DEVELOPING SOME NEW EXERGETIC INDICES FOR ASSESSING THE PERFORMANCE OF BUILDINGS

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ABSTRACT

Buildings account for a large part of the yearly energy utilization in modern societies. Within the European Union, the energy utilization by the built environment amounts to more than 40% of the total energy consumption. In this context, for evaluating the whole performance of buildings, various national and international standards as well as energetic indices (or metrics or indicators or indexes) have been developed. In addition, some building performance metrics that can be used by building owners, energy managers, and operators to track the performance of commercial facilities have also been proposed.

In recent years, the concept exergy has become very popular and been considered a very useful tool in the design, analysis and performance assessment of energy-related systems. Among these systems, buildings play a very essential role in terms of the relatively low number of exergetic applications. The present contribution aims at developing some new exergy-based performance assessment indicators for buildings. In this regard, some energy-based indices are given first. Modifying these from the exergetic points of view, new exergy-based ones are then proposed. Finally, an illustrative example of a shopping center is presented while listing some concluding remarks. It may be concluded that the most effective way of assessing the performance of a building seems to apply the low-exergy approach.

Keywords: Buildings, Exergy, Building Performance, Exergy Indice, Exergy Indicator.

INTRODUCTION

Buildings play a very essential role in the EU's energy efficiency policy because about 40% of final energy consumption (and 36% of greenhouse gas emissions) is in houses, offices, shops and other buildings. Moreover, buildings offer the second largest untapped cost effective potential for energy savings after the energy sector (EC, 2012). Since the beginning of the 1990s, the Member States in Europe have dealt with the legal regulations on energy consumption to reduce carbon dioxide emissions, according to Kyoto Protocol. Turkey is also responsible to provide regulations to comply for the latest European Energy Performance of Buildings Directive 2010/31/EC (EC, 2010; Erlalelitepe et al., 2011). Over 55 years, literally hundreds of building energy programs have been developed, enhanced, and are used throughout the building community. The whole-building energy simulation programs are the core tools in the building energy field. These programs provide users with key building performance indicators, such as energy use and demand, temperature, humidity, and costs (Crawley et al., 2005). In measuring building performances, various mathematical calculation models have been utilized. These models include a wide range of studies (i.e., from simplified statistical models to specialized physical simulations) (Schlueter and Thesseling, 2009).

Nowadays, most of analyses in building energy systems are based on the energy conservation principle. The classical exergy analysis method enables to pinpoint the location, to understand the causes of inefficiencies, and to establish the true magnitude of waste and losses. Exergy analysis is, therefore, an important and efficient tool for the design of systems due to providing the designer with answers to two important questions of where and why the losses occur (Costeexergy, 2013).

Exergy may be defined in various ways, as listed in Ref. (Hepbasli, 2012). According to one definition, it is the maximum theoretical useful work (shaft work or electrical work) obtainable as the system is brought into complete thermodynamic equilibrium with the thermodynamic environment while the system interacts with this environment only (Tsatsaronis, 2007). The environmental benefits and economics of energy technologies may also be identified better than energy through exergy. In this context, exergy should be utilized by engineers and scientists, as well as decision and policy makers, involved in green energy and technologies in tandem with other objectives and constraints (Rosen et al., 2008).

In the literature, various attempts have been made towards developing energetic and exergetic indices (or indexes or indicators or metrics) for assessing and comparing the performance of buildings. In this regard, Olofsson et al. (2004) studied on how to rate the energy performance of buildings. They presented a brief review of recent approaches to energy rating while different strategies of setting

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energy efficiency standards were discussed. Entrop et al. (2010) compared the methodologies and accuracies of three Dutch energy performance indicators and applied them to to eight houses. They linearly correlated the actual domestic energy use with the estimated energy consumption given by the energy performance indicators, being 7–25% lower.
Greensfelder et al. (2010) investigated building performance metrics that can be used by building owners, energy managers, and operators to track the performance of commercial facilities. They prepared a report and aimed at clarifying and simplifying the options for promoting market adoption. This report included the methods and findings of this research, a discussion on important topics related to selecting, comparing, and tracking metrics, lists of recommended. As far as exergy-based performance indices are concerned, their number is relatively low compared to the energy-based ones, as will be seen in the following section. The main objectives of the present contribution are twofold, namely (i) to present available exergetic indices for buildings, and (ii) to develop and propose some new ones.

