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Measuring the productivity impacts of energy-efficiency: The case of high-efficiency buildings

Souran Chatterjee *, Diana Ürge-Vorsatz

Central European University, Nador-9, 1051 Budapest, Hungary

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ABSTRACT

High-efficiency buildings do not only save energy but also have multiple further impacts or co-benefits. These impacts are often excluded from the policy evaluation partly because their quantification and integration into cost-evaluations have challenges. Thus, the purpose of this paper is to develop a method to quantify labour productivity which is one of the key multiple impacts, as well as demonstrate the use of the method for calculating the productivity impacts of high-efficiency buildings. The paper uses Germany and Hungary as examples to conduct the quantifications. The result of the study shows that high-efficiency buildings can result in substantial health and labour productivity benefits. Concretely, a German worker can gain 5.2 productive days a year, while a Hungarian 2.2 days by avoiding sick days, after living in high-efficiency buildings. Similarly, through high-efficiency retrofits or high-efficiency new constructions in the tertiary building sector, German and Hungarian workers can gain 2.4 and 1 productive days a year, respectively, by avoiding sick days. The monetary equivalent of the total number of days gained would be as high as 337 million and 7 million Euros/year only from the residential building sector, and 398 million and 3 million Euro/year from the tertiary building sector for Germany and Hungary respectively. In addition to the productive workdays gain, by avoiding mental stress, the German and Hungarian workforce can gain 95 and 2 million Euro respectively in a year by improving work performance from working in high-efficiency tertiary buildings. Furthermore, this paper shows that along with more workdays and improved work performance, both Germany and Hungary can gain 1870 and 3849 healthy life years/million population which is equivalent to 277 and 134 million Euros per year respectively. The findings of this study would provide a strong motivation to the policymakers to design policies that promote construction and renovation of buildings at the passive-house or NZEB standards. The substantial productivity impacts of high-efficiency buildings can be an entry-point for the policymakers as any policy that promote high-efficiency buildings would fit in well in the multi-objective policy framework of the European Union.

1. Introduction-motivation and aim of the paper

Globally, the building sector accounted for 54% of the final electricity demand in 2014 which is equivalent to 23% of global energy-related carbon dioxide (CO_2) emissions (Rogelj et al., 2018). However, if process-related greenhouse gases (GHG) are considered, then the building sector contributes 39% of global GHG emissions (Ürge-Vorsatz et al., 2020). Thus, to limit global temperature rise by 1.5°, the final energy demand of the building sector needs to be reduced substantially (Rogelj et al., 2018). Reducing energy demand without affecting the well-being of the occupant, is now the biggest challenge as GHG mitigation actions are mostly perceived as - obtaining only global benefits such as limiting global temperature without resulting any or little, national/local benefits (Chatterjee, 2019). Nevertheless, numerous studies (for example, see; Jakob, 2006; MacNaughton et al., 2018; Bleyl et al., 2019) have demonstrated that investment in energy-efficient buildings, would result in energy savings as well as many other benefits such as improved health, labour productivity and comfort level, GDP growth, energy security and employment generation. Some studies (for example, see Chapman et al., 2009; Grimes et al., 2012) show that some of these non-climate benefits can yield a higher value than energy savings. In the literature, these non-climate benefits are commonly referred to as 'co-benefits', and 'multiple benefits'. However, in this paper, we will refer to these non-climatic benefits as 'multiple impacts' (MIs) as it was referred in Ürge-Vorstaz et al. (2016) study.

Although the MIs of building-related energy efficiency measures

* Corresponding author.
E-mail addresses: souran.chatterjee@gmail.com, chatterjees@ceu.edu (S. Chatterjee), vorsatzd@ceu.edu (D. Ürge-Vorsatz).

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have been gaining importance within the scientific community, they often do not get factored into policy evaluations as they have not been clearly defined and suffer from methodological and quantification challenges (Ürge-Vorsatz et al. 2014, 2016). Consequently, the potential of energy-efficient buildings or any building-related energy-efficiency measure is undervalued and hence, underinvested. Therefore, the aim of this paper is to develop a set of methods to rigorously quantify the MIs of energy-efficient/high-efficiency buildings and demonstrate method for calculating them. To do so, this paper quantifies the productivity impacts of high-efficiency buildings in Germany and Hungary as examples, to show the significance of MIs empirically at the national level.

This paper quantifies productivity impacts because productivity especially labour productivity is crucial for both the society as well as the economy (Brynjolfsson et al., 1998). Furthermore, labour productivity often is defined broadly in the literature as the ratio between labour input and output, but rarely considers all the different aspects of labour productivity that can result from various GHG mitigation measures. Therefore, apart from quantifying labour input efficiency by using well-defined productivity indicators, this paper also measures workforce productivity impacts and healthy life years gain for Germany and Hungary, to evaluate the significance of productivity impacts in the context of welfare, well-being and quality of life.

Quantifying productivity for these two countries provides a difference in perspectives to study the role of energy-efficient buildings in achieving higher welfare, and well-being through labour productivity in the context of EU climate and energy policies. More precisely, Hungary is taken as a representative case of Eastern Europe where the constitution recognizes the right to healthy living and working environment along with the need for decent housing. These rights are recognized by the Hungarian constitution post1989 reforms, and thus provide a legal ground to have a healthy work and living environment. Furthermore, it is important to remember that Hungary is an energy import dependent country. On the contrary, Germany can be considered as a representative of the more economically powerful and politically stable Western Europe where labour productivity is considered as a key instrument to accelerate economic growth. Therefore, by taking these countries as an example, this study shows that high-efficiency buildings can play a crucial role by improving labour productivity substantially through improving health conditions that can further accelerate economic growth and well-being. The objective of taking these two countries is not to compare them. Instead, it aims to show how substantial productivity impacts can be achieved by having more energy-efficient buildings in two different EU member states.

2. The effects of high-efficiency buildings

There are no specific definitions of energy-efficient or high-efficiency buildings, but rather these concepts primarily depend on the energy performance standards of the buildings (Chel et al., 2015; Ürge-Vorsatz et al., 2020). Therefore, energy-efficient/high-efficiency buildings may not always be new construction. Existing building stocks can also be renovated as per the high-energy efficiency standard. Moreover, within high-efficiency buildings, energy performance standards vary according to the building types. For instance, the passive house standard specifies that heating-related energy consumption of a house should not exceed 15 kWh/(m^2,year), while the nearly zero energy buildings (NZEB) standard does not specify any heating energy consumption limits (Chel et al., 2015). However, both passive houses and NZEBs must meet their energy demands from building-integrated renewable energy sources to a large extent (Kurnitski, 2013). Apart from low energy consumption and the presence of integrated renewable energy sources, few other components such as a high level of airtightness, heat recovery system, minimum thermal bridges, ventilation and filtration systems, and energy-efficient windows are mandatory in both passive houses and NZEBs (Schnieders and Hermelink, 2006). Due to the efficiency standards, energy-efficient buildings consume 80% less energy compared to existing buildings and reduces up to 30% building-related CO2 emissions (C40 CITIES, 2011). Sun et al. (2018) study shows that energy-efficient buildings with active designs such as energy-efficient lighting, use of sensors and solar panels, can save 40–45% energy consumption in a tropical climate.

This paper refers to three types of buildings as high-efficiency buildings, passive houses, NZEBs and deep-retrofitted buildings that are retrofitted to the passive house or NZEB standards. These types of buildings consume significantly less energy compared to conventional buildings and have certain non-energy benefits. For instance, 80% of indoor exposure to air pollutants can be avoided in high-efficiency buildings, which results in health and productivity benefits (Bonetta et al., 2010). The components of high-efficiency buildings such as building envelope, mechanical heating, ventilation, and air-conditioning system (HVAC) with filtration, control and determine indoor air quality. Among these components, the mechanical HVAC system has a significant role in improving the indoor environment by facilitating constant wind flow between the rooms through mechanical processes which also reduces moisture and improves thermal comfort level (Li, 2007). Studies (see (WHO, 2006; Asikainen et al., 2016) show that adequate air exchange can reduce humidity, and exposure to other indoor pollutants such as carbon dioxide, and bio effluents. In the section below, both the health and productivity effects of high-efficiency buildings are discussed.

2.1. Health effects of high-efficiency buildings

Most of the health effects of high-efficiency buildings depend on two building components namely the mechanical HVAC system, and an airtight building envelope with high thermal insulation. The HVAC system has two effects- 1) reducing indoor pollutant concentration (such as allergens, formaldehyde, micro-organisms, and fungal spores) by maintaining an adequate and constant air exchange rate (Levetin et al., 1995; Che et al., 2019), and 2), causing an inflow of outdoor pollutants which can include particulates of biological origin (for example micro-organisms, or pollen), particulate matter, ozone (O3), and nitrogen oxides (NOx) (Asikainen et al., 2016). Therefore, filtration is installed in the HVAC system to prevent the intrusion of outdoor pollutants indoors. Moreover, buildings with high levels of thermal insulation and inadequate air exchange,[1] increases indoor humidity and moisture resulting in higher microbial growth and dust mites and consequently, a high 'burden of diseases'[2] (Fisk and Rosenfeld, 1997; Fernandes et al., 2009; Nagendra and Harika, 2010; Chen et al., 2018; Mondal and Paul, 2020). HVAC systems in less airtight conventional buildings have a minimum on human health as outdoor pollutants, such as particulate matter and NOx, can enter through the envelope cracks which could result in building-related illnesses (BRI) (Hänninen and Asikainen, 2013).

