DEVELOPMENT OF A NEW INTEGRATED SUSTAINABILITY ASSESSMENT MODEL FOR ENERGY SYSTEMS

BY

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Abstract

While the globe yet to adopt a sustainability assessment model, this thesis presents a novel and comprehensive sustainability assessment model for energy systems. The model features an integrated approach and encompasses various multi-disciplinary dimensions, which influence energy system. These dimensions include energy, exergy, environment, economy, technology, social, education and the Size of the energy system. Each dimension is assessed using a number of indicators. The methodological approach and the integration of thermodynamic-based concepts and mathematical equations is novel and provides consistency, robustness and accuracy for this sustainability assessment model. Normalization of data is conducted using target values where each indicator is normalized based on an optimal and preferred value. Various aggregation and weighting methods are used in this thesis to counteract the subjectivity of the assessment. Two case studies are used to implement this model including solar PV and wind energy systems. The case studies are constructed to meet the demand of 150 Ontario households for electricity, heating, cooling and hot water. The energy and exergy efficiencies of the solar PV system are 66% and 30% respectively. On the other hand, the energy and exergy efficiencies of the wind system are 31% and 24% respectively. Furthermore, the sustainability index for the wind energy system varies between 0.55 and 0.58 using the weighted geometric mean. On the other hand, the sustainability index of the solar PV system varies between 0.56 and 0.59 using the same method. In conclusion, the solar PV and wind energy system models result in similar sustainability indexes according to the assessment model developed in this thesis.

Acknowledgment

This thesis is dedicated to my father. His continuous support and encouragement have been an inspiration throughout this journey.

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Nomenclature

Cost_0	*Project initial cost, $*
$\dot{\mathrm{E}}\mathrm{x}_{\mathrm{in}}$	*total exergy input, kW*
$\mathrm{E}_{\mathrm{S,Y}}^{\mathrm{SW}}$	*incident radiation flux, kW/m2*
$\dot{\mathrm{E}}\mathrm{x}$	*Exergy Rate, kW*
$\dot{\mathrm{m}}$	*Mass flow rate, kg s-1*
$\dot{\mathrm{N}}$	*net negative cash flow, $*
$\dot{\mathrm{P}}$	*maximum operational hours in a year, hours yr-1*
$\ddot{\mathrm{P}}$	*net positive cash flow, $*
$\dddot{\mathrm{P}}$	*Total project investment, $*
PI_{i}	*project's net income in a given year, $*
$\dot{\mathrm{Q}}$	*Heat rate, kW*
$\dot{\mathrm{S}}$	*Entropy rate, kW K-1*
$\dot{\mathrm{S}}\mathrm{S}$	*System size, kW*
$\dot{\mathrm{W}}$	*Work rate, kW*
Cp	*Power coefficient*
Ex	*Specific exergy, kJ kg-1*
H	*Specific enthalpy, kJ kg-1*
kWp	*Kilowatt peak*
MATAI	*Median after-tax annual income, $ yr-1*
MH	*Mixing height, m*
Mtoe	*Million Tonnes of Oil Equivalent*
PCF	*Periodic Cash flow, $ yr-1*
Pmax	*maximum power output, MW*
Pop	*Population*
PR	*Production rate, tonnes yr-1*
R	*Recoverable reserves, kg*
S	*Specific entropy, kJ kg-1 K-1*

T	*Time, year*
T	*Temperature, K*
V	*Specific volume, m3 kg-1*
W	*Weighting factor*
WAM	*Weighted arithmetic mean*
WGM	*Weighted geometric mean*
X	*Dimensional sustainbiility indicator*
Y	*Non-dimensional sustainability indicator*
YP	*Yield production, kWh kWp-1*

Greek Letters

α	*Adjustment factor*
η	*Energy efficiency*
τ	*Residence time, hr*
ψ	*Exergy efficiency*

Subscript

(T)	*Target value*
amb	*Ambient*
Comb	*Combustion*
Cond	*Condense*
D	*Destruction*
ED	*Exergy destruction*
ef	*Efficiency of the system, %*
ef(T)	*Target efficiency, %*
ENV	*Environment*
ER	*Energy*

Evap	*Evaporator*
EX	*Exergy*
Sust	*Sutainability*
0	*Reference environment*

Abbreviations

ADP	*Abiotic Depletion Potential*
AP	*Acidification Potential*
AT	*Air Toxicity*
BCR	*Benefit-Cost Ratio*
CFC	*Chlorofluorocarbon*
COMM	*Commercialiazability*
DCB	*Dichlorobenzene*
DHW	*Domestic Hot water*
EES	*Engineering Equation Solver*
EL	*Educational Level*
EP	*Eutrophication Potential*
EPA	*Environmental Protection Agency*
GHG	*Greenhouse Gas*
GWP	*Global Warming Potential*
HH	*Human Health*
HW	*Human Welfare*
IC	*Innovation and Creativity*
IN	*Innovation*
JC	*Job Creation*

LCA	*Life-Cycle Assessment*
LCOE	*Levelized Cost of Electricity/Energy*
LU	*Land Use*
NPV	*Net Present Value*
ODP	*Ozone Depletion Potential*
PA	*Public Awareness*
PBT	*Payback Time*
PM	*Particulate Matter*
PV	*Photovoltaic*
SA	*Smog Air*
SA	*Social Acceptance*
SC	*Social Cost*
TR	*Technology Readiness*
TRAIN	*Training*
WC	*Water Consumption*
WE	*Water Ecotoxicity*

Chapter 1: Introduction

Sustainability has become a major highlight in modern civilization. In fact, it is a crucial phenomenon that is always present in political debates, educational programs, social trends and scientific advancements. However, the concept of sustainability has always been present throughout human civilizations. Indeed, humans always planned and their concern for resource availability was on the top of their priority list. This was the reason for humans to shift from hunting into farming. *Nachhaltigkeit,* a German coin that referred to “sustained yield” was the original term for sustainability, which was found in a forestry book in 1713. Sustainability does not have a standard definition. Scientists defined sustainability in a variety of ways, depending on the context and the scientific field of use. In the Oxford dictionary, sustainability is defined as the avoidance of the depletion of natural resources in order to maintain an ecological balance. Encyclopedia Britannica defines sustainability as the long-term viability of a community, set of social institutions, or societal practice. Table 1.1 provides a list of definitions that are used for sustainability. Sustainability and sustainable development can be used interchangeably as the latter could also mean a continuous or sustained development. Development indeed is a qualitative improvement to a system, which is distinct from growth. Growth denotes to quantitative increase in physical scale.

The concept of sustainability has closely been associated with energy consumption. The early humans started to use the fire for specific foods, which may have altered the natural composition of the planet and animal species (Scholes, 2003). Civilizations then transformed from hunting to more sustainable societies by introducing agriculture. In fact, agrarian communities depended largely on their environment (Clarke, 1977). The longevity of societies and an important factor that determined its flourishment or destruction was sustainable development. Energy is a critical element, which effects the interaction between nature and societies. In the past, increases in energy demands was associated with economic and technological advancements. However, currently the rise in energy consumption could have detrimental social, environmental and even economic effects. These effects could include local and global health impacts. The development of civilizations and the introduction of various energy sources evolved the concept of sustainability. While early civilizations utilized limited amounts of energy, industrial societies relied on abundant energy sources. Transportation, heating and compose the main needs of humans. However, with the industrial revolution and the technological advancements, novel energy resources have shaped the modern human civilization. Coal, oil, natural gas and other conventional energy sources have caused an exponential increase in human consumption of resources.

Table 1.1 Selected definitions of sustainability, sustainable development or sustainability sciences.

Source	**Definition**
(Brundtland Commission of the United Nations, 1987)	Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.
(Pearce et al., 1989)	Sustainable development involves devising a social and economic system, which ensures that these goals are sustained, i.e. that real incomes rise; that educational standards increase that the health of the nation improves; that the general quality of life is advanced.
(Harwood, 1998)	Sustainable agriculture is a system that can evolve indefinitely toward greater human utility, greater efficiency of resource use and a balance with the environment which is which is favorable to humans and most other species.
(Morelli, 2011)	Meeting the resource and services needs of current and future generations without compromising the health of the ecosystems that provide them. In specific, sustainability is a condition of balance, resilience, and interconnectedness that allows human society to satisfy its needs while neither exceeding the capacity of its supporting ecosystems to continue to regenerate the services necessary to meet those needs nor by our actions diminishing biological diversity.
(Forum for the Future, 2008)	Sustainable development is a dynamic process which enables people to realize their potential and improve their quality of life in ways which simultaneously protect and enhance the earth's life support systems

This in turn triggered environmentalism and the introduction of new fields such as ecology and environmental sciences. The unprecedented increase in energy demand, population and economy led the world to realize the impacts of energy use on the economy, environment and socially. Energy conservation, sustainable energy options and renewable energy sources were therefore explored further. Indeed, this concern has been widely addressed globally. The United Sustainability in its modern context refers to a relatively complex topic that is multi-disciplined. The meaning could vary depending on the context and the field. Indicators of development towards sustainability provide meaningful data that could characterize systems' sustainability level. Sustainability assessment relies on a number of indicators. These indicators could differ from one study to another. Concerned about economy, energy, society and environment, governments have been introducing regulations and local/regional bylaws that aim to enhance sustainability measures.

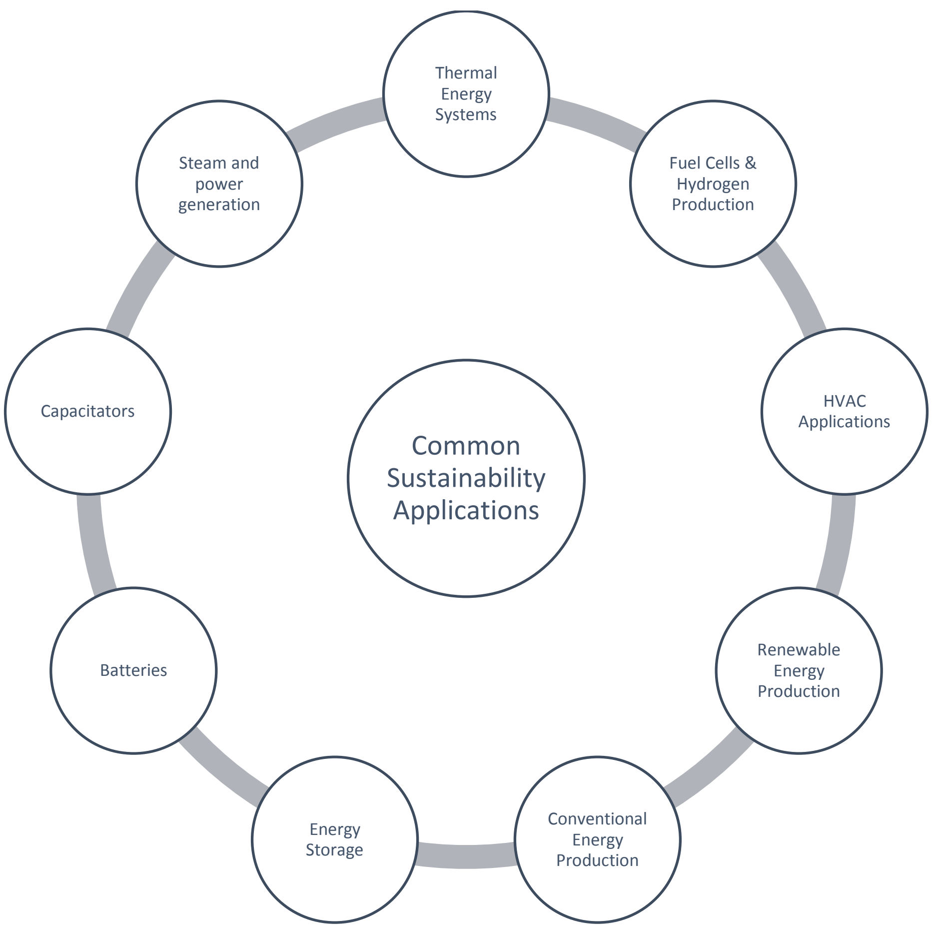

Figure 1.1 Illustration that highlights the use of sustainability in various disciplines and applications.

However, these efforts often include non-rigorous assessment methods that are mainly qualitative in nature. Sustainability is a complex and interdisciplinary concept, which relates to each of the presented domains in Figure 1.2. In order to assess the sustainable development of energy systems, resources, energy and the economy must be taken into detailed consideration. Furthermore, the environmental footprint, social impact, cultural paradigms surrounding these programs as well as public policy and political aspects need to be studied thoroughly in order to comprehensively and objectively understand sustainability.

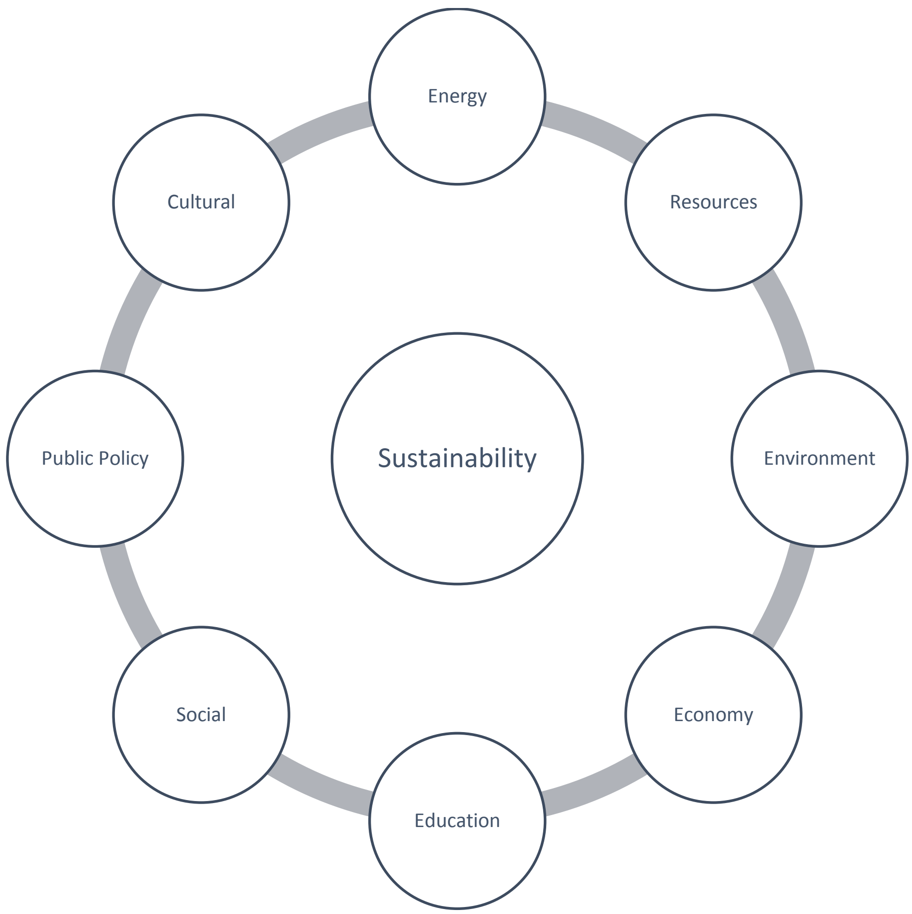

Figure 1.2 The backbone of sustainable development and the major domains that contribute to the understanding of the sustainability concept.

Moreover, some of these concepts are interdependent. For example, the economic dimension could influence the social dimension and public policy. Overall, the road towards an objective understanding and assessment of sustainability springs from sound and deep analysis of all factors and elements that contribute to this concept whether directly or indirectly.