SOME ENERGETIC AND EXERGETIC INDICES FOR BUILDINGS

Baselines and Normalizing the Indexes

Baselines are used to compare a building with internal data sets to understand how the building is performing. This term has been widely used in industry for defining the performance of a building before energy efficient upgrades are established. The main aim behind this is to measure the impact of utility-sponsored projects/programs. In creating the baseline data, past measured performance of a building is considered to understand if building performance is improving, degrading, or constant. For this purpose, historic utility and metric data should be stored for future comparisons. In this regard, properly normalizing the data is very essential for making proper comparisons. In most cases, the only normalization needed will be based on climate, but it may also be necessary to normalize data for changing operational patterns or building physical characteristics (Greensfelder et al., 2010).

In the following, some energy and exergy-related indices used to assess the performance of various buildings are briefly described while their main relations are presented.

Energetic Indices

a) Energy utilization (or use or unit) index (EUI)

This is a widely used metric expressing the total energy consumption for each building. It is defined as the total energy use normalized to the floor area. In other words, each energy type is converted to a common unit (kJ) for comparison and calculation of total energy consumed. The EUI is expressed in kJ/m^2·yr and can be used to compare energy consumption relative to similar building types or to track consumption from year to year in the same building. The EUI is calculated by converting annual consumption of all fuels to kJ and then dividing by the gross square meter of the building. It can be a good indicator of the relative potential for energy savings. A comparatively low EUI indicates less potential for large energy savings. The metric can be studied based on statistical averages, medians, percentiles etc. Analyses with median metrics prove to be successful, because of less sensitivity to individual buildings (Sharp, 1996; Thumann and Younger, 2003; Olofsson et al., 2004).

b) Energy indicators developed for the Netherlands

Three indicators have been used in the Netherlands to express the energy performance of buildings, as listed in Table 1. These indicators are evaluated in MJ/m^2·yr.

Table 1. Various energy performance indices for the Netherlands (Adapted from Entrop et al. (2010)).

Type of energy performance indice	*Relation used*	*Factors*	*Eq. no*
Energy Performance Coefficient for new buildings regulated in 1995	$EPC = \dfrac{E_{total,EPC}}{CF_{EPC}\,(C_1 A_{tgs,EPC} + C_2 A_{tts,EPC})}$	C_1, C_2: numerical correction factor (330 MJ/m^2, 65 MJ/m^2) CF_{EPC}: correction factor to fit past EPC results	(1)
Old Energy Index for existing buildings voluntary proposed in 2000	$EI_{old} = \dfrac{E_{total,EI,old} A_{tts,EI,old} C_3}{C_4 A^2{}_{tts,EI,old} + C_5 E_{total,EI_{old}} + A_{tgs,EI,old}}$	C_3, C_4, C_5: numerical correction factors 0.13, 56 (MJ/m^2), 0.06	(2)
New Energy Index for existing buildings regulated in 2008	$EI_{new} = \dfrac{E_{total,EI,new}}{C_6 A_{tgs,EI,new} + C_7 A_{tts,EI,new} + C_8}$	C_6, C_7, C_8: numerical correction factors 155 (MJ/m^2), 106 (MJ/m^2) and 9560 (MJ).	(3)

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c) Categorizing energy metrics

Within the framework of the building performance tracking project, funded by the California Energy Commission, various building performance metrics were investigated. Based on a comprehensive literature review and phone interviews with professionals from the building controls industry, performance metrics were divided into four categories:, namely (i) basic energy metrics, (ii) advanced energy metrics, (iii) basic system metrics, and (iv) advanced system metrics (Greensfelder et al., 2010).

Table 2 lists some basic energy and system metrics for the whole building. Advanced metrics tables include more detailed metrics, providing a more in-depth picture of building performance. the full list of metrics may be found in Ref. (Greensfelder et al., 2010).

Table 2. Some basic energy and system metrics for the whole building (Adapted from Greensfelder et al. (2010)).

Type of metric	*Sub-system*	*Metric (Indicator)*	*Units*
Basic energy	NA	Energy use	$kJ/m^2 \cdot yr$
		Energy use	$kJ/annual\ operating\ hours \cdot m^2 \cdot yr$
	Electric	Energy use	$kWh/m^2 \cdot yr$
	Gas	Energy use	$kJ/m^2 \cdot yr$ or $therms/m^2 \cdot yr$
	Electric	Utility cost	$\$/m^2 \cdot yr$
	Gas	Utility cost	$\$/m^2 \cdot yr$
Basic system	NA	**%** Hours uncomfortable	% hours outside of space temperature range
		Comfort index	Average comfort index (0-100)

Basic energy metrics: These utilize *the* whole building utility meter data and are relatively easy to track, and should be tracked by all buildings.