BRIs due to poor indoor building conditions consists of many diseases including asthma, cold and flu, lung cancer, and cardiovascular diseases especially ischemic heart disease (Redlich, 1997; Jones, 1999; Asikainen et al., 2016). Indoor exposure induced BRIs could be as high as 10,000 disability-adjusted life years loss (DALY) per million in Europe (Hänninen and Asikainen, 2013). Furthermore, exposure to indoor air pollution also affects mental health (Apte et al., 2000; Zabiegala et al.,

[1] Air exchange rate from 10 to 20 l/s (liters/second) per person is considered to be an inadequate rate of exchange for the residential buildings (Wargocki et al., 2002). For tertiary buildings, 25 l/s per person is considered to be as an adequate air exchange rate (Asikainen et al., 2016). However, it is important to note that the rate of air exchange depends on the occupancy rate.

[2] Burden of disease describe death and loss of health due to diseases (https://www.who.int/foodsafety/foodborne_disease/Q%26A.pdf). Apart from the burden of diseases, two other terminologies are used to refer to these diseases and symptoms related to poor building conditions, namely- 1) 'Sick Building Syndrome' (SBS), and 2) 'Building Related-Illness' (BRI).

2007). The BRIs vary in residential and tertiary buildings due to exposure time and occupancy rate, rather than the type of building itself. For instance, more time spent in residential buildings compared to tertiary buildings exposes occupants of residential buildings to BRIs such as asthma and, cancer whereas higher occupancy rate in tertiary buildings compared to residential buildings increases the intensity of contagious BRIs such as influenza types cold and flu, and eye infections in the tertiary buildings (Kreiss, 2005; Crook and Burton, 2010).

2.2. Productivity effects of high-efficient buildings

Labour productivity and indoor air quality are strongly correlated (Mahbob et al., 2011). A healthy indoor environment can improve labour productivity by improving labour input efficiency-more precisely by increasing workdays, performance, and by improving the quality of output (Brook, 2004; Bleyl et al., 2019). Both the quality and quantity of labour output can be impacted by the indoor environment. For instance, poor indoor environments can affect mental well-being and consequently work performance (Liddell and Guiney, 2015; Gray, 2017). Similarly, poor air quality can lower labour productivity by affecting the health of the occupant/user (as discussed in the section above) resulting in sick leaves from work that translates into productivity losses (Fisk and Rosenfeld, 1997).

To summarise, high-efficiency buildings improve labour productivity through various intermediate impacts. For instance, the primary effects of using a high-efficiency building result in improvement in the indoor air quality and comfort (both thermal and acoustic comfort) level. The indoor air quality improvement occurs due to better ventilation rate, filtering and high levels of insulation. More precisely, the adequate rate of ventilation reduces indoor pollutant concentrations and simultaneously filters outdoor pollutants while high levels of insulation minimise infiltration of outdoor pollutants indoors. Thus, the indoor air quality in any high-efficiency building is better than any shallow retrofitted buildings. A lower concentration of pollutants further results in improved state of health as the risk of certain diseases would be minimised due to less exposure to indoor and outdoor pollutants. The improved state of health then results in improved labour productivity that translates into higher well-being. The impact pathway map presented below showcase these various impacts of using a high-efficiency building: (see Fig. 1)

Despite all the evidence, productivity has not been clearly defined in the context of MIs. One of the main reasons behind not precisely defining productivity is the lack of standard metrics of productivity (Sennett, 2002). Different aspects of productivity are not clearly defined, and hence, productivity impact remains undervalued. Therefore, this paper quantifies productivity impact due to improved indoor quality by quantifying different indicators of productivity impact, thereby providing a comprehensive idea about the potentiality of the impact.

3. Methodological framework of the research

To quantify the productivity impacts of high-efficiency buildings, a three-tier methodological approach is presented in this paper. In the first tier, two precise indicators are used to define the scope of labour productivity. In the second tier, a scenario analysis is conducted where productivity impacts are quantified for two different scenarios to understand the magnitude of productivity impacts. Lastly, incremental productivity gain is monetised to understand the magnitude of productivity impact from a monetary perspective. Each of these steps (except the monetization method which is discussed in section 4 for each of the indicators) is discussed briefly in the section below.

3.1. Productivity indicators

A standard metric or indicator is required to quantify labour productivity impacts due to BRIs. In this paper, we have used two indicators that were used in our previous paper (see Bleyl et al. (2019): 'change in active days', and 'workforce performance'. Each of these indicators is discussed briefly in the section below.

Change in active days: Change in active days reflects the changes in workdays due to time spent in high-efficiency buildings with the help of two specific components namely 'sick days', and 'healthy life years' (Bleyl et al., 2019). Bleyl et al. (2019) discussed that sick day is considered to be "a linear combination of absenteeism (absent from work due to building-related illness) and presenteeism (see (Caverley et al., 2007), where presenteeism can be defined as working with illness or working despite being ill (see (Mattke et al., 2007)". An example of presenteeism could be, for instance, an individual would work slower than expected with respiratory illness and even may make mistakes in work while experiencing respiratory sicknesses. This paper considers both non-attendance/absenteeism and presenteeism as the loss of labour input efficiency and hence, a combination of absenteeism and presenteeism is used to quantify the effects of BRIs on labour productivity.

It is important to note that a sick day only reflects the morbidity aspect of the working population, whereas BRI has a significant impact on morbidities of both working and non-working populations. For example, fatal diseases such as cancers or, cardiovascular diseases have the same if not larger, impacts on the nonworking population such as housewife/househusband, retired population, and children. The BRIs affect their daily activities such as household work, taking care of the family/friends, and volunteering which have significant societal values and hence, are referred to as social productivity (Wahrendorf et al., 2008). Thus, to quantify the change in active days for both the working and non-working population, and also to quantify both mortality and morbidity aspects, the 'healthy life years' indicator is used in this study along with sick days.

Workforce performance: Workforce performance can be defined as "the labour input by per unit of time of the entire workforce where workforce is defined as the total working population at the workplace" (Bleyl et al., 2019). Good indoor air quality and thermal comfort have a significant positive impact on labour productivity (Wargocki, 2009; Tham, 2016). Studies (such as Seppänen et al., 1999; Wargocki et al., 2000; Singh, 2005) show how indoor air quality and thermal comfort can enhance individual performance. In two ways: 1) improving mental well-being as high-efficiency buildings ensure constant fresh air supply through a mechanical HVAC system which renews the concentration ability, thereby boosting the energy to work (Bleyl et al., 2019), and, 2) improving concentration ability by avoiding sick-building syndrome (SBS) due to improved air quality and constant exposure to fresh air (Budaiova and Vilcekova, 2015; Kapalo et al., 2018). The performance improvement by working in high-efficiency buildings is important to measure as the productivity gain by the employees also benefits the employer as labour input efficiency gain implies more profit. Furthermore, the productivity gain through improving mental well-being and better concentration ability do not get considered in presenteeism as this is not resulting from any illness. Instead, the productivity gain is an additional benefit occurring by working in the high-efficiency buildings. Therefore, quantifying workforce performance along with changes in active days provide a holistic overview of the productivity benefits of high efficiency buildings.

3.2. Method of quantification

To quantify the two indicators discussed in section 3.1, a distinct set of equations were developed that can measure the change in active days and workforce performance indicators. Each aspect of the productivity indicators is discussed mathematically in the sections below.

3.2.1. Equations to quantify the change in active days

The change in active days indicator has two aspects; sick days and healthy life years. In terms of productivity, there will be some avoided sick days and healthy life years gained by avoiding exposure to indoor

