Exergy-based Index for the assessment of building sustainability

Ahmed El shenawy

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Dr. T. Zayed	Examiner
Dr. R. Zmeureanu	Thesis Supervisor

Approved by

Dr. M. Elektorowicz Graduate Program Director

May. 21, 2013

Dr. Robin A.L. Drew, Dean

Faculty of Engineering & Computer Science

ABSTRACT

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Ahmed El shenawy, Ph.D.

Concordia University, 2013

The declining state of the environment, combined with the increasing scarcity of natural resources and economic recession, presents us with the need to discover building practices that are capable of producing sustainable buildings. Building promoters are racing to certify the sustainability of their projects, aware that building sustainability assessment will delineate the features of current and future building practice. A sustainable building implies that resource depletion and waste emissions are considered during its whole life cycle. This research project proposes a new methodology and Exergy-based Index to assess building sustainability and to assist decision makers comparing building alternatives, since the wrong decisions can lead to serious consequences and even precipitate crises. The proposed methodology uses the SBTool that has been utilized for defining the criteria for analysing and ranking the environmental performance of buildings. Over the past decade, significant efforts have been made in developing Sustainable Building (SB) assessment tools that allow all stakeholders/actors to be aware of the consequences of various choices and to assess building performance. These SB tools, approaches, rating systems, indices and methods of assessment have already been utilized in the market (e.g., Multi-Criteria Assessment (MCA) methods, such as LEED and SBTool, Life Cycle Analysis (LCA) systems, like ATHENA, and the Single Index (SI) approach (Ecological footprint)). However, are existing SB assessment tools actually capable of considering the regional issues? Is it possible to use them to assess all types of buildings? Are they objective, easy to customize? Is it easy to interpret their final assessment results and are those results transparent to the end users? Despite the usefulness of the current assessment methods in contributing towards a more sustainable building industry, some of the limitations and critiques of these assessment methods indicate that the tools should evolve toward a genuinely generic and scientifically global SB assessment tool.

After discussing and summarizing the limitations of the existing definitions, indices and rating systems for building sustainability assessment, a definition of a sustainable building in terms of thermodynamics is proposed, mainly based on the exergy concept. This proposal is supported by a general mathematical calculation for the exergy-based index of building sustainability. The index uses the comparison between the available solar exergy (considered to be the only renewable energy source) and the exergy lost due to a building's construction and operation to measure the a building's sustainability. Moreover, the selection and transfer of data from the SBTool, and the assumptions and additional calculations required for the assessment of the exergy-based index of sustainability are presented and quantified. A rating scale is also presented along with the index of building sustainability. Finally, case studies of residential and commercial buildings are used to demonstrate the framework's reliability. The contribution of the proposed Exergy-based index is evaluated by comparing its similarities and differences with a selection of the available building assessment tools and methods.

Keywords: sustainable buildings, assessment tools, rating systems, single index, exergy

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my family; Basima Elserngawy, Mohamed, Moataz, Lina and Linda

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LIST OF ACRONYMES

Name	Definition
SB	Sustainable Building
MCA	Multi-Criteria Assessment
LCA	Life Cycle Analysis
SI	Single Index
LEED	Leadership in Energy and Environmental Design
BREEAM	Building Research Establishment Environmental Assessment Method
SBTool	Sustainable Building Tool
ExSI	Exergy-based Index of Sustainability
CERF	Civil Engineering Research Foundation
CIB	International Council for Research and Innovation in Building and Construction
CNC	Critical Natural Capital
EIA	Environmental Impact Assessment
IEA	International Energy Agency
USGBC	U.S. Green Building Council's
ISO	International Organization for standardization
BEES	Building for Environmental and Economic Sustainability
ENVEST	Environmental impact estimating software
BEAT	Building Environment Assessment Tool
SD	Sustainable Development
CVM	Contingent Valuation Method
CBA	Cost Benefit Analysis
ISEW	Index of Sustainability Economic Welfare
EF	Ecological Footprint
EMA	Emergy Analysis
SBTool	Sustainable Building Tool
CExC	Cumulative exergy consumption
iiSBE	International Initiative for a Sustainable Built Environment
GBTool	Green Building Tool
GBC	Green Building Challenge
Nw	Nominal weight
SN	Suggested nominal default values
W	Weighted percent
EN	Energy
EX	Exergy
AR	Amortization rate
S	Entropy
A	Area
DUR	Ratio between initial embodied energy and total initial embodied energy for durable material
Non-DUR	Ratio between initial embodied energy and total initial embodied energy for non durable material
N	Replacement frequency

ENC	Energetic cost
TEC	Thermoeconomic cost
EXC	Exergetic cost
TAWP	Total Annual Potable Water
IPCC	Intergovernmental Panel on Climate Change
GWP	Global Warming Potential
ODSs	Ozone Depleting Substances
CFCs	Chlorofluorocarbons
HCFCs	Hydrochloroflourocarbons
EEB	Energy Efficient Building
NZEB	Net Zero Energy Building
PDF	Probability Density Function

NOMENCLATURE

Symbol		**Units**
Roman		
$\dot{m}$	Mass flow rate	kg/s
T	Temperature	°C
Cp	Specific heat	kJ/kg .^{o}C
Greek		
η	Energy efficiency	
τ	Percentage by cost of salvaged materials	
θ	Percentage of contribution of recycled materials	
μ	Percentage by cost of bio-based products cost from off-site	
$\boldsymbol{\alpha}_{\boldsymbol{ex}}$	Exergy index of renewability	
$\psi_{srad,max}$	Maximum efficiency ratio	
Subscript		
Iss	Issue	
Cat	Category	
Crit	Criterion	
b1.1	Criterion b1.1	
Ns	New structural element	
Nw	New wall	
Es	Existing structural element	
Ew	Existing wall	
H	Heavy material	
D	Demolished	
R	Refurbished	
service	Building life span	
Hc	Heavy materials (not subjected to manufacturing process)	
Hm	Heavy materials (subjected to manufacturing process)	
O	Annual	
a	Average	
max	Maximum	
m	Material	
molecular wt	Molecular weight	
ch	Specific chemical	
Ch-stand	Standard chemical	
total	Total	
E	Electricity	
F	Fossil fuel	
net	Net area	
occ	Occupancy	
gen	generation	
HW	Hot water	
loss	loss	
gas	Natural gas	
w	water	
g-boiler	Natural gas-fired boiler	
flame	flame	
out	Leaving the boiler	

in	Entering the boiler
net	Net area
Non-DUR	Ratio between initial embodied energy and total initial embodied energy for non durable material
total	total
salvaged	Salvaged material
recycled	Recycled material
Bio-based	Bio-based material
non-native	Non-native species
irrigation-rate	Irrigation rate
rate	Rate
operation	Operation
pt	Per time
pd	Per day
fix	Fixture
w-treat	Water treatment
DHW	Domestic hot water
supply	Supply water temperature
inlet	Inlet water temperature
BFP	Building footprint
i	Month i

1 INTRODUCTION

1.1 Background

Buildings have a profound impact on the quality of our lives all along the different stages of their life cycle. They are a visible stamp of our culture on the environment. Buildings provide countless benefits to society, especially in more inclement areas such as the Canadian climate (Canadians spend about 90% of their time indoors), and they also have a dramatic impact on their occupants and the environment.

As our planet becomes more populated, ever more buildings have been constructed to fulfill human aspirations, with corresponding material, water and energy consumption. This use of resources is not even distributed equitably, but indicates a shameful contrast in resource use between rich and poor countries, as well as between the elites and the lower classes. European environmentalists have determined that 80% of the world's resources are consumed by 20% of the world's population (Holladay 2010). The prospects for the global system do not look promising.

The estimated material, water and energy consumption since the 1980's have superseded the environment's ability to replenish itself (DeArmon 2009). Certainly, little attention was paid to the environmental impacts of unsustainable practices before then. Today, the voracious use of our planet's finite resources, which consists in part of non-renewable fossil fuel energy and the resulting increases in carbon emissions and disposal of wastes, is accompanied by global environmental deterioration (Chichilnisky 1997). Matters could soon reach the point of instability.

Kravanja (2012) stated that, based on detailed measurements, that the earth's global energy balance is being progressively modified. Our planet is currently absorbing .5 PW more than what is being emitted back to the universe, which is 30 times more than the total world energy consumption (16 TW)) and results in total climate forcing of about 1.8 W/m^2 relative to 1880. .

Global warming is just one of the many environmental problems caused by or related to the intensive use of materials, water and conventional energy resources, generally related to unsustainable practices and particularly due to unsustainable building practices through construction and operations. Unsustainable practices are often coupled with the releasing of vast amounts of anthropogenic-based materials. Canada's anthropogenic GHG emissions on a per capita net basis are relatively high compared to other nations. While Canada produces 2.2% (720 million tonnes of CO_2 equivalent) of total global GHG emissions, it only roughly has .5% of the world's population (Canada 2001). Moreover, one of the estimates suggests that the building sector in Canada alone accounts for 33% of energy production, 50% of extracted natural resources, 25% of landfill waste, 10% of airborne particulates and 35% of greenhouse gases (Lucuik 2005). Furthermore, ozone layer depletion, global warming, ecosystem destruction and resource depletion are considered to be some of the most serious environmental crises that have increasing importance in our daily life, linked directly or indirectly with the sector of building construction (Ding 2005). The scale of these environmental problems has extended from local to global, capturing the world's attention. Climate change has been the focus of constant mass media reports nationally and worldwide, which gives an indication of how human activity has already reached levels at which it could alter the planet's climate and its biological viability unless revolutionary sustainability measures are employed.

1.2 Problem statement

A significant number of environmental problems are caused by or related to the intensive use of materials, water and conventional energy resources for building construction and operations. The evolution of those environmental impacts generated by building construction and operation has stimulated the development of several tools, methods and assessment approaches assessment for engineers, architects and researchers.

Considerable efforts have been made in developing the Sustainable Building (SB) assessment tools which enable all stakeholders/actors to be aware of the consequences of various design choices and to assess building performance. Sustainable building assessment tools aim to go beyond the design stage to consider the importance of sustainable choices throughout the project appraisal stage when environmental matters are best incorporated. A large variety of SB tools, approaches, rating systems, indices and methods of assessment have been developed and are in use by different stakeholders (Seo 2002). Despite the usefulness of the existing assessment methods and rating systems in contributing towards a more sustainable building industry, these methods and assessment tools still have several problems and limitations.

Many of these approaches, rating systems and assessment methods are limited in that they only address isolated elements based on a single-dimensional approach, or based on multi-criteria analysis. A single-dimensional approach uses separate indicators or benchmarks (e.g., use a single criterion to monitor air quality and indoor comfort) while sustainability assessment requires a multi-dimensional approach due to the complexity of the system (a building in this case). The single-dimensional approach focuses on only one aspect of the issue and does not allow the evaluation of alternatives where lower consumption of materials could be offset by higher GHG emissions or vice versa. Multi-criteria Analysis (MCA) is a decision making tool developed for complex problems. By using Multi-criteria Analysis (e.g., LEED, BREEAM and SBTool) the members of an evaluation committee do not have to reach a general consensus in a multidisciplinary application, but merely agree on the relative importance of the criteria or the ranking of the alternatives. Each member enters his or her own judgment and makes a distinct, identifiable contribution to a jointly-reached conclusion. These approaches consider the pillars of sustainability separately, and so fail to meet the increasingly popular desires of decision makers who ask that the links between these pillars are better-defined and quantified using linkage-based frameworks for sustainability assessment (Waheed et al. 2009). This challenge has not yet been solved, but some progress has been made in the last decade with the introduction of a two-part coupled framework (Dietz et al. 2009) and (Prescott-Allen 2001).

There remains much room to improve the basis for sound decision making, such as the integration of many complex issues into a single decision criterion while providing simple and individual objectives that a busy decision maker can understand and use for comparison purpose. The fundamental challenge due to the complexity of sustainability requires a shift to systems thinking, to go beyond a mere collection of parts (considering the pillars of sustainability separately) and apply a more holistic assessment based on a science-oriented approach to consider the sustainability of the whole system, the building, as composed of interacting subsystems.

The use of a single index for assessing the progress towards sustainability is not a common practice. Two such sustainability metrics are monetary and biophysical. They utilize a common currency/denominator (e.g., money, land or energy).

To date, no approach has been proposed by the building industry to assess building sustainability using a single index approach. Monetary tools have been set aside for their over-dependence on subjective valuations, and because they are not flexible enough to assess the progress towards sustainability in holistic manner. In addition, monetary metrics are inadequate since sustainability assessment goes beyond economic or what some call the profitability versus the environment debate (Schley and Laur 1996). Among the biophysical metrics, exergy has been widely used as a thermodynamic property of a system, and some authors (Rosen and Dincer 2001; Wall and Gong 2001a) have advocated using the exergy concept as a sustainability indicator, while others have based their buildings' designs on exergy (e.g., 'Minimum-energy house' built in 1982–1983 by architect Jon Kristinsson).

Therefore, a new prototype framework is proposed in this thesis for the estimation, at the conceptual design stage, of a building's sustainability over its assumed life span using an Exergy-based Index as an effective single decision indicator. This index is structured to allow the potential design alternatives to be explored in the search for the best sustainable alternative.

1.3 Organization

This dissertation is organized as follows:

Chapter 2 is a literature review of the definitions of sustainability, sustainable building and sustainability assessment. In addition to presenting a literature review of earlier categorizations of sustainability assessment tools, methods and approaches, a review about existing sustainability assessment methods is presented. An attempt to overcome the limitations of existing assessment methods was the major driver for the formulation of the proposed framework. A review about previous related indices of sustainability focused on using exergy is also presented. In chapter 3, a sensitivity analysis is applied to SBTool in order to investigate which issues to select for consideration based on the extent of their importance in influencing the final SBTool assessment results. Chapter 4 gives a detailed presentation of the proposed Exergy based-Index of Sustainability (ExSI) methodogy. Chapter 5 introduces several case studies to demonstrate the application of the proposed framework. Finally, chapter 6 ends this dissertation with conclusions, contributions and future work.

2 LITERATURE REVIEW

A deep understanding of the existing tools, methods and approaches of building sustainability assessment is required in order to grasp their characteristics. Building assessment methods are often used to evaluate building performance against specific standards or benchmarks. According to Kates et al. (2001), sustainability assessment assists decision makers in their evaluation of systems in both the short and the long term in order to determine which action should be taken to attain sustainable achievement. For a better understanding of the methodology behind the development of the proposed framework, the progress in sustainability assessment is reviewed in this thesis in the following three domains: (i) analysis of the definitions of sustainability and sustainable building and the conceptual challenges of sustainability (e.g., time- and location-dependence, capturing diversity), (ii) classification and the (earlier) categorizing of tools and assessment methods are presented and a brief outline is provided for each category, complemented by identification of their key aspects, and (iii) evaluation of the existing sustainability assessment tools, approach, indices and methodologies. Finally, based on analysis of the published information about conceptual limitations and critiques of the existing tools and methods of assessment, the objectives for this study are set.

2.1 Sustainability and sustainable buildings

Sustainability has been defined in a variety of ways; virtually all are covered in the following section.

2.1.1 Sustainability definitions

The concept of sustainability has been reviewed in different fields in an attempt to clarify the use of the term. Linguistically, Brown et al. (1987) define sustainable as "capable of being upheld; maintainable" according to the Oxford English Dictionary. Sustainability thus is the capacity of a system or a process to maintain itself indefinitely in harmony with the biophysical systems of the planet. In resource management, Tivy et al. (1981) define sustainable yield as the "management of a resource for maximum continuing production, consistent with the maintenance of a constantly renewable stock." In terms of carrying capacity, sustainability is defined as "the maximum population size that the environment can support on a continuing basis" as well as "the number of people that a given amount of land can support". A sustainable society is seen by Brown (1981) as "an enduring one, self-reliant and less vulnerable to external forces", which means that a sustainable society is more independent. Although these definitions contain many differences, overall they have a set of common foci which is based on a social, economic, or ecological perspective. The meaning of sustainability varies according to who is using it and in what context.

Becker (1997) shows the normative and scientific aspects of sustainability. He also indicates that a critical analysis of the normative concept of sustainability is required in order to avoid its misuse for ideological objectives and/or economic interest. Hill et al. (1997) represent some of the writers' and economists' opinions on how to achieve sustainability. Writers such as Leopold (1949) and Carson (1962) call on people to embrace a lifestyle that shows much more consideration for our Earth's life support systems. They (and many others since their time) advocate for a so-called post-materialistic society that gives precedence to spiritual and psychological well-being rather than materialistic consumption. Economist Solow (1993) proposed practical steps toward sustainability and argued that its development will cause some drawdown of current non-renewable resource stocks, and so sustainability should mean more than merely the preservation of natural resources; other steps to offset these drawdowns are necessary. Clifton (2010) discusses how humans could live sustainably on the Earth and how they might go about achieving that goal. He noted that existing typologies (e.g., sustainable world dimension typologies that focus on presenting a picture of what is meant by a sustainable world) are useful but they remain merely descriptive. These observations support the growing need for tools to assess the progress of achieving sustainable world outcomes. The sustainability concept has undergone a period of maturing in terms of basic understanding of what sustainability implies, which is well described by Hueting et al. (2004) and Laws et al. (2004). In just a few years, sustainable development received more than 200 formal definitions through the work of Parkin (2000).

Glavic et al. (2007) provide the results of their literature survey of sustainability terms and their definitions. They suggest that a hierarchical classification and the relationships of sustainability terms needs to be developed to achieve improved and easier understanding among the varied fields it touches.

2.1.2 Sustainable buildings definitions

The term “Sustainable construction” or more specifically “sustainable building’ is always introduced in the context of sustainability, introduced for the first time in Tampa

(1994) as "the creation and responsible maintenance of a healthy built environment based on the resource efficient and ecological principles" (Kibert, 1994). That broad definition can be viewed as a starting point from which to build and develop a more objective definition for sustainable construction. Since then, the international research symposia of the Civil Engineering Research Foundation (CERF) in 1996 and of the International Council for Research and Innovation in Building and Construction (CIB) in 1998 served as platforms to answer questions about the consequences of sustainable development in the construction industry (Brochner et al. 1999). In 1998, the CIB report presented the contributions of the 14 participating countries towards a definition of sustainable construction after describing their national constraints and specific issues that provided the context to those definitions (Bourdeau 1999). In the same context, Brown elaborated that the term sustainability is strongly dependent upon the context and that it will be much more useful if the temporal and spatial scales are being considered (Brown et al. 1987).

Some of the synonyms for sustainable buildings that have been used by different authors and organizations are: "energy-efficient buildings", "environmental buildings", "eco-buildings", "green buildings" and "high-performance buildings" (Keeping 2000). Hill and Bowen (1997) presented the semantic problems of describing sustainable construction as an activity that can continue forever, while a construction project has a limited lifespan (e.g., 75 years).

The dynamic versus the static features of the meaning of sustainability have been discussed by Kemmler et al. (2007) and Zmeureanu (2006). Kemmler et al. (2007) explained that while sustainability, in theory at least, is an ultimate goal for nations, communities, and firms, its quantification remains difficult since it does not have a fixed condition, nor is there a final sustainable state. It is inherently a dynamic process, as successive generations, with different knowledge, technology, and needs, will define sustainability in their own way based on a society's worldviews and values. On the contrary, Zmeureanu (2006) specified that in order to achieve sustainability, the final destination must be defined in such a way that sustainability indices can be measured and compared with accepted benchmarks. Lee et al. (2007) stated that preferences must be made explicitly in the decision-making process when choosing between options. Furthermore, in the absence of full knowledge, a measurement must be based on judgments about what is important.

2.2 Challenges to sustainability assessment

The ultimate goal of sustainability assessment is to assist designers, developers and regulatory bodies to overcome the challenges they face when potential design alternatives are explored in the search for the most sustainable alternative while balancing the often conflicting requirements of short-term political success, social progress, economic growth and environmental sustainability. This goal raises a number of challenges that have not yet been addressed satisfactorily. In this section, we consider some challenges that our approach specifically raises: conceptual challenges of sustainability, time and location dependence, capturing diversity, users' involvement and their building capacity, and scales.

2.2.1 Conceptual challenges

Consensus on how to change sustainability from a buzz word to a meaningful concept that could then become useful for decision making on a broad basis remains a distant goal.

The uncertainty over the meaning of sustainability has given those involved in sustainable development the opportunity to add their own input to the meaning of sustainability. All definitions can thus remain fashionable, and this may, in fact, be self-reinforcing and sustainable on its own. Kidd (1992) argues that since people differ in their economic, social, and environmental conditions, it is probably not possible or even desirable to have a single definition to promote across this diversity. Such a dynamic concept must evolve and be refined as our knowledge, experience and understanding develops.

However, the lack of general consensus on the definition of sustainable buildings is a good reason to return to the fundamental definition of sustainable development as given by Brundtland's report as "a way to meet the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland 1987). A crucial matter in this definition is that, " meeting the needs" is a rather ambiguous phrase since it does not define the current needs, the future generation's needs, the type of resources that would be used (renewable or non-renewable) and their availability. The definition implies that all required resources are available and ignores that there are ultimate limits to the stock of material resources, of certain energy sources and to the environment's ability to absorb wastes and other stresses (Lélé 1991). The lack of clear definition of those elements makes the quantification of sustainability very difficult and eliminates the possibility to operationalize it into a concept that can be used to build a suitable framework with which to measure sustainable buildings. Bender et al. (1997) proposed the degree of consensus as a measure for achieving sustainability, which calculates the level of agreement between the set of interested or affected stockholders about the ranking for each alternative.

The need for a scientifically-based definition that can be used as an acceptable platform for an assessment tool is certainly one of the numerous challenges to sustainability.

2.2.2 Spatial and temporal dimensions of sustainability

A global consensus on the path toward sustainability and its corresponding targets and measures would be a very practical achievement. In this context, the spatial and temporal scales at which a system is observed are the key elements for achieving sustainability (Gavrilescu et al. 2011). The scale limitations of assessment tools affect their utility for decision-making (Ness et al. 2007). The importance of where the system boundary resides, the 'spatial' boundaries of assessment, is already recognized when the concept of sustainability is concerned. Such problems gave rise to the concept of 'life cycle assessment' or LCA, also known as cradle-to-grave analysis. The spatial scale may correspond to a single-family home up to the whole planet. However, these scales are interlinked and it is not easy to separate them. While Mayer (2008) shows that the data availability tends to be complete for politically-bounded systems, it remains sparse for smaller and non-politically-bounded defined systems. Bell et al. (2008) argue that political boundaries such as those of a city may not be of much theoretical use if that boundary is heavily influenced or even dependent upon what happens outside the area. The smaller the scale, the less and the more precise the data that needs to be collected (e.g., in the case of micro-level assessment, only building-specific data is considered). Scales can be “gate-to-gate” (narrow), “cradle-to-gate” (broad), or “cradle-to-grave” (with a very broad boundary) (Hammond and Jones 2008). Unsustainability states, trends, and drivers may be apparent only when an appropriate spatial scale is considered. To illustrate this need for an appropriate scale, a relevant example is given by (Moldan and Dahl 2007), in which a local community can appear sustainable if it exports its unsustainable consumption or waste disposal. This is highlighted as a leakage phenomenon (Mayer 2008). Jeswani et al. (2010) present the importance of spatial differentiation to integrate environmental problems on different system levels.

The temporal scale over which sustainability needs to be achieved is a further challenge. If one only considers the sustainability of a system across a short time horizon rather than the whole life span, the picture could be quite different. Mayer (2008) shows that a common resolution for sustainability data is one year. However, Bell et al. (2008) argue that different systems may require different timescales, and that even in the same system different components of sustainability may best be measured in different time frames. The interpretation of the sustainability trend may be quite different based on which duration is considered (Harrington 1992). Moreover, sustainability could fluctuate with time. While some periods could show unsustainability as the quality of the system declines, other periods could show a marked sustainability due to a rapid increase in the system quality after renovation. The importance of the reference point for gauging sustainability is thus quite obvious, as careful selection of both the scale and reference point, can be used to prove almost any conclusion.

There are several different conceptual foundations currently used in quantitative sustainability research, which generally fall within either a weak or a strong sustainability approach category.

2.2.3 Weak sustainability versus strong sustainability

Within the same system and time scale, it is quite possible to arrive at different judgements depending upon what some call the costs of achieving sustainability, or what Schely et al. (1996) call the 'profitability versus environmental debate'. The debate currently focuses on the substitutability between the economy and the environment. A debate is captured in terms of "weak" vs. "strong" sustainability (Neumayer, 2003), and a number of frameworks have been proposed. The two different visions of sustainability can be regarded as mutually exclusive rather than as two ends of a spectrum. The strong sustainability viewpoint equates to what some have called ecological sustainability. In this case, there is little if any consideration of the financial and other costs of attaining sustainability, and the system quality is assessed in terms of the physical measures of things. To better assess strong sustainability, a stock of resources that cannot be substituted by other stocks or capital to perform the same functions were introduced by the concept of critical natural capital (CNC) (Ekins et al. 2003). In this vision of sustainability there is no trade-off between economic gains and long-term environmental quality; the health of the environment is clearly highest priority.

At the other end of the sustainability spectrum, weak sustainability inevitably equates to a sort of economic sustainability in which financial value is a key element of system quality. This concept promotes a type of assessment in which environmental quality can be traded against economic gain, which simply means that environmental quality is valued in monetary terms. Ayres (2007) considers the arguments for weak vs. strong sustainability. He supports the strong sustainability vision and concludes that new technology can and will create viable substitutes for natural capital. Optimum technological solutions remain to be discovered, since they have not yet proven to be better or less costly.

As mentioned above, unless the sustainability challenges are met in a satisfactory way, sustainability cannot be achieved because they contain the context in which the process must take place.

2.3 Sustainability assessment methods

The process of developing a more appropriate measurement framework requires both a critical assessment of the existing methods and an innovative approach that can handle the limitations of existing assessments (see section 2.4). The existing sustainability assessment methods are explored to define their limitations and to gain from their lessons to develop an effective framework for sustainability assessment. That framework is presented in detail in the proposed methodology, chapter 4.

2.3.1 Sustainability assessment definitions

Some of the definitions for sustainability assessment that have been proposed by different authors include : "a tool that can help the decision makers and the policy makers decide which action they should or not take in an attempt to make society more sustainable" (Devuyst et al. 2001). "a process by which the implications of an initiative on sustainability are evaluated, where the initiative can be a proposed or existing policy, plan, program, project, piece of legislation, or a current practice or activity" (Pope et al. 2004). Later, (Gasparatos et al. 2008) defined sustainability assessment as a framework or tool that provides guidance for a shift towards sustainability as well as a measure for that shift. Handfield et al. (2001) concluded that sustainability will not be successfully incorporated into firm actions until there are effective ways to measure progress towards it. He also mentioned that the first way for an engineer to optimize their design for sustainability is to measure. The above-mentioned definitions implicitly highlight the main functions of the assessment tools: (i) decision-making, (ii) performance assessment, (iii) support tools, and (iv) measurement methods.

2.3.2 Existing categorization of sustainability assessment methods

Based on a limited understanding of the sustainability concept, and based on what dimensions have been considered and employed by different authors and organizations, several classifications have been introduced to understand the state of the art in the field of building assessment. A classification of the assessment tools, methods, and indicators has demonstrated that they are categorized based on numerous factors or dimensions, such as the nature of input data, the scope, the timing, etc., or they are based on the certification type, which can follow a standard or custom and non-standard rating system (Foliente et al. 2007). Haapio et al. (2008) added that assessment tools can be categorized based on their content and characteristics. These characteristics include: 1) the building type, 2) the tools' users, 3) the life cycle phases, 4) the tools' databases, and 5) the forms of the results (the results of a building assessment can be presented in the form of graphs, tables, grades, certificates, and/or reports). Forsberg et al. (2004) use contextual and methodological aspects to compare different tools conceptually and analytically. Contextual aspects include the type of decision maker, the overall purpose, the specific objective/primary type of building and the object(s) analysed, while methodological aspects include the dimensions investigated, the type of environmental parameters, the system boundaries, the presentation of the results and the aggregation of the results.

i. Forsberg et al. (2004) classified assessment tools into qualitative and quantitative types; the first category is based on scores and criteria (e.g. LEED and SBTool are examples of widespread and well-known tools), and the second category is based on physical life cycle assessment with quantitative input and output data indicating the flows of matter and energy.

ii. Gasparatos et al. (2008) suggested that sustainability assessment tools have thus far relied either on reductionist methodologies (e.g. monetary tools and biophysical models) or a holistic approach (e.g., multi-criteria assessment). The former is adopted for a better understanding and description of a system while the latter is referring to as the set of considerations that have to be addressed by the analyst and decision makers during the assessment stage.

iii. Ness et al. (2007) classified assessment tools based on their temporal focuses which either look back in time as retrospective indicators/indices (e.g., Ecological Footprint), or are forward-looking (prospective, forecasting) integrated assessment tools. (e.g., Multi-Criteria Analysis (MCA)).

iv. Pope et al. (2004) reviewed the evolving concept of sustainability assessment and its origins that include environmental impact assessment and strategic environmental assessment. He also discussed their expansion to include social and economic considerations in the forms of EIA-driven integrated assessment and objective-led integrated assessment. The previously-mentioned approaches are classified as 'direction to target' approaches (the exact position on the scale between less sustainable and more sustainable is not defined as well as the sustainable target is). Pope also concluded that the 'distance from target' approach is becoming more useful as a means to assess whether an initiative is, or is not sustainable.

v. Haapio et al. (2008) mentioned two of the well-known classification systems for building environmental assessment tools. One was developed by the ATHENA Institute (AthenaTM, 2007) and the other by IEA Annex 31 (IEA, 2001). While Athena classification has three levels which are mainly dependent upon where in the assessment process they are used and for what purpose, IEA Annex classification is much broader (see table 2.1).

Table 2.1: Athena versus IEA Annex 31 classifications

Athena	**IEA Annex 31**
	1. Energy Modelling software
Level 1: product comparison tools and information sources (e.g., BEES 3.0 and TEAM™)	2. Environmental LCA Tools for Buildings and Building Stocks ▪ **Level 1**: BEES 3.0 and TEAM™
Level 2: whole building design or decision support tools (e.g., ATHENA™, BEAT 2002, BeCost, Eco-Quantum, Envest 2, EQUER, LEGEP® and PAPOOSE)	▪ **Level 2**: ATHENA™, BEAT 2002, BeCost, Eco-Quantum, Envest 2, EQUER, LEGEP® and PAPOOSE
Level 3: whole building assessment frameworks or systems (e.g., EcoEffect, ESCALE, EcoProfile, BREEAM, Environmental Status Model, and LEED®)	▪ **Level 3**: EcoEffect and ESCALE 3. Environmental Assessment Frameworks and Rating Systems ▪ Level 3: EcoProfile, BREEAM, and LEED®
	4. Environmental Guidelines or Checklists for Design and Management of Buildings
	5. Environmental Product Declarations, Catalogues Reference Information, Certifications and Labels.

vi. IEA (2001) described interactive software and passive tools, the former includes the first and second category presented in IEA 31 and the latter includes the third, fourth and fifth category. Interactive tools provide calculation and evaluation methods which enable the user or decision maker to explore a range of options in an interactive way, while passive tools support decisions without much interaction with the user and without the degree of customization and the computational support given by life cycle analysis tools and simulation models. Table 2.2 summarizes these approaches towards categorizing sustainability assessment.

Table 2.2: Existing categorization of methods, tools and indicators of sustainability assessment

Categorization dimensions	Category no.1	Category no.2	Reference
Nature of data	Qualitative	Quantitative	Forsberg and von Malmborg, 2004
Approach	Holistic approach	Reductionist approach	Gasparatos et al., 2008
Temporal	Prospective	Retrospective	Ness et al., 2007
Achievement	Direction to target	Distance from target	Pope et al., 2004
Scale (assessment level)	Whole building	Building products	Haapio and Viitaniemi, 2008; Trusty 2003
Interaction	Passive tools	Interactive tools	IEA, 2001

Integrating two categories of assessment tools into one hybrid tool has been suggested by some authors, such as Soebarto and Williamson (2001) and Trusty and Horst (2002). Soebarto et al. (2001) integrate a holistic and a reductionist approach. They suggest a new methodology for approaching a multi-criteria problem, converting it into a two-criterion problem by forming a weighted sum of the benefits and cost for each solution and formulated it in terms of a familiar benefit-cost analysis model to then calculate the net benefit for the solution. Trusty et al. (2002) clarify the significant benefits of integrating LCA tools into criteria scoring systems, which may also reduce assessment complexity and cost. The U.S. Green Building Council's USGBC work to incorporate the life cycle assessment of buildings materials as part of the LEED program is a direct result.

2.4 Critical analysis of existing sustainability assessment methods

The building sustainability assessment field has provided a key focus for building research and practice in the past decades since it is used as an interface between environmental, social, and economic concerns in a decision making framework which enables all the stakeholders/actors to be aware of the consequences of various choices.

There is a variety of tools and methods of assessment that have been used and tested with different goals as to what objectives to analyse. These assessment methods are at different stages of development. Suggestions about the insufficiencies of current building assessment methods are available in the literature. It is necessary to study the existing tools and methods in sufficient detail in order to learn lessons from their strengths and weaknesses. Therefore, critical analysis is conducted after grouping the existing methods based on the proposed categorization (see table 2.2).

Haapio and Viitaniemi (2008) clarify the importance of analyzing the building sustainability assessment methods in groups rather than separately, which enables the investigation of shared aspects and common features, emphasizes the differences, and makes it easier to identify the limitations and weaknesses. Therefore, the current situation of building assessment methods tools is analyzed in groups (see section 2.4.2).

2.4.1 Categorization of existing tools/methods of sustainability assessment

Over the last two decades, sustainability assessment has witnessed a rapid increase in the number of building assessment methods. A new categorization is proposed and an appraisal of contemporary assessment methods addressing sustainability at the micro (individual building) level is conducted to understand the mechanics of assessment.

The proposed categorization of building sustainability assessment consists of three general categorizations: 1) Multi Criteria Assessment (MCA), 2) Life Cycle Analysis (LCA), and 3) Single Index (SI). Life Cycle Analysis is categorized separately for its uniqueness in using a unique single indicator, such as life cycle cost, life-cycle energy consumption, life cycle impact, life cycle exergy lost and life cycle CO_2 emissions, or using more than one indicator. ISO (1997) presents the importance of using a single indicator, as it may reduce the difficulty of comparing different design alternatives by decreasing the number of objective functions that will be handled through the assessment.

2.4.1.1 Multi Criteria Assessment (MCA) methods

Multi criteria assessment (MCA) is an approach that allows the designer or the user to test the design strategies against different sets of criteria where the performance of a building is always compared to a reference building. References are usually selected to lend meaning and to give political weight to the available data. They are mostly used in the results' interpretation. These references might be threshold values (distance to collapse), baselines (distance to a certain meaningful state), targets (distance to political, hard or soft targets), or benchmarks (difference from another country or standard). Multi-criteria assessment can also be used to investigate incremental improvement assessed against a single criteria (i.e., reduced energy consumption) (Soebarto and Williamson 2001). Criteria scoring systems are considered as a type of subjective assessment.

Assessment methods within this category have the advantage of covering the most issues and providing detailed insights, but these sets are complex and difficult to interpret.

Two types of approaches can be distinguished by how they describe a building's overall performance: with a single value or with an array of values. Two steps are used to reduce the overall assessment score to a single value: starting with the simple designation of a number of points for each criterion, using a different scoring system and without concern for the relative importance of one criterion relative to others, and then using a simple aggregation to provide a total score. The array method uses a common scale as the basis for assessing all criteria and then applies weightings to acknowledge the different significance of each criterion prior to deriving the aggregate score (Cole 1999). While a single result approach is easy to understand, the array approach provides more detail. LEED is as an example of an assessment methodology utilizing the single number approach, while SBTool uses the array approach.

2.4.1.2 Life Cycle Assessment (LCA) of energy, cost and emissions

Life cycle assessment is a methodological framework for estimating and assessing the environmental impacts (e.g., climate change, stratospheric ozone depletion, eutrophication, acidification, toxicological stress, depletion of resources, water use and others). It is an analytical tool to assess a product, whether goods or services, by taking a "systems" perspective across all life phases. It considers all attributes or aspects of human health, ecosystem quality, resource and life cycle cost attributable to the life cycle of a product, process, or service across all life phases except the operation phase (Rebitzer et al. 2004; Szalay 2007). Simpson et al. (2011) described LCA as an extension of first-law analysis since it tracks the mass and energy of the inputs and outputs of a system.

Crawley et al. (1999) clarify the difference between Environmental Impact Assessment EIA and LCA, since the former focus on assessing the actual performance of an object located on a given site and in given context, whereas LCA is formulated to assess the non-site-specific potential environmental impacts. LCA considers all the phases of the building process. The life cycle of a building spans from resource extraction to final demolition and recycling, through production, construction and sometimes maintenance and renovation throughout the operation stage. LCA requires some assumptions such as the expected lifetime of a building and user behaviour (Nibel et al. 2005).

According to Wang et al. (2000), four major phases are recognized through the LCA process: 1) goal definition and scoping (the purpose and the temporal and spatial boundaries are defined); 2) inventory analysis (input and output are quantified using the same unit; otherwise, transformations between different units are involved); 3) impact analysis (evaluation of the potential impacts of inflow and outflow following some mandatory steps, as well as one or more of the optional steps). Mandatory steps include the selection of impact categories, classification, and characterization; optional steps include normalization, grouping and weighting; and 4) interpretation (verification of the impact assessment results according to predefined goals from the first phase and reporting them in a neutral and informative manner).

Distinctions between two types of LCA, attributional and consequential, have been presented by many authors (e.g., Heintz et al. (1992); Weidema (1993); and Ekvall

(2000)). The distinction between these types of LCA, which is based on their goals, is quite important since it affects how the product system is modeled. While the term "attributional LCA" is used to describe a product system and its environmental exchanges, "consequential LCA" describes the expected change of the system as a result of actions taken in the system.

Functional units, technological change and data- and labor-intensive aspects are the three issues that most need to be addressed in LCA building assessment. According to Finnveden et al. (2009), LCA differs from other assessments in its definition of functional units (e.g., emission to air) and in how the boundary between a system, a building, and the environment is drawn (extended in time and space) -- a definition which is often decisive for the result of an LCA study. Frijia et al. (2012) elaborate on that concept and argue the importance of applying a restricted functional unit, bounding the functional unit to a climate-controlled space rather than to the activities that occur within the building space. If restricted functional is applied, the building's life cycle energy that can be attributed to materials and construction is increased from 0.4-11% to approximately 30%. LCA is criticized for its retrospective approach which can be overturned by technological developments. Forecasting retrospective trends in material flows or constructing future technology scenarios and then relating such scenarios to material flows are two of the means suggested to deal with the consequences of technological changes. Since LCA is data- and labor-intensive, parametric models could be implemented to address those challenges.

Some examples of LCA-based tools include BEES (U.S.A), ENVEST (UK), ATHENA (North America), EcoQuantum (Netherlands), EcoEffect (Sweden), Ecoprofile

(Norway), and BEAT 2000 (Denmark) (Seo 2002). ENVEST (UK) is one of the tools that calculates the operating energy consumption with simplified methods and that also brings a broader range of considerations to the assessment process (Cole et al. 2005). If the LCA is combined with life cycle costing (LCC) then two pillars of sustainable development (environmental and economic) will be covered. Baouendi et al. (2005) developed EEE as a prototype tool that is coupled life-cycle energy consumption, greenhouse emissions, and life cycle cost for house.

