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Research Article

A Comprehensive Index for Evaluating the Effectiveness of Ventilation-Related Infection Prevention Measures with Energy Considerations: Development and Application Perspectives

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In the wake of the COVID-19 pandemic, prioritizing indoor air quality has emerged as a crucial measure for preventing infections. Effective ventilation is vital in mitigating airborne pathogen transmission and maintaining a healthy indoor environment by diluting and removing infectious particles from enclosed spaces. However, increasing the supply of pathogen-free air to enhance infection control can lead to a rise in energy consumption. Nevertheless, evaluating the overall efficacy of ventilation-based infection prevention strategies while considering their energy requirements has posed challenges. This scientific paper introduces the ICEE (Infection Control's Energy Efficiency) index, a newly developed simple integrated index to assess the effectiveness of ventilation strategies in reducing infection risks while accounting for associated energy demands. The paper reviews the current understanding of ventilation strategies, their impact on infection prevention, and their corresponding energy consumption. By employing a straightforward analytical approach, this metric offers a comprehensive framework to optimize ventilation systems for both infection prevention and energy efficiency. To quantify infection risk, a simplified equation model is utilized, incorporating factors such as ventilation effectiveness and filter efficiency, in case of recirculation. Energy demand is determined using approximations and relevant values from existing literature. Reference cases are defined, distinguishing between natural and mechanically ventilated scenarios, as these reference situations influence the energy-related effects of any implemented measures. The paper outlines the methodology employed to develop the index and illustrates its applicability through exemplary measures. The proposed index yields valuable insights for the design, operation, and retrofitting of ventilation systems, enabling informed decision-making towards fostering a healthier and more sustainable built environment.

1. Introduction

The likelihood of occurrence of extreme pandemics, similar to COVID-19, increases in the coming decades [1]. Other endemic pathogens also have a significant and frequent impact on people's health and well-being. Indoor environments have long been recognized as potential hotspots for the transmission of infectious diseases, particularly respiratory illnesses caused by airborne pathogens. The recent COVID-19 pandemic has underscored the pressing need for effective infection prevention measures within indoor settings [2, 3]. Consequently, not only the World Health Organization (WHO) but also various national health authorities and the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) [4–9] have issued guidelines that emphasize the importance of sufficient ventilation as a key preventive measure against respiratory infections.

Specifically, in the context of reducing the risk of SARS-CoV-2 infection, the WHO recommends increasing supply flow rates of outdoor air to a minimum of 36 m^3/h per person which relates to a CO_2 concentration of 1000 ppm. The concentration of 1000 ppm has been established since many decades as the target level, known as the Pettenkofer number [10], for indicating hygienically acceptable indoor air. CO_2 is often used as an indicator for other emitted or exhaled contaminants of humans like infectious aerosols (both are airborne) [11, 12] and therefore a scale for the general indoor air quality as it provides the possibility of assuming the flow rate of outdoor air. Good et al. [13] showed that respiratory aerosol emissions are somewhat related to a person's CO_2 emissions. However, infectious aerosol particles and CO_2 have slightly different physical behavior. For example, infectious aerosol particles can be filtered, which is not the case for CO_2. Therefore, at high filtration rates, the CO_2 concentration can be high and the aerosol concentration still low. A study by Satish et al. [14] showed that reductions in human performance can be observed also in the case of exposure to elevated CO_2 levels excluding other human pollutants.

Increasing the flow rate of contaminant-free supply air enhances the dilution of the emitted loads, including pathogens [9]. More precisely, the number of inhaled pathogens is reduced leading to a lowered probability of transmission [15]. Determining the precise air requirements necessary to contain the spread of a particular pathogen is exceedingly complex due to the multitude of influencing factors and their intricate effects on transmission dynamics [16]. In a retrospective cohort study by Buonanno et al. [17] could be shown that for classrooms equipped with mechanical ventilation systems, the relative risk of infection of students significantly decreased compared to naturally ventilated classrooms. Also, a clear correlation between risk reduction and ventilation rate was obtained. Further studies showed that there is a clear correlation between higher ventilation rates (resulting in better indoor air quality) and a decreasing risk of sick leave and productivity gains [18, 19].

Considering the concept of natural ventilation, it is observed that maintaining an outdoor airflow rate of at least $36\,m^3/h$ per person while ensuring the thermal comfort of the occupants is often not possible in practice [20]. This is primarily due to insufficient air exchange resulting from climatic conditions, such as a small temperature difference between indoor and outdoor air or the absence of wind during the summer months. Additionally, inadequate manual opening of windows by occupants further contributes to the challenge of achieving sufficient ventilation fitting the building's energy concept [21, 22]. Various factors contribute to suboptimal ventilation behavior, e.g., increased heating cost due to ventilation heat loss or discomfort during the cold season. In contrast, heating, ventilation, and air conditioning systems (HVAC) can provide a defined contaminant-free airflow rate. An increase in the airflow rate in a ventilation system has a significant impact on the energy needs. The power requirement of the fan $\dot{P}$ theoretically increases with the cube of the rotational speed or airflow change (n or $\dot{V}$) in a system [23]. The ventilation-related heating demand rises proportionally with the airflow rate (according to BS EN 12831-1 [24] and VDI 2078 [25]).

During the planning phase of conventional ventilation systems, often energy efficiency and thermal comfort are prioritized [26–28]. However, these are not always compatible with infection control requirements [29]. In conclusion, increasing the ventilation rates to reduce the risk of airborne transmission can lead to higher energy consumption, resulting in increased greenhouse gas emissions compared to the reference and increased operating costs for building owners [30].

Kurnitski et al. [26] developed an infection model based on the Wells-Riley equations to provide the required ventilation rate for fixed event reproduction numbers of respiratory infections. They reported that in large classrooms or small offices, high ventilation rates are required. In contrast, they stated that for most other rooms the ventilation rate of category I [31] (according to Table 1) almost sufficed. Moreover, they showed a significant decrease in the individual risk level when applying mask factors.

Further, Pang et al. [32] conducted a building energy simulation and an infection risk analysis with the Wells-Riley-based Gammaitoni-Nucci model for a medium-sized office building. They found that an increase in the outdoor airflow rate in office buildings led to a reduction in the infection risk of COVID-19. However, the HVAC energy consumption increased, especially in hot and cold climates. Moreover, the local climate and season influenced the infection risk significantly. The risks were lower in cities with cold winters and hot summers due to the higher ventilation rates needed to remove heating or cooling loads.

In a case study carried out in China, a 128% rise in HVAC system energy use during the pandemic was reported [33]. Guo et al. [34] outlined that at least 13% of the global energy is expended by HVAC systems. Sample calculations by Fisk et al. revealed that the potential financial gains from enhancing indoor environments far outweigh the associated costs, with benefits exceeding expenses by a substantial margin [27, 35]. Nevertheless, current global climate policy emphasizes the need to save energy.

In the study of Guo et al. [34], an infection risk energy demand model was developed based on the Wells-Riley model for different indoor environments. Here, the supply airflow rate of different indoor environments is to be optimized considering the energy demand by adjusting the reproduction number R_0 for different age groups, daily routines, and building types to holistically achieve a reproduction number less than or equal to 1. Additionally, selected infection control measures are applied. A metric for evaluating infection control measures is not presented. The energy savings quantified in the study that consider selected measures (recirculating air filtering devices, wearing of masks, etc.) refer to the reference case of strict compliance with $R_0 = 1$ through sufficient fresh air supply without further measures. They found ventilation rates near or below $60\,m^3/h$ per person to be most necessary in order to reduce R_0. A comparison of different infection prevention measures is not made in their study. Also, it does not aim to offer suitable methods and formulas to evaluate engineering infection control techniques in a nuanced manner, based on energy demand, air quality, and infection control, which describes the research gap. Furthermore, Xu et al. [36] introduced a modeling framework designed to assess the trade-offs among health, energy, and human thermal comfort. While this research also shows the tension between infection control and energy requirements, it does not aim to distinguish individual and combinations of infection control measures in a comprehensive and simple way.