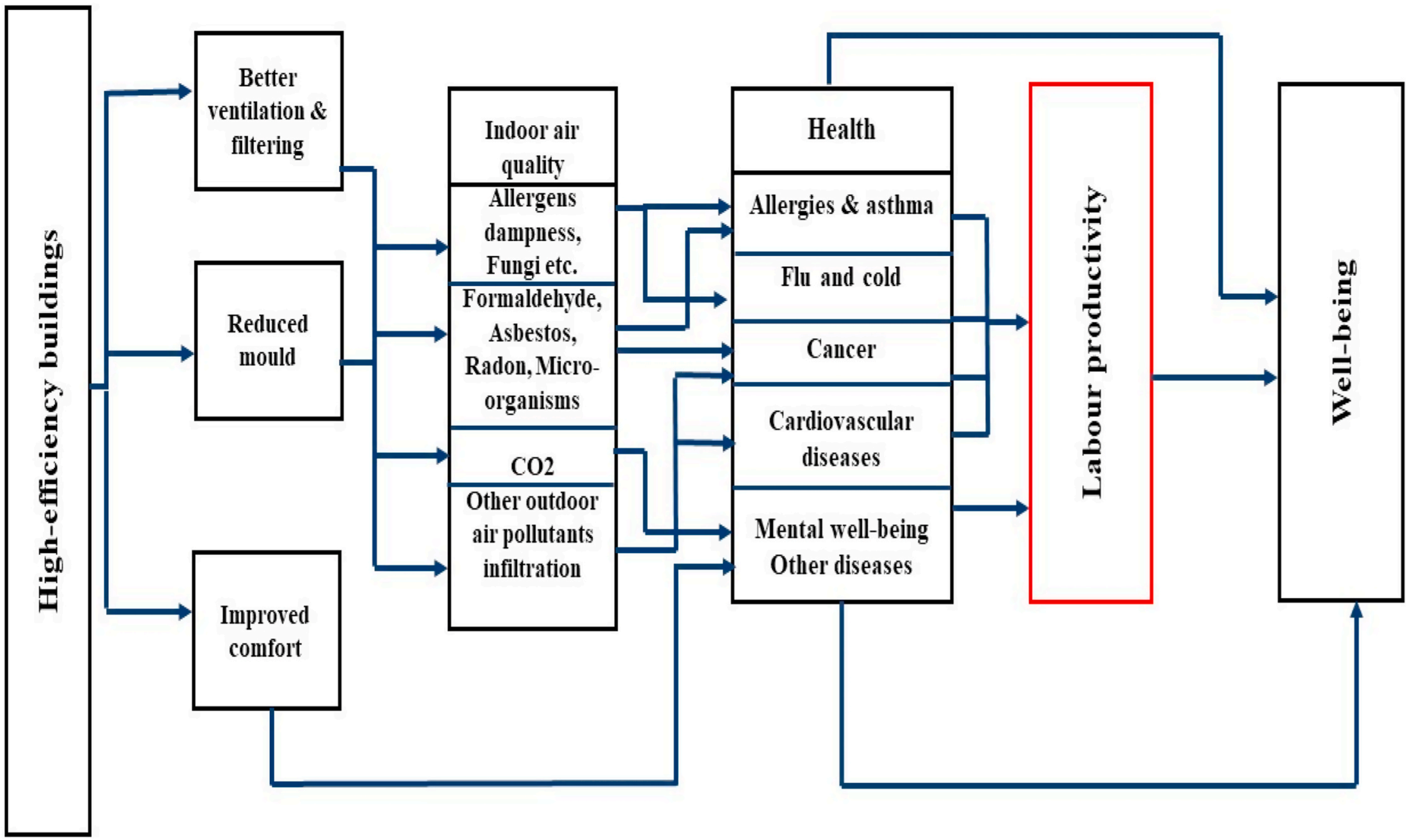

Figure 1. Impact pathway map showing how high-efficiency buildings can obtain a higher level of labour productivity and well-being.

pollutant. Sick days (SD) is a combination of absenteeism and presenteeism which can be mathematically expressed as:

SD = Ab + Pr, where, Ab is absenteeism, and Pr is presenteeism. To calculate avoided SD both avoided Ab and Pr need to be calculated. However, since there are no readily available data on disease-specific Ab and Pr, we need to calculate them first with Equation (1);

$$\sum_{V=1}^{4}\sum_{i=0}^{p} \boldsymbol{Ab_{X_v}^{ri}} = \sum_{v=0}^{4}\sum_{i=0}^{p}\{(\boldsymbol{ASLc} \times \boldsymbol{ri}) \times \boldsymbol{X_v}\} \quad (1)$$

where i represents different types of retrofitted residential buildings and r denotes the working population living in residential buildings. Together r_i depicts the working population living in different types of retrofitted residential buildings such as the populations living in non-retrofitted buildings (r_0), low retrofitted buildings (r_1), medium retrofitted buildings (r_2), deep retrofitted buildings (r_3), new nearly zero energy buildings (r_4) and passive houses (r_p). Similarly, v represents the types of diseases, and X is the percentage of sick leaves. Together they represent the percentage of disease-specific sick leaves taken. For instance, sick leaves taken by asthma in a year are represented by X_0 while cold and flu, cardiovascular disease, and allergy-related sick leaves are represented by X_1, X_2, and X_3, respectively. Lastly, average sick leaves (ASLc) represent the average leave taken per person annually in a country due to being sick.

Similarly, disease specific Pr can be calculated by using Equation (2);

$$\sum_{v=0}^{4}\sum_{i=0}^{p} \mathrm{Pr}_{X_v}^{ri} = \sum_{v=0}^{4}\sum_{i=0}^{p}\{(AVPc \times ri) \times P_v \times \mu_v\} \quad (2)$$

where $AVPc$ represents per person annual average number of presenteeism days in a country and μ is the total productivity loss at work due to v types of illness. Lastly, Pv represents the percentage of disease-specific presenteeism days.

In the same way, Ab and Pr can be calculated for the population working in the tertiary buildings-for instance, disease-specific absenteeism can be calculated by using the equation below:

$$\sum_{v=1}^{4}\sum_{j=0}^{p} Ab_{X_v}^{ti} = \sum_{v=1}^{4}\sum_{j=0}^{p}\left\{\left(ASLc \times t_j\right) \times X_v\right\} \quad (3)$$

Where the population who work in the tertiary buildings is presented by t and j represent different types of retrofitted tertiary buildings.

After calculating disease-specific Ab and Pr, the total avoided sick days per country can be calculated by using the following equation:

$$\sum_{v=0}^{4}\sum_{i,j=0}^{p} ASDc_{X_v}^{ritj} = \sum_{v=1}^{4}\sum_{i=0}^{p}\left[\left\{SDc_{X_v}^{ritj} \times \left(1 - HGc_{vij}\right)\right\} \times TSF_t\right] \quad (4)$$

Here, $\boldsymbol{ASDc_{X_v}^{ritj}}$ represents avoided sick days of working adult population living and working in each type of retrofitted buildings for each of the countries (denoted by c). HGc_{vij} represents the disease-specific health gain factor for both residential and tertiary retrofitted buildings in each country. The exposure time is expressed as the time spent factor which is denoted by TSFt.

Lastly, the active days for the entire population in this study can be expressed mathematically as;

$$\sum_{v=0}^{4}\sum_{i=0}^{p} HLY_{X_v}^{ri} = \sum_{v=1}^{4}\sum_{i=0}^{p}\{DALY_{X_v}^{ri} \times (1 - HGc_{vi})\} \quad \text{Equation 5}$$

where HLY represents the healthy life years gain for the total population living in each type of retrofitted residential buildings. DALY denotes disability-adjusted life years which represents the loss of healthy life.

3.2.2. *Equation to quantify the improvement in workforce performance*

The workforce performance (WFP) indicator is measured by a single equation:

$$\sum_{j=0}^{p} \boldsymbol{WFPtj} = \sum_{j=0}^{p}\left\{\left(\boldsymbol{AVH} \times \boldsymbol{t_j}\right) + \left(\left(\boldsymbol{AVH} \times \boldsymbol{t_j}\right) \times \boldsymbol{PI}\right)\right\} \quad \text{Equation 6}$$

where, WKP_{tj} represents the performance of the workforce in different types of tertiary retrofitted buildings, while the average annual hours worked per worker is denoted by AVH. Lastly, PI is the performance improvement factor that takes place by improving mental well-being.

3.2.3. *Data and assumptions*

Two of the most important parameters of the active days indicator are the health gain factor (HGc_{vij}) and the time spent factor (TSFt). As data are not readily available for these parameters, this paper calculates the value for these two factors based on some assumptions and secondary data available in the literature. For instance, zero, low and medium building retrofits, can have negligible or even negative health impacts due to a lack of airtightness or adequate air exchange rate. Thus, for these types of buildings the value of HGc_{vij} is assumed to be zero. For the high-efficiency buildings, the value for the health gain factor is calculated based on the exposure dose and time which are taken from source control scenario figures of the 'healthvent project[3]'. The healthvent project has calculated 'source control scenario' with the assumption that, due to adequate air exchange rate and also by controlling (for example, by retrofitting the building shell) some of the indoor pollutant sources, a significant reduction - for instance, a 90% reduction in radon, carbon monoxide and second-hand smoke, 50% reduction in volatile organic compounds (VOC) and dampness exposure, and 25% reduction in particulate matter (PM2.5), can be obtained (Hänninen and Asikainen, 2013). The disease-specific value of HG is presented below in Table 1 for both of the countries:

The values presented in Table 1 are calculated for residential buildings only. However, it is important to note that the health gain factor or any indoor exposure-related health gain depends on the exposure time (Schweizer et al., 2007). Thus, a variable is required to distinguish between the health gains of the residential and tertiary sectors based on exposure time. Therefore, in this research, we have assumed a time spent factor (TSFt) to calculate residential and tertiary building sector-specific avoided sick days separately. The value of TSFt is assumed to be 33%[4] considering the standard working hours spent in the office, in a day. However, for contagious diseases, such as colds and flus, where there is a higher possibility of getting infected from tertiary buildings due to its higher occupancy rate, the TSFt is assumed to be 50%.

Lastly, this study applies the average per person presenteeism days in

Table 1
Disease-specific value of HG for Hungary and Germany.

	Diseases	Value of HG
Germany	Asthma and allergies	57%
	Cardiovascular diseases	44%
	Lung (trachea & Bronchus) cancer	53%
	Chronic obstructive pulmonary disease (COPD)	45%
Hungary	Asthma and allergies	52%
	Cardiovascular diseases	38%
	Lung (trachea & Bronchus) cancer	55%
	Chronic obstructive pulmonary disease (COPD)	39%

Source: Calculation is conducted based on healthvent project data.

[3] https://www.rehva.eu/eu-projects/project/healthvent.

[4] It is calculated by dividing the standard hours spent in the office in a day which is 8 h/day with total hours in a day which is 24 h. Since previously no such residential and tertiary building sector-related disease-specific productivity indicators are calculated, we have to make such an assumption.

Europe, which is 3.1 days/year per person for both countries (Garrow, 2016). For absenteeism, annual absenteeism data is available for both countries in the Organisation for Economic Co-operation and Development (OECD) annual sick leave database portal (OECD, 2017). However, disease-specific absenteeism and, presenteeism data are not readily available. Thus, these data are collected from various literature. Table 2 below presents the disease-specific absenteeism and presenteeism data:

Here, only those diseases are considered which can be caused by exposure to indoor pollutants. Thus, the total of the table does not add up to 100%. The data for allergy and asthma-related presenteeism together is reported to be 17% (Lamb et al., 2006). The diseases in Table 2 can also stem from other conditions such as genetic dysfunction, which are not related to indoor air exposure. Thus, the HGvij factor strictly accounts for the health impact due to indoor exposure. Furthermore, presenteeism days does not imply a full working day loss. For example, due to asthma, cold and flu 2.3 work hours are lost in a workday which is equivalent to a 29% loss of productivity (Lamb et al., 2006). Lastly, since no separate data are available for cold and flu disease-related HG, this study applies asthma and allergy-related HG value for cold and flu.