1.1 Motivation

The concept of sustainability has evolved and matured throughout generations, however, there is no universal standard for sustainability assessment. This gap in the scientific development of sustainability triggered my interest to introduce an integrated assessment model that is simple, robust, and comprehensive. In fact, Bebbington et al. (2007) suggest that there is a pressing need for societies to find metrics, systems, models and tools that will enable the articulation of sustainability. Moreover, the main intent of sustainability assessment is to be informed of decisions that are made and making sure that options have been evaluated and examined for their short and long-term effects on society, economy, environment and other elements (Ness et al., 2007). In other words, with the introduction of novel energy system for commercial and residential use, sound sustainability assessment is both wise and crucial before dwelling into the execution phase of these novel ideas. On the same token, think twice, act once is an idiom that referred to considering something more carefully by weighing the positives and negatives before coming to a conclusion. Therefore, Kates et al. (2001) proposed that the objectives of sustainability must be clearly outlined before selecting appropriate indicators to assess sustainability. Increase of energy consumption of nations was considered a sign of growth, prosperity, development and economic strength (Midilli et al., 2011). This phenomenon has

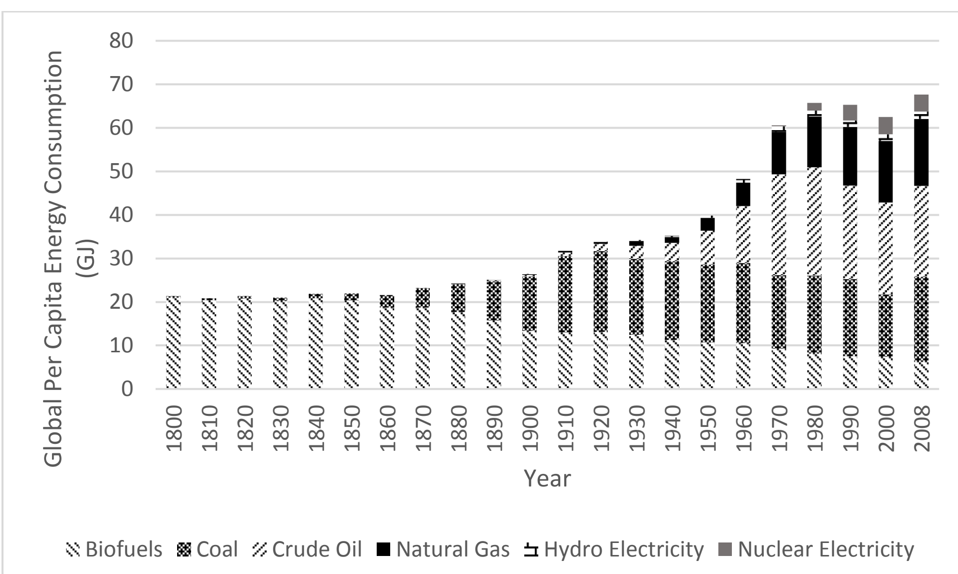

Figure 1.3 World's per capita annual energy consumption per fuel type from 1800 - 2008 (Data from: Source: Vaclav Rycroft, 2008).

changed now as the increase of energy consumption is now viewed as increased environmental impact unless renewable energy is utilized. Even though renewable energy systems are being more explored after a globally aware culture, fossil fuels still account for the majority of the world's energy demands. The obstacle of meeting the world's energy demands through environmentally benign methods remains a challenge until today. In fact, the International Energy Agency published that the world's energy consumption in 2014 was 13,699 Mtoe compared to 6,101 Mtoe in 1973. Figure 1.3 illustrates the world's per capita annual energy consumption between 1800 to 2008 by fuel type. Transportation, industrial, electric and even residential energy demands are largely met by the use of fossil fuels. Although readily available and the technology being commercially viable, fossil fuels pose a major environmental risk by emitting greenhouse gases into the atmosphere. Furthermore, they also may have other social and economic impacts that may be undesirable. On the other hand, the world's energy demand is increasing exponentially over time, which makes the nature of this study of extreme importance and necessity. Environmentally benign technologies that have positive economic and social impacts while being commercially viable is the type of technology that the world needs. Efficient energy systems lead to more prosperous economies, which consequently trigger positive social developments.

The novelty of this discipline is due to the vast and rapid changes of human civilization. At first, early humans were at a stage where they learned to adjust and adapt to earth and all the natural resources around them. Humans' impact on earth and its ecological and physical properties were minimum or negligible. As human civilizations evolved from hunting and gathering to more agricultural communities, the social dynamics also changed. Furthermore, human civilization further evolved from agricultural communities to industrial societies. Currently, human civilization is evolving towards a digital and informational-based society. In these latter stages of human civilization evolution, humans started to influence the normal and physical processes of the planet. This enormous transformation in human civilization is very costly. Indeed, the rate at which the world's economic, societal, environmental and cultural are transforming is very concerning and perhaps not sustainable as suggested by Figure 1.3. Furthermore, in order to contain these major concerns, major norms of current human civilization need to be reevaluated. Therefore, the sustainability assessment of energy system, which plays an integral part in the current civilization, is critical.

1.2 Objectives

The world has not yet adopted a universal sustainability assessment model. This is mainly because models are commonly criticized for their subjectivity, understanding of sustainability or the lack of clarity of that model. This thesis aims to provide an integrated sustainability assessment model that is robust, simple and comprehensive. This model includes parameters that contribute to assessing the sustainability of energy systems. While social, environmental and economic parameters have been studied before, this thesis assesses other contributing factors such as the educational, social, technological, thermodynamic, and Size factors of energy systems. Furthermore, the introduction of target values is also novel as previous research about sustainability models were confined to discussing indicators of each dimension in isolation with other dimensions (i.e. Environment, economy, social, each individually). Moreover, this thesis highlights the intimate relationship between renewable energy and sustainable development. Often, the value of renewable energy is not deeply understood and thus it is categorized as cost-ineffective compared to other technologies (Dincer, 1999).

The specific objectives of this thesis are as follows:

1. Identify key parameters that influence the sustainability of energy systems considering the major contributing domains to sustainability such as energy, environment, social, education, and economic dimensions.
2. Integrating various categories into a coherent and comprehensive assessment model. In order to be able to normalize the data, dimensionless values for each indicator and dimension are determined in order to obtain an aggregated sustainability result.
3. Provide a logically sound and thermodynamically accurate methodology to quantify the criteria proposed in order to qualify and quantify sustainability assessment for energy systems.
4. Validate the proposed model using two case studies, highlighting renewable energy sources as a viable option for multi-generation in order to meet the residential electricity,

heating and cooling, and hot water demand for 150 Ontario homes. In order to conduct this testing, Engineering Equation Solver (EES) is used to build and solve a mathematical model detailing balance equations for the proposed systems including their sub components such as the compressor, condenser and evaporator.

5. Using the lifecycle assessment (LCA) approach, compare the environmental impact of each proposed system with respect to a conventional gas-fired energy system.

Chapter 2: Background and Literature Review

Sustainability is a very complex concept with multi-disciplinary relationships. As presented in the previous chapter, there is no exact definition for sustainability; however, the Brundtland Commission of the United Nations' definitions on sustainability is the most popular one. While researchers and scientists have proposed many sustainability assessment models, until today there is not a universally recognized assessment model. This opportunity to formulate an integrated sustainability assessment model, which is both robust and simple, is extremely valuable. There have been many attempts and a number of sustainability assessment methodologies, which exist for evaluating the performance of companies, cities, energy systems, and product manufacturing (Ramachandran, 2000). In fact, sustainability management in industries were triggered by the evolution of a number of sustainability literature such as the World Business Council for Sustainable Development (WBCSD, 1997), the development of sustainability standards (OECD, 2002) and the emerging of the Global Reporting Initiative (GRI, 2002a, b). Initiated by the United Nation Environment Programme (UNEP) in partnership with American environmental organizations, the GRI was launched in 1997 with the intent of enhancing the quality, structure and layout of sustainability reporting. On that note, the UN Commission on Sustainable Development (CSD) introduced a list of 140 indicators that touch on various aspects of sustainability (CSD, 2001). While the GRI assesses sustainability based on three major dimension (social, economic, and environmental), the Wuppertal Institute developed a sustainability framework, which examines the four dimensions identified by the United Nations CSD (social, economic, environmental, and institutional).

2.1 Sustainability Assessment Categories

2.1.1 Energy Impact

Energy analysis is a thermodynamic tool that has been used to assess energy systems' sustainability. Thermodynamic-based indicators in sustainability is novel and the concept is slowly growing within the scientific community. Utilizing the first law of thermodynamics and assessing sustainability quantitatively based on accurate and robust thermodynamic data is an added advantage. Gnanapragasam et al. (2010) introduced a methodology for assessing the sustainability of hydrogen production form solid fuels. This methodology incorporated different aspects of energy under different categories in their research. Energy rate, denoting the rate at which energy can be supplied by the element or process was assessed along with net energy consumption, which referred to the Energy requirement of the element to transport it to the point of use and utilize it in the operation of processes. Moreover, efficiency was also a key factor in the sustainability assessment of this model. Caliskan et al. (2011) investigated a solar-ground based heat pump with thermal energy storage. The sustainability of this model included energy analysis comprising of: energy input rate (solar radiation), energy storage rate, efficiency assessment derived from the collector and other heat losses. More recently, alternative fuels were assessed for Thailand to replace the current diesel fuel, which is widely used. In this assessment, the net energy ratio is used as an indicator within the lifecycle assessment of the proposed alternatives (Permpool and Gheewala, 2017). Furthermore, Lo Piano and Mayumi (2017) developed an integrated assessment model using MuSIASEM (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism) in order to investigate the performance of PV power stations for electricity generation. Economic indicators with reference to energy have been suggested such as Energy Payback time and Energy Return on Investment. Those indicators will be discussed under other categories. In this study, a major category was Energy Accessibility. This factor was measured by considering into account the primary energy source type and energy carriers. Jones et al. (2017) further explored the combination of net energy analysis and life cycle assessment of distributed electricity generation. In this explorative research, the net energy analysis tool took into consideration the number and type of distributed generations deployed and the rate of the power generation. They also examined the electricity storage options and the electricity generation mix. Caliskan et al. (2013) modeled hybrid energy systems namely hybrid geothermal energy-wind turbine-solar photovoltaic panel, inverter, electrolyzer, hydrogen storage system and Proton Exchange Membrane Fuel Cell (PEMFC). Energy analysis was a pillar tool that they used to model these systems. Energy analysis included energy balance, the net energy input rate, the energy loss in the form of heat, the electric power production, and the electricity production. Furthermore, other proposed sustainability measurement approaches of renewable energy productions include that of Pierie et al. (2016) when they focused on modeling the green gas production pathways. In this model, they measured direct and indirect energy flow rates in order to determine efficiency. Moreover, Dincer and Zamfirescu (2012) introduced a new thermodynamic concept to greenize energy systems. For this, they assess the energy efficiency and energy balance and mass equations of their case studies. In addition, the environmental impact of energy systems is associated with the energy-resource utilization along with inexpensive and stable energy supply (Dincer and Rosen, 2011). Hydrogen fuel cell systems were examined by Dincer and Rosen (2011) for sustainability. Energy was a major aspect of determining the sustainability as they measured the efficiency of the hydrogen fuel cell systems along with considering other aspects. The summary of these energy indicators are illustrated in Figure 2.1.

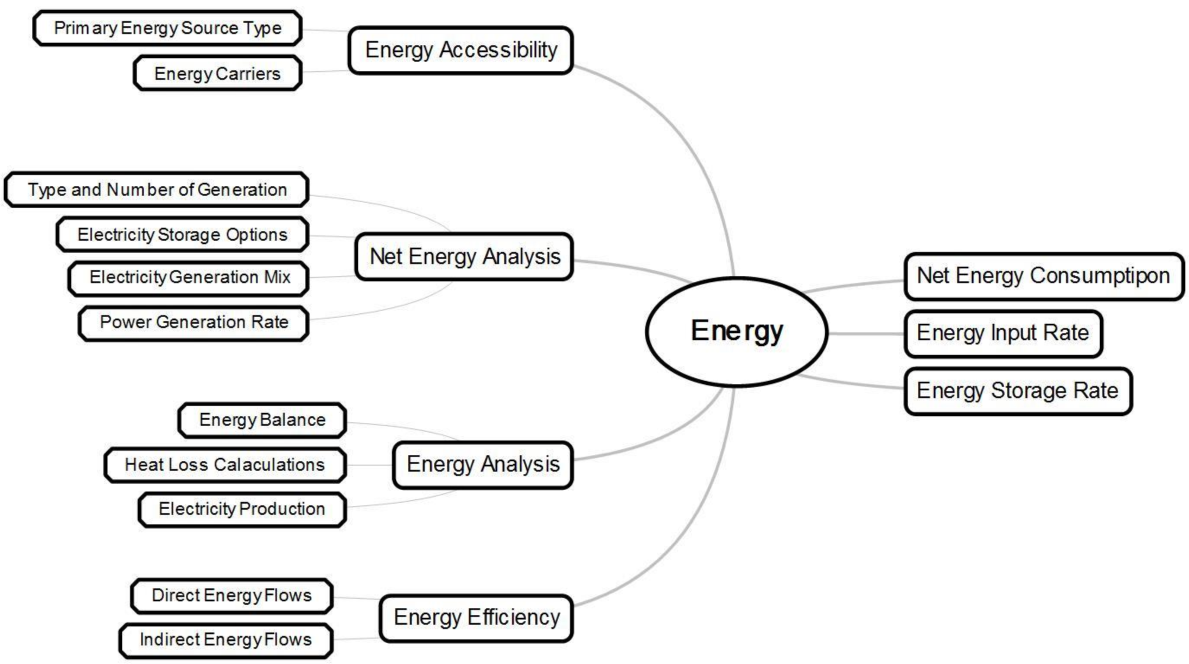

Figure 2.1 Concept map of the energy dimension and the distribution of various parameters used in the literature to account for the energy factor in sustainability assessment.

In summary, it is evident that energy analysis in various forms, stages and capacities have been incorporating in sustainability assessment since the last two decades. The use of thermodynamic-based variables in presenting quantifiable values that mirror the sustainability of energy systems is of utmost importance. Thus, in my thesis, I have selected the energy efficiency (percentage) and the production rate (TWh/year) to be the factors that will simply and accurately assess the sustainability of energy systems based on energy performance. As can be observed from the literature, the reasons behind the variety of energy indicators presented in the mind map lie in two main reasons: first, studies varied in their nomenclature of different indicators and the majority of indicators could be grouped accordingly in order to avoid allocation of results. Secondly, studies differed on their research focuses and thus certain parameters were selected based on the specific system being studied. Overall, I would like to suggest that the efficiency of the energy system defined as the ratio of the useful energy output given by the energy system to the total energy expended; is a comprehensive parameter that will accurately reflect the sustainability aspects of the energy analysis of systems. The production rate is also suggested as systems that have higher energy productions than others with competitive energy demands are also more beneficial and more attractive than systems that have high energy demands with low energy output.

2.1.2 Exergy Impact

Exergy analysis is another thermodynamic-based tool that has been emerging into the sustainability assessment models. It is related directly to the second law of thermodynamics, where exergy is always destroyed when a system involves irreversible reactions such as heat loss to the environment. Another factor that emerges is the entropy of the system in relation to the destruction of exergy. Therefore, exergy analysis is a vital tool can be used specifically to assess energy systems' sustainability (Dincer and Rosen, 2007). Those systems with higher exergy efficiencies reflect more sustainable processes that do not have much irreversibilities and vice versa. Dincer (2007) conducted sustainability assessment on green energy systems and concluded that the use of exergy analysis as a tool for assessment of green energy systems is essential to increasing efficiency, and decreasing environmental effect. In fact, in 2004, exergy was highlighted as a driver for achieving sustainability by Dincer and Rosen (Dincer and Rosen, 2004). Exergy is a measure of deviations between the system and environmental equilibrium. They concluded that the potential usefulness of exergy analysis in addressing sustainability matters and resolving environmental challenges is substantial. Hacatoglu et al. (2016) studied the sustainability of a wind-hydrogen energy system and applied their novel assessment index.

Exergy efficiency was measured by finding the ratio between exergy outputs and the exergy of the wind. When compared to the gas-fired system, the exergy efficiency considered the chemical exergy of the fuel as part of the calculation. Exergy destruction ratio has been used as an indicator in the sustainability assessment of hydrogen production from solid fuels by Gnanapragasam et al. (2010). This tool was utilized to assess the technological aspect of the sustainability assessment of this study. Furthermore, Caliskan et al. (2011) particularly selected exergy analysis as a function of the sustainability assessment of the solar-ground based heat pump with thermal energy storage. In this study, the rate of maximum exergy input, exergy losses, and exergy storage have been determined based on reference parameters. Exergy efficiency was also considered in this study. Moreover, even more exergetic indicators have been introduced and proposed by other scientists in the literature. For example, Midilli et al. (2012) researched about the environmental and sustainability aspects of a recirculating aquaculture system. In their study, they proposed the following exergetic indicators: exergetic efficiency, waste exergy ratio, exergy recoverability ratio, exergy destruction ratio, environmental impact factor, and exergetic sustainable index. Caliskan et al. (2013) conducted exergy efficiency analysis on the case studies they performed as an indicator of sustainability. Caliskan et al. (2011) also considered exergetic parameters when assessing the sustainability of three types of air cooling systems for building application. They namely used the specific exergy flow, exergy efficiency, and specific exergy destruction as indicators of the exergetic index of these air-cooling systems. Furthermore, Caliskan et al. (2012) conducted exergoeconomic and sustainability analyses on a novel air cooler in which they used exergy input, output, loss, destruction rates, exergetic coefficient of performance, primary exergy ratio and exergy efficiency. On the economic side, they also calculated the exergetic cost rate. Dincer and Acar (2015) highlighted the importance of investigating irreversibilities, energy and exergy efficiencies and considered them as critical steps in order to obtain sound sustainability assessment. The summary of these exergy indicators are illustrated in Figure 2.2.