2.4.1.3 Single Index (SI) methods

Sustainability indicators are considered as an effective means for assessing the degree of sustainable development (SD). Useful indicators are those that can be adopted effectively to translate abstract concepts into quantifiable data and describable measures. SI methods are capable of characterizing various aspects of sustainability, such as cumulative indices or collections of indicators into a useful metric. However, it is a challenge to turn indicators into a decision-support system. Numerous researchers have indicated the four main categories of issues that need to be resolved: 1) the ability to monitor the progress towards sustainability, 2) ease of use, with indicators that are easily understood by decision makers, 3) flexibility in selecting indicators and units of analysis, and 4) providing research results in a format that is clear to non-professionals.

The usefulness of a sustainability assessment method depends on the number of indicators: too few may not provide an adequate description, and too many could make the cost of completing the assessment prohibitively high. Identifying the best indicators and the optimal number that present the issues of sustainability will be a real advance. It is extremely difficult to interpret the results of assessments that do not combine their indicators into a small set of indices, whereas those that do combine their indicators into a limited number of indices can provide a clear picture of an entire system. However, the aggregation itself may have a significant influence on the overall scores, which could intentionally or unintentionally introduce arbitrary weightings or other user-controlled features.

Single index (SI) assessment is the third category of sustainability assessment methods, and provides evaluations through the development and utilization of single sustainability metrics. Mayer (2008) defines an index as a single measure that can quantitatively aggregate the value of several indicators to provide a simplified, coherent, and multidimensional view of a system. Even though SI methods are quite contrary to the MCA in approach, they are also complementary. The MCA analyses the elementary components of a system (criteria-based) in order to evaluate it, whereas the SI approach seeks to consider the entire system in its complete complexity by using one single index. ISO (1997) presents the importance of a using single indicator that may reduce the difficulty of comparing different design alternatives by decreasing the number of objective functions that will be handled through the assessment. Two metrics that can be put into practice as sustainability metrics are monetary and biophysical metrics, which have a similar procedure of initial quantification and subsequent aggregation for the diverse issues of sustainability (Gasparatos et al. 2008). These tools utilize a common currency/denominator (e.g., money, land or energy) which is defined as the tool's metric.

Pearce et al. (1989) and Pezzey et al. (2002) noted that monetary tools were the ones first proposed for assessing sustainability, but, due to the inadequate expression of environmental and social issues in monetary terms. Other measures with a solid foundation in natural science using biophysical models were subsequently proposed.

Monetary tools

Monetary measures of sustainability represent an attempt by economists to incorporate the concept of sustainability into an existing theoretical framework. Monetary indices are classified into two types, those pertaining to green national accounting and those attempting to measure general well-being (Farrell and Hart 1998).

A number of monetary tools that have the potential for assessing sustainability are reviewed by Gasparatos et al. (2008): the Contingent Valuation Method (CVM), Cost Benefit Analysis (CBA), and the Index of Sustainability Economic Welfare (ISEW), where money is used as common denominator or currency. Adapting existing monetary tools to assess sustainability has gained validity due to their strong theoretical foundations in economic theory. Pearce et al. (1989) argue that money is a useful metric because of the intensity of that preference, and because monetary values are relatively easy to be understood by non-experts and relevant stakeholders. However, Alberti (1996) shows that monetary tools are over-dependent on subjective valuations, not flexible enough to assess the progress towards sustainability in a holistic manner, and inadequate, since sustainability assessment goes beyond economic efficiency.

Furthermore, several criticisms related to the methodological and conceptual aspects of valuing certain environmental and social issues (e.g., placing dollar values on human life) have recognized that some issues cannot be translated meaningfully into a valuation in terms of product services in existing markets. This aspect renders the generalization of research results quite problematic (Pearce et al. 1989). Sinden (2004) observes that the monetary approach lacks authenticity as to how individuals actually value diverse goods. Howarth (1996) adds that discounting is an important and controversial aspect, performed in order to compare future values with present ones. Consequently, future impacts with long time horizons and a greater discount rate count for very little in the present, which is contrary to the goal of equity between different generations.

Biophysical tools

The foregoing criticisms related to monetary tools were the major drivers behind the establishment of biophysical tools that use a metric other than money (Nonmonetary tools). Ecological footprint (EF), emergy synthesis and exergy analysis are the most comprehensive tools in this category, and to date are the only three that have gained some acceptance among academics.

Ecological Footprint was founded by M. Wackernagel and W. Rees (Wackernagel and Rees 1996). It is based on the area of land as a limiting factor. The most acceptable definition that conveys the meaning of the approach is an accounting tool that estimates the productive land area, measured by "global hectares" (gha) that is required to sustain the current load of resource consumption and waste discharge by a defined human population or economy, using existing technology (Hau and Bakshi 2004). This index is sensitive to geographical location, and it is criticized because it requires a large number of conversion coefficients to be developed.

Emergy analysis (EMA) is a type of quantitative analysis that explicitly determines the value of ecological and economic aspects (Brown and Herendeen 1996), services and commodities in common units of solar energy, abbreviated as sej (Odum

1988). It is described by Sciubba et al. (2005) as a "Top-down" process. Emergy flows are aggregated to provide a simplified picture of the metabolism of a system, linked to relevant aggregated flows such as renewable resources (R), non-renewable production (N), and purchased services (imports/exports) (F) (Giannetti et al. 2006). The attractive features and criticisms of EMA have been clarified (Hau et al. 2004; and Gasparatos et al. 2008). Among these attractive features are: 1) the ability to compare different materials/energy sources, using its common unit; 2) it jointly addresses economic and ecological systems which could be considered as an alternative for many holistic approaches that go beyond the single process; and 3) it takes into account the contribution of the ecosystems to human well-being. Inversely, some of emergy analysis' criticisms are that: 1) it ignores the human preference, and 2) it has an uncertainty in its utilized transformity values.

2.4.2 Review of building assessment methods

Some of the existing approaches are studied in detail to learn from their strengths and weaknesses. The review covers the three categories of assessment methods. The choice of these assessment methods was guided by the need to study methods that assess the whole individual buildings and systems; assessment methods at an urban scale and for products are excluded as their objectives are not within the scope of this research. Most of the selected assessment methods are already in use in Canada. The main reasons for selecting these methods are summarized in Table 2.3.

Table 2.3: Reasons for selecting assessment methods and tools for review

	Category	Assessment method	Reasons for selection	Reviewed Table
1	LCA	ATHENA	Construction oriented, considers overlap, waste and other miscellaneous ancillary materials	Table A.1
2	MCA	LEED	Uses single number approach Wide international acceptability	Table A.2
3		SBTool	Uses array approach One of the most comprehensive approaches Internationally tested in more than 14 countries	Table A.3
4	SI	Cost Benefit Analysis	Universal applicability of the concept Money is used as a single metric	Table A.4
5		Ecological footprint	General applicability Area is used as a single metric	Table A.5
6		Exergy	Universal applicability of the concept Exergy is used as a single metric	Table A.6

Each method was assessed for its ability to address sustainability as a function of social, economic, and environmental factors. The structural organization, functional and performance aspects as well as several other aspects were examined, including: framework (defines the theoretical approach underpinning the method); scale (defines the level of assessment that can be handled, spans from building product to urban); scope (defines the range of criteria, and the temporal and spatial boundaries); approach (defines the dynamics of the assessment process adopted by the tool); objectives (define the relationship between objectives, methods and results); indicators (determine which aspects of the building are being assessed); methods of measurement (define the techniques and data that are required to achieve the objectives; weighting (defines how weighting is used to show the relative importance of the issues assessed); and reporting results (how the final results are presented to be understood by people).

2.4.3 Limitations of existing rating systems and indices

Despite the usefulness of the current assessment tools and methods in contributing towards more sustainable buildings, these tools have limitations that may affect their future effectiveness in the context of assessing building sustainability. Some of these limitations are applicable to the three types of assessment tools and methods and some are more specific to one type.

Specific limitations emerging from the experience of reviewing building assessment methods include the following:

i. The scope and boundaries of the existing tools do not cover the whole life cycle of a building which limits their credibility;

ii. Most of the existing tools are not complete since they are limited to a few parameters (each parameter includes several criteria) and none of these methods incorporate all of the parameters, especially economic and social aspects (e.g., ATHENA indicators cover only primary energy, global warming, solid waste, air pollution index, and water pollution index);

iii. Most of the assessment tools and methods are not widely utilized because they entail a level of complexity and require significant time to input and process the data. The expense incurred to prepare the assessment makes such tools unattractive to users;

iv. The current tools have different options to define, customize and quantify benchmarks in order to evaluate indicators. Benchmarks are location- and time-dependent variables. The time dependency of a benchmark makes it difficult to be defined as it is a function of future building standards. Over time, benchmarks need periodic review and eventually modification in order to comply with new standards (e.g., LEED benchmarks are adapted yearly based on new standards) (LEED 2007). The location-dependency of benchmarks explains the need for a third party to define some user-defined benchmarks to comply with regional applications (e.g., SBTool is not valid as an assessment tool unless it is calibrated to local conditions). In many tools the benchmarks were developed to satisfy a specific context (local use) and do not allow for national or regional variations. Benchmarks are essential for building assessment but they should not use skewed standards to assess today's building alternatives;

v. The subjective nature of the scoring system makes it difficult to provide reliable results, since existing tools are mainly based on relative performance. These tools evaluate a building against specific requirements rather than measuring building performance against carrying capacity (Cooper 1999);

vi. Most of the existing assessment tools and methods use the approach of weighting different criteria in order to calculate a single performance index. Applying weightings emphasizes the difference among criteria and summarizes the performance results using an aggregated score, but does so at the expense of introducing some subjectivity into the tools and assessment frameworks. It is also diminishes the ability to highlight priority issues to address. LEED allocates equal weights to each criterion, and SBTool allocates weights through a subjective voting process.

vii. There is no sensitive scale with which to differentiate between the potential building alternatives based on the methods used to assess the indicators. Existing approaches use either a binomial approach (e.g., in LEED, a building earns a point if it meets certain requirements or loses a point if it fails to satisfy a predefined requirement) or rang-based models (e.g., SBTool subdivides the level of performance achievement using a rang-based model from -1 to +5);

viii. There is an absence of a clear target (a clear objective function) to be achieved or to be optimized; and

ix. The variety of sustainability indicators poses a huge problem, especially since decision makers demand an aggregate index that can be clearly interpreted and easily communicated to non-expert users and the general public.

2.5 Indices of sustainability using exergy-based methods

Exergy is defined as the maximum amount of useful work that can be delivered by a system as it undergoes a reversible process from the specified initial state to the state of its environment (dead state) (Cengel and Boles 2008). Exergy analysis can evaluate quantitatively the cause of thermodynamics imperfection of the process. While energy analysis can be misleading since it does not measure the approach to ideality, exergy does by taking into account the quantity of energy available as well as the quality of that energy, the first and second law thermodynamics. Therefore, exergy gives a clear indication of where system inefficiencies are located as well as the locations, types and true magnitudes of wastes and losses (Dincer and Rosen (2007)).

After introducing earlier categorizations of sustainability assessment methods and the new categorization, this section focuses on those indices that are used to assess sustainability in terms of environmental impacts.

- Wall (1977) observed that resources can be quantified based on exergy flows since society is dependent either on exergy flows from finite deposits, exergy in minerals or exergy flows from funds (e.g., forest and fields which convert solar energy). He suggested that quality is what is consumed during the conversion of energy and matter.
- Kotas (1985) and Szargut et al. (1988) explained that exergy analysis is focused on the efficiency of the production process. It is implemented either for single processes or for a whole production chain. The former usage compares the total exergy included in the products, the by-products, and the heat and waste that is utilized from the exergy embodied in resources. The later shows the overall efficiency of the production chain through the ratio of the exergy embodied in the product over the cumulative exergy consumption (CExC). This analysis shows the depletion of environmental resources induced by product generation.
- An exergy tax was suggested by Wall (1993) as a first step to decrease environmental destruction and to improve present resource use.
- Cornelissen (1997) suggested that exergy losses should be minimized to obtain sustainable development, and he also showed that environmental effects associated with emissions and resource depletion can be expressed in terms of an exergy-based indicator.
- Dewulf et al. (2000) used a set of three sustainability indicators to express the sustainability of technological processes: α for renewability (resource utilization), η for the conversion of the energy in the process, and ξ for the environmental compatibility of the process. The first two indicators are scaled between 0 and 1. The

value of zero for both parameters means a zero fraction of renewable exergy in the resource use and an efficiency of zero. The value of 1 means 100% renewable-based and efficient processes. The third indicator ξ relates the exergy required to run the process to the exergy required to run the process in an environmentally sound way. The environmental parameter goes to 1 only if a process requires no abatement exergy. Dewulf et al. combined the second and third indicators into an overall efficiency parameter $\eta_{overall}$. They defined the overall sustainability coefficient S as an average of the two sustainability parameters α and $\eta_{overall}$.

- Rosen et al. (2001) illustrated how sustainability increases and environmental impact decreases as the exergy efficiency of a process increases (e.g., when exergy efficiency approaches 100%, environmental impact approaches zero, since there is no exergy loss corresponding to the conversion from one form to another, and the sustainability index approaches infinity when a process approaches reversibility).
- Gong et al. (2001) found that the proposed thermodynamic conditions of sustainable life support system based on Delin's definition of sustainability offers an accurate measurement for sustainability. Moreover, the measurement is insensitive to political and economic effects. Delin's definition implies that exergy must be stored on the earth, which means that the incoming energy from the sun has to be greater than the outgoing energy (Zmeureanu 2006). Gong et al. used the life cycle exergy analysis to define sustainable engineering. If the input of exergy used to build any building application is less than the output of exergy over the service life for that application then it is considered to be sustainable.

- Arons et al. (2004) revised the quantification method expressed earlier by Dewulf et al. (2000) in a set of three independent sustainability indicators, α, η, and ξ. The first parameter is completely different from the element given by Dewulf while the second and third are revised elements. He calculates α using resource time depletion, τ, instead of considering renewable versus non-renewable sources. The depletion time is used as a measure for the rate at which the known reserves of a resource are being depleted (based on the gap between the consumption and regeneration rate of that resource).
- Dewulf et al. (2005) considered two other sustainability indicators which reflect the integration of the process with the natural ecosystem: (i) the re-use indicator ρ is the fraction of waste used as a resource in the overall package of resources, and (ii) the recoverability indicator σ is the fraction of the generated product that can be recovered later.
- Cornelissen et al. (2002) concluded that the exergetic life cycle assessment can be applied to determine the depletion of a natural resource as the difference between the life cycle irreversibility $I_{lifecycle}$ and the exergy content of the renewable $Ex_{renewable}$ (the positive effects of the exergy absorption are assigned on the moment when the exergy is absorbed in renewable fuels, since the CO_2 emissions from using renewable resources do not increase the greenhouse effect).
- Rosen et al. (2008) expressed the sustainability of a fuel resource as a sustainability index; the inverse of the depletion number. The depletion number is defined as the ratio between the exergy destroyed (Ex_D) and the exergy input (Ex_{in}) by fuel consumption. The relationship between depletion factor and efficiency is also

represented by the difference between the ideal state (when the exergy input is equal to the network produced by the system) and the depletion number.

- Lee et al. (2007) implemented a sustainability index for Taipei city that clearly belongs to the weak sustainability approach. Statistical data is adopted to identify the trend of SD from 1994 to 2004. The sustainability index was calculated for the four dimensions (economic, social, environmental and institutional) for Taipei as a whole. Standard deviation was the basic method for calculating the sustainability index, as has been applied in this study. It standardizes the indicator values so that each standardized value falls between 0 and 1. Finally, the equal weight method was applied for initial integration and to analyze the overall sustainability trend.

2.6 Objectives of the thesis

Based on the overview of research on the sustainability assessment, this study focuses on the use of the exergy concept to quantify building sustainability. A global assessment framework capable of considering the regional issues, valid to assess all types of buildings, that is easy to customize, objective, and easy to interpret is needed in the field today. The primary objective of this research is to develop a new methodology for the estimation, at the conceptual design stage, of a building's sustainability over its assumed life span, $L_{service}$, that allows for the potential design alternatives to be explored in the search for a sustainable design alternative. A new index is proposed along with a rating scale.

Other sub-objectives of this thesis are:

i) The development of a new quantitative and scientifically based definition of building sustainability that can be used as an acceptable platform for a reliable framework that allows the level of building sustainability to be systematically evaluated;

ii) The measurement of building sustainability within its wider context, in relation to energy and non-energy natural resources;

iii) The development of benchmarks to meet the need for temporal and spatial changes in a building, and to compare buildings in the same city or in different countries;

iv) The development of an objective assessment and elimination of the use of subjective weights; and

v) The estimation of the potential for improving building performance.

2.7 Scope and methodology

This research proposes a new methodology for the estimation, at the conceptual design stage, of a building's sustainability over its assumed life span, which produces and utilizes a new Exergy Index of Sustainability (ExSI). The prototype tool presented in this thesis uses data extracted from SBTool; however, work should be done to have a stand-alone evaluation tool that can accept data from other tools (via text files) and/or receive inputs from users. ExSI is built on the limitations of existing methods and tools of assessment. In order to satisfy the stated objectives, the research proceeds as explained in the four main phases shown in Figure 2.1.

In phase no.1, a literature review was conducted to examine the existing assessment methods, tool rating systems, and approaches. This review was mainly devoted to exploring the key aspects that exist either implicitly or explicitly in all assessments (e.g., scope and boundaries, scale of measurement, references and benchmarks, scaling increments, target performance, and interpretation). The review extended to cover the classification of sustainability assessment methods to better understand the state of the art. A review of selected building assessment methods covering the three categories of assessment methods helped to structure their limitations in a useful fashion. The indices of sustainability using exergy-based methods were also presented.

The SBTool is detailed in the second phase as a sustainability assessment framework, one that has been widely adopted in different countries and that is rated higher than many multi-criteria rating tools. SBTool is the most nominated method to assess the buildings sustainability, despite some shortcomings (weighting). SBTool exposes and addresses a broad range of aspects of building performance (179 criteria can be used to assess building sustainability), including some that are still controversial.

Sensitivity analysis was used to focus the research scope so that the most significant issues for assessing building performance could be identified. The results given by the SBTool is the starting point for this study. To assess building sustainability by calculating the proposed exergy-based index, the following steps are conducted:

Step 1: Extraction of the results from the SBTool for each criterion;

Step 2: Process the results from SBTool and perform additional calculations, when needed, to estimate the energy use for each criterion;

Step 3: Calculate the exergy lost for each criterion;

Step 4: Calculate the annualized total exergy lost due to the building construction and operation, as a sum of the corresponding values for all criteria;

Step 5: Calculate the annual exergy index of renewability α_{ex}.The annual exergy index of renewability α_{en} is the ratio between the annual available solar exergy that can be harvested by the building footprint (horizontal plane) and the exergy lost in the building construction and operation;

Step 6: Calculate the annual exergy index of building sustainability (ExSI) by using the corresponding index of renewability α_{ex}; and

Step 7: Evaluate the overall performance using a proposed rating scale.

The third phase in the research methodology deals with applying the proposed framework to several case studies. Detailed calculations of the proposed methodology are only presented for case study no.1, while for the other case studies only the major results and findings are presented. The benefits of using the proposed exergy-based index is demonstrated by conducting a comparison between the results obtained using the proposed ExSI and the results obtained using the sustainability indices found in the literature. Index disparities are discussed and methodological issues are directly addressed. The final phase, phase no.4, is the final part of the research methodology which is devoted to presenting the research conclusions, contributions, and recommendations for future work.

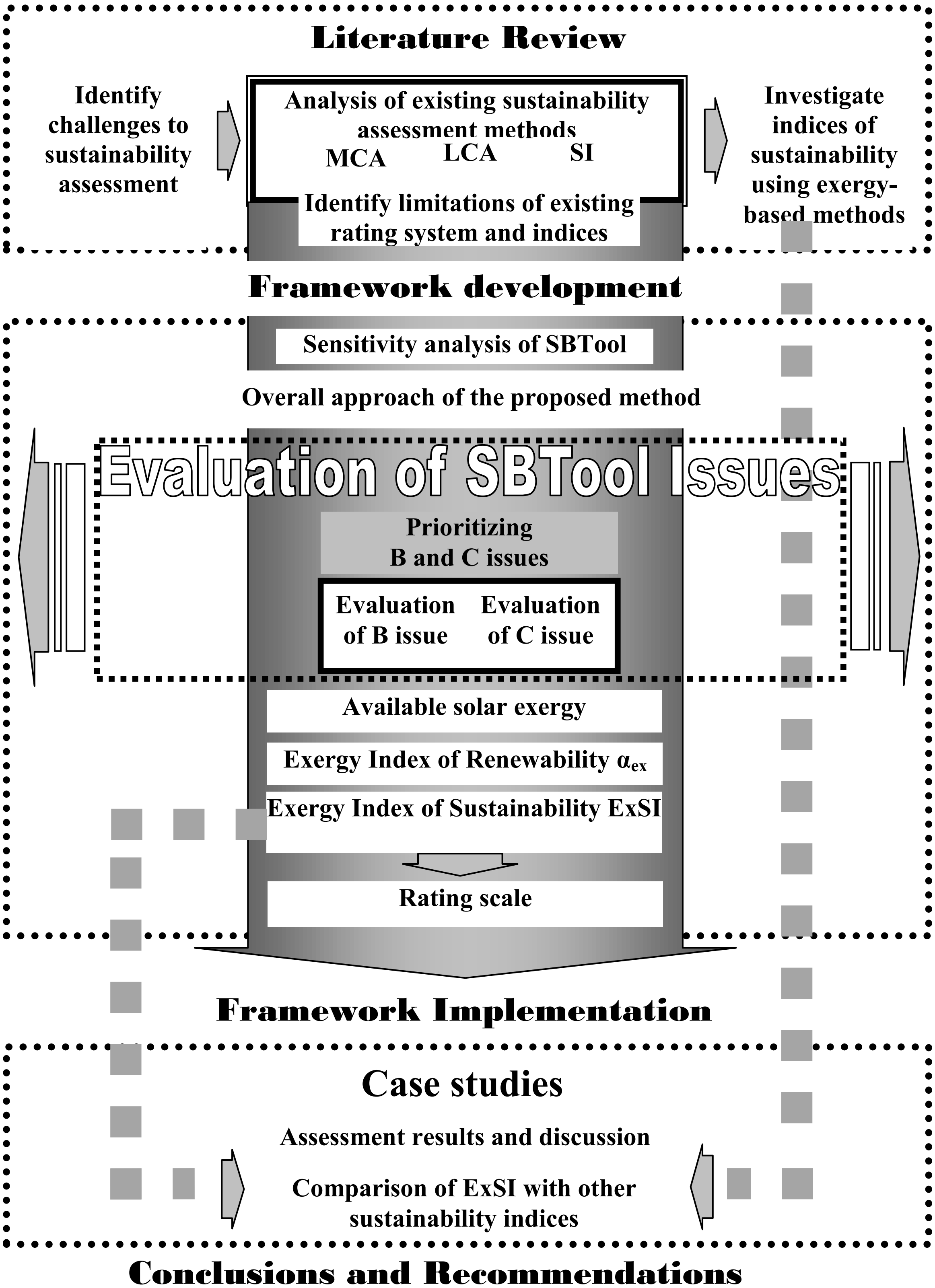


Figure 2.1: Research methodology

3 SBTOOL FLOW PROCESS

SBTool (iiSBE, 2010) was developed by an international committee and is structured so that it can be tailored to respond to national specifications. It assesses buildings in terms of seven issues: site selection, energy and resource consumption, environmental loading, indoor environmental quality, service quality, social and economic aspects, and cultural-perceptual aspects. Each issue is divided into several categories, and in each category there are a specific number of criteria, assessed and assigned a score ranging from -1 to +5. Individual criteria are weighted to indicate their importance, their scores are multiplied by these weights and the resulting values are summed.

3.1 SBTool's Features

SBTool is the latest version of software formally known as GBTool, promoted by the Green Building Challenge (GBC). It was initially launched by Natural Resource Canada in 1996, but responsibility was handed over to the International Initiative for a Sustainable Built Environment (iiSBE) in 2002. The generic framework has been calibrated and is being used and developed through collaborative work supported in more than 20 countries. The change of the name reflects the inclusion of a range of issues that includes socio-economic variables. SBTool has three levels of parameters: Issue as parameter no.1 (e.g., B issue Energy and Resource Consumption); Category as parameter no. 2 (e.g., B1 category Total life cycle non-renewable energy); and Criterion as parameter no. 3 (e.g., B1.1 criterion Annualized non-renewable primary energy embodied in construction materials), see Figure 3.1.

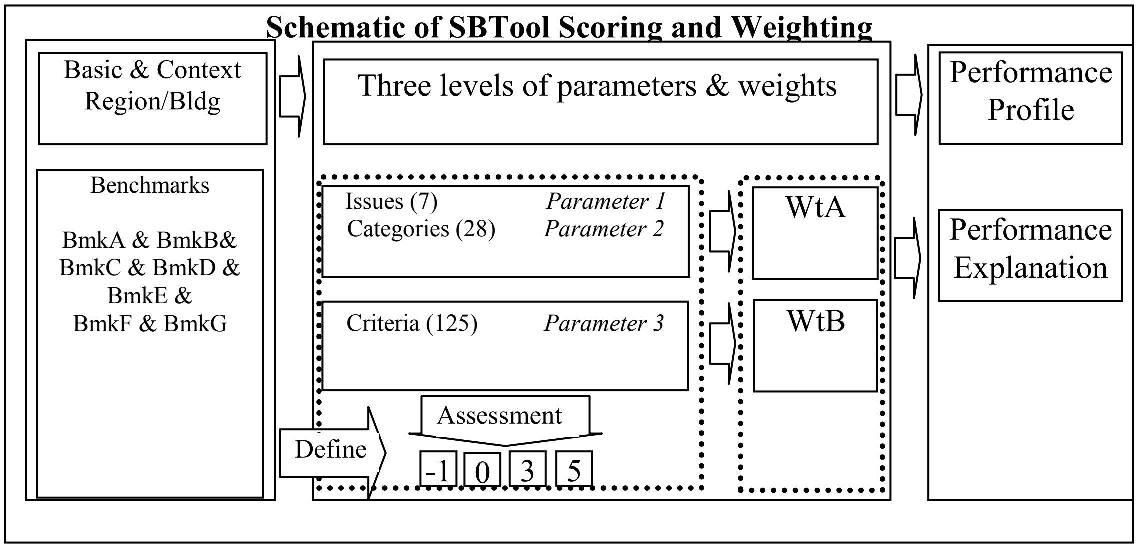


Figure 3.1: Schematic of SBTool scoring and weighting

The issues covered by SBTool include: A (site selection, project planning and development), B (Energy and resource consumption), C (Environmental loadings), D (Indoor environmental quality), E (Service quality), F (Social and economic aspects), and G (Cultural and perceptual aspects). The scope of the SBTool can be modified to cover as much as desired, from a minimum of 6 to a maximum of 125 criteria; a reflection of the system's flexibility. The scope can be defined in different forms, as shown in Figure 3.2: a form that suits the definition of a Sustainable Building, another form that suits the definition of a green building, or a compact form suitable for agencies. The most important feature of the SBTool is that it can handle all four major phases of the building life-cycle for both new and renovation projects, with up to three occupancy types (out of a total of 18 different occupancy types) in a single project.

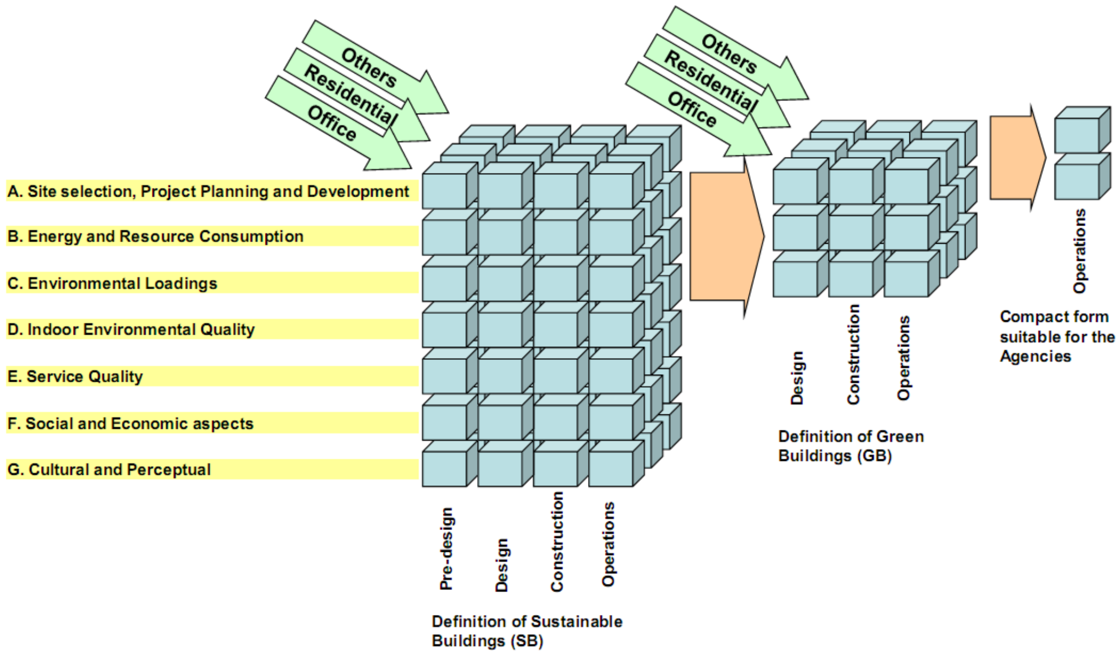


Figure 3.2: Scope of the SBTool system

3.2 SBTool Flow Process

SBTool is a rating framework, and is only valid as a rating tool when a third party calibrates it for their region by setting scope, context, weights and performance benchmarks according to the local conditions (see Figure 3.3).

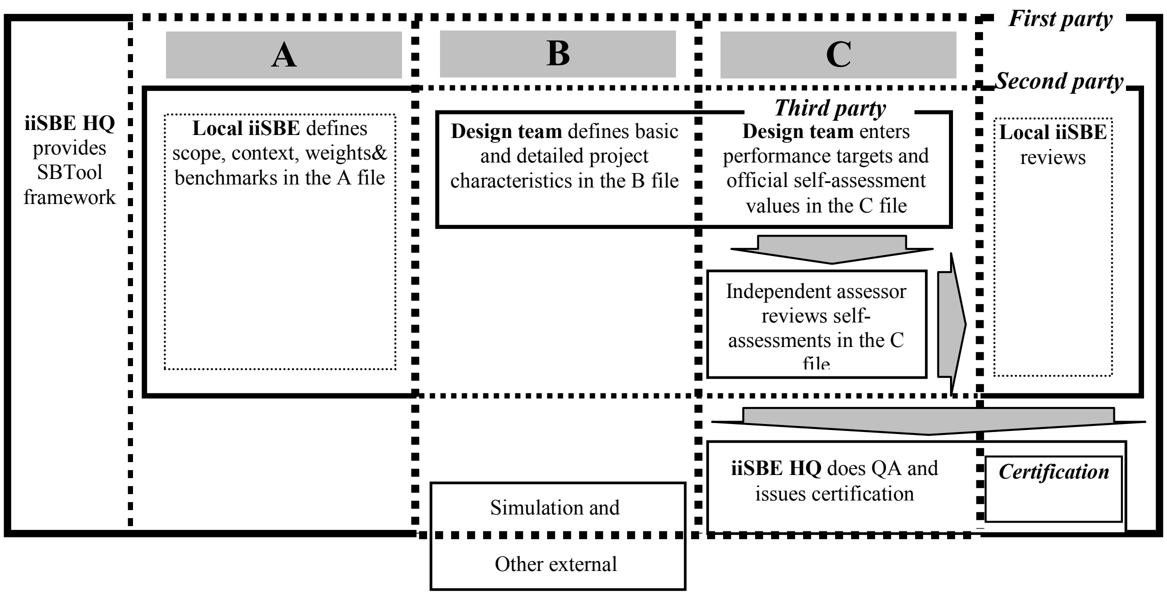


Figure 3.3: SBTool flow process

SBTool is designed to incorporate consideration of regional conditions and values without destroying the value of a common structure and terminology.

The SBTool system consists of three interconnected modules using excel files A, B, and C as presented in Figure 3.3. File A is used by regional third-party organizations to establish the context information, occupancy type, locally-valid weights, and benchmarks settings (through a review of regulations or by consensus within small expert groups), defines the associated assessment score of from -1 to 5 for each benchmark, and establishes parameter weights that reflect the relative importance of issues, categories, and criteria in each region. File B represents both the "input module" and the "assessment module". The input module contains a considerable amount of information related to the case study building and its context, and the assessment module influences where the performance scores are assigned to the different criteria being examined in the assessment process. File C represents the output module, which is used to identify the design target and self-assessed scores and also presents the results for all these calculations along with the absolute performance results.

3.3 Sensitivity Analysis of SBTool

The sensitivity analysis for the SBTool evaluates how the total final building score changes with the change of actual performance as per contract documents (SBTool, 2007), or with a change in the selected weights.

3.4 Sensitivity analysis of the SBTool final score to change for each criterion

A sensitivity analysis was conducted to assess how sensitive the final building score is to changes in the actual performance, assuming that SBTool default weights are used. The change of the actual value of the Annualized non-renewable primary energy embodied in construction materials (B1.1 criterion) is given as an example. The predicted embodied energy for materials used in the structure and building envelope is changed from 115 MJ/m^2 per yr or –1 as the lowest performance score (worst scenario for actual performance) to 67 MJ/m^2 per yr or 5 as the best performance that can be achieved (best scenario for the actual performance). The incremental change of each weighted score is equivalent to 8 MJ/m^2 per yr. The actual performance for criterion B1.1 is tied to a specific weighted score, as shown in Figure 3.4. The relationship between the weighted score for each criterion in SBTool versus the actual performance is a linear one.

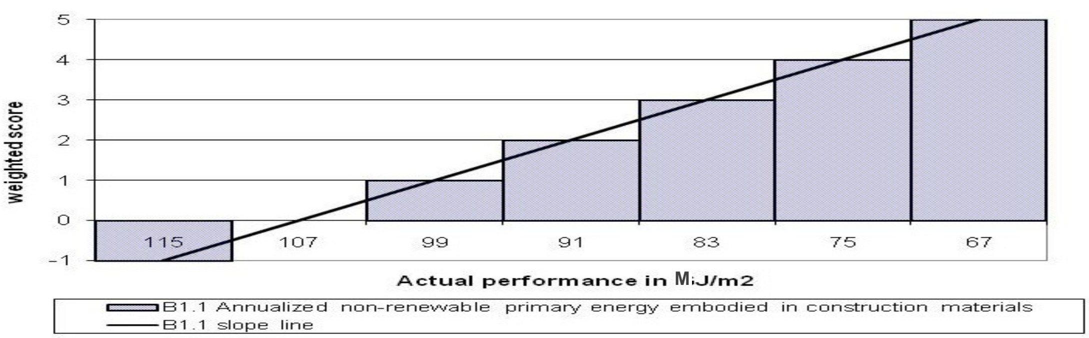


Figure 3.4: Linear relationship between the weighted score for the B1.1 criterion versus the actual performance

The following steps were followed:

i. Changing the values of the actual performance score for each criterion. Note that all the values of the actual performance for each criterion were evenly distributed; linked to the weighted scores in a range of -1 to +5. Table 3.1 is an example of the changing values for the actual performance score of the (B1.1) Annualized non-renewable primary energy embodied in construction materials.

Table 3.1: The change of weighted score (-1, 0, 3, and 5) for criterion B1.1 and its effect on the relative performance results given by the total weighted building score

Issue	B Energy and Resource Consumption		
Categoery	B1 Total life Cycle Non-Renewable Energy		
Criteria	B1.1		
	Actual performance		
Weighted score	Apartment	Retail	Indoor parking
-1	115	168	152
0	107	160	147
3	83	136	131
5	67	120	120
Unites used	MJ/m2 per yr	MJ/m2 per yr	MJ/m2 per yr
		Active Weights	Weighted scores
Change the weighted score to **-1** for B1.1 criterion	A Site selection	8.1%	2.68
	B Energy and Resource Consumption	22.5%	2.64
	C Environmental Loading	27.0%	2.23
	D Inddor Environmental Quality	18.0%	2.60
	E Service Quality	16.2%	2.19
	F Social and Economic aspects	5.4%	2.51
	G cultural and Perceptual	2.7%	3.50
Total weighted building score (Self-Assessment Score)			**2.47**
Change the weighted score to **0** for B1.1 criterion	A Site selection	8.1%	2.68
	B Energy and Resource Consumption	22.5%	2.68
	C Environmental Loading	27.0%	2.23
	D Inddor Environmental Quality	18.0%	2.60
	E Service Quality	16.2%	2.19
	F Social and Economic aspects	5.4%	2.51
	G cultural and Perceptual	2.7%	3.50
Total weighted building score (Self-Assessment Score)			**2.48**
Change the weighted score to **3** for B1.1 criterion	A Site selection	8.1%	2.68
	B Energy and Resource Consumption	22.5%	2.82
	C Environmental Loading	27.0%	2.23
	D Inddor Environmental Quality	18.0%	2.60
	E Service Quality	16.2%	2.19
	F Social and Economic aspects	5.4%	2.51
	G cultural and Perceptual	2.7%	3.50
Total weighted building score (Self-Assessment Score)			**2.51**
Change the weighted score to **5** for B1.1 criterion	A Site selection	8.1%	2.68
	B Energy and Resource Consumption	22.5%	2.91
	C Environmental Loading	27.0%	2.23
	D Inddor Environmental Quality	18.0%	2.60
	E Service Quality	16.2%	2.19
	F Social and Economic aspects	5.4%	2.51
	G cultural and Perceptual	2.7%	3.50
Total weighted building score (Self-Assessment Score)			**2.53**

ii. Identifying the relationship between Y, the total relative weighted score for the building and X, the weighted score (Figure 3.4).

