



Improving Sustainability Concept in Developing Countries

Green Retrofitability Index (GRI) as an Indicator for Decision-Makers in Green Retrofitting Projects

Karim M. Ayyad^{a*}, Ahmed A. Fekry^b

^aAssociate Lecturer, Dept. of Architecture, Faculty of Engineering, Modern Sciences and Arts University, 6th of October City 12564, Egypt,
PhD Candidate, Dept. of Architecture, Faculty of Engineering, Cairo University, Cairo 12613, Egypt

^bProfessor of Green Architecture, Department of Architecture, Faculty of Engineering, Cairo University, Cairo 12613, Egypt

Abstract

Most green retrofitting efforts adopt case-by-case studies to evaluate retrofitting projects and the economic feasibility of greening a given existing building. These case-by-case studies can only be done by well-informed and well-trained architects or practitioners, and do not give a whole image that can help the decision-maker decide which building to green in a set of alternatives, hindering the spread of green retrofitting. A comprehensive framework with a standard reference index that can be easily computed for each building can help create an updatable database for existing buildings in each town/city, allowing owners, investors and decision-makers to evaluate the different alternatives themselves. This paper addresses the problem by presenting the suggested GRI reference index that can be used in the green retrofit decision-making process, and presents the different factors that affect it and how they can be computed.

© 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of IEREK, International experts for Research Enrichment and Knowledge Exchange

Keywords: Green Retrofitability; Retrofits; GRI; Existing Buildings; Sustainability Indices

1. Introduction

With the green building movement on the rise for the third decade, research interest in greening existing buildings has been also increasing. Existing buildings still consume up to an average of 40 per cent of total energy consumption in today's world. Thus, it is essential to study the process of greening and the different available protocols to achieve it. Studies have been focused mainly on economic benefits of green retrofitting, and on the

* Corresponding author. Tel.: +20-100-999-1089; fax: none.
E-mail address: kayyad@msa.eun.eg

social/organizational involvement in the process. However, less attention has been given to standardization of the process itself. Studies in the field have been conducted by both individual scientists and organizations working in the field. Some of these organizations are national but have global credibility, such as; the United States DOE, USGBC, and RMI, while others are international bodies such as; UNEP, WGBC, BPIE and WBCSD.

With respect to the denomination of economic benefits, research has started as early as 1994, when Joseph Romm from the U.S. DOE and William D. Browning from RMI conducted a study that has been cited by numerous studies in the field of green retrofitting afterwards, concluding that green retrofitting of existing buildings can have 'substantial' economic returns¹. Afterwards, several scientists and corporations have researched the various economic issues related to green retrofitting. Breslau of Jones Lang LaSalle and CoreNet Global has also conducted a survey in real estate market in the U.S. proving that demand for greening existing buildings exceeds supply, which presents a good investment opportunity². Pike Research based in Boulder, Colorado, estimates that the 2009 market for major green renovations in the United States is \$2.1 billion a year and will grow to over \$6 billion a year by 2013³. Another 2009 study also proved that green retrofitting of an existing building would also increase its capital value by 16%⁴. Olgay and Seruto (2010) found that existing buildings in the U.S. were being retrofitted at a rate of 2.2%, with an average energy saving from these retrofits reaching approximately 11%⁵. In 2010, Durmus-Pedini and Ashuri of the University of Georgia have conducted research addressing the benefits and risk factors of greening existing buildings. They have concluded that greening existing buildings benefits exceed risks, and that those risks can be easily managed⁶. Globally, several bodies have been conducting research about the economics of green retrofitting since the late 2000s. According to the World Business Council on Sustainable Development (WBCSD), energy savings of 10% can be reached with an investment of less than \$1/square foot [= \$10.76/sq.m.] in greening existing buildings⁶.

Studies concerned with the social/organizational aspects of green retrofitting, followed later. A 2011 study by Britnell and Dixon, for the Retrofit2050 program in the UK, surveyed the factors that shape current and future retrofitting activities. The study found that the key trigger to advance the retrofit agenda would be achieving financial gain from undertaking retrofit measures, followed closely by legislation and tax incentives⁸.