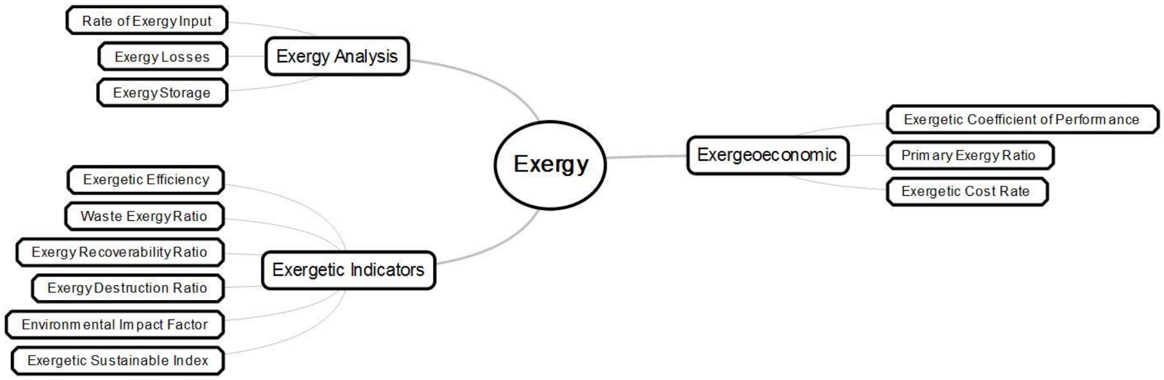

Figure 2.2 Concept map of the exergy dimension and the distribution of various parameters used in the literature to account for the exergetic factor in sustainability assessment

As exergetic analysis is highlighting its importance in determining sustainability of energy systems, its use is growing steadily. Exergy analysis has not been as commonly used as energy analysis, yet it is equally important as it relates to the second law of thermodynamics. Exergy adds to the quantitative parameters that are used to assess sustainability. Such parameters shape the sustainability model and add robustness and accuracy to the model by involving data-based factors in the assessment and limiting the subjectivity of the assessment as much as possible. Exergy as presented in Figure 2.2 has been assessed through a number of indicators and parameters. Efficiency has been redundant throughout many studies while other factors such as storage, losses and exergy destruction have been specifically selected to measure aspects of the system that otherwise would be unknown. There is some overlap between the exergy indicators and therefore I have limited my exergy analysis to only two main factors. In my thesis, I chose efficiency (percentage) and exergy destruction ratio as the main indicators that will adequately and accurately reflect the exergy performance of the target energy systems. From the second law of thermodynamics, it is established that no system will ever be 100% efficient. Thus, exergy efficiency is a reliable tool that has been repetitively used in the literature to measure the exergy of systems. Since all thermodynamic processes are governed by the laws of conservation of energy and mass, the laws entail that the mass and energy can neither be destroyed or created in a process. Since exergy is not conserved, it is therefore destroyed by irreversible processes within the system. Therefore, exergy destruction is an integral part of the exergy balance calculation. I propose that exergy efficiency and the exergy destruction ratio are two indicators that will comprehensively echo the exergy of the energy system of interest. In fact, using the exergy as a tool to assess sustainability yields in performance improvements, efficient analysis and effective design of energy systems (Dincer, 2007). Other variables would not be necessary in this model to avoid replication of results and thus exaggerating the effect. Overall, the objective behind this dimension is to deeply understand the efficiency and performance of the energy system thermodynamically.

2.1.3 Environmental Footprint

Sustainability has been associated with environmental aspect since its inception. In fact, the harmful environmental impacts of conventional energy sources, which triggered global warming and climate change account for the emerging of modern sustainability. Thus, the literature is filled with sustainability assessments, models, and reviews encompassing environmental factors. Environmental factors have been even considered in building sustainability assessments. Environmental performance included climate change, emissions to air, water and soil, water efficiency, and resource depletion (Braganca et al., 2010). Most researches in the literature use the Lifecycle Assessment (LCA) to measure the environmental impacts of the systems. Braganca et al. (2010) considered local environmental impacts along with cultural aspects in their research. Although they highlighted energy as a major key issue when addressing sustainability, they did not use it in their model. Hacatoglu (2015) considered more environmental factors in his assessment. In fact, three major assessment categories were environmentally based while the other 3 accounted for technical, economic and efficiency parameters. He used 12 environmental indicators to assess the global environmental impact potential, air pollution potential and water pollution potential. Lifecycle assessment was also used to conduct the environmental aspect of this sustainability assessment. Gnanapragasam et al. (2010) had ten environmental indicators to be part of his sustainability assessment model. He categorized them under ecological indicators and accounted for one third of his sustainability indicators. He used twenty other indicators for social and technology-based dimensions. Dincer and Acar (2015) considered global warming potential, social carbon cost and acidification potential in their overview assessment on clean energy solutions for better sustainability. Furthermore, while they only used these three indicators, they also normalized rankings of potential nonair environmental impacts such as land use, water consumption, water quality of discharge, solid waste and ground contamination, and biodiversity. They also conducted a SWOT analysis for different energy options considered. Moreover, environmental dimension was taken into consideration in desalination supply chain performance assessment (Balfaqih et al., 2017) as well as sustainability assessment of groundwater remediation technologies (Da et. Al., 2017). Overall, the environmental dimension was vivid in most of the studies reviewed in this literature review. The exceptions were the works of Caliskan et al. (2011, 2012) as the focus of these studies were exergetic performance. Lifecycle assessment is the tool that was widely used in most of these studies to assess the environmental indicators. LCA is a tool used to investigate the environmental impacts of a product or a system while taking into account all the lifecycle stages they go through. Figure 3 illustrates the various environmental indicators used in the literature in various studies. Overall, the environmental dimension is well established and widely used in the assessment of sustainability. The tools to measure environmental impacts quantitatively through LCA and other tools make it readily accessible and convenient for the researcher to analyze environmental impacts of energy systems. While Figure 2.3 presents various environmental indicators, for this thesis, I chose to have a comprehensive collection of environmental indicators of various types (climate change, air, water etc.). Thus, my proposed model is composed of 10 environmental indicators presented in Figure 2.4. I suggest that these 10 indicators are sufficient to provide an accurate environmental assessment of energy systems for sustainability purposes. Air pollution potential includes assessment of particulate matter, SO_2, CO, NO_2, O_3 and Pb. Furthermore, water pollution potential includes eutrophication potential, freshwater ecotoxicity potential, and marine ecotoxicity potential. Ecological indicators refer to more general concepts such as availability, adaptability, environmental capacity, timeline, material rate, energy rate, ecological balance and endurance. Global environmental impact potential represent the environmental impacts that effect the globe universally such as the global warming potential, stratospheric ozone depletion potential and abiotic depletion potential. In addition, nonair impacts include land imprint, biodiversity, social carbon cost, solid waste and quality of discharged water.

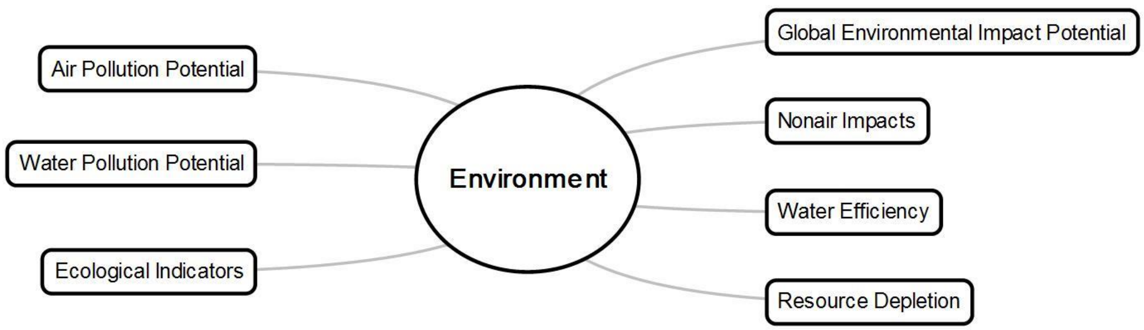

Figure 2.3 Concept map of the environment dimension and the distribution of various parameters used in the literature to account for the environmental factor in sustainability assessment.

When analyzing the environmental impact that energy systems have, all types of impacts must be accounted for in order to have an accurate environmental assessment. In my proposed model, I account for air pollution by investigating the global warming potential, ozone depletion potential, air toxicity and smog air resulting from the utilization of the system.

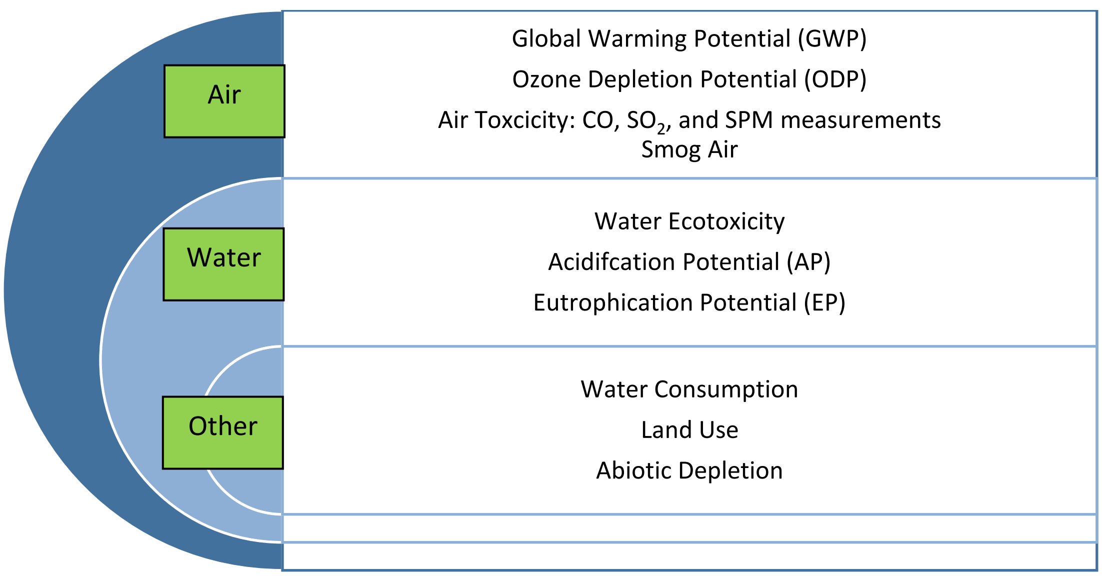

Figure 2.41 Environmental indicators adopted for the proposed sustainability assessment model highlighting air pollution, water pollution and other forms of pollution as well.

I also account for water pollution by measuring the water ecotoxicity, acidification potential and eutrophication potential. Other impacts are also considered such as the land use, water consumption and abiotic depletion.

2.1.4 Education

While some studies investigated the social dimensions when assessing sustainability, the educational dimension has been majorly neglected. This dimension refers to the level of training and education available in a project or proposed energy system.

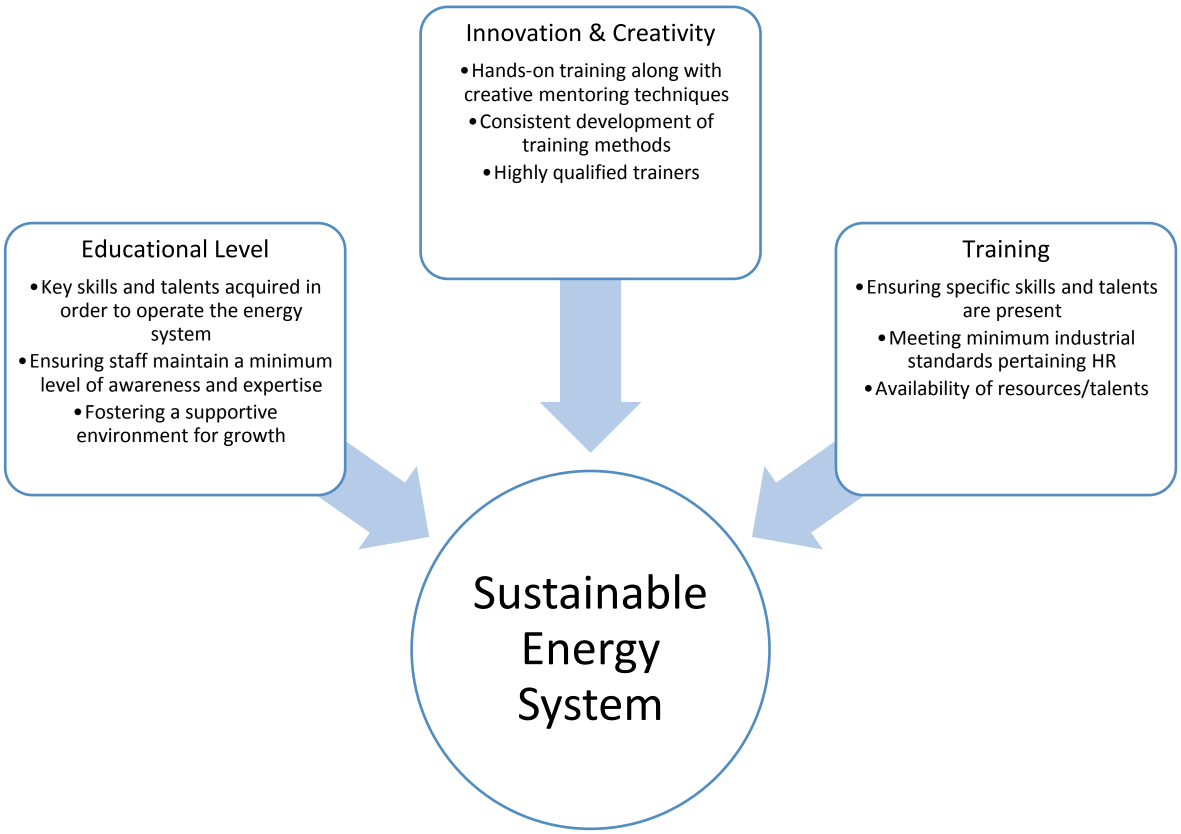

Figure 2.5 The relationship between education and sustainable development of energy systems.

Of course, the more educated and trained personnel available, the more sustainable the project and vice versa. So far, I was not able to find any study that dwelled into this dimension or even considered it as part of their sustainability assessment model. My proposal is to investigate the educational aspect of the energy system by analyzing three main aspects illustrated in Figure 2.5. Further elaboration on the descriptions of these aspects will be presented in the following chapters. Since this model provides a new integrated sustainability assessment model, internal parameters of a project or a system must also be considered when conducting the assessment. Thus, the educational dimension is an effective dimension to evaluate the general health and safety as well as the level of resource effectiveness and longevity of the project. Traditionally, training, innovation and creativity would be assessed under education. In my model, I am distinguishing between the three concepts and assessing each concept individually.

2.1.5 Economic Impact

Economic aspects have always been in the core of sustainability assessment along with the environmental and social factors. Understanding the financial repercussions and outcomes of projects or energy systems is vital to understanding its sustainability. Furthermore, the economic dimensions is very crucial to decision-making in various industries as well as to government agencies. Therefore, various sustainability assessment studies across the literature investigated the economic aspect in order to reach to a reasonable sustainability assessment model. Braganca et al. (2010) took into account the economic performance when assessing building sustainability for instance. Namely, they considered life-cycle costs including costs before the use of the building, maintenance costs, operational costs, and costs after building use and residual value. Furthermore, Hacatoglu (2015) considered the affordability and commercial viability of energy systems to assess their economic effect. Economic assessment is also present in the works of Jin and Sutherland (2016), Da et al. (2017), and Balfaqih et al. (2017). On the other hand, Gnanapragasam et al. (2010) considered some economic factors, yet they were dispersed as indicators of sociological and technological dimensions. They considered economic benefit, policy, and per capita demand. Dincer and Acar (2015) considered a number of indicators in their design including production cost, investment cost, operation and maintenance cost, and social carbon cost. The exergeoeconomic and enviroeconomic aspects were examines for a novel air cooler (Caliskan et al., 2012). The exergeoeconomic tool is used to assess the exergetic cost, which translates to exergy based economic analysis, in which costs are distributed among outputs. The method used involved showing correlations between capital costs, working hours and exergy destruction.