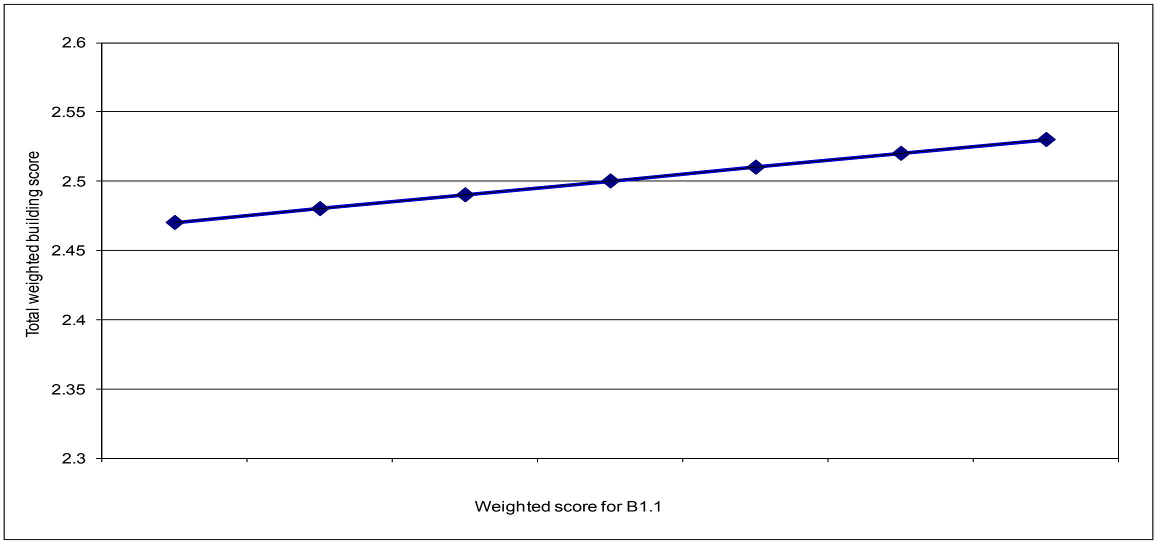


Figure 3.5: Relationship between the total building score and the weighted score for the B1.1 criterion under the B1 Total Life cycle Non-Renewable Energy category

iii. Identifying the sensitivity of the final building score by finding the slope of each linear relationship "e.g., the B1.1 slope". The greater the slope the more sensitive is the final score to the change of the weighted score of that criterion.

The results found by changing the score for each criterion reveal that the final score is more sensitive to changes in the actual performance related to issue B (Energy and resource Consumption), and C issue (Environmental Loadings) than to the D, G, E, and A issues (Indoor Environmental Quality, Social and Economic aspects, Service Quality, and site selection, respectively). This approach is applied to all criteria. The results of changes to issue B are presented in Table 3.2.

If we consider the slope of .01 as the threshold value, then those criteria with slopes greater than .01 are considered to have significant effect on the final assessment results. The total weighted building score is thus more sensitive to those criteria.

As an example, issue B (Energy and Resource Consumption) includes 18 criteria, 13 of which have a trend line with a slope bigger or equal to .01. The proportion of the issue B criteria with a relatively high effect on the final assessment result as judged by the change in the actual performance is 72 % (Table 3.2).

Table 3.2: issue B criteria whose relationship between the total weighted building score and the weighted score can be represented by a trend line with slope ≥ .01

B. Energy and Resource Consumption		
B1. Total Life Cycle Non-Renewable Energy		**2/2**
B1.1	Annualized non-renewable primary energy embodied in construction materials.	y = **0.01**x + 2.46
B1.2	Annual non-renewable primary energy used for facility operations	y = **0.0311**x + 2.32
B2. Electrical peak demand for facility operations		**1/1**
	Electrical peak demand for facility operations	y = **0.0118**x + 2.49
B3. Renewable Energy		**2/2**
B3.1	Use of off-site energy that is generated from renewable sources.	y = **0.0118**x + 2.48
B3.2	Provision of on-site renewable energy systems.	y = **0.0118**x + 2.48
B4. Materials		**6/10**
B4.1	Re-use of suitable existing structure(s).	y = **0.0221**x + 2.41
B4.5	Re-use of salvaged materials.	y = **0.0136**x + 2.43
B4.6	Use of recycled materials from off-site sources.	y = **0.01**x + 2.52
B4.7	Use of bio-based products obtained from sustainable sources.	y = **0.0136**x + 2.44
B4.8	Use of cement supplementing materials in concrete.	y = **0.02**x + 2.47
B4.10	Design for disassembly, re-use or recycling.	y = **0.0143**x + 2.46
B5. Potable Water		**2/3**
B5.1	Use of potable water for site irrigation.	y = **0.0121**x + 2.48
B5.2	Use of potable water for occupancy needs.	y = **0.0129**x + 2.45
Number of criteria that have slope ≥ .01 to the total number of criteria under each category		**13/18 = (72%)**

One can conclude that 72% of the issue B criteria and 63% of issue C criteria (those with slopes greater than .01) have led to significant change in the total weighted building score. Only 18%, 6%, and 7% of the criteria related to the D, E, and F issues, respectively, have the same condition (a slope greater than .01). This conclusion justifies why this study only addresses B & C issues through the suggested proposed approach for assessing building sustainability.

3.5 Sensitivity analysis of SBTool in relation to a subjective selection of weights

A sensitivity analysis is conducted to evaluate the effect of changing the subjective selection of weights for the three parameter levels (Issues, Category, and criteria) on the total weighted building score. The weights are implemented throughout the system, which strongly affect the validity of the system. The SBTool system uses the weights, which should be adjusted depending on the relative importance of the issues, categories, and criteria parameters for the building types and the regions. Although the default weights for the issues level might be seen as having some consensus relevance, the default weights for the categories requires adjustment to suit various project types within different regions. It is desirable to have a scientific basis to select such weights, and such a scientific basis is not yet available (Larsson 2007).

The process of conducting the sensitivity analysis for a subjective selection of weights for the highest two levels of parameters (Issues and Categories) follows these steps:

- **i.** Change the weights for each issue; weights range from 0 to 5. The change of the subjective selection of weights for issue B is represented as an example in Table 3.3. The weight for issue B (Energy and Resource Consumption) is changed from 0 to 5.
- **ii.** Calculate the nominal weights adjusted for number of active Categories using equation (3-1); the calculated values are listed in the third column of Table 3.3. Equation (3-2) is then used to calculate the weighted percent for issue B, and finally the total weighted building scores are obtained.

$$Nw_{Iss} = \frac{Numbers\ of\ categories\ in\ one\ issue}{Number\ of\ categories\ in\ all\ issues} \cdot \frac{Numbers\ of\ all\ categories}{Number\ of\ \ all\ issues} \cdot SN_{Iss}\ (subjective; e.g., user\ selects\ 5) \qquad (3\text{-}1)$$

$$Nw_{Iss}$$
$$= Nominal\ weight\ for\ issue\ (e.g., B. Energy\ and\ Resource\ Consumption)$$

$$= \frac{5\ categories}{28\ categories} \cdot \frac{28\ categories}{7\ issues} \cdot 5 = 3.6$$

$$W_{Iss} = \frac{Nw_{Iss}}{\sum Nw_{Iss}} \tag{3-2}$$

$$W_{Iss}$$
$$= Weighted\ percent\ for\ issue\ (e.g., B. Energy\ and\ Resource\ Consumption)$$
$$= \frac{3.6}{1.3 + 3.6 + 4.3 + 2.9 + 2.6 + .9 + .4} = .225 = 22.5\%$$

iii. The percentage of change for the total weighted building score (last column in Table 3.3) is then calculated as a ratio of the difference between the maximum and the minimum total weighted building score and the intervals of the score (e.g., 6 intervals between -1 and 5).

Table 3.3: Effect of the subjective selection of weights for issues B Energy and Resource Consumption and C Environmental loading on the Total weighted building score

	Issues	Weights	Nominal weights adjusted for number of active Categories	Weighted percent	Total weighted building score	% of change for total building score
B	**Energy and Resource Consumption**					
		0	0.0	0.0%	2.42	**1.8%**
		1	0.7	5.5%	2.45	
		2	1.4	10.4%	2.47	
		3	2.1	14.9%	2.49	
		4	2.9	18.9%	2.51	
		5	3.6	22.5%	2.53	
C	**Environmental Loading**					
		0	0.0	0.0%	2.64	**1.8%**
		1	0.9	6.9%	2.61	
		2	1.7	12.9%	2.59	
		3	2.6	18.2%	2.57	
		4	3.4	22.9%	2.55	
		5	4.3	27.0%	2.53	

The maximum percentage of the changes in the total building weighted score does not exceed 1.8%. A process similar to performing the sensitivity analysis for the subjective selection of weights for Categories is followed, and the maximum percentage for the change in the total building weighted score does not exceed the 2.7% for the C6 category. To conclude, the system is sensitive to the subjective selection of weights in both levels: the issues level and the categories level, which proves that SBTool could produce different results depending on the weights selected. Therefore, an alternative approach to remove subjective selection and improve the system is urgently needed.

3.6 Conclusion

As a sustainability assessment framework, SBTool is ahead of many other multi-criteria rating tools, making it the most-nominated method to assess building sustainability, despite some shortcomings. A sensitivity analysis is therefore conducted to evaluate the objectivity and validity of the assessment process. Weighting, one of the characteristic assessment methods, remains one of the most problematic issues on the route to achieving a completely objective assessment. Weighting is considered to be a real challenge facing the recently-developed rating system. SBTool's sensitivity to local issues was essential to achieve the most powerful outcome, which implicitly highlights the importance of a weighting system inherited from the rating system as a tool to represent the relative importance of different issues. Recent weighting systems use either an equal weight, such as the LEED weighting system, or subjectively address their weights, as with the SBTool weighting system, which prompts us to avoid using the weighting system until it has been adopted scientifically.

The main conclusion from this sensitivity analysis is that the total weighted building scores are 72% and 63% sensitive to change for the criteria linked to issue B

(Energy and Resource Consumption) and issue C (Environmental Loading), respectively. Therefore, the sensitivity analysis indicates that the B and C issues of SBTool are the most important issues to be considered through the proposed exergy-based index for assessing building sustainability as a prototype tool.

Several authors have reinforced the previous conclusion. Aotake et al. (2005) showed that the highly weighted coefficients of the items related to energy and pollution (equivalent to issue B and C issues, SBTool) exist in many tools such as CASBEE, BREEAM98 and LEED 2.1 are .5, .27 and .25, respectively). Chang (2005) investigated the results of assessment weighting values according to different field experts (designers and industry, government, and academic and civil authorities) using the AHP (Analytic hierarchy process) method and showed that the statistics indicate the prioritizing of the B and C issues of GBTool (SBTool recently) over the other issues. Moreover, in their study of the priority weightings of issues and category parameters of SBTool in the Indian context, Bhatt et al. (2010) showed that 9 of top-11 ranked parameters are related to B and C issues.

4 PROPOSED FRAMEWORK FOR THE ASSESSMENT OF BUILDING SUSTAINABILITY

The literature review (Chapter 2) presented different rating systems and assessment methods to evaluate building sustainability, including the multi-criteria assessment approach, life cycle assessment and single index. Among the existing assessment methods and tools, developed and used by different stakeholders, there is a marked lack of a unique metric for articulating the extent to which, and the ways in which most current buildings are unsustainable. We show the growing acknowledgement of the limitations of current tools and methods and their failure to fulfill fundamental scientific requirements (e.g., no generally-accepted procedure for normalization and weighting) as well as their often misleading decision making advice.

The developers of an assessment method or a rating system should aim for a balance between "heavy science" that few people understand and a simpler approach. The approach proposed in this thesis, based on applied thermodynamics, belongs to the heavy science view, which would give more accurate and science-based accounts of sustainability, as a viable alternative to simpler approaches such as LEED ratings that are based on experience, consensus, and market forces, and which are more easily accepted by the market. While based solely on applied thermodynamics, future developments, especially in terms of the calibration of a rating scale, should involve using or modifying the market-driving forces.

The proposed framework uses the strong sustainability approach rather than the weak sustainability approach. While the strong sustainability approach requires that different types of natural capital must be maintained indefinitely for future generations, the weak sustainability approach provides some allowance for the substitutability of different sources (between human-made capital, or between different sources) (Ayres et al. 1998).

In this context, solar radiation, which is renewable and expected to be available on very large time scale, is a natural capital available for building construction and operation. The use of the exergy of solar radiation brings together the amount of energy received and used, as well as the quality of the energy flows. The available solar exergy, which is harvested on the building footprint, is used exclusively to define the maximum natural capital, and a building's sustainability is defined with respect to that maximum value. In the proposed index, natural capital is seen as the foundation on which all building activity is based. Therefore, available solar exergy is used exclusively to define building sustainability. Solar exergy was the only renewable energy source considered here for many reasons: i) it is inexhaustible and offers many benefits compared to conventional energy sources; ii) all energy sources present on the earth are actually derived to a great extent from the solar radiation incident on earth. Potential energy in water masses, the energy content of biomass and crops or fossil fuels is to a great extent derived from incident solar radiation, for implicitly solar energy is their primal driver; and iii) Solar energy systems can easily be integrated on a building-level, in turn decreasing the impact of electricity production and transformation (Hepbasli 2008).

According to this new definition, a 100 % sustainable building has an exergy index of sustainability ExSI equal to 100. This definition implies that any building exergy lost, due to construction and operation, can be substituted by the available solar exergy, which is harvested on the building's footprint.

The proposed framework is a combination of three categories: Multi-criteria assessment, Life Cycle Analysis (LCA), and Single Index (see Table 4.1). The purpose of nesting the three approaches is to enhance the efficiency in measuring building sustainability. Multi-criteria assessment uses the holistic approach to cover all of the building aspects that help the designer understand the building within its wider context. SBTool is the selected tool for this category. The ATHENA Impact Estimator is the selected tool for the Life Cycle Assessment of buildings and their consequences on the surrounding environment. Finally, exergy is used as single commodity to aggregate the multi-criteria scores into one single score that describes how much a building can achieve in sustainability based on the proposed rating scale.

Table 4.1: The combination of the three approaches in the proposed Exergy-based index

<table>
<tr><td></td><td>Categorization dimensions</td><td colspan="5"></td></tr>
<tr><td>1</td><td>Nature of data</td><td colspan="2">Qualitative</td><td></td><td colspan="2">Quantitative</td></tr>
<tr><td>2</td><td>Approach</td><td colspan="2">Holistic approach</td><td></td><td colspan="2">Reductionist approach</td></tr>
<tr><td>3</td><td>Temporal</td><td colspan="2">Prospective</td><td></td><td colspan="2">Retrospective</td></tr>
<tr><td>4</td><td>Achievement</td><td colspan="2">Direction to target</td><td></td><td colspan="2">Distance from target</td></tr>
<tr><td>5</td><td>Scale (assessment level)</td><td colspan="2">Whole building</td><td>Building/ Products</td><td colspan="2"></td></tr>
<tr><td>6</td><td>Interaction</td><td colspan="2">Passive tools</td><td>Interactive tools</td><td colspan="2"></td></tr>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">Multi Criteria Assessment (MCA)</td><td>LCA</td><td colspan="2">Single Index (SI)</td></tr>
<tr><td>LEED</td><td>SBTool</td><td>Life cycle analysis (ATHENA)</td><td>Biophysical models (Exergy)</td><td>Monetary tools</td></tr>
<tr><td colspan="3"></td><td colspan="3">Proposed Exergy-based Index</td><td></td></tr>
</table>

A new index is proposed in order to fulfill the thesis objectives, with the following goals: 1) to measure building sustainability within its wider context, in relation to energy and non-energy natural resources; 2) to easily adjust benchmarks to fit the need of temporal and spatial changes in a building; 3) to provide an objective assessment and eliminate subjective weights; 4) to provide a yardstick that can be used to compare buildings whether in the same city or in different countries; and 5) to find the potential for improving building performance.

4.1 Overall approach of the proposed method

This chapter presents the underlying mathematical models used to calculate the exergy lost as a first step in the proposed framework, which provides a new Exergy Index of Sustainability (ExSI). The prototype tool is currently connected with the SBTool from which most data are extracted; it assumes that SBTool had already been used by a design team for assessing building performance, and therefore that such data is available. However, it can be developed as a standalone tool. We selected two issues for presenting our proposed methodology, energy and resource consumption and environmental loading. These two issues are among the most influential in the assessment of buildings based on sensitivity analysis, as presented in chapter 3. Several other issues could be included in the evaluation of building sustainability; some can be quantified, such as energy use and durability, and others can only be discussed in qualitative terms such as satisfaction with indoor environments or the social benefits of knowledge generated in buildings. The integration of all of the issues contributing to the assessment of such an index of building sustainability is beyond the scope of this thesis.

To achieve the main purpose of the research, that is, to assess building sustainability by calculating the proposed index of sustainability, the steps of our proposed methodology are presented in Figure 4.1 and commented on below:

Step 1: Extraction of results from the SBTool for each criterion (e.g, Criterion B1.1 refers to the annualized non-renewable energy embodied in construction materials, see Table

4.3). In this study, only the energy and resource consumption (B issue), and the environmental loadings (C issue) are considered. Our sensitivity analysis proved that these two issues have the highest impact on the total building score.

Step 2: Processing of the results from SBTool and perform additional calculations, when needed, to estimate the energy use for each criterion.

Step 3: Calculation of exergy lost for each criterion.

Step 4: Calculation of annualized total exergy loss due to the building construction and operation as a sum of the corresponding values for all criteria.

Step 5: Calculate the annual exergy index of renewability α_{ex}. This value is determined by equation (4-1):

The annual exergy index of renewability α_{en} is the ratio between the annual available solar exergy that can be harvested by the building footprint (horizontal plane), and the annualized exergy lost in the building construction and operation.

$$\text{Exergy index of renewability } \alpha_{ex} = \frac{Annual\ available\ solar\ exergy}{Annual\ exergy\ lost} \cdot 100\ \% \qquad (4\text{-}1)$$

The available exergy could be solely dependent upon solar energy or it may also depend on other renewable sources such as geothermal or wind, which can be used at the building level (e.g. a small wind system or a geothermal system). Other renewable energy sources such as nuclear and hydro power would not be taken into consideration because they cannot be used at the site level.

Step 6: Calculation of annual exergy index of building sustainability (ExSI), by using the corresponding index of renewability α_{ex}.

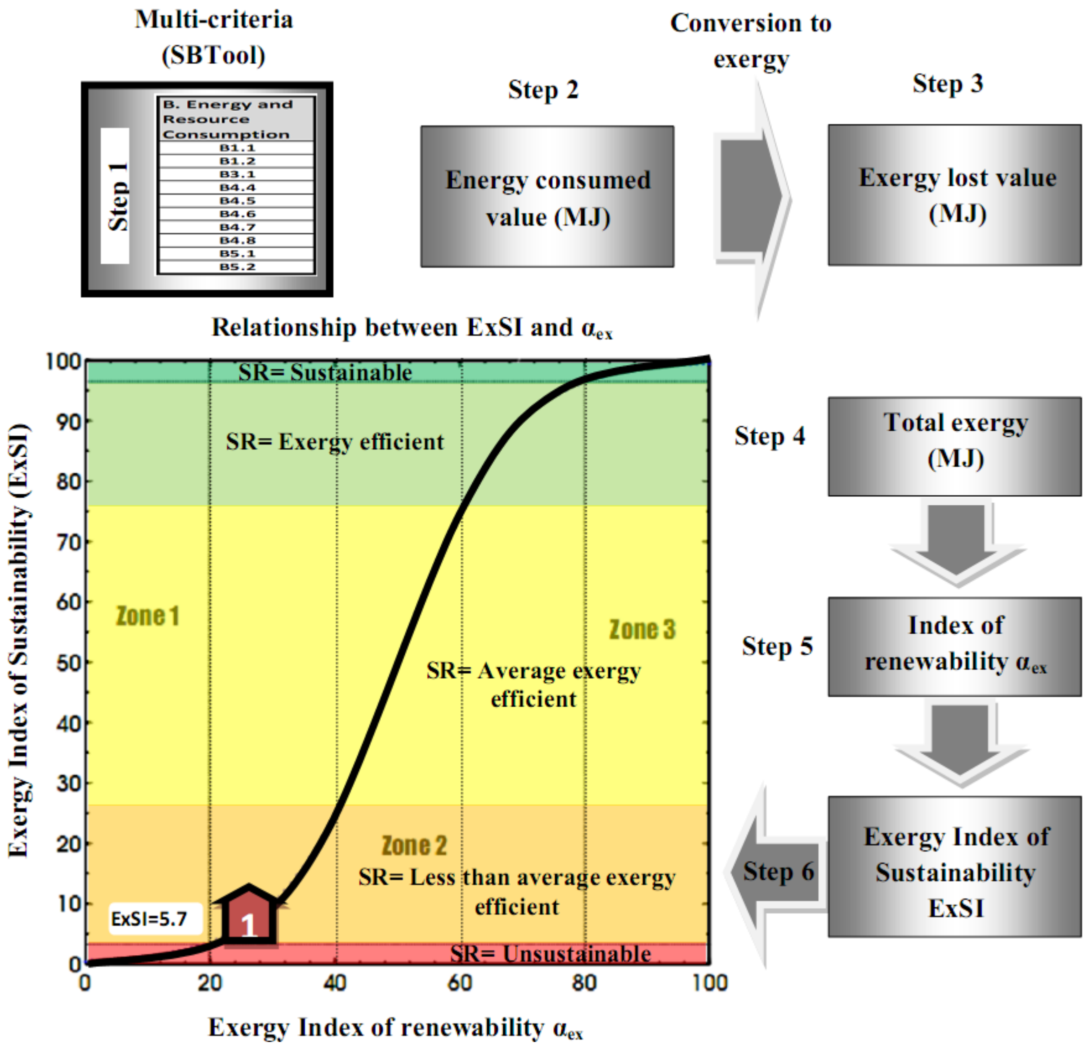


Figure 4.1: Proposed methodology to assess the building exergy-based index

To define the research scope for the proposed assessment framework, two parameters have to be considered: the system boundary and the functional unit.

The system boundary is used to determine the scope of the research. It is difficult and time consuming to compile of all of the possible criteria that are used to evaluate the building performance in a quantitative way (e.g. 179 criteria are used to assess sustainable buildings using SBTool (iiSBE 2010)). Therefore, the proposed framework includes only those criteria that are characterized by the outputs with a significant impact on the final result of the building assessment process. The research scope is identified by the dashed line (Table 4.2). It includes two of the most significant issues used to assess building performance, i.e., energy and resource consumption (issue B), and environmental loading (issue C). Other issues (A, D, E, F, or G) could be integrated in future studies. Only issues B and C are covered in the thesis.

Table 4.2: Research scope covered in this study from the SBTool issues.

	Issues
A	**Site Selection, Project Planning and Development**
B	**Energy and Resource Consumption**
C	**Environmental Loadings**
D	**Indoor Environmental Quality**
E	**Service Quality**
F	**Social and Economic aspects**
G	**Cultural and Perceptual Aspects**

The functional unit in the case of office buildings is 1 m^2 of conditioned floor area. Therefore, the comparison between several alternatives for evaluating existing buildings will be based in this study on MJ per m^2 of conditioned floor.

The results given by the SBTool is the starting point for this study. One challenge of this study is to find the most suitable ways for converting the selected outputs from the SBTool, which are measured in different units, into the corresponding exergy lost. The total exergy lost for the building construction and operations becomes one unique measure of building performance by including different aspects such as embodied energy, operating energy, the energy used for water treatment, etc.

4.2 Evaluation of annualized exergy loss for energy and resource consumption (issue B of SBTool)

This section presents the calculation method of the exergy lost for selected criteria, based on the SBTool results (Table 4.3). There are substantial criteria that can be used to carry out a detailed sustainable building assessment. Some simplifications are made based on the following principles: (1) the criteria that have no effect on the total exergy lost are excluded in the calculation of the final balance equation; (2) criteria that assess the adaptability of a building to future renewable technologies are excluded; and (3) criteria that are not building-specific are excluded since that would be beyond the scope of this research.

Table 4.3: B and C issues criteria in the SBTool

B	**Energy and Resource Consumption**	**Units**
B1.1	Annualized non-renewable primary energy embodied in construction materials.	MJ/m^2*yr
B1.2	Annual use of purchased electricity for operations, delivered	MJ/m^2*yr
B3.1	Use of off-site energy that is generated from renewable sources (delivered)	% by energy
B4.4	Use of durable materials.	% by cost
B4.5	Re-use of salvaged materials from off-site	% by cost
B4.6	Use of recycled materials from off-site sources.	% by cost
B4.7	Use of bio-based products obtained from sustainable sources.	% by cost
B5.1	Use of potable water for site irrigation.	m^3/m^2
B5.2	Use of potable water for occupancy needs.	L/pp/day
C	**Environmental Loadings**	
C1.1	Annualized GHG emissions embodied in construction materials	kg/m2·yr
C1.2	Annualized GHG emissions from all energy used for facility operations	kg/m2·yr
C2.1	Emissions of ozone-depleting substances during facility operations	g/m2·yr
C2.2	Emissions of acidifying emissions during facility operations	kg/m2·yr
C2.3	Emissions leading to photo-oxidants during facility operations	g/m2·yr

The exergy lost as calculated in this section, using the final balance equation (4-2), is equal to the denominator of equation (4-1). The final balance equation for annual exergy lost EX_{Total} is calculated as follows:

$$
\begin{aligned}
EX_{Total} \quad &= EX_B \ + EX_C \\
&= EX_{b\,1.1} \ + EX_{b\,1.2} \ - EX_{b\,3.1} \ + EX_{b\,4.4} \ + EX_{b\,4.5} \ + EX_{b\,4.6} \\
&+ EX_{b\,4.7} \ + EX_{b\,5.1} \ + EX_{b\,5.2} \ + EX_{c\,1.1} \ + EX_{c\,1.2} \ + EX_{c\,2.1} \\
&+ EX_{c\,2.2} \ + EX_{c\,2.3}
\end{aligned} \tag{4-2}
$$

where the subscript b1.1 makes reference to the first criterion B1.1 (see Table 4.3).

The Total annualized exergy lost is used to unify all the considered criteria and to facilitate calculating the exergy index of renewability using the formula of (4-1). An example of the relationship of dependent and independent criteria (of issue B) used to evaluate the building sustainability is presented graphically in Figure 4.2.

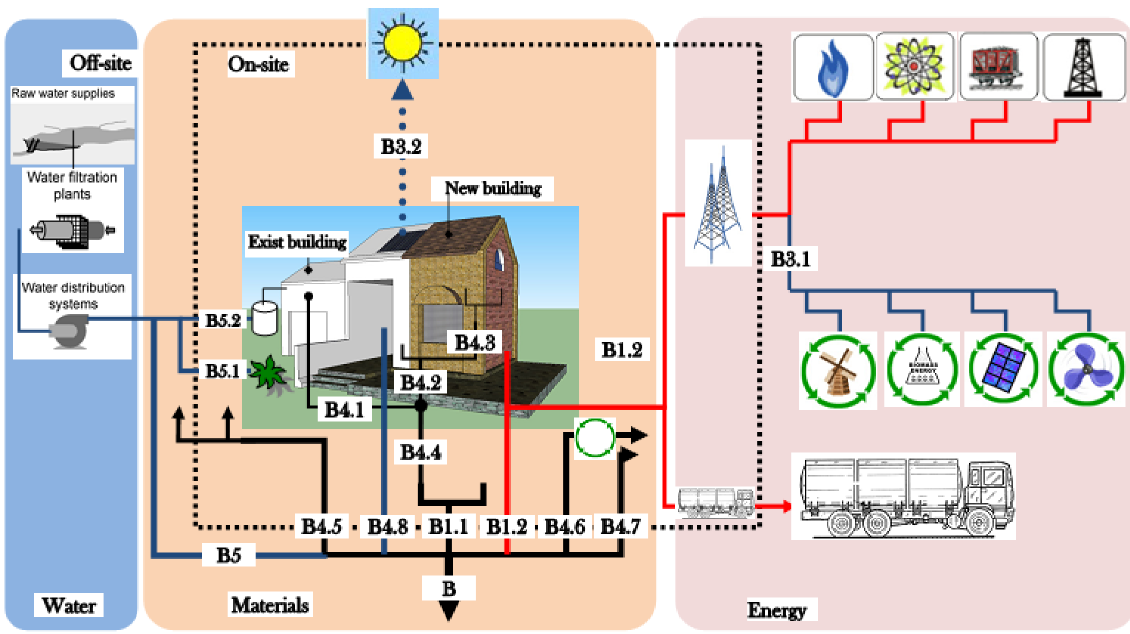


Figure 4.2: Relationship of dependent and independent criteria used to evaluate sustainability building

The following sections present in detail the calculation method for converting the results from each criterion to exergy lost. Subsequently, the results are integrated into the final balance equation that calculates the total amount of energy consumption or exergy lost. The description stage, extraction stage and finally the formulas used to convert the values of energy, emissions and other criteria given by the SBTool into equivalent exergy values are presented.

4.2.1 Annualized non-renewable embodied energy in construction materials (B.1.1)

Generally the embodied energy is subdivided into two main categories: 1) initial embodied energy; and 2) recurring embodied energy. The initial embodied energy refers to the energy consumed in the acquisition of raw materials, processing, manufacturing, transportation to the site, and construction. The recurring embodied energy considers the energy consumed in the maintenance, replacement and demolition phases. The total embodied energy $\mathrm{EN_{b1.1}}$ as well as the embodied energy for each component of the building is clearly defined in the SBTool. The criterion (B1.1) considers only the initial embodied energy. Mechanical, electrical, pumping and vertical transportation systems are not included in this analysis.

The total annualized embodied energy $\mathrm{EN_{b1.1}}$, [MJ/yr] for the project as listed by the SBTool is the sum of the total embodied energy for new structural elements $\mathrm{EN_{Ns_{b1.1}}}$ and walls $\mathrm{EN_{Nw_{b1.1}}}$[MJ], existing structural elements $\mathrm{EN_{Es_{b1.1}}}$and walls $\mathrm{EN_{Ew_{b1.1}}}$[MJ], and heavy materials $\mathrm{EN_{H_{b1.1}}}$[MJ], see equation (4-3):

$$EN_{b1.1} = \frac{EN_{Ns_{b1.1}} + EN_{Nw_{b1.1}} + EN_{Es_{b1.1}} + EN_{Ew_{b1.1}} + EN_{H_{b1.1}}}{L_{service}} \quad (4\text{-}3)$$

where

$L_{service}$: is the assumed building life span in years.

The embodied energy of the existing structural elements and walls $\mathrm{EN_{E_{b1.1}}}$is calculated according to the following conditions: (a) if the existing building is at the end of its service life and it will be demolished then the embodied energy will be equal to the estimated embodied energy used in the process of demolition $EN_{D_{b1.1}}$; hence the demolition of an existing building is penalized; and (b) if the existing building is to be renovated then the existing embodied energy will be the difference between the embodied energy of the new materials, components and systems $EN_{N_{b1.1}}$ and that energy either removed during refurbished $EN_{R_{b1.1}}$ or assumed to be decreased with the time passing of the estimated service life. The flowchart for the process used by the SBTool in the calculation for the total annualized embodied energy $EN_{b1.1}$ is given in Figure 4.3.

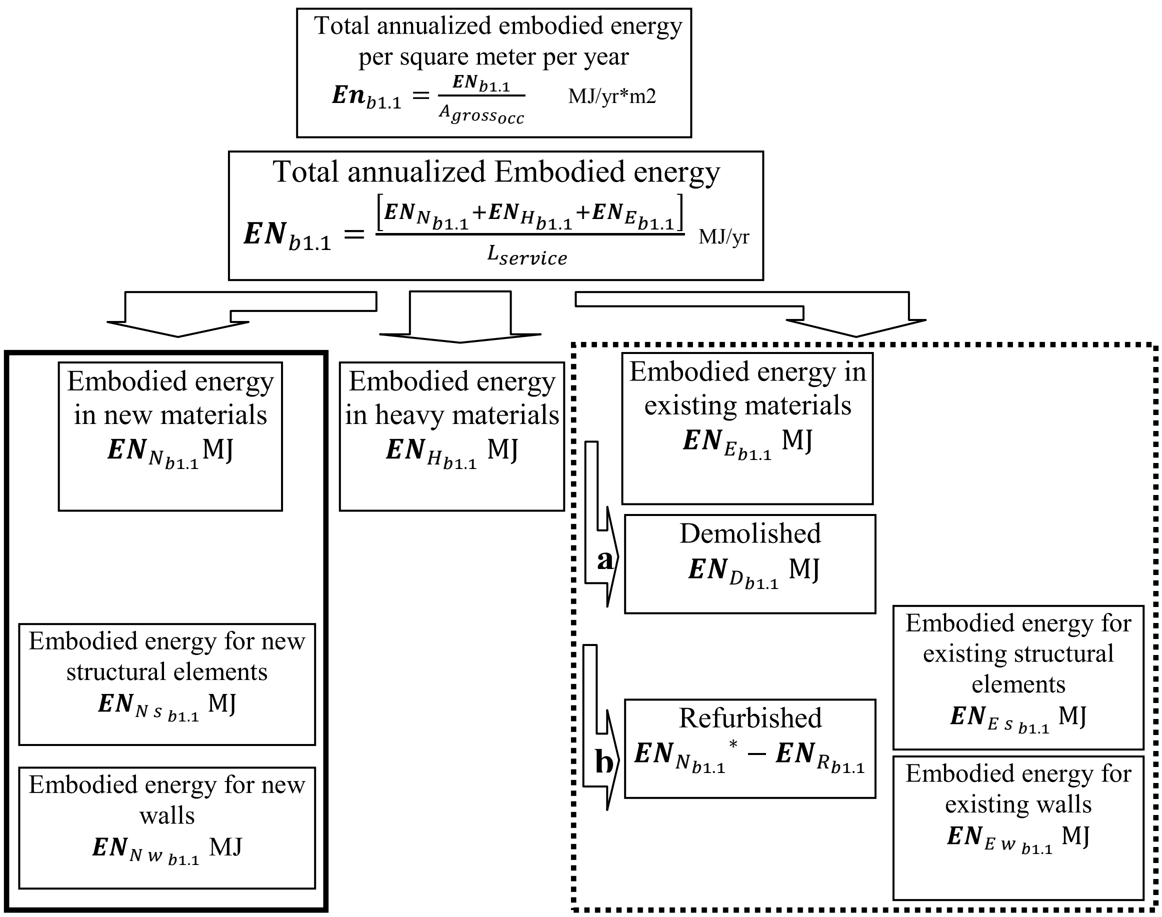


Figure 4.3: The total embodied energy En b 1.1 and its subcomponents assessed by B 1.1

The corresponding annualized exergy lost is calculated as follows:

$$EX_{b1.1} = \frac{EX_{Ns_{b1.1}} + EX_{Nw_{b1.1}} + EX_{Es_{b1.1}} + EX_{Ew_{b1.1}} + \left[EX_{Hc_{b1.1}} + EX_{Hm_{b1.1}}\right]}{L_{service}} \tag{4-4}$$

where

$EX_{b1.1}$: is the total annualized exergy lost, MJ/yr;

$EX_{Ns_{b1.1}}$: is the exergy lost corresponding to the embodied energy in the new structure, MJ;

$EX_{Nw_{b1.1}}$: is the exergy lost corresponding to the embodied energy in new walls, MJ;

$EX_{Es_{b1.1}}$: is the exergy lost corresponding to the embodied energy in the existing structure, MJ;

$EX_{Ew_{b1.1}}$: is the exergy lost corresponding to the embodied energy in the existing walls, MJ;

$EX_{Hc_{b1.1}}$: is the chemical exergy lost corresponding to the embodied energy in heavy materials that are not subject to any manufacturing process, MJ; and

$EX_{Hm_{b1.1}}$: is the exergy lost corresponding to the embodied energy in heavy materials (subjected to a manufacturing process), MJ.

The exergy lost for new building components (structural and walls) and for heavy materials (masonry, steel, and glass) are calculated as follows:

The embodied energy is extracted from the SBTool, and both the annual average temperature $Tk_{o,a}$ (reference environmental temperature) and the maximum temperature Tk_{max} in the process are pre-set.

$$EX_{Ns_{b1.1}} = \sum_{m} EN_{Ns_{b1.1}} \cdot \left(1 - \frac{Tk_{o,a}}{Tk_{max}}\right) \tag{4-5}$$

$$EX_{Nw_{b1.1}} = \sum_{m} EN_{Nw_{b1.1}} \cdot \left(1 - \frac{Tk_{o,a}}{Tk_{max}}\right) \tag{4-6}$$

$$EX_{Hm_{b1.1}} = \sum_{m} EN_{Hm_{b1.1}} \cdot \left(1 - \frac{Tk_{o,a}}{Tk_{max}}\right) \tag{4-7}$$

where

$EX_{Ns_{b1.1}}$: is the exergy lost corresponding to the embodied energy in the new structure, MJ;

$EN_{Ns_{b1.1}}$: is the embodied energy in the new structure, MJ;

$EX_{Nw_{b1.1}}$: is the exergy lost corresponding to the embodied energy in new walls, MJ;

$EN_{Nw_{b1.1}}$: is the embodied energy in new walls, MJ;

$Tk_{o,a}$: is the annual average outdoor air temperature, K; RETScreen software (RETSceen International, 2007) is used to extract the annual average outdoor air temperature, which is assumed to be the reference environmental temperature $TK_{o,a}$.

Tk_{max} : is the maximum temperature in the overall manufacturing, transportation and installation process, K;

m : the material;

$EX_{Hm_{b1.1}}$: is the exergy lost corresponding to the embodied energy in heavy materials, MJ; and

$EN_{Hm_{b1.1}}$: is the embodied energy in heavy materials, MJ.

The chemical exergy of any substance is defined as the maximum work which can be obtained when the considered substance is brought in a reversible way from a restricted dead state to the state of the reference substance present in the reference environment, which is called the dead state (Xiang et al. 2004). To obtain the chemical exergy for any substance (chemical compound) the following process must be followed:

1) define the chemical formula for the substance; 2) define the molar Gibbs free energy in KJ/mol (http://www2.ucdsb.on.ca/tiss/stretton/Database/inorganic_thermo) at fixed conditions 289.15 K and 101.325 KPa (Rivero and Garfias 2006) ; 3) calculate the standard chemical exergy for the chemical formula using the advanced exergy calculator KJ/mol (http://www.exergoecology.com/excalc) with the results of steps 1 and 2 as inputs to calculate the standard chemical exergy; 4) calculate the molar weight for the formula in g/mole using a molecular weight calculator (http://www.lmnoeng.com/molecule); 5) calculate the specific exergy KJ/g using the formula given in equation (4-8); and finally, 6) the total exergy can be calculated using formula (4-9):

$$EX_{ch} \quad = EX_{ch-stand} \cdot \frac{1}{molecular\ wt} \tag{4-8}$$

$$EX_{Hc_{b1.1}} \quad = EX_{ch} \cdot M_{total} \cdot \frac{1{,}000{,}000}{1000} \tag{4-9}$$

where

EX_{ch} : is the specific chemical exergy, KJ/g;

$EX_{ch-stand}$: is the standard chemical exergy, KJ/mole;

$molecular\ wt$: is the molecular weight, g/mole;

$EX_{Hc_{b1.1}}$: is the total chemical exergy lost, MJ; and

M_{total} : is the total mass, t.

Similar calculations are performed for the exergy lost due to existing structures $\mathrm{EX}_{\mathrm{Es}_{\mathrm{b1.1}}}$ and walls $\mathrm{EX}_{\mathrm{Ew}_{\mathrm{b1.1}}}$. A gradual reduction in the embodied energy for existing structures and walls is applied by using the amortization rate (AR) and the age of the existing structural elements (n); see formula (4-10) (SBTool, 2010):

$$EN_{E_{b1.1}} = \sum_{m} EN_{N_{b1.1}}{}^{*} \cdot (1 - AR^2 \cdot n) \tag{4-10}$$

$$EX_{Es_{b1.1}} = \sum_{m} EN_{Es_{b1.1}} \cdot \left(1 - \frac{Tk_{o,a}}{Tk_{max}}\right) \tag{4-11}$$

$$EX_{Ew_{b1.1}} = \sum_{m} EN_{Ew_{b1.1}} \cdot \left(1 - \frac{Tk_{o,a}}{Tk_{max}}\right) \tag{4-12}$$

The total annualized exergy lost $EX_{b1.1}$ is added to the final balance equation.