3.3. Scenario analysis-definition of scenarios and their assumptions

Scenarios can be used to better understand the magnitude of MIs based on present data which can be useful for devising sustainable energy policies (Raskin and Kamp-Benedict, 2002; Ürge-Vorsatz et al., 2016). Thus, this research explores a reference and efficiency scenario, in accordance with the COMBI project (University of Antwerp, 2018) which details an employed population living and working in different types of buildings, to assess the effects of MIs on productivity (please refer to table- A1 and table- A2 in the appendix section). The reference scenario assumes that 2015 policies remain unchanged till 2030. Under this assumption, Germany and Hungary will respectively have 23% and 52% residential high-efficiency buildings and 21% and 22% high-efficiency tertiary buildings among their total building stocks by 2030. The efficiency scenario assumes that ambitious policies and technologies are implemented until 2030 (University of Antwerp, 2018). Under the efficiency scenario, Germany and Hungary will respectively have 25% and 57% high-efficiency residential buildings and 28% of high-efficiency tertiary buildings by 2030. Considering these high-efficiency building percentages and the country-specific share of the employed population living and working in a building, the total employed population living and working in different types of buildings is calculated for both reference and efficiency scenarios.

4. Results and discussion

4.1. Result and analysis-change in active days

Results-avoided sick days: The effects of living and working in high-efficiency buildings on sick days are calculated separately for the tertiary and residential building sectors. Firstly, sick days due to each type of diseases (such as asthma and allergies, cold and flu, and cardiovascular diseases) are calculated for each of the scenarios and each type of retrofitted buildings by using Equations (1)–(3). The disease-specific sick days are then aggregated and multiplied with the health gain factor for both Germany and Hungary to measure the country-specific change in sick days due to high-efficiency buildings in both reference and efficiency scenarios for the year 2030 by using Equation (4). The difference between the two scenarios provides the value for change in sick days indicator which gets monetised by multiplying active days with daily net wage.

By following the above-mentioned steps, Germany and Hungary can respectively avoid around 5 and 0.4 million sick days in 2030 by respectively having 3% and 4% more high-efficiency residential buildings compared to the reference scenario. Similarly, Germany and Hungary can respectively avoid around 5 and 0.2 million sick days in 2030, by respectively having 7% and 5% more high-efficiency tertiary buildings. The total number of sick days for each of the scenarios and each country is presented in Table 3 while Fig. 2 presents country-specific avoided sick days per capita.[5]

Analysis of the result of avoided sick days/active days gains: There are two main factors behind the relatively high gain of Germany; 1) higher values of health gain factor for each of the diseases. For instance, the value of the HG for asthma and allergy or in other words, the reduction potential of asthma and allergy and cardiovascular diseases are 57% and 44% respectively for Germany (refer to Table 2). On the other hand, in Hungary, the value of HG for asthma and allergy, and cardiovascular diseases, are 52% and 38% respectively. Therefore, these higher values of HG result in higher avoided sick days for Germany; 2) the number of sick leaves (absenteeism) reported by each of the countries - the sick leave data used in this research are compensated sick leave data, that is the number of sick leaves compensated by the government, or the employer. The reported annual compensated sick leave is higher in Germany (18.3 days/person) than in Hungary (7.9 days/person) (OECD, 2017). The reason behind the high number of sick leaves reported in Germany is two-folded a) a well-designed social security system, and b) the presence of strong labour law. The German labour law dictates that in the case of any leave taken due to an illness, the employer is legally obliged to pay the entire wage for up to six weeks (Entgeltfortzahlungsgesetz, EntgFG) and after six weeks in case of long-term illnesses, 70% of the gross salary is covered by the health insurance (Kraemer, 2017). Moreover, the termination of a contract of employment when an employee is on sick leave is forbidden until an improper activity is discovered (Kraemer, 2017). However, for Hungary, only 70% of the salary is covered in the case of sick leaves under the Hungarian labour code (Kiss and Belyó, 2017). Therefore, the country-specific presenteeism value for Hungary would have played a vital role because, in the case of a less secure employment contract, employees tend to take more presenteeism days. However, since country-specific presenteeism data was not available, we used the average EU presenteeism data.

However, even with the average presenteeism data, and country-specific sick-leave data, if the relative gain is analysed, both countries gain a significant number of active days. For instance, Germany reduces its annual sick days per capita, which stands at 21.4 days/person year (sum of absenteeism and presenteeism), by 36% (or 7.7 days/person, year) with a 10% increase in high-efficiency residential and tertiary buildings while Hungary reduces its sick days by 29% by increasing its high-efficiency building stock by 9%. A disease specific impact or reduction potential due to living/working in high-efficiency buildings would provide more insight into the analysis.

The bars in charts A and B in Fig. 3 present the percentage of avoided sick days by disease due to living and working in high-efficiency buildings. The savings of sick days from cold and flu have a higher share in Germany and Hungary in tertiary buildings compared to residential buildings for the following two main reasons:

1. Cold and flu diseases can be contagious and the risk of catching a cold and flu from tertiary buildings is higher as more people work there. Thus, considering the infectious nature of this disease, the time spent factor (TSF) for this disease is assumed to be higher (50%) for cold and flu, compared to other diseases (33%).
2. As per the COMBI scenario data for the building sector, more people would shift to high-efficiency tertiary buildings, compared to

[5] It is important to note that active days gain data are presented at per person scale in Fig. 2, where only those people are included who have shifted to high-efficiency residential buildings as they are the only one who would enjoy the gain. Instead, dividing the total avoided sick days by total working population would have underestimated the per capita scale.

Table 2
Disease-specific absenteeism and presenteeism data.

	Sick leaves taken due to a disease (Absenteeism)	Data source	Presenteeism days due to a disease	Source of the presenteeism data
Asthma	14%	Alexopoulos and Burdorf (2001)	17%	Johns (2010)
Allergy	20%	Lamb et al. (2006)		Lamb et al. (2006)
Cold and flu	19%	Alexopoulos and Burdorf (2001)	17%	Johns (2010)
Cardiovascular diseases	6%	Price (2004)	10%	Price (2004)
Total	59%		44%	

Table 3
Change in sick days in each scenario.

	Building types	Sick days (in million) in the reference scenario	Sick days (in million) in the efficient scenario	Active (difference between two scenarios) days gain (in million)	Active days gain/ Per person (number of days)
Germany	Residential	357.9	352.1	5.8	5.2
	Tertiary	133.9	128.2	5.8	2.4
Hungary	Residential	14.4	13.9	0.4	2.2
	Tertiary	6.3	6.1	0.2	1.0

database. The annual net income for Hungary and Germany reported in 2019 are 4549 and 18,081 Euros respectively (Eurostat, 2020). From the annual net income, first, the monthly net income (dividing the annual net income by total number of months in a year i.e. 12), and then the daily net income (dividing the monthly net income by 22[6]) is calculated. The daily net income for Germany and Hungary calculated based on annual net income, are 68 and 17 Euro respectively. Thus, to monetise avoided sick days, the daily net income is multiplied by the total avoided sick days per country. For instance, Germany can gain around 397 and 398 million Euros respectively in 2030 from avoided sick days as a direct result of high-efficiency residential and tertiary buildings. Similarly, Hungary can gain 7 and 3 million Euros respectively in 2030, from avoided sick days as a direct result of high-efficiency residential and tertiary building. If the per person monetary gain is calculated, then it can be seen that Germany and Hungary, can gain 356 and 38 Euros annually respectively by avoiding sick days due to residential high-efficiency buildings, whereas for high-efficiency tertiary buildings, 164 and 17 Euros can be gained respectively for Germany and Hungary. The substantial difference in monetary gains between Germany and Hungary is due to the differences in annual net incomes, which is almost four times higher in Germany than Hungary (Eurostat, 2020) and the substantially larger German labour force, which result in a higher absolute productivity gain and monetary gain in Germany compared to Hungary.

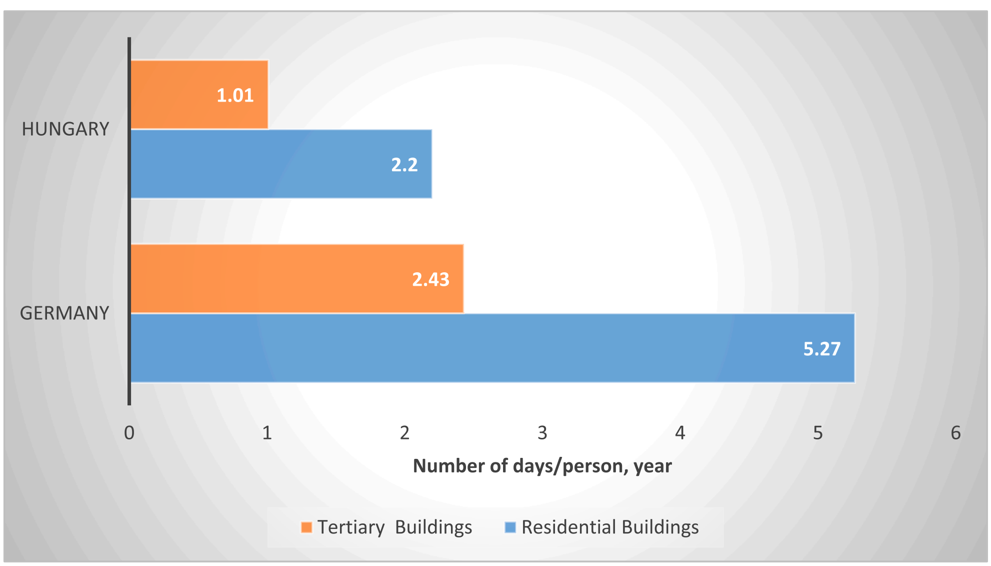

Fig. 2. Avoided sick days/active days gained/per person in the year 2030 due to high-efficiency buildings.

residential buildings. For instance, in Germany, 2 million more people will be working in high-efficiency tertiary buildings in the efficiency scenario compared to the reference scenario by 2030, whereas in the residential sector, 1 million more working population will be living in high-efficiency residential buildings in the efficiency scenario than in reference scenario by 2030 (refer to Table A1 and A2). Thus, the incremental gain due to having more people working in the tertiary buildings in the efficiency scenario is much higher in the tertiary sector. For Hungary, the data is almost the same for the residential and tertiary sectors-for instance, both in the residential and tertiary sectors in the efficiency scenario, almost 0.2 million more people are residing and working in the high-efficiency buildings than reference scenario by 2030.

