Health-Equivalent Energy Efficiency Factor, combined metric of harm and energy use

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ABSTRACT

The inclusion of health-based performance indicators and metrics in ventilation system design and research is a widely discussed topic in recent years. This is due to increased awareness about the health implication of indoor air quality and due to the need for innovative ventilation system control (smart ventilation) to limit building energy use.

The main target of most smart ventilation systems on the market today is limiting the building energy use while maintaining a comfortable indoor environment. The health aspect is therefore often overlooked although it would lead to a dilemma is ventilation system optimization: to what extend does achieving energy saving justify an increase in the concentration levels of unhealthy pollutants?

The rationale behind a new metric is introduced that combines and quantifies the combined performance of energy saving and a harm based metric of a smart ventilation system compared to a chosen reference as the ratio between the energy use indicator of the smart ventilation system and the energy use of the reference line at equal harm: The Health-Equivalent energy efficiency factor. The used reference can be either a pre-defined ventilation concept (e.g. continuous ventilation) or based on energy and health targets.

Eight smart ventilation strategies are modelled, simulated, and analysed and for each, the health-equivalent energy efficiency factor is calculated using two possible references. The first refence-line is defined by the base continuous ventilation system simulated at 10%, 50% and 100% of the nominal flow rate, η_{system}. The second reference-line is a straight line connecting two extreme, theoretical scenarios: (1) which energy use is acceptable for a situation with *no harm* and (2) what is the minimum target of harm for a situation *without any energy use,* η_{linear}.

Based on the results and insights gained while applying the metric, η_{linear} is preferred as it results in more versatile and more widely applicable metric. The application of the metric shows that only one of the smart ventilation systems under investigation is unable to provide health-equivalent indoor air quality energy efficient based on both η_{system} and η_{linear}. The performance of the nominal reference system C (mechanical extract ventilation) is unacceptable based on η_{linear}.

KEYWORDS

Health performance, Energy efficiency, Smart ventilation, Performance-based design

1 INTRODUCTION

The inclusion of health-based performance indicators and metrics in ventilation system design and research is a widely discussed topic in recent years. This is due to increased awareness concerning the health implication of indoor air quality (Morantes et al. 2022; Liu et al. 2023; Asikainen et al. 2016; De Jonge and Laverge 2022) and due to the need for innovative ventilation system control (smart ventilation) to limit building energy use (De Jonge, Ghijsels, and Laverge 2023; Guyot et al. 2019). Recently, also on a legislative level the (public) health implication of indoor air quality, ventilation systems and how they are controlled has gained importance with the topic of health being addressed in the drafts of the EN15665 and EN 16798-1-3 standards, the health based equivalence approach adopted in the ASHRAE 62.2 standard (Sherman, Walker, and Logue 2012) and the explicit inclusion of indoor environmental quality in the new EPBD directive advocating for improving energy efficiency and indoor environmental quality in parallel when buildings are renovated (Council of the European Union - General Secretariat of the Council 2023).

This context creates a need for practical indicators used by Indoor Air Quality (IAQ) management system designers or R&D to be able to decide on optimal solutions with regards to both the energy use and health implication, which are often of conflicting interest (e.g. for continuous airflow ventilation systems, increasing the overall ventilation airflow rates typically lowers the health impact but increases the related energy use). This type of indicator could potentially become part of national implementation of the new EPBD directive or other legislative or standardisation initiatives.

This paper outlines and applies an indicator specifically developed to support the decision making in health-focused IAQ-management system design and control. The results of this paper are part of a larger study that describes a consistent set of indicators that also address other focus points of IAQ-management (e.g. comfort, acute health effects, mold prevention) (De Jonge 2023).