4.2.2 Annual non-renewable delivered energy used for facility operations (B.1.2)

The annual non-renewable energy used for facility operation $EN_{b1.2}$ is given by SBTool:

$$EN_{b1.2} = \sum_{occ} \left(EN_{E_{b1.2}} \cdot A_{net_{occ}} + EN_{F_{b1.2}} \cdot A_{net_{occ}}\right) \tag{4-13}$$

where

$EN_{b1.2}$: is the total non-renewable annual delivered energy consumption, MJ/yr;

$EN_{E_{b1.2}}$: is the annual electrical energy consumption delivered; can be between 100% from hydro sources or 100% from fossil sources, MJ/m^2*yr;

$EN_{F_{b1.2}}$: is the annual fuel-based delivered energy consumption, MJ/m^2*yr; and

$A_{net_{occ}}$: is the net area for each occupancy type, m^2.

The annual on-site exergy lost is calculated as follows, based on the information extracted from SBTool:

$$EX_{b1.2} = EX_{E_{b1.2}} + EX_{F_{b1.2}} \tag{4-14}$$

where

$EX_{b1.2}$: is the total annual exergy lost, MJ/yr;

$EX_{E_{b1.2}}$: is the annual exergy lost due to the electricity delivered and used on site, MJ/yr; and

$EX_{F_{b1.2}}$: is the annual exergy lost due the use of fossil fuel (e.g., for a natural gas fired boiler), MJ/yr.

The exergy lost due to electricity use $\mathrm{EX}_{\mathrm{E}_{\mathrm{b1.2}}}$ is equal to the on-site electricity use $\mathrm{EN}_{\mathrm{E}_{\mathrm{b1.2}}}$. To calculate the exergy lost due to using fuel on-site, first the entropy generation within the boiler has to be calculated under steady state conditions, and then the exergy lost can be obtained:

$$S_{gen} = S_{HW} + S_{loss} - S_{gas} \tag{4-15}$$

The terms S_{gen} represents the total entropy generation within the system boundary and S_{HW} and S_{loss} are the entropy transfers from the hot water and the entropy generation, respectively, due to the energy losses of the boiler (e.g., through the chimney). The last term in the equation, S_{gas}, is the entropy input by the natural gas flame (see Figure 4.4).

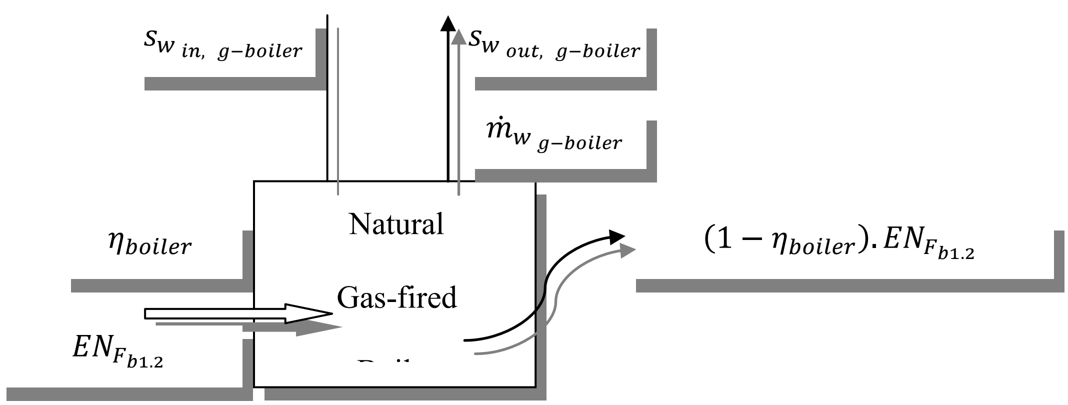


Figure 4.4: Natural gas-fired boiler

$$S_{gen} = \dot{m}_{w\ g-boiler}\left(s_{w\ out,\ g-boiler} - s_{w\ in,\ g-boiler}\right) + \left(EN_{F_{b1.2}} \cdot A_{net_{occ}}\right) \cdot \left(\frac{1-\eta_{boiler}}{Tk_{o,a}}\right) - \frac{\left(EN_{F_{b1.2}} \cdot A_{net_{occ}}\right)}{TK_{flame}} \cdot \eta_{boiler} \tag{4-16}$$

where

S_{gen} : is the entropy generation within the natural gas-fired boiler, MJ/K*yr;

$m_{w\ g-boiler}$: is the mass flow rate of water going through the natural gas-fired boiler, kg/yr;

$s_{w\ out,\ g-boiler}$: is the specific entropy of the water leaving the boiler at $T_{w,\ out\ g\text{-}boiler}$, Patm, kJ/kg. K;

$s_{w\ in,\ g-boiler}$: is the specific entropy of the water entering the boiler at $T_{w,\ in\ g\text{-}boiler}$, Patm, kJ/kg. K;

$EN_{F_{b1.2}}$: is the annual natural gas energy used, delivered to the building, MJ/m^2*yr;

$A_{net_{occ}}$: is the net area for each occupancy type, m^2;

η_{boiler} : is the energy efficiency of the natural gas-fired boiler, in percentage;

$Tk_{o,a}$: is the annual average outdoor air temperature, K; and

Tk_{flame} : is the adiabatic boiler flame temperature, K.

The typical efficiency of the natural gas fired boiler is assumed to meet the minimum performance levels proposed by Natural Resources Canada at.82 (Energy Efficiency Regulations, 2009).

$$EX_{F_{b1.2}} = S_{gen} \cdot Tk_{o,a} \quad (4\text{-}17)$$

The total annualized exergy lost, $EX_{b1.2}$, is added to the final balance equation (see formula (4-2)).

4.2.3 Use of on-site energy generated from renewable sources (B.3.1)

In our case this criterion applies only to electricity. Therefore, it would be simpler and more accurate to calculate this item by considering the on-site electrical delivered energy instead of the off-site energy consumed, since it is the delivered energy data that is commonly available. SBTool applies a conversion factor (gross-up factor) to delivered energy values to convert them to primary energy, including the combustion and delivery loss.

This criterion shows the percentage of annual purchased electricity that is obtained from renewable energy sources. The energy consumed and the exergy lost values are calculated based on the following data given by SBTool: 1) the annual amount of delivered electrical energy used for operation $\mathrm{EN}_{\mathrm{E}_{\mathrm{b1.2}}}$, MJ/m^2*yr; 2) the net area of each occupancy types $\mathrm{A}_{\mathrm{net}_{\mathrm{occ}}}$, m^2; and 3) the percentage of electricity purchased annually from renewable energy sources extracted from the SBTool as B 1.3. Based on these data the annual amount of electricity purchased from renewable energy sources [MJ/yr] is calculated using (4-18)).

$$EN_{b\ 3.1} = \sum_{occ} EN_{E_{b1.2}} \cdot A_{net_{occ}} \cdot \frac{annual\ purchased\ \%}{100} \qquad (4\text{-}18)$$

where

$EN_{b\ 3.1}$: is the annual purchased of electricity from renewable energy sources, MJ/yr; and

$EN_{E_{b1.2}}$: is the annual electrical energy delivered and used in the operation stage of the buildings, MJ/m^2*yr.

The exergy lost is identical to the annual on-site electricity purchased from renewable energy sources:

$$EX_{b\ 3.1} = EN_{b\ 3.1} \tag{4-19}$$

The exergy lost given by this criterion will be deducted from the final exergy balance equation since it is from renewable sources, see formula (4-2).

4.2.4 Use of durable materials (B.4.4)

The calculation of the exergy lost due to the recurring embodied energy comprises three steps: 1) the percentage of the initial embodied energy of durable materials (materials that are predicted to meet or exceed service life expectations),walls and heavy materials, to the total initial embodied energy (DUR) is estimated from the SBTool data as the ratio between the cost of durable materials and the total construction materials costs; 2) the number of replacements (N) of non-durable materials is calculated using the service life expectation (e.g., $M_{service}$ for concrete is 40 years) (Scheuer et al., 2003), $M_{exist\ service}$ and $L_{service}$ (given by SBTool); Equations (4-20) and (4-21) apply to new and existing building materials, respectively, (the first part of equation (4-21) is then approximated to the first decimal degree); and 3) the recurring energy used or the exergy lost are calculated with Equations (4-22) and (4-23), respectively.

$$N_{new} = \frac{L_{service}}{M_{service}} \tag{4-20}$$

$$N_{exist} = \frac{L_{service} - (M_{service} - M_{exist\ service})}{M_{service}} + \frac{(M_{service} - M_{exist\ service})}{M_{service}} \tag{4-21}$$

$$EN_{non-DUR} = \left(1 - \frac{DUR}{100}\right) \cdot \left(\sum_m EN_{Nw_{b1.1}} \cdot N_{new} + \sum_m EN_{Ew_{b1.1}} \cdot N_{exist} + \sum_m EN_{H_{b1.1}} \cdot N_{new} \right) \tag{4-22}$$

$$EX_{non-DUR} = \left(1 - \frac{DUR}{100}\right) \cdot \left(\sum_m EX_{Nw_{b1.1}} \cdot N_{new} + \sum_m EX_{Ew_{b1.1}} \cdot N_{exist} + \sum_m EX_{H_{b1.1}} \cdot N_{new} \right) \tag{4-23}$$

The annualized recurring energy used and the corresponding annualized recurring exergy lost are calculated as follows:

$$EN_{b4.4} = \frac{EN_{non-DUR}}{L_{service}} \quad (4\text{-}24)$$

$$EX_{b4.4} = \frac{EX_{non-DUR}}{L_{service}} \quad (4\text{-}25)$$

The annualized recurring exergy will be added to the final balance equation since B1.1 and B1.2 only consider the initial embodied energy and the operation energy, respectively, without considering the recurring exergy evaluated by this criterion.

4.2.5 Re-use of salvaged materials (B.4.5)

The indicator implemented to evaluate this criterion is the percentage, τ in % by cost of materials that are salvaged and refurbished or re-used from on-site or from off-site sources (as extracted from the SBTool). Salvaged materials differ from the existing materials that are considered by the B 1.1 criterion as they have to be adapted to meet their functional requirements with a moderate amount of renovation. The cost of re-use given by the SBTool implicitly considers the cost of the materials themselves as well as the cost of renovating the salvaged materials to meet their functional requirements. While the costs for installation, operation and maintenance of the buildings are conventionally based on energy, many researchers (Silveira et al., 2010), however, recommend that costs are better distributed among outputs based on the exergy. They recognize that exergy, and not energy, is the commodity of value in the system.

To calculate the energy use in salvaged materials, in terms of both energetic cost (ENC) in MJ and the thermoeconomic cost (TEC) in $ have to be determined. The values of ENC and TEC are calculated using (4-26) and (4-27) respectively.

$$ENC = EN_{Ns_{b1.1}} + EN_{Es_{b1.1}} + EN_{H_{b1.1}} + EN_{Nw_{b1.1}} + EN_{Ew_{b1.1}} \tag{4-26}$$

$$TEC = TEC_{total} - (TEC_{salvaged} + TEC_{recycled} + TEC_{bio-based}) \tag{4-27}$$

The unit energetic cost (energy used per unit capital construction cost) [MJ/$] is determined using the following equation:

$$enc = \frac{ENC}{TEC} \tag{4-28}$$

The cost of salvaged materials is calculated using the following equation:

$$TEC_{salvaged} = \sum_{occ} (TEC_{total} \cdot \tau) \tag{4-29}$$

Knowing the cost of the salvage materials (given by the SBTool) and the unit energetic cost (calculated), the energetic cost for using salvaged materials on-site and off-site can be calculated using (4-30):

$$EN_{b4.5} = \frac{enc \times TEC_{salvaged}}{L_{service}} \tag{4-30}$$

The unit exergetic cost (exergy lost per unit capital construction cost) [MJ/$] is determined using the following equation:

$$exc = \frac{EXC}{TEC} \tag{4-31}$$

where EXC is the exergy lost due to the initial embodied energy (MJ),calculated using (4-32).

$$EXC = EX_{Ns_{b1.1}} + EX_{Es_{b1.1}} + EX_{H_{b1.1}} + EX_{Nw_{b1.1}} + EX_{Ew_{b1.1}} \tag{4-32}$$

The annual exergy lost from re-used salvaged materials is calculated using the following:

$$EX_{b4.5} = \frac{exc \times TEC_{salvage}}{L_{service}} \tag{4-33}$$

Calculating the unit energetic cost based on the assumption that the construction cost TEC (thermoeconomic cost) does not include the cost of salvaged, recycled and bio-based materials. The annualized exergy lost associated with the use of salvaged materials $\mathrm{EX}_{\mathrm{b4.5}}$ has to be added for the final exergy balance equation.

4.2.6 Use of recycled materials from off-site sources (B.4.6)

The intent is to encourage the use of recycled materials from off-site as part of a new facility. Using recycled materials is highly recommended, especially for those materials that are energy intensive in production such as steel, which also has the advantage of being highly recyclable. The cost of recycled materials $\mathrm{TEC_{recycled}}$ is calculated based on the percentage of the contribution of recycled materials, θ in %, of the total building cost, given in equation (4-34):

$$TEC_{recycled} = \sum_{occ} TEC_{total} \cdot \theta \tag{4-34}$$

The annualized energy used and annualized exergy lost for using recycled materials from off-site sources are calculated using the formulas in eqns (4-35) and (4-36), respectively:

$$EN_{b\,4.6} = \frac{enc \cdot TEC_{recycled}}{L_{service}} \tag{4-35}$$

$$EX_{b\,4.6} = \frac{exc \cdot TEC_{recycled}}{L_{service}} \tag{4-36}$$

Based on the assumption that the cost of recycled material $\mathrm{TEC_{recycled}}$ is not included in the construction cost TEC as previously mentioned (see section 4.2.5), the corresponding value for embodied exergy lost $\mathrm{EX_{b\,4.6}}$ attributable to using recycled material has to be added to the final balance equation.

4.2.7 Use of bio-based products obtained from sustainable sources (B.4.7)

The indicator used to assess this criterion is the percentage by cost, μ in %, of bio-based products' cost from off-site. It is expected that most of these products will have a more benign effect on the environment, will be biodegradable, and will have lower disposal and cleanup costs than the fossil energy-based products they will replace.

The cost of the bio-based products is calculated using the following equation:

$$TEC_{bio-based} = \sum_{occ} TEC_{total} \cdot \mu \qquad (4\text{-}37)$$

The annualized exergy lost by using recycled materials from off-site sources due to the use of bio-based products is calculated as follows:

$$EN_{b\,4.7} = \frac{enc \cdot TEC_{bio-based}}{L_{service}} \qquad (4\text{-}38)$$

$$EX_{b\,4.7} = \frac{exc \cdot TEC_{bio-based}}{L_{service}} \qquad (4\text{-}39)$$

Based on the assumption that the cost of bio-based products $TEC_{bio-based}$ is not included in the construction cost TEC, the exergy lost $EX_{b\,4.7}$ due to using bio-based materials has to be added to the final balance equation, given by formula (4-2).

4.2.8 Use of potable water for site irrigation (B.5.1)

The annual energy expended for water treatment to be used for the irrigation of site areas, landscaped with non-native species Anon-native [m^2], (excluding stored rainwater or grey water used for this purpose) is calculated using equation (4-40):

$$EX_{b\,5.1} = EN_{b\,5.1} = A_{non-native} \cdot I_{irrigation-rate} \cdot EN_{rate} \qquad (4\text{-}40)$$

where $I_{irrigation-rate}$= irrigation rate [$m^3/m^2 \cdot yr$], EN_{rate}=.452 [KWh/m^3]=1.6272 [MJ/m^3], the specific energy expended for water treatment in Montreal [MJ/m^3] (Dumas, 2010). The exergy lost is equal to the electrical energy used, which is mostly used in the treatment process. The value of $EX_{b\,5.1}$ is added to the final exergy balance (Equation (4-2)).

4.2.9 Use of potable water for occupancy needs (B.5.2)

The predicted building annual water use at the design stage ($TAPW_{occ}$), [m^3/yr] is calculated using equation (4-41):

$$TAPW_{occ} = \sum_{occ} P \cdot d_{oper} \cdot \sum_{fix} \left(\frac{L_{pt} \cdot T_{pd}}{1000} \right) \quad (4\text{-}41)$$

where

$TAPW_{occ}$: is the predicted total annual potable volume of water for occupancy fixtures and use, m^3/yr;

L_{pt} : is the amount of water in liters used per unit time for occupancy need, (L /pp);

T_{pd} : is the number of "L" used per day per person, (1/day);

P : projected population;

d_{oper} : number of days of operation, (day).

Since electricity is the energy used for the water treatment, the exergy lost is equal to the energy use:

$$EX_{occ\ w-treat} = EN_{occ\ w-treat} = TAPW_{occ} \cdot EN_{rate} \quad (4\text{-}42)$$

The annual energy used for the heating of domestic hot water (using either gas or electric water heaters) is calculated with equation (4-43), and the corresponding exergy lost with equation (4-44) or (4-45):

$$EN_{hot\ DHW} = \frac{1}{EF} \cdot \left(1000 \cdot TAPW_{hot-occ} \cdot C_p \cdot (T_{supply} - T_{inlet})\right) \quad (4\text{-}43)$$

$$EX_{hot-g\ DHW} = EN_{hot-g\ DHW} \cdot \left(1 - \frac{Tk_{o,a}}{Tk_{flame}}\right) \quad (4\text{-}44)$$

$$EX_{hot-E\ DHW} = EN_{hot\ DHW} \quad (4\text{-}45)$$

where C_p= specific heat of water, J/ (kg. ^oK); assumed to be constant in the calculation (4186 J/kg. ^oK); Tsupply = supply water temperature [K]; T_{inlet}= 6-10 ºC, the inlet water temperature from city main; $TAPW_{hot-occ}$= estimated total annual domestic hot water use for occupancy fixtures and uses [m^3/yr] using equation (4-46):

$$TAPW_{hot-occ} = \sum_{occ} P \cdot d_{operation} \cdot \sum_{fix} \left(\frac{L_{pt}}{1000} \cdot T_{pd} \cdot \alpha_{hot-water} \right) \qquad (4\text{-}46)$$

The electrical energy and the corresponding exergy lost due to fixture operation is calculated using the following formula:

$$EX_{oper\,fix} = EN_{oper\,fix} = \sum_{fix} (Op_h \cdot E_{load} \cdot D_{cycle} \cdot P \cdot d_{oper} \cdot N_{fix}) \qquad (4\text{-}47)$$

where Op_h = operating hours per day for the fixture, [h/day]; E_{load} = electricity load for the fixture [kW]; D_{cycle} = the duty cycle, which is the proportion of time during which a component or device is operated [%]; and N_{fix} = the number of fixtures in the building. The total annual energy used for potable water is calculated as follows:

$$EN_{b\,5.2} = EN_{occ\ w-treat} + EN_{hot\ DHW} + EN_{oper\,fix} \qquad (4\text{-}48)$$

The corresponding exergy lost is calculated using either (4-49) for a gas water heater or (4-50) for an electric water heater.

$$EX_{b\,5.2} = EX_{occ\ w-treat} + EX_{hot-g\ DHW} + EX_{oper\,fix} \qquad (4\text{-}49)$$

$$EX_{b\,5.2} = EX_{occ\ w-treat} + EX_{hot-E\ DHW} + EX_{oper\,fix} \qquad (4\text{-}50)$$

Assuming that the annual energy consumption calculated for B1.2 does not include the energy consumption for hot water, water treatment and the energy used by water fixtures, then the annual exergy lost EX b5.2 will be added to the final exergy balance equation.

4.3 Evaluation of annualized exergy lost due to environmental loading (issue C of SBTool)

The exergy assessment in section 4.2 is proposed to quantify the exergy lost due to energy and resource consumption, while this section considers the pollutant discharges which have been analyzed with reference to the abatement exergy. The exergy assessment of building environmental loading thus formulated contains two aspects, one from the aspect of building materials using the ($EX_{C1.1}$) indicator, and one from the aspect of building energy utilization, using the ($EX_{C1.2}$, $EX_{C2.1}$, $EX_{C2.2}$, $EX_{C2.3}$) indicators (Liu et al. 2010). Assessing the environmental impact from the pollutant discharge is complex (e.g., quantifying the impacts on the atmosphere) since it is difficult to evaluate these systems uniformly. Neutralization of the environment is therefore required in order to avoid these impacts. Subsequently, all of the pollutants are required to be released in a harmless state so that they can be assimilated by the ecosphere or at least do not affect the ecosphere's normal production capacity. Methods that could be employed to measure waste emissions using exergy are: (1) Direct Measurement (DM), (2) Ecological Cost Coefficient (ECC), and (3) Abatement Exergy (AE) methods. Significant shortcomings of the first and second methods have been identified. A detailed review of these shortcomings is provided by Szargut et al. (1988) and Wang (2005).

Considering the weaknesses of the previous two methods using exergy, this thesis uses abatement exergy. Abatement exergy consumption is proposed to evaluate environmental loading, which can be quantified under certain conditions with existing technology by regulating pollutants into the exergy consumption during their neutralization.

According to Barnthouse et al. (1998) in their study of global and long term environmental impacts, a relatively high precision can be obtained, whereas uncertainty about the precision of the results is realized in local environmental impacts such as bio-toxicity. This thesis therefore only refers to pollutants and discharges that cause global warming, ozone-depletion, acidification, and photo-oxidants.

4.3.1 Annualized GHG emissions embodied in construction materials (C.1.1)

An estimate of the emission profile for a building can be obtained from the fuel breakdown of the energy associated with the building materials' production, assembly and process emissions. This information can either be obtained using programs such as ATHENA or by using historical data of building stock with similar building constructions. Should a comprehensive emission profile not be available, an evaluation of Greenhouse Gas emissions GHG can be made by multiplying the total annualized embodied energy derived in criterion B1.1 by the national or regional average CO_2 for the building industry (a_{aver}).

The abatement exergy approach is used in this study to assess the environmental impact of emissions because of its advantages: (i) easy to apply once the abatement exergy is known for each waste emission, (ii) the availability of some waste emission data in the literature, and (iii) the possibility of adding the corresponding exergy value directly to the exergy lost values of other indicators.

The annualized abatement exergy lost corresponding to the emissions embodied in construction materials is calculated as follows:

$$EX_{C1.1} = EN_{b1.1} \cdot a_{aver} \cdot e_{abat} \qquad (4\text{-}51)$$

where

$EX_{C1.1}$: is the abatement exergy lost corresponding to the embodied energy, MJ/yr;

$EN_{b1.1}$: is the total annualized embodied energy, MJ/yr;

a_{aver} : is the assumed regional fuel emission value kg of CO_2 per GJ of primary operating energy (e.g., the emissions for residential usage taken from average Canadian building stock values for 1999 (SBTool) is 55, kg CO_2/GJ), kg CO_2/GJ; and

e_{abat} : is the specific abatement exergy (e.g., according to reference data, exergy consumption in CO_2, SO_2, and NO_x processing are 5.86 MJ/kg (Dewulf et al. 2001), 57 MJ/kg (Bashford and Robson 1995), and 16 MJ/kg (Cornelissen 1997), respectively).

The total annualized abatement exergy $EX_{C1.1}$ corresponding to the annualized GHG emissions embodied in construction is added to the final balance equation.

4.3.2 C 1.2 Annualized GHG emissions from all the energy used for facility operations

This criterion assesses the annualized greenhouse gas emissions kg CO_2 equiv/yr associated with building operation. GHG emission is emerging as a major consideration in building assessment. Among many activities throughout the building process, the use of energy represents by far the largest source of emissions. The calculation of the major GHG emissions (e.g., Carbon Dioxide (CO_2), Nitrous Oxide (N_2O) and Methane (CH_4)) for facility operations is achieved by the breakdown of the primary energy by fuel type (e.g., Natural gas, Oil and Coal) and multiplication by the appropriate regional emission coefficient for on-site use for various fuel sources (g/MJ). The annual equivalent CO_2 emission is calculated (for the most part) based on two major components: (1) the off-site generation of electricity $EN_{P_{b1.2}}$, and (2) the on-site fossil fuel $EN_{F_{b1.2}}$ consumption. The former is calculated using equation (4-52) and the latter is calculated using equation (4-53).

$$CO2_{eq\ Elec} = \left[\sum_{ij} a_{ij} \cdot \sum_{j} \alpha_j \cdot \sum_{occ} \left(EN_{P_{b1.2}} \cdot\ A_{net_{occ}} \right) \right] \cdot GWP_i \qquad (4\text{-}52)$$

where

$CO2_{eq\ Elec}$	: is the annual equivalent CO_2 emissions related to electricity generation, kg /yr;
a_{ij}	: the pollutant coefficient for each i GHG for specific energy sources j used for off-site generation of electricity only, given by SBTool (e.g., $a_{CO2-\ N.G}$ is 131.39), Kg/GJ;
α_j	: the contribution percentage of different energy sources j to the off-site generation of electricity, (e.g., contribution percentages in Ontario are 24.6, .5, 8.4, 40.8, 24.9 and .7 for coal, oil, natural gas, nuclear, hydro and other sources, respectively, given by SBTool in percentage;
$EN_{P_{b1.2}}$	: is the annual primary operating energy corresponding to electricity consumption, MJ/m^2*yr;
$EN_{F_{b1.2}}$	: is the annual fuel-based energy consumption, MJ/m^2*yr; and
$A_{net_{occ}}$	: is the net area for each occupancy type (OCC), m^2.

On the other hand, the annual equivalent CO_2 emissions due to the on-site fossil fuel use are calculated by multiplying the estimated annual operating energy consumption by the regional emission coefficients from combustion in g/MJ for GHG, as presented in Table 4.4 for the province of Ontario. Scientifically sound conversion factors based on environmental impact assessment often enable us to aggregate other emissions into a single index that could consider the relative harmfulness of certain individual pollutants (e.g., GWP). A set of the Intergovernmental Panel on Climate Change (IPCC) values has produced a set of GWP indicators that compare the global warming impact of 1 kg of any GHGs and I kg CO_2 (e.g., GWP for CO_2, CH_4, and N_2O are 1, 310 and 21, respectively (IPCC 1996))(Houghton et al. 1996). The equation (4-53) is implemented.

$$CO2_{eq\,Fuel} = \left[a_{ij} \cdot \sum_{occ} \left(EN_{F_{b1.2}} \cdot A_{net_{occ}}\right)\right] \cdot GWP_i \qquad (4\text{-}53)$$

where

$CO2_{eq\,Fuel}$: is the annual equivalent CO_2 emissions related to on-site fossil fuel use, kg /yr;

a_{ij} : is the pollutant coefficient for each i GHG for specific energy sources j used for on-site heating or cooling only (e.g., $a_{CO2-\,N.G}$ is 50.95), for other pollutant coefficients for Ontario province, see table 3.5, Kg/GJ;

$GWP_{a,i}$: the Global warming potential, a dimensionless weighting factor for the emitted substance i integrated over years a and measured in kg of CO_2 equivalent per unit mass of the substance i, kg CO_2 eq./kg; and

$EN_{F_{b1.2}}$: is the annual fuel-based energy consumption, MJ/m^2*yr.

Table 4.4: Pollutant coefficients [g/MJ] for the province of Ontario

Pollutant coefficient, a_{ij} Fuel used for on-site heating or cooling only, j	Emissions data for each GHG, i			
	CO_2	CH_4	NO_x	SO_2
Natural gas	50.95	.00117	.04201	.00041
Propane or LPG	57.52	.00113	.04531	.00197
Light Oil	72.94	.00067	.01427	.45412
Heavy Oil	73.57	.00286	.17400	.06286
Coal	81.37	.47059	.13889	.46732

Finally the annual abatement exergy is obtained by multiplying the value of total equivalent $CO2_{eq\ total}$ emissions [Kg $CO_{2\ eq}$.] (calculated only for CO_2 and CH_4) by the value of the unit Abatement exergy for CO_2, which is found in the literature to be 5.86 MJ/kg (Dewulf et al. 2001), see equation (4-54).

$$EX_{C1.2} = CO2_{eq\ total} \cdot e_{abat\ Co2} \tag{4-54}$$

where

$CO2_{eq\ total}$: is the total annual equivalent CO_2 emissions, the sum of $CO2_{eq\ Fuel}$ and $CO2_{eq\ Elec}$, kg /yr; and

$e_{abat\ Co2}$: is the specific abatement exergy for CO_2, MJ/kg.

Another method, using an assumed average value of CO_2 per GJ of primary operating energy (a_{aver}), given by SBTool, could be implemented to calculate $EX_{C1.2}$ as follows:

$$EX_{C1.2} = a_{aver} \cdot \sum_{occ} \left(EN_{b1.2} \cdot A_{net_{occ}} \right) \cdot e_{abat\ Co2} \tag{4-55}$$

The total annualized abatement exergy $EX_{C1.2}$ corresponding to the annualized GHG emissions from the total energy used for facility operations is added to the final balance equation.

4.3.3 C 2.1 Emissions of ozone-depleting substances during facility operations

The intent of this criterion is to minimize ozone depletion from the leakage of CFC-11eq. The main concern stem from the release of Ozone Depleting Substances (ODSs), via (i) normal refrigeration equipment leakage, (ii) the threat of potential accidental catastrophic discharge, or (iii) due to the ultimate safe disposal of ODS when they outlast their usefulness in specific application. Up to the 1930s, carbon dioxide, ammonia and other fluids were used as refrigerants; later on Chlorofluorocarbons (CFCs), Hydrochloroflourocarbons (HCFCs) and halocarbons quickly occupied the market. After alarming ozone depletion, an international agreement for limiting the HCFCs was concluded in 1992 and a phase-out schedule to 2030 has been in place for some time (Halozan 2007).

Emissions due to specific amounts and types of refrigerants, emitted during building construction and operation, are one of the causes of the decomposition of the stratospheric ozone layer. This decomposition in turn has caused increased UV radiation, leading to multiple impacts on humans (e.g., skin cancer, cataracts) (http:// www.irs.gov/.../Ozone-Depleting-Chemicals-(ODC)-Excise-Tax-Audit-Techniques-Guide – August 03, 2012).

This criterion assesses the environmental impact based on the predicted annual emissions of CFC-11eq, in $g/m^2 \cdot yr$ (normalized for net usable building area). The value for annual CFC-11eq is the accumulated value assigned to the total the potential hazard offered by each type of refrigerant, as given by equation (4-56), and which in turn is obtained by multiplying the quantity of each substance by its Ozone Depleting Potential ($ODP_{\infty,i}$).

The value obtained for each CFC is normalized for the net usable building area. The total Ozone Depletion, OD, is expressed in kg of the reference substance, CFC-11. Values of $ODP_{\infty,i}$ factors are given by the (http://www.epa.gov/ozone/science/ods/classone.html). Examples are given in Table 4.5.

Table 4.5: $ODP_{\infty,i}$ factors

ith substance	Ozone Depletion factor $ODP_{\infty,i}$
CFC-11	1
CFC-115	.6
Halon 2402	6

$$CFC-11_{eq} = \frac{\sum_i ODP_{\infty,i} \cdot m_i}{A_{net_{occ}}} \quad (4\text{-}56)$$

where

$CFC-11_{eq}$: is the total annual equivalent CO_2 emissions corresponding to an ozone-depleting substance, g/m^2·yr;

$ODP_{\infty,i}$:is the steady-state Ozone Depletion Potential for the emitted substance i measured in kg of CFC-11 equivalent per unit mass of substance i, (kg CFC-11eq./kg);

m_i : is the quantity of the emitted substance i, kg; and

$A_{net_{occ}}$: is the net area for each occupancy type (OCC), m^2.

The total annualized exergy $EX_{C2.1}$ corresponding to the emission of ozone-depleting substances during facility operations is obtained using equation (4-57), and it will be added to the final balance equation.

$$EX_{C2.1} = .001 \cdot CFC-11_{eq} \cdot A_{net_{occ}} \cdot GWP_{CFC-11} \cdot e_{abat\,Co2} \quad (4\text{-}57)$$

where

GWP_{CFC-11} : Global warming potential (GWP) for CFC-11; and

$e_{abat\,Co2}$: is the specific abatement exergy for CO_2, MJ/kg.

4.3.4 C 2.2 Emissions of acidifying emissions during facility operations

The criterion assesses the gas emissions associated with a building's operation that lead to acidification; SO_2 and NO_x are the major emissions that cause acid precipitation. Specialists have considered that the current accepted levels for these emissions is not acceptable in practice, since they affect the productivity and health of many lakes, rivers and forests (Jeffries et al. 2003). The indicator used to assess this criterion is the annual kg of SO_{2eq} normalized for the net usable building area A_{netocc}, given by the SBTool or calculated using equation (4-58), while the corresponding annual abatement exergy is calculated using (4-59), and which will be added to the final balance equation. All calculations are mainly based on primary energy use and take into account the characteristics of available fuels. The potency factor for atmospheric acidification ($ACID_i$) are presented in (Tallis 2002). Examples are given in Table 4.6.

Table 4.6: $ACID_i$ factors

i^{th} Substance	Potency Factor PF
SO_2	1
HCl	.88
HF	1.6
NO_2	.7
H_2SO_4 mist	.65

$$SO_{2eq} = \frac{\sum_i ACID_i \cdot m_i}{A_{net_{occ}}} \quad (4\text{-}58)$$

$$EX_{C2.2} = SO_{2eq} \cdot A_{net_{occ}} \cdot e_{abat\,SO2} \quad (4\text{-}59)$$

where

SO_{2eq} : the total annual sulphur dioxide equivalent corresponding to acidification is the unit of the ith environmental burden, kg/m^2·yr CO_2;

$ACID_i$: is the potency factor of substance i for acidification as an environmental burden, (kg $SO_{2eq.}$/kg);

w_i : is the weight of substance i emitted, including accidental and unintentional emissions, kg;

$A_{net_{occ}}$: is the net area for each occupancy type (OCC), m^2; and

$e_{abat\,SO2}$: is the specific abatement exergy for SO_2, MJ/kg.

4.3.5 C 2.3 Emissions leading to photo-oxidants during facility operations

An annual emission of gases leading to the formation of photo-oxidants from building operations is assessed through this criterion. The indicator measures the annual Ethane equivalent normalized for net usable building area, in gm, see equation (4-60).

$$C_2H_{6\,eq} = \frac{\sum_i PCOP_i \cdot m_i}{A_{net_{occ}}} \tag{4-60}$$

where

$C_2H_{6\,eq}$: is the emission of Ethane equivalent per year in gm per unit area corresponding to the photo chemical oxidant potential, g/m^2·yr;

$PCOP_i$: is the potency factor of substance i for photo chemical oxidants' potential as an environmental burden, (kg $C_2H_{6\,eq.}$/kg);

m_i : is the weight of substance i emitted, kg; and

$A_{net_{occ}}$: is the net area for each occupancy type (OCC), m^2.

The potency factors for this category are obtained from the potential of substances to create ozone photo chemically, see (Tallis 2002). Some examples are given in Table 4.7.

Table 4.7: Photo-oxidant i factors

ith substance	**Ozone Depletion factor $ODP_{\infty,i}$**
Methane	0.034
Ethane	0.14
Propane	0.411
Propylene	1.08
Nitrogen dioxide	0.028
Sulphur dioxide	0.048
Carbon monoxide	0.027

The aggregation of pollutants to total environmental burdens due to photo-oxidants is based on the concept of equivalency potentials. For example, methane destroys only

0.034 times as many ozone molecules before being removed from the stratosphere as ethylene, it is assigned photo-oxidant potential of .034. All photochemical ozone substances are multiplied by their potency factor and then summed up to give the total pollution load in ethane equivalents. Since the abatement exergy for ethane C_2H_4 has not been found in the literature, it is derived by assuming it is proportional to the global warming potential index. The value of $GWP_{C_2H_6}$ is found in the literature to be extremely small, about 20 (Zhu et al. 2006). The constant value .001 takes into account the conversion from g to Kg. The total annualized abatement exergy $EX_{C2.3}$ corresponding to photo-oxidants is calculated using equation (4-61), and it is added to the final balance equation.

$$EX_{C2.3} = .001 \cdot C_2H_{4\,eq} \cdot A_{net_{occ}} \cdot GWP_{C_2H_6} \cdot e_{abat\,Co2} \tag{4-61}$$

4.4 Available solar exergy

Our planet is a thermodynamic system open to solar radiation and almost closed to any material flux from the universe. Therefore the solar radiation can be considered as the sole sustainable energy source. Many studies have been undertaken on this topic Petela (1964), Landsberg et al. (1976), and Press (1976), including various approaches to calculate the exergy-to-energy ratio for radiation for determining the available exergy due to thermal emission at the solar radiation temperature (TKsun). Among these, the first one, which is called the maximum efficiency ratio (ψ), is calculated as proposed by (Petela 1964), Eq. (4-62).

$$\Psi_{srad,max} = 1 + \frac{1}{3}\left(\frac{To_i}{T}\right)^4 - \frac{4To_i}{3T} \tag{4-62}$$

The maximum efficiency ratio term was also been derived by Szargut et al. (1988), who presented a simple system that transformed radiation energy into mechanical or electrical work assuming that solar radiation has a similar composition to that of a black body. The history of Eq. (4-62) is presented by Millan et al. (1996). It has been reported that the most widely used formula for heat radiation exergy are those derived by (Petela 1964), (Spanner 1964), and (Jeter 1981), see Table 4.8.

Table 4.8: Energy efficiency of radiation utilization by different researchers

Researchers	*Output (numerators)*	*Input (denominators)*	*Energy efficiency of radiation*
(Petela 1964)	Radiation exergy or Useful work	Radiation energy	$\Psi_{srad,max} = 1 + \frac{1}{3}\left(\frac{To_i}{T}\right)^4 - \frac{4To_i}{3T}$
(Spanner 1964)	Absolute work	Radiation energy	$\Psi_{srad,max} = 1 - \frac{4To_i}{3T}$
(Jeter 1981)	Net work or a heat engine	Heat	$\Psi_{srad,max} = 1 - \frac{To_i}{T}$

The annual available solar energy and the annual available solar exergy on a building's footprint (BFP) are calculated using Eqs. (4-63) and (4-64) :

$$EN_{sun-horz} = \sum_i I_i \cdot A_{BFP} \tag{4-63}$$

$$EX_{sun-horz} = \sum_i I_i \cdot A_{BFP} \cdot \left[1 + \frac{1}{3}\left(\frac{To_i}{Tsun}\right)^4 - \frac{4To_i}{3Tsun}\right] \tag{4-64}$$

where To_i = the average environmental temperature for month i [K]; T_{sun} = solar radiation temperature 6000 K (Petela 2005); I_i= total incident solar energy per unit area of horizontal surface for month i (extracted by using TRNSYS software [kWh/m^2.month]; and A_{BFP}= building footprint [m^2] (Klein et al. 2004).