Monetization of sick days: Avoided sick days are monetised by using the daily net wage derived from annual net wage data from the Eurostat

[6] The total number of working days in a month is assumed to be 22 days per month.

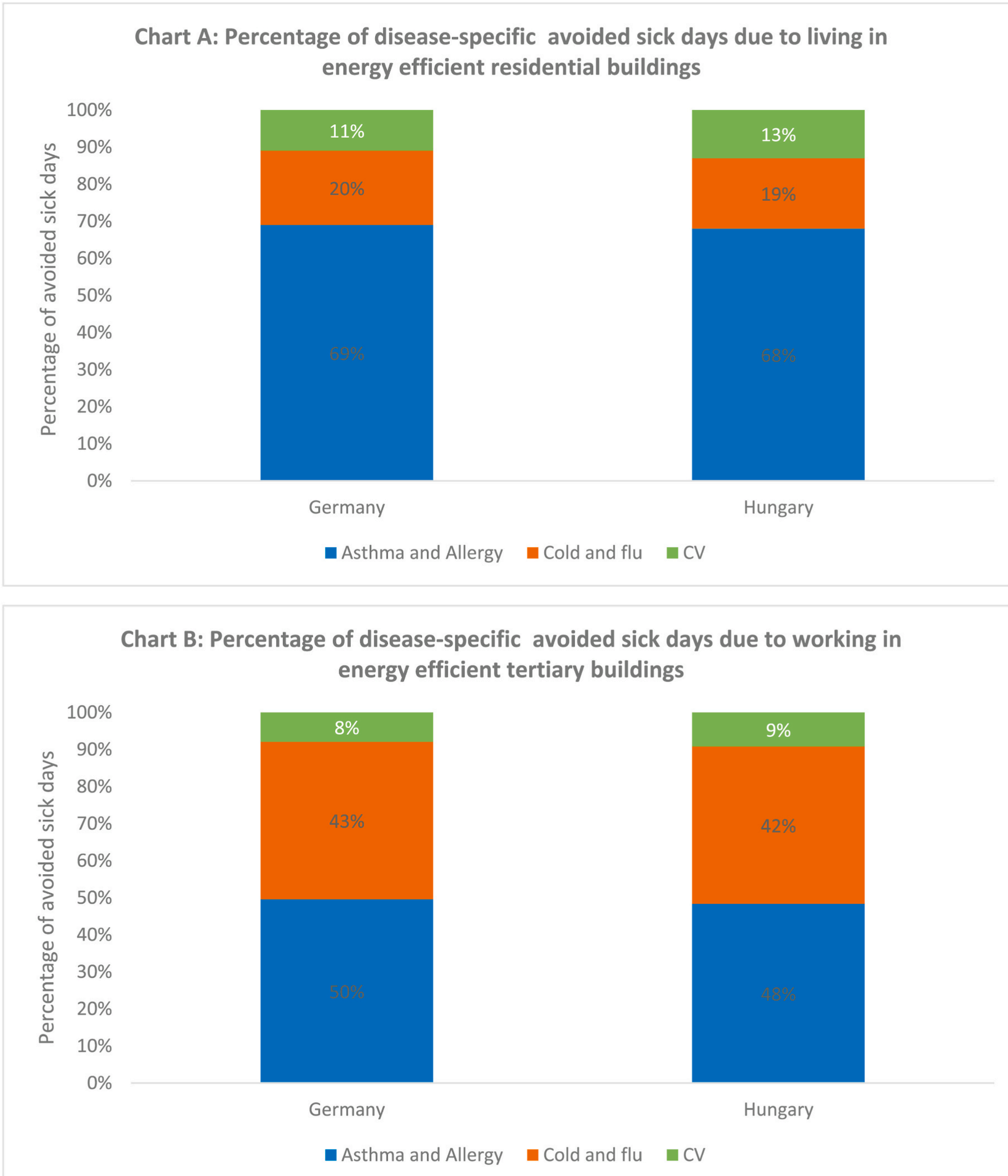

Fig. 3. Disease-specific sick days avoided for Hungary and Germany in the year 2030 due to living/working in high-efficiency buildings.

These findings provide motivations to reassess the potential benefits associated with high-efficiency buildings by incorporating all their health and productivity benefits. Since, this study constitutes a first attempt to quantify the productivity impacts of high-efficiency buildings at the national scale with scenario analysis, the findings are not directly comparable to any existing other studies. Although, some studies show evidence of reducing sick leaves due to adequate ventilation (for example, refer to studies conducted by Fisk, 2000; Milton, 2000) or thermal comfort (for example, refer Seppänen and Fisk (2006) study) they do not examine the MIs associated with high-efficiency buildings. In addition, these studies do not quantify productivity impacts from a holistic perspective by incorporating both absenteeism and presenteeism. For instance, Milton et al. (2000) showed that with adequate ventilation rates in tertiary buildings located in Massachusetts USA, 35% of sick leaves can be avoided which translates into 1.2–1.9 days/person, year. Although, their results are similar to our study, it is important to note that for our research, even for the tertiary building sector, both absenteeism and presenteeism days are considered whereas, the Milton et al. (2000) study calculated only the avoided sick leaves from 1994 US absenteeism data. Moreover, the geographical coverage is different in our research compared to the Milton et al. (2000) study. Thus, a direct comparison of the results is not possible even for the tertiary building sector alone.

Like any empirical research, this study is also subject to some uncertainties. For instance, in some cases, the technical potential of the high-efficiency buildings may not be fully optimised. For example, if

HVAC systems are poorly maintained or installed, health gains would be minimal. On the contrary, if HVAC systems are installed with proper air quality sensors, the health impacts of high-efficiency buildings would be higher than usual. Thus, a sensitivity analysis is required to estimate the uncertainty range of this model. The sensitivity analysis contains two more scenarios exploring the case of low health impact in case of sub-optimal use of high-efficiency buildings, and higher health benefits in case of full optimization of high-efficiency buildings. In case of minimum health impacts, it is assumed that exposure to radon would be reduced by 80%, carbon monoxide and second-hand smoke would be reduced by 25%, and volatile organic compound (VOC) and dampness would be reduced by 25% (Hänninen and Asikainen, 2013). According to the level of exposure, the value of HG would also change (refer to Table A4). However, if the full potential of high-efficiency buildings is utilised as discussed above, then it is assumed that exposure to radon would be reduced by 100%, carbon monoxide and second-hand smoke would be reduced by 75%, and VOC and dampness would be reduced by 75% exposure (Hänninen and Asikainen, 2013). For our easy reference, the low health impact scenario is referred to as the low scenario and high health impact scenario is referred to as the high scenario. The exposure level used in this study (refer to section 3.2.3) is referred to as the study scenario. As per these scenarios, the avoided sick days from the residential high-efficiency buildings would range from 4 to 7 days for Germany (where the high scenario results in 6.6 days gain and the low scenario results in 4.3 days gain), and 2–3 days (where the high scenario results in 2.7 days, and low scenario results in 1.8 days gain), per person annually for Hungary. Similarly, for the tertiary high-efficiency buildings, the avoided sick days would range from 2 to 3 days for Germany (where the high scenario results in 3.7 days gain and the low scenario results in 1.9 days gain), and 0.9–1.25 days for Hungary (where the high scenario results in 1.2 days gain and the low scenario results in 0.9 days gain) annually per person (refer to Figure A1 and A2). The findings of the sensitivity analysis show that even with a low health scenario where the potential of high-efficiency buildings has not been fully utilised, the productivity gain would still be positive for both of the countries. Furthermore, the findings of the sensitivity analysis show that the study uses a moderate value of the exposure level that is less than the health impacts of the high scenario and greater than the health impact of the low scenario. Thus, our study scenario provides a balanced estimate of the productivity gain.

Results-healthy life years gain: As discussed in section 3.1, the exposure to indoor pollutants would have a similar, if not more impact on the non-working population (such as children, housewives/househusbands, and elderly persons) and some of the BRIs such as cancer, cardiovascular disease, and asthma can be fatal. Therefore, this research uses 'healthy life years' to explore the effect of high-efficiency buildings for the entire population, including the people who are not in the labour market. Similar to avoided sick days, healthy life years gain is calculated for the reference and efficiency scenarios by using Equation (5) and the differences between the two of the scenarios are presented as healthy life years gained. The results show that by having 3% and 4% more high-efficiency residential buildings by 2030, Germany and Hungary could respectively save 1870 and 3849 healthy life years/million population annually.

