition of the building. The amount of carbon dioxide and sulphur dioxide produced during the life cycle of buildings was determined by analysing and extending the building assessment data by the SBToolCZ methodology, which was subsequently valued and incorporated into the lifetime costs. The data from 17 case studies from the Czech environment were analysed. Taking these environmental impacts into account, valuing them and analysing the cash flows of investors and society shows the importance of paying increased attention to sustainable construction and reducing its negative impact on the environment and climate. Research data shows that 30% of the operating costs of buildings are the societal costs associated with CO_{2,eqv.} and SO_{2,eqv.} production.

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1. Introduction

The production of carbon dioxide and sulphur dioxide in the construction sector is closely linked to the energy intensity of buildings and the processes associated with their construction, maintenance and operation [1]. These gases are products of burning fossil fuels, which are often used for heating, cooling and lighting in buildings. In addition, sulphur dioxide is also released during the production of building materials such as concrete [2]. As the construction sector accounts for a significant proportion of the total production of these greenhouse gases, it is necessary to analyse and assess their impact on society and the environment. The importance of this issue is also reflected in the Paris Agreement, which is considered to be a historic step in the fight against climate change and a major international achievement, as it has been signed by almost all countries of the world [3]. The Green Deal was adopted by the European Commission as a framework for achieving the targets set out in the Paris Agreement on climate change [4]. The aim of the Green Deal is to reduce greenhouse gas emissions in the European Union and to achieve climate neutrality by 2050. The Green Deal therefore specifically describes, expands and makes demands on the construction sector in the main areas of renovation and energy efficiency. The article deals with the evaluation of the economic efficiency of the construction of residential buildings both from the perspective of the user and from the point of view of the impact of the building on the public space in which it is located. The research methodology is based on monitoring the direct costs of the investor (investment and operating costs of the building) and indirect costs (societal costs) related to the environmental impact of the building. The environmental impact of the implementation and operation of the buildings related to the global warming potential ($\text{CO}_{2,\text{eqv.}}$ emissions) and the environmental acidification potential ($\text{SO}_{2,\text{eqv.}}$ production) has been valued and incorporated into the economic cash flow in the framework of the research activity. This means the valuation of negative externalities from the perspective of economic sciences.

2. State of art

In recent decades, there has been a growing awareness of the negative impacts of carbon dioxide and sulphur dioxide emissions on health, the environment and the economy. According to the International Energy Agency (IEA), the construction sector is responsible for 36% of global energy consumption and 39% of greenhouse gas emissions in 2017, making it one of the largest sources of emissions in the world [5]. As a result, governments and industry are trying to reduce emissions of these substances and change their approach to energy production. Carbon dioxide and sulphur dioxide cause a number of negative impacts on society and the environment [6]. Sulphur dioxide (SO_2) is one of the main pollutants produced by industry and energy sources, including the construction sector. Its presence in the air can have a negative impact on human, animal and plant health, as well as on infrastructure and the environment. Concerning the construction industry, SO_2 can cause corrosion of metal structures, deterioration of facades and damage to building materials. This acidic gas can also accumulate indoors and create hazardous working conditions, which can endanger human health [7].

Research carried out by Sartori and Hestnes [8] based on 60 case studies of the energy life cycle of buildings shows that at least 54% of the energy consumption of low-energy buildings and 62% of the energy consumption of traditional buildings occur during the operational phase. This phase, therefore, represents one of the main factors of overall consumption.

The common situation assumes compliance with policies that plan for "net-zero" GHG emissions in the operational phase of the building. This trend is also visible in the European Union legislation, where the term NZEB (near zero-energy buildings) appears in several directives and regulations. Furthermore, in 2018 the European Union adopted a new Energy Efficiency in Buildings Directive 2018/844, which replaces the original Directive 2010/31/EU [9]. These structures are supposed to be energy self-sufficient through the use of renewable energy. Taking into account the assumption of future reduction of greenhouse gases (GHG) emissions from the operational phase of buildings, it directs attention to the equally important GHG emissions tied up in the construction of buildings [10].