While the proposed approach considered the technical boundary by using sun as an infinite heat source at 6000 K, another approach considering the physical boundary is proposed and explained by Torio and Schmidt (2010). With physical boundary, the maximum possible collector temperature is considered when determining the exergy efficiency rather than using the sun temperature as proposed in this thesis.

4.5 Exergy Index of Renewability α_{ex}

The exergy index of renewability is the ratio between the theoretical available solar exergy (as presented in section 4.4) and the total annualized exergy lost within the building (as presented in sections 4.2 and 4.3), equation (4-2).

The Exergy Index of Renewability, Eq. (4-1), is the ratio between the annual theoretical available solar exergy on the building footprint (as presented in section 4.4), equation (4-64), and the total annualized exergy lost due to the building construction and operation (as presented in section 4.3), equation (4-2).

This approach implicitly considers the theoretical potential of 100% of the solar exergy being harvested. However, the theoretical potential is reduced by losses associated with the conversion from the primary source to the secondary resource. Würfel (2002) discussed the thermodynamic limitation on solar energy conversion based on the entropy concept, and that the upper efficiency is calculated to be 86%, this is identified as a “technical potential” for solar technology. The technical potential is made possible at cost levels that are competitive with other energy sources (commercial PV cells have efficiencies from 2 to 8% as calculated by Sahin et al. (2007)), which can also be identified as an “economic potential”.

The rating scale is developed based on some assumptions: (i) the renewability index of buildings (α_{ex}) follows a normal distribution around the average value, (ii) 50% of the buildings on the market are assumed to be Energy Efficient Buildings (EEB), with

α_{ex} between 40&60. These buildings will receive an "average exergy efficient" under the proposed rating scale, (iii) the probability of finding a Net Zero Energy Building (NZEB, wich α_{ex} between 60 and 80) on the market is only half that of finding an EEBs, or .21. These buildings received an exergy efficiency rating scale; and (iv) this new probability, along with the performance of the buildings that could compensate for 80% of their exergy lost due to construction and operation by the available exergy that could be harvested on their horizontal footprint, represent only 1-4 % of the building market today, with α_{ex} of between 80 and 100. These are called Sustainable Buildings (SB). Figure 4.5 shows the probability density function (PDF) for the Exergy Index of Sustainability (ExSI).

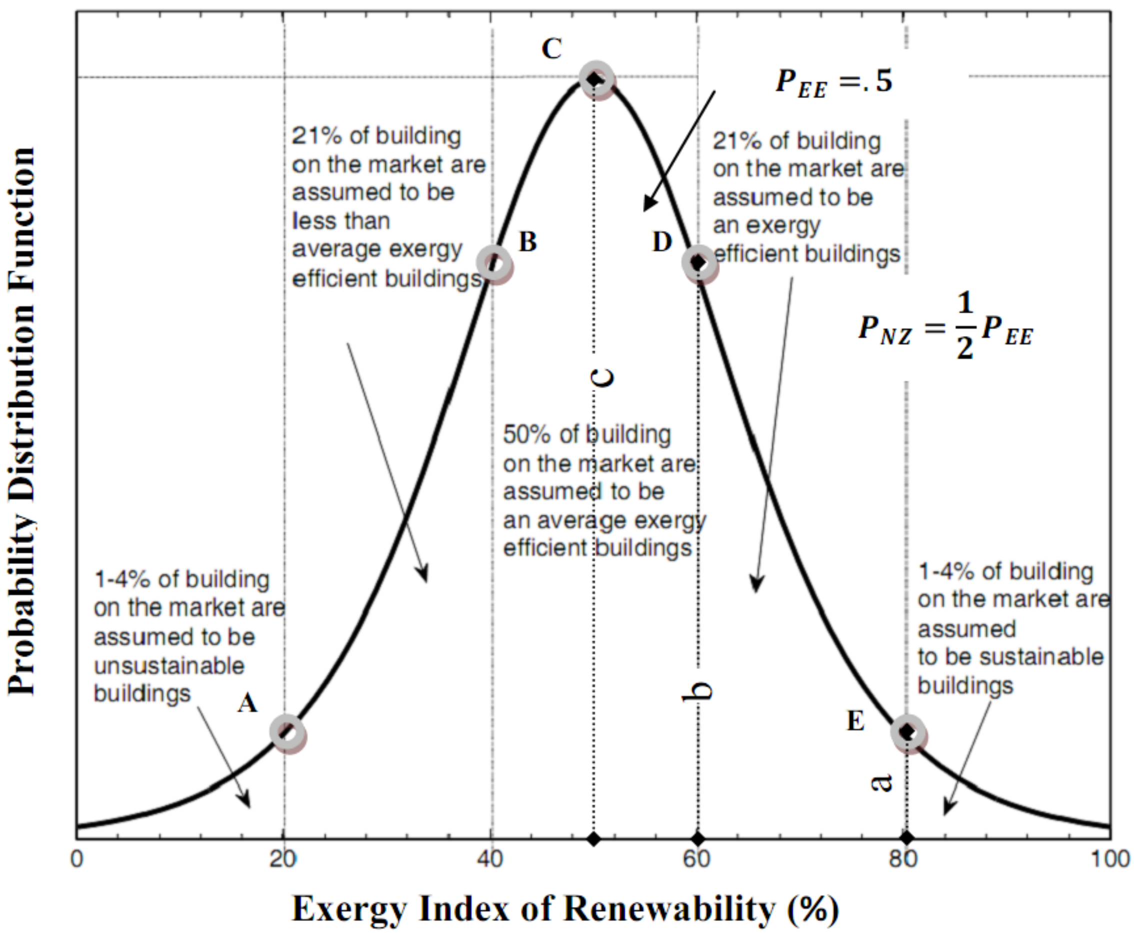


Figure 4.5: Probability density function for Exergy Index of Sustainability (ExSI)

The cumulative distribution function, which presents the Exergy Index of Sustainability, is presented in Figure 4.6.

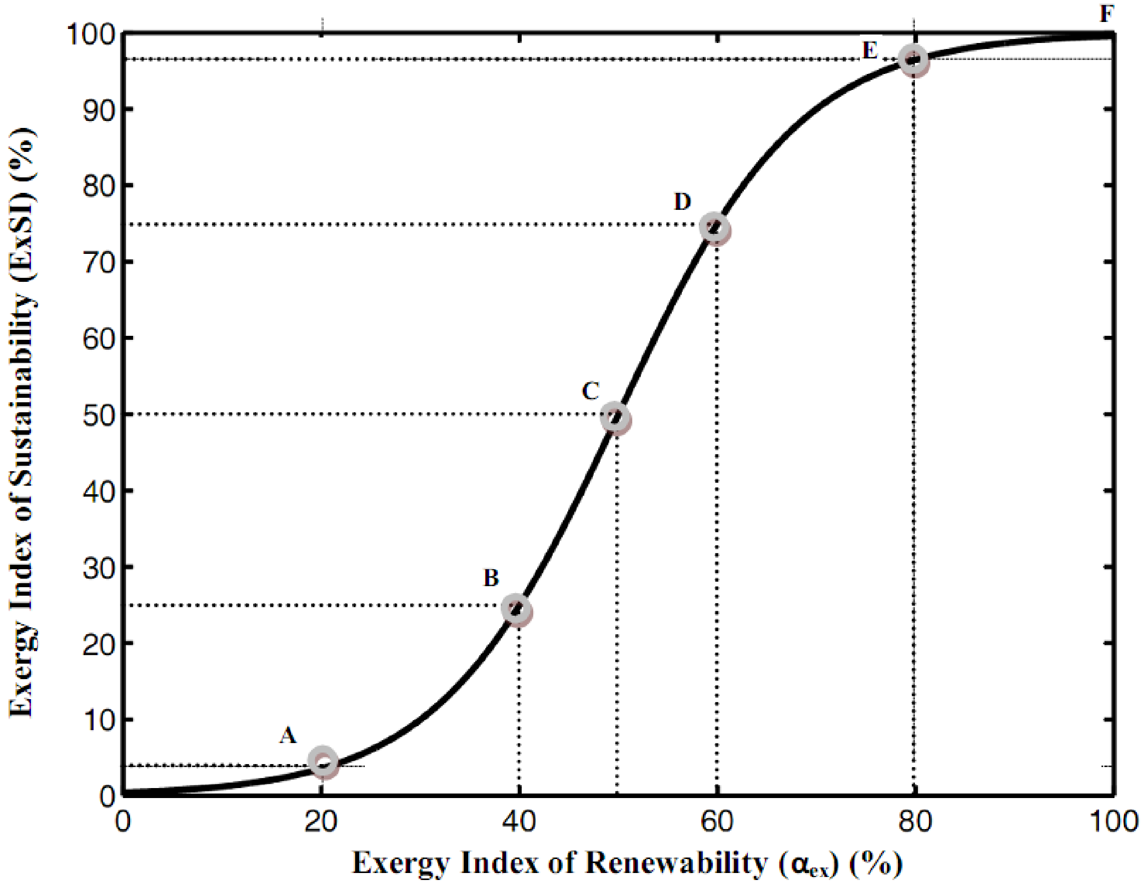


Figure 4.6: Exergy Index of Sustainability versus the Exergy Index of Renewability (α_{ex})

4.6 Exergy Index of Sustainability (ExSI)

The ExSI was developed by imposing the following three constraints: (a) the index should tend to zero when the Exergy Index of Renewability tends to zero, (b) the index should tend to 100 when the Exergy Index of Renewability tends to 100%; in this last case, exergy lost due to building construction and operation is equal to or less than the available exergy that can be harvested on the horizontal surfaces; and (c) the ExSI of 50 corresponds to the Exergy Index of Renewability (α_{ex}) of 50%.

The rating scale has an asymptotic variation when the index approaches the two extremes, i.e., when the building is either unsustainable or sustainable. The nonlinearity causes the exergy sustainability index ExSI to be less sensitive at a small renewability index and at a high renewability index. Since the ExSI is less sensitive at these two extreme conditions, it can be improved only if the building achieves significant reduction of exergy lost, for a given location and footprint. Such reduction will enable breakthrough solutions to take place rather than incremental technological improvements.

The Exergy index of Sustainability (ExSI) is calculated in terms of renewability exergy(α_{ex}) as follows:

$$ExSI = \frac{100}{1 + exp[- \lambda \cdot (\alpha_{ex} - 50)]} \quad (4\text{-}65)$$

Buildings with identical exergy loss may achieve different ratings if different rating scales are implemented. The proposed rating system uses a continuous unipolar function. The value of parameter λ in Equation (4-56) represents the strength of the policy implemented. To help achieve sustainability in the building sector; this parameter determines the slope and spread of the relationship between the sustainability index ExSI and the renewability index α_{ex}. A policy may involve any positive initiative, which could include a variety of recycling programs, reducing pollutions and wastes, and conservation of energy and or water. The value of λ, of between 0 and 1, is set by the developer of a rating scale based on local or national goals, market penetration of technologies and shareholders surveys. If a specific ExSI rating scale is set as a target to be achieved (e.g., ExSI=4) then the renewability index, which is only a function of the total normalized annual exergy lost, has to satisfy an extra reduction under a restrictive sustainability policy (Figure 4.7a) rather than what should be satisfied if a lenient sustainability policy is implemented (Figure 4.8b).

In this study we propose setting λ = 0.11 (Figure 4.7 b), which allows for a Gaussian-type distribution of buildings in terms of exergy performance. Implementing a restrictive sustainability policy, for instance by using λ = 0.9 (Figure 4.7a), would exclude many buildings from being considered as sustainable. The effect of changing the value of lambda is graphically represented (see Figure 4.7).

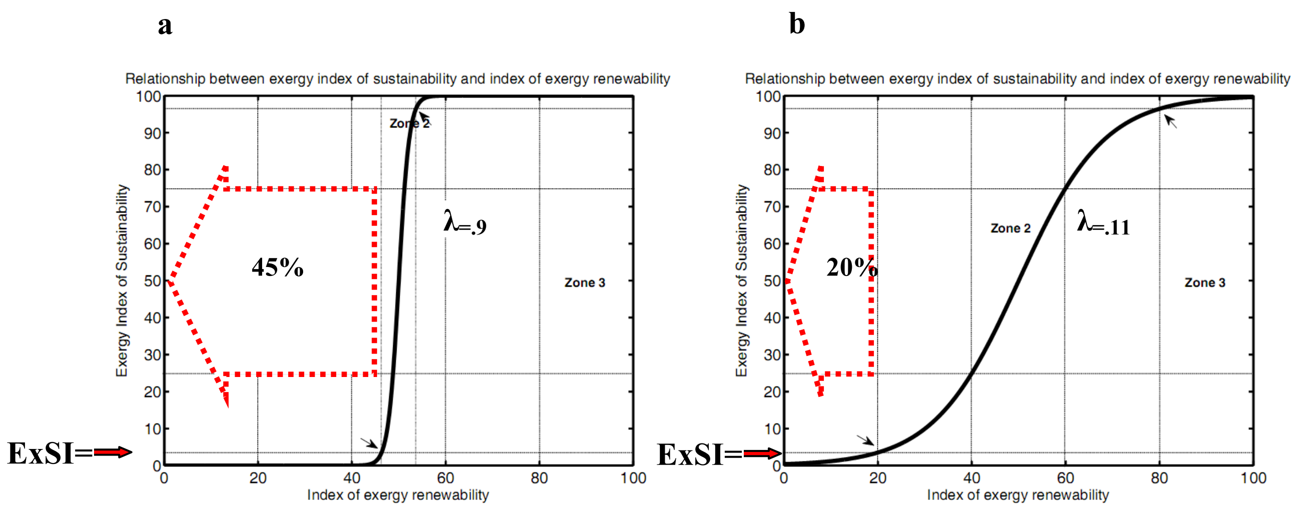


Figure 4.7: Graphical representation of Eq. (4-65) and change of ExSI as a function of λ

4.7 Rating scale for building sustainability

Rating systems achieve different levels of sensitivity based on the method used to assess their indicators. In the best case, earlier rating systems used binomial approaches or rang-based models to evaluate their indicators. In LEED systems, a binomial approach is used where points are given to a building if it meets certain requirements, or are deducted if it fails to satisfy predefined requirements. In SBTool, however, the interval approach is used; the level of performance achievement for each criterion is normalized, and values are converted into a scale bounded between -1 and 5. The difference between the previous approaches and the proposed framework is presented graphically in Figure 4.8.

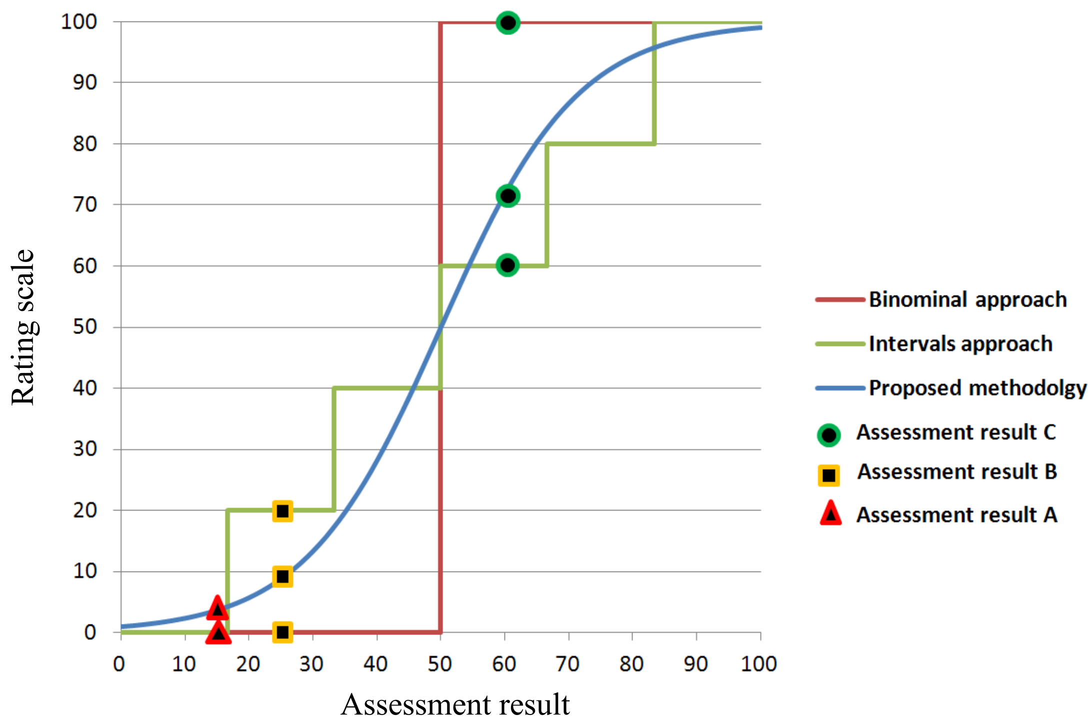


Figure 4.8: Sensitivity of the proposed rating scale versus the previous ones

Different rating scales and their corresponding linguistic representation have been used by different authors. These rating typically take the form of a singular, easily recognizable designation, e.g. ‘Gold’, ‘Excellent’, or they use a numerical index. The former is more market-oriented while the latter is more effective at supporting decision makers.

Ahluwalia (2008) listed some of the available rating scales that have been used for buildings. The rating scale proposed in this study is an extension of Zmeureanu et al.

(1999), which was itself compared against rating scales such as ERHA, STAR POINT, and HERS, using energy use. The proposed rating scale is based on exergy lost instead of energy cost to avoid geo-political and market condition influences. The proposed rating scale assesses building sustainability in five categories, in terms of the Exergy Index of Sustainability: Sustainable, Exergy efficient, Average exergy efficient, Less than average exergy efficient, and Unsustainable Table 4.9.

Table 4.9: Rating scale based on ExSI value.

Rating scale	Range of ExSI value
Sustainable	96 % $<$ExSI $\leq$ 100 %
Exergy efficient	75 % $<$ ExSI $\leq$ 96 %
Average exergy efficient	25% $<$ ExSI $\leq$ 75 %
Less than average exergy efficient	4 % $<$ ExSI $\leq$ 25 %
Unsustainable	0% $\leq$ ExSI $\leq$ 4 %

4.8 Conclusion

An exergy-based index is an attempt to help guide decision making towards sustainability through sustainable building practice. The goal is to develop a simple but powerful rating system that gives a viable assessment of building sustainability. It could be very useful as a compass, rather than as a route map, while also serving as a single proactive indicator that permits an ex-post analysis as well as ex-ante measures. The developed exergy-based index can support decision makers as they evaluate, compare and improve building performance. This index could also be useful to rank and to define the relative importance of each criterion based on the percentage of their contribution to the total annualized exergy loses; thereby identifying the criterion to prioritize for further investigation before making a decision. The proposed exergy-based index uses an innovative approach, in which the annualized exergy lost is compared with a single benchmark, the available solar exergy that can be harvested on a building's footprint. Using this benchmark provides a yardstick that can easily be used to evaluate a building's sustainability locally as well as globally. The proposed exergy-based index attempts to overcome the limitations of the subjectively-defined weights that are allocated to different criteria used in the assessment of building sustainability. The proposed exergy-based index is generic, since it can be used at every stage and it is valid for all building types. The distinctive characteristic of the proposed framework is the calculation and aggregation of different sustainability dimensions into a single commodity, exergy. Even though other SBTool issues, besides the B and C issues, are important to be mentioned, the lack of sufficient data did not allow for the inclusion of exergy losses corresponding to those issues in this thesis. It would be desirable to include some of those important issues in the evaluation procedure in future research work. Changing the constraints that define sustainability as a moving target (i.e. a temporal function) that depends on scientific understanding of sustainability concepts and of the transient nature of technology has been avoided through the proposed framework by using the maximum theoretical available solar exergy.

5 CASE STUDIES

Fourteen carefully-designed case studies were conducted to study various aspects of the proposed framework for evaluating the energy and exergy sustainability indices (ExSI) of a building by means of the exergy approach. The proposed methodology was numerically implemented based on the data given by the SBTool and according to the theoretical procedure used to estimate the ExSI (as presented in chapter 4).

For simplicity, the detailed calculations (all of the required calculations, from extracting the data from SBTool to calculating the ExSI) are only presented for case study no.1; the major results and finding of all the others (nos. 2-14) are presented in tabulated format in section 5.8.

5.1 Case Studies' Description

The proposed assessment method was applied to fourteen case studies. The following paragraphs give only a few indications about each case. For more detailed information, readers are encouraged to consult the following references ((SBTool 2010), (Leckner and Zmeureanu 2012), (Bin and Parker 2011), (Scheuer et al. 2003), and (Monteiro and Freire 2012)). The critical characteristics of case studies (2-14) are listed in Table 5.1: Critical characteristics of case studies (2-14).

Table 5.1: Critical characteristics of case studies (2-14)

Design Parameter	Case studies						
	Case no.2 (BCH)	**Case no.3 (NZEH)**	**Case no.4 (REEP)**	**Case no.5 (REEP)**	**Case no.6 (SH)**	**Case no.7 (EEH)**	**Case nos 8-14**
Location	Montreal, Quebec	Montreal, Quebec	Kitchener, Ontario	Kitchener, Ontario	Detroit, Michigan	Detroit, Michigan	Coimbra, Portugal
Total heated area m^2	208.4	208.4	280	280	657	657	132
Building types	Single detached	Single detached	Two story single detached brick house 1910	Two story single detached brick house retrofit in 2007	Two story single detached	Two story single detached	Single family house
Net area of the overall plan m^2	83.6	83.6	140	140	228	228	70
L service (yr)	40	40	100	70	50	50	50
Envelope							
Insulation of above ground walls (RSI-value)	3.52 $m^2 \cdot K/W$ 140 mm mineral wool	6.25 $m^2 \cdot K/W$ 235 mm improved mineral wool	13	44	15 fibreglass insulation	35 cellulose insulation	.47 -.51 ($W/m^2 {}^{*o}C$) U value
Window/Floor Area Ratio	11%	20%	8%	16%	(14%) 337 ft2	(20%) 490 ft2 (337 (old glass)+153 Low E glass, argon)	11%
Windows:	Double Pane 0.391 $m^2 \cdot K/W$	All Triple Pane Argon Filled. 1.03 $m^2 \cdot K/W$	Double-glazed windows	Double-glazed windows	Double glazing	double glazing, low E coatings with argon fill	Double glazing U=1.1
Natural Air Infiltration (ACH)	0.1635 (3.27 ACH @ 50 Pa)	0.061 (1.22 ACH @ 50 Pa)	N/A	N/A	.67 effective leakage area ELA=153 in2	.4 effective leakage area ELA=20 in2	.6 air change per hour

Energy Efficient Equipment							
Lighting type	Incandescent	CFL	Incandescent	CFL	Incandescent	CFL	Incandescent
Appliances	Standard models	Energy Efficient	Standard models	Energy Efficient	Energy Efficient	Energy Efficient run on NG.	N/A
Annual energy used kWh/yr	25,615 (123 kWh/m^2)	11,600 (67 kWh/m^2)	61380	11000	14493 GJ (50 yrs)	4725 GJ (50 yrs)	905500 MJ
Embodied energy kWh	281,193	511,825 160,709 (due 4 solar collector and 35.8 PV)	133000 77.8% from clay	68000 49.9 % from Polyurethane	1540 GJ (50 yrs)	1703 GJ (50 yrs)	597630 MJ
Domestic Hot Water Use	236 litres/day	Low flow faucets: 165 litres/day	N/A	N/A	N/A	N/A	N/A
	Electric heating element in the tank (5.5 kW)	Solar Collector & Electric Heating (1 kW)	N/A	N/A	N/A	N/A	N/A
DHW Energy Recovery	N/A	Drain Water Heat Recovery Effectiveness of 0.6	N/A	N/A	N/A	Copper waste water heat exchanger coil, decrease NG use by 40%	N/A
Renewable Energy Technologies							
Heating System	Electric Baseboard Heaters	Radiant Floor Heating (2 kW & 4 kW electric elements)	the fuel used to heat the REEP house is natural gas	N/A	passive solar heating	natural gas heating system	N/A
Furnace	N/A	N/A	furnace is 80% efficiency	furnace is 96% efficiency	80%	95%	N/A
Electricity	Electrical Utility	Photovoltaic Panels	Electrical Utility	Electrical Utility	Electrical Utility	Electrical Utility	Electrical Utility
Emissions	N/A	N/A	33882 kg (1.902kgCO_2/m^3)	15397 kg	1013 t CO_2.eq	374 t CO_2.eq	12.9 kg CO_2 eq/m^2.yr or 85 t CO_2eq over (50 yrs)

5.1.1 Case study no.1

Case study no.1 is a large commercial and residential building located in Ottawa, Ontario, Canada (SBTool 2010) and has three occupancy types (apartment, retail, and indoor parking), with total floor area of 11,200 m^2 and building footprint of 800 m^2. The building's life span is considered to be 75 years. Aluminum and glass curtain walls and 30 cm reinforced concrete walls are the main type of building envelope. The building cost, excluding the operation cost, is \$ 10,800,000, \$ 15,200,000, \$ 2,900,000 for the apartment, retail, and indoor parking sectors, respectively. The cost includes the construction cost (thermoeconomic cost), salvaged, recycled, and bio-based materials costs.

The value of the annual exergy lost is calculated for the building footprint A_{BFP} corresponding to each criterion. These values are case-sensitive because they incorporate specific technologies and processes for materials, including their extraction, manufacturing, transportation, and installation.

5.2 Energy consumption and Exergy lost

The components contributing to all of the energy consumption and exergy lost within the building are evaluated based on the SBTool criteria. Each component is presented according to the sequence followed in the calculation of energy consumption exergy lost.

The calculation method for several criteria is presented in this section along with some numerical results for case study no.1. The results from the other case studies are presented is section 5.8. The process begins with the data extracted from the SBTool (see

Table 5.2). Next, the procedure used to calculate the energy consumption within the building is described and carried out, finishing with the equation that converts the energy consumed to the associated exergy lost, with the implementation of the set of equations presented in the theoretical/methodology chapter.

Table 5.2: Selected criteria of issue B as extracted from the SBTool

B	Energy and Resource Consumptions	Units	Extracted data from SBTool			Total
			Apart.	Retail	Indoor parking	
B1.1	Annualized non-renewable primary energy embodied in construction materials.	$MJ/m^2 \cdot yr$	296			296
B1.2	Annual use of purchased electricity for operations, delivered.	$MJ/m^2 \cdot yr$	111	533	36	680
B3.1	Use of off-site energy generated from renewable sources, delivered.	% by energy	22	22	22	14,960
B4.4	Use of durable materials.	% by cost	4			
B4.5	Re-use of salvaged materials from off site.	% by cost	700,000	2,200,000	2,200,000	5,100,000
B4.6	Use of recycled materials from off-site sources.	% by cost	200,000	300,000		500,000
B4.7	Use of bio-based products obtained from sustainable sources.	% by cost	1,400,000	2,700,000		4,100,000
B5.1	Use of potable water for site irrigation.	$m^3/m^2 \cdot yr$	2.5	2.5	2.5	
B5.2	Use of potable water for occupancy needs.	L/pp/day	148	41	41	

5.2.1 Annualized non-renewable embodied energy in construction materials (B.1.1)

The total embodied energy for the project is 404,050,142 MJ, which is the sum of the embodied energy for new structural elements (368,782,744 MJ), new walls (5,562,000 MJ), heavy materials (10,477,500 MJ), existing structural elements (15,006,260 MJ), and existing walls (4,221,638 MJ). The total annualized non-renewable primary energy embodied in construction materials is calculated using formula (4-3):

$$EN_{b1.1} = \frac{EN_{Ns_{b1.1}} + EN_{Nw_{b1.1}} + EN_{Es_{b1.1}} + EN_{Ew_{b1.1}} + EN_{H_{b1.1}}}{L_{service}} \quad (4\text{-}3)$$

$$EN_{b1.1} = \frac{(368{,}782{,}744 + 5{,}562{,}000 + 15{,}006{,}260 + 4{,}221{,}638 + 10{,}477{,}500)}{75}$$

$$= 5{,}387{,}335\ MJ/yr$$

The calculation of the exergy lost from new RC slabs, beams, and columns is given as an example for new structural elements. This exergy is calculated using the formula (4-5). The embodied energy for new RC slabs, beams and columns is given by the SBTool as 190,747,316 MJ. The embodied energy is calculated based on the RC slabs', beams' and columns' total volume (20,817.1 m^3), their density (2,450 Kg/m^3) and specific energy (00374 GJ/Kg). The annual average temperature $Tk_{o,a}$ in Ottawa is 5.8°C (278.95 K). The maximum temperature T_{max} occurs when the raw meal or slurry is fed to a rotary kiln, where it is heated to a temperature of about 1450°C (1723 K) to convert slurry into clinker (Athena™ 2005).

$$EX_{Ns_{b1.1}} = \sum_{m} EN_{Ns_{b1.1}} \cdot \left(1 - \frac{Tk_{o,a}}{Tk_{max}}\right) \quad (4\text{-}5)$$

$$EX_{Ns_{b1.1}} = 190{,}747{,}316 \cdot \left(1 - \frac{278.95}{1723}\right) = 159{,}868{,}424\ MJ$$

The exergy lost from new 20 cm masonry walls ($EX_{Nw_{b1.1}}$) and from steel as heavy materials ($EX_{Hm_{b1.1}}$) are given as examples, calculated using formulas (4-6) and (4-7), respectively.

$$EX_{Nw_{b1.1}} = \sum_{m} EN_{Nw_{b1.1}} \cdot \left(1 - \frac{Tk_{o,a}}{Tk_{max}}\right) \quad (4\text{-}6)$$

$$EX_{Nw_{b1.1}} = 165{,}000 \cdot \left(1 - \frac{278.95}{649}\right) = 115{,}088\ MJ$$

$$EX_{Hm_{b1.1}} = \sum_{m} EN_{Hm_{b1.1}} \cdot \left(1 - \frac{Tk_{o,a}}{Tk_{max}}\right) \quad (4\text{-}7)$$

$$EX_{Hm_{b1.1}} = 8{,}000{,}000 \cdot \left(1 - \frac{278.95}{1329.15}\right) = 6{,}321{,}032\ MJ$$

A similar process is followed for all the other new structural elements, walls and heavy materials, except for sand and aggregate, to obtain the values for the exergy lost.

The chemical exergy lost for sand is calculated using the steps described in section 4.2.1. The chemical formula is SiO_2; the molar Gibbs free energy is -856.7 KJ/mol; the standard chemical exergy is 1.37 KJ/mol; and the molar weight for sand is 60 g/mol. The specific exergy is calculated as 02283 KJ/g using formula (4-8), and in the last step, the total exergy is calculated using formula (4-9) and found to be 2,283 MJ.

$$EX_{ch} = EX_{ch-stand} \cdot \frac{1}{molecular\ wt} \tag{4-8}$$

$$EX_{ch} = 1.37 \cdot \frac{1}{60} = .02283\ KJ/g$$

$$EX_{Hc_{b1.1}} = EX_{ch} \cdot M_{total} \cdot \frac{1{,}000{,}000}{1000} \tag{4-9}$$

$$EX_{Hc_{b1.1}} = .02283 \cdot 100 \cdot \frac{1{,}000{,}000}{1{,}000} = 2{,}283\ MJ$$

The exergy lost by the existing structure and by its walls is calculated using equations (4-10) and (4-11), respectively. The exergy loss calculation for the existing reinforced slabs, beams and columns is presented as an example. The energy used is 14,651,637 MJ, the amortization rate is .02 per year and the estimated age of the existing structure is 12 years; all of these values are given by the SBTool.

$$EN_{E_{b1.1}} = \sum_{m} EN_{N_{b1.1}}{}^{*} \cdot (1 - AR^2 \cdot n) \tag{4-10}$$

$$EN_{Es_{b1.1}} = 14{,}651{,}637 \cdot (1 - .02^2 \cdot 12) = 14{,}581{,}309\ MJ$$

$$EX_{Es_{b1.1}} = \sum_{m} EN_{Es_{b1.1}} \cdot \left(1 - \frac{Tk_{o,a}}{Tk_{max}}\right) \tag{4-11}$$

$$EX_{Es_{b1.1}} = 14{,}581{,}309 \times \left(1 - \frac{278.95}{1{,}723.15}\right) = 12{,}220{,}832\ MJ$$

The total exergy for new structural elements, new walls, for two types of heavy materials, and for existing structural elements and existing walls are 300,539,383 MJ, 4,643,865MJ, 8,197,805 MJ, 9,133 MJ, 12,556,598 MJ, and 3,432,967 MJ, respectively (see Table 5.3).

Table 5.3: Energy consumption and exergy lost for the building materials

Building materials	**Energy**	**Exergy**
New RC slabs, beams & columns	190,747,316	159,868,424
New steel deck & concrete topping	12,920,000	10,208,467
New precast concrete slabs, beams & columns	165,115,427	130,462,492
New structural elements [$EX_{Ns_{b1.1}}$]	**368,782,744**	**300,539,383**
30 cm. RC	4,200,000	3,520,088
20 cm. Masonry*	165,000	115,088
Curtain wall, glass/alum.	1,197,000	1,008,689
New walls [$EX_{Nw_{b1.1}}$]	**5,562,000**	**4,643,865**
Existing RC slabs, beams & columns	14,581,309	12,220,832
Existing steel columns & beams or joists	424,950	335,766
Existing Structural elements [$EX_{Es_{b1.1}}$]	**15,006,260**	**12,556,598**
X 30 cm. RC	1,642,080	1,376,254
X 20 cm. Masonry*	806,112	562,263
X Curtain wall, glass/alum.	1,773,446	1,494,450
Existing walls [$EX_{Ew_{b1.1}}$]	**4,221,638**	**3,432,967**
Masonry*	1,250,000	871,876
Steel	8,000,000	6,321,032
Glass	1,192,500	1,004,897
Heavy material [$EX_{Hc_{b1.1}}$]	10,442,500	**8,197,805**
Sand*	5,000	2,283
Aggregate*	30,000	6,850
Heavy material [$EX_{Hm_{b1.1}}$]	35,000	**9,133**
Total heavy materials	**10,477,500**	**8,206,938**
ENC and EXC	**404,050,142**	**329,379,751**

**Renewable materials*

The total annualized exergy lost from materials is calculated using the following formula (4-4):

$$EX_{b1.1} = \frac{EX_{Ns_{b1.1}} + EX_{Nw_{b1.1}} + EX_{Es_{b1.1}} + EX_{Ew_{b1.1}} + \left[EX_{Hc_{b1.1}} + EX_{Hm_{b1.1}}\right]}{L_{service}} \quad (4\text{-}4)$$

$$EX_{b1.1} = \frac{300{,}539{,}383 + 4{,}643{,}865 + 12{,}556{,}598 + 3{,}432{,}967 + 8{,}197{,}805 + 9{,}133}{75}$$

$$= 4{,}391{,}730\ MJ/yr$$

The total annualized exergy lost (4,391,730 MJ/yr) will be added to the final balance equation (see equation (4-2)).

5.2.2 Annual non-renewable delivered energy used for facility operations (B.1.2)

The total delivered operating energy amounts are given by SBTool; $2{,}579{,}200\ \mathrm{MJ/yr}$ for the electrical energy and $2{,}575{,}000\ \mathrm{MJ/yr}$ for the fuel-based energy (see Table 5.4). The total delivered operating energy $\mathrm{EN_{b1.2}}$ is extracted from the SBTool and is $5{,}154{,}200\ \mathrm{MJ/yr}$.

Table 5.4: Operating energy consumption used for facility operations

Performance calculations for operating energy consumption	Delivered energy			Total project
	Apartment	**Retail**	**Parking**	
Total net area, m^2	4,520	3,750	2,200	10,470
Annual amount of fuel-based energy used for operations, MJ/m^2*yr	442	87	114	246
Project fuel-based MJ/year	2,000,000	325,000	250,000	**2,575,000**
Annual amount of electrical energy used for operations, MJ/m^2*yr	111	533	36	246
Project electrical MJ/year	500,000	2,000,000	79,200	**2,579,200**
Total non-renewable delivered energy, MJ/yr				**5,154,200**

The annual on-site exergy due to electricity use per square meter $\mathrm{EX_{E_{b1.2}}}$ is equal to the electricity consumed per square meter on site $\mathrm{EN_{E_{b1.2}}}$; therefore the exergy lost $\mathrm{EX_{E_{b1.2}}}$ is 246 MJ/m^2*yr.

The entropy gain in the natural gas boiler is calculated as follows (see eqn. 4-16), starting from the assumption that its efficiency is assumed to meet the minimum performance level proposed by Natural Resource Canada, at .82 (Natural Resource Canada, 2009a). The building's estimated annual water consumption is given by the SBTool for each occupancy type as: 2431, 713, and 15 (m^3/yr), for the apartment, retail and indoor parking sectors, respectively. The total potable water yearly demand is 3,158 m^3. The mass flow rate is calculated based on the potable water demand with an equivalent mass of 3,158,000 Kg/yr, assuming that the density of water is 1000 kg/m^3, then the mass flow rate will be 3,158,000 Kg/year. The specific entropy of the water leaving the boiler at 55 C° $\left(s_{w\ out,\ g-boiler}\right)$ is .7679 KJ/ kg. K. The specific entropy of the water entering the boiler at 10 C° $\left(s_{w\ in,\ g-boiler}\right)$ is .1510 KJ/ kg. K.

$$S_{gen\ g-boiler} = \dot{m}_{w\ g-boiler}\left(s_{w\ out,\ g-boiler} - s_{w\ in,\ g-boiler}\right) + \left(EN_{F_{b1.2}} \cdot A_{net_{occ}}\right) \cdot \left(\frac{1-\eta_{boiler}}{Tk_{o,a}}\right) - \frac{\left(EN_{F_{b1.2}} \cdot A_{net_{occ}}\right)}{TK_{flame}} \cdot \eta_{boiler} \quad (4\text{-}16)$$

$$S_{gen\ g-boiler} = \left[3{,}158{,}000 \cdot (.7679 - .1510) \cdot \frac{1}{1000}\right] + \left[246 \cdot 10{,}470 \cdot \left(\frac{1-.82}{278.95}\right)\right] - \left[\left(\frac{246 \cdot 10{,}470}{2{,}528.15}\right) \cdot .82\right]$$

$$S_{gen\ g-boiler} = 4{,}444.94 \quad MJ/K * yr$$

The exergy lost in a process due to the fuel used on-site $EX_{(OS)Fuel\ on-site}$ is the product of entropy generation $S_{gen\ g-boiler}$ in the same process, with the reference environment temperature $Tk_{o,a}$ (278.95 K).

$$EX_{F_{b1.2}} = 4{,}444.94 \times 278.95 = 1{,}239{,}916 \ \ MJ/yr \quad (4\text{-}17)$$

The total exergy lost is calculated using (4-14) formula as follows:

$$EX_{b1.2} = 2{,}579{,}200 + 1{,}239{,}916 = 3{,}819{,}116\ MJ/yr \quad (4\text{-}14)$$

The annual exergy lost due to using non-renewable energy will be added to the final energy/exergy balance equations.