Table 1: Categories for indoor environment quality (IEQ) concerning the airflow rate of outdoor air according to DIN EN 16798-1 [31].

Category/expectation of indoor environment quality	Flowrate of outdoor air q_{pers} in m^3/h (l/s) per person	Resulting CO_2 level in ppm (assumed CO_2 level in the outdoor air of 400 ppm and human CO_2 emissions of 20 l/h per person)
I/high	36.0 (10)	950
II/medium	25.2 (7)	1200
III/moderate	14.4 (4)	1750
IV/low	<14.4 (4)	>1750

In conclusion, striking a balance between infection prevention and energy efficiency is crucial in developing sustainable and effective ventilation strategies to reach global carbon neutrality and improve human health. Ensuring optimal ventilation in buildings presents a complex challenge. Mechanical ventilation systems can provide a controlled supply of virus-free air and promote effective air exchange. However, it is important to acknowledge that as the supply airflow rate increases, so does the associated energy demand. Evaluating the effectiveness of such measures while considering their energy requirements is a multifaceted problem that requires a comprehensive and systematic approach. Currently, there is a lack of a holistic index that considers both infection prevention effectiveness and energy consumption.

To address this gap, this paper presents a newly developed metric, the Infection Control's Energy Efficiency (ICEE) index, which offers an extensive framework for evaluating the overall effectiveness of ventilation-related infection prevention measures while accounting for their energy requirements. The idea of the here presented work is the possibility to compare individual measures differentiated by calculating one index and therefore help decision makers in choosing the most appropriate options. Therefore, a generic analytical concept is pursued. The methodology includes comprehensive research on standards and regulations to determine the analytical energy demand of various ventilation concepts and the assessment of infection risk and other relevant variables that influence pathogen load, such as ventilation effectiveness. By integrating these different parameters, the index provides a comprehensive and balanced evaluation of ventilation strategies.

The index can be utilized to identify strengths and weaknesses related to infection prevention and energy demand in different baseline situations. It cannot be used to determine the ventilation rates required to completely prevent the indoor transmission of pathogens.

This study also contributes to the development of evidence-based guidelines for ventilation systems that optimize infection prevention while minimizing energy demand. Nontechnical measures, such as the use of masks or reduced occupancy times, can also be included in the index. This allows alternative or transitional measures to be justified simply by comparing the ICEE. Such guidelines will assist policymakers, architects, engineers, planners, and building operators in making informed decisions when designing, retrofitting, or operating buildings to create healthy and sustainable indoor environments. The index can be used to find suitable control strategies by differentiating the individual boundary conditions.

2. Methods

The following sections provide a comprehensive derivation of the Infection Control's Energy Efficiency (ICEE) index, introducing the variables required for calculating the metric. The index encompasses the evaluation of infection control and generalized energy calculations. Here, the subscript "0" is used for the reference case, explained in Section 2.1, and the subscript "x" represents the situation after a measure has been implemented.

2.1. Derivation of the Index. The ICEE index presented in this study is a dimensionless metric that always refers to a reference scenario. It implements the infection risk by using a simplified infection risk model for determining theoretically newly infected individuals (situational reproduction number R_S) and analytical energy demand calculations. The index is calculated according to Equation (1). It captures the factor of improved infection control, $R_{S,0}/R_{S,x}$ (Equation (2)), in relation to the corresponding relative increase in primary energy demand, $Q_{pers,prim,x}/Q_{pers,prim,0}$ (Equation (4)). The larger the ICEE index, the more favorable and efficient the measure. In this version of the index, energy needs and infection control are assumed to be equally important, which is not necessarily the case as mentioned above by referring to Fisk et al. [35]. Also, thermal comfort is neglected in this equation.

$$\mathrm{ICEE} = \frac{R_{S,0}/R_{S,x}}{Q_{pers,x}/Q_{pers,0}} = \frac{R_{S,0}}{R_{S,x}} \cdot \frac{Q_{pers,prim,0}}{Q_{pers,prim,x}}. \quad (1)$$

In DIN EN 16798-1 [31], categories for indoor air quality are defined and summarized in Table 1. Category I, characterized by high expectations for indoor quality, is achieved at a supply rate of outdoor air of 36 m^3/h per person or above. At an airflow rate of 14.4 m^3/h per person or lower, the level of expectations for indoor air quality is moderate or low (category III), and at 25.2 m^3/h, it is of medium level (category II).

As per DIN EN 16798-1, it is recommended for health considerations that the minimum outdoor airflow rate should never be lower than 14.4 m^3/h per person during occupancy [31] which would correspond to a CO_2 level of 1750 ppm assuming a sedentary light activity. Therefore, in this study, a naturally ventilated reference case A is defined based on category III. For the mechanically ventilated reference case B, the design airflow rate is based on category II assumed to be 25.2 m^3/h per person (~1200 ppm):

Reference Case A: naturally ventilated room with an air supply of 14.4 m^3/h or 4 l/s per person

Reference Case B: mechanically ventilated room (with both supply and exhaust air) without heat recovery with an air supply of 25.2 m^3/h or 7 l/s per person

2.1.1. Evaluation of Infection Protection. In previous work by Kriegel et al. [16], the situational reproduction number R_S was introduced. This simplified approach allows for estimating the theoretical number of individuals who could become infected in the presence of an infected person. During an infectious outbreak, the R_S value should ideally not exceed 1, indicating that no more than one additional person should be infected to contain the exponential spread of the pathogen.

For R_S, Equation (2) is applied, as proposed by Kriegel et al. [16]. Here, V_F represents the virus-specific factor, encompassing the emission rate and the number of viral particles required to cause an infection. Time t denotes the duration of exposure in the situation. In Equation (2), it is assumed that only one infected and contagious person is present in the transmission event. The person-related flow rate of outdoor air q_{pers} relates the total airflow rate to the number of occupants. $Q_{\text{b,in}}$ denotes the inhaled air volume per person, assumed to be 0.54 m^3/(h·person) for a light seated activity [37, 38]. In the case of filtering of recirculated air, also the additional filtered recirculated airflow rate $q_{\text{pers,filter}}$ and the corresponding filter efficiency η_{filter} of the total filter stages are utilized. The mask factor f_M evaluates the filtration efficiency of masks as a ventilation-independent measure. When no mask is worn, this factor equals 1. The mask factor is calculated based on the principles outlined in references [15, 39], taking into account the leakage during inhalation and exhalation. The particle size associated with the highest total leakage is considered in each case.

$$R_S = V_F \cdot \frac{t}{q_{\text{pers}} \cdot \varepsilon^c_{\text{exp}} + q_{\text{pers,filter}} \cdot \eta_{\text{filter}}} \cdot Q_{\text{b,in}} \cdot f_M. \quad (2)$$

When assessing the infection risk, the pathogen concentration in the inhaled air plays a crucial role. To account for this, the hygienically effective person-related airflow rate for an individual can be corrected using the contaminant removal effectiveness (CRE) of the air volume inhaled by a person $\varepsilon^c_{\text{exp}}$. It is calculated using Equation (3), where c_{in} represents the concentration in the supply air. It relates to contaminant concentration in the exhaust c_{ex} to the concentration in the inhaled air c_{exp} [40]. It serves as a metric for ventilation effectiveness. In ideal mixing ventilation, $\varepsilon^c_{\text{exp}}$ is 1. Therefore, $\varepsilon^c_{\text{exp}}$ describes a factor by which a considered ventilation system is superior or inferior to the ideal mixing case in terms of contaminant removal. A $\varepsilon^c_{\text{exp}}$ of 2 results in a contaminant concentration being only half of the analytical value obtained under complete mixing and therefore being twice as effective. In terms of infection protection, this is equivalent to doubling the pathogen-free supply airflow rate at mixing ventilation.

$$\varepsilon^c_{\text{exp}} = \frac{c_{\text{ex}} - c_{\text{in}}}{c_{\text{exp}} - c_{\text{in}}}. \quad (3)$$