The study by Yahong Dong compares the results of a building life cycle assessment (LCA) study in a harmonised comparison of 105 building cases published in the last decade. These cases were analysed in terms of the entire life cycle of the buildings, including production, use and end-of-life. The results were presented in the form of statistics for 7 impact categories and 3 damage categories. This research could both contribute to a better understanding of

LCA results in the construction sector and serve as a reference point for the comparison of the environmental impacts of buildings [11].

This paper [12] seeks to provide an overview of the current state of life cycle assessment (LCA) in the construction sector, both in regulatory measures and academic case studies. A systematic method of comparing the impact categories is needed when trying to contrast the results of LCA studies of buildings.

The importance of early design decision-making has been widely studied and acknowledged. Significant decisions in the design process are made in the early design stages and different design alternatives must be compared even when complete building information is not available. Designing energy-efficient buildings requires a step by step calculation of GHG emissions during the building design process. The procedure should be implemented step by step in a systematic way. The designer should understand the importance of preliminary calculations at each stage of the design process [13]. The main approach to achieving a lower energy and environmental impact on buildings is to choose the optimal variant for both building renovation [14] and new construction. However, the selection of these measures is complicated due to the complexities involved in finding the optimal combination of measures [15]. For this reason, several studies should include either single or multi-objective [16] optimization methods to choose the most appropriate combination of measures for specific building types. In addition, measures can be evaluated using different criteria and valuation methods, with more sophisticated financial valuation methods requiring more complex calculations [17].

The societal costs of carbon dioxide involve monetising the damage caused by releasing one tonne of harmful emissions such as CO₂ and SO₂ into the atmosphere. Damage monetisation is essential for determining optimal climate policies. Pricing negative externalities in the form of harmful emissions provide the right economic incentive to reduce current emissions. It can also serve as an indicator for clearer decision-making [18].

The SBTool methodology consists of several categories such as energy efficiency, renewable energy usage, water use and many others. The evaluation is done through a point system where points are allocated for meeting different criteria in each category. The SBTool methodology is used worldwide and there are several versions for different countries and regions [19] [20]. One of the aspects that SBTool includes is the assessment of the energy performance of buildings and the amount of greenhouse gas emissions such as carbon dioxide or sulphur dioxide.

This paper focuses on a methodology for assessing the monetary impacts of carbon dioxide and sulphur dioxide associated with the construction, operation and demolition of buildings from a societal perspective.

3. Data and methods

The research sample consisted of 17 residential buildings, which were implemented in the Czech Republic mainly in the South Moravian Region. Energy performance certificates were developed for all buildings and specific annual energy consumption in MJ/m² of total floor area was determined with the support of the certification tool SBToolCZ [21]. SBToolCZ assesses primary energy consumption, which takes into account the life cycle of the whole process of energy acquisition and delivery to the place of consumption, and bundled energy consumption, which takes into account the material of the building structures. The evaluation consists of two assessments according to the life cycle phases of the building. Thus, the production phase is assessed to determine the bundled energy consumption (including consideration of the renewal of the structure after its potential end of service life) and the operational phase is to determine the primary energy consumption from non-renewable sources according to the energy performance of the building and the energy carriers used.

The basic data for the subsequent economic analysis are presented in Table 1. below. These are total built-up and floor area in m², built-up space in m³, and specific annual consumption of the bundled, primary and total energy in MJ/m² of total floor area.

Table 1. Input parameters of the apartment buildings of the research sample.