Other individual studies elaborated on LEED-EB and LEED-EBOM (LEED-Existing Buildings: Operations & Maintenance), investigating the economic and organizational aspects for the application of LEED-EB such as the work of Dirksen and McGowan of MIT, titled 'Greening Existing Buildings with LEED-EB'⁹. The study concluded that LEED-EB can be very useful for Class-A commercial buildings' owners, while it is still not attractive enough for their Class-B counterparts. In 2009, Delp, Stewart and Appelbaum of UCLA Institute for Research on Labour and Employment conducted a study that recommends green retrofits based on LEED-EB as a way to provide green, safe, jobs¹⁰. In 2012, Nils Kok, Norman G. Miller, and Peter Morris conducted a study to assess the market performance of LEED-EB certified buildings and the results indicated that investments in green retrofits are incorporated by the market and are economically viable¹¹.

The third and least-studied denomination is the standardization of the green retrofitting process. Such research was conducted by USGBC for the formulation of LEED-EB certification and the LEED-EBOM. Since then, very little work has been done in this denomination until April 2015, when Michael Bendewald, Douglas Miller and Scott Muldavin of RMI released, 'How to Calculate and Present Deep Retrofit Value: A Guide for Investors' in April 2015¹². It presents a way to calculate the deep value of the retrofitting process, making the decision easier for the investor.

As a further step in the denomination of standardization of the greening process, this work presents the Green Retrofitability Index (GRI) as an indicator for evaluating different alternatives for greening a set of buildings. The paper discusses the different possible factors that can affect the GRI value and hence suggests the formula to compute it. The study then tests the theoretic credibility of the formula on a set of buildings to assess its results and benefits for the decision-making process.

Nomenclature

BPIE	Building Performance Institute Europe
CBECs	Commercial Buildings Energy Consumption Survey
DDH	Discomfort Degree Hours
DOE	United States Department of Energy
DRV	Deep Retrofit Value
EPA	United States Environmental Protection Agency
EPI	Energy Performance Index
GRI	Green Retrofitability Index
LEED	Leadership in Energy and Environmental Design
RMI	Rocky Mountain Institute
UNDP	United Nations Development Program
UNEP	United Nations Environmental Program
USGBC	United States Green Building Council
WGBC	World Green Building Council
WBCSD	World Business Council on Sustainable Development
WHO	World Health Organization

2. Green Retrofitability and GRI

Green ‘retrofitability’ is a new term that means the relative attractiveness of the building to be greened. Before the formulation of this term, it has been referred to with terms like; ‘ability to retrofit’³, ‘the building’s energy renovation potential’¹³, or ‘applicability, level of benefit, and terms’¹². The term green retrofitability indicates the building status with respect to the issue of retrofitting, taking into consideration the technical and economic factors.

The GRI reference index is a new indicator suggested by this study to give a picture of any given building’s green retrofitability. It encompasses all the factors that encourage or discourage greening. It is important here to note that, by definition, buildings that are non-green will have a higher GRI value than their greener counterparts. That is to say, buildings with worse environmental performance will have a higher GRI value than those with the same conditions except environmental performance. That is because GRI is concerned with ‘attractiveness’ of the building to be greened, which pre-requires that the building is not green in the beginning.

3. Factors affecting green retrofitability

In order to be able to generate a formula to compute the GRI, the factors affecting a building’s green retrofitability have to be analyzed and evaluated. Similar factors were reflected in recent studies to appraise potential greening projects. The BPIE stated that the main steps for appraising green retrofitting projects are;

- Building stock analysis¹³;
- Cost effectiveness appraisal of renovation options;
- Quantification of energy saving potential;
- Development of a long-term investment horizon; and;
- Quantification of other benefits.

The RMI has also populated the components affecting the Deep Retrofit Value (DRV) as follows¹²;

- Retrofit costs;
- Development costs/taxes;
- Energy cost savings;
- Non-energy opex;

- Tenant-based revenues; and;
- Sale Proceeds.

The factors affecting green retrofitability have much in common with these ones. They cover issues like the need to retrofit, the feasibility of retrofitting, and relative attractiveness compared to other buildings. They are populated as follows:

- Building market value;
- Building age/lifetime;
- Building performance, with its main components;
 - Building envelope performance;
 - Energy consumption rate; and;
 - Water consumption rate
- Occupancy;
- Retrofitting cost; and;
- Built-up area.