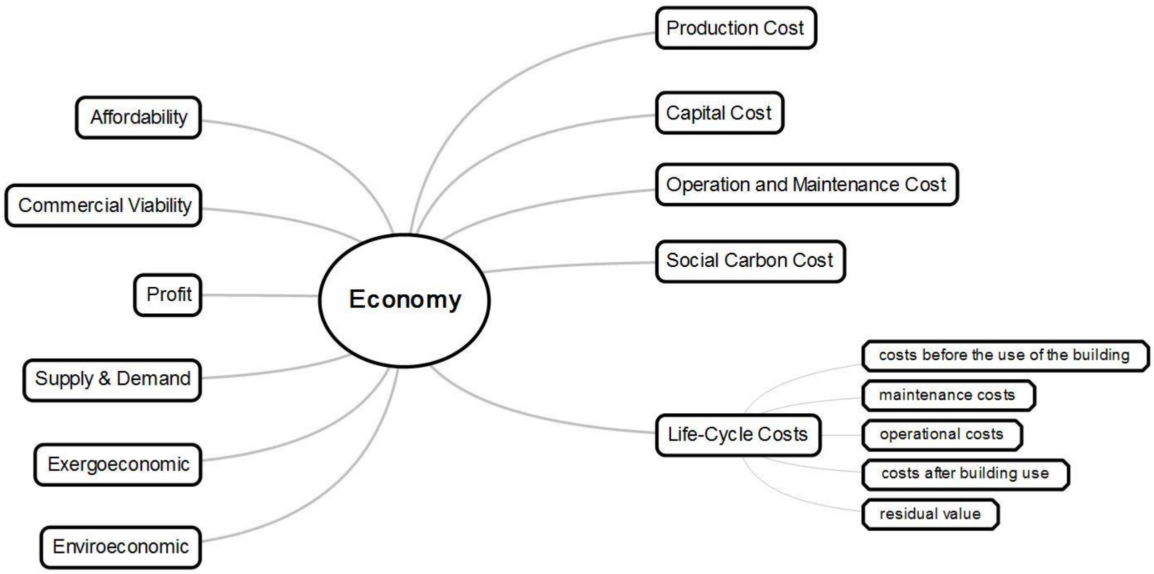

Figure 2.6 Concept map of the Economic dimension and the distribution of various parameters used in the literature to account for the economic factor in sustainability assessment.

The enviroeconomic tool was mainly composed of the carbon dioxide emission price. Paolotti et al. (2017) examined the economic assessment of agro-energy wood biomass supply chain. Santoyo-Castelazo and Azapagic (2014) included three main indicators to assess the economic dimension of their sustainability model. They used capital costs, total annualized costs, and levelized costs in order to assess the sustainability of energy systems. Figure 2.6 shows the various economic indicators used in the literature to assess the economic dimension of sustainability assessment. In this thesis, I used some of the indicators found in the literature and added to them in a way that the economic impact of the energy system is clearly and concisely factored in the sustainability assessment. Figure 2.7 shows the indicators proposed for this model. These three elements of the economic dimension relate to each other, as they are able to affect one another. For example, if an energy system has a high benefit-cost ratio, the levelized cost of electricity would be lower and the payback time of the system would be shorter. On the contrary, if the payback time of the system is long, the benefit-cost ratio decreases and thus the levelized cost of electricity peaks. The levelized cost of electricity represents the affordability aspect of sustainability.

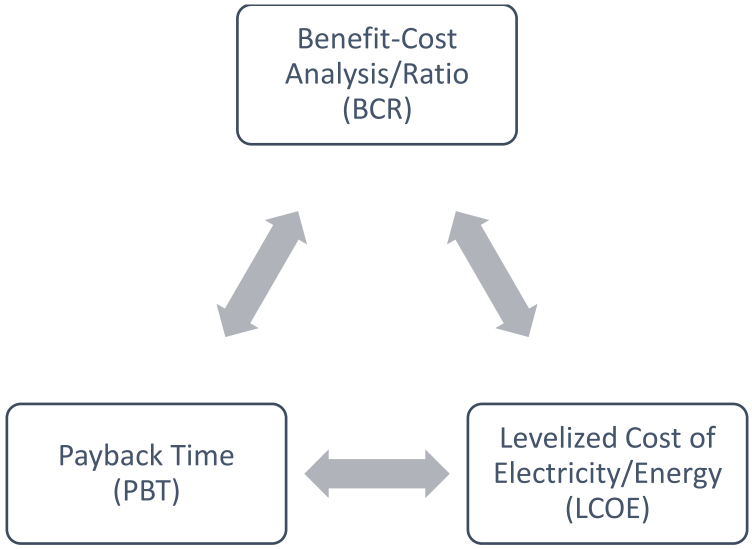

Figure 2.7 Economic indicators proposed for the sustainability assessment in this model.

Affordable energy is definitely more sustainable. Similarly, energy systems must be profitable and economically sound from a business-perspective. Thus, the benefit-cost ratio cannot be in the negative and must always maintain a good margin. Maintaining high benefit ensures the speed in paying back the initial capital investment of the system, which enables the system to collect profit thereafter. Therefore, these three concepts of the economic domain are interrelated and influence one another.

2.1.6 Technology

Indicators to reflect the energy system's technology is novel to sustainability assessment. Unlike economic, social and environmental dimensions, this technology dimension brings another outlook to the suitability assessment of energy systems. Not many indicators found in the literature to reflect the technology of the product. Gnanapragasam et al. (2010) had a technological dimension in his proposed model. This dimension was assessed along with sociological and ecological dimensions with ten indicators for each dimension. In the technological dimensions, they mixed between energy, exergy, efficiency and actual technology-related indicators. Specifically, they examined demonstration, commercialization, impact and evolution of the technology as indicators towards the assessment model. Lo Piano and Mayumi

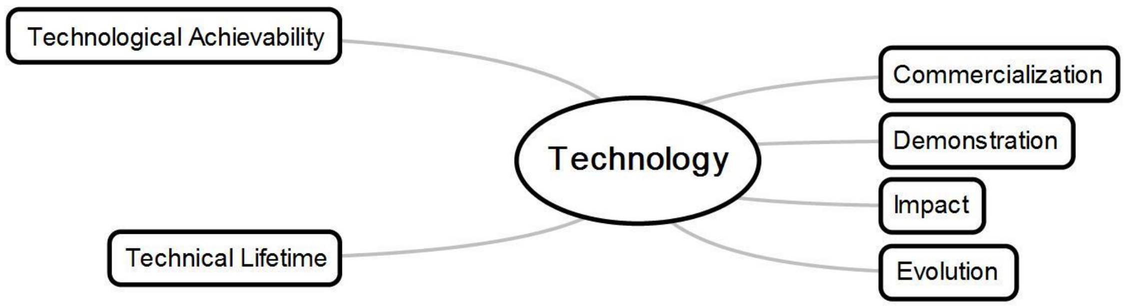

Figure 2.8 Concept map of the technology dimension and the distribution of various parameters used in the literature to account for the technology factor in sustainability assessment.

(2017) had technological achievability along with three other pillar dimensions as the basis of

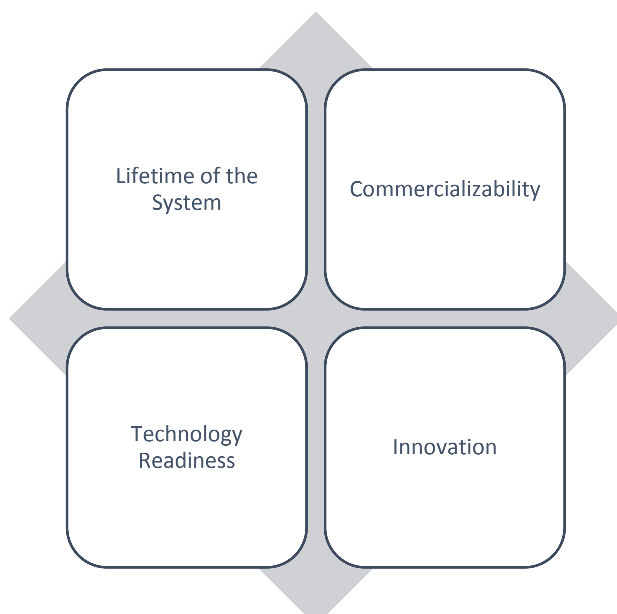

Figure 2.9 Technological indicators proposed for the sustainability assessment in this model.

their model. Pierie et al., (2016) did not consider the technological aspect in detail, however they assessed the lifetime of the system. The technical lifetime of a green gas production pathway was taken into account as part of the long-term dynamics of the system. Figure 2.8 illustrates the different indicators that have been used in previous studies to assess the technology dimension. For the purposes of this thesis, I expanded more on this dimension in order to obtain realistic assessment of the technology aspect. Figure 2.9 shows the indicators I propose to use for this assessment model. Systems vary in their technological competitiveness. Some are commercially viable with large-scale market competition while other systems are yet to evolve. A system could be technology-ready, but not commercially viable. Furthermore, the lifetime of systems vary depending on many manufacturing, operation and maintenance factors. Further detailing of each of these indicators will be discussed in the next chapter.

2.1.7 Social Impression

The social dimension of the sustainability assessment is majorly composed of qualitative and subjective indicators. Social aspects have been an integral part when discussing sustainability assessment models along with environmental and economic dimensions. In the literature, there have been various social indicators to account for this dimension in different models. Some of the indicators within this dimension are categorized as weak indicators while others are considered strong. When assessing building sustainability, Braganca et al. (2010) used various social indicators that related to buildings rather than energy systems. The used indicators such as hydrothermal comfort, indoor air quality, and visual comfort. Gnanapragasam et al. (2010) used ten social indicators to assess this dimension. Indicators used included human resources, public opinion, living standards and human convenience along with other economic and environmental aspects. The social cost of carbon was examined by multiple studies, namely Dincer and Acar (2015). Lo Piano and Mayumi (2017) examined the socioeconomic effect as part of their integrated assessment of the performance of photovoltaic power stations for electricity generation purposes. Afgan and Carvalho (2004) covered the social dimension by focusing on job and area indicators. Job indicator represents the number of hours of new job to be opened corresponding to the respective option in the following 10 years. The area indicator represents parameter, which defines the number of m^2 per unit power. Santoyo-Castelazo and Azapagic (2014) investigated the social dimension more comprehensively than other studies by investigating security and diversity of supply of energy, public acceptability, health and safety, and intergenerational issues. The summary of used indicators in the literature is illustrated in

Figure 2.10. Overall, my proposed list of indicators to account for the social dimension are illustrated in Figure 2.11.

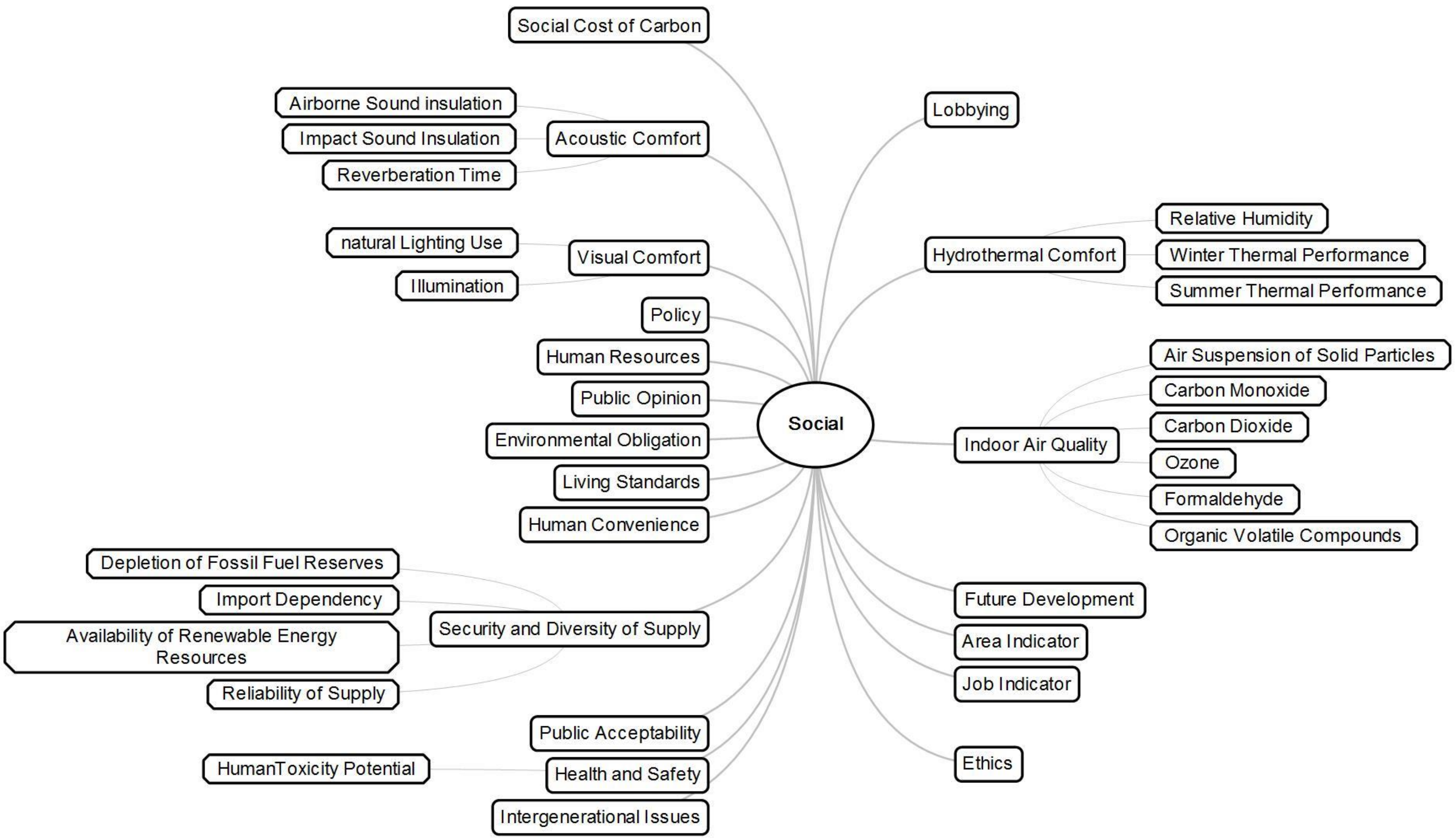

Figure 2.10 Concept map of the social dimension and the distribution of various parameters used in the literature to account for the social factor in sustainability assessment.

2.1.8 Size Factor

The Size factor is a dimension that mirrors the size of the energy system. The bigger the system, the more energy output can be yielded and vice versa. Bigger systems also need more maintenance and are more costly and thus it is a function of many factors to determine the sustainability of specific energy systems. Hacatoglu (2015) covered the same dimension in his assessment model taking into consideration the volume, mass and area. This dimension is greatly neglected in the literature and is not considered in most assessment models as such. In this thesis, I propose to take into account the Size factor of energy systems by calculating the volume, mass and area.

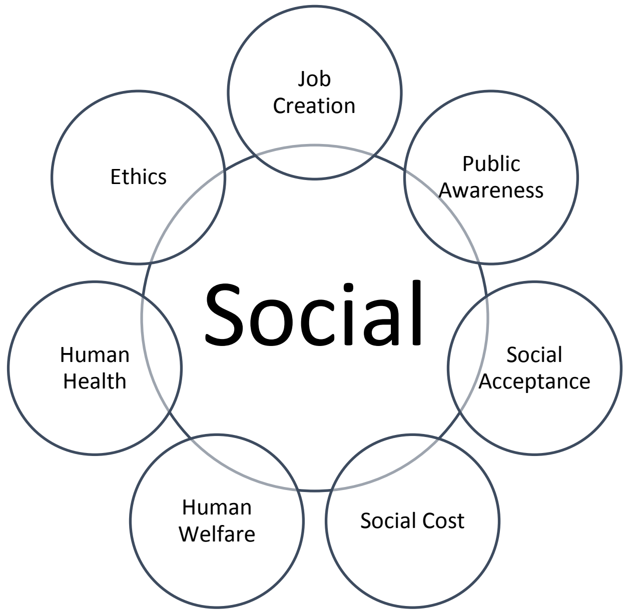

Figure 2.11 Social indicators proposed for the sustainability assessment in this model.