Advanced energy metrics: These utilize *the* whole building utility meter data, but require more advanced analysis than basic energy metrics, or metrics that require additional meters beyond whole building energy use meters.

Basic system metrics: These utilize existing points from the building automation system (BAS) or maintenance management system while they are relatively easy to track.
Advanced system metrics: These require additional points to be added to the BAS or maintenance management system while this category also includes metrics that use both meter data and BAS data.

d) Primary energy ratio

The primary energy ratio (PER) is defined as the ratio of delivered useful energy (thermal, electric, mechanic) to the supplied primary fossil energy (derived from natural gas, fuel oil or coal), as expressed below (Gonçalves et al., 2013):

$$PER = \frac{Q_{heating}}{E_{primary}} \tag{4}$$

where $Q_{heating}$ is the heating load.

e) Building energy index

The building energy index (BEI) was developed by McLean et al. (2011) as an overall performance indicator for building design strategy. It consists of the climate related and climate unrelated energy loads, which are respectively derived from the climate energy index (CEI) and benchmark data for nonspace conditioning energy uses. The CEI is calculated based on psychrometric chart. It calculates the energy required to condition any weather hourly ordinate to the nearest boundary of a human comfort zone and operates on a unitary air flow. The BEI may be obtained from (McLean et al., 2011)

$$BEI = \frac{CEI\ [(kWh/yr)/(m^3/h)]\ \dot{V}_{bd}\ [m^3/h]}{A_{floor}\ [m^2]} + NBL\ [kWh/m^2 yr] \tag{5}$$

where $\dot{V}_{bd}$ is the building design airflow rate and NBL is the normalized benchmark load for actual occupancy hours (normalized non-space conditioning benchmark load).

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f) Normalized performance indice

The normalized performance indice (NPI) is defined as the ratio of the annual building energy use to the floor area. Two separate indices are calculated; one for electricity and the other for fossil fuels while additionally, CO_2 and cost performance indexes are used. The NPI is also normalised for weather and exposure, indicating the actual performance of the building (Canbay et al., 2004). For example, performance assessment (yardstick) for fossil fuels and electricity in the supermarkets are given as follows: Fossil fuels: <160, 160–290 and >290 Electricity: < 670, 670–920 and >920 for low, medium and high consumptions in kWh/m^2 (EEO, 1994).

Exergetic Indices

Exergy analysis has the potential to optimize building energy demand, since exergy consumption can, to a certain extent, be minimized. As an initial step of exergy application for building design, a reference environment of buildings needs to be properly defined (Sakulpipatsin, 2009).

a) Total exergy system efficiency index

This is defined as the ratio of the exergy demand of the room to the total exergy load of the room as follows, while its detailed calculation has been given in more detail elsewhere (Schlueter and Thesseling, 2009):

$$\varepsilon_{system} = \frac{Ex_{room}}{Ex_{total}} \tag{6}$$

In other words, dividing the remaining exergy that leaves the room through the envelope by the total exergy load of the room results in an exergy system efficiency index. It displays the ratio of exergy that is actually used to heat the room. The exergy demand of the room is estimated by multiplying the heat demand with the quality factor of the room. The quality factor is estimated by the Carnot efficiency using the outside and inside temperature of the room. The total exergy load indicates the total amount of exergy necessary to supply the building and depends on building construction, geometry and system selection. Optimization can be achieved by balancing between these three different fields (Schlueter and Thesseling, 2009).

b) Primary exergy ratio

This is defined as the useful exergy demand rate (exergy heat demand rate at room) to the primary exergy input rate, as given below (Gonçalves et al., 2013):

$$PExR = \frac{\dot{E}x_{room}}{\dot{E}x_{primary}} \tag{7}$$

c) Exergy flexibility factor

It is defined as the ratio of the exergy demand of the heating subsystem (i.e., radiator, direct electric heating, wall heating, radiating heating, slab heating) to the total exergy input of the building, as given below:

$$ExF = \frac{\dot{E}x_{HS}}{\dot{E}x_{total,building}} \tag{8}$$

which expresses the possibility of replacing a given subsystem by any other subsystem. The flexibility factor elaborates on the notion that not all subsystems are appropriate for meeting all types of exergy demand while it changes between zero and one. A relatively large flexibility factor expresses a higher ability of a system to operate with a broader range of energy sources (Sakulpipatsin et al., 2006; Hepbasli, 2012):

d) Exergy index of sustainability

This index (ExSI) is calculated in terms of exergy index of renewability (α_{ex}), which is defined as the ratio of the annual solar exergy on the building footprint to the total annualized exergy lost due to the building construction and operation as follows (El Shenawy and Zmeureanu, 2013):