These factors have direct effects on the building's retrofitability; therefore they must be analyzed and quantified in order to be computed in one formula to produce an indicative number. They are discussed in the following sections;

3.1. *Building market value*

Buildings with higher market values, given that they are equal to their comparable counterparts with respect to the other factors, are more attractive for greening as the process will help keep and maintain their capital values. Greening the buildings with the highest market value will increase their lifetime and keep them as valuable assets for the community and their respective owners. Moreover, greening an existing building is an investment that consumes a considerable amount of money, therefore it is not advisable to green a building with an amount of money that is already too big compared to the initial market value of the building. Hence, green retrofitability and market value are directly proportional. The value is expressed in the equation in USD as to standardize the calculation of GRI globally. The median residential square meter price varies greatly from one country to another. In the United States the average city center apartment cost around \$18,500/sq.m., while in Canada it costs around \$8,288/sq.m.¹³ (2014 estimates). In Europe, prices vary from €24,000/sq.m. (= \$26,280/sq.m., Oct. 2015 exchange rate) in Monaco to €944/sq.m. (= \$1,033/sq.m., Oct. 2015 exchange rate) in Moldova¹⁴ (2014 estimates). In developing countries, prices are much lower. A median of \$500/sq.m. is taken as a reference value in the calculation of GRI.

3.2. *Building age/lifetime*

If an existing building is near the end of its lifetime, then it is not very attractive for green retrofitting. The feasibility of the greening decision will be low, as there is only little time to gain the benefits of the project for that building, even though green retrofitting can help elongate building lifetime to a certain extent. However, building age must be compared to the building estimated lifetime in order to get the complete picture. Buildings with longer time remaining in their expected lifetime are more attractive for greening given that they are equal to their comparable counterparts in the other factors. Therefore, green retrofitability and building age -with respect to its estimated lifetime- are inversely proportional.

Based on analysis of data from Commercial Buildings Energy Consumption Survey (CBECS), the median building lifetime value ranges from 65 to 80 years depending on the type of building¹⁵. The actual life of a given building will typically depend on a number of factors, including the type of building (e.g., retail, office, single-family), physical characteristics of building materials, exposure to weathering, maintenance regime, and frequency of use. In addition, the behavior of building owners will play a role in determining the life of a building. In the GRI formula, elapsed building age with respect to the estimated lifetime is represented as Y/L , where Y is the building age in years and L is its expected lifetime in years as well.

3.3. Building performance

Building performance is a main issue when addressing green retrofitability, as the main goal of green retrofitting is to enhance building performance to the ‘green’ level. Green building rating systems have been developed worldwide to rate buildings according to their environmental performance and consciousness. However, the complexity of measuring building performance hinders the spreading of greening efforts. Moreover, in some cases it was reported that some LEED-certified buildings performed worse than non-green buildings⁶. Instead, measuring building performance can be simplified by measuring how successful the building design and envelope performance are in reducing resource consumption rates. That is because a building with advanced building envelope and advanced systems incorporated into its design can greatly help reduce the consumption of resources like energy and water, while at the same time provide a productive environment for occupants with minimum user intervention. These parameters will be discussed in the following sections.

3.3.1. Building envelope performance

A building envelope is the medium that controls the relationship between the building and its surrounding environment, with all its factors such as temperature, wind, humidity, sunlight, pollution, view and others. The design of the building envelope and its materials greatly shape its performance, and hence its influence on the indoor environment of the building. In general, the poorer the building envelope performance is, the more attractive it is for green retrofitting. That is to say, GRI is inversely proportional with building envelope performance. However building envelope performance evaluation depends on the evaluation of several parameters, such as; internal air temperature (T_{air}), internal surface temperatures (T_{Si}), discomfort degree hours (DDH), and Cooling/heating loads¹⁶. Such parameters are very versatile during both the year and hours of the day, let alone the big number of spaces of different areas that exist in the given building, which would be too complex to compute in the GRI calculation. Instead, the factors on which building envelope performance depends are considered in order to facilitate the evaluation of building envelope performance. These factors are discussed in the following points.

3.3.1.1. Average U-value

The average U-value is the overall heat transfer coefficient of the building envelope with respect to thermal energy moving into or out of the building, or the area-weighted average U-value of all exposed elements of the building¹⁶. Exposed elements include walls, roofs, floors, windows and doors that are prone to outdoor conditions. According to Elessawy and Maserà, it can be calculated statistically by computing the area-weighted average u-value of the different spaces using the following formula¹⁶;

$$U_{avg} = \frac{\sum UA}{\sum A} \quad (1)$$

It can also be calculated by dividing the total rate of heat loss/gain per degree Kelvin on the total external surface area of the building envelope. It is measured in W/m^2K , according to the following formula¹⁷;

$$U_{avg} = \frac{\text{Total rate of heat loss or gain per degree}}{\text{Total external surface area}} \quad (2)$$

Since the U-value represents the heat transmittance into and out of the building, the higher it gets means that the building has less ability to resist outside weather conditions and maintain a comfortable indoor environment for occupants. Hence, it is generally correct to say that a building with higher U-value is more attractive for greening, i.e. GRI and average U-value are directly proportional. It is also important to note that the accepted reference for average U-value of the whole building is $2.1 W/m^2K$, which is the reference value used to fulfill the UK requirements for domestic energy certification under the European Union Energy Performance of Buildings Directive¹⁸. Projects such as the Crystal building in London, the first building in the world to have obtained Platinum LEED and Outstanding BREEAM certifications, could reach an average U-value as low as $1.0 W/m^2K$ ¹⁹, however this level of insulation is too high to be considered a datum for GRI calculation.