2.1.9 Summary

In summary, sustainability assessment models in the literature have focused on environmental, economic and social aspects. However, in order to have a comprehensive and coherent assessment that is reliable and robust, other critical factors must be included as well. It is observed that studies in the literature tended to focus on certain dimensions while neglecting other dimensions. For example, some studies focused on the economic aspect of sustainability assessment, while others focused on environmental aspect. Furthermore, some studies have proposed novel assessment models that are integrated and some that are comprehensive. However, even these studies lack some major elements in certain dimensions. Furthermore, some studies is largely composed of qualitative assessment while the presence of quantitative assessment is limited, which decreases from its effectiveness and reliability.

2.2 Indicators

Indicators enable us to summarize, simplify and condense complex and dynamic information to more meaningful and manageable information (Godfrey and Todd, 2001). Furthermore, some indicators might not be meaningful or useful if reference values such as thresholds are not provided (Lancker and Nijkamp, 2000). Some researchers used the ‘top-down’ approach in their sustainability model by defining the target sustainability and consequently selecting indicators that would mirror the sustainability of the system. Others used the 'bottom-up' approach, which requires systematic participation of stakeholders in order to ensure the development of indicators and the shaping of the sustainability framework simultaneously. Booysen (2002)

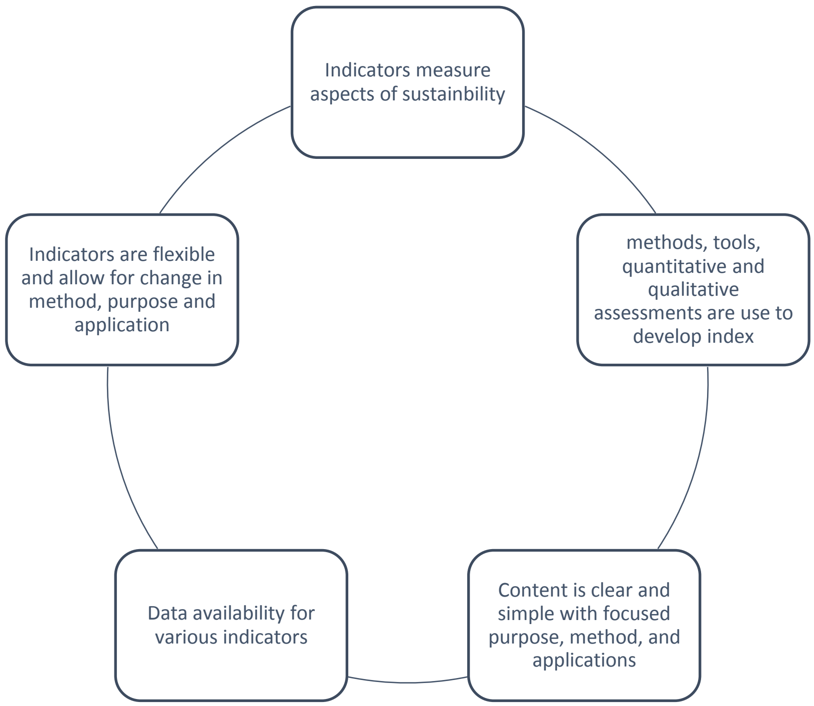

Figure 2.12 Indicator characterization and evaluation criteria based on Booysen (2002).

introduced an assessment, which can be used to investigate the viability of indicators. He suggests that the classification and evaluation of indicators must be done based following general dimensions of measurement illustrated in Figure 2.12. Furthermore, data need to be of high quality and accuracy. The techniques used to normalize, weight, or aggregate these values can also effect the results on sustainability assessment. Thus, methods and techniques need to be justified and chosen carefully.

Chapter 3: Model Development & Framework

In this chapter, the approach of evaluation will be described thoroughly. Sustainability is a complex and multi-disciplinary concept, which requires detailed analysis and sensitive study in order to comprehensively understand its scope. Sustainability relates to the environment, economy, society, and other important factors. This chapter will describe the assessment methodology and elaborate more on the aggregation and weighting of data.

3.1 Methodology

The proposed sustainability assessment methodology will be discussed in depth in this chapter. To begin, it is important to note that sustainability is often only roughly measured. Thus, giving more of an estimation along with some economic and social indications. Until today, sustainability assessment does not have a universal standard, which makes this a crucial opportunity for scientists. Sustainability assessment must be accurately and reliably comparable and measurable (De Vries et al., 2012). It is also vital to understand that sustainability assessment is a complex process with various inputs that need to be methodically quantified in order to obtain reliable, robust and accurate information. Furthermore, the assessment ought to be comprehensive and taking into account the actual factors that relate to sustainability. Therefore, it is evident that a systematic method for identifying and generating sustainable solutions, which is shared universally, is still to be found. Some gaps are evident in the development of sustainability assessment that I absorbed after reviewing the literature. These include, but are not limited to the following:

1. Absence of universally adopted and shared understanding of sustainability.
2. Sustainability assessment models that are specifically geared towards a specific application.
3. The focus on specific dimensions and neglect of major dimensions in some models.
4. The double-counting trend when investigating similar indicators.
5. The absence of target/reference values to compare to actual values. Lifecycle values are given a non-dimensional score without relationship to a target value.

This thesis aims to build on the research already conducted by scientists in this field by addressing these concerns. First, the model proposed is a comprehensive sustainability assessment model, which considers various aspects when assessing energy systems applications. The comprehensiveness of this model is novel and unprecedented. Figure 3.1 illustrates the various dimensions and indicators used to assess sustainability. Secondly, the composition of the indicators was designed to be midway between the various research aspects, so that no aspect is neglected. Furthermore, each indicator has a purpose and measures a specific area of the energy system. All combined, a sustainability score is derived, which is accurate and meaningful for decision-making.

3.1.1 Energy Impact

Energy is a vital dimension of sustainability assessment as it reflects the systems' ability to produce reliable and useful energy that can be used for electric generation, heating or other applications. Various types of energy systems share this dimension and they vary among themselves in the efficiency and the production rate. For example, while renewable energy sources are mainly intermittent and rely on external factors for production, conventional energy sources are more reliable and would have higher production rates. Furthermore, efficiencies of energy systems vary greatly. Moreover, since the essence of energy systems is to provide useful energy for the growing demand of the world, it is only logical to consider the aspects around the energy production as crucial factors towards the sustainability assessment of these energy systems. In fact, energy-related impacts on sustainability are triggered by a rapidly increasing energy and global population demand (Dincer and Rosen, 2011). The energy dimension is assessed using two indicators, efficiency and productivity. The score for this dimension is calculated as such:

$$Y_{ER} = (\eta \times W_{\eta}) + (Y_{Pr} \times W_{Pr}) \tag{3.1}$$

where Y_{ER}refers to the total score of this dimension that is calculated by the addition of the scores of the two indicators.

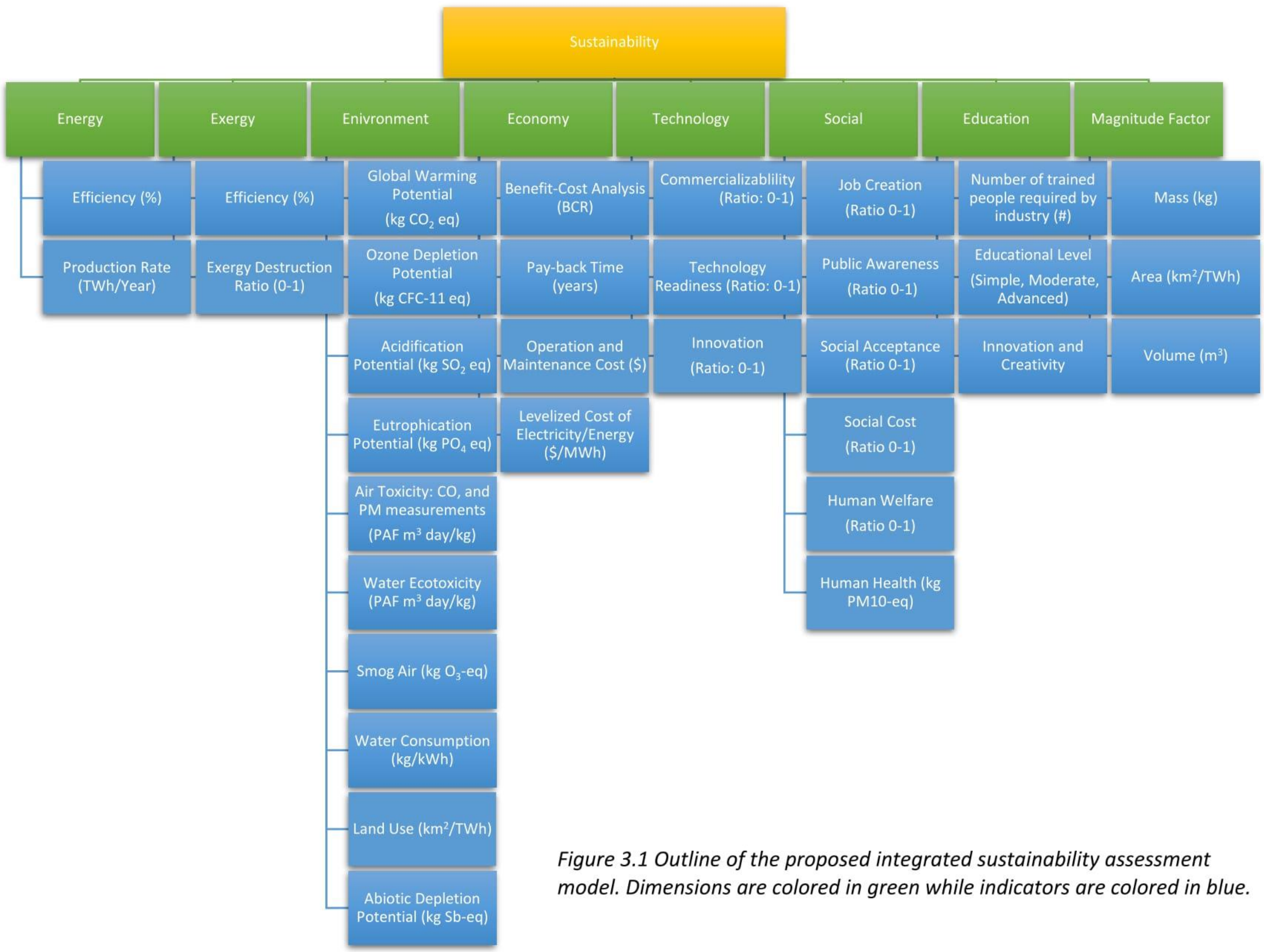

Figure 3.1 Outline of the proposed integrated sustainability assessment model. Dimensions are colored in green while indicators are colored in blue.

η refers to the non-dimensional score of the efficiency of the energy system; W_{η} refers the arithmetic weight that is given for this indicator. Y_{Pr} represents the non-dimensional score of the productivity of the energy system and W_{Pr} represents the weight associated with that indicator.

3.1.1.1 Energy Efficiency

Efficiency refers to the level of performance that describes a process, in which the lowest amount of inputs are used to derive the greatest amount of outputs. It is a measurable concept, which is calculated by determining the ratio between the useful output and the total input. In achieving the desired output, the concept of efficiency minimizes the waste of resource such as energy inputs, physical resources, or time. This indicator is critical to understanding the energy dynamics in any given energy systems. Indeed, efficiency energy systems are better able to operate and produce useful energy in a sustainable manner. More efficient energy systems are also more environmentally benign and perform better economically while less efficient energy systems cause environmental pollution and are less economically favorable. Efficient energy systems have a direct impact on social trends in society such as maintaining a higher standard of living, including living in homes with running water and electricity as well as being mobile. Therefore, efficiency of energy efficiency is a suitable, important and reflective indicator to be used in sustainability assessment. Energy efficiency is directly correlated to the first law of thermodynamics. Thus, energy efficiency refers to the ratio of useful energy output in relation to the initial energy input. The actual efficiency of energy systems is always smaller than the upper limit thermodynamic efficiency. This is because the upper limit reflects the reversible reactions while all energy transformations include irreversibilities that decrease the efficiency below the targeted upper limit. Since the target efficiency is always larger than the actual efficiency, the non-dimensional value for this energy efficiency indicator is calculated as follows (Hacatoglu, 2014):

$$\eta = \frac{1-X_{ef(T)}}{1-X_{ef}} \tag{3.2}$$

where $X_{ef(T)}$ refers to the target energy efficiency, which is the upper and reversible energy efficiency of the system. X_{ef} refers to the actual energy efficiency achieved by the system, including all the irreversibilities. The term $(1 - X_{ef(T)})$ refers to the minimum amount of unavailable energy while $(1 - X_{ef})$ refers to the actual unutilized incoming energy.

3.1.1.2 Production Rate

Production rate compares the design value of the system. Energy systems that produce electricity at higher rates and with lager Size are more favorable than the systems that have intermittent or low production rates. The non-dimensional value for this indicator is calculated as follows:

$$Y_{Pr} = \frac{X_{Pr}}{X_{Pr(T)}} \tag{3.3}$$

where X_{Pr} is the actual production rate of the energy system per hour. $X_{Pr(T)}$ is the upper target value for production rate in a year. It is calculated using the following equation:

$$X_{\mathrm{Pr}(T)} = PR \times \dot{P} \tag{3.4}$$

where PR is the production rate (tonnes/hour) and $\dot{P}$ is the number of maximum operational hours in a year (hour/year). This number varies depending on the type of the system. For example, solar energy is intermittent and dependent on irradiance and sun availability while nuclear energy is independent of external weather factors. This way, each system is evaluated based on its internal value and function.

3.1.2 Exergy Impact

Exergy relates to the second law of thermodynamics, which is instrumental in providing meaningful and clearly comprehensible information towards environmental impacts. The most appropriate link between the environmental impact and the second law of thermodynamics has been namely exergy, mainly because exergy is a measurement of the departure of the state of a system from that of the environment (Kanoglu et al., 2009). The states of both the system and the environment both effect the degree of exergy. In practice, prior to exergy analysis, thermodynamic analysis of the system is conducted by the evaluation of mass and energy balances. Only energy conversion and transfers of the system are taken into consideration in the energy analysis while exergy analysis focuses on the quality of energy by measuring the degradation of energy or material in the system. Therefore, exergy analysis is associated to the first and second laws of thermodynamics and has the ability to identify the energy quality issues in the system or the work potential. Thus, exergy directly correlates with sustainability, as the assessment should also focus on the loss of energy quality along with the loss of energy itself in the system. Simply, exergy is an effective tool to measure the usefulness of an energy system and the degree of environmental impact an energy system has on the environment. Moreover, in order for energy systems to be considered smart, they need to be exergetically sound (Dincer and Acar, 2017). This implies that the system reduces exergy destruction to the minimum while simultaneously increases exergy efficiency to a maximum. The exergy dimension therefore, is assessed using two main indicators: efficiency and exergy destruction. The non-dimensional score of this dimension is calculated as such:

$$Y_{EX} = (\psi \times W_{\psi}) + (Y_{ED} \times W_{ED}) \tag{3.5}$$

where Y_{EX} represents the total score for the exergy dimension. The score is non-dimensional and is calculated by adding both indicators. ψ represents the exergy efficiency of the system and W_{ψ} represents the allocated geometric weight for this indicator. Y_{ED} is the dimensionless score of the exergy destruction indicator and W_{ED} is the geometric weight associated with it.

3.1.2.1 Efficiency

Exergy efficiency could be a more important indicator than energy efficiency as it usually gives a finer understanding of performance (Caliskan et al., 2011). Exergy efficiency highlights that losses and internal irreversibilities are to be assessed in order to improve performance. Higher exergy efficiency reflects higher energy quality used in the system, which consequently make the system more sustainable while lower exergy efficiencies reflect energy losses and internal irreversible reactions; thus, low energy quality and worse sustainable score. Furthermore, exergy analysis enables the identification of energy degradation in an energy system and provides an accurate measure of the useful work that can be utilized from the system. Therefore, the exergy efficiency indicator is a useful tool for maximizing the benefit and efficiently using the resources

Similar to the energy efficiency, the exergy efficiency non-dimensional score is calculated as such (Hacatoglu, 2014):

$$\psi = \frac{1-X_{\psi ef(T)}}{1-X_{\psi ef}} \tag{3.6}$$

where $X_{\psi ef(T)}$ represents the reversible exergy efficiency of the system while $X_{\psi ef}$represents the actual exergy efficiency of the system.