The per capita healthy life years gained is higher in Hungary compared to Germany which contrasts with the results of avoided sick days, where Germany has more days gain compared to Hungary. One of the key reasons behind this result is the inclusion of diseases such as lung cancer, chronic obstructive pulmonary disease (COPD), and cardiovascular disease-related mortalities. Fig. 4 below presents disease-specific life-year gains for both of the countries:

The total healthy life years values in two different scenarios are presented in the Table 4 below for both the countries:

Analysis of the result- Healthy life years saved: Unlike avoided sick days, Hungary has a higher healthy years gain compared to Germany. There are several possible reasons for this. For example, Hungary has a higher level of outdoor pollution concentration especially PM2.5 concentration compared to Germany (Hänninen and Asikainen, 2013; WHO, 2016). Hungary had the second-highest level of PM2.5 concentration among the EU member states in 2014 (21 μg per cubic meter

Table 4
Healthy life years in different scenario.

Country	Loss of healthy life years/ million population in the reference scenario	Loss of healthy life years/ million population in the efficiency scenario	Total gain of healthy life years/million population (difference between the reference and efficiency scenarios)	Percapita healthy life years gain/ million population
Germany	295,592	291,530	4062	1870
Hungary	65,898	64,241	1657	3849

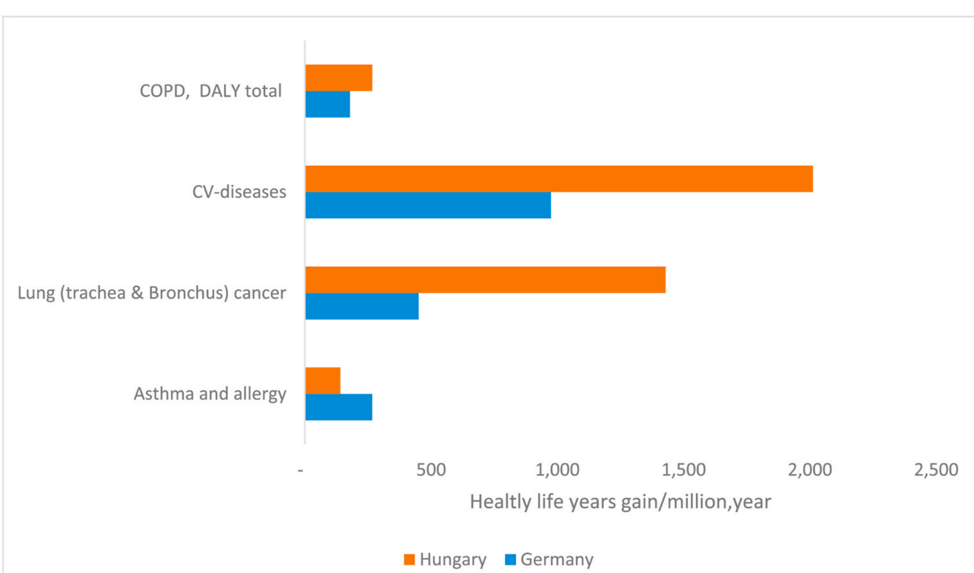

Fig. 4. Healthy life years gain/million population, year from each of the diseases.

(ug/m3) annually compared to 14 μg/m3 annually in Germany) (WHO, 2016). Both countries had a much higher PM2.5 annual concentration level than the World Health Organisation (WHO) standard.[7] Consequently, diseases such as lung cancer, and cardiovascular diseases linked to PM2.5 exposure were higher in Hungary. High-efficiency building envelopes that are more airtight prevent pollutants such as PM, and VOCs from infiltrating indoors lowering cardiovascular and cancer disease risks. With more outdoor pollution concentration, Hungary would gain more healthy life years at the per-capita level by avoiding indoor exposure to pollutants - which is reflected in Fig. 4. Furthermore, the World Cancer Research Fund data shows that, Hungary reported the highest number of lung cancer cases in Europe (International cancer research fund, 2012). High pollutant concentrations and high cancer cases, reported in Hungary, are reflected in healthy life years loss. For instance, 838 years and 2571 years, million population healthy life years were lost due to lung cancer due to indoor exposure to pollutants in Germany and Hungary respectively in 2012 (refer to table- A3). Therefore, by preventing infiltration of outdoor pollutants, especially PM 2.5, VOCs, and radon exposure, Hungary would have a higher per capita gain than Germany by saving healthy life years from cancer. This reflects in the HG data where the value of the health gain factor for cancer is 55% in Hungary, and 53% in Germany.

Monetization of healthy life years: To monetise healthy life years, this paper uses the estimates of' 'Value of a life year (VOLY)' reported in the Mzavanadze et al. (2018) study. The values of VOLY for Germany and Hungary are reported to be 148,220 and 34,853 Euros respectively (Mzavanadze et al., 2018). Therefore, the monetary value of per capita healthy life years for Germany and Hungary is 277 and 134 million Euros respectively. The monetization of health impact has certain ethical concerns related to value of life. More precisely, the critics of the monetization of health impact suggest that "human life is the ultimate example of a value that is not a commodity and does not have a price" (Ackerman, and Heinzerling, 2002). However, it needs to be understood that monetization of health indicators such as the VOLY does not value an actual life. Instead, it values the amount of money that can be spent or the amount of money saved to avoid a certain type of health risk (Fiúza et al., 2006). If the health impacts are not monetised then they would simply not be accounted for, and hence, considered in policy evaluations. Furthermore, this research accounts for the change in sick days that only incorporates the morbidity aspect. However, there is an immense impact of BRIs on mortality as well. Thus, to show the full magnitude of the health impacts of high-efficiency buildings, this paper monetizes it by using the VOLY.

The active days can be gained by avoiding different diseases which enhances the quality of life. Avoided sick days can translate into more earning opportunities, and thus, a higher economic well-being is attainable by living and working in high-efficiency buildings. However, similar to avoided sick days, the values of healthy life years are subject to the same uncertainties due to sub-optimal/full utilization of high-efficiency residential buildings. Thus, with the same assumptions on the exposure level like in the case of avoided sick days, the healthy life years gain for Hungary ranges between 4761 and 3849 years/per million population (where the high scenario results in 4761 years, and the low scenarios results in 3595 years) and for Germany, the same ranges between 2454 and 1870 years (where the high scenario results in 2454 years, and the low scenarios results in 1737 years) per million population, year (refer to figure A3). Similar to the avoided sick days, the scenario used in this study provides a moderate result which is greater than the low scenario and lower than the high scenario.

[7] As per WHO standard the PM2.5 concentration should not exceed 10 μg/m3 annually.

4.2. Results and analysis-workforce performance

As discussed in section 3.1, the workforce performance indicator is calculated for the entire workforce by using a performance improvement factor with the number of workers working in tertiary buildings. Due to data and methodological challenges, it was not possible to estimate individual performance due to working in the energy-efficient buildings at the national level as this would have required surveying a larger sample size with a control group. Thus, the value of the individual performance factor was obtained from the literature for this research and was calculated at the national level by using Equation (6). The result shows that Hungary and Germany can respectively gain around 0.4 million and 4 million working hours annually by improving mental well-being.

The productivity improvement factor (PI) used in this study is unique as it reflects the additional productive working hours from improved mental well-being which is additional to presenteeism days avoided. The PI was obtained from Singh et al. (2010), which presents data on incremental work hours in a year, per worker after shifting into 'green buildings'. Therefore, using this PI and equation derived for this research, a country with a higher workforce working in high-efficiency buildings would gain higher additional productive hours. For example, Germany has a 7% increase in high-efficiency tertiary buildings resulting in a 7% increase in their workforce working in those buildings in the efficiency scenario compared to the reference scenario. On the other hand, in Hungary, in 5% more high-efficiency tertiary buildings, around 5% more Hungarian workforce would work in the efficiency scenario compared to its reference scenario (refer to table- A2 in the appendix section). Thus, Germany would gain higher additional productive hours compared to Hungary due to a higher number of working population working in energy-efficient buildings (refer to Table 5 below).

The actual hours working data for each country are sourced from the OECD database (OECD, 2017).

Monetization of workforce performance: Workforce productivity is monetised by multiplying mean hourly earning with the total actual work hours gain per country. The mean hourly earnings is taken from the Eurostat 'Labour market database'. The mean hourly earnings for Germany and Hungary were reported to be 20 and 6 Euros respectively in 2018 (Eurostat, 2018). Thus, the total monetary value of workforce performance improvement for both Germany and Hungary is around 95 and 2 million Euros respectively.

The total workforce performance gain is dependent on the value of PI which is contingent on the nature of the job performed by the worker. In this study, both repetitive and non-repetitive jobs are considered, as the value of PI is used for the national workforce performance calculation. However, if only repetitive jobs, such as typing, and, proof-reading, are considered then much higher work performance can be gained by working in high-efficiency buildings. For instance, Wargocki et al. (2000) estimated that a 1.4% increase in work performance could be gained by shifting into a retrofitted-building office building. This shows that similar to change in active days, the workforce performance indicator is also subject to uncertainties such as the nature of the job and individual well-being. If the nature of the job is repetitive, then the work performance or actual hours worked would increase by 1.4% (as per Wargocki et al., 2000), which would translate into an additional 19 and 25 working hours gained for each worker in Germany and Hungary

Table 5
Labour input in actual hours working in two scenarios.

Country	Actual hours workings in 2016 (Hours/ per person, year)	Total Actual hours workings in the reference scenario in 2030 (In billions)	Total Actual hours workings in the efficient scenario in 2030 (In billions)	Total work hours gain/ year in 2030 (In millions)
Germany	1363	46	46	4
Hungary	1761	6	6	0.4

respectively. The work hours gained with repetitive jobs, are much higher than the scenario used in this study. However, since we are calculating national workforce productivity, this study provides a balanced estimate of workforce performance for each of the countries by considering both repetitive and non-repetitive jobs. This uncertainty analysis sheds light on the huge potential for workforce performance improvements via improving mental well-being enabled by working in high-efficiency buildings.