2.1.2. Energy Demand Assessment. The necessary person-related primary energy demand $Q_{\text{pers,prim}}$ is used for the calculation of the index. It consists of the person-related ventilation heat losses $Q_{\text{pers,Heat}}$ and the person-related auxiliary energy $Q_{\text{pers,el}}$ (Equation (4)), while considering the primary energy factors $f_{\text{prim,Heat}}$ for heat and $f_{\text{prim,el}}$ for electricity required for the ventilation technology. The assumed primary energy factors are 1.8 $kWh_{\text{primary}}/kWh_{\text{heat}}$ (based on the electricity mix in Germany) and 1.1 $kWh_{\text{primary}}/kWh_{\text{heat}}$ (assuming natural gas/heating oil) [41].

$$Q_{\text{pers,prim}} = Q_{\text{pers,Heat}} \cdot f_{\text{prim,Heat}} + Q_{\text{pers,el}} \cdot f_{\text{prim,el}}. \quad (4)$$

The ventilation heat losses $Q_{\text{pers,Heat,x}}$ are calculated using Equation (5), which takes into account the temperature difference ΔT between outdoor and indoor air, the temperature efficiency η_t of the installed heat recovery unit (HRU), and the airflow rate q_{pers}. The equation considers a potential naturally ventilated airflow rate fraction $x_{\text{naturalvent}}$ in the case of hybrid or mixed mode ventilation, meaning the combination of mechanical and natural ventilation. The product of air density ρ_{air} and specific heat capacity $c_{\text{p,air}}$ is assumed constant at 0.34 Wh/(m^3·K). For the assumed reference cases, no HRU is considered, so $\eta_{t,0} = 0$. The heat transfer from the fan to the supply air in the case of an air-handling unit is neglected.

$$\begin{aligned} Q_{\text{pers,Heat,x}} = \Big(& q_{\text{pers,x}} \cdot (1 - x_{\text{natural vent,x}}) \cdot (1 - \eta_{\text{t,x}}) \\ & + q_{\text{pers,x}} \cdot (x_{\text{natural vent,x}}) \Big) \\ & \cdot \rho_{\text{Luft}} \cdot c_{\text{p,Luft}} \cdot \Delta T_x \cdot t_x. \end{aligned} \quad (5)$$

The electrical auxiliary energy demand required for the ventilation technology $Q_{\text{pers,el}}$ is calculated using Equations (6) or (7). The specific fan power of the supply and exhaust air lines (P_{SFP}) is summarized here, taking into account recommended values from GEG 2020 [41], DIN EN 16798-3 [28], or publications such as Schild [42]. Equation (6) applies to the reference case of a naturally ventilated room (A). For determining the electrical auxiliary energy demand after implementing a measure, factors such as the increase in outdoor airflow rate, recirculated air filtering, heat recovery, optimization of the system by adjusting the specific fan power $P_{\text{SFP,x}}$, and the possible contribution of natural ventilation (hybrid ventilation) are taken into account. $\dot{Q}_{\text{pers,el,filter}}$ represents the additional electrical power consumption due to the pressure drop of the filter stages, and $\dot{Q}_{\text{pers,el,HRU}}$

represents the additional electrical power consumption due to the pressure drop of the HRU. In the case of naturally ventilated reference scenarios, the auxiliary energy demand is 0 Wh.

$$Q_{\text{pers,el,x}} = \left(\frac{P_{\text{SFP,x}}}{3600\ \text{s/h}} \cdot q_{\text{pers},x} \cdot (1 - x_{\text{natural vent,x}}) + \dot{Q}_{\text{pers,el,flter}} + \dot{Q}_{\text{pers,el,HRU}} \right) \cdot t_{\text{x}}. \tag{6}$$

In the reference case of a mechanically ventilated room (B), changes in the airflow rate within the system have a significant impact on the power or auxiliary energy demand. Specifically, the power demand is influenced by the third power of the airflow rate, as indicated by Equation (7). When adjusting the number of occupants in a room to increase the person-related airflow rate, Equation (6) must be applied to the mechanically ventilated reference case (B). This is because the actual airflow rate and air velocities within the air-handling unit remain unchanged.

$$Q_{\text{pers,el,x}} = \left(\frac{P_{\text{SFP,x}}}{3600\ \text{s/h}} \cdot q_{\text{pers,0}} \cdot (1 - x_{\text{natural vent,0}}) \cdot \left(\frac{q_{\text{pers,x}} \cdot (1 - x_{\text{natural vent,x}})}{q_{\text{pers,0}} \cdot (1 - x_{\text{natural vent,0}})} \right)^3 + \dot{Q}_{\text{pers,el,filter}} + \dot{Q}_{\text{pers,el,HRU}} \right) \cdot t_{\text{x}}. \tag{7}$$

The electrical power consumption $\dot{Q}_{\text{pers,el,HRU}}$ resulting from pressure losses in the heat recovery system can be calculated using Equation (8), as defined by DIN EN 13053 [43]. In this equation, Δp_{HRU} represents the sum of pressure losses in the heat recovery system (supply and extract air), η_{D} denotes the average total static efficiency of power consumption, which is assumed to be 60% [43], and $\dot{Q}_{\text{pers,el,HRU,aux}}$ accounts for additional electrical power consumption (e.g., pumps in closed-loop systems), specified in Equation (9). When calculating $\dot{Q}_{\text{pers,el,HRU}}$, the naturally provided airflow ratio $x_{\text{natural vent,x}}$ must be subtracted from the total airflow rate.

$$\dot{Q}_{\text{pers,el,HRU}} = q_{\text{pers,x}} \cdot (1 - x_{\text{natural vent,x}}) \cdot \Delta p_{\text{HRU}} \cdot \frac{1}{\eta_{\text{D}} \cdot 3600\ \text{s/h}} + \dot{Q}_{\text{pers,el,HRU,aux}}. \tag{8}$$

According to DIN V 18599-7 [44], Equation (9) is applicable to calculate the additional electrical power consumption $\dot{Q}_{\text{pers,el,HRU,aux}}$ for closed-loop systems (CLS) and rotary heat exchangers.

$$\dot{Q}_{\text{pers,el,HRU,aux}} = \begin{cases} q_{\text{pers,x}} \cdot 0,03\,\dfrac{\text{Wh}}{\text{m}^3} & \text{for non} - \text{regulated pumps (CLS)}, \\ q_{\text{pers,x}} \cdot 0{,}015\,\dfrac{\text{Wh}}{\text{m}^3} & \text{for regulated pumps (CLS)}, \\ q_{\text{pers,x}} \cdot 0{,}007\,\dfrac{\text{Wh}}{\text{m}^3} & \text{for rotary heat exchanger}. \end{cases} \tag{9}$$

The additional electrical power usage resulting from recirculating and filtering air, denoted as $\dot{Q}_{\text{pers,el,filter}}$, is determined through the application of Equation (10). This equation involves the specific fan power $P_{\text{SFP,filter}}$ needed for air handling and the filtration processes and the person-related airflow rate through the filter unit $q_{\text{pers,filter}}$. In scenarios where a mobile air purifier is deployed, the relevant data from the manufacturer's specifications can be utilized for accurate calculations.

$$\dot{Q}_{\text{pers,el,filter}} = q_{\text{pers,filter}} \cdot \frac{P_{\text{SFP,filter}}}{3600\ \text{s/h}}. \tag{10}$$

2.2. Relative Indoor Air Quality. For an additional evaluation of the measures, the relative indoor air quality is assessed which is not included in the index. The relative indoor air quality IAQ_{rel} is defined by Equation (11) and represents the ratio of the reference CO_2 concentration $c_{CO_2,0}$ to the CO_2 concentration under specific indoor air conditions $c_{CO_2,\text{x}}$ caused by a measure. An outdoor air CO_2 concentration $c_{\text{CO2,OA}}$ of 400 ppm is assumed, which can vary depending on the location and level of agglomeration and tends to increase [45, 46].

$$\text{IAQ}_{\text{rel}} = \frac{c_{CO_2,0} - c_{CO_2,\text{OA}}}{c_{CO_2,\text{x}} - c_{CO_2,\text{OA}}}. \tag{11}$$

2.3. General Boundary Conditions. In order to conduct a general assessment of the measures, an average annual outdoor air temperature is considered. This average temperature is determined based on the Test Reference Year (TRY) 2015 data for the Berlin site [47] and is calculated to be 10.3°C. To approximate the average heating demand, a temperature difference (ΔT) of 10 K is assumed.