3.3.1.2. Air infiltration rate

It is defined as the average volume of air that passes through unit area of the structure of the building envelope when subject to an internal to external pressure difference of 50 Pa. It is also measured in ACH50 (Air Changes per Hour at 50 Pa pressure difference). The higher the air infiltration rate is, the less integral is the building envelope, and hence the more attractive the building is for greening. That is to say that air infiltration rate and green retrofitability are directly proportional.

The average air infiltration rate differs greatly from one building to another, according to the quality of fitting of windows and external doors. However, according to Fennell et al. (2005), various studies were conducted to estimate the average air infiltration rate for countries such as the US, Canada, Sweden and England. They are listed in the following table²⁰;

Table1. Average air infiltration rates (in ACH50) in residential buildings in selected countries according to different studies.

Country	Zilin, 1986	Biggs et al., 1987	Katz, 1994
U.S.	5.5	-	4.0-8.0
Canada	-	4.4	-
Sweden	-	3.7	-
England	-	13.9	-

It is to be noted from the table above that the average air infiltration rates, except that of England, are around the value of 4.0 ACH50. This specified level is taken as a datum for median GRI calculation. Any air infiltration rate above this level means diminished integrity of building envelope, and hence higher attractiveness for green retrofitting.

3.3.2. Energy consumption rate

As mentioned in section 3.3, low rate of consumption of resources is one of the indicators for high building performance, either by informed design or incorporating resource-saving systems. On the other hand, buildings with higher energy consumption rate have a higher priority for greening, as they are draining resources faster than others. Both the government and the owners of such properties can benefit from the greening process, as the government will reduce the burden on the central power grid and owners will save considerable amounts of money. Therefore, high energy consumption, especially on lighting and HVAC systems, increases the attractiveness of the building to be greened. As a result, green retrofitability and energy consumption rate are directly proportional.

It is important to note that energy prices vary greatly from one region/area to another and some segments receive energy subsidies. Therefore energy consumption is quantified in kWh instead of monetary terms. In this concern, there are several indices that measure energy performance of a building, such as EPI (Energy Performance Index), which was used by Boyd et al. as a statistical benchmarking and was adopted by the US EPA Energy Star program to assess industrial plant energy efficiency²¹. EPI is simply the total energy consumed per year (in kWh) per square meter of built-up area. It can be calculated using the following formula;

$$EPI = \frac{\text{Annual Energy Consumption}}{\text{Built-up Area}} = \frac{E}{A} \quad (3)$$

However, EPI calculation does not take the number of occupants into consideration. A building consuming a given amount of energy per year with 10 occupants living in, is greener than another one with the same built-up area and the same energy consumption rate but with 5 occupants only. Nevertheless, the inclusion of the number of

occupants in the equation raises questions about the differences in energy consumption due to occupant behavior. This issue is to be addressed by dealing with the building and occupant combination as a whole, which is sometimes referred to as a 'household', i.e. the first household in the previous case is greener than the second. But since the term often refers to residential buildings and families dwelling in them, it might be safer to use the term 'building+occupants combination' to be suitable for all building types. The global average energy consumption per person in 2008 was 72.39 million Btu (21,215 kWh) per year²². Since 40 per cent of energy is consumed inside buildings, the average energy consumed inside buildings per occupant is around 8,500 kWh per year. This rate of consumption is taken as a datum in GRI calculation for the average household, or the average 'building+occupants combination'.