2 HEALT-EQUIVALENT ENERGY EFFICIENCY FACTOR

2.1 Rationale

2.1.1 Health impact indicator

The proposed health impact indicator is the chronic population health effect attributable to the exposure to the indoor air. This impact can be expressed in terms of Disability-Adjusted Life-Years (DALYs), which is a wel known and widely used metric of harm (C. J. Murray 1994; C. J. L. Murray et al. 1996). For this research the health impact indicator was derived from simulated individual exposure concentration data using combined Building Energy Simulation and Indoor Air Quality (BES-IAQ) dynamic simulation and by use of the novel dynamic DALYs concept (De Jonge and Laverge 2022).

Other health effects like acute health effects should be accounted for using acute exposure limits (e.g. AEGL, DNEL). To limit the health effects from exposure to spores from mold, a source control strategy is proposed where mold-growth is prevented. A separate indicator is included in the larger consistent set of indicators to limit this risk (De Jonge 2023) but is not further discussed in this paper.

2.1.2 System energy use indicator

The definition of the energy use indicator depends partly on the methods and models used for the estimation of the performance and consist of the most representative sum of energy use. The proposed method is the use of dynamic combined BES-IAQ dynamic models as they allow for a prediction of the building heating energy use which includes the direct and indirect impact of IAQ-management systems on the building heating energy use as well as dynamic variation of outdoor condition (e.g. higher impact of ventilation on the energy demand when outdoor temperatures are low; higher natural infiltration rates when indoor-outdoor temperature difference are higher; thermal performance of heat exchangers and by-pass systems). The electric fan energy use associated with the air handling unit makes up the second part of the energy use indicator.

2.1.3 Combined metric

For each IAQ-management system, the associated health impact indicator and system energy use indicator can be determined. However, as previously mentioned, two IAQ-management strategies can result in conflicting results where the first solution has a minimal impact on health and a high energy use indicator while the latter has a low associated energy use but a higher impact on health. To aid the decision making in such case, the health-equivalent energy efficiency factor can be determined.

This factor is the ratio between the energy use indicator of the IAQ management strategy and the energy use of the reference line at equal harm.

This concept extends on the approach used in support of the current Belgian EPB legislation that applied a similar method to determine the comfort equivalent energy efficiency for smart ventilation control strategies (Caillou et al. 2014).

2.2 Definition

For a system with relative indicators [E_{sys}, D_{sys}]:

$$\eta = \frac{E_{sys}}{E_{sys,ref}(D_{sys})} \tag{1}$$

With

η	[-]	Health equivalent energy efficiency factor
E_{sys}	[kwh]	System relative energy use indicator value
$E_{sys,ref}(D_{sys})$	[kwh]	Reference relative energy use indicator value for D_{sys}
D_{sys}	[yr]	System relative health indicator value

Figure 1 illustrates how the health-equivalent energy efficiency factor is derived from a plot where energy use indicator is the x-axis and health impact indicator is the y-axis. One IAQ-management strategy shows as one point on the plot.

From an energy-efficiency point of view, systems that lie above their respective reference line should not be allowed to market as its use only contributes negatively to the relative energy efficiency. In other words, they are not pareto-optimal with regards to their reference systems.