When considering ventilation systems for the basic mixing ventilation case, an ideal mixed condition is assumed. When evaluating a displacement ventilation (DV) system, CRE is assumed to be above 1 [48–52]. The principle of DV has been under investigation for many decades. In widely recognized compendiums [53, 54] and guidelines [55], approximate values for CRE are provided for preliminary planning purposes varying from 1.5 to 5.0. In an experiment conducted at the Hermann-Rietschel-Institutat Technische Universität Berlin, Germany, in a room airflow laboratory, simulating a transmission event with one infectious individual and three susceptible persons, the CRE was investigated for the use of DV at various person-related airflow rates (publication pending). The following values for the CRE in the inhalation zone ε^{c}_{exp} were obtained:

$$\varepsilon^{c}_{exp} = \begin{cases} 1.7 \text{ for } 25\,\text{m}^3/(\text{h} \cdot \text{person}), \\ 2.2 \text{ for } 36\,\text{m}^3/(\text{h} \cdot \text{person}), \\ 2.4 \text{ for } 50\,\text{m}^3/(\text{h} \cdot \text{person}). \end{cases} \quad (12)$$

As the investigations were conducted under laboratory conditions, a lower CRE of 1.7 is assumed for the following examinations at an airflow rate of $36\,\text{m}^3$/h per person.

2.4. Boundary Conditions of the Air Handling Unit (AHU). An assumed specific fan power (P_{SFP}) of $2500\,\text{Ws/m}^3$ is considered for an HVAC system with both supply and exhaust air [28, 42]. Extended P_{SFP} allowances are taken into account based on DIN EN 16798-3 [28] These allowances cover additional mechanical filter stages, HEPA filters according to EN 1822-3 [56], or heat recovery systems classified as H2 or H1 (according to DIN EN 13053 [43]). Table 2 presents the specific P_{SFP} allowances for different components.

In the context of the HRU, both temperature efficiency η_t and energy efficiency η_e are crucial factors to consider. Energy efficiency encompasses not only the coefficient of performance but also takes into account the pressure loss induced by the system. Based on η_e, according to DIN EN 13053, the HRUs are divided into classes H1 to H5 [43]. In the exemplary application of the index, a HRU of class H1 is considered. In a study by Kaup [57], an exemplary heat recovery system with a pressure drop of 211 Pa and a heat recovery coefficient of 78.6% was evaluated. In the presented study, the same values are assumed for the HRUs in measures 4, 5, 8, and 10. The dependence of η_t and the air velocity is not considered.

2.5. Considered Measures. In order to make the application of the index more comprehensible, exemplary measures were selected for the two reference cases, described in Section 2.1. The following Table 3 displays the considered measures and their respective parameter changes compared to the reference situation. Some measures are applicable only to reference case A (naturally ventilated room), while others apply also to reference case B (mechanically ventilated room).

Measure 1 assumes achieving an average CO_2 concentration of 1000 ppm. Various strategies can be applied to enhance the ventilation rate within a naturally ventilated setting. One approach involves implementing a ventilation schedule that prescribes specific window opening times, known as intermittent ventilation. Alternatively, a continuous and slight opening of windows can be maintained throughout the day. By strategically reducing occupancy, the airflow rate per person naturally increases. In general, CO_2 monitoring is recommended to assume the airflow rate and to notice the occupants to manually open the windows. Furthermore, the concept of controlled natural ventilation (CNV) introduces a technologically advanced solution. Through the integration of actuators and sensors, CNV enables automated adjustments of window openings based on real-time indoor air conditions. The energy demand associated with CNV is minimal compared to traditional HVAC systems and therefore neglected here.

Table 2: Extended P_{SFP} allowances of different components according to DIN EN 16798-3 [28].

Component	P_{SFP} in Ws/m^3
Additional mechanical filter stage	+300
HEPA filter according to EN 1822-3 [56]	+1 000
Heat recovery class H2 or H1	+300

In measure 6 for reference case A, natural ventilation is increased to $25.2\,\text{m}^3$/h per person (corresponding approximately to a CO_2 concentration of 1200 ppm), so that category II air quality (DIN EN 16798-1) is achieved. In addition, $10.8\,\text{m}^3$/h per person is recirculated by means of a mobile recirculating air filter unit (HEPA purifier) to support natural ventilation. The room air is assumed to be ideally mixed and the specific fan power (P_{SFP}) is assumed to be $180\,\text{Ws/m}^3$. In reference case B, the HVAC system is supported by the mobile air purifier.

Measure 7 implements recirculation using filters according to Hartmann et al. [58], using two compact filters ISO ePM1 60% achieves a minimum separation efficiency of 75% to 80%, even in the critical size range of virus-laden aerosol particles (0.3 to $0.5\,\mu$m). The additional filter stage increases the P_{SFP} value by $300\,\text{Ws/m}^3$. A specific power consumption of $2800\,\text{Ws/m}^3$ is assumed for the recirculated air portion and the outdoor air portion.

For measures 9 and 10, a 50% reduction in auxiliary energy consumption is assumed [59]. Many studies state considerable energy savings due to hybrid ventilation while an appropriate IAQ can be maintained [60]. The actual savings potential depends on the location and temperature conditions throughout the year [61].

3. Results

3.1. Relation between Primary Energy Demand and Supply Rate of Outdoor Air. Referring to Figure 1, the approximate primary energy demand per person and time of stay can be estimated as a function of the supply rate of outdoor air based on Equations (4)–(8) and the boundary conditions in Sections 2.3 and 2.4. An existing HVAC system without HRU (solid black line) and a newly designed HVAC system without HRU (solid grey line) and with HRU (dashed black line) are compared. The primary energy demand is given per person and per hour of occupancy. The assumed existing system has a design airflow rate of $25.2\,\text{m}^3$/h per person ($P_{SFP} = 2500\,\text{Ws/m}^3$ at $25.2\,\text{m}^3$/h per person), corresponding to the reference cases from the calculations for the ICEE index. In the newly designed unit, the design airflow rate corresponds to the desired airflow rate (dotted line), and therefore, a constant P_{SFP} of $2500\,\text{Ws/m}^3$ is assumed. For the case with HRU, $332\,\text{Ws/m}^3$ is added according to Equation (8) ($\Delta p_{HRU} = 211\,\text{Pa}$). The grey-shaded vertical fields represent the necessary flow rates required to meet indoor air quality categories I to III according to DIN EN 16798-1

TABLE 3: Investigated exemplary measures for insufficient ventilation conditions and the definition of the reference cases (including the assumed boundary conditions).