3.3.3. *Water consumption rate*

Water is a precious resource that is getting scarce in many countries, and is likely to cause conflicts in various regions of the world. As a result, many green building codes and building regulations have set limits for the sustainable use of water resources. Proper design of sanitation systems and the installation of smart sanitary fittings such as infra-red activated water taps can greatly reduce water consumption rates. Like energy consumption, buildings with higher water consumption are more attractive for greening. Therefore, it is generally correct to say that green retrofitability and water consumption rate are directly proportional. The average person in the US uses around 400 liters of fresh water a day²³. Roughly 70 percent of this use occurs indoors. However, international norms set by organizations such as the World Health Organization (WHO) and the United Nations Children and Education Fund (UNICEF) suggest a minimum requirement of 20 liters a day. Bathing and laundry needs would raise the need amount to about 50 liters a day per person (ibid.). This average rate of consumption is taken as a datum in GRI calculation for the average household. It is important to note that in GRI calculation, water consumption rate must be considered with respect to built-up area due to its use in cleaning purposes, as well as with respect to the number of occupants.

3.4. *Occupancy*

Given that all other factors have the same value, including energy and water consumption, households with higher occupancy levels are usually performing better. The term 'household performance' here indicates the behavior of the building and the occupants combined, i.e. 'building+occupant combination' as discussed in the previous section. However, it is impossible to calculate the behavior of each individual in each building to determine his/her consumption pattern. Therefore, considering a standard average pattern of consumption for occupants of both buildings, a building that is consuming the same resources as another comparable counterpart while having a bigger number of occupants is considered to be performing better and consequently less attractive for retrofitting. Therefore, it is safe to say; given that all other factors are similar to a comparable household/building+occupants combination, the number of occupants is inversely proportional to green retrofitability. The datum used in median GRI calculation is the global average number of occupants per household recorded in 2012 which is 3.49²⁴.

3.5. *Retrofitting cost*

Although retrofitting cost is an important factor when deciding which building to green, it is not essential to compute when calculating GRI. In the white paper, 'The Economics of LEED-EB for Individual Buildings, 2008 Edition', the study concluded that 'the level of certification of the building after greening is dependent on the pre-LEED-EB implementation performance of the building rather than on the LEED-EB implementation expenditures'. This means that spending more money on greening a given building does not necessarily lead to achieving higher performance. Also, the wide range of retrofitting options for a single building and the combinations between them makes the greening costs very flexible, ranging from \$0.02 to \$5.01/sq.ft. (\$0.21 to \$53.93/sq.m.)²⁵, which does not make it a crucial point of comparison. However, retrofitting cost is partially represented in the computation of GRI by incorporating pre-retrofitting building performance and built-up area, which are the two main components on which the retrofitting cost depend, given that the optimum solution is applied. That is to say, that pre-retrofitting building performance –which is inversely proportional with retrofitting cost– and built-up area –which is directly proportional with retrofitting cost– are the two main factors on which retrofitting cost depend on and they are

already represented in the GRI equation.

3.6. Built-up area

Built-up area of a given building is related to many of the factors above, since most of them must be computed with respect to unit area of the given building. Therefore, built-up area must be calculated and integrated in the formula for GRI. At the same time, when comparing two buildings with similar parameters and consumption rates, while one has a larger built-up area, the larger one is considered greener. That is to say, green retrofitability and built-up area are inversely proportional. The average household built-up area per person varies from 15sq.m in Hong Kong and 20sq.m. in China to 77sq.m. in the United States and 89sq.m. in Australia²⁶. The global median household built-up area per person is around 35sq.m. This figure is taken as a datum in GRI calculation for the average household or building+occupants combination.

4. Calculation of GRI

Since GRI is a reference index to measure relative green retrofitability of a given building, its calculation will be based on the factors that affect it as discussed above. It is important to note that GRI is used for comparing the retrofitability of one building to another, so there is no need to use fixed constants in the formula as they will only make the number bigger for both buildings in the same proportion. Also, the parameters used in the formula are measured in SI units. Any parameter with imperial units has been converted into SI system. The formula is generated as follows:

Since;

$$GRI \propto \text{Bldg. Market Value per Area}$$

$$\text{i.e. } GRI \propto V/A \quad (4)$$

$$GRI \propto 1/(\text{Building Age/Lifetime})$$

$$\text{i.e. } GRI \propto L/Y \quad (5)$$

$$GRI \propto \text{Average heat transmittance of bldg. envelope (U – value)}$$

$$\text{i.e. } GRI \propto U$$

$$GRI \propto \text{Air Infiltration Rate}$$

$$\text{i.e. } GRI \propto I \quad (6)$$

$$\text{From (3), and } GRI \propto \text{Annual Energy Consumption per Area per Occupant}$$

$$\text{i.e. } GRI \propto E/(A \cdot O) \quad (7)$$

$$GRI \propto \text{Annual Water Consumption per Area per Occupant}$$

$$\text{i.e. } GRI \propto W/(A \cdot O) \quad (8)$$

$$GRI \propto 1/(\text{No. of Occupants})$$

$$\text{i.e. } GRI \propto 1/O \quad (9)$$

$$GRI \propto 1/\text{Built up Area}$$

$$\text{i.e. } GRI \propto 1/A \quad (10)$$

Therefore; from 4,5,6,7,8,9 and 10;

$$GRI = \frac{V \times E \times W \times L \times U \times I}{Y \times O^3 \times A^4} \times 10^{-3} \quad (11)$$