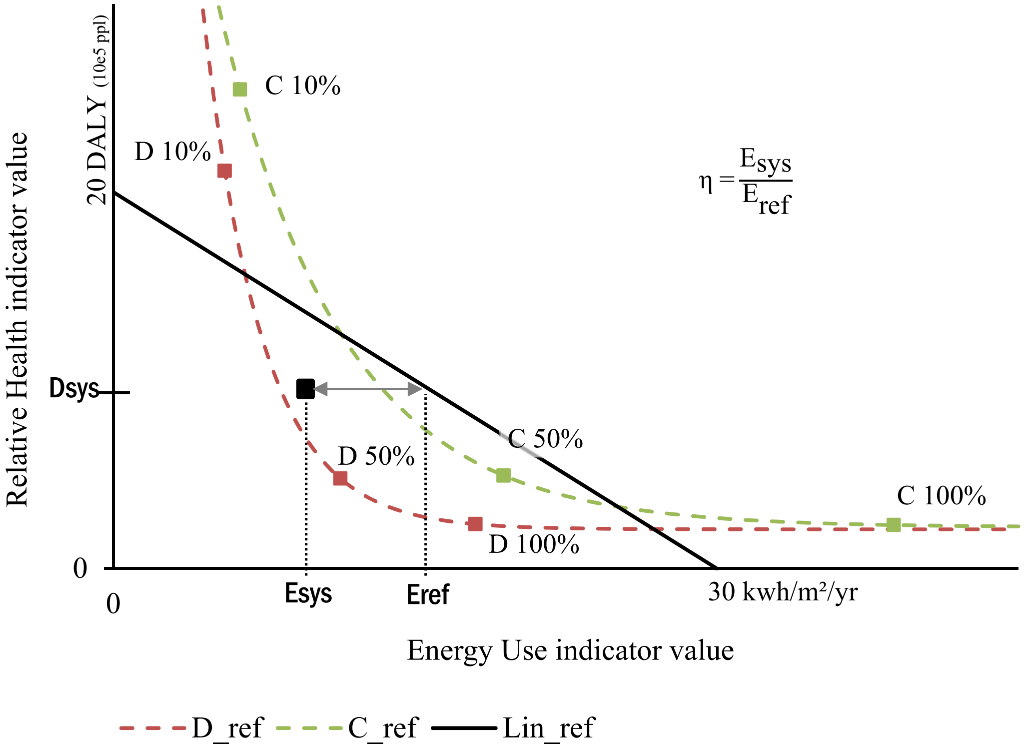

Figure 1 Plot graphically explaining the principle of the health-equivalent energy efficiency factor and the different investigated reference lines. The full line represents a linear reference line based on two target values. The dotted lines represent two reference lines based on simulations of two continuous airflow Belgian standard systems (system C- MEV and system D with heat recovery -MVHR).

2.3 Reference lines

The references show as continuous lines on Figure 1. The choice of reference has an important impact on the results and should be well considered. Two options for the reference lines were investigated and will be discussed:

1. The use of reference IAQ-strategies
2. The use of targets for health-impact and energy use.

2.3.1 Reference systems

In line with the methods for comfort-equivalent energy efficiency factors, the reference line can be based on a reference system (Caillou et al. 2014), η_{system}.

In Belgium the NBN D50-001 describes four types of ventilation systems (BIN 1991). These systems, operated with a continuous and constant airflow rate (without any smart control strategies) can serve as reference systems. The IAQ-strategy under investigation can then be compared to the reference line defined by the ‘standard system’ which is conceptually most alike.

The reference lines shown in Figure 1 (dotted lines) are defined by means of the unique exponential decay function that cross three point: the results for the standard nominal ventilation system C and system D at 100%, 50% and 10% nominal airflow rate.

The used equation is as follows:

$$D_{sys,ref}\left(E_{sys,ref}\right)=Ae^{B\cdot E_{sys,ref}}+C \tag{2}$$

With

$D_{sys,ref}$	[kwh]	Reference system relative health indicator value
$E_{sys,ref}$	[kwh]	Reference system relative energy use indicator value
A, B, C	[varies]	Derived parameters, $A > 0$, $B < 0$ and $C > 0$

Although the installation of a ventilation system is required in Belgium, it is not mandatory for the building users to operate the system at full capacity (100% nominal flow rate). Therefore, these lines represent the actual possible outcomes of the energy-use indicator and the health-impact indicator that can be expected of a standard compliant system.

If the health-equivalent energy efficiency factor is below 1, this indicates that the proposed IAQ-strategy (e.g. a smart control) is more energy-efficient efficient in safe-guarding an indoor air quality achievable by the chosen reference system.

One issue with this approach is that the factor is directly tied to the prescriptive continuous ventilation system legislation (for Belgium: NBN D50-001) and thus, that the performance of the nominal systems is satisfactory, which is not necessarily the case, especially given the age of the standard (1991).