Nr.	Measure	For reference case	Parameter changes		
0 (A)	Reference case A: natural ventilation 1750 ppm	—	$q_{\text{pers},0}$ =	14.4	$m^3/(h\cdot Per)$
			$x_{\text{natural vent},0}$=	1	
			$\eta_{t,0}$=	0	
			$\varepsilon^{c}_{\exp,0}$=	1	
			$f_{M,0}$=	1	
0 (B)	Reference case B: HVAC without HRU	—	$q_{\text{pers},0}$ =	25.2	$m^3/(h\cdot Per)$
			$P_{\text{SFP},x}$ =	2500	Ws/m^3
			$x_{\text{natural vent},0}$=	0	
			$\eta_{t,0}$=	0	
			$\varepsilon^{c}_{\exp,0}$=	1	
			$f_{M,0}$=	1	
1	Natural ventilation at about 1000 ppm (CO_2)	A	$q_{\text{pers},x}$ =	36	$m^3/(h\cdot Per)$
2	HVAC system without HRU	A, B	$q_{\text{pers},x}$ =	36	$m^3/(h\cdot Per)$
			$P_{\text{SFP},x}$ =	2500	Ws/m^3
			$x_{\text{natural vent},x}$=	0	
3	Exhaust air system	A	$q_{\text{pers},x}$ =	36	$m^3/(h\cdot Per)$
			$P_{\text{SFP},x}$ =	1000	Ws/m^3
4	HVAC system with HRU (class H1)	A, B	$q_{\text{pers},x}$ =	36	$m^3/(h\cdot Per)$
			$P_{\text{SFP},x}$ =	2500	Ws/m^3
			$\eta_{t,x}$=	0.78	
			Δp_{HRU} =	211	Pa
			$x_{\text{natural vent},x}$=	0	
5	Efficient HVAC system with HRU (class H1)	A	$q_{\text{pers},x}$ =	36	$m^3/(h\cdot Per)$
			$P_{\text{SFP},x}$ =	800	Ws/m^3
			$\eta_{t,x}$=	0.78	
			Δp_{HRU} =	211	Pa
			$x_{\text{natural vent},x}$=	0	
6	Mobile HEPA purifier and natural ventilation is increased to reach about 1200 ppm (CO_2)	A, B	$q_{\text{pers},x}$=	25.2	$m^3/(h\cdot Per)$
			$x_{\text{natural vent},0}$=	1 (A)/0 (B)	
			$q_{\text{pers,Filter}}$=	10.8	$m^3/(h\cdot Per)$
			η_{Filter}=	99.995	%
			$P_{\text{SFP,Filter}}$=	180[1]	Ws/m^3
7	HVAC system with recirculation mode and 2 compact filters ISO ePM1 60% [58]	A, B	$q_{\text{pers},x}$ =	25.2	$m^3/(h\cdot Per)$
			$P_{\text{SFP},x}$=	2800	Ws/m^3
			$q_{\text{pers,Filter}}$ =	10.8	$m^3/(h\cdot Per)$
			η_{Filter}=	75	%
			$P_{\text{SFP,Filter}}$ =	2800	Ws/m^3

Table 3: Continued.

Nr.	Measure	For reference case	Parameter changes		
8	HVAC system with displacement ventilation (DV) and HRU (class H1)	A	$q_{pers,x}$ =	36	$m^3/(h{\cdot}Per)$
			$P_{SFP,x}$ =	2500	Ws/m^3
			$x_{natural\ vent,x}$ =	0	
			$\varepsilon_{exp,x}$=	1.7	
			$\eta_{t,x}$=	0.78	
			Δp_{HRU} =	211	Pa
			$x_{natural\ vent,x}$=	0	
9	Hybrid/mixed mode ventilation: additional intermittent window ventilation	B	$q_{pers,x}$ =	36	$m^3/(h{\cdot}Per)$
			$x_{natural\ vent,x}$=	0.5	
10	Hybrid/mixed mode ventilation with HRU (class 1)	A	$q_{pers,x}$ =	36	$m^3/(h{\cdot}Per)$
			$x_{natural\ vent,x}$=	0.5	
			$\eta_{t,x}$=	0.78	
			Δp_{HRU} =	211	Pa

[1]Based on averaging various manufacturer data.

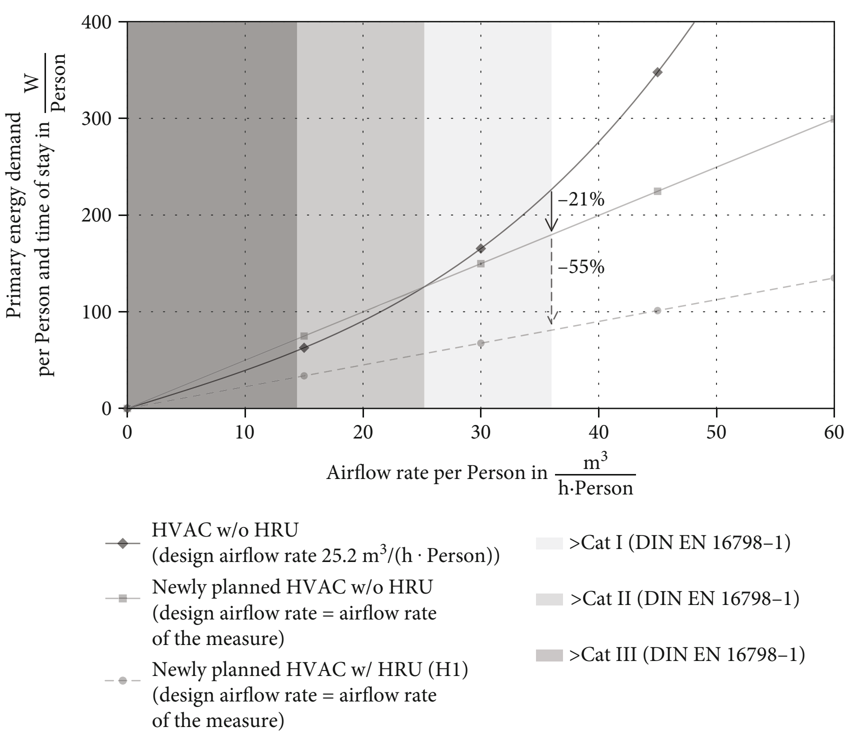

Figure 1: Dependence of the primary energy demand on the outdoor airflow rate; the grey areas mark the supply flow rates of outdoor air to achieve the indoor environment quality categories according to DIN EN 16798-1 [31]; the assumed temperature difference is 10 K.

[31]. In a newly designed system with HRU, where an appropriate P_{SFP} value according to the state of the art (2500 Ws/m^3) is achieved, to fulfill category I, the primary energy demand is approximately 80 Wh per person per hour of occupancy. In a unit without heat recovery, the primary energy demand would be more than twice as high (180 Wh per person per hour). When accounting for lower outdoor air temperatures, the influence of HRU is more significant, which is shown in Figure 2. Assuming an adjustment of the airflow rate in an existing system without HRU (solid black line), the primary energy increases significantly with elevated airflow rates. To achieve category I, the demand

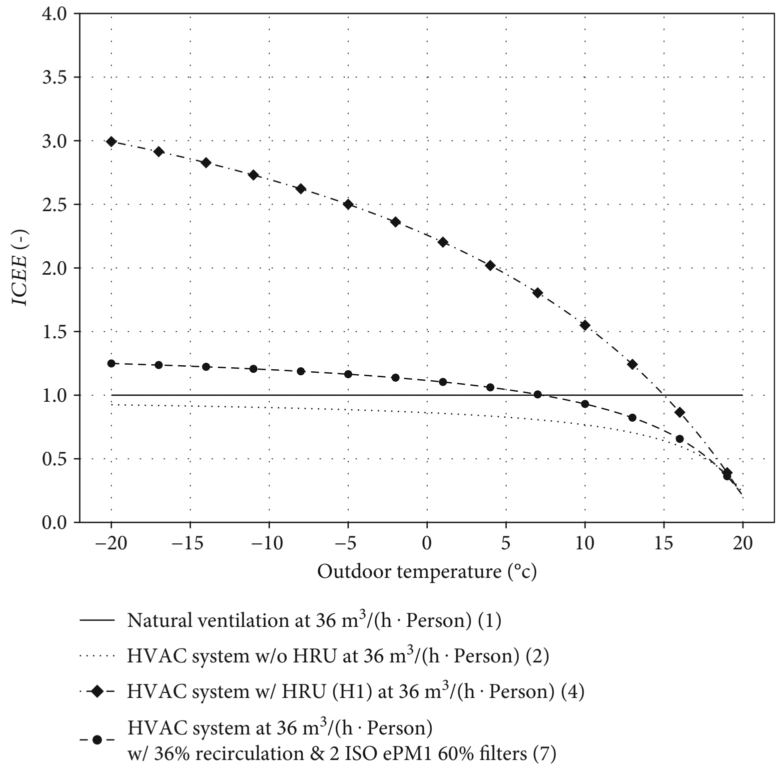

Figure 2: Illustration of the relationship between the ICEE index and the outdoor temperature at an assumed indoor air temperature of 21°C for the selected measures using reference case A (14.4 m^3/h per person naturally ventilated).

would be about 225 Wh per person per hour. Therefore, the solid vertical arrow illustrates the difference in energy need (21% less) when lowering the number of occupants instead of increasing the airflow rate in the existing system. The benefits of lowering the occupancy instead of increasing the airflow rate get even more pronounced at higher person-related airflow rates, lower outdoor air temperatures, and therefore higher temperature differences. The dashed vertical arrow visualizes the energy savings due to the HRU, which is about 55% at the assumed temperature difference of 10 K.