No.	Total floor area (m ²)	Built-up space (m ³)	Built-up area (m ²)	Specific annual consumption of bundled energy (MJ/m ² ·a)	Specific annual consumption of primary energy (MJ/m ² ·a)	Total specific annual energy consumption (MJ/m ² ·a)

1	808	2,656	256	177	312	489
2	831	2,850	238	104	277	381
3	3,587	14,690	529	77	327	404
4	878	2,751	351	146	914	1,061
5	2,151	4,484	233	92	214	307
6	1,811	6,256	1,264	215	458	672
7	810	2,995	187	155	303	458
8	228	805	111	91	427	517
9	1,155	4,930	408	197	469	666
10	647	2,010	285	123	539	663
11	275	1,081	163	132	530	662
12	1,427	4,017	309	116	534	651
13	1,654	7,607	495	125	87	212
14	1,690	5,468	468	233	533	766
15	433	1,492	313	139	644	782
16	965	4,922	343	68	470	538
17	987	3,428	328	234	535	769

The corresponding specific annual CO_{2,eqv.} and SO_{2,eqv.} emission productions were determined on the basis of the total energy consumption, which, as well as energy, were determined in the production phase for the determination of the bundled CO_{2,eqv.} and SO_{2,eqv.} emission production, and in the operational phase for the determination of the CO_{2,eqv.} and SO_{2,eqv.} emission production, e.g., resulting from the energy consumption in the operation phase of the building. The values of both potential values are given in Table 2.

Table 2. Global warming and acidification potential values of the buildings under research.

No.	Specific annual bundled CO _{2,eqv.} emission production	Specific annual CO _{2,eqv.} emission production	Total specific annual bundled CO _{2,eqv.} emission production	Specific annual bundled SO _{2,eqv.} emission production	Specific annual SO _{2,eqv.} emission production	Total specific annual bundled SO _{2,eqv.} emission production
	<i>kg CO_{2,eqv.}/(m²·a)</i>	<i>kg CO_{2,eqv.}/(m²·a)</i>	<i>kg CO_{2,eqv.}/(m²·a)</i>	<i>kg SO_{2,eqv.}/(m²·a)</i>	<i>kg SO_{2,eqv.}/(m²·a)</i>	<i>kg SO_{2,eqv.}/(m²·a)</i>
1	13.77	35.54	49.31	0.0395	0.0689	0.1084
2	10.13	27.23	37,36	0.0240	0.0445	0.0685
3	7.20	27.22	34,42	0.0193	0.0348	0.0541
4	14.53	192.94	207.47	0.0220	0.5451	0.5671
5	5.60	18.06	23.66	0.0351	0.0277	0.0628
6	14.90	38.80	53.70	0.0546	0.0495	0.1040
7	19.71	29.20	48.91	0.0440	0.0643	0.1083
8	5.81	35.28	41.09	0.0230	0.0450	0.0680
9	12.95	36.93	49.88	0.0419	0.0395	0.0814
10	9.02	71.38	80.40	0.0285	0.1663	0.1948
11	9.62	47.62	57.24	0.0277	0.0676	0.0953

12	8.02	68.27	76.29	0.0220	0.1465	0.1685
13	9.20	13.82	23.02	0.0299	0.0394	0.0693
14	17.04	46.82	63.86	0.0500	0.0678	0.1178
15	9.00	135.82	144.82	0.0284	0.3837	0.4121
16	5.88	46.47	52.35	0.0172	0.0764	0.0936
17	29.62	47.59	77.21	0.0291	0.0664	0.0955

4. Results and discussion

The economic CF for determining the partial lifetime costs of individual buildings consists of the following items: investment costs, operating costs for repairs and maintenance and external costs of societal (damages) associated with the production of CO_{2,eqv.} and SO_{2,eqv.}. For the calculation of external costs, a price of 167 €/t is considered for the production of CO_{2,eqv.} emissions equivalent and 24,697 €/t for SO_{2,eqv.} sulphur dioxide emissions from Departmental Guideline [22]. The lifetime costs can be calculated based on the following relation:

$$WLC = \sum_{i=0}^n \frac{C_i}{(1+r)^i} + \sum_{i=0}^n \frac{Ex_i}{(1+r)^i} \quad (1)$$

WLC Whole Life Costs,
 C Costs in the year *i*,
 Ex Costs of externalities in the year *i*,
 n Number of years of the assessed period,
 r Discount rate % / 100.