3.1.2.2 Exergy Destruction Ratio

Exergy destruction is a measure of resource degradation. While exergy efficiency measures the quality of exergy the system is harnessing, exergy destruction ratio is assessing the degraded resources and specifies the elements in the system where destruction is occurring. The exergy destruction ratio is calculated as such:

$$\dot{E}x_d = (1 - \psi)\,\dot{E}x_{in} \tag{3.7}$$

where $\dot{E}x_{in}$is the total exergy input to the system. For example, solar irradiance is the exergy input to solar energy applications while chemical and physical exergy of fossil fuels is the exergy input to fuel-based energy applications.

3.1.3 Environmental Footprint

Humans have been cherishing the concept of sustainability since the early civilization developments. Sustainable development however was environmentally friendly. The key milestone that created the gap between energy and the environment is the use of coal for energy production. The industrial revolution and the use of coal have transformed energy production forever because of the environmental impact it had through the massive emissions of greenhouse gases. The regular pollution caused by the coal revolution and later on followed by the oil revolution have rapidly triggered global warming and climate change. Fossil fuels and conventional energy sources have revolutionized the human lifestyle and social trends. Coal and oil (also known as black gold) have had a tremendous impact on the modern human civilization. However, the ease of lifestyle and comfort in standard of living came at the cost of environmental vulnerability of the planet. Environmental impacts could be local and specific to certain regions or global and widespread without geopolitical considerations. Furthermore, environmental impacts could also be short or long term. This dimension has been the most commonly used dimension in all sustainability assessment models. Energy systems are assessed according to their level of pollution and environmental impact. Various indicators are used in order to comprehensively reflect the impact of various energy systems on the environment. The non-dimensional score of this dimension is calculated as such:

$$Y_{ENV} = (Y_{GWP} \times W_{GWP}) + (Y_{ODP} \times W_{ODP}) + (Y_{AP} \times W_{AP}) + (Y_{EP} \times W_{EP}) + (Y_{AT} \times W_{AT}) + (Y_{WE} \times W_{WE}) + (Y_{SA} \times W_{SA}) + (Y_{WC} \times W_{WC}) + (Y_{LU} \times W_{LU}) + (Y_{ADP} \times W_{ADP}) \quad (3.8)$$

where Y terms refer to the dimensionless value for the indicators used while W terms refer to the arithmetic weights assigned for the indicator. GWP refers to the global warming potential, ODP to the ozone depletion potential, AP to the acidification potential, EP to the eutrophication potential, AT to air toxicity, WE to water ecotoxicity, SA to smog air, WC to water consumption, LU to the land use and ADP to the abiotic depletion potential. These ten indicators are carefully selected to account for all of the emissions and environmental impression that energy systems leave throughout manufacturing and operation of these systems. Further explanation follows for each indicator.

3.1.3.1 Global Warming Potential

Greenhouse gases contribute to the global climate change and global warming as they warm Earth by absorbing the incoming solar energy from the sun and trapping it within the atmosphere. Acting like a blanket insulating earth, they slow the rate at which energy escapes. Most common greenhouse gases that account for this include carbon dioxide (CO_2) and methane (CH_4) and chlorofluorocarbons (CFCs). The element carbon is the common factor among the different greenhouse gases. Global warming potential (GWP) is a measure that was developed to compare the impact of different gases on the atmosphere. Specifically, it is a measure of how much energy is absorbed when 1 ton of a specified gas is released to the atmosphere over a period, relative to the emission of 1 ton of carbon dioxide. In this case, the larger the GWP, the more negative it is for the environment. CO_2 equivalence (CO_2-eq) is used as a measure for GWP. The time usually used for GWP is 100 years. Thus, the GWP indicator in this thesis considers the 100 year warming potential of all greenhouse gases throughout their lifecycle. The following equation illustrates the calculation of the dimensionless GWP score (Hacatoglu, 2014):

$$Y_{GWP} = \frac{x_{GWP(T)}}{x_{GWP}} \quad (3.9)$$

where X_{GWP} represents the actual greenhouse gas emissions for the period of 100 years. $X_{GWP(T)}$ represents the target value for this time period, which is the minimum greenhouse gas emissions, achieved by solely relying on renewable energy sources. This means, conventional energy sources such as fossil fuels are not considered in any stage of the energy production of the system. These values can be extracted by SimaPro as part of the lifecycle impact assessment.

3.1.3.2 Ozone Depletion Potential

While life on earth is impossible without light from the sun, solar radiations contain harmful ultraviolet (UV) rays. The ozone layer, located in the lower level of the earth's stratosphere, fortunately blocks these UV rays from reaching the earth's surface. Although some UV rays are beneficial, prolonged exposure is detrimental. Man-made chlorofluorocarbons (CFCs) have adversely affected the ozone layer. These CFCs react with the UV rays in the ozone layer and form chlorine (Cl) through a chain reaction. Chlorine then reacts with the ozone (O_3) and breaks its formation into (O_2). The breaking of the ozone layer causes a thinner ozone layer and a more opportunity for UV rays to infiltrate and reach earth's surface. First used as working fluids in refrigerators, CFCs have been banned by the Montreal Protocol. However, CFCs have long residence time (45 – 1700 years) and old equipment that are still in use keep emitting these substances, which result in a very slow recovery for the ozone layer. CFC-11 is used to describe all ozone depleting substance emissions. The following equation illustrates the calculation of the dimensionless ODP score (Hacatoglu, 2014):

$$Y_{ODP} = \frac{X_{ODP(T)}}{X_{ODP}} \qquad (3.10)$$

where X_{ODP} represents the actual annual CFC-11 emissions per capita. $X_{ODP(T)}$represents the limit of the CFC-11 emissions per capita. Setting this limit for the CFC-11 emissions per capita is a challenging task. This is because it acts as the target value and had it been set to zero, and then the solution would not be practical or realistic. To counteract this challenge, Hacatoglu (2015) proposed another way to calculate an acceptable amount of ozone depletion over the time scale of considering sustainability. The following is the proposed method of calculation (Hacatoglu, 2014):

$$X_{ODP(T)} = \frac{O_3}{k_{Cl-O_3} \text{ x } f_{CFC-11} \text{ x } n_{Cl} \text{ x } POP_{world} \text{ x } t_{Sust}} \text{ x } \alpha_{ODP} \qquad (3.11)$$

where k_{Cl-O_3} represents the relationship between the concentration of stratospheric chlorine and ozone depletion. f_{CFC-11} represents the fate factor for CFC-11 when emitted from the earth's surface. n_{Cl} represents the number of chlorine atoms in a single CFC-11 molecule. t_{Sust} is the timescale considered for the sustainability assessment. While the timescale for sustainability assessment can range from five years to infinity, using an infinite value will yield in a zero target value. This reflects that there is no tolerance for stratospheric ozone depletion. The timescale used for this thesis is 100 years. This goes in line with the typical GWP calculation. SimaPro is used to conduct all lifecycle assessments in order to estimate the lifecycle emissions and the impact of pollutants. Input data used to assess the ozone depletion is presented in Table 3.1

Table 3.1 input parameters used in the lifecycle assessment of the ozone depletion indicator for energy systems (Hacatoglu, 2014).

Parameter	**Value**
AreaS_ON	97281 km^2
ΔO3	2%
fCFC-11	2.8×10-9
GHG	5.8 Gt CO_2eq yr^{-1}
$K_{Cl\text{-}O3}$	0.02
MATAI	\$69,300 yr^{-1}
n_{Cl}	3
ODP	0.017
Population_{S_ON}	12.11 million
$\text{Population}_{WORLD}$	7 billion
R_{Sb}	4.63×1015 kg
t_{Sust}	100

3.1.3.3 Acidification Potential

Acidification potential refers to the compounds that are precursors to acid rain. These include sulfur dioxide (SO_2), nitrogen oxides (NOx), nitrogen monoxide (NO), nitrogen dioxide (N_2O), and other various substances. Acidification potential is usually characterized by SO_2-equivalnce. These acid gases are usually released into the atmosphere as a result of fuel combustion. On the other hand, newly constructed coal-fired power plants have a desulfurization technique to limit the SO_2 emissions to the environment. Acidification occurs with substances varying in their acid formation potential. The following equation illustrates the calculation of the dimensionless AP score (Hacatoglu, 2014):

$$Y_{AP} = \frac{X_{AP(T)}}{X_{AP}} \tag{3.12}$$

where X_{AP} represents the calculated acidification potential (concentration of SO_2) in the local environment. $X_{AP(T)}$ is the latest set standard by EPA for the ambient air quality, which is 190 µg m^{-3} (EPA, 2011). X_{AP} is calculated using the following equation:

$$X_{AP} = SO_2, 0 + \frac{SO_2}{Area_{Community} \text{x}\, MH_{SO2}} \text{ x } \frac{\tau_{SO2}}{8760} \tag{3.13}$$

Where $SO_2, 0$, $SO_2, \tau_{SO2}, MH_{SO2}$ represent the background concentration, annualized life-cycle emissions, residence time, and vertical mixing height of SO_2 respectively (Hacatoglu, 2014). For this thesis, $Area_{Community}$ represents the total area that a community of 150 households occupy. According to the National Association of Home Builders (2014), the average subdivision contains 60 households and a median area of 24 acres.

3.1.3.4 Eutrophication Potential

Eutrophication is a leading cause of impairment for many coastal marine and freshwater ecosystems. It is characterized by excessive growth of algae and plant due to increased availability of one or more limiting growth factors, which are needed to conduct photosynthesis. Eutrophication is characterized by phosphate equivalence (PO_4-eq) in life cycle impact assessments. Eutrophication is often detrimental to plants and ecosystems and leads to the vulnerability of economic and social structures. The following equation illustrates the calculation of the dimensionless EP score (Hacatoglu, 2014):

$$Y_{EP} = \frac{X_{EP(T)}}{X_{EP}} \tag{3.14}$$

Where X_{EP} represents the actual lifecycle emissions of PO_4 per capita per year. $X_{EP(T))}$ represents the target value, which is calculated using the following equation (Hacatoglu, 2014):

$$X_{EP(T)} = EP_{ref} \times \alpha_{EP} \tag{3.15}$$

Where EP_{ref} represents the global annual per capita of PO_4 emissions and α_{EP}represents the adjustment factor.

3.1.3.5 Air Toxicity

Air pollution is very common with the rise of industrial projects, innovative transportation means and residential applications. A polluted air imposes a health and safety risk for inhabitants of this world. A number of substances will be assessed under this indicator. Fine particulate matter ($PM_{2.5}$) inflict a health concern as they make their way to the lungs. While the composition of particulate matter varies with regions, it generally indicates a mixture of solid particles and liquid droplets in the air. $PM_{2.5}$ refers to the particulate matter that are 2.5 microns in diameter or less. In Ontario, $PM_{2.5}$ is largely composed of nitrate and sulfate particles, elemental and organic carbon. Furthermore, while some $PM_{2.5}$ is carried into Ontario form the US, it is primarily formed from chemical reactions, mainly from the transportation and residential applications. Another sub-indicator is the coarse particulate matter (PM_{10}), which is 10 micros or less. Carbon monoxide is also assessed in the toxicity of air. It results from incomplete combustion of fossil fuels. It is also a precursor for ground level ozone formation and smog air. The following equation illustrates the calculation of the dimensionless AT score (Hacatoglu, 2014):

$$Y_{AE} = \frac{X_{AE(T)}}{X_{AE}} \tag{3.16}$$

where X_{AE} is the calculated Air Toxicity from the annual lifecycle emissions. $X_{AE(T)}$ is the target emission value periodically published by EPA for various regions across the world. For the purpose of this study, the target value of the USA, which is 2.5 μg/m^3 for $PM_{2.5}$ is used (Hacatoglu, 2014).

3.1.3.6 Water Ecotoxicity

Similar to eutrophication, water ecotoxicity can cause harm to aquatic ecosystems. Emissions of toxic and lethal substances to water bodies is detrimental to the organisms and the sea life. The common unit to measure water ecotoxicity is measuring 1,4-dichlorobenzene (1,4-DCB). The following equation illustrates the calculation of the dimensionless WE score (Hacatoglu, 2014):

$$Y_{WE} = \frac{X_{WE(T)}}{X_{WE}} \tag{3.17}$$

where X_{WE} represents the lifecycle emissions of 1,4-DCB per capita per year. $X_{WE(T)}$ represents the target emissions to freshwater systems per capita per year. The upper target value is calculated as such (Hacatoglu, 2014):

$$X_{WE(T)} = WE_{ref} \times \alpha_{WE} \tag{3.18}$$

where WE_{ref} represents the global annual per capita of 1,4-1DCB emissions to freshwater systems and α_{WE} is the adjustment factor.

3.1.3.7 Smog Air

Smog air is mainly composed of ground level ozone and particulate matter formed near the troposphere. It usually appears as haze in the air due to the mixture of smoke, gases and particles. Smog air has been linked to a number of adverse health and environmental impacts. Health impacts associated with smog air include thousands of premature deaths and increased hospital visits in several communities. Furthermore, adverse environmental impacts on vegetation, visibility, and structures have been traced to smog air. Warmer temperatures and hotter climate makes a perfect ingredient for smog air and thus it is more common in the summer season. However, smog air is present in the winter as well. Smog's residence time in the troposphere is quiet short (1 hour). The following equation illustrates the calculation of the dimensionless SA score (Hacatoglu, 2014):

$$Y_{SA} = \frac{X_{SA(T)}}{X_{SA}} \tag{3.19}$$

where X_{SA} represents the calculated concentration of the ground level ozone (O_3). $X_{SA(T)}$ represents the upper threshold for ground level ozone set by the latest environmental protection agency standards, which is 150 μg m^{-3} (EPA, 2011). The calculated concentration of the ground level ozone is calculated using the following equation:

$$X_{SA} = O_3, 0 + \frac{O_3}{Area_{Community} \text{ x } MH_{O3}} \text{ x } \frac{\tau_{O3}}{8760} \text{x} \tag{3.20}$$

where $O_3, 0, O_3, \tau_{O3}, and\ MH_{O3}$represent the background concentration, annualized life-cycle emissions, residence time, and vertical mixing height of O_3respectively (Hacatoglu, 2014).

3.1.3.8 Water Consumption

Water consumption is an important factor to consider when assessing sustainability of energy systems, especially in arid climates such as Australia, where water evaporation rates are quiet high. While some LCAs have ignored the water requirements and availability for thermal systems, some have recently introduced them. Water consumption refers to the amount of water lost during the process of energy production. The following equation illustrates the calculation of the WC score:

$$Y_{WC} = \frac{X_{WC(T)}}{X_{WC}} \tag{3.21}$$

where X_{WC} represent the actual used water in the lifecycle of the energy system and Table 3.2 shows different values that will be used for each system based on the works of Inhaber (2004). $X_{WC(T)}$ represents the target values for water consumption based on Spang et. Al (2014).

Table 3.2 Water consumption of electricity generation from various sources (kg/kWh) (Source: Inhaber, 2004)

Energy Source	**X_{WC} (kg / kWh)**
Photovoltaic	10
Hydro	36
Wind	1
Geothermal	12 – 300
Gas	78
Coal	78

3.1.3.9 Abiotic Depletion Potential

Abiotic depletion potential is a factor that is assessed in lifecycle assessments. It refers to the measure of the use of non-renewable sources for energy production. The following equation illustrates the calculation of the ADP score (Hacatoglu, 2014):

$$Y_{ADP} = \frac{X_{ADP(T)}}{X_{ADP}} \tag{3.22}$$

where X_{ADP} represents the lifecycle use of antimony and its equivalents per capita per year. $X_{ADP(T)}$ represents the annual sustainable antimony allocation. The threshold value is calculated using the following equation (Hacatoglu, 2014):

$$X_{ADP(T)} = \frac{R_{Sb}}{POP_{world} \text{ x } t_{sust}} \text{ x } \alpha_{ADP} \tag{3.23}$$

where R_{Sb} represents the recoverable reserves of antimony.

3.1.4 Economic Impact

Economy is a critical dimension when assessing sustainability of energy systems. What does an economically sustainable energy system look like? This critical question must be addressed in any project before embarking on the execution journey. Furthermore, while conventional energy sources are relatively cheaper, renewable energy sources remain quiet expensive. However, improved economic planning and the progress towards cheaper renewable and clean energy is making the competition tougher between energy systems. Moreover, economic factors involved in the operation and design of energy conversion systems have brought the thermal energy storage for example to the forefront of its industry (Dincer and Rosen, 2007). Several thermal energy storage technologies are indeed present in the industry and are used side by side with on-site energy sources to economically buffer variable rates of supply and demand. In addition, an energy system is economically sustainable when they meet the following standards:

1. The economic benefit of the energy generation outweigh operational, capital and maintenance cost. Simply, the project is economically viable.
2. Energy systems with shorter payback periods are preferred over systems with longer payback periods. This attracts investors.
3. Lower levelized cost of energy/electricity. Energy available for everyone at a relatively lower cost.