3.2. Comparison of Measures in a Naturally and Mechanically Ventilated Indoor Space. In Figure 3, for reference case A (natural ventilation), the relative indoor air quality IAQ_{rel}, the infection control benefit $R_{S,0}/R_{S,x}$, the energy efficiency $Q_{pers,prim,0}/Q_{pers,prim,x}$, and the calculated metric ICEE are shown separately in this order in different colored bars for each measure. The measures are sorted in ascending order of the ICEE index. For a simplified overview, the grey vertical line marks the value 1 corresponding to the reference case for the parameters indoor air quality, infection control, energy efficiency, and ICEE index.

With regard to the increased natural ventilation (measure 1), the energy requirements, specifically the ventilation heat losses, vary antiproportionally to the enhancements in infection control. This correlation yields an index value of 1. The most efficient measure from the exemplary examined ones is the central HVAC with heat recovery and DV principle. Due to enhanced CRE, the infection control is notably high (more than 4 times higher compared to the reference). With the low power consumption of an efficient ventilation unit and minimal ventilation heat losses through heat recovery, measure 5 exhibits a decrease in primary energy demand compared to the naturally ventilated reference case, although the airflow rate is 2.5 times higher. Hybrid or mixed-mode ventilation enables savings in auxiliary energy demand, making it an efficient solution. Measure 6, which involves a portable recirculating air filter device with low auxiliary energy demand, also shows an ICEE above 1. However, it should be noted that the air quality, as measured by the CO_2 concentration, does not meet the minimum requirements due to the lack of fresh air supply in this case. The same applies to measure 7, where the outdoor airflow rate is only increased to 25.2 m^3/h per person.

Figure 4 presents the outcomes for a selection of potential measures within an existing HVAC system (reference case B at a design airflow rate of 25.2 m^3/h per person). An actual increase in the airflow rate within the system results in an increase in the primary energy demand, negatively impacting the ICEE index. Without HRU, the index descended lower than 1. Incorporation of a heat recovery system (HRU) exerts a positive influence on ventilation heat losses, thereby enhancing the overall scenario and yielding an index above 1. The augmentation of the HVAC system with a mobile air purifier (measure 6) exhibits a comparable value to the measure involving an increased flow rate with HRU. Due to the low energy demand of the purifier, increasing the filtered airflow rate would significantly increase the

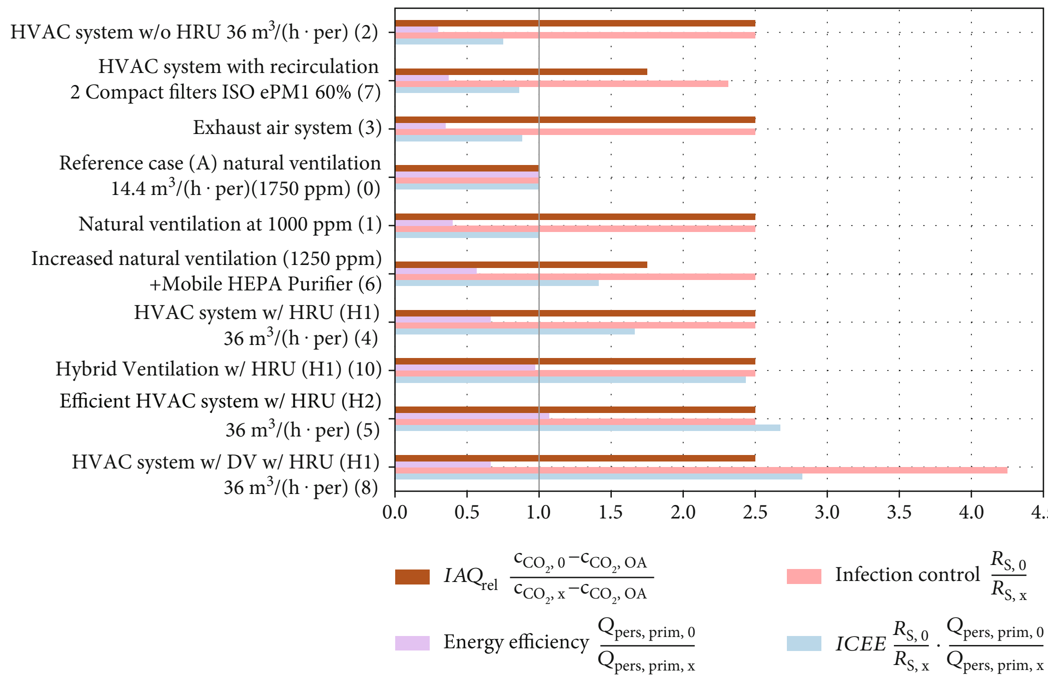

FIGURE 3: Comparison of the selected measures with reference case A in terms of relative indoor air quality (IAQ_{rel}), energy efficiency ($Q_{pers,prim,0}/Q_{pers,prim,x}$), infection control ($R_{S,0}/R_{S,x}$), and Infection Control's Energy Efficiency (ICEE) Index (top to bottom), sorted by ICEE (ascending order), calculated based on primary energy demand; the measure numbers can be seen in the brackets.

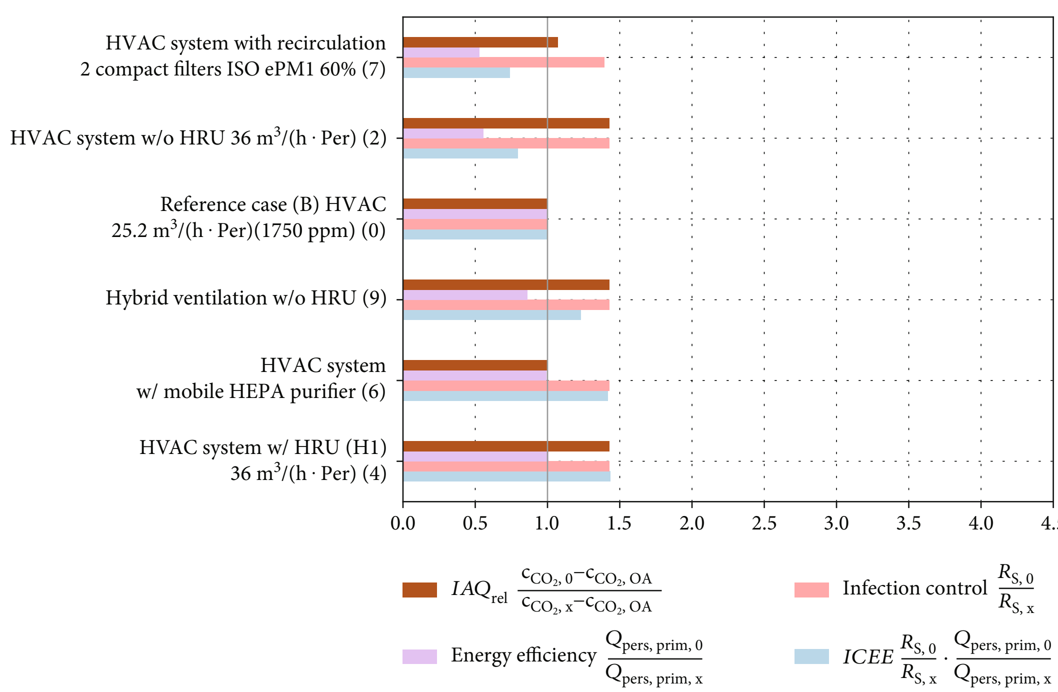

FIGURE 4: Comparison of the selected measures with reference case B in terms of relative indoor air quality (IAQ_{rel}), energy efficiency ($Q_{pers,prim,0}/Q_{pers,prim,x}$), infection control ($R_{S,0}/R_{S,x}$), and Infection Control's Energy Efficiency (ICEE) Index (top to bottom), sorted by ICEE (ascending order), calculated based on primary energy demand; the measure numbers can be seen in the brackets.