A second issue is that not for each IAQ-management strategy, the 'conceptually most alike system' is clear and requires additional simulations/models and analysis to define the reference line. For smart ventilation systems that do not intervene too much in the design of the system components or expected flow patterns, the choice is clear. But for other IAQ-management strategies like the use of stand-alone aircleaning, the chosen reference could be debated.

A third issue is that because of changing references, the results obtained by means of different reference systems lose the ability to be easily compared.

2.3.2 Targets

An alternative approach that counters the issues raised for the reference system approach is to define only one reference line based on targets for energy efficiency and health impact, η_{linear}. This would yield a truly performance-based approach. Any IAQ-strategy strategy, type of ventilation system, design flow rates applied to the same situation could be compared.

Note that the values set as targets will inherently be coupled with the decision on which pollutants to consider as part of the health-impact indicator and which energy fluxes are included in the energy-use indicator.

The reference line shown in Figure 1 (continuous line) connects a set number DALYs at a theoretical point of zero energy use and a maximum energy use at a theoretical point of 0 DALYs. The points are defined by [0;20] and [30;0]. The second point being the total theoretical maximum energy use of the households set at a target of 30kwh/m^2/yr/household. The first point was derived by setting the maximum allowable harm of IAQ to harm as ± 0.1% of the total burden of disease in Belgium for 2019 (Devleesschauwer, Scohy, and Van Den Borre 2023).

If the health-equivalent energy efficiency factor is below 1, this indicates that the proposed IAQ-strategy (e.g. a smart control) can provide IAQ that meets both targets, and we can state that this is achieved in an acceptably energy efficient manner. As a designer, you can increase the health-equivalent energy efficiency by decreasing the energy use and/or by decreasing the health impact indicator (e.g. source control)

The main issue with this approach is that it requires the definition of the targets which is a matter of (public) debate and (political) decision and touches upon questions like: “what is acceptable risk?” (Morantes et al. 2023).

However, if this is successful, a target driven approach allows to easily compare any technological solution or combination of solutions which makes it the more versatile solution.

3 APPLICATION & RESULTS

To illustrate the developed metric, it is applied to eight smart ventilation systems. Four systems are based on the Belgian standard MEV system (NBN D50-001 – system C). The system airflow rates and other design decisions follow the standard, but the airflow rates are varied between a minimum of 10% and maximum of 100% of the nominal airflow rates according to rule-based controls linked to CO_2, RH and/or presence sensors. Likewise for the other four systems but then based on the Belgian standard MVHR (NBN D50-001 – system D with heat recovery if possible). Table 1 summarizes the different control strategies of the smart ventilation systems. The case-study building is a typical Belgian apartment which has been used for several previous studies on smart ventilation performance in Belgium (Caillou et al. 2014; Laverge and Janssens 2013).