5. Conclusion and policy relevance

High-efficiency buildings contribute significantly less to GHG emissions compared to conventional buildings. In addition to lower GHG emissions, the findings of this study show that substantial health and productivity benefits can also be obtained from high-efficiency buildings. Health and productivity impacts are often ignored in policy evaluations due to quantification challenges. This paper provides a novel set of methods that rigorously quantify the potential labour productivity impacts of high-efficiency buildings. Each of the equations used in this research is novel and hence, contributes significantly to the methodological research of quantifying MIs. This study is the first attempt at rigorously quantifying the productivity impacts of high-efficiency buildings for both working and non-working populations at a national scale.

The findings of this study show that a higher level of well-being can be attained by living and working in high-efficiency buildings as the standard of living and quality of life would be improved significantly by avoiding sick days, gaining healthy life years, and improving work performance. Furthermore, higher levels of well-being can be enjoyed by both-working and non-working population since living in high-efficiency buildings would improve the labour productivity as well as social-productivity. The findings of this study provide strong motivations to design policies that promote the construction and renovation of buildings in accordance with the passive-house or NZEB standards. The substantial productivity impacts of high-efficiency buildings can be an entry-point for policymakers seeking to develop policies that can mitigate GHG emissions while improving human well-being. The findings of this research translate into a series of recommendations;

1. High-efficiency buildings and policies-related to high-efficiency buildings should be reassessed by incorporating all the MIs and particularly the productivity impacts. The findings of this study suggest that more high-efficiency buildings would result in significant productivity gains which would further help achieve a higher level of well-being for the entire population.
2. Most of the productivity gains directly result from health improvements and disease avoidance. Health is a priority for many governments and avoiding building-related illnesses raises the importance of high-efficiency buildings.
3. Social security systems, such as the sick leave policies of Hungary, need to be strengthened to minimise productivity losses. Presenteeism days could be a good indicator to measure the strength of social security systems, but country-specific presenteeism data is not available. Therefore, more studies on presenteeism days should be conducted.
4. The health and productivity impacts among people in the lower-income group would be much higher since they have a higher marginal utility of income. However, purchasing or renovating existing buildings to high-efficiency standards is costly compared to conventional buildings, and may not be affordable for people in the lower-income group. Thus, incentives such as subsidies should be designed for the lower-income group to invest in higher efficiency buildings.

Like any empirical study, this study has uncertainties and limitations. For instance, if the technical optimization of high-efficiency buildings is not completely utilised then the health effects could be lower than estimated. Furthermore, this study uses national data to calculate productivity impacts which may vary at the individual level. More precisely, reaction towards exposure to pollution may vary from person to person. However, it is beyond the scope of this study to account for individual differences as the primary objective of the study is to estimate productivity impacts at the national scale. Nevertheless, this study performs sensitivity analysis for each of the indicators to present the sensitivity range of productivity impacts of high-efficiency buildings. Despite these uncertainties and limitations, this study produces the first ever evidence of labour productivity impacts at the national scale to illustrate the significance of high-efficiency buildings.

In the next steps, the authors will quantify other MIs of high-efficiency buildings. Also, several data and research-related gaps have been identified while quantifying productivity impacts that provide the scope of future research opportunities to further the science of quantifying MIs. Defining and quantifying all the MIs of high-efficiency buildings will allow for conducting comprehensive cost-benefit analyses.

CRediT authorship contribution statement

Souran Chatterjee: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft. **Diana Ürge-Vorsatz:** Methodology, Writing – review & editing, Supervision.

Declaration of competing interest

This research was done during first author Souran Chatterjee's doctoral dissertation at the Central European University, Budapest which was submitted in the year 2018, September. The doctoral dissertation was a part of a project 'Calculating and Operationalising the Multiple Benefits of Energy Efficiency in Europe' (COMBI) which received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 649724 (2015–2018). The authors are grateful to ABUD kft, especially the CEO of ABUD Kft. Dr. Andras Reith, for taking care of all the administrative works of the research during the COMBI project.

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This research was conducted as a part of Souran Chatterjee's doctoral dissertation at the Central European University, Budapest which was submitted in the year 2018, September. The doctoral dissertation was a part of a project 'Calculating and Operationalising the Multiple Benefits of Energy Efficiency in Europe' (COMBI) which received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 649724 (2015–2018). The authors are immensely gratefull to the doctoral commitee memebers of Souran Chatterjee for providing their useful comments during the dissertation process.The authors are grateful to ABUD kft, especially, CEO of ABUD Kft. Dr. Andras Reith, for taking care of all the administrative works of the research during the COMBI project. The authors would like to thank COMBI project partners, especially the University of Antwerp for the scenario data. We would also like to thank our institution Central European University (CEU) for providing intitutional support and facilities to conduct research. Last but definitely not least, our sincere gratitude to Healthvent project researcher Dr. Arja Asikainen (National Institute for Health and Welfare, Finland (THL) for supporting us with the data from the healthvent project and all her wise advice.

Appendix

Table A1
Number of persons living in different types of residential buildings in the year 2030
Source: COMBI project.

	Germany		Hungary	
	Reference scenario	Efficiency scenario	Reference scenario	Efficiency scenario
Number of persons living in surviving non -retrofitted buildings (in million)	*56*	*46*	*4*	*3*
Number of persons living in light (shallow) retrofitted dwellings (in million)	*3*	*7*	*0.1*	*0.1*
Number of persons living in medium retrofitted dwellings (in million)	*4*	*8*	*0.2*	*0.5*
Number of persons living in deep retrofitted dwellings (in million)	*2*	*4*	*0.4*	*0.9*
Number of persons living in new dwellings - minimum required standard 2015–2020 (in million)	*2*	*2*	*0.1*	*0.1*
Number of persons living in new nZEB dwellings (in million)	*9*	*6*	*2*	*1.5*
Number of persons living in new Passive House dwellings (in million)	*8*	*11*	*2*	*3*

Table A2
Number of employed populations living and working in different types of residential and tertiary buildings in the year 2030.
Source: COMBI project.

Type of buildings/Country, Scenario		Germany		Hungary	
		Reference scenario	Efficiency scenario	Reference scenario	Efficiency scenario
Employed population in surviving non -retrofitted buildings (in million)	In residential buildings	28	23	2	2
	In tertiary buildings	25	22	2	2
Employed population in light (shallow) retrofitted dwellings (in million)	In residential buildings	2	3	0.03	0.06
	In tertiary buildings	1	2	0.2	0.4
Employed population in medium retrofitted dwellings (in million)	In residential buildings	2	4	0.1	0.2
	In tertiary buildings	0.5	1	0.1	0.1
Employed population in deep retrofitted dwellings (in million)	In residential buildings	1	2	0.2	0.4
	In tertiary buildings	0.4	3	0.1	0.3
Employed population in new dwellings - minimum required standard 2015–2020 (in million)	In residential buildings	0.9	0.9	0.1	0.1
	In tertiary buildings	0.7	0.7	0.1	0.1
Employed population in new nZEB dwellings (in million)	In residential buildings	5	3	1	0.7
	In tertiary buildings	6	4	0.6	0.4
Employed population in new Passive House dwellings (in million)	In residential buildings	4	5	1	1
	In tertiary buildings	1	3	0.1	0.3

Table A3
Values of burden of diseases (in DALY) from Healthvent project

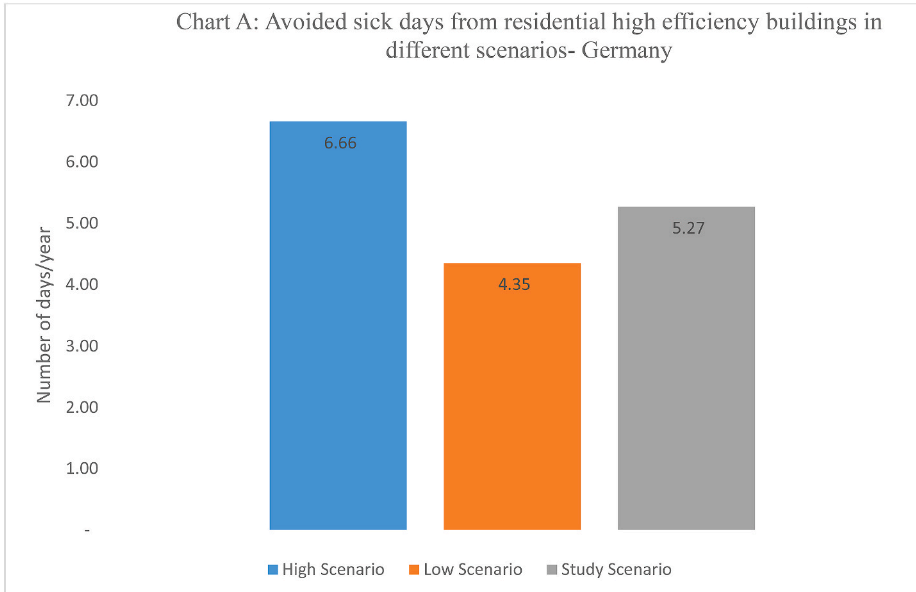
	Diseases	Baseline DALY (Total DALY/million pop)	Source control with ventilation scenario (Total DALY/million pop)
Germany	Asthma and allergies	467	201
	Cardiovascular diseases	2298	1280
	Lung (trachea & Bronchus) cancer	838	387
	COPD	462	254
Hungary	Asthma and allergies	271	129
	Cardiovascular diseases	5376	3352
	Lung (trachea & Bronchus) cancer	2571	1142
	COPD	768	467

Source: Healthvent project.