ICEE. Nevertheless, in this instance, the CO_2 criterion is not met. Reinforcing the HVAC system with window ventilation (measure 9, hybrid ventilation) also improves the situation.

3.3. Influence of the Outdoor Air Temperature on the ICEE. Examining Figure 2 reveals the relationship between the ICEE index and outdoor air temperature. Reference case A serves as the initial situation for the index calculation. An assumed naturally ventilated increased airflow rate (solid line) results in an index of 1 regardless of the outdoor air temperature, due to the proportional relationship of ventilation heat losses and infection control to the air exchange. As the outdoor temperature decreases, energy savings of the heat recovery measures (4: HRU and 7: recirculation) increase due to reduced ventilation heat losses, consequently yielding a higher index value. Conversely, at higher outdoor air temperatures when heat losses become less relevant, the demand of auxiliary energy of HVAC systems leads to index values below 1 also for the system with HRU, signifying a deterioration of the overall scenario. The comparison of measure 4 (air handling unit with HRU) and measure 7 (air handling unit with 36% recirculated air without additional HRU) shows, based on the significantly higher ICEE index of measure 4, that the use of 100% fresh air with HRU in an air handling unit is more efficient than increasing the recirculated air proportion and filtering it. In addition, the general air quality diminishes with an increase in the recirculation air share.

4. Discussion

The presented index aims to offer a simplified approach for the approximate assessment of measures intended to control airborne pathogen transmission in terms of their effectiveness and energy efficiency. As extensively demonstrated in various studies, the quantity of virus-free supply air is pivotal for ventilation-related infection control [16, 62–64]. The improved exemplary ventilation scenario with 36 m^3/h per person was selected based on the guidelines of WHO [4]. The actual needed airflow rate strongly depends on the virus characteristics itself and the situation. The purpose of the presented study was not to find out appropriate volume flow rates but to develop a methodology to compare different measures and HVAC setups. The energy requirements are contingent upon the used ventilation system and external conditions. Crucial factors are flow rates of outdoor air and filtered air, CRE, and temperature conditions. Through the index, diverse system solutions exemplified in Table 3 could be compared.

The impact of temperature conditions on the index is illustrated in Figure 2. Lower outdoor temperatures accentuate the significance of HRUs for mitigating ventilation-related heat losses. The saved heat losses can substantially offset the increased auxiliary energy demand. With increasing outdoor temperatures and decreasing ventilation heat losses, the auxiliary energy demand of HVAC systems becomes more dominant and leads to index values smaller than 1. This clearly demonstrates the optimization potential by providing support with natural ventilation (hybrid ventilation) at suitable temperatures starting at 15°C (depending on the use case). Nevertheless, given that the airflow in natural ventilation is influenced by the temperature difference between indoors and outdoors, it becomes less dependable as outdoor temperatures rise. Consequently, the anticipated level of air exchange depicted in Figure 2 may not be reliably sustained. Therefore, it is advisable to avoid categorically regarding natural ventilation as the ideal solution in situations characterized by higher outdoor temperatures.

4.1. Interpretation of Measures Evaluation. As evident in Figure 3, when comparing measures 4 and 7, and as depicted in Figure 2, when planning a new system, utilizing filtered recirculated air proves less efficient compared to the utilization of 100% outdoor air coupled with HRUs. HVAC systems employing supply and exhaust fans without HRUs offer only marginal cost-effectiveness [65], rendering this alternative unviable due to the lower ICEE index. When looking at existing HVAC systems, actually increasing the airflow rate within the system showed elevated auxiliary energy demand. A more efficient measure would be adjusting the occupancy in the corresponding indoor environment, as seen in Figure 1. Reducing the number of occupants increases the person-related airflow rate while maintaining the total airflow rate.

In instances of natural ventilation, the air exchange rate remains uncertain without monitoring CO_2 concentration. Especially in the context of hybrid ventilation, comprehensive year-long system simulations are advantageous, given that the efficacy of natural ventilation is contingent upon variable conditions. In practice, the necessity for CO_2 monitoring to enforce set thresholds and estimate fresh air supply is paramount. The calculated index is rooted in assumptions. Measures 9 and 10 assume a 50% reduction in auxiliary energy use [59]. Numerous studies report significant energy savings with hybrid ventilation while maintaining adequate IAQ [60]. The actual savings vary with location and year-round temperature conditions [61]. A comprehensive study by Chenari et al. [60] analyzed global research data and highlighted substantial energy-saving potential through hybrid ventilation. Fan energy savings of up to 90% [66] have been reported depending on the control strategy used. Another study by Ezzeldin and Rees also demonstrated hybrid ventilation or mixed-mode systems achieving energy savings of over 40% [67]. Therefore, especially for hybrid ventilation, a dynamic approach, as mentioned in Section 4.2, is recommended to evaluate the actual energetic benefits.

The demand for DV systems becomes more pertinent as air quality requirements escalate. These systems offer an energy-efficient approach to amplify hygienically effective air exchange rates due to significantly increased CRE, especially at high airflow rates [48]. Decentralized HVAC solutions, where a ventilation unit serves one or only a few rooms proved efficient. Low-pressure losses, the fresh air supply to the room, and reduced heat losses are advantages of these solutions.

If as an initial situation a HVAC system is installed (reference case B), required modifications are less substantial, as air exchange can be guaranteed. Nevertheless, adjustments are recommended to ensure a virus-free air supply of 36 m^3/h per person. As seen in Figure 4, measures involving increased airflow rate within the system yielded lower ICEE index values. This encompasses measures 2 (without HRU) and 7 (recirculation and filtering in the central systems without HRU). The significant rise in auxiliary energy demand is pivotal, here. The incorporation of additional filtration stages in an existing HVAC system can substantially alter system parameters. Particularly, the use of HEPA filters can lead to undesirable reductions in air volume due to increased pressure drops. In most cases, retrofitting HEPA filters for recirculation in an HVAC system is either technically unfeasible or impractical [68]. An increase in airflow rate alongside heat recovery showed a higher index value. The use of mobile air purifiers is justified in cases where an increase in the airflow rate is not possible or linked with considerable energy input. Mobile air purifiers can therefore support the fundamental hygiene offered by an HVAC system [62, 69]. As such, operating points far above the design airflow rate can be avoided. For new designs, a minimum of $36\,m^3/h$ per person (about 950 ppm CO_2) should be attained to enable infection-preventive ventilation [4]. Depending on the context, even higher airflow rates may be necessary.

In naturally ventilated spaces, a mobile air purifier offers a promptly implementable means of elevating virus-free air supply. The calculated ICEE index attests to the efficacy of this measure, although ongoing air quality monitoring (CO_2) remains imperative. The high efficacy of this measure is based on ideal boundary conditions including an appropriate location and airflow rate of the device, resulting in an assumed CRE of 1 for the device. Guidance on the selection and operation of an air purifier is provided in the new ASHRAE Standard 241-2023 [70]. For the mixing ventilation cases in general, the CRE is assumed to be 1 as well. In practice, the CRE varies with boundary conditions, like source location, the position of air inlet and outlet, airflow pattern, and temperatures. Therefore, the range for the CRE in mixing ventilation is about 0.8 to 1.0 [71]. For DV under unfavorable circumstances like supply temperature above room temperature, CRE approaches the value 1.