Where;

V ≡ Bldg. market value in USD

E ≡ Annual energy consumption in kWh

W ≡ Annual water consumption in Liters

L ≡ Est. bldg. Lifetime in years

U ≡ Average overall U-value of bldg. in W/m²K

I ≡ Average air infiltration rate of bldg. envelope in ACH50

Y ≡ Bldg. age in years

O ≡ No. of Occupants

A ≡ Bldg. built up area in sq.m.

The resultant GRI value is multiplied by 10^{-3} in order to truncate the value into a 2 or 3 digit number. This will help make the GRI value easier to comprehend and compare.

5. Testing the GRI formula

A set of buildings of different parameters are assumed for applying the GRI calculation on, in order to test the credibility of the formula. To observe the effect of each parameter on the final GRI value, the first building X was given the reference values in all parameters, then afterwards parameters are doubled one at a time with respect to nine assumed buildings and GRI values are noted. They are as follows;

Table2. GRI calculations for a set of assumed buildings.

Bldg. No.	Market Value (V) (USD)	Av. Annual Energy Consumption (E) (kWh)	Av. Annual Water Consumption (W) (Liters)	Est. Bldg. Lifetime (L) (yrs.)	U-value (U) (W/m ² K)	Air Infiltration Rate (I) (ACH 50)	No. of Occupants (O)	Building Age (Y) (yrs.)	Built-up Area (sq.m.)	GRI × 10 ⁻³	Scaled GRI
X	61,075	8,500	63,736	100	2.10	4.00	3.49	40	122	73.79	50.00
X1	122,150	8,500	63,736	100	2.10	4.00	3.49	40	122	147.57	100.00
X2	61,075	17,000	63,736	100	2.10	4.00	3.49	40	122	147.57	100.00
X3	61,075	8,500	127,472	100	2.10	4.00	3.49	40	122	147.57	100.00
X4	61,075	8,500	63,736	200	2.10	4.00	3.49	40	122	147.57	100.00
X5	61,075	8,500	63,736	100	4.20	4.00	3.49	40	122	147.57	100.00
X6	61,075	8,500	63,736	100	2.10	8.00	3.49	40	122	147.57	100.00
X7	61,075	8,500	63,736	100	2.10	4.00	6.98	40	122	9.22	6.25
X8	61,075	8,500	63,736	100	2.10	4.00	3.49	80	122	36.89	25.00
X9	61,075	8,500	63,736	100	2.10	4.00	3.49	40	244	4.61	3.12

The standard building X has the median value parameters as discussed in the previous sections. The following building, X1, has the same parameters except for the first one, market value, which is doubled. The following building, X2, has the same parameters as X, with the exception of annual energy consumption which is doubled, and so on. The different factors are doubled one at a time in order to observe the changes that occur to GRI value. It is obvious that doubling any of the values of the factors in the numerator of the equation results in doubling the GRI value. While doubling the parameter Y results in cutting the GRI value in half. Doubling of the parameters O and A reduces the GRI value greatly due to their exponential state in the denominator of the formula. This shows the intense influence of occupancy and built-up area of a given building on its green retrofitability, which is understandable as the number of occupants and area of a space play two crucial roles in its rate of consumption.

A scaled version of GRI is created using the GRI value of the standard building X. The GRI values are multiplied by a constant value of 0.6776. The standard building X then has a scaled GRI value of 50. This is considered to be the moderate benchmark for green retrofitability, as it was calculated based on the median values of parameters. A

building with such a GRI value has a moderate green retrofitability, as it follows a moderate pattern of consumption. The formula for calculating the scaled GRI is as follows:

$$GRI = \frac{V \times E \times W \times L \times U \times I}{Y \times O^3 \times A^4} \times 10^{-3} \times 0.6776 \quad (12)$$

Buildings with a scaled GRI value near zero means that the building is not retrofitable, either because it is already green or because it is not attractive enough due to one or more of the factors discussed above. Therefore, the value of 100, double the median GRI value, is considered to be the ceiling for high retrofitability index. The GRI scale is then divided into three segments between 0 and 100. A building with GRI value from 0 to 33.33 has a low green retrofitability. Another with a scaled GRI value from 33.33 to 66.67 has a moderate green retrofitability. A building with a scaled GRI value from 66.67 to 100 has a high green retrofitability. Any scaled GRI value above 100 means the building has a very high green retrofitability.