Table 1 Summary of the investigated smart ventilation control strategies

System	**Description/Notable feature**	**Control algorithms**	
		Sensors	**Controls**
C1	Local exhaust only, CO□ only in kitchen	CO2 in kitchen, RH in bathroom and service room, Presence in Toilet	Extract airflow rates vary room-to-room based on the sensor in that room
C2	Local exhaust only, CO□ in all dry spaces	CO2 in kitchen, Living room and bedrooms, RH in bathroom and service room, Presence in Toilet	Extract rates vary room-to-room based on the sensor in that room AND increase of all extract airflow rates based on MAX CO_2 level.
C3	2-zone (bedrooms - living) with additional mechanical exhausts in dry spaces	CO2 in kitchen, Living room and bedrooms, RH in bathroom and service room, Presence in Toilet	Extract rates vary room-to-room based on the sensor in that room (including additional extract points in bedrooms and living). AND MIN CO_2 determines which zone is limited to 10% nominal flowrate.
C4	Automatic trickle vents	CO2 in kitchen, Living room and bedrooms, RH in bathroom and service room, Presence in Toilet	Like C1 but with an automatic control of the trickle-vent opening area based on local CO_2 concentration.
D5	As C1, but with mechanical supply	CO2 in kitchen, RH in bathroom and service room, Presence in Toilet	Extract airflow rates vary room-to-room based on sensor in that room. The supply airflow rates are varied to keep the total supply and total extract airflow rates equal.
D6	1-Zone (P-controller)	CO2 in Living room and bedrooms, RH in kitchen, bathroom, service room and Toilet	MAX RH decides minimum whole house ventilation rate based on a proportional controller AND Supply airflow rates vary room-to-room based on the sensor in that room. Total extract and total supply airflow rates are kept equal.
D7	2-zone (bedrooms - living) nominal supply in dry spaces	CO2 in Living room and bedrooms, RH in kitchen, bathroom, service room and Toilet	MAX RH decides minimum whole house ventilation rate based on a proportional controller AND MAX CO2 decides the supply airflow rates and which zone is supplied. (The other limited to 10%) Total extract and total supply airflow rates are kept equal.
D8	Decentralized supply (no heat recovery)	CO2 in Living room and bedrooms, RH in kitchen, bathroom, service room and Toilet	Extract and Supply airflow rates varied room-to-room based on sensor in that room. Total extract and total supply airflow rates are kept equal.

3.1 Results

The simulations where done using a combination of the open-source IDEAS Modelica library (Jorissen et al. 2018; De Jonge et al. 2021) and proprietary Modelica libraries for airflow modelling and the modelling of sources and sinks of pollutants and moisture buffering. The combination provides a combined model for BES-IAQ simulations. Table 2 includes the results for all eight smart ventilation systems as well as the results for the continuous reference systems at full nominal airflow rate. To acquire the data for each of the tested smart controls, 10 simulations were done with changing households to lower the influence of this parameter on the results (De Jonge, Ghijsels, and Laverge 2023).

Table 2 Energy indicator value, Health indicator value and derived health-equivalent energy efficiency factors for all investigated systems.

System	Energy	Health	η		
			η_{system}		η_{linear}
	kWh/m²	yr/yr		[-]	[-]
C_{nom}	39.8	2.3	C_{nom}	1	1.46
$D_{nom,hr85}$	18.5	2.4	$D_{nom,hr85}$	1	0.68
C1	13.1	7.8	C_{nom}	0.85	0.70
C2	28.8	3.2	C_{nom}	1.11	1.12
C3	14.9	6.7	C_{nom}	0.89	0.73
C4	11.3	8.8	C_{nom}	0.78	0.65
$D5_{hr85}$	7.9	9.1	$D_{nom,hr85}$	0.91	0.47
$D6_{hr85}$	8.4	7.8	$D_{nom,hr85}$	0.90	0.45
$D7_{hr85}$	7.3	10.9	$D_{nom,hr85}$	0.91	0.52
D8	12.3	8.1	-	-	0.67

* $_{hr85}$ indicates that this system includes a heat recover system with a constant efficiency of 85%; $_{nom}$ indicates that it is the nominal system operated at the full nominal airflow rate.

Figure 2 shows the health-equivalent energy efficiency factor for all systems. If the reference system is used to calculate the factor, it is only used to compare with the chosen reference and with systems that use the same reference.

For the system C based ventilation system controls, C4 obtains the best health-equivalent energy efficiency factor while system C2 obtains the worst with a η_{system} reaching above 1. This indicates that the simple control strategy of system C2 is not able to perform better than the prescribed Belgian standard system C.

For the system D based ventilation system controls, D5, D6 and D7 score very much alike with η_{system} equal to 0.91, 0.90 and 0.91 respectively. For system D8, η_{system} could not be calculated as results from a correct reference system that is conceptually close (mechanical supply and extraction without heat recovery) were not available.