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$$ExSI = \frac{100}{1+\exp\,[-\lambda.(\alpha_{ex}-50)]} \tag{9}$$

with

$$\alpha_{ex} = \frac{Annual\ available\ solar\ exergy}{Annual\ exergy\ lost}.100 \tag{10}$$

In the α_{ex} approach, the exergy efficiency of 100% of harvesting the solar exergy is considered. However, the theoretical potential is reduced by losses associated with the conversion from the primary source to the secondary resource. The value of parameter λ in Eq. (9) indicates the strength of the policy implemented for achieving sustainability in the building sector; this parameter determines the slope and spread for the relationship between the sustainability index ExSI and the renewability index α_{ex}. The value of λ, between 0 and 1, is set by the developer of rating scale based on local or national goals, market penetration of technologies and shareholders surveys. The proposed rating scale assesses the building sustainability in five categories in terms of the ExSI as follows: Sustainable (96%≤ ExSI ≤100%), exergy efficient (75%≤ ExSI ≤96%), average exergy efficient (25% ≤ExSI≤75%), less than average exergy efficient (4% ≤ExSI ≤25%), and unsustainable (0% ≤ExSI ≤4%) (El Shenawy and Zmeureanu, 2013).

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As can be seen from the developed and proposed exergy based-indices, the exergy load of the room is considered and this is compared to the whole building exergy load or the heating sub-system`s exergy rate. As far as the EXSI is concerned, there exists a categorization. In terms of energy-based indices, yearly energy utilization (fuel or electrical) or energy cost is compared to the building floor area.

In this context, there may be various ways of developing new exergetic indices. One way would be to modify some energy-based indices and hence to proposed the corresponding exergy-based ones. So, specific exergy utilization index (SExUI) may be defined for fuel and electricity as follows:

$$SExUI_{fuel} = \frac{Ex_{yr,\,fuel}}{A_{building}} \tag{11a}$$

$$SExUI_{elec} = \frac{Ex_{yr,elec}}{A_{building}} = \frac{E_{yr,elec}}{A_{building}} \tag{11b}$$

where $Ex_{yr,\,fuel}$ is exergy of the yearly fuel consumption in kJ/yr. The exergy (or chemical exergy) of fuel should be calculated. Based approximation method for fuel chemical exergy, the following relations are widely used (Hepbasli, 2008).

$$\beta_{LHV} = \frac{Ex_{CH}}{LHV} \tag{12}$$

$$\beta_{HHV} = \frac{Ex_{CH}}{HHV} \tag{13}$$

where β is the proportionality constant (or quality factor or exergy coefficient), while LHV and HHV denote the lower heating (net caloric) and higher heating (gross caloric) values, respectively. Because electrical energy is not affected by ambient conditions, it is equivalent in work and can be treated as totally convertible to work. Exergy content of electricity equals its energy content (Hepbasli, 2008). Table 3 lists typical chemical exergy content of some fuels (Kotas,1995; Ayres, 2005; Hepbasli, 2008).

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Table 3. Typical chemical exergy content of some fuels
(Adapted from Refs. (Kotas,1995; Ayres, 2005; Hepbasli, 2008)).

Type of fuel	β_{LHV} (Ayres, 2005)	β_{LHV} (Kotas, 1995)
Coal	1.088	
Different types of coal		1.06-1.10
Different fuel oils and petrol		1.04-1.08
Coke	1.06	1.05
Fuel oil	1.073	
Natural gas	1.04	1.04±0.5%
Diesel fuel	1.07	
Fuelwood	1.15	
Wood		1.15-1.30
Geothermal	β_{HHV}=0.29	

Fuel and electricity utilization may be combined under the term of the normalized SExUI (NSExUI) as follows:

$$NSExUI = \frac{Ex_{yr,\,fuel} + Ex_{yr,elec}}{A_{building}} \tag{14}$$

An Illustrative Example

In the following, an illustrative example of a shopping center in Izmir, Turkey is presented to indicate how the proposed NSExUI will be applied to this center. One should note that the values given here are taken from Canbay et al. (2004) and have not been updated.