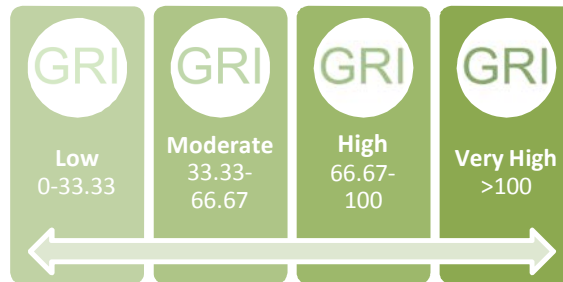


Fig.1. Scaled GRI classification ranges

6. Discussion

In the shown cases, GRI value gave a relative indication for how retrofitable each household/building is, in comparison with a group of other households/buildings. It can be useful when deciding which building to retrofit first within a group of buildings of similar conditions. However, in some cases where the given household/building has extreme conditions, GRI value can be extremely high or low compared to other households/buildings.

For example, a building in the center of a major city can have a market value 10 times that of a similar building with a similar consumption pattern and parameters but exists in a suburb or a less attractive area. That will result in a GRI value 10 times that of the building in the suburb. This indicates that buildings in city centers will probably be more retrofitable than their counterparts in suburbs, let alone those in towns and villages, even if they are performing similarly. This phenomenon, however, is not misleading, as buildings in city centers usually enjoy benefits that are usually more than those anywhere else, and that is mainly why their market values are relatively higher. They also have access to services and resources that are not always available to their counterparts in small towns or villages. Major cities also contribute to global warming and climate change more than towns and villages, due to their relatively higher carbon emissions and pollution related to consumption. Therefore, the relatively high GRI value in city centers will encourage starting retrofitting efforts there, which correlates to the mentioned issues. At the same time, the GRI formula suggests that increasing the number of occupants in a household in city center will effectively lower its GRI value even with the very high market value. This fact corresponds to efficiency issues, suggesting that buildings with high market values are considered greener if a bigger number of occupants use them.

In another case, if the building is very new, i.e. the value of Y parameter is as low as 1 or 2, the GRI value would be very high too even if the building is performing around to the average pattern. However, this correlates to the big potential the building has in saving resources, since it still has 80-100 yrs of lifetime ahead. That is to say, that

newer buildings are much more attractive to greening, even if they are performing slightly below norms. Also, a newer building is expected to perform better than old ones, with respect to consumption rates and envelope performance, due to the recent advancements in green building and the availability of green building knowledge and professionals in the current era more than any time before. Thus, it is no longer acceptable for a new building to perform like 40 years old buildings that are taken into consideration in the median GRI calculation, and obviously it is not acceptable for new buildings to perform worse than them.

Therefore, the extreme cases that result in very high or very low GRI values are still coherent with the main concept of green retrofitability and do not give misleading indicators on the issue of the building relative retrofitability.

Conclusion

It is to be concluded from this work that the suggested GRI reference index is an easily computed indicator that can be used in comparing potential green retrofitting projects, and hence making more-informed decisions. By doing so, the decision-maker can rationally select the buildings to green first, and hence save more resources in a shorter period of time. However, the GRI reference index and green retrofitability concept in general are still in the beginning. It is important to continue researching this new approach in green indexing in order to study the different complexities that occur in the process, and the more complicated parameters that can affect GRI calculation.

It is also important to note that the suggested benchmarks for GRI reference index cannot be used as-is locally. The market value parameter and consumption rates can be very different from one country to the other, depending on climatic, social and economic factors. It is recommended that separate studies would be carried out for each country/state/region to study its local parameters, and produce local benchmarks and hence a GRI index that is fine-tuned to local or regional conditions.

Acknowledgements

The authors are obliged to the teachings of the late Prof. Dr. Bahaa Bakry, who has been a source of knowledge and inspiration for generations of green architects and researchers.