The WHO recommended a minimum airflow rate of $36\,m^3/(h\cdot person)$ and a maximum CO_2 concentration of 1000 ppm cannot be achieved by all measures. Recirculating air filtration devices increase infection control but improve indoor air quality only to a limited extent. The elevated concentrations are usually accompanied by increased levels of other human-emitted pollutants that affect human comfort (odors/VOCs). These pollutants can be partially removed from indoor air by high-efficiency filtration. However, the assumption that highly efficient filtered indoor air can replace fresh air is not justifiable. In studies, as conducted by Satish et al. [14], it was demonstrated that exposure to elevated concentrations of solely CO_2 without any further emissions caused by humans can lead to reductions in human performance. The CO_2 concentration of indoor air thus remains an important criterion with regard to the evaluation of indoor air, irrespective of the protection against infection.

4.2. Limitations of the Index. Epidemiologically, a differentiation is made between near-field transmission (by droplets or aerosol particles) and far-field transmission (aerosol particles) [72]. In this study, the assessment of infection risk exclusively encompasses far-field transmission attributed to aerosol particles. Particularly, in situations where physical distancing is not maintained, the relevance of short-range transmission becomes pronounced.

From the standpoint of public health, effective pandemic prevention should be designed to minimize the infection risk to an extent that effectively halts or decelerates epidemic progression, thereby achieving reproduction numbers of ≤ 1. For determining absolute reproduction numbers, key infection risk factors are necessary which include the virus-specific emission rate and infection-initiating virus copies, represented by the virus factor.

Guo et al. considered real SARS-CoV-2 data, specified indoor conditions, and identified ventilation rates around or below $60\,m^3/h$ per person as crucial for reducing R_0 [34], showing the significance of high airflow rates. However, pathogens diverge, and numerous variants may evolve during a pandemic. The emission rate is contingent upon the specific pathogen, the individual host, and the host's activity, causing substantial fluctuations concerning the general particle emission rate [16]. Also, the quantity of virus copies necessary for initiating an infection is highly dependent on the pathogen and the individual. Due to these dependent variables, a relative metric was chosen, making the index universal and independent from the virus. Consequently, the index may not provide absolute insights into infection risk, but it facilitates the comparative evaluation of measures under standardized reference conditions. This, in turn, empowers decision-makers to discern and implement the most suitable and effective interventions.

Nontechnical measures such as the wearing of face masks are not exemplified in this study. In the context of assessing the energy efficiency of face mask use, it is important to recognise that the number of masks used over a period of time can substantially impact the embodied primary energy requirement [73], which is not explored in this study. It is worth noting that the index does neither incorporate embodied energy nor investment cost considerations, therefore lacking the capacity to articulate ecologically or economically optimal solutions. Moreover, the fit of the mask highly influences its actual filtration efficiency. For example, the mask factor of an FFP2 mask can exceed 0.1 and be closer to that of a surgical mask (0.6).

The energy demand for air humidification and varying fan efficiencies at different partial load conditions are also neglected in this study. It should also be noted that the study does not take into account cooling requirements, as this is a limited necessity in northern areas. The additional outdoor airflow can potentially be used for cooling purposes when outdoor air temperatures are lower than indoor air temperatures (free cooling) introducing dynamic complexities when considering the cooling scenario. Therefore, the focus of the investigation primarily revolves around the heating and auxiliary energy demand. The cooling energy demand can play a significant role in warm regions. The index can therefore be further expanded by taking into account the annually averaged cooling energy demand.

As seen in Figure 2, ventilation heat losses are dependent on the outdoor air temperature. The consideration of this dependency would enable system simulations. System simulations consider individual boundary conditions and the dynamic course of the year. Therefore, a more exact determination of the index by system simulations, which can additionally consider the cooling energy demand and varying internal heat loads and occupancy patterns, is both feasible and useful. Thus, a more precise annual ICEE index can be determined and serve as an evaluation parameter. However, the presented static investigation aims to provide general statements that are applicable to the majority of the building stock. The exemplary evaluation of selected measures supports the applicability of the index by showing that the most efficient measures matched with the recommended measures by REHVA [9].

Natural ventilation is inherently subject to air exchange uncertainties, and the person-specific volume flow rate values used in the calculations are based on assumptions. Depending on factors such as room size, occupancy density, and external boundary conditions, the actual air exchange rate may vary. Measuring the CO_2 concentration in the room can provide an estimate of the person-related airflow rate. Even if sufficient fresh air can be supplied by means of window ventilation, comfort is likely to be negatively affected (noise, temperature, and draught risk) by unfavorable boundary conditions. Ventilation systems with supply and exhaust air and heating and cooling options, on the other hand, can ensure thermal comfort regardless of the external boundary conditions. In this study, to preserve the simplicity of the index, thermal comfort is not investigated. As natural ventilation is prone to cause thermal discomfort [74], thermal comfort within the index would be an option for further investigation.

5. Conclusions

As the likelihood of occurrence of extreme pandemics, similar to COVID-19, increases in the coming decades [1], energy-efficient infection protection plays a crucial role in designing indoor environments. The index presented provides a first approach to evaluate and compare infection control measures and to assess their energy efficiency through simplified calculations. From this, the most appropriate and efficient solutions can be derived.

The required interventions vary depending on the existing ventilation setup and thermal boundary conditions, influencing the energy perspective. The most effective and efficient solutions can be identified for each individual baseline situation. The index does not account for CO_2 levels of the indoor environment. This was separately considered as IAQ_{rel}, for indicating measures not improving the indoor air quality. The usefulness of implementing IAQ_{rel} within the ICEE index will be discussed in future research.

The index does not allow any absolute statements to be made on the airflow rate required to maintain a defined reproduction number. However, during an infection wave, it is important to maintain the highest possible air quality, even if R_0 cannot be kept lower than 1, and a greater pathogen-free supply air rate causes fewer infections and consequently serves human health. For recommendations concerning airflow rates, in the new ASHRAE Standard 241-2023 [70], minimum equivalent clean airflow per person in the breathing zone is defined for an infection risk management mode of operation (IRMM) for various occupancy categories, reaching from 10 l/s per person (e.g., warehouse) to 45 l/s per person (waiting rooms in health care).

The combination of measures (including ventilation-independent ones) is useful to meet the infection control target with lower energy demand. The analytical energy demand calculations provide approximate annual averages, where the external air temperature is considered an annual mean value. Future research will also consider dynamic system simulations as validation for the analytical calculations making the implementation of thermal comfort within the index reasonable as well.

The index assigns equal importance to infection control and energy efficiency. Studies, such as those by Fisk et al. [27, 35], highlight the advantages related to health, performance, and reduced absenteeism resulting from higher ventilation rates significantly outweigh the associated energy expenses. Future research will aim to establish a more nuanced weighting system for these two factors, allowing infection protection to be given greater emphasis depending on specific circumstances including epidemiological information such as incidence and general virus-specific data.

Thus, this work provides a fundamental basis for further research focusing on finding the right balance between infection control and energy requirements based on individual disease situations. Taking into account weather and energy costs in different indoor environments as well, the control strategy can be highly individualized. This responsiveness should be implemented in codes and standards, as it is necessary to promote human health without neglecting energy needs. The new ASHRAE 241 [70] standard is a good example of the coming importance of high-performance buildings with appropriate infection control. This will also be reflected in policy objectives trying to provide infection control where necessary and energy savings were possible to fulfill global climate policy targets.

The utilization of an integrated index offers numerous advantages in various aspects. It provides valuable insights for the planning of new buildings, retrofitting existing ventilation systems, and establishing guidelines for ventilation standards. The index serves as a comprehensive tool for optimizing ventilation systems, striking a balance between infection prevention and energy efficiency in indoor environments. Thereby, the results of this study have practical implications for building designers and engineers involved in developing effective and sustainable approaches for infection control. Therefore, further economic evaluations should be conducted to provide a comprehensive understanding of the cost-effectiveness of different ventilation measures under various conditions. Such evaluations will help in selecting the most suitable interventions for specific scenarios and benefit reasonable policy targets.

Data Availability

The table data and python codes used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Authors' Contributions

The authors are responsible for the content of the article.

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