5.2.3 Use of on-site energy generated from renewable sources (B.3.1)

The total annual delivered on-site electrical energy used is 2,579,200 MJ/yr (renewable and non-renewable on-site energy), given by the SBTool. The annual delivered electrical energy use of each occupancy type is 111 MJ/m^2*yr for apartment, 5,333 MJ/m^2*yr for retail and 36 MJ/m^2*yr for indoor parking. The net area for each occupancy type is 4520 m^2 for apartment, 3750 m^2 for retail, and 2200 m^2 for indoor parking. The percent of annual renewable purchased electricity is 22% of the total electrical energy used, as extracted from the SBTool. The annual renewable purchased electricity is calculated by using (4-18), using Table 5.5.

$$EN_{b\,3.1} = \sum_{occ} EN_{E_{b1.2}} \cdot A_{net_{occ}} \cdot \frac{annual\ purchased\ \%}{100} \quad (4\text{-}18)$$

$$EN_{b\,3.1} = \left[111 \cdot 4520 \cdot \frac{22}{100}\right] + \left[533 \cdot 3750 \cdot \frac{22}{100}\right] + \left[36 \cdot 2200 \cdot \frac{22}{100}\right]$$

$$EN_{b\,3.1} = 567{,}424\ MJ/yr$$

Table 5.5: Breakdowns for annual energy consumption (renewable and non-renewable)

Occupancy types	**Net area, m²**	**Non-renewable**		**Renewable**	
		B 1.2	**B 1.2**	**B 3.1**	**B 3.2**
		Fuel	**Electricity**		renewable on-site
			Non-renewable	renewable	
		MJ/yr	MJ/yr	MJ/yr	MJ/yr
Apartment	4,520	2,000,000	390,000	110,000	320,000
Retail	3,750	325,000	1,560,000	440,000	65,000
Indoor parking	2,200	250,000	61,776	17,424	8,000
Total		2,575,000	2,011,776	**567,424**	393,000

The exergy lost, $EX_{b\,3.1}$, is equal to the annual electricity purchased from renewable sources, 567,424 MJ/yr. The value obtained for exergy lost is deducted from the final energy/exergy balance equations.

5.2.4 Use of durable materials (B.4.4)

The percentage of durable materials by cost, i.e., of those materials predicted to meet or exceed Service Life expectations (excluding structural materials) is given by the SBTool as 4%. Calculating the recurring embodied energy lost based on the .96 figure for non-durable materials follows the three steps presented below.

1) Assume that the 4% of each material by cost (given by SBTool) which will not be replaced is equivalent to the percentage of embodied energy used for these materials.
2) Estimate the replacement frequencies (N). For an example, a new curtain wall from glass and aluminum is expected to be replaced once over the predicted service life

expectation, $M_{service}$ = 40 yr (Scheuer et al. 2003), as given in formula (4-20). For other materials see Table 5.6.

$$N_{new} = \frac{L_{service}}{M_{service}} \tag{4-20}$$

$$N_{new} = \frac{75}{40} \cong 1$$

Table 5.6: Recurring embodied energy and recurring exergy

Parameter	Curtain wall, glass/alum	X 30 cm. RC	X 20 cm. Masonry	X Curtain wall, glass/alum	Glass	Total
Initial embodied energy, MJ	1,197,000	1,642,080	806,112	1,773,446	1,192,500	20,261,138
Initial exergy, MJ	1,008,689	1,376,254	562,263	1,494,450	1,004,897	16,283,820
Predicted service life expectation, Yr	40	63	63	28	40	
Frequencies of replacement	1	1	1	2	1	
Total recurring embodied energy, MJ	1,149,120	1,576,397	773,868	3,405,016	1,144,800	**8,049,201**
Total recurring exergy, MJ	968,341	1,321,204	539,772	2,869,344	964,701	**6,663,363**

3) Calculate the recurring embodied energy due the non-durable material and due to the recurring exergy using formulas (4-22) and (4-23), respectively.

$$EN_{non-DUR} = \left(1 - \frac{DUR}{100}\right) \cdot \left(\sum_m EN_{Nw_{b1.1}} \cdot N_{new} + \sum_m EN_{Ew_{b1.1}} \cdot N_{exist} + \sum_m EN_{H_{b1.1}} \cdot N_{new} \right) \tag{4-22}$$

$$EN_{non-DUR} = \left(1 - \frac{4}{100}\right) \cdot (1{,}197{,}000 \cdot 1 + 1{,}642{,}080 \cdot 1 + 806{,}112 \cdot 1 + 1{,}773{,}446 \cdot 2 + 1{,}192{,}500 \cdot 1) = 8{,}049{,}201\ MJ$$

$$EX_{non-DUR} = \left(1 - \frac{DUR}{100}\right) \cdot \left(\sum_m EX_{Nw_{b1.1}} \cdot N_{new} + \sum_m EX_{Ew_{b1.1}} \cdot N_{exist} + \sum_m EX_{H_{b1.1}} \cdot N_{new} \right) \tag{4-23}$$

$$EX_{non-DUR} = \left(1 - \frac{4}{100}\right) \cdot (1{,}008{,}689 \cdot 1 + 1{,}376{,}254 \cdot 1 + 562{,}263 \cdot 1 + 1{,}494{,}450 \cdot 2 + 1{,}004{,}897 \cdot 1) = 6{,}663{,}363\ MJ$$

The total annualized recurring embodied energy is calculated using equation (4-24):

$$EN_{b4.4} = \frac{8{,}049{,}201}{75} = 107{,}323\ MJ/yr \tag{4-24}$$

The total annual exergy lost due to replacement for non-durable materials is calculated using:

$$EX_{b4.4} = \frac{6,663,363}{75} = 88,845\ MJ/yr \qquad (4\text{-}25)$$

The total annual exergy lost (88,845 MJ/yr) values due to replacement of non-durable material will be added to the final balance equation given in section 4.2.

5.2.5 Re-use of salvaged materials (B.4.5)

To calculate the energetic cost of using salvaged materials, the unit energetic cost needs to be determined using Eq. (4-28)). Consequently, both the energetic cost (ENC) and the thermoeconomic cost (TEC) need to be estimated, using the formulas given in Eqns. (4-26) and (4-27), respectively.

The values of all of the materials re-used from salvaged sources on site and/or from off-site sources, as a percent of total construction cost, τ in % by cost, are given by the SBTool and presented in Figure 5.7.

Table 5.7: Cost of salvaged materials, recycled, and bio-based materials

Given data from SBTool	Apartment	Retail	Indoor parking	Total
Total cost of the building construction (structural, wall, and heavy materials), $	10,800,000	15,200,000	2,900,000	**28,900,000**
τ in % by cost	6.5%	14.5%	75.9%	
Cost of salvaged materials (on-site and off-site), $	700,000	2,200,000	2200000	**5,100,000**
θ in % by cost	1.85%	1.97%	0%	
Cost of recycled materials, $	200,000	300,000	0	**500,000**
μ in % by cost	12.96%	17.76%	0%	
Cost of bio-based materials, $	1,400,000	2,700,000	0	**4,100,000**

The energetic cost (ENC) and the exergetic cost (EXC) are calculated for the construction phase (structural, walls, and heavy materials) using (4-26) and (4-32) respectively, see Table 5.3.

$$ENC = EN_{Ns_{b1.1}} + EN_{Es_{b1.1}} + EN_{H_{b1.1}} + EN_{Nw_{b1.1}} + EN_{Ew_{b1.1}} \qquad (4\text{-}26)$$

$$ENC = 368{,}782{,}744 + 15{,}006{,}260 + 10{,}477{,}500 + 5{,}562{,}000 + 4{,}221{,}638 = 404{,}050{,}142\ MJ$$

Knowing: i) the total building cost of 28,900,000 $ (10,800,000 $ for apartment, 15,200,000 $ for retail and 2,900,000 $ for indoor parking); and ii) the cost of salvaged, recycled, and bio-based materials, given by SBTool, based on the percentage of their contribution to the total construction cost using τ, θ, and μ % respectively, the thermoeconomic cost (TEC) can be obtained using eqn. (4-27).

$$TEC = TEC_{total} - (TEC_{salvaged} + TEC_{recycled} + TEC_{bio-based}) \quad (4\text{-}27)$$

$$TEC = 28{,}900{,}000 - (5{,}100{,}000 + 500{,}000 + 4{,}100{,}000) = 19{,}200{,}000\ \$$$

The unit energetic cost (enc) is calculated using (4-28):

$$enc = \frac{ENC}{TEC} \quad (4\text{-}28)$$

$$enc = \frac{404{,}050{,}142}{19{,}200{,}000} = 21.04\ MJ/\$$$

Knowing the cost of salvage materials (given by the SBTool) and the unit energetic cost (calculated), the energetic cost for using salvaged materials on-site and off-site can be calculated using (4-30):

$$EN_{b4.5} = \frac{enc \times TEC_{salvaged}}{L_{service}} \quad (4\text{-}30)$$

$$EN_{b4.5} = \frac{21.04 \times 5{,}100{,}000}{75} = 1{,}430{,}720\ MJ/yr$$

Similar to the process used for calculating the energetic cost (the energy consumed for salvaged materials), the exergetic cost (EXC), and the unit exergetic cost (exc) are calculated using (4-32) and (4-31):

$$EXC = EX_{Ns_{b1.1}} + EX_{Es_{b1.1}} + EX_{H_{b1.1}} + EX_{Nw_{b1.1}} + EX_{Ew_{b1.1}} \quad (4\text{-}32)$$

$$EXC = 300{,}539{,}383 + 12{,}556{,}598 + 8{,}206{,}938 + 4{,}643{,}865 + 3{,}432{,}967 = 329{,}379{,}751\ MJ$$

$$exc = \frac{EXC}{TEC} \quad (4\text{-}31)$$

$$exc = \frac{329{,}379{,}751}{19{,}200{,}000} = 17.16\ MJ/\$$$

The exergetic cost for using salvaged materials is calculated using (4-30):

$$EX_{b4.5} = \frac{exc \ \times TEC_{salvage}}{L_{service}} \tag{4-33}$$

$$EX_{b4.5} = \frac{17.16 \times \ 5{,}100{,}000}{75} = 1{,}166{,}880 \ MJ/yr$$

The annual exergy lost by using salvaged materials both on-site and off-site is 1,166,880 MJ/yr. This value will be added to the final energy and exergy balance equations (see Table 5.10).

5.2.6 Use of recycled materials from off-site sources (B.4.6)

Given the total construction cost (TEC_{total}) and the percentage of θ, the cost of the recycled materials can be calculated using (4-34):

$$TEC_{recycled} = \sum_{occ} TEC_{total} \cdot \theta \tag{4-34}$$

$$TEC_{recycled} = \ 10{,}800{,}000 \cdot 1.85\% + 15{,}200{,}000 \cdot 1.97\% + 2{,}900{,}000 \cdot 0\%$$

$$TEC_{recycled} = \ 500{,}000 \ \$$$

The annual energy used and the annual exergy lost by using recycled materials from off-site sources are calculated using formulas (4-35) and (4-36), respectively.

$$EN_{b\ 4.6} = \frac{enc \cdot TEC_{recycled}}{L_{service}} \tag{4-35}$$

$$EN_{b\ 4.6} = \frac{21.04 \ \cdot \ 500{,}000}{75} = 140{,}295 \ MJ/yr$$

$$EX_{b\ 4.6} = \frac{exc \cdot TEC_{recycled}}{L_{service}} \tag{4-36}$$

$$EX_{b\ 4.6} = \frac{17{,}16 \ \cdot \ 500{,}000}{75} = 114{,}368 \ MJ/yr$$

The annual exergy lost by using recycled materials from off-site, 114.368 MJ/yr, will be added to the final energy and exergy balance equation (see Table 5.10).

5.2.7 Use of bio-based products obtained from sustainable sources (B.4.7)

The cost or value of bio-based materials from sustainable sources that are certified by a recognized certification agency is calculated using (4-37), based on the total construction cost and value of μ in %, extracted from the SBTool.

$$TEC_{bio-based} = \sum_{occ} TEC_{total} \cdot \mu \quad (4\text{-}37)$$

$$TEC_{bio-based} = 10{,}800{,}000 \cdot 12.96\% + 15{,}200{,}000 \cdot 17.76\% + 2{,}900{,}000 \cdot 0\%$$

$$TEC_{bio-based} = 4{,}100{,}000\ \$$$

The unit energetic cost (21.04 MJ/$), as well as the unit exergetic cost (17.16 MJ/$), were calculated using (4-28) and (4-31), respectively. The annual energetic and exergetic cost for using bio-based products are then calculated using equations (4-38) and (4-39), respectively:

$$EN_{b\,4.7} = \frac{enc \cdot TEC_{bio-based}}{L_{service}} \quad (4\text{-}38)$$

$$EN_{b\,4.7} = \frac{21.04 \cdot 4{,}100{,}000}{75} = 1{,}150{,}421\ MJ/yr$$

$$EX_{b\,4.7} = \frac{exc \cdot TEC_{bio-based}}{L_{service}} \quad (4\text{-}39)$$

$$EX_{b\,4.7} = \frac{17.16 \cdot 4{,}100{,}000}{75} = 937{,}817\ MJ/yr$$

The annual energy consumed and the exergy lost by using bio-based products obtained from sustainable sources are 1,150,421 MJ/yr and 937,817 MJ/yr, respectively. The cost of the bio-based products $\mathrm{TEC_{bio-based}}$ (4,100,000 $) is not included in the construction cost TEC corresponding to the initial embodied energy used ENC (see formula (4-26)) or exergy lost EXC (see formula (4-32)), therefore the exergy lost (937,817 MJ/yr) calculated for the bio-based products will be added to the final energy and exergy balance equation (see Table 5.10).

5.2.8 Use of potable water for site irrigation (B.5.1)

The site area landscaped with appropriate native species that do not require watering, A_{native} = 3400 m^2 and the site area landscaped with non-native species that requires watering $A_{non\text{-}native}$ = 400 m^2. Both areas are given by the SBTool. The irrigation rate $I_{irrigation\text{-}rate}$ is 2.5 m^3/m^2*yr (extracted from the SBTool) which indicates the volume of water used for one square meter of the landscaped site area. The energy rate EN_{rate}=.452 [KWh/m^3] =1.6272 [MJ/m^3]. The annual energy used for treating this water is calculated using formula (4-40):

$$EX_{b\ 5.1} = EN_{b\ 5.1} = A_{non-native} \cdot I_{irrigation-rate} \cdot EN_{rate} \tag{4-40}$$

$$EX_{b\ 5.1} = EN_{b\ 5.1} = 400 \cdot 2.5 \cdot 1.6272 = 1{,}627.2\ MJ/yr$$

The annual energy consumption and the annual exergy lost due to site irrigation for non-native species are identical since it is mainly in the form of electricity (1,627.2 MJ) which will be added to the final exergy balance equation.

5.2.9 Use of potable water for occupancy needs (B.5.2)

The predicted total potable water, in [L/pp/day], used for each occupancy type based on occupancy, fittings and fixtures is given by the SBTool. The daily use per person, the number of uses per day, the days of operation and the estimated population are given in Table 5.8. The ($TAPW_{occ}$) is calculated using (4-41):

$$TAPW_{occ} = \sum_{occ} P \cdot d_{operation} \sum_{fix} \left(\frac{L_{pt} \cdot T_{pd}}{1000} \right) \tag{4-41}$$

$$TAPW_{occ} = 45 \cdot 365 \cdot \left[\frac{6 \cdot 2}{1000} + \frac{6 \cdot 4}{1000} + \frac{70 \cdot .8}{1000} + \frac{90 \cdot .2}{1000} + \frac{15 \cdot .2}{1000} + \frac{40 \cdot .2}{1000} \right] + 55 \cdot 320 \cdot \left[\frac{6 \cdot 2}{1000} + \frac{1.5 \cdot 3}{1000} + \frac{6 \cdot 4}{1000} \right] + 1 \cdot 364 \cdot \left[\frac{6 \cdot 2}{1000} + \frac{1.5 \cdot 3}{1000} + \frac{6 \cdot 4}{1000} \right] = 3{,}158 \frac{m^3}{yr}$$

Table 5.8: the total predicted annual potable water

Type of occupancy	Apartment							Retail							Parking						
Type of fixture	Toilet	Urinal	Lavatories	Showers	Bathtub	Kitchen sinks	Washing machines	Toilet	Urinal	Lavatories	Showers	Bathtub	Kitchen sinks	Washing machines	Toilet	Urinal	Lavatories	Showers	Bathtub	Kitchen sinks	Washing machines
Lpt (L/ pp)	6	1.5	6	70	90	15	40	6	1.5	6	70	90	15	40	6	1.5	6	70	90	15	40
Tpd (1/Day)	2	3	4	0.8	0.2	2	0.2	2	3	4	0.8	0.2	2	0.2	2	3	4	0.8	0.2	2	0.2
Liters per day (L/pp/Day)	**12**	4.5	**24**	**56**	**18**	**30**	**8**	**12**	**4.5**	**24**	56	18	30	8	**12**	**4.5**	**24**	56	18	30	8
Number of fixture	75	0	75	65	60	20	20	8	4	2	0	0	0	0	1	1	1	0	0	0	0
Area of occupancy	4,800							4,000							2,400						
Contribution for cold water	1.00	1.00	1.00	0.50	0.50	0.43	0.77	1.00	1.00	1.00	0.50	0.50	0.43	0.77	1.00	1.00	1.00	0.50	0.50	0.43	0.77
Contribution for hot water	0.00	0.00	0.00	0.50	0.50	0.57	0.23	0.00	0.00	0.00	0.50	0.50	0.57	0.23	0.00	0.00	0.00	0.50	0.50	0.57	0.23
L pp/ day	148.0							40.5							40.5						
Estimated population	45							55							1						
Assumed days of operation	365							320							364						
TAPW, m3*yr	2,431							713							15						
Total	**3,158**																				

The annual energy consumption for treating potable water for occupancy needs and the corresponding exergy lost are equal, since the energy used is the electricity, calculated using (4-42):

$$EX_{occ\ w-treat} = EN_{occ\ w-treat} = TAPW_{occ} \cdot EN_{rate} \qquad (4\text{-}42)$$

$$EX_{occ\ w-treat} = EN_{occ\ w-treat} = 3158 \cdot 1.6272 = 5{,}139\ MJ/yr$$

The amount of potable hot water is estimated using equation (4-46):

$$TAPW_{hot-occ} = \sum_{occ} P \cdot d_{operation} \cdot \sum_{fix} \left(\frac{L_{pt}}{1000} \cdot T_{pd} \cdot \alpha_{hot-water} \right) \qquad (4\text{-}46)$$

$$TAPW_{hot-occ} = \left[(45 \cdot 365) \cdot \left(\frac{70 \cdot .8 \cdot .5}{1000} + \frac{9 \cdot 2 \cdot .5}{1000} + \frac{15 \cdot 2 \cdot .57}{1000} + \frac{40 \cdot .2 \cdot .23}{1000} \right) \right] = 919\ m^3/yr$$

By assuming that the temperature for the domestic hot water T_{tank} is 55 ^{o}C (328.15 ^{o}K), and assuming the T_{inlet} from the city main is 10 ^{o}C (283.15 ^{o}K), then the annual energy consumption to deliver hot water through the plumbing fixtures is calculated using (4-43):

$$EN_{hot\ DHW} = \frac{1}{EF} \cdot \left(1000 \cdot TAPW_{hot-occ} \cdot C_p \cdot (T_{supply} - T_{inlet}) \right) \qquad (4\text{-}43)$$

$$EN_{hot\ DHW} = \frac{1}{.7} \cdot 1000 \cdot 919 \cdot 4186 \cdot (328.15 - 283.15) = 247{,}302.9\ MJ/yr$$

The annual average outdoor air temperature is 5.8°C (278.95 °K) (Natural Resources Canada RETScreen, 2007) and the adiabatic flame temperature for natural gas Tk_{flame} is (2255 °K) (Williamson et al. 2003). The exergy lost using gas water heaters $EX_{hot-g\ DHW}$ and electric water heaters $EX_{hot-E\ DHW}$ are calculated using (4-44) and (4-45) formulas respectively:

$$EX_{hot-g\ DHW} = EN_{hot-g\ DHW} \cdot \left(1 - \frac{Tk_{o,a}}{Tk_{flame}}\right) \quad (4\text{-}44)$$

$$EX_{hot-g\ DHW} = 247{,}302.9 \cdot \left(1 - \frac{278.95}{2255}\right) = 247{,}302.9 \cdot .876 = 216{,}710.8 MJ/yr$$

$$EX_{hot-E\ DHW} = 247{,}302.9\ MJ/yr$$

The electrical energy used to operate water fixtures such as washing machines and the corresponding exergy lost is calculated using (4-47):

$$EN_{oper\ fix} = \sum_{fix} \left(Op_h \cdot E_{load} \cdot \frac{D_{cycle}}{100} \cdot P \cdot d_{operation} \cdot N_{fix}\right) \quad (4\text{-}47)$$

$$EX_{oper\ fix} = EN_{oper\ fix} = \left(.9 \cdot 1.8 \cdot \frac{20}{100} \cdot 45 \cdot 365 \cdot 20\right) = 106{,}434\ kWh/yr$$
$$= 383{,}162.4\ MJ/yr$$

The total annual energy consumption for potable water use is the sum of equations (4-42), (4-43) and (4-47):

$$EN_{b\ 5.2} = EN_{occ\ w-treat} + EN_{hot\ DHW} + EN_{oper\ fix} \quad (4\text{-}48)$$

$$EN_{b\ 5.2} = 5{,}139 + 247{,}302.9 + 383{,}162.4 = 635{,}604.3\ MJ/yr$$

The total annual exergy lost is calculated using either eqn. (4-49) or (4-50):

$$EX_{b\ 5.2} = EX_{occ\ w-treat} + EX_{hot-g\ DHW} + EX_{oper\ fix} \quad (4\text{-}49)$$

$$EX_{b\ 5.2} = 605{,}012.2\ MJ/yr$$

$$EX_{b\ 5.2} = EX_{occ\ w-treat} + EX_{hot-E\ DHW} + EX_{oper\ fix} \quad (4\text{-}50)$$

$$EX_{b\ 5.2} = 635{,}604.3\ MJ/yr$$

The total annual energy consumption due to water use is 635,604.3 MJ/yr and the total annual exergy lost is either 605,012.2 MJ/yr, using gas water heaters, or 635,604.3 MJ/yr using electric water heaters. The values calculated for this criterion will be added to the final exergy balance equations (see Table 5.10).

5.3 Evaluation of annualized exergy lost for environmental loading issue C (SBTool)

This section evaluates the annualized abatement exergy that is lost in order remove harmful pollution from the waste discharged to the environment (see Table 5.9). The product of the waste emissions mass and its unit abatement exergy is used to calculate the annualized abatement exergy consumption.

Table 5.9: Selected criteria of C issue as extracted from the SBTool

C	Environmental loadings	Units	Data Extracted from SBTool
C1.1	Annualized GHG emissions embodied in construction materials	$kg/m^2 \cdot yr$	16.19
C1.2	Annualized GHG emissions from energy used for facility operations	$kg/m^2 \cdot yr$	42.3
C2.1	Emissions of ozone-depleting substances during facility operations	$g/m^2 \cdot yr$	.07
C2.2	Emissions of acidifying emissions during facility operations	$kg/m^2 \cdot yr$	.42
C2.3	Emissions leading to photo-oxidants during facility operations	$g/m^2 \cdot yr$	.15

5.3.1 Annualized GHG emissions embodied in construction materials (C.1.1)

The abatement exergy method is implemented in this research to assess the environmental impact of emissions. It has several advantages: easy to apply once the exergy is known for each waste emission, the availability of some specific waste emissions in the literature, and the possibility of adding the corresponding exergy value directly to the exergy lost value of another indicator(s). The method evaluates the exergy required to remove or isolate harmful emissions from the environment.

The annualized abatement exergy lost corresponding to the emissions embodied in construction materials is calculated as follows:

$$EX_{C1.1} = EN_{b1.1} \cdot a_{aver} \cdot e_{abat} \quad (4\text{-}51)$$

$$EX_{C1.1} = 5{,}387{,}335 \cdot \frac{55}{1000} \cdot 5.86 = 1{,}736{,}338\ MJ$$

where a_{aver} = the regional annual fuel emission value kg CO_2 per embodied GJ (e.g., the emissions for residential units taken from average Canadian building stock values for 1999 (SBTool 2010) is 55 kg CO_2/GJ; e_{abat} = specific abatement exergy (e.g., the abatement exergy for CO_2 is found to be 5.86 MJ/kg (Dewulf et al. 2001)).

5.3.2 Annualized GHG emissions from the energy used for facility operations (C.1.2)

The total annualized abatement exergy, $EX_{C1.2,}$ corresponding to the annualized GHG emissions from the overall energy used for facility operations is added to the final balance equation and is calculated using the following equation:

$$EX_{C1.2} = a_{aver} \cdot \sum_{occ} \left(EN_{b1.2} \cdot A_{net_{occ}}\right) \cdot e_{abat\ Co2} \quad (4\text{-}55)$$

$$EX_{C1.2} = \frac{55}{1000} \cdot 8{,}043{,}614 \cdot 5.86 = 2{,}592{,}457\ MJ/yr$$

5.3.3 Emissions of ozone-depleting substances during facility operations (C.2.1)

The predicted annual emission of CFC-11_{eq} is 0.07 g/m^2·yr (SBTool). The total annualized exergy $EX_{C2.1}$ corresponding to the emission of ozone-depleting substances during facility operations is obtained using equation (4-59). In Equation (4-57), the net areas for each occupancy type A_{netocc} are automatically derived from the building definition; the specific abatement exergy for CO_2 is 5.86 MJ/kg, based on the technology used (Dewulf et al. 2001).

$$EX_{C2.1} = .001 \cdot CFC - 11_{eq} \cdot A_{net_{occ}} \cdot GWP_{CFC-11} \cdot e_{abat\ Co2} \quad (4\text{-}57)$$

$$EX_{C2.1} = .001 \cdot .07 \cdot 10{,}470 \cdot 3500 \cdot 5.86 = 15{,}032\ MJ/yr$$

5.3.4 Emissions of acidifying emissions during facility operations (C.2.2)

The annual emissions of SO_{2eq} normalized for the net usable building area A_{netocc} is 0.42 (SBTool), while the corresponding annual abatement exergy is calculated using equation (4-59). The abatement exergy for SO_x is 57 MJ/kg (Dewulf et al. 2001). The annual abatement exergy will be added to the final balance equation.

$$EX_{C2.2} = SO_{2eq} \cdot A_{net_{occ}} \cdot e_{abat\,SO2} \qquad (4\text{-}59)$$
$$EX_{C2.2} = 0.42 \cdot 10{,}470 \cdot 57 = 250{,}652\ MJ/yr$$

5.3.5 Emissions leading to photo-oxidants during facility operations (C.2.3)

The annual Ethane equivalent normalized for net usable building area is 0.15 $g/m^2 \cdot yr$ (from SBTool). The annual abatement exergy is calculated using Equation (4-61).

$$EX_{C2.3} = .001 \cdot C_2H_{4\,eq} \cdot A_{net_{occ}} \cdot GWP_{C_2H_6} \cdot e_{abat\,Co2} \qquad (4\text{-}61)$$
$$EX_{C2.3} = .001 \cdot .15 \cdot 10{,}470 \cdot 20 \cdot 5.86 = 184\ MJ/yr$$

5.4 Accumulative annualized exergy lost

The exergy lost values for case no.1 are summarized and given in Table 5.10 and presented in Figure 5.1. The total exergy lost calculated for case no.1 with Equation (4-2) is 15,152,635 MJ/yr. This value is equal to the denominator of Equation (4-1).

Table 5.10: Total annual exergy lost for the B and C criteria

Criteria		Annual exergy lost
B1.1	+	4,391,730
B1.2	+	3,819,116
B3.1	-	567,424
B4.4	+	88,845
B4.5	+	1,166,880
B4.6	+	114,368
B4.7	+	937,817
B5.1	+	1,627
B5.2	+	605,013
C1.1	+	1,736,338
C1.2	+	2,592,457
C2.1	+	15,032
C2.2	+	250,652
C2.3	+	184
Total		**15,152,635**

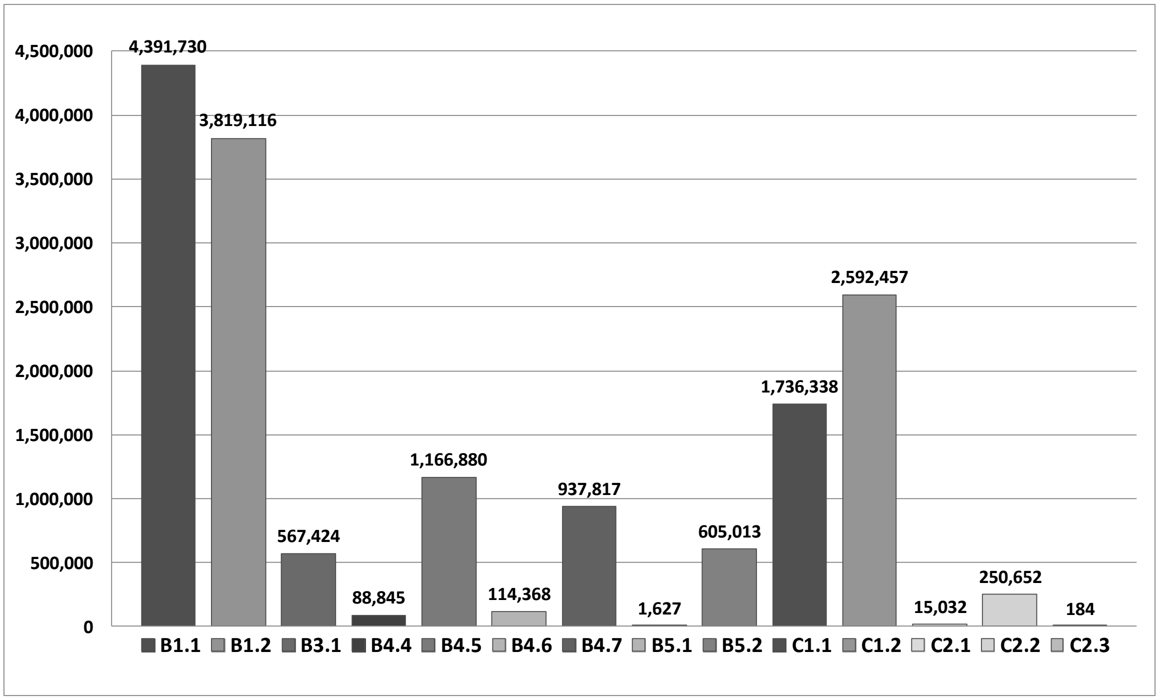


Figure 5.1: Distribution of exergy lost among B & C criteria of case no.1

5.5 Available solar energy/Available solar exergy

The monthly available solar energy on the building footprint was extracted from the TRNSYS program for Ottawa (Klein et al. 2004) and presented in Table 5.11for case study no.1. The reference environment is defined by using the monthly mean values of outdoor air temperature. Petala's method is used to calculate the exergy of solar radiation using equation (4-46); the calculation of available solar exergy in January is given as an example, for other values see Table 5.11.

$$EX_{sun-\,horz} = 51.67 \cdot \left[1 + \frac{1}{3} \cdot \left(\frac{263.4}{6000}\right)^4 - \frac{4 \cdot 263.4}{3 \cdot 6000}\right] \cdot 800 = 38{,}921\ kWh$$
$$= 140{,}115.6\ MJ \quad (4\text{-}64)$$

Table 5.11: Available solar energy and available solar exergy in the horizontal surface

Month	To_i (K)	Total monthly solar radiation- kWh/m^2	Total monthly available solar energy radiation (horizontal) kWh	Total monthly available solar exergy radiation (horizontal) kWh
Jan	263.4	51.67	41,340	38,921
Feb	265.0	77.66	62,125	58,467
Mar	271.5	122.92	98,333	92,401
Apr	279.8	141.79	113,436	106,384
May	287.0	179.86	143,892	134,717
Jun	292.1	187.09	149,670	139,956
Jul	295.0	186.54	149,230	139,449
Aug	293.4	155.41	124,332	116,227
Sep	288.5	117.30	93,841	87,826
Oct	282.1	78.04	62,435	58,522
Nov	275.2	40.28	32,222	30,251
Dec	266.6	38.48	30,782	28,959
Total solar radiation (kWh)			1,101,637	1,032,081
Total solar radiation (MJ)			3,965,893	**3,715,491**

Available solar energy and available solar exergy results for other case studies are presented in Table 5.12.

Table 5.12: Available solar exergy in the horizontal surface for case studies 2-14

Month	Case no. 2 &3		Case no. 4 &5		Case no. 6 &7		Case no. 8 – 14	
	To_i (K)	Ex_{avail}	To_i (K)	Ex_{avail}	To_i (K)	Ex_{avail}	To_i (K)	Ex_{avail}
Jan	263.9	3,861	267.3	6,058	271.2	9,856	267.3	1,742
Feb	265.4	5,710	267.2	8,836	272.6	14,372	267.2	2,258
Mar	271.8	9,390	272.2	13,890	276.9	22,596	272.2	3,497
Apr	279.9	10,785	279.6	17,765	283.5	28,905	279.6	4,623
May	287.1	13,807	286.1	23,008	289.9	37,437	286.1	5,604
Jun	293.0	14,578	291.6	24,392	295.3	39,690	291.6	5,594
Jul	295.0	14,603	294.1	25,202	298.0	41,005	294.1	5,500
Aug	293.6	11,806	293.2	21,870	296.9	35,586	293.2	4,766
Sep	288.7	9,462	289.4	15,654	292.6	25,475	289.4	3,939
Oct	282.5	6,174	283.1	10,614	286.0	17,273	283.1	2,969
Nov	275.8	2,884	276.4	5,190	279.8	8,446	276.4	1,900
Dec	267.3	2,866	270.1	4,501	273.8	7,323	270.1	1,483
Total		**105,927**		**176,981**		**287,964**		**43,876**
Total		**381,336**		**637,130**		**3,052,416**		**157,952**

5.6 Exergy index of renewability α_{ex}

The exergy index of renewability is the ratio between the theoretical available solar exergy, 3,715,491 MJ (as presented in section 4.3) and the total annualized exergy lost within the building, 15,152,635 MJ:

$$Exergy\ index\ of\ \ renewability\ \alpha_{ex} = \frac{3{,}715{,}491}{15{,}152{,}635} \cdot 100 = 24.52\ \% \qquad (4\text{-}1)$$

5.7 Exergy Index of Sustainability

The exergy index of sustainability (ExSI) is calculated in terms of the renewability exergy (α_{ex}) as follows:

$$ExSI = \frac{100}{1 + exp[- \lambda \cdot (\alpha_{ex} - 50)]} \qquad (4\text{-}65)$$

$$ExSI = \frac{100}{1 + exp[-.11 \cdot (24.52 - 50)]} = 5.7\ \%$$

The Exergy Index of Sustainability (ExSI) of case study no. 1, a large commercial and residential building located in Ottawa, is equal to 5.7%. This figure indicates that from the ideal conversion rate of 100% of solar energy, only 5.7% of the annualized exergy lost could be compensated by the incident exergy of solar radiation on the building footprint.

5.8 Rating scale for building sustainability (ExSI)

According to the proposed rating scale, with an ExSI=5.7% case study no. 1 would be qualified as a “less than average exergy efficient” building in terms of sustainability. This is the maximum value of the theoretical index of sustainability that this case study building could achieve. There is very little likelihood that this building will become a more “sustainable” building.

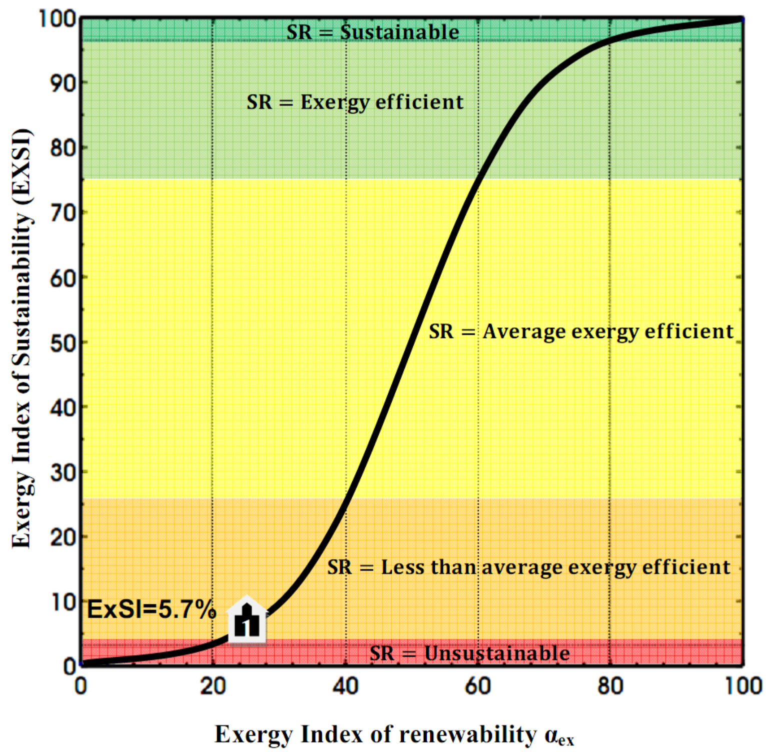


Figure 5.2: The proposed rating scale based on the ExSI

To keep this thesis reasonably succinct, for the other case studies (nos. 2-14) only the major results are presented, in section 5.10.

5.9 Other case studies' descriptions

Case studies nos.2 and 3 are two-storey houses in Montreal, Quebec, Canada (Leckner and Zmeureanu 2012), each with a building footprint of 84 m^2 and a total heated floor area of 208 m^2. Case study no.2 is an energy-efficient house, built in compliance with current codes using electric baseboard heaters; while case study no.3 is a Net-Zero Energy House with a solar combisystem for heating and domestic hot water, plus photovoltaic panels for electricity and a radiant floor heating system. The thermal insulation value of above ground walls is 3.52 $m^2 \cdot K/W$ and 6.25 $m^2 \cdot K/W$ for cases no.2 and 3, respectively. The houses' life spans are considered to be 40 years.

Case study no.4 is a two-storey single-detached brick house (see Fig. 5.3) of 140 m^2 heated floor area built in 1910, in Kitchener, Ontario, Canada (Bin and Parker 2012). The house's life span is considered to be 100 years. Outside bricks account for most of the initial embodied energy and the corresponding GHG emissions (Bin and Parker 2011).

The same house became case study no. 5 after renovation with increased thermal insulation. Natural gas is the energy source for heating and domestic hot water in both cases. An old furnace was used in case no.4, with an average efficiency of 80%, while a new furnace with 96% efficiency is used in the renovated house, case 5.

Like the previous four cases, case studies 6 and 7 are also paired. Case study no.6 is a residential home (referred to throughout this thesis as the Standard Home, SH) built in Ann Arbor, Michigan, United States (see Figure 5.4, Scheuer et al. 2003). The total floor area is 228 m^2. Published data were used to determine the annual energy consumptions and environmental burdens. The life span is assumed to be 50 years.

Case study no.7 (referred to as the Energy Efficient Home, EEH) mirrors the original size and layout of case no. 6, which was then modeled to examine the effect of design changes made to reduce life cycle energy demands, using various energy efficiency strategies and substitutions of selected materials with lower embodied energy (e.g., cellulose insulation instead of the fiberglass insulation in the SH). Its 12'' thick and R-35 walls, constructed from double 2 x 4 studs with 3.5" spacing between the inner and outer wall studs are some of the defining features that show how the EEH evolved into a much more energy efficient structure. Furnace efficiency was increased from 80% to 95%.