References

1. Romm JJ, Browning WD. Greening the building and the bottom line: increasing productivity through energy-efficient design. Snowmass, Columbia: Rocky Mountain Institute; 1994.
2. Breslau B. Sustainability in the Corporate Real Estate Industry: Perceptions and Trends. Jones Lang LaSalle, CoreNet Global. Jones Lang LaSalle; 2007.
3. Lockwood C. Building Retrofits. *Urban Land*; 2009;6:48–49.
4. Eichholtz P, Kok N. & Quigley, J. Doing well by doing good? Green Office Buildings. *American Economic Review* 2010, 100 (5):2492-2509.
5. Olgyay V, Seruto C. Whole-Building Retrofits: A Gateway to Climate Stabilization. ASHRAE; 2010.
6. Durmus-Pedini A, Ashuri B. An Overview of the Benefits and Risk Factors of Going Green in Existing Buildings. *International Journal of Facility Management* 2010, 1 (1).
7. World Business Council for Sustainable Development (WBCSD). Energy Efficiency in Buildings – Transforming The Market. ISBN: 978-3-940388-44-5; 2009. Retrieved November 2012 from <<http://www.wbcd.org/Pages/EDocument/EDocumentDetails.aspx?ID=11006&NoSearchContextKey=true>>
8. Britnell J, Dixon T. Retrofitting in the private residential and commercial property sectors – survey findings. ISSN 2052-1618; 2011. Retrieved August 2015 from <www.retrofit2050.org.uk/sites/default/files/resources/WP20111.pdf>
9. Dirksen T, McGowan M. Greening Existing Buildings with LEED-EB! [Master Thesis]. Massachusetts Institute of Technology; 2008;75.
10. UCLA Institute for Research on Labour and Employment. Research and Policy Brief; 2009. Retrieved August 2015 from: <<http://www.urbanhabitat.org/files/LAGreenJobs.pdf>>
11. Kok N, Miller NG, Morris P. The Economics of Green Retrofits. *Journal of Sustainable Real Estate*, 4(1); 2012; 4–22.
12. Rocky Mountain Institute. How to Calculate and Present Deep Retrofit Value - A Guide for Investors. Boulder, CO: Rocky Mountain Institute; 2015. Retrieved August 2015 from: http://www.rmi.org/retrofit_depot_deepretrofitvalue

13. BPIE. A Guide to Developing Strategies for Building Energy Renovation - Delivering Article 4 of the Energy Efficiency Directive. BPIE; 2013. Retrieved August 2015 from www.bpie.eu/.../BPIE/Developing_Building_Renovation_Strategies.pdf
14. Global Property Guide. Price per Square Meter North-America | Cost per Square Meter. Globalpropertyguide.com; 2015.
15. Cort KA. Analyzing the Life Cycle Energy Savings of DOE-Supported Buildings Technologies. Pacific Northwest National Laboratory, DOE; 2009. Retrieved from www.pnl.gov/main/publications/external/technical.../PNNL-18658.pdf
16. Eleessawy A, Masera G. The influence of internal insulation on the thermal inertia in existing residential building envelopes in hot arid climates. Proceedings of BS Cairo 2013 Conference. AGD Publishing Group; 2013; p374.
17. UK Government. Building Regulations 2000 Approved Document L1: Conservation of Fuel and Power. London: NBS Publishing; 2000;44-52.
18. European Commission. Directive of the European parliament and of the council on the energy performance of buildings (Recast). Brussels: European Commission; 2008.
19. Plummer M. The First LEED Platinum & BREEAM Outstanding Building. CIBSE Case Studies: CIBSE; 2013. Web. 29 Oct. 2015. <http://www.cibse.org/knowledge/case-studies/cibse-case-study-the-first-leed-platinum-breeam-ou>
20. Fennell H, Haehnel J. Setting airtightness standards. *ASHRAE Journal*; 2005;47-28.
21. Boyd G, Dutrow E, Tunnessen W. The evolution of the ENERGY STAR energy performance indicator for benchmarking industrial plant manufacturing energy use. *J Cleaner Prod*; 2008; 709-715.
22. EIA.gov. International Energy Statistics; EIA; 2015. Retrieved October 2015 from <http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=44&pid=45&aid=2&cid=regions&syid=2005&eyid=2009&unit=QBTU>
23. UNDP. Human Development Report 2006. 1st ed. New York: Palgrave Macmillan; 2006; 5-9.
24. Laurent C. *Tomorrow's world*. Singapore: Wiley; 2013.
25. Leonardo Academy. The Economics of LEED for Existing Buildings. 1st ed. Madison, WI: Leonardo Academy Inc.; 2008; 6.
26. [Shrinkthatfootprint.com](http://shrinkthatfootprint.com). How big is a house? Average house size by country; 2013; Retrieved October 2015 from <http://shrinkthatfootprint.com/how-big-is-a-house>