In summary, energy systems are economically sustainable if they are profitable, serviced at lower cost for the consumer and contain the elements of a successful business idea. The non-dimensional score of this dimension is calculated as such:

$$Y_{ECO} = (Y_{BCR} \times W_{BCR}) + (Y_{PBT} \times W_{PBT}) + (Y_{LCOE} \times W_{LCOE}) \tag{3.24}$$

where Y_{BCR}, Y_{PBT}, $and\ Y_{LCOE}$ refer to the non-dimensional indicators of benefit-cost ratio, payback time, and the levelized cost of energy/electricity respectively. 'W' terms refer to the arithmetic weight associated with each indicator.

3.1.4.1 Benefit Cost Ratio

This indicator aims to explore the relationship between the benefit and cost of any proposed energy system. This indicator is informative both quantitatively and qualitatively as it analyzes all the possible benefits and costs. All benefits associated with an energy system are summed while all costs are subtracted. While this analysis is routinely conducted in any business matter, it is novel to the sustainability assessment of energy systems. When conducting a cost-benefit analysis, results that are more accurate are achieved by analyzing the net present value (NPV) of all future costs and benefits. Simply, if NPV is negative, the project will never pay for itself and thus it is a financially losing project. However, if NPV is positive, the profits outweigh the costs and the project will pay for itself over time and eventually generate profits. The net present value is calculated using the following equation:

$$NPV = \sum_{i=1}^{N} \left(\frac{PI_i}{(1+r)^i}\right) - Cost_0 \tag{3.25}$$

where PI_i represents the project's net income in a given year. N represents the number of years over which the project income occurs. r is the discount rate and $Cost_0$ is the project cost, typically assumed in the initial year (0). On the other hand, the benefit-cost ratio is another method of analyzing the benefits and costs of a given energy system. The following equations are used to determine the benefit cost ratio:

$$BCR = \frac{\ddot{P}}{\dot{N}} \tag{3.26}$$

where $\ddot{P}$ represents the present value of the net positive cash flow and $\dot{N}$ represents the present value of net negative cash flow.

3.1.4.2 Payback Time

The payback period is an indicator used to assess the short and long-term benefits of the proposed energy systems if any. Logically, energy systems with shorter payback periods are more economically favorable than those with longer payback periods. Thus, shorter payback period is associated with higher sustainability. The payback time refers to the time it takes in order for the project to recover all invested amounts and is usually expressed in years. Payback method does not take into account the time value of money unlike the previous indicator (net present value or benefit-cost ratio). The calculation of the payback time is simple. The following equation is used to determine the payback period:

$$PBT = \frac{\ddot{P}}{PCF} \tag{3.27}$$

where $\ddot{P}$ represents the total project investment in ($) and PCF represents the periodic cash flow in ($/year). Table 3.3 shows the judgement criteria set to non-dimensionalize the PBT indicator.

Table 3.3 Dimensionless scorecard for payback time.

Dimensionless Score	Payback Time (PBT)	Notes
0.76 – 1	0 < PBT < 5	Shorter payback time is advantageous and more attractive.
0.51 – 0.75	6 < PBT < 11	Longer payback time is relatively less sustainable.
0.26 – 0.5	12 < PBT < 17	
0 – 0.25	18 < PBT < 23	

3.1.4.3 Levelized Cost of Electricity/Energy

The levelized cost of electricity or energy (used interchangeably) refer to the cost of energy. It accounts all lifetime costs of the system including operation, maintenance, construction, taxes, insurance and other financial obligations of the project. They are then divided by the expected total energy outcome in the system's lifetime (kWh). Cost and benefit estimates are adjusted to account for inflation and are discounted to reflect the time-value of the money. It is indeed a very valuable tool to compare different generation methods. Lower LCOE values resemble low energy cost, which in turn reflects back with high financial profit to the investors and vice versa.

$$LCOE = \frac{\sum_{i=0}^{N}[\frac{I_i+O_i+F_i-TC_i}{(1+r)^i}]}{\sum_{i=0}^{N}[\frac{E_i}{(1+r)^i}]} \tag{3.28}$$

where I_i is investment costs in year I , O_i represent the operation and maintenance costs in year i, $F_i$represents the fuel costs in year i, TC_i represents the total tax credits in year i, E_i represents the energy generated in year i, r is the real discount rate, and N is the economic lifetime of the system.

The value of the LCOE includes the capital cost average, fixed operation and maintenance cost average, variable operation and maintenance average as well as the fuel cost average. The non-dimensional LCOE value is determined by the following equation:

$$Y_{LCOE} = \frac{X_{LCOE(T)}}{X_{LCOE}} \tag{3.29}$$

Where X_{LCOE} represents the actual LCOE of the energy system presented in Table 3.4. $X_{LCOE(T)}$ represents the target value for the future and long term LCOE for that system. For the purpose of this study, the values published by the US Energy Department for the LCOE for various energy systems in the year of 2040 will be used in the case studies for the values of $X_{LCOE(T)}$

Table 3.4 presents the actual values for the LCOE of various ways of energy generations (Lazard, 2014).

Energy Source	LCOE (US $/MWh)
Photovoltaic	80
Hydro	36
Geothermal	116
Gas	73
Coal	110
Nuclear	113

3.1.4.4 Operation and Maintenance Cost

Energy systems that require frequent maintenance and operational follow up are considered less sustainable as they are resource depleting, time and financially consuming. On the other hand, energy systems that function with minimal operational follow up, or maintenance is more favorable and considered more sustainable. Operational and maintenance costs can be very high and thus for a system to reduce these costs, it is more sustainable. A value of 1 is assigned to systems that have low operational and maintenance cost and a value of 0 is assigned to systems that have high cost.

3.1.5 Technology

Technological indicators are used as part of this proposed assessment model and are considered important. Energy technology have transformed modern civilization, starting from the industrial revolution and the utilization of coal. Indeed, coal has revolutionized humans on earth and introduced new applications in transportation, heating and electricity generation. Furthermore, oil has also been a considerable milestone in human history as it introduced numerous novel technologies. Furthermore, the technological indicators assist in analyzing the performance, design and production aspects of the energy system in question. Therefore, understanding the technological aspects of the proposed energy systems is important and vital to its sustainability.

Commercializability and technology readiness are the two indicators that will be used to assess the technological dimension of this study. The non-dimensional score of this dimension is calculated as such:

$$Y_{TECH} = (Y_{COMM} \times W_{COMM}) + (Y_{TR} \times W_{TR}) + (Y_{IN} \times W_{IN}) \quad (3.30)$$

where Y_{COMM}, Y_{TR} and Y_{IN} refer to the non-dimensional indicators of commercializability and technology readiness and innovation. 'W' terms refer to the arithmetic weight associated with each indicator.

3.1.5.1 Commercializability

While commercial viability is considered a weak point and sometime a threat of clean energy systems, there is an opportunity window for energy security and independence (Dincer and Acar, 2015). Commercialization refers to the potential for the energy system or technology to be commercially viable and enabling sustainable operation within the system. Mature and commercialized technologies are automatically considered more favorable than non-commercialized technologies that are still in the R&D stage. Technologies that are less

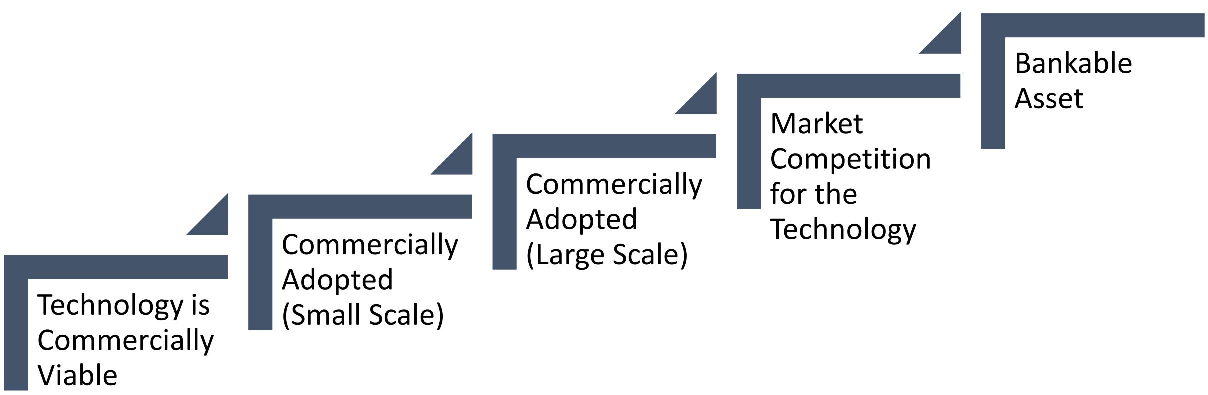

Figure 3.2 scale of 1 to 5 to assess the commercializability of energy systems.

commercially viable are considered less sustainable and a smaller value is appointed to them. Furthermore, multigenerational energy systems for example provide more commercial outputs, which increases their commercializability (Dincer and Acar, 2017). A value of 1 is assigned to systems that have reached the bankable assets phase and a value of 0 is assigned to systems that are not commercially viable yet (Hacatoglu, 2015 and Gnanapragasam et al., 2010). Figure 3.2 shows the scale that assess the commercializability of the energy system. A number of factors will be taken into consideration to determine the accurate level of the system including the technical performance of the system, the stakeholder investment and acceptance of the technology, market opportunity, financial performance (cost and revenue) as well as the regulatory framework for that system. All in all, when a system is a bankable asset, it is considered most sustainable. If the system has some research progression and shows a commercially viability, it is the start towards more sustainable system.

3.1.5.2 Technology Readiness

Whether a technology is available or not in the current market is an important indicator to assess this dimension. Sustainable availability and readiness of the proposed energy system is important. Some technologies still need further research, experimentation, analysis or legal work. On the other hand, some technologies have already been well established and are currently operational. A value of 1 is assigned to technologies or energy systems that are currently available in the market and commercially profitable and a value of 0 is assigned to technologies that do not exist in the market (Gnanapragasam et al., 2010). The value is typically higher for any

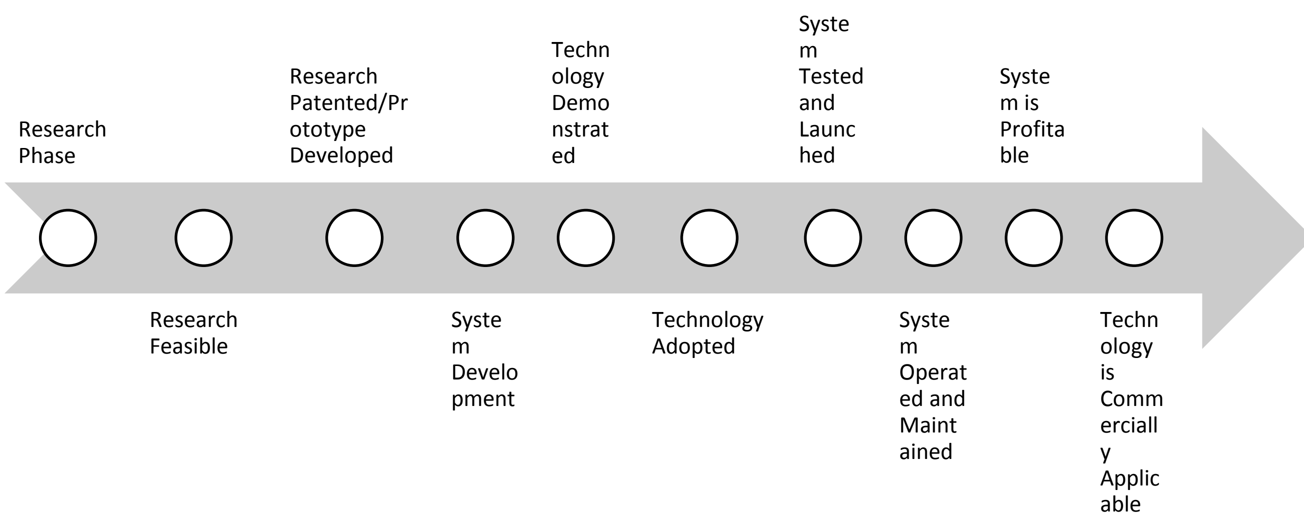

Figure 3.3 Scale from 0 to 1 to assess the readiness of the technology

technology that is available and ready. Figure 3.3 illustrates the criteria that is used to assess the technology readiness level.

3.1.5.3 Innovation

Innovation is an important criterion to be considered when analyzing technologies. Technologies that promote innovation and constantly enhance their development, research and technology competitiveness are considered more favorable and sustainable. On the other hand, technologies that are stagnant and have limited enhancements to the technology is considered degraded and less sustainable. Innovation supported by scientific research as well commercialization yield in the birth of new technologies, which in turn flourish economic activities and lead to prosperous and enriched societies (Dincer, 2017). A value of 1 is given to the systems that incorporate innovative research and development and a value of 0 is given to the systems that do not have innovative progression.

3.1.6 Social Impression

Social aspects of energy systems are very important for their sustainability. Social indicators help assess the impacts on the social system, which is composed of the beneficiaries of the energy system, whether directly or indirectly. In fact, proper utilization of renewable energy for example can have a direct impact socially and economically with further development of secure and sustainable energy supply (Dincer and Acar, 2015). On another important note, social morals and ethics is also a critical component of the social dimension as illustrated in Figure 2.11. When addressing the concept of sustainability, adhering to a common set of principles and values can help govern the dynamics and the limits of energy systems. It is important to correctly identify and quantify the social indicators as they contribute to the acceptance and awareness socially. Figure 3.4 illustrates some social indicators used to analyze this dimension and the interconnection between them. These elements are interconnected because job creation in a community causes awareness publicly and eventually leads to social acceptance. Furthermore, if a system is accepted socially, public awareness has the environment to flourish. On the other hand, if a system is rejected socially, the other two elements are adversely effected.

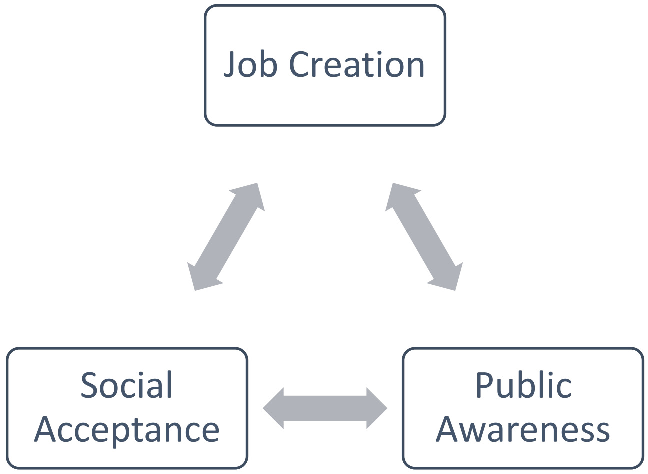

Figure 3.4 illustration of the main indicators used for assessing the social dimension of the sustainability assessment model.

The non-dimensional score of this dimension is calculated as such:

$$Y_{SOC} = \left(Y_{JC} \times W_{JC}\right) + \left(Y_{PA} \times W_{PA}\right) + \left(Y_{SA} \times W_{SA}\right) + \left(Y_{SC} \times W_{SC}\right) + \left(Y_{HW} \times W_{HW}\right) + \left(Y_{HH} \times W_{HH}\right) \quad (3.31)$$

where Y_{JC}, Y_{PA}, Y_{SA}, Y_{SC}, $Y_{HW}, and\ Y_{HH}$ refer to the non-dimensional indicators of job creation, public awareness, social acceptance, social cost, human welfare, and human health respectively. 'W' terms refer to the arithmetic weight associated with each indicator.

3.1.6.1 Job Creation

Energy systems have ever grown in the past few centuries and they created many niches around them. When assessing an energy system, it is important to understand the social dimension behind the project and analyze the number of jobs that can be created to the local community or the larger region. Of course, more job creation is considered advantageous as that city prospers and attracts employees, talents from all over the surrounding regions. This increases the social life and the social activity in that local city, thus yielding in favorable results. It is considered sustainable when energy systems have high employment factor. The International Renewable Energy Agency (2013) published a report on employment factors for wind and solar energy technologies. For the purpose of this study, the job creation factor is assessed based on the number of jobs created after each newly installed MW. The employment factor is presented in the units of (jobs/MW). Table 3.5 presents the judgement criteria for assessing this indicator.