If the fixed target approach is used, for all systems a health-equivalent energy efficiency factor can be calculated and can be compared. This illustrates that as this approach can achieve a truly performance-based approach. In case of the target reference approach, the health-equivalent energy efficiency factor combines the performance of the heat recovery and the smart controls.

This also explains why η_{linear} for the smart MVHR systems achieve the best scores. System C2 still performs the worst, it is not capable of energy efficiently providing health equivalent IAQ.

Note that the nominal systems do not obtain an η_{linear} score of 1. Here, for instance, does the nominal reference system C fail the pragmatic limit of $\eta_{linear} > 1$, and thus should not be allowed from a combined health and energy point of view. Nominal system D with heat exchanger, D_{85}, is able to meet the target with η_{linear}=0.68. Here I would like to repeat that the linear target line is shown as an example of a straightforward, possible, approach but that other target points or ‘shapes’ can also be considered.

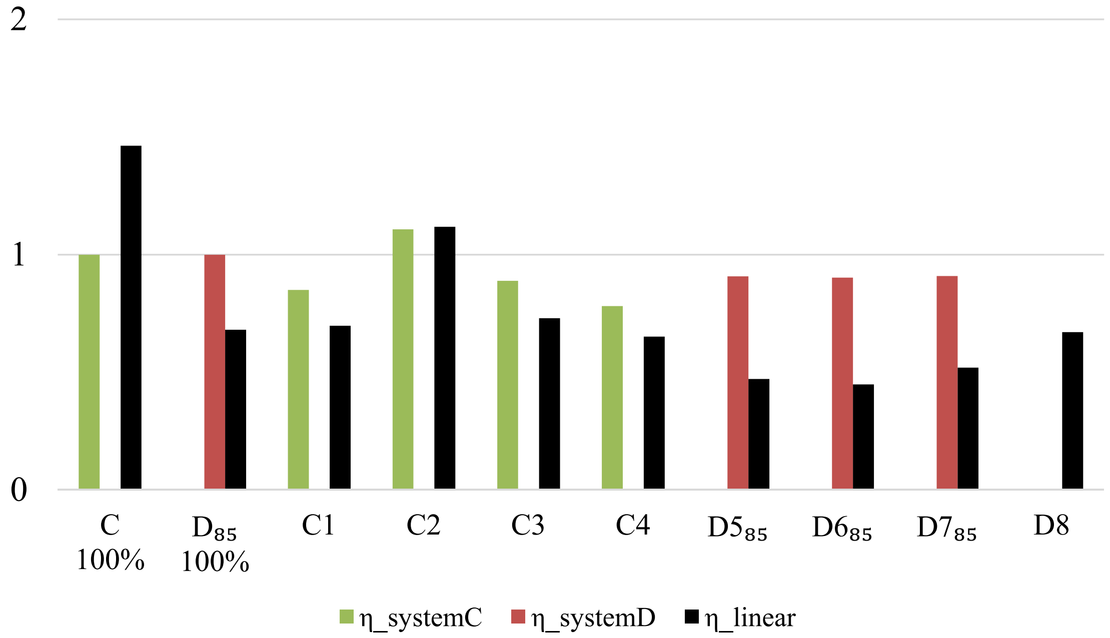

Figure 2 The different available Health-equivalent energy efficiency factors for each smart ventilation system and two reference systems (100%)

4 CONLUSIONS

The health-equivalent energy efficiency factor is a metric developed to combine two indicators for the performance of IAQ-management strategies, namely the system energy use indicator and the health impact indicator into one indicator that can be used to score the overall performance of the system. Two possible methods to come to the proposed metric are described and evaluated. Based on the results and insights gained while applying the metric, the approach where the reference line is defined by means of target values is preferred as it results in more versatile and more widely applicable metric. The application of the metric shows that only one of the smart ventilation systems under investigation is not able to provide health-equivalent indoor air quality energy efficient. The performance of the nominal reference system C would score unsatisfactory for η_{linear}.

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