Table A4
Disease specific health gain factor under different under different scenarios to calculate the uncertainty range

	Germany			Hungary		
	High Scenario	Low scenario	Study scenario	High Scenario	Low scenario	Study scenario
Asthma & allergy	72%	46%	57%	64%	43%	52%
Lung (trachea & Bronchus) cancer	70%	47%	53%	68%	48%	55%
COPD	60%	42%	45%	50%	37%	39%
Cardiovascular diseases	58%	43%	44%	47%	37%	38%

Source: Healthvent project.



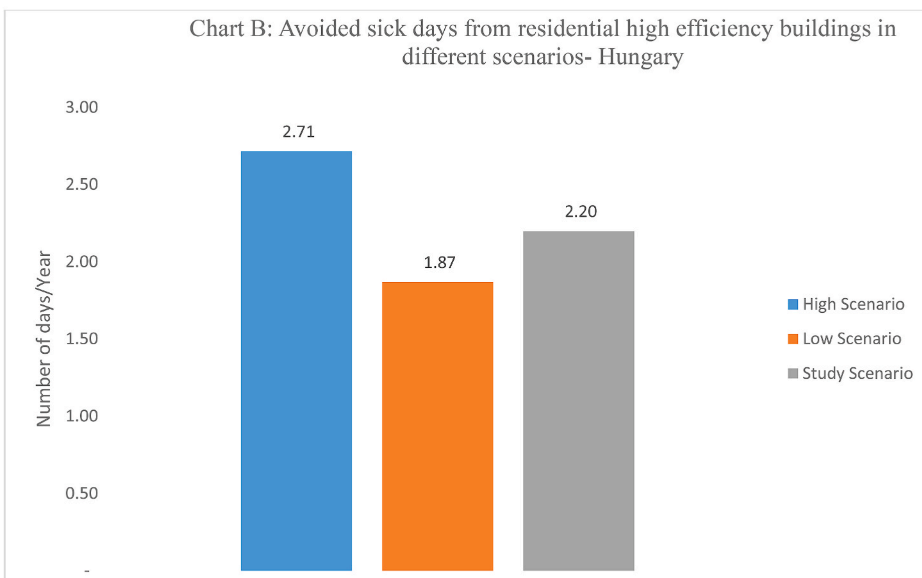


Fig. A1. Avoided sick days from the residential high-efficiency buildings in different scenarios- Sensitivity analysis.

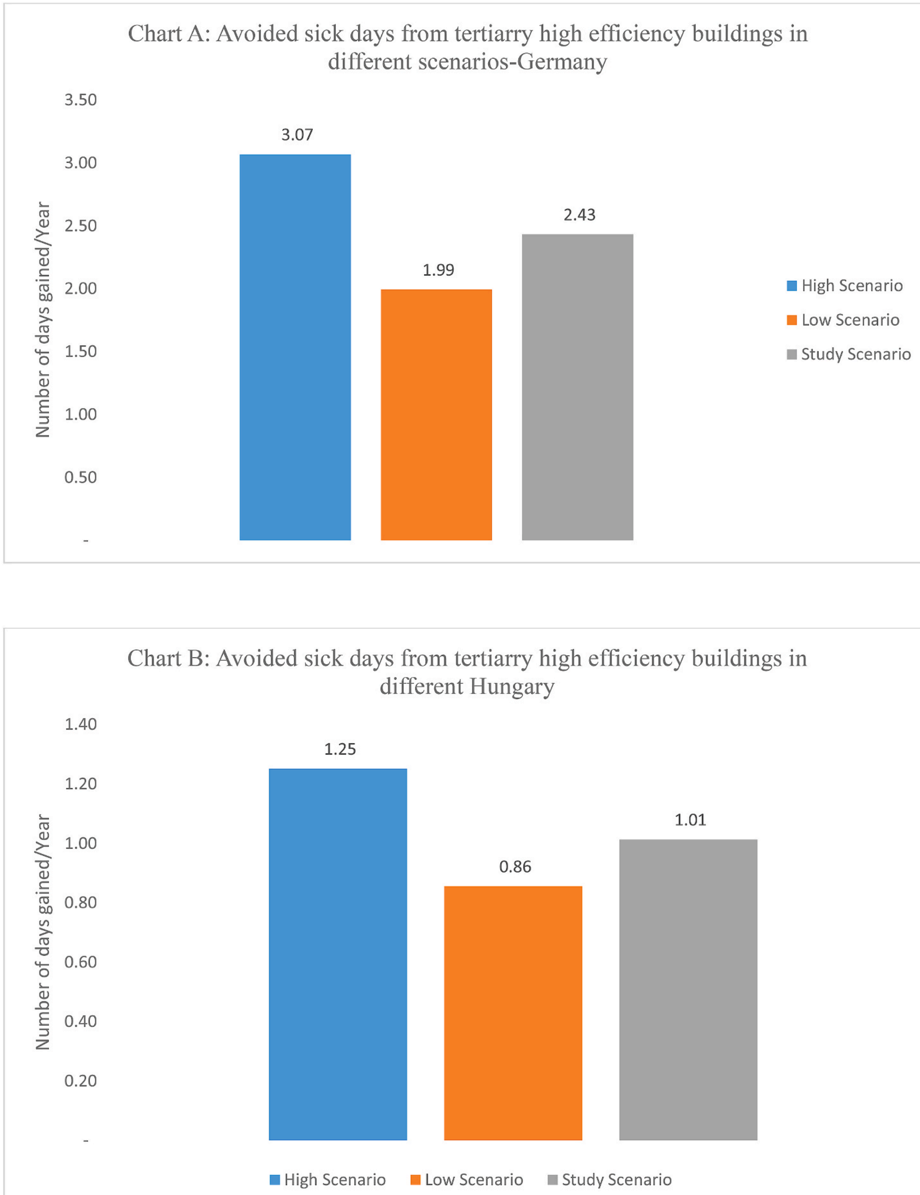
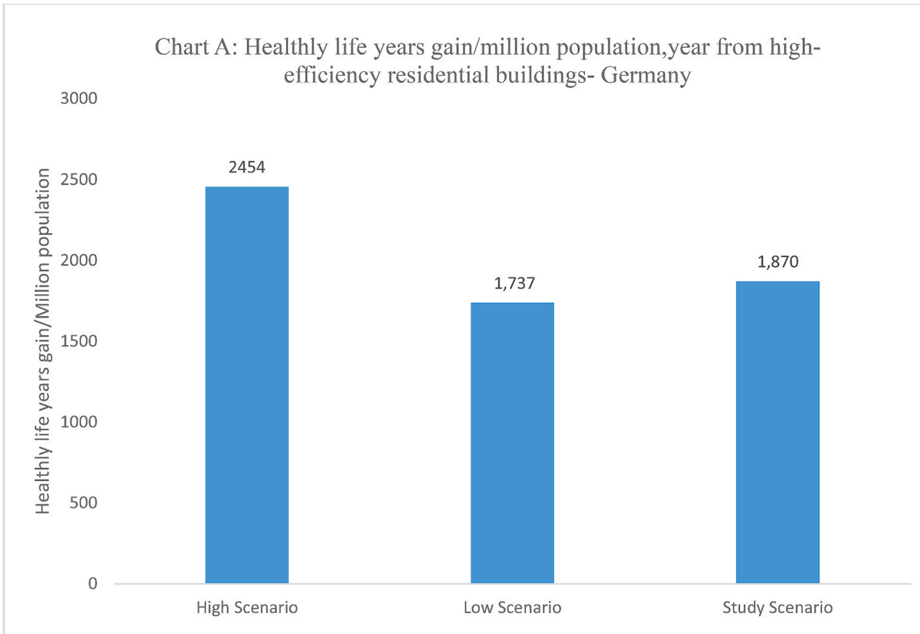


Fig. A2. Avoided sick days from the tertiary high-efficiency buildings in different scenarios- Sensitivity analysis.



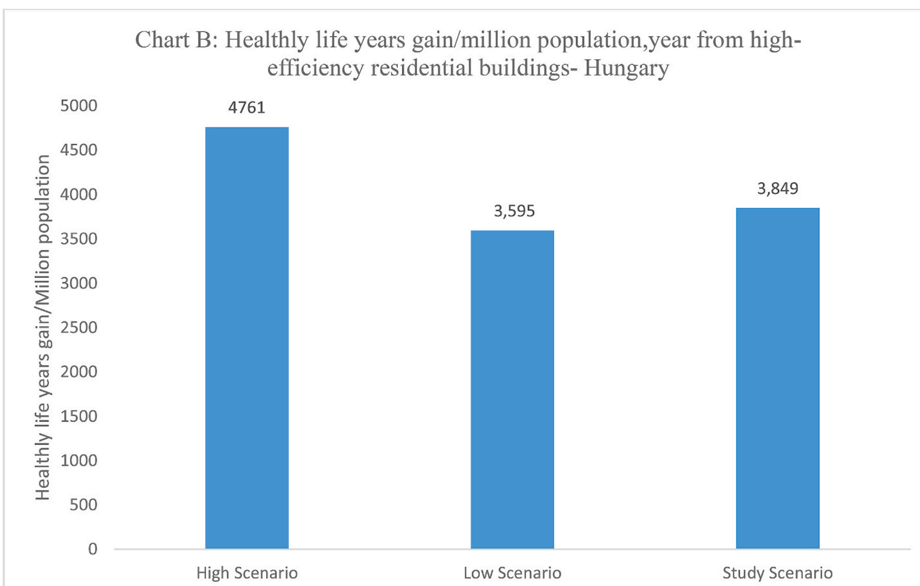


Fig. A3. Healthy life years gain from the tertiary high-efficiency buildings in different scenarios- Sensitivity analysis.

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