Total energy consumption (kWh)	2,958,216 for LPG	4,363,104 for electricity
Normalized energy use (kWh)	3,918,688	6,735,929
Floor area (m^2)	16,000	16,000
NPI (kWh/m^2)	245	421

In this regard, the performance of the shopping center considered is assessed using the NPI values of 245 and 421 kWh/m^2 based on the yardsticks given earlier. As a result, the building electricity and fossil fuel (LPG) consumption values are defined to be *medium level* and *low level*, respectively.

Using Eqs. (11a) and (14), and taking β = 1.04 from Table 3, the values for the SExUI and NSExUI are calculated to be 254.71 and 675.71 kWh/m^2, respectively. The SExUI value seems to be very close to the NPI. As expected, this is due to the factor of β = 1.04. To make a comparison between various buildings, this may be utilized, but one also should consider a categorization in terms of various levels, such as low, medium and high levels, by producing different yardsticks (comparative reference values). This needs a detailed work to determine them. There may also be another approach to determining yardsticks. For example, the values of the exergy-based indicators may be scored with various percentage values while they may be transformed to the scale of 0 to 10.

CONCLUSIONS

Performance indices give a measure of the energy/exergy utilization of a building, which can be compared to various energy and exergy-based yardsticks. They can present the potential for possible improvements while they can also be used to indicate progress over the time. These indices enable us to compare buildings in a group or estate.

We have reviewed various energy and exergy-based indices for evaluating the performance of buildings in this study. We have also developed and proposed two exergy-based indices.

We can extract the following concluding remarks from this study:

a) The number of energy-based indices is higher than that of the exergy-based ones.
b) Some countries have developed energy-based indicators by considering their own needs. For similar buildings operated under similar conditions to decide which building is more ‘low-energy’ than another building is less difficult. To generalize these for other countries, a normalization is needed by considering various factors, such as weather, exposure.

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c) The proposed exergetic indices here may also be combined with exergetic prices of various energy sources and CO_2-emissions.
d) Considering some exergy-based concepts, such as exergy audit (Yasni and Carrington, 1988) and low exergy (Hepbasli, 2012), exergy management and becoming an increasingly important aspect of exergy, one should develop more exergy-based indices.
e) As highlighted elsewhere (Hepbasli, 2012), the concept of energy active buildings may be extended and improved through the concept of the exergy active building. In this context, it is recommended that Leadership in Energy, Exergy & Environmental Design (LEExED) could be established by modifying Leadership in Energy & Environmental Design (LEED).
f) The most effective way of assessing the performance of a building seems to apply the low-exergy approach and to utilize low-exergy based indices because all the building components are assessed from the primary energy production to the building envelope.

NOMENCLATURE

A	area, m^2
BEI	building energy index, $kWh/m^2\cdot yr$
C	numerical correction factor, MJ/m^2
CF	correction factor,-
E	characteristic yearly energy use of the house (or building), MJ/yr
EI	climate energy index, (kWh/yr)/(m^3/h)
EPC	energy performance coefficient, $MJ/m^2\cdot yr$
Ex	exergy amount, kJ
ExF	exergy flexibility factor,-
ExSI	exergy index of sustainability, -
EUI	energy utilization (or use or unit) index, $kJ/m^2\cdot yr$
HHV	higher heating value, kJ/kg
HV	heating value, kJ/kg
LHV	lower heating value, kJ/kg
NBL	normalized benchmark load for actual occupancy hour, $kJ/m^2\cdot yr$
NSExUI	normalized specific exergy utilization index, $kJ//m^2\cdot yr$
PER	primary energy ratio, -
PExR	primary exergy ratio, -
Q	heating load, kJ
SExUI	specific exergy utilization index, $kJ//m^2\cdot yr$
$\dot{V}$	volumetric air flow rate, m^3/h

Greek Letters

α	index of renewability, -
β	proportionality constant or quality factor or exergy coefficient, -
ε	exergy efficiency, -

Subscripts

bd	building design
CH	chemical
EI	energy index
elec	electrical
EPC	energy performance coefficient
ex	exergy
HHV	higher heating value
HS	heating system
LHV	lower heating value
tgs	total ground surface
tts	total thermal transmission surface
yr	year

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