The lifetime costs presented in Table 3 were determined based on the above-stated relation and using the discount rate of 5% applied to public projects in the Czech Republic in the EU programme period 2021-2027, an assessed period of 10 years (*t*₀ - investment costs, *t*₁ to *t*₁₀ - operating costs of buildings and operating costs of externalities).

Table 3. Whole life costs in €.

No.	Investment costs	Annual operating costs of the building	Annual externalities	WLC	WLC/m ²	The ratio of building costs and externalities
	(a)	(b)	(c)	(d)	(e)	(f) = (c)/((b) + (c))
1	992,694	21,064	8,808	1,165,104	1,443	29%
2	1,065,203	21,655	6,589	1,222,183	1,470	23%
3	5,490,466	92,893	25,389	6,098,929	1,700	21%
4	1,028,306	34,395	42,676	1,546,117	1,762	55%
5	1,675,919	29,333	11,829	1,898,820	883	29%
6	2,338,288	55,628	20,884	2,789,608	1,540	27%
7	1,119,532	24,508	8,777	1,310,998	1,619	26%
8	300,761	7,445	1,942	355,476	1,563	21%
9	1,842,614	32,224	11,936	2,079,625	1,801	27%
10	751,248	20,204	11,801	950,838	1,469	37%
11	404,030	9,674	3,278	480,037	1,744	25%

12	1,501,375	41,129	24,109	1,909,638	1,338	37%
13	2,843,157	48,223	9,187	3,129,967	1,892	16%
14	2,043,694	39,221	22,932	2,403,450	1,422	37%
15	557,456	14,943	14,855	750,046	1,734	50%
16	1,839,665	38,776	10,657	2,115,591	2,193	22%
17	1,281,233	32,294	15,047	1,568,368	1,589	32%

Column (e) of Table 3 shows the WLC per m² of floor area, which ranges from 883 (building 5) to 2,193 €/m² (building 16), mainly due to differences in the average heat transfer coefficient of the building envelope depending on the material characteristics and construction technology.

Column (f) shows the ratio of the annual operating costs of the building to the external societal costs associated with negative externalities. The values range over a fairly wide range from 16% (building 13) to 55% (building 4). The differences in the observed cost ratios are mainly due to the main energy carrier (an energy source for heating, DHW, lighting, etc.), its energy conversion factor and its environmental impact in terms of CO_{2,eqv.} and SO_{2,eqv.} pollution. Building 4 uses a mix of electricity for its operation while building 13 is connected to the municipal natural gas-powered heating plant.

5. Conclusions

The paper summarises the initial results of the authors' research into the valuation of the lifetime costs of buildings. The costs related to negative externalities in the form of CO_{2,eqv.} and SO_{2,eqv.} generation during the building life cycle are added to the basic cash flows of investors/developers (investment costs and operating costs of buildings). These have been valued based on data from building energy performance certificates and SBTtoolsCZ building assessment tool. It is clear from the research sample of 17 projects that the societal costs related to the above-mentioned negative externalities are quite high, on average accounting for 30% of the operating costs of buildings. The differences in the resulting values are mainly due to the average heat transfer coefficient of the building envelope, which depends on the material characteristics and construction technology, as well as the main energy carrier (the predominant source of energy used). Seventeen projects were systematically chosen based on the criterion of their classification as residential buildings, which may limit the generalization of the findings to other building scenarios. The sample size and diversity of the projects could influence the representativeness of the results. Furthermore, it is important to note that the limitation of the study may lie in the relatively small sample size of 17 projects, and therefore, expanding the sample size would be beneficial for broader generalization of the findings. Future research activities will be aimed at identifying and valuing other related benefits and harms that buildings bring to their public space.

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