Blanchard et al. (1998) describe the major energy-efficient strategies investigated in the design of the EEH.

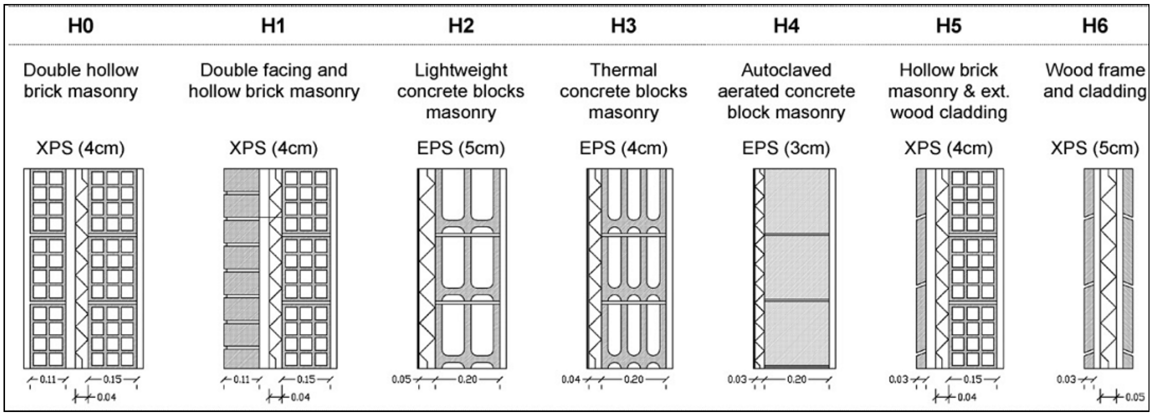
Figure 5.3: REEP House (case nos. 4 and 5) (Bin and Parker 2011)

Figure 5.4: South elevation of "Priceton home", Standard Home (SH), (case no.6 and 7)(Scheuer et al. 2003)

Case studies nos. 8-14 are all based on a single-family home in Portugal with seven alternative exterior wall solutions. The walls have different materials in their composition, as detailed in Table 5.13. A similar global thermal coefficient (U-values 0.47- 0.51 W/m^2 ^{o}C) is obtained by using insulation layers with different thicknesses. The house is located in Coimbra, has 132 m^2 of living area and an expected life span of 50 years.

Table 5.13: Different exterior walls scenarios (Monteiro and Freire 2012)

Exterior walls	H0	H1	H2	H3	H4	H5	H6
	kg	kg	kg	kg	kg	kg	kg
Masonry hollow brick (30*20*11)	25879	49433	8141.1	8141.1	8141.1	8141.1	8141.1
Light weight concrete blocks	0	0	40860	0	0	0	0
Thermal concrete blocks masonry	0	0	0	24730	0	0	0
Auto calved aerated concrete blocks	0	0	0	0	24730	0	0
Ext. wood cladding	0	0	0	0	0	3662.9	8500
Cement mortar	13321	17059	7290.8	11287	11287	11287	2406.8
Water	1998.1	2558.8	1093.6	1693	1693	1693	361
XPS- extruded polystyrene	377.6	377.6	111.6	111.6	111.6	377.6	377.6
EPS- expanded polystyrene	0	0	12.432	9.9456	7.4592	0	0
Masonry hollow brick (30*20*15)	21527	21527	0	0	0	21527	0



5.10 Assessment results and discussion

Table 5.14 presents the annualized exergy lost, calculated for each case study for selected criteria from issues B and C, the Exergy Index of Renewability and the Exergy Index of Sustainability.

Table 5.14: Exergy-based Index of Sustainability calculated for fourteen case studies using the B and C issues from SBTool

	LEGEND: + : **Added to the final balance equation** - : **Subtract from the final balance equation**		**Annual exergy use [MJ/yr]**				
	Criteria		**Case study no.1**	**Case study no.2**	**Case study no.3**	**Case study no.4**	**Case study no.5**
B1.1	Annualized non-renewable primary energy embodied in construction materials	+	4,391,730	20,625	37,542	3,710	2,108
B1.2	Annual use of purchased electricity for operations, delivered	+	3,819,116	63,158	33,196	183,541	27,507
B3.1	Use of off-site energy that is generated from renewable sources (delivered)	-	567,424	0	40,478	0	0
B4.4	Use of durable materials	+	88,845	0	0	0	4,542
B4.5	Re-use of salvaged materials from off-site	+	1,166,880	0	0	0	0
B4.6	Use of recycled materials from off-site sources.	+	114,368	0	0	0	0
B4.7	Use of bio-based products obtained from sustainable sources.	+	937,817	0	0	0	0
B5.1	Use of potable water for site irrigation.	+	1,627	113	57	0	0
B5.2	Use of potable water for occupancy needs.	+	605,013	29,195	7,380	21,860	6,277
C1.1	Annualized GHG emissions embodied in construction materials.	+	1,736,338	8,156	14,846	1,985	1,628
C1.2	Annual GHG emissions from all energy used for facility operations.	+	2,592,457	20,356	10,699	89,330	15,330
C2.1	Emissions of ozone-depleting substances during facility operations.	+	15,032	299	299	402	402
C2.2	Emissions of acidifying emissions during facility operations.	+	250,652	4,989	4,989	6,703	6,703
C2.3	Emissions leading to photo-oxidants during facility operations.	+	184	4	4	5	5
	Total annualized exergy lost [MJ/yr]		15,152,635	146,895	68,535	307,537	64,502
	Available solar exergy [MJ/yr]		3,715,491	381,336	381,336	637,130	637,130
	Building footprint [m^2]		800	83.7	83.7	140	140
	Exergy Index of Renewability α_{ex}		25%	260%	556%	207%	988%
	Exergy Index of Sustainability estimated at 100% (theoretical potential)		5.7%	100.0%	100.0%	100.0%	100.0%
	Exergy Index of Sustainability estimated at 40% (technical potential)		1.2%	99.7%	100.0%	97.4%	100.0%
	Exergy Index of Sustainability estimated at 20% (technical potential)		.7%	55.3%	100.0%	28.0%	100.0%
	Exergy Index of Sustainability estimated at 5 % (economical potential)		.5%	1.7%	8.0%	1.3%	48.3%

(Continued)

Table 5.14 (Continued): Exergy-based Index of Sustainability calculated for fourteen case studies using the B and C issues from SBTool

	Criteria		Annual exergy use [MJ/yr]				
			Case study no.6	**Case study no.7**	**Case study no.8**	**Case study no.9**	**Case study no.10**
B1.1	Annualized non-renewable primary energy embodied in construction materials	+	14,601	10,383	6,486	6,486	5,790
B1.2	Annual use of purchased electricity for operations, delivered	+	178,301	92,806	217,320	217,320	217,320
B3.1	Use of off-site energy that is generated from renewable sources (delivered)	-	0	0	0	0	0
B4.4	Use of durable materials	+	6,270	4,958	1,144	1,216	1,299
B4.5	Re-use of salvaged materials from off-site	+	0	0	0	0	0
B4.6	Use of recycled materials from off-site sources.	+	0	0	0	0	0
B4.7	Use of bio-based products obtained from sustainable sources.	+	0	0	0	0	0
B5.1	Use of potable water for site irrigation.	+	0	0	0	0	0
B5.2	Use of potable water for occupancy needs.	+	0	0	19,845	19,845	19,845
C1.1	Annualized GHG emissions embodied in construction materials.	+	11,566	10,237	4,816	5,509	4,234
C1.2	Annual GHG emissions from all energy used for facility operations.	+	353,712	112,944	1,984	2,029	1,945
C2.1	Emissions of ozone-depleting substances during facility operations.	+	943	943	2	2	2
C2.2	Emissions of acidifying emissions during facility operations.	+	15,729	15,729	31	33	32
C2.3	Emissions leading to photo-oxidants during facility operations.	+	12	12	2	2	2
	Total annualized exergy lost [MJ/yr]		581,133	248,012	251,629	252,801	250,469
	Available solar exergy [MJ/yr]		3,123,650	3,123,650	157,952	157,952	157,952
	Building footprint [m^2]		228	228	70	70	70
	Exergy Index of Renewability α_{ex}		538%	1259%	63%	62%	63%
	Exergy Index of Sustainability estimated at 100% (theoretical potential)		100.0%	100.0%	80.3%	79.8%	80.8%
	Exergy Index of Sustainability estimated at 40% (technical potential)		100.0%	100.0%	6.1%	6.0%	6.1%
	Exergy Index of Sustainability estimated at 20% (technical potential)		99.8%	100.0%	1.6%	1.6%	1.6%
	Exergy Index of Sustainability estimated at 5 % (economical potential)		7.3%	80.6%	0.6%	0.6%	0.6%

(Continued)

\+ **: Added to the final balance equation**

\- **: Subtract from the final balance equation**

Table 5.14 (Continued): Exergy-based Index of Sustainability calculated for fourteen case studies using the B and C issues from SBTool

	Criteria		Annual exergy use [MJ/yr]			
			Case study no.11	**Case study no.12**	**Case study no.13**	**Case study no.14**
B1.1	Annualized non-renewable primary energy embodied in construction materials	+	5,812	6,354	6,517	6,531
B1.2	Annual use of purchased electricity for operations, delivered	+	217,320	217,320	217,320	217,320
B3.1	Use of off-site energy that is generated from renewable sources (delivered)	-	0	0	0	0
B4.4	Use of durable materials	+	1,268	1,252	1,131	1,034
B4.5	Re-use of salvaged materials from off-site	+	0	0	0	0
B4.6	Use of recycled materials from off-site sources.	+	0	0	0	0
B4.7	Use of bio-based products obtained from sustainable sources.	+	0	0	0	0
B5.1	Use of potable water for site irrigation.	+	0	0	0	0
B5.2	Use of potable water for occupancy needs.	+	19,845	19,845	19,845	19,845
C1.1	Annualized GHG emissions embodied in construction materials.	+	4,751	4,729	3,574	2,309
C1.2	Annual GHG emissions from all energy used for facility operations.	+	1,979	1,978	1,902	1,819
C2.1	Emissions of ozone-depleting substances during facility operations.	+	2	2	2	2
C2.2	Emissions of acidifying emissions during facility operations.	+	31	36	31	29
C2.3	Emissions leading to photo-oxidants during facility operations.	+	2	2	2	2
	Total annualized exergy lost [MJ/yr]		251,009	251,517	250,323	248,890
	Available solar exergy [MJ/yr]		157,952	157,952	157,952	157,952
	Building footprint [m^2]		70	70	70	70
	Exergy Index of Renewability α_{ex}		63%	63%	63%	63%
	Exergy Index of Sustainability estimated at 100% (theoretical potential)		80.6%	80.3%	80.9%	81.5%
	Exergy Index of Sustainability estimated at 40% (technical potential)		6.1%	6.1%	6.2%	6.3%
	Exergy Index of Sustainability estimated at 20% (technical potential)		1.6%	1.6%	1.6%	1.6%
	Exergy Index of Sustainability estimated at 5 % (economical potential)		0.6%	0.6%	0.6%	0.6%

\+ **: Added to the final balance equation**

\- **: Subtract from the final balance equation**

In case no.1, a large, multi-storey commercial and residential building, the annualized exergy lost due to energy use for construction and operation is 10,518,756 MJ/year or about 70% of the total annualized exergy lost considered in this study. The annualized exergy used due to purchased electricity accounts for 36% of exergy lost due to the energy used. These proportions are 83,783 MJ/year (75%) for case no. 2, 70,738 MJ/year (47%) for case no. 3, 187,251 MJ/year (98%) for case no. 4, 34,157 MJ/year (81%) for case no. 5, 199,172 MJ/year (90%) for case no. 6, 108,147 MJ/year (86%) for case no. 7, 224,949 MJ/year (97%) for case no. 8, 225,382 MJ/year (96%) for case no. 9, 224,409 MJ/year (97%) for case no. 10, 224,400 MJ/year (97%) for case no. 11, 224,926 MJ/year (97%) for case no. 12, 224,968 MJ/year (97%) for case no. 13, and 224,884 MJ/year (97%) for case no. 14. The most significant reduction in the exergy lost due purchased electricity is achieved by case study no.3 (NZEH), due to its capturing of solar energy using solar collectors and PV modules (renewable sources); whereas case study no.4 has the highest percentage of contribution of exergy lost due to purchased electricity. This is because that house was originally poorly insulated and so its energy efficiency was low compared to the standard.

Traditionally, the majority of building assessment methods and rating systems have linked a building's energy use to its operation, and therefore much attention has been dedicated to reducing this energy through technical innovation and regulatory controls. However, this effort is sometimes accompanied by an increasing amount of materials and systems dedicated to reducing operational energy use. The results indicate that a large increase in exergy loss is due to non-renewable primary energy embodied in construction materials, as shown by case no.2's 20,625 MJ/year before adding solar technologies and case no.3's 37,542MJ/year with solar combisystem technologies installed. The contribution of the total annualized exergy lost due to the embodied energy in construction materials increased from 14% in case no.2 to 54.8% in case no.3, and from 1.2% to 3.3% for case nos.4 and .5, respectively. The reduction of exergy lost due to operation is accompanied with an extra 47% decrease of exergy lost due to emissions. Compared to the annualized exergy lost for building operations, the annual exergy lost due to GHG emissions from all the energy used for facility operations represents about 30% in cases no.2 and 3, 50% in cases no. 4 and 5, and close to 1% in case studies 8-14.

In case no.1, the available solar exergy can compensate for only 25% of the exergy lost due to the construction and operation of that large, multi-purpose building, while for case studies 8-14 the available solar exergy can compensate for 63% of the exergy lost due to construction and building operation (see Table 5.14). In the other six case study houses (case no.2-7), the available solar exergy can entirely compensate for the exergy lost: the Exergy Index of Renewability is equal to 260% for case no.2, 556% for case no.3, 207% for case no.4, 988% for case no.5, 538% for case no.6, and 1259% for case no.7. In case studies 2-7, the building consumes much less exergy than it could theoretically harvest on its horizontal footprint.

The Exergy Index of Sustainability (ExSI) of the large commercial building (case study 1) is 5.7. This result shows that under the ideal conversion of 100% of solar exergy, only 5.7% of the annualized exergy lost is compensated by the incident exergy of solar radiation on the building footprint. According to the proposed rating scale, the case study building with ExSI=5.7 receives the qualification of a "Less than average exergy efficient" building. This is the maximum value of the theoretical index of sustainability that this case study building could achieve. There is very little likelihood that this building could become a more "sustainable" building, according to the definition proposed in this thesis.

The case study houses nos. 2 to 7 achieve an ExSI=100, and so receive the qualification of "Sustainable" under the proposed definition.

As can be seen in Figure 5.5, case study no.14 (wood frame and cladding) has the lowest total annualized exergy lost, 248,890 MJ/year, and achieved an ExSI=81.5, while case study no.9 (double facing and hollow brick masonry) has the highest exergy lost among the seven alternative exterior wall solutions at 252,801 MJ/year, and it achieved an ExSI of 79.8 (see Table 5.14).

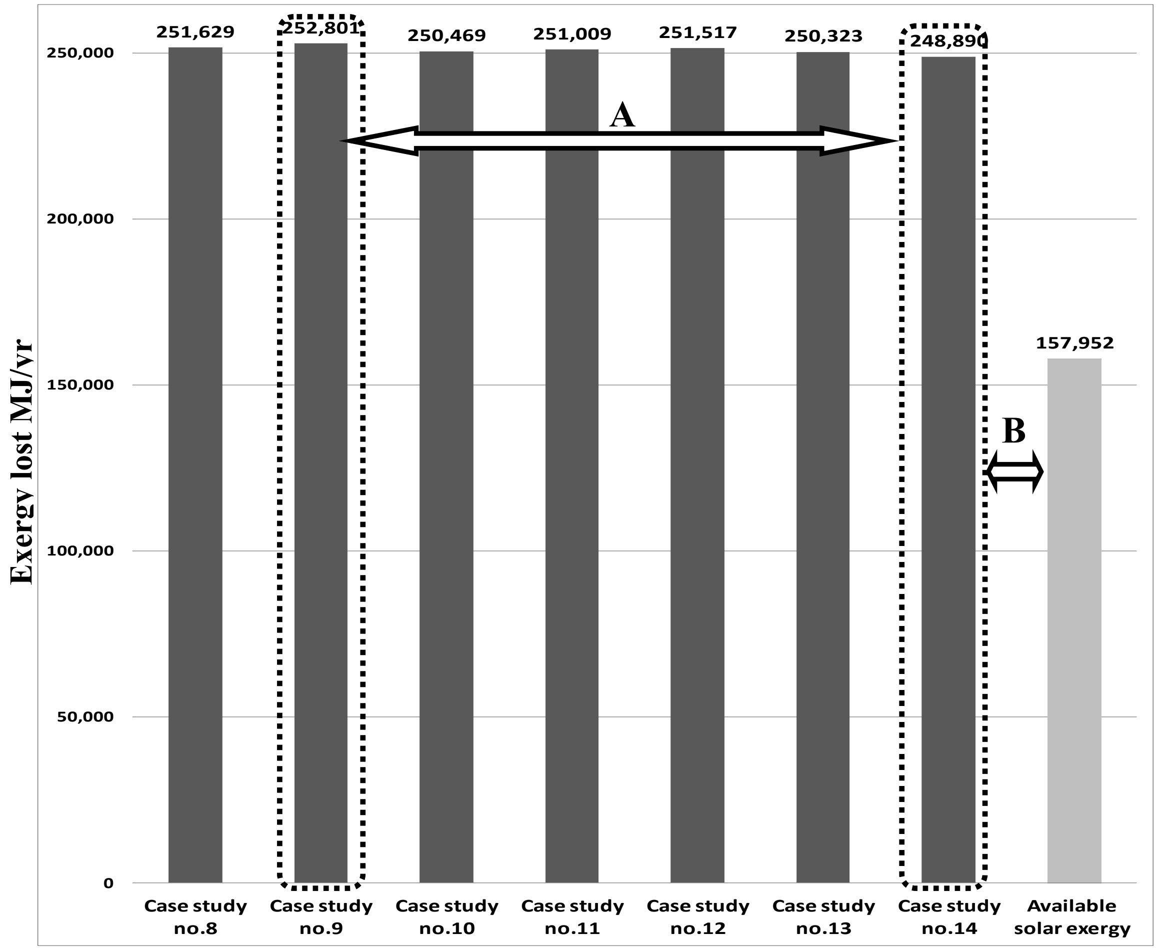


Figure 5.5: First level (A) of applicable comparison between different building scenarios.

However, a more detailed assessment shows that case no. 9 has 58.1%, 15%, 10.4%, and 4.6% more exergy lost compared to case study no.14 in terms of GHG emissions due the construction process (C1.1), the use of durable materials (B4.4), GHG emissions due operation (C1.2), and the annual non-renewable primary energy (B1.1), respectively (see Figure 5.6).

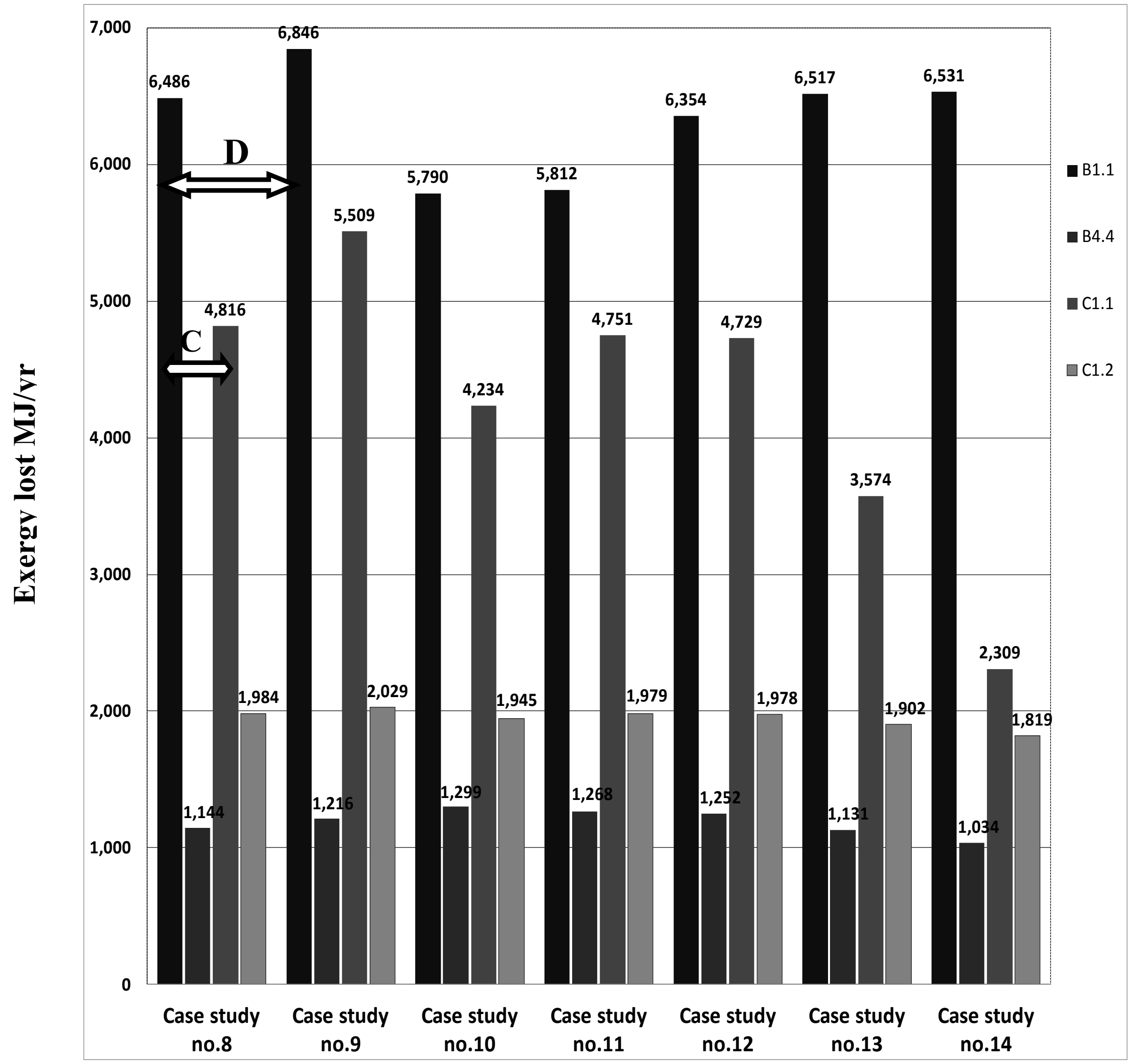


Figure 5.6: Second- and third-levels (C& D issues) of applicable comparison between different building scenarios.

If a photo-voltaic (PV) system with an overall system efficiency of 5% (Sahin et al. 2007) is used, the Exergy Index of Sustainability drops from 100 to 1.7 (case no.2), to 8 (case no.3), to 1.3 (case no.4), to 48.3 (case no. 5), to 7.3 (case no.6), and to 80.6 (case no.7). For all other case studies, the ExSI drops from 63 to .6. These values correspond to the economical potential of such PV systems.

Case studies 8-14 represent a single-family detached house in Portugal with different exterior wall scenarios and with different material compositions, comparatively assessed based on the corresponding exergy loss of each criterion to support the selection of more sustainable exterior wall solutions.

Assessing the results (criterion by criterion, the following variations between the alternatives with the lowest and highest exergy lost were determined: for B1.1, annualized exergy lost due construction, case no.10 has 15.4% less of a loss than case no.9. Regarding the other criterion, case no.14, the scenario with wood frame and cladding, has the lowest exergy lost (see Figure 5.6), and has an ExSI=81.5, which is more sustainable than the other scenarios and therefore is the most preferable option. Case no. 14 achieved the qualification of "exergy efficient" under the proposed definition and according to the proposed rating scale.

The ExSI is evaluated using PV systems with overall system efficiencies of 20% (Hoffmann 2006) and 40% (www.reuk.co.uk/40-Percent-Efficiency-PV-Solar-Panels.htm), which correspond to the technical potential of such PV systems. The results emphasize the large difference between the maximum theoretical index of sustainability and the potential for sustainability by applying the current and potential technologies (see Figure 5.7).

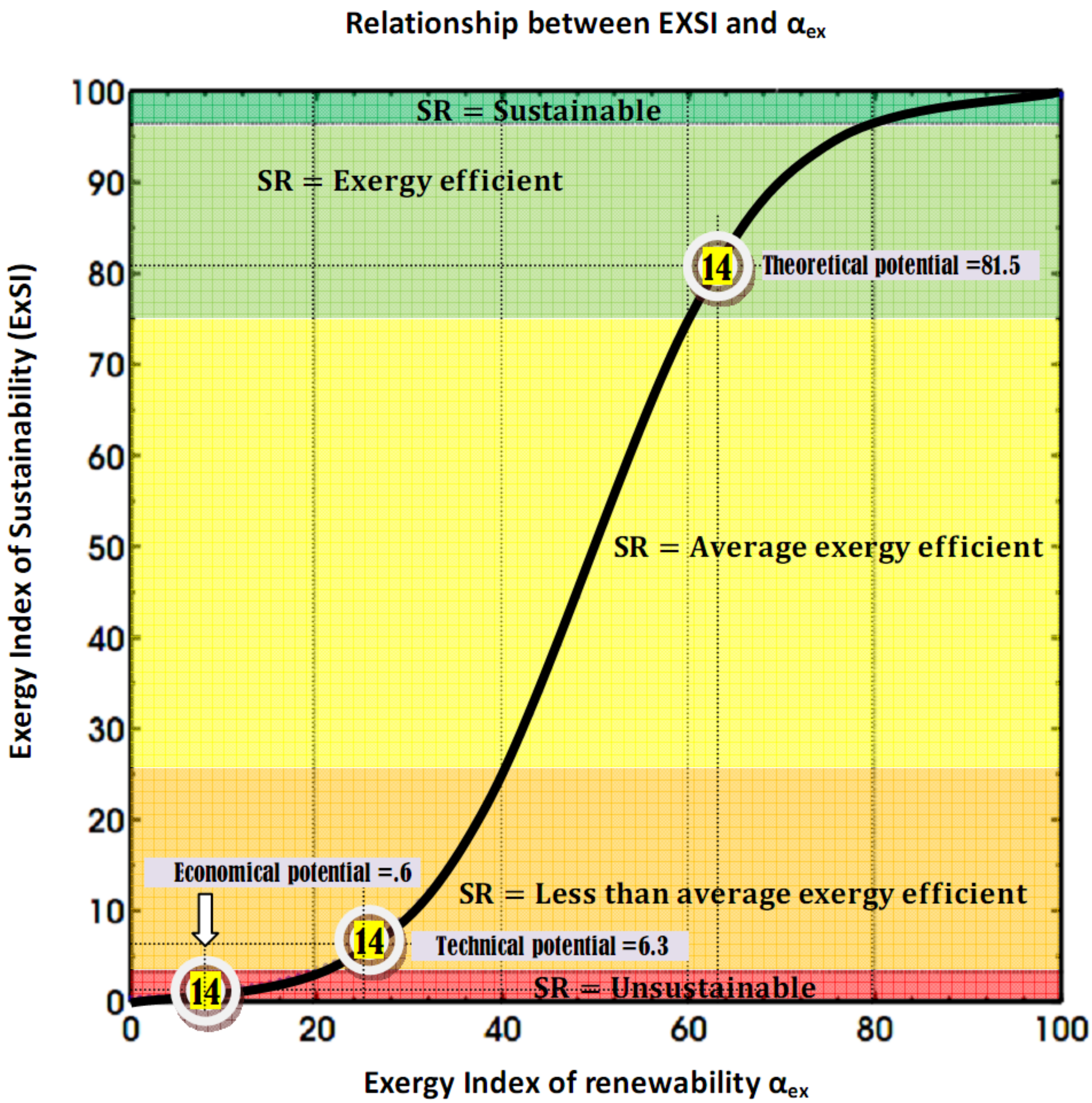


Figure 5.7: Exergy Index of sustainability estimated for theoretical, technical and economical potential.

Two cases have a high potential to become more sustainable: case studies nos. 5 and no.7 (Figure 5.8). As can be deduced from comparing case study no.1 to case no.7, based on the economic potential, implementing residential energy efficiency retrofits (as in case no.5) and employing various energy efficient strategies as in case no.7 is found to be exergy efficient and sustainably sound (see Figure 5.8).

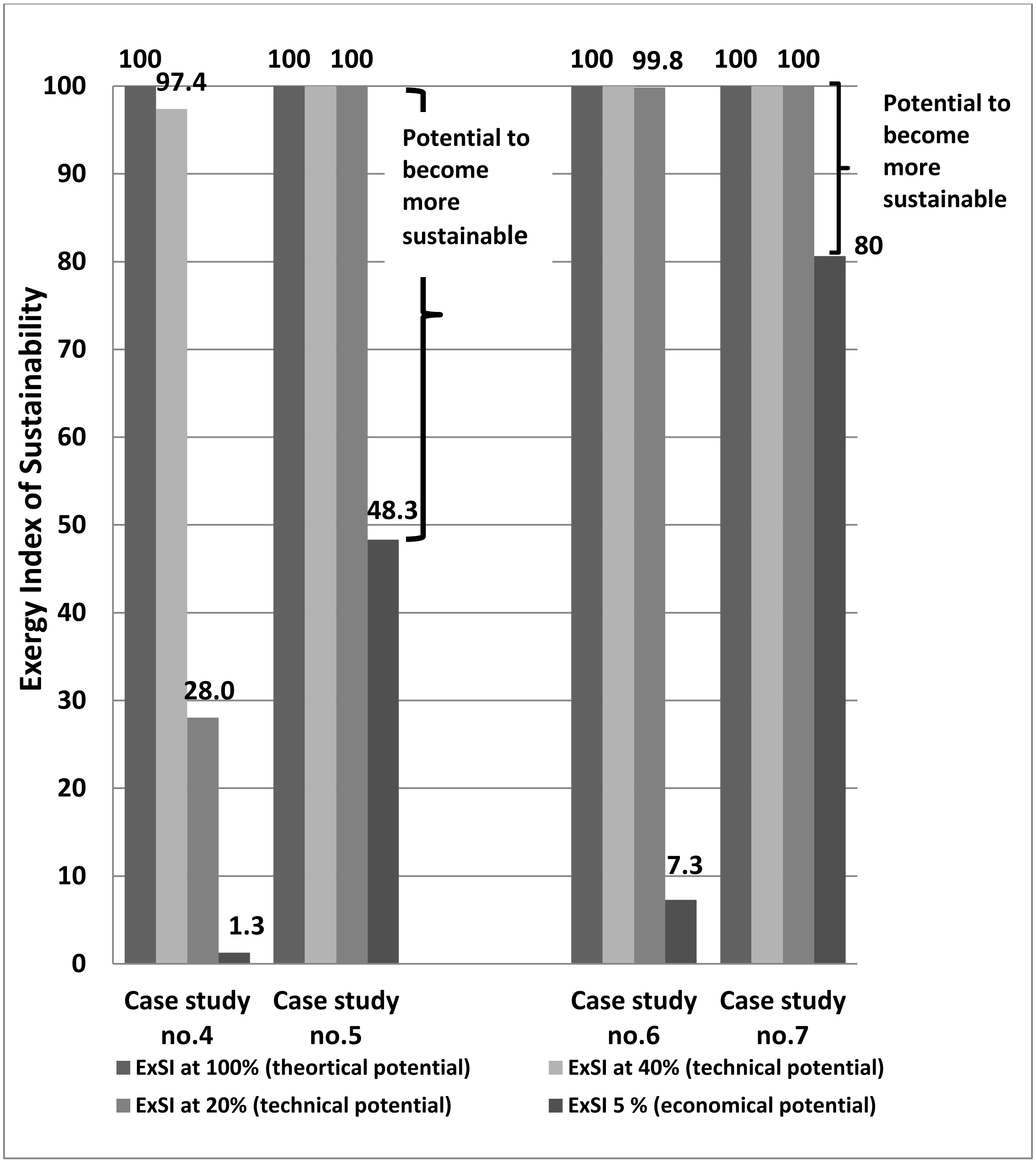


Figure 5.8: Exergy Index of Sustainability (ExSI) estimated at 100, 40, 20, and 5% using PV systems for cases no.4 to .7

As illustrated in Figure 5.9 , there is an inversion of the most significant exergy lost from case study nos.2 and 3, the net-zero energy house (NZEH). The increase of exergy lost due to implementing solar technologies and the corresponding GHG emissions, which is 2.6, is totally compensated by the decrease of exergy lost in building operations and the corresponding GHG emissions.

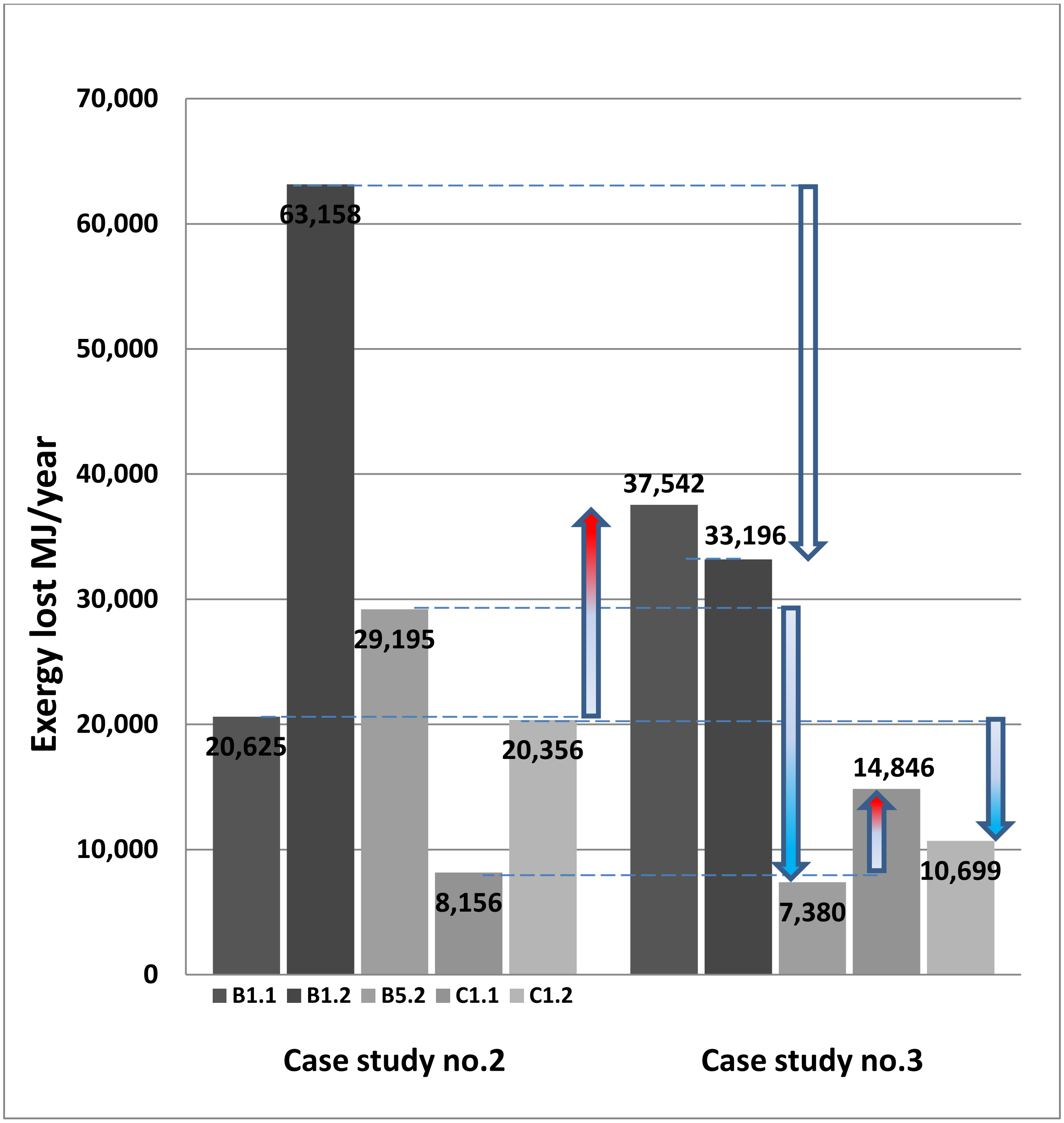


Figure 5.9: Comparison between the exergy loss of significant criteria for case no. 2 vs. case no. 3

5.11 Conclusion

Data was extracted in detail from the SBTool for case study no.1, while for the other case studies some information was extracted from the published literature or estimated using software (e.g, ATHENA for estimating the embodied energy and emissions), which was more suitable for the defined locations. Using different software to estimate embodied energy and energy consumption may affect the final assessment results. Therefore, for comparison purpose, it is recommended to use the same software to derive the required information. A software program that will allow greater flexibility for estimating embodied energy and its corresponding emissions is needed. The proposed exergy-based index would be enhanced by such generic estimation software.

The application of the proposed exergy-based index revealed that large commercial buildings with several floors cannot achieve a high level of sustainability by using only the building's footprint as the reference surface for harvesting solar energy. This type of building is a candidate for the weak sustainability approach, with a partial use of non-renewable energy sources. All four residential buildings could achieve the highest theoretical potential of building sustainability and the highest technical potential by using PV technologies with 40% efficiency.

The results of case studies indicated that there is a substantial difference between the maximum theoretical index of sustainability (as proposed in this paper) and the potential for sustainability of current PV technologies with 5 to 20% efficiency.

5.12 Comparison of ExSI with other indices

This section presents the comparison of the proposed exergy-based index against other indices that are recommended in the literature (see section 2.5) for the assessment of sustainability of processes or systems. Equations used to calculate those indices are presented in Table 5.15, and Table 5.17 lists the numerical results of case studies 1, 2, and 3.

Table 5.15: Original equations used to present sustainable indices (SIs)

Index	Formula	Reference
Cumulative exergy consumption indicator	$\eta = \frac{Ex_{\ embodied}}{CExC}$	Kotas (1985)
Sustainability coefficient	$\alpha = \frac{Ex_{\ in\ Renewable}}{Ex_{\ in}}$ $\eta = \frac{Ex_{\ out}}{Ex_{\ in}}$ $\xi = \frac{Ex_{\ in}}{Ex_{\ in} + Ex_{\ in,abat}}$ $\boldsymbol{S} = \frac{1}{2} \cdot (\alpha + [\eta \cdot \xi])$	Dewulf et al. (2000)
Sustainability Index	$\boldsymbol{SI} = \frac{1}{Dp} = \frac{Ex_{\ in}}{Ex_{\ destroyed}}$	Rosen (2008)
Exergy Index of Sustainability	$\alpha_{ex} = \frac{Ex_{\ available}}{Ex_{\ lost}}$ $\boldsymbol{ExSI} = f(\alpha_{ex})$	El shenawy et al. (2013)

where

CExC : Cumulative exergy consumption; the total amount of exergy that has to be invested from the natural ecosystem to deliver the desired product, MJ;

$Ex_{embodied}$: the exergy embodied in the product, MJ;

$Ex_{in,renewable}$: the exergy input from renewable resources, MJ;

$Ex_{\ out}$: the useful exergy output, MJ;

Ex_{in} : the exergy input to the production process, MJ;

Ex_{abat} : the exergy required to abate the emissions and wastes of the production process, MJ;

$Ex_{\ lost}$: the total exergy lost; called the exergy destruction in Rosen's formula, MJ; and

$Ex_{available}$: the annual available solar exergy of the building footprint, MJ.

Although some of previously-discussed indices (see section 2.5, literature review) were not developed for assessing building sustainability, their application is expanded to buildings and discussed in this section. The following equivalences between terms are presented and their values calculated and listed in Table 5.17, in relation to the case studies in this thesis.

The sustainability index defined by Rosen et al. (2008) is the closest formulation to the ExSI. In general terms, both indices are calculated as the ratio of exergy input to the system divided by the exergy lost (destroyed) in the system or process. The terms used in ExSI are defined in relation to the proposed concept of building sustainability. $Ex_{available}$ is the available exergy that could potentially become the exergy input, as generated by a renewable energy source, solar energy; Ex_{lost} is the life cycle exergy lost, including the embodied exergy, abatement exergy and operation exergy. Rosen's index is defined in generic terms as the ratio of exergy input to the exergy destroyed. If the two indices (ExSI and SI) use the same definition of terms and the same boundary, then they have the same meaning and numerical values.

The clarification of why those indices are considered to be indicators of building/system/process sustainability is given below:

The CExC index proposed by Kotas assessed resource degradation as an indicator of sustainability by focusing on the production process/system analysis in terms of the efficiency through the comparison of the embodied exergy in the final product versus the cumulative exergy consumption that has to be extracted from the natural ecosystem in order to deliver the desired product.

The S index proposed by Dewulf shows that different aspects of process, system and building sustainability can be quantified by using three of the sustainability parameters: (1) renewability, which focuses on the sustainable nature of the resource used in the process and distinguishes between renewable and non-renewable resources; (2) an efficiency parameter, based on the production process; and (3) the environmental compatibility parameter, which defines the extra exergy needed to abate the emissions and to run the system so that it is compatible with the natural environment.

The SI index proposed by Rosen is considered as an indicator of sustainability since it is defined as the inverse of the depletion number that characterizes the efficiency of the process/system or building using a ratio of exergy destruction to the exergy input.

The ExSI index evaluates the building sustainability based on the renewability factor, which compares the exergy lost using life cycle analysis to the maximum theoretical available solar exergy as a single benchmark to enhance the advantage of openness on the earth surface and of utilizing solar power instead of degrading finite resource that must be extracted from the earth.

Systematic diagrams have been created to facilitate relative comparisons of sustainability indices, see Table 5.16.

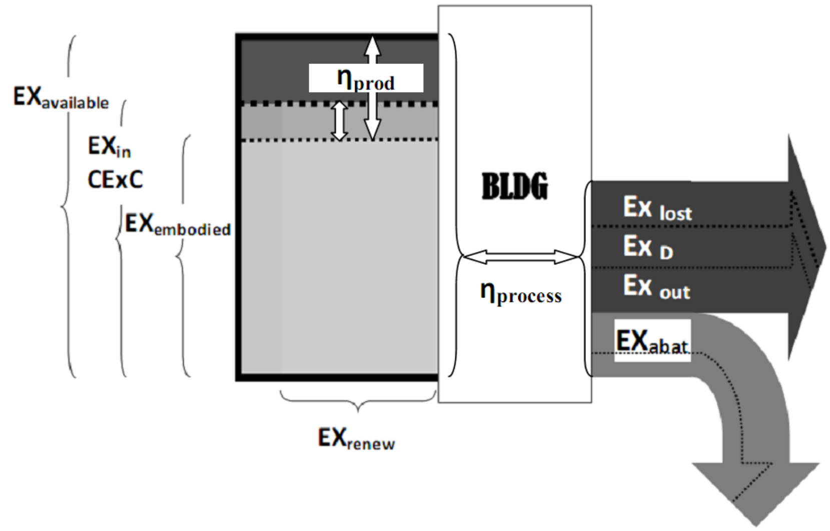
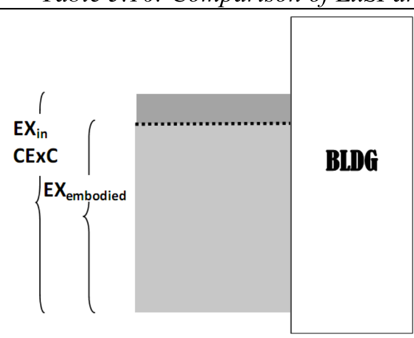
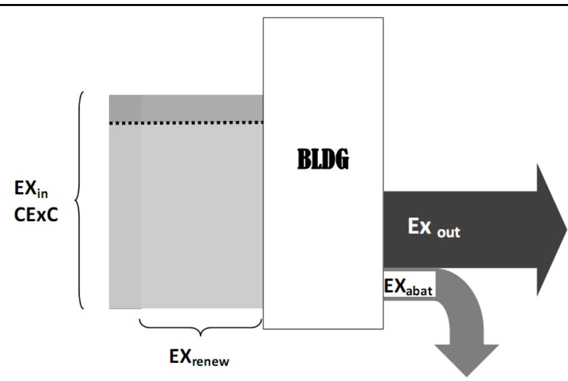
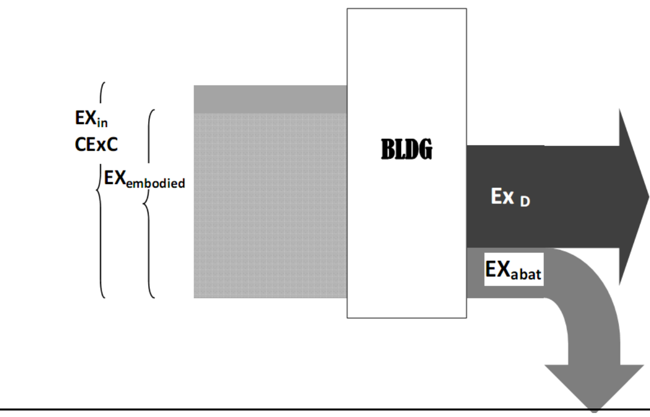
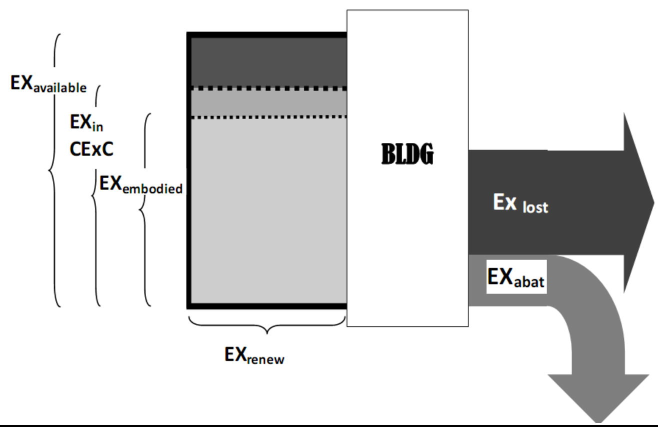


Figure 5.10: Equivalence between terms used in formulas

Table 5.16: Comparison of ExSI and sustainability indices found in the literature

a		• The CExC indicator as proposed by Kotas (1985) is used to describe the efficiency of a production or process. It should also reflect the other sustainability issues illustrated in Table 5.15 (renewability, compatibility, and efficiency of the process).
b		• The environmental parameter ζ considers the abatement of emissions. It should account for the abatement of all negative effects related to the process itself. By doing this, a system's compatibility with the environment can truly be determined. • The combination of the three parameters to obtain S is highly subjective.

c		• The index compares the $Ex_{destroyed}$ against the Ex_{in}.
d		• The results have two considerations: one factor reflects the importance of increasing the reliance on renewable resources by using $Ex_{available}$ instead of Ex_{in} and compares it against total life exergy lost attributable to construction, operation, and emissions instead of ($Ex_{embodied}$), as presented by (Kotas 1985), or (Ex_{oper}) as presented by (Rosen et al. 2008).

The comparison led to several observations:

- Despite the efforts invested in developing an index that adequately represents the sustainability of a building, according to this comparison, existing sustainability indices are not yet completely satisfactory since they do not fully reflect all of the sustainability issues (renewability, compatibility, and efficiency of the process). The comparison shows that the previous indices need to be improved to fully cover all of the sustainability issues.
- The common grounds for comparison are based on two parameters: production efficiency η_{prod}, and process efficiency $\eta_{process}$, (see Figure 5.10). As the depletion of resources was the main focus of the CExC, it only covers the first parameter, while the second parameter, process efficiency η_{prod}, was not covered at all. It is worth

noting that a high value of overall efficiency does not necessarily guarantee a high level of sustainability, since this index does not consider renewability as part of sustainable resource utilization. Furthermore, the interaction between the production and consumption process and the environment is neglected.

- With the available exergy $Ex_{available}$ as a single benchmark to compare against, the focus can now be on enhancing building sustainability by using renewable solar energy rather than using Ex_{in} provided by the earth. Our planet is neither an infinite supplier of resources, nor an infinite absorber of waste (unless when geothermal energy is used). In this context, the exergy-based index might help us to test whether the exergy losses of buildings are within those buildings' capacities based on the available solar exergy that can be harvested on the buildings' horizontal footprints. Using $Ex_{available}$ instead of Ex_{in} implicitly considered that the efficiency production η_{prod} = 1, all resources used in the process are renewable using solar energy $\propto_{renew}$ = 1, and no exergy is needed to abate harmful emissions ξ = 1.

Table 5.17: Exergy calculations and exergy-based indices

Exergy calculations	**Process/system or building**		
	1	**2**	**3**
$Ex_{in, renewable}$, MJ/yr	2,125,784	107,759	24,767
$Ex_{abat,}$ MJ/yr	4,594,663	33,804	30,838
$Ex_{in,}$ MJ/yr	16,285,856	146,895	149,434
$Ex_{destroyed}/Ex_{lost,}$ MJ/yr	15,152,635	146,895	68,535
$Ex_{out,}$ MJ/yr	11,123,769	112,978	78,118
$Ex_{available,}$ MJ/yr	3,715,491	381,336	381,336
α	0.13	0.73	0.17
η	0.68	0.77	0.52
ζ	0.22	0.19	0.17
S (Sustainability coefficient)	**0.14**	**0.44**	**0.13**
SI (Sustainability Index)	**1.07**	**1.00**	**2.18**
ExSI estimated at the economic potential (5% efficiency)	**.5%**	**1.7%**	**8.0%**
ExSI estimated at the technical potential (35% efficiency)	**1 %**	**98.9%**	**100%**
ExSI estimated at the theoretical potential (100% efficiency)	**5.7%**	**100%**	**100%**

A summary of exergy calculations is presented in Table 5.17. These calculations are based on the detailed exergy lost given in Table 5.14. The exergy-based index (ExSI) is shown in the last three rows. As can be seen from Table 5.17, the Ex_{lost} has different values than the Ex_{out}, due to differences in the boundaries used to calculate the terms. The boundary considered in the calculation of the first term is the whole life cycle.

The efforts to (approximately) achieve an NZEH (case no.3), and thus to attain a lower loss of operational exergy, do not come without drawbacks. This smaller amount of lost exergy is accompanied by a drop in renewability α, efficiency η, and compatibility ζ , from 0.73, 0.77, and 0.19 in case no.2 (BCH) to 0.17, .52, and 0.17 in case no.3 (NZEH), respectively.

Table 5.17 shows that the sustainability indices proposed by Rosen and by this research produce the same conclusion, that case no.3 (NZEH) is more sustainable than case no.2 (BCH). However, the indices cannot be compared in an equitable fashion unless the boundaries are set to be identical to validate the calculation of the terms used in the exergy calculation. The ExSI estimated at the technical potential with the maximum laboratory PV efficiency of 35 % is used in the comparison with other exergy-based indices (Green et al. 2004).

The sustainability level of case no.2 (BCH) was rated at 98.9% using the ExSI index, which is very close to the 1.0 rating using the SI index. The NZEH (case no.3) was rated at 100% using ExSI, while it was rated at 2.18% using SI.

The $Ex_{in,\ renewable}$ of case no.1 (2,125,784 MJ/yr) is based on detailed calculations of the renewable materials in Table 5.3 (1,558,360 MJ/yr) and of the off-site renewable energy (B3.1) in Table 5.14 (567,424 MJ/yr). The $Ex_{in,\ renewable}$ of case studies no.2 and 3 (107,759 and 24,767 MJ/yr, respectively) are estimated based on re-modeling those two case studies by using ATHENA to consider only the renewable materials that were used in each case, see Table 5.18.

Table 5.18: Athena table report

Base Case House Environmental Assessment		40 year Life Cycle		
		Hydroelectricity MJ	**Total (Primary Fuels) (MJ)**	**Total Energy (MJ)**
Manufacturing	Material	93,637	365,808	459,445
	Transportation	0	7242	7,242
Construction	Material	2,203	237	2,440
	Transportation	0	32,308	32,308
Operations & Maintenance	Material	55,033	166,337	221,370
	Transportation	0	3,990	3,990
	Operating Energy	3,577,903	384,362	3,962,265
End-of-Life	Material	0	18	18
	Transportation	0	5,641	5,641
Total	Material	150,873	532,400	683,273
	Transportation	0	49,181	49,181
	Operating Energy	3,577,903		3,577,903
		3,728,776	581,581	4,310,357
Total (MJ/yr)		**107,759**		

Net Zero Energy House Environmental Assessment		40 year Life Cycle		
		Hydroelectricity MJ	**Total (Primary Fuels) (MJ)**	**Total Energy (MJ)**
Manufacturing	Material	128,096	493,881	621,977
	Transportation	0	9,469	9,469
Construction	Material	2,090	225	2,315
	Transportation	0	33,580	33,580
Operations & Maintenance	Material	88,523	224,107	312,630
	Transportation	0	5,365	5,365
	Operating Energy	0	0	0
End-of-Life	Material	0	21	21
	Transportation	0	5,329	5,329
Total	Material	218,709	718,234	936,943
	Transportation	0	53,743	53,743
	Operating Energy	0	0	0
		218,709	771,977	990,686
Total (MJ/Yr)		**24,767**		

6 SUMMARY, CONCLUSIONS, LIMITATIONS AND FUTURE WORK

The work undertaken to complete this research and thesis, as well as the expected contributions are presented in this chapter.

6.1 Summary and conclusions

Despite the obvious advantages of the existing assessment methods in contributing towards more sustainable buildings, some limitations have been recognized. While weighting is recognized as an essential part of many of the current assessment tools as a means to reduce assessment scores to a manageable number, the basis behind these weightings and the manner in which the weighting process itself affects the interpretation of the aggregated result is considered one of the critical limitations that needs to be addressed. Other user-controlled features that can influence the results, such as defining the critical threshold of each criterion or using a reference building have been also considered. These limitations have led towards the development of a scientifically-based SB assessment tool.

Furthermore, the spatial and temporal dimensions of sustainability have been observed to be key elements of achieving sustainability and therefore the impact of changing a building's location and the temporal scale over which sustainability is assessed have been taken into account in the proposed methodology. The long-term building sustainability is therefore assessed by comparing the annualized life cycle exergy lost due a building's construction and operation, over the building's life time, with the annualized available solar exergy that could be harvested on the building footprint, assumed to be the sole sustainable energy source.

Using the available solar exergy as a single, theoretical benchmark avoids the need for periodic reviews as well as for any modification in order to comply with new standards. The solar exergy benchmark also eliminates the need to comply with regional applications, which in turn nullifies SBTool's requirement for a third party to define user-defined benchmarks to facilitate that compliance.

This research contributes to the development of a generic sustainable building assessment framework. It is an attempt to improve building-design decision making towards sustainability through a thermodynamic-based assessment process. This is partly achieved by proposing a new definition of building sustainability based on a strong sustainability concept that requires various categories of natural capital to be maintained indefinitely for future generation. This scientifically-based definition is used as an acceptable platform for the proposed assessment framework.

The proposed approach is an attempt to achieve a balance between the "heavy science" that few people understand, and a simpler approach that still offers a practical meaning. The approach proposed in this thesis, based on applied thermodynamics, belongs to the former category, and will provide a more accurate and science-based accounting of sustainability. The simpler approaches, such as LEED, are based on experience, consensus, and market forces, and are more easily accepted by the market. This research is solely based on applied thermodynamics; future developments however, especially in relation to the calibration of a rating scale, should involve those who utilize or modify the market driving forces.

The integration of the three main categories of assessment tools: multi-criteria assessment, life cycle analysis and single index, minimized the limitations that may affect their future effectiveness in the context of assessing building sustainability. SBTool, as one of the most comprehensive sustainability assessment frameworks, is ahead of other many multi-criteria rating tools, making it the most-nominated method to assess building sustainability, despite some shortcoming. Two issues of SBTool, energy and resource consumption (issue B), and environmental loading (issue C) are among the most influential issues in building assessment, based on the sensitivity analysis. Several other issues could be included in the evaluation of building sustainability, some can be quantified, such as energy use and durability, and others can only be discussed in qualitative terms such as satisfaction with the indoor environment or the social benefits of knowledge generated in buildings. The integration of all of the factors contributing to the assessment of such an index of building sustainability could be considered in the future for assessing building sustainability as a prototype tool.

ATHENA provides detailed evaluations that make it possible to retroactively design buildings. It involves a construction-oriented life cycle perspective that considers overlap, waste products and other global warming, among other issues. Exergy is the single index implemented throughout this study for its distinguished features over other methods of assessment to the best of the author's knowledge. An exergy approach is employed to detect and to quantitatively evaluate the causes of the thermodynamics imperfection of a building under certain conditions and therefore can indicate the practicality of possible improvements. It is a significant tool in addressing the impact of energy resource utilization on the environment and to determine the true magnitude of wastes and losses. Using exergy analysis to address sustainability issues is effective, as it is not affected by geo-political or market conditions. Exergy is also the unit to which costs could be assigned.

The proposed assessment framework enables different types of useful comparisons to be made: (1) a comparison of the overall building sustainability, locally or internationally (A and B level of comparison, see Figure 5.5) which invariably requires the reduction of the overall assessment score to a single value by normalizing the scoring values. Such a challenge was implicitly considered through the distinctive characteristic of the proposed framework which calculates and aggregates different sustainability dimensions into a single commodity using exergy; (2) a comparison of performance based on the exergy loss of one criterion (C level of comparison, see Figure 5.6) with other criteria for the same building to identify where trade-offs and compromises could be made; and (3) comparing the performance with that of another building either in the same or in a different location reflects the importance of using absolute scoring values rather than a relative score (D level of comparison, see Figure 5.6).

The applicability of implementing the proposed methodology was examined through fourteen case studies of different building types and locations.

For case study no.1 the data was collected from the SBTool, while for other case studies data was extracted either from the published literature or estimated using software (e.g., ATHENA), whichever was more suitable for the defined locations.

The application of the proposed exergy-based index revealed that large commercial buildings with several floors cannot achieve a high level of sustainability by using only the building's footprint as the reference surface for harvesting solar energy.

This type of building is a candidate for the weak sustainability approach, with a partial use of non-renewable energy sources. The residential case study buildings could achieve the highest theoretical potential of building sustainability, and the highest technical potential by using PV technologies with 40% efficiency.

The case study results also indicated that there is a large difference between the maximum theoretical index of sustainability (as proposed in this thesis) and the potential for sustainability by using current PV technologies with 5% to 20% efficiency.

The results obtained using the proposed framework are compared with the results obtained by using an applicable single index found in the literature. The sustainability index based on exergy efficiency defined by Rosen et al. (2008) is the closest formulation to the ExSI. If the two indices (ExSI and SI) use the same definition of terms and the same boundary, they have the same meaning and numerical values.

6.2 Research Limitations

The developed method has some limitations that are listed below:

- The research is mainly focused on two issues, the energy and resource consumptions and the environmental aspects. These two issues are among the most influential in the assessment of buildings. Several other issues could be included.
- This study used the following scale: (1) Sustainable (96 % $<$ExSI $\leq$ 100 %); (2) Exergy efficient (75 % $<$ ExSI $\leq$ 96 %); (3) Average exergy efficient (25% $<$ ExSI $\leq$ 75 %); (4) Less than average exergy efficient (4 % $<$ ExSI $\leq$ 25 %); and

(5) Unsustainable (0% ≤ ExSI ≤ 4 %), however other scales could be studied, in the future work.

6.3 Contributions

The study aims at enhancing sustainability assessment at the micro level (building). An exergy-based index is developed to aid in the assessment of building sustainability. The research contributions can be summarized as follows:

1. A new definition of sustainable buildings in the absence of general consensus on specific definitions is introduced;
2. Critical analysis of several existing assessment methods was conducted to learn from their strengths and weaknesses;
3. The proposed exergy-based index overcomes the limitations of subjectively defined weights allocated to different criteria for building sustainability assessment. It is also much more beneficial to use a single numerical benchmark (available solar exergy) that can easily be adjusted to temporal and spatial changes in a building than to utilize several of benchmarks for which there is no consensus on how to define, customize and quantify them;
4. A distinctive characteristic of the proposed framework is the calculation and aggregation of different sustainability dimensions into a single commodity, the exergy. The annualized exergy lost can easily be used to compare building sustainability locally as well as globally;

5. Applying the proposed index to 14 case studies of different types and at different locations proved the validity of a universally applicable assessment tool that can be widely and easily adopted in different countries;
6. This approach allows a new perspective on the sustainability of buildings, a question of concern to all citizens; and
7. Using the annualized exergy lost can improve decision processes by providing a quantifiable sustainability target.

6.4 Recommendations for Future work

Several avenues for work, building on the framework presented here, are suggested and can be summarized as follows:

1. Expanding the proposed exergy-based index to consider other issues from the SBTool rating tool;
2. Evaluating other available exergy that can be harvested on vertical outside surfaces and studying the shading effect of surrounding buildings, as well as considering other renewable energy sources using the strong sustainability approach for assessing building sustainability. It would also be interesting to evaluate hybrid systems for their potential to meet the technical challenges and address the intermittency of renewable energy;
3. Evaluating other building sustainability assessment approaches, using the weak sustainability concept, where some percentage of energy/exergy will be provided by non-renewable sources;

4. We considered solar energy as the sole sustainable energy source because of its long term availability. Certainly a discussion about the long term availability of hydropower or geothermal sources would be of interest;
5. The development of a user interface for the proposed exergy-based index;
6. The development of a stand-alone prototype tool, independent of SBTool;
7. Improving the proposed rating scale that is derived based on assumptions; and
8. Many of the issues addressed in this thesis may be manifested in the restructuring of SBTool, and its application can continue to contribute to the wider debate on building sustainability assessment.

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APPENDICES

A. REVIEW OF BUILDING ASSESSMENT METHODS

Table A.1: Summary of an appraisal of ATHENA (LCA category)

	ATHENA		
A	Structural organization	Description	• An LCA-based environmental decision support tool. • Practical, ease-to-use decision support tool using preset assembly dialogues. • Easily tracks your entries through the tree that is built by the spreadsheet software. • Checks the effects of assembly addition and pinpoints which one is causing a particular environmental effect.
		Developer	Athena Sustainability Institute in 2000 (now the Athena Sustainable Materials Institute)
		Purpose	To improve the sustainability of buildings through the implication of LCA by encouraging the selection of alternatives with lower environmental impacts.
		Type assessed	Industrial, institutional, office, single and multi-unit residential buildings
		Present status	First commercial version of Athena Environmental Impact Estimator, Athena 2.0, was released in June, 2002.
B	Functioning and performance	Functioning	• Describes a building in architectural terms; • Helps architects assess and compare the environmental implications of designs for both new building and major renovations; • Incorporates ATHENA's databases, which cover structural and envelope systems that are typically used in residential and commercial buildings, adapted for various climate regions.
		Social performance	N.A
		Economic performance	N.A
		Environmental performance	Provides users with LCA-based environmental evaluations of proposed alternative designs and materials choices.
C	Aspects examined	Framework	Ecological, long-range economic.
		Scale	Whole-building and building assemblies
		Scope	Life Cycle Analysis: embodied energy used, global warming potential, solid waste emissions, pollutants to air, pollutants to water, and natural resources use.
		Objectives	Provides high quality environmental data to allow informed environmental choices.
		Indicators	Energy or resource and environmental impact (Global warming potential, solid waste emissions, pollutants to air, pollutants to water and natural resource use)
		Measuring	Total embodied energy (material extraction and manufacturing, related transportation, construction, maintenance, repair, replacement, demolition and disposal).
		Weighting	No weighting
		Reporting	A comparison dialogue feature allows side-by-side tabular and graphical comparison of as many as five separate conceptual designs.

		Limitations	Complexity, cost [1], uncertainty (because a building may undergo many changes during its life span) [2]. Evaluation is limited to only a few parameters. There could be a lack of data in the early design phase.

Table A.2: Summary of an LEED appraisal (MCA category)

	LEED		
A	Structural organization	Description	LEED (Leadership in Energy & Environmental Design) is currently the dominant system in the United States and Canadian market. It was developed and piloted in the United States in 1998 by the U.S. Green Building Council (USGBC) as a consensus-based building rating system [9].
		Main developer	U.S. Green Building Council in 2000
		Purpose	Voluntary, market-driven rating system
		Type assessed	New and existing commercial; institutional; office; and high-rise residential buildings
		Present status	400 building have received LEED ratings and 3400 buildings have been registered.
B	Functioning and performance	Functioning	• Identifies and acknowledges sustainable buildings and distinguished professionals working in this area. • Provides guidelines and training program for moving closer to sustainable buildings [5].
		Social performance	N.A
		Economic performance	N.A
		Environmental performance	• provides the opportunity for building owners and operators to reduce the impacts of their building in environment and on occupant health.
C	Aspects examined	Framework	Ecological and economic
		Scale	whole building
		Scope	Multiple: site; energy; materials and resources and indoor environmental quality
		Objectives	Ratings
		Indicators	Sustainable site, water efficiency, reducing energy consumption and CFC in HVAC equipment, materials and resources; indoor environmental quality ; and innovation credits
		Measuring	Checklist. Credits are earned for satisfying each criterion. Users define criteria for scoring. Each category (e.g., Sustainable site) has a specific number of prerequisites and credits.
		Weighting	• Each criterion is specified with its credits, users select criteria for scoring. • Criteria are weighted equally, except for the number of points assigned [3].
		Reporting	• Points are assigned to each criteria/sub-criteria and then a building is certified as " certified" 26-32 points-"Silver" 33-38 points, "Gold" 39-51 points or "Platinum" 52-69 points)[6].
		Limitation	• The lack of quantitative metrics and the subjective nature of the scoring system make it difficult to provide in-depth results. • Cannot be customized to reflect regional bias [8]. • Users can choose the criteria to be included in the final score, a situation which does not allow the negative aspects to be reflected and therefore the score does not reflect the strengths and weaknesses of the building [10]. • Unable to compare structurally different buildings [4].

Table A.3: Summary of an appraisal of SBTool (MCA category)

	SBTool		
A	Structural organization	Description	• The Green Building Challenge (GBC) assessment frame work prompted the development of SBTool (formally known as GBTool) for assessing building performance. It began in Canada, but responsibility was handed over to the international initiative for a Sustainable Built Environment (iiSBE) in 2002 [40]. • The SBTool is mainly concerned with the advancement of assessment methods and building performance [11].
		Developer	National Resource Canada (NRC) in 1995
		Purpose	Research/contribute to the state-of-the-art of building design and modification.
		Type assessed	19 types of buildings can be assessed, such as detached and attached houses, apartments, hotels - Motels, offices, day cares, theatres - Cinemas, retail, food service, supermarkets, etc.,
		Present status	Participating teams from more than 25 countries [9]
B	Functioning and performance	Functioning	• SBTool is calibrated by each national team and is tested by building case studies to establish a common language for describing green buildings (results are presented at international SB conferences). • Its strength lies in its ability to reflect regional conditions and values while maintaining the value of a common structure and terminology. • Provides building owners and other decision makers with common and variable sets of criteria as a means and mechanism to influence the building market.
		Social performance	Assesses certain qualitative issues such as quality of service, quality of amenities, thermal optical and acoustic comfort.
		Economic performance	Several social aspects have been examined such as construction accidents, access for physically handicapped persons, access to private open space and to views from work areas; access to/effects of direct sunlight, levels of visual privacy and the social utility of a building's primary function.
		Environmental performance	SBTool deals with greenhouse gas emissions; ozone depletion; acid rain, solid and liquid waste generation; impacts on sites and adjoining properties; and consumption of materials, energy, water and land.
C	Aspects examined	Framework	Ecological, economic and social
		Scale	Whole building
		Scope	Multiple: assessment elements of SBTool are classified into three levels: the highest level is called performance issues, the second level is called categories (29 categories), and the third level is called criteria (125 criteria). Seven performance issues are included in the highest level such as: site selection; energy and resource consumption; environmental loading; indoor environmental quality; functionality and controllability of building systems, long-term performance, and social and economic aspects.
		Objectives	Advancement of assessment methods and building performance.
C		Indicators	Net annual consumption of primary energy for building operations; GHG emissions and waste water from building operations, and net land area consumed for building and related works.
		Measuring	N.A

		Weighting	• Weighting factors are established by a third party to reflect the varying importance of issues in each region. • Factors are used to transpose scores from one level to another. (e.g., category scores are obtained by aggregating the weighted scores of constituent criteria). • Criterion weight is set to zero if it is not applicable to a region and all other weights are re-distributed amongst other active criteria [12].
		Reporting	• A linear scale from -1 to +5 is used to express the evaluation. The scale is interpreted as -1 indicates negative performance, 0 minimum acceptable performance (usually but not always defined by regulation), 3 good practice and 5 best practice. In the case of numeric parameters, scoring is done by setting two numeric values at 0 and +5 levels, and then numeric values for -1 and +3 performance levels are defined based on the slope of the line. It is more subjective for text-based parameters: default text benchmark statements are provided to describe a range of conditions from negative (-1) to best practice (+5) (Lee, 2006, iiSBE, 2007a).
		Limitation	• Neglects the interrelationship between criteria; • Allows subjectivity in weighting the criteria; • It has to be prepared by first customizing the benchmarks to reflect regional conditions; • Is too complex and expensive due to its extensive demand for data and local adaptation; •Is not commonly known; • Benchmarks are inconsistent and lose their validity over time due to technological changes; and • Uniform integration is difficult because SBTool includes different indicators for different issues.

Table A.4: Summary of an appraisal of Cost Benefit Analysis (SI category)

	Cost Benefit Analysis		
A	Structural organization	Description	Cost Benefit Analysis (CBA) estimates the value of the monetary costs and benefits that would be applicable to a community. It is a generic tool that can be adapted to utilize metrics other than money [12].
		Developer	A formalized CBA was first used by the US Corps of Engineers in 1936.
		Purpose	• To determine a project's feasibility by comparing the sum of the anticipated benefits against their costs; • To estimate a project's impact on national net income, net exports and labor markets.
		Type assessed	Used in different disciplines to assist other tools when monetary values are needed for goods and service not found in the marketplace.
		Present status	Very few, if any, sustainability assessments have yet attempted CBA. .
B	Functioning and performance	Functioning	Provides a framework for project assessment using two stages of computations: first calculate annual costs and benefits, and then estimate the current worth by applying depreciation to the future values.
		Social performance	Public participation is something this process invokes a great deal. Social costs can be described in terms of dollars and assessment effectiveness depends on how discounting is applied.
		Economic performance	Used for putting a value on projects by taking into account the value of money over time (appreciation and depreciation). Provides a good "bottom line" for decision-making in equivalent monetary value.
		Environmental performance	Evaluates the pollution created by waste generated throughout the process, using environmental protection authority licensing fees as well as the cost of measures taken to mitigate emissions.
C	Aspects examined	Framework	Economic
		Scale	Multiple
		Scope	Single: using money as single metric
		Objectives	Project evaluation using monetary values under a given set of conditions.
		Indicators	Real cash (used for economic assessment) and theoretical cash (used for social assessment).
		Measuring	project cost and project benefit are compared
		Weighting	No weighting
		Reporting	Reported in dollars as the common currency/denominator utilized in this method.
		Limitation	• CBA is criticized for being in opposition/contradiction to one of the particular aspects of sustainability -- the need for intergenerational and intragenerational equity) due to its discounting and aggregation methods [13]; • Is exclusively biased towards the current generation, unless the current net benefits can be reinvested to benefit future generations; • Does not evaluate how far a project meets its objectives [12]; • It is inherently difficult to represent natural phenomena in monetary terms; • Its over-reliance on subjective valuations; • It gives values for what is used by humans, other aspects will not be considered, which restricts its ability to assess if a project will pose a threat to the natural environment or to biodiversity; and
			Comparison between monetized quantities is relatively easy and straightforward and, easily understood by non-experts and others alike.

Table A.5: Summary of an Ecological footprint (SI category) appraisal

	Ecological footprint		
A	Structural organization	Description	Ecological footprint (EF) is an inverse of the carrying capacity concept, as it quantifies "the total area of productive land and water ecosystems required to produce the resources that the population consumes and to assimilate the wastes that the population produces, where on Earth that land and water may be located' [15]. It not only reflects the demand but also indicates the direction to move towards.
		Developer	Mathis Wackernagel and William Rees in the early 90's
		Purpose	Quantify humanity's long-term impact on the global environment
		Type assessed	The EF of a sub-national level (population or product) using a component-based approach, and the EF of a national and global level (countries) using compound-based method.
		Present status	It is an evolving methodology and still needs a considerable amount of research before the approach can be standardized.
B	Functioning and performance	Functioning	• Used an intuitive approach for investigating the demand of a given population or, in a different manner, to measure both the ecological supply account and the human demand account, where both are measured with a common unit of measurement (ghr), making their comparison feasible. . • Component-based and compound-based approaches have been recognized as two distinct methodologies, used by the ecological footprint approach; the former has characteristics of a "bottom-up" approach and the later has those of a "top-down"[13].
		Social performance	• The entire analysis is based on the assumption of global equity (which may not be recognized by all 'parties'. • It is a powerful educational and awareness method thanks to the simplicity of the concept, which makes it easily understood by everyday people as well as professionals.
		Economic performance	EF has great flexibility to incorporate all of the desired criteria within the assessment process. The method begins by assessing the economic health of societies and later expands to assess other sustainability aspects.
		Environmental performance	• Assessing the impact of humanity on nature has been set as EF's primary objective, assuming that resource consumption by humanity is the main culprit of unsustainable development. • Quantifying pollution or biodiversity levels or impacts are not included in its current form. • Provides guidelines and training programs for moving closer to sustainable buildings [5].
C	Aspects examined	Framework	Ecological and economic
		Scale	Multiple scales: regional, city, institution, household and product level;
		Scope	Multiple: site; energy; materials and resources and indoor environmental quality
		Objectives	To quantify the amount of natural resources appropriated for human consumption.
		Indicators	Based on a small group of indicators.
		Measuring	Measures the area land required to supply resources or to absorb wastes.
C	Aspects examined	Weighting	Criteria are equally weighted and their actual estimate aggregated for the final result.

		Reporting	Results are reported in terms of global hectares of land per person per year.
		Limitation	• Pollution levels and the state of biodiversity are not incorporated in EF's current form which means it can produce misleading information when comparing different products or even at the national level. • Only covers a few major resources (subsumed within land types) and consumption activities. • Is very limited in terms of measuring recycling. • It neglects the multifunctional nature of land. • Artificial, political boundaries, the use of ecological productivity averages and the assumed static nature of resource productivity; all contribute to the production of unconvincing comparisons based purely on consumption and availability, which does not lend any credibility to the accuracy of the results. • In its e current state, EF does not account for dynamic entities such as technological development, or social health issues, since it is dependent upon static estimates.

Table A.6: Summary of an Exergy (SI category) appraisal

	Exergy		
A	Structural organization	Description	• Is an important thermodynamic concept which can be used to better assess and more accurately present the whole picture of a system and precisely measure its sustainability based on the combination of the first and second law of thermodynamics (Simpson and kay, 1989); • Considers the physical aspects of a system and its uses (building's uses influence the internal heat load, lighting and power demand); • Can provide for better understanding of energy utilization and the location of inefficient areas to target for improvement.
		Developer	The roots of the exergy analysis concept can be traced to the 19th Century and the pioneering work of S. Carnot and W. Gibbs, while the term was coined and presented for the first time in 1956 by Z. Rant [17].
		Purpose	Measures the degradation of energy quality during a process based on the second law of thermodynamics. It is also used in energy optimization studies.
		Type assessed	Energy conversion system and heating system [18], [19]
		Present status	N.A
B	Functioning and performance	Functioning	• Can determine the location and magnitude of exergy loss in the production process where only the exergy of relevant materials and products is needed [16]; • Is ideal for the design and analysis of energy systems, as its methodology combines the conservation of mass and energy with the second law of thermodynamics; • Quantifies waste and energy losses so it can provide important information for more efficient resource use .
		Social performance	Can be extended to handle societal metabolism [22].
		Economic performance	Suggests avoiding energy use at a significantly higher level than needed for a task for economic reasons.
		Environmental performance	• Was used to study depletion of natural resources in 1974 (later, Szargut introduced several interesting related concepts) [21]; • Can be used to calculate the exergy lost in an irreversible process during the use of non-renewable resources, and to try to minimize this loss to obtain sustainability; and • Has been used to express all the environmental effects associated with emissions [21],[23].
C	Aspects examined	Framework	Ecological and economic
		Scale	Whole building, systems, energy sources [20]
		Scope	Multiple
		Objectives	Measuring the efficiency and quality of energy sources and their use.
		Indicators	Uses a single metric based on exergy
C	Aspects examined	Measuring	Measures energy consumption and the corresponding exergy lost through the process, and estimate the difference between the overall energy efficiency and overall exergy efficiency [25].
		Weighting	Does not use weights.
		Reporting	Single number [MJ/m2*year]

		Limitation	• Exergy analysis has been widely applied in parallel with energy analysis in order to find the most rational use of energy, and therefore it cannot be used separately, which means it is an extra time consuming analysis [24]; • Exergy analysis may be more sensitive to the reference environment than energy, especially when indoor conditions are close to the reference ones; • A general agreement on the proper choice of the dead state is not found in the literature.

References For Appendices					
[1]	Trusty, 2002	[10]	Percio, 2007	[18]	Zhang, 1995
[2]	Mer'Eb, 2008	[11]	Cole et al., 2000	[19]	Cornelissen and Hirs
[3]	Seo, 2002	[12]	Taylor, 2001	[20]	Dincer et al., 2004
[4]	DeArmon, 2009	[13]	Gasparatos et al., 2008	[21]	Cornelissen, 1997
[5]	Sinou and Kyvelou, 2006	[14]	Graham and Royal Melbourne Institute of, 1997	[22]	Wall, 1993
[6]	Council, 2002			[23]	Wang and Feng, 2000
[7]	Gowri, 2004	[15]	Rees and Wackernagel, 2008	[24]	Torío et al., 2009
[8]	Todd et al., 2001	[16]	Dincer, 2002	[25]	Kondo, 2009
[9]	Fowler and Rauch, 2006	[17]	Bejan et al., 1999		