Table 3.5 Judgement criteria for assessing the job creation indicator (Source: IRENA, 2013)

Dimensionless Score	Employment factor (jobs/MW)
0 – 0.25	0 < Employment factor < 9
0.26 – 0.5	10 < Employment factor < 29
0.51 – 0.75	30 < Employment factor < 49
0.76 - 1	50 < Employment factor < 69

3.1.6.2 Public Awareness

Enhancing public knowledge and understanding about the issues that the energy industry is facing is vital to ensuring growth, energy sustainability and security in our communities. Government programs, incentives and other means of raising awareness all contribute towards creating an informed society. Indeed, innovative and coordinated awareness campaigns have had an impact on Scotland's perspective on renewable energy for example (McLaughlin and Smith, 2002). In this assessment model, it is considered that bigger positive public awareness is sustainable while smaller awareness is less sustainable. A value of 1 is assigned to systems that have big public awareness and a value of 0 is assigned to systems that have little awareness. Surveying is used to determine the public awareness of the project in interest.

3.1.6.3 Social Acceptance

The power of the people is immense and thus for an energy system to be sustainable and operational, it must be accepted and perceived positively by society. For example, debates are still ongoing in several countries against wind energy, mainly because of its visual impacts on landscapes. Social acceptance therefore is an influential factor that could be a powerful barrier to the achievement of the energy targets of the system. This indicator has been neglected at the start of 1980s when policy programs were drafted at first. Later on, this factor surfaced to prove that it is essential before establishing an energy system in any locality. Therefore, successful energy systems are the ones that succeeded in integrating in the daily life of societies today (Dincer and Acar, 2017). Community acceptance goes hand in hand with social acceptance and are essential for sustainability assessment. For this model, the dimensionless social acceptance value will be determined by surveying the social acceptability of the project in interest. A value between 0 and 1 will be assigned to this indicator.

3.1.6.4 Social Cost

This indicator brings a number of factors together in one value. The social cost is related to the economic dimension as well as the environmental, energy and social dimensions. Energy systems usually come with a cost socially. This indicator has been assessed by calculating the social cost of carbon. This value helps determine the monetary benefit/cost of regulations in reducing carbon emissions. Cost-free behavior of using fossil fuels has led to an addiction over these depleting resources.

3.1.6.5 Human Welfare

Human welfare is a soft indicator that is used in this model to assess energy systems. Energy systems that take into consideration the welfare of society are more favorable and thus more sustainable. On the other hand, systems that are aversive to human welfare are considered less sustainable. A value of 1 is assigned to systems that have positive impact on human welfare and a value of 0 is assigned to systems that have negative impacts.

3.1.6.6 Human Health

With evolving technologies and innovative research, humans are exposed to various inputs that are constantly changing. The human health criteria is a social indicator used to assess energy systems on the effects of any toxic substances on human health. Being exposed to various substances on a regular basis definitely has an impact. As a result, this indicator is considered important in order to comprehensively assess the sustainability of energy systems. A value of 1 is assigned to systems that have minimal human health impacts and a value of 0 is assigned to systems that have high human health impacts.

3.1.7 Education

Education within the various stakeholders involved in the construction, operation and maintenance of the energy system is vital to the sustainability and performance of that system. For example, staff that are more educated reflect more competent and skilled talents, which increases the sustainability score. On the other hand, poorly trained or educated staff could conduct the project in an unsustainable manner. Therefore, this dimension is calculated by assessing three main indicators. The non-dimensional score of this dimension is calculated as such:

$$Y_{EDU} = (Y_{TRAIN} \times W_{TRAIN}) + (Y_{EL} \times W_{EL}) + (Y_{IC} \times W_{IC}) \quad (3.32)$$

where $Y_{TRAIN}, Y_{EL}, and\ Y_{IC}$ refer to the non-dimensional values of the number of trained people required by the industry, educational level, and innovation and creativity in education. 'W' terms refer to the arithmetic weights associated with each indicator.

3.1.7.1 Training

Industrial policies, increased health and safety standards and general workplace awareness all contributed to creating healthier and more fruitful workplaces. The number of trained people required by the industry is an indicator that can help us assess the educational dimension of energy systems. For example, if the energy system requires specific skilled staff, specific education and rare talents, the system is perceived as less sustainable. On the other hand, when the systems' requirements on skills, trainings are widely available then the system is more sustainable. A value of 1 is assigned to systems that meet the industrial standards of trainings and education and a value of 0 is assigned to systems that do not abide by these standards.

3.1.7.2 Educational Level

The educational level is divided into three main categories: simple, moderate and advanced. Advanced educational level is considered most sustainable while simple education is considered least sustainable. Table 3.6 shows the categorization of the different levels and the associated score.

Table 3.6 Educational level and respective score for each level

Dimensionless Score (Y_{EL})	Educational Level
0.75 – 1	Advanced
0.3 – 0.74	Moderate
0 – 0.29	Simple

3.1.7.3 Innovation & Creativity

Inventing novel methods of learning, training and educating is useful in this fast-growing society. Incorporating creativity, originality and innovation in education is an indictor reflecting sustainable development and efficient planning. Energy systems that invest in innovation and creativity in their education stand out as most sustainable. A value of 1 is assigned to systems that effectively incorporates innovative and creative educational methods and a value of 0 is assigned to systems that do not integrate such strategies in their educational plan if present.

3.1.8 Size Factor

The size of the energy system is another important dimension to consider when considering their sustainability. Indeed, the dimensions of the proposed energy system could be a limiting factor. The Size factor of the energy system in this sustainability assessment model will look at three main indicators: mass, land use, and volume. The non-dimensional score of this dimension is calculated as such (Hacatoglu, 2014):

$$Y_{MF} = (Y_M \times W_M) + (Y_{LU} \times W_{LU}) + (Y_V \times W_V) \tag{3.33}$$

where Y_M, Y_{LU}, and Y_V refer to the non-dimensional values of mass, land use, and volume respectively. 'W' terms refer to the arithmetic weights associated with each indicator.

3.1.8.1 Mass

The mass of the energy system is considered in this assessment by comparing the actual and target masses of the system. The following equation will be used to assess this indicator (Hacatoglu, 2014):

$$Y_M = \frac{X_{M(T)}}{X_M} \tag{3.34}$$

where X_M represents the actual mass of the system. $X_{M(T)}$ represents the target mass. Heavier systems are considered less sustainable. A value between 0 and 1 is assigned to mirror the appropriate condition of the system from this indicator's perspective.

3.1.8.2 Land Use

Land use is another important indicator to assess energy systems sustainability. In specific, renewable energies are claimed to require large landmass, which interferes with agriculture and biodiversity. Photovoltaics and wind have similar land requirements. Moreover, while photovoltaics can be mounted on rooftops, thus providing a negligible footprint during use, wind turbines can be installed in agricultural lands. In both cases, dual use of sites reduces the footprint caused by these technologies.

The following equation illustrates the calculation of the LU score:

$$Y_{LU} = \frac{X_{LU(T)}}{X_{LU}} \tag{3.35}$$

where X_{LU} represents the actual land use of an energy system. $X_{LU(T)}$ represents the target land use from the literature presented in Table 3.7. Different references have been used to find the upper limit for each energy system.

Table 3.7 Land use of various energy systems with no dual-purpose allocation (km²/TWh)

Energy Source	**$X_{LU(T)}$ (km²/ TWh)**	**Source**
Photovoltaic	28-64	(Lackner and Sachs, 2005)
Hydro	750	(Evrendilek and Ertekin, 2003)
Wind	72	(Gagnon et al., 2001)
Geothermal	18-74	(Bertani, 2005)

3.1.8.3 Volume

The volume of the system is also taken into consideration to coherently assess the Size factor of the system. Mobile energy production systems may be limited due to the volume of the energy system. Therefore, the following equation will be used to assess this indicator (Hacatoglu, 2014):

$$Y_V = \frac{X_{V(T)}}{X_V} \tag{3.36}$$

where X_V represents the actual volume of the system. $X_{V(T)}$ represents the target volume. Bigger systems with larger volumetric values are considered less sustainable. A value between 0 and 1 is assigned to mirror the appropriate condition of the system from this indicator's perspective.

3.2 Multi-Criteria Decision Analysis

Since the data collected based on this proposed model are already dimensionless, normalization is already accounted for (Rowley et. Al., 2012). In MCDA, normalization refers to the any process where diverse-unit cardinal scores are converted into a dimensionless numerical value with a common direction (Rowley et. Al., 2012). For this thesis, all variables are converted to values between 0 and 1 (score of 0 is less desirable than the score of 1). This step is usually a precursor to aggregation and weighting in various life cycle assessments. Furthermore, in LCA, normalization is already embedded in the process during the lifecycle impact assessment. For example, ReCiPe method adopts normalizations schemes based on the report of Sleeswijk (2007). In SimaPro, other methods are available and each one of them usually has a normalization method that is adopted as part of the LCA assessment.

3.2.1 Compensability

Compensability refers to "the possibility of offsetting a disadvantage on some criteria by a sufficiently large advantage on another criterion" (Munda, 2005). For example, the energy efficiency is preferred to be as high as possible, but at the same time, the benefit-cost analysis is preferred to maintain its positive value. Increasing efficiency might require additional costs associated with technological upgrades and other miscellaneous costs. Therefore, in compensatory methods, a relatively lower efficiency is accepted while the benefit-cost analysis is of positive value. In non-compensatory methods, a higher efficiency is obtained regardless of the outcome in other criteria. When it comes to sustainability, the choice of algorithm requires that we define sustainability as weak or strong. Weak sustainability perspective enables the substitution of different forms of capital. In other words, the loss of rainforest, which is an ecological capital, may be offset by the financial gain capital gained from the development erected in its place. Strong sustainability perspective is the opposite, where certain natural capital are considered highly critical and cannot be substituted by man-made capital (Munda, 2005). Strong sustainability perspective is the preferred method mainly because it meets the accurate intent of the concept of sustainability. Therefore, for the purpose of this thesis, strong sustainability perspective is adopted, which entails using the non-compensatory method of aggregation. This is because each category is considered critical and important for assessing the sustainability of energy systems.

3.2.2 Aggregation

As discussed earlier, non-compensatory aggregation is used in this model to ensure that each dimension is valued accordingly without undermining any important criteria. Once each indicator value is determined, they are all aggregated within one dimension in order to obtain a total value. For example, the economy dimension is assessed using four different indicators. These indicator values are grouped together in order to obtain the aggregated and total value for the economic dimension. Weighted arithmetic mean is used to aggregate values, where each indicator is assigned a specific weight, with all indicators totaling to 100%. While determining weighting factors for each indicator might be controversial, many sustainability assessment models avoid the drawbacks around the subjectivity of the weighting by assuming equivalent weighting (Rowley et al., 2012). Therefore, equal weighting is used to aggregate values within one dimension. The following equation illustrates the weighted arithmetic mean calculation:

$$WAM_{(Y,w)} = \sum_{i=1}^{n} w_i Y_i \tag{3.37}$$

where w_i is the weight associated with each indicator, Y_i represents the non-dimensional value of the indicator and n represents the number of indicators in a given dimension. Linear aggregation assumes compensability among the indicators at this level (Juwana et al., 2012). This means that a very high value of an indicator can be compensated by a very low value of another indicator.

Another aggregation method used in this study is the weighted geometric mean. Once the non-dimensional values are determined for both the indicators and subsequently the dimensions, these values need to be aggregated once more in order to come to a final aggregated score, representing the sustainability index of the energy system in study. Weighted geometric is a type of mean that indicates the central tendency of a group of values using the product of these values rather than their sum (arithmetic mean). With weighted geometric mean, some data points can contribute more to the final score than other data points in the model. The following equation illustrates the weighted geometric mean calculation:

$$WGM_{(Y,w)} = \prod_{i=1}^{m} ({Y_i}^{w_i}) \tag{3.38}$$

where w_i is the weight associated with each dimension, Y_i represents the non-dimensional value of the dimension and m represents the number of dimensions used in this model.

3.2.2 Weighting

Weighting is a very subjective tool, which may put the sustainability model at stake for biases and inaccuracies. One must acknowledge this weakness and try to minimize the subjectivity around weighting in various ways. In this thesis, five different characterization schemes are used to assess the sustainability of the case studies. These schemes include the individualist, hierarchist, egalitarian, panel, and equal weighting methods. Figure 3.5 summarizes the different characterization methods and their differences. The hierarchist method stands out as moderate and balanced. Another common method to assign weighting factors is the panel method, where a panel of experts and stakeholders are consulted and weighting factors are distributed between the different dimensions in this model. Figure 3.6 illustrates the process the data goes through in order to come to a final sustainability index, which is a value between 0 and 1.

Figure 3.52 Summary of characterization methods used in weighting. Hierarchist method is used in this study for its balanced approach.

Moreover, Table 3.8 shows the different weights adopted for this model after conducting the panel review. One shortcoming of this approach is that the panel must have current and unbiased knowledge across enough of the impacts. Since, non-compensatory aggregation is used in this model, importance coefficients are needed to reflect the value for each dimension. Figure 3.7 illustrates further details pertaining the panel method.

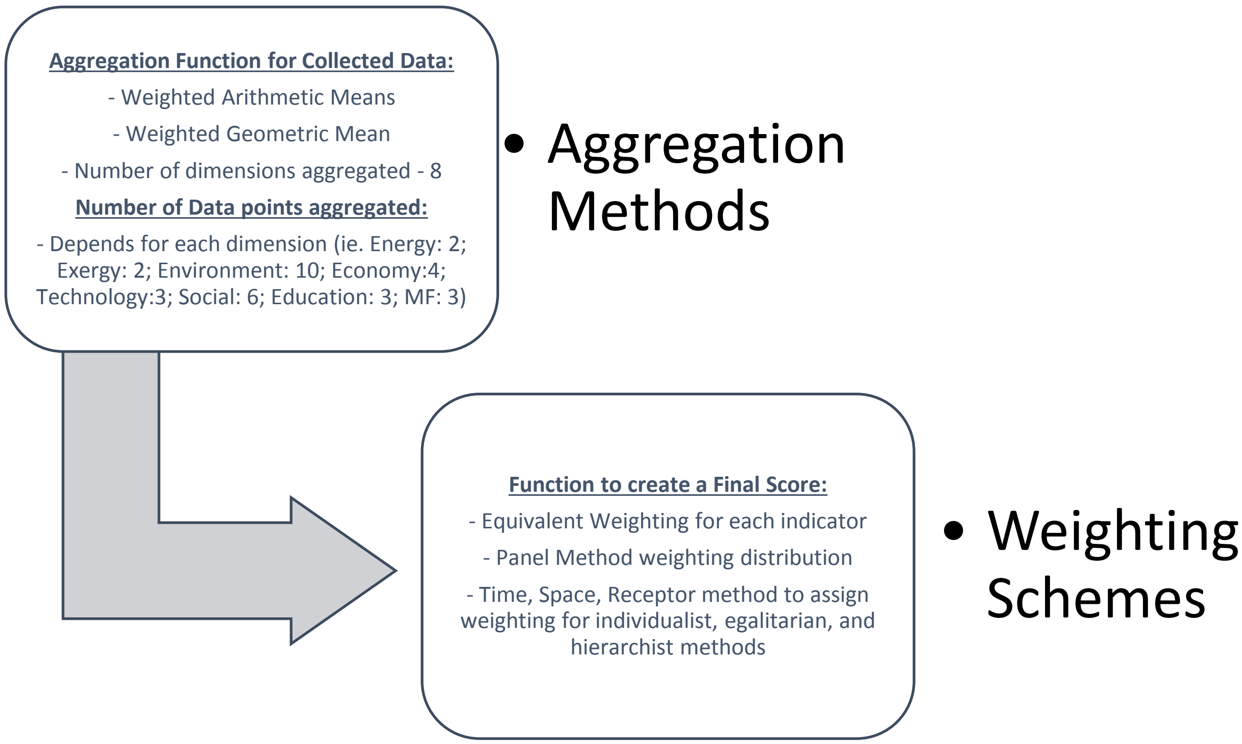

Figure 3.6 Data processing including aggregation and weighting. Indicators are aggregated and then weighting is applied to determine the final sustainability index

Weighting will always be subjective in one way or another. It is important for the scientist to acknowledge this disadvantage and work towards minimizing the subjectivity as best possible. For the panel method, the panel composed academic and faculty experts in the field of sustainability from various Canadian universities including Ryerson University, University of Western Ontario, University of Toronto and University of Ontario Institute of Technology. Having a non-biased composition is important in such assessments, which is the approach I tried to maintain throughout this thesis. Furthermore, all panel participants received the same information in the same format to reduce error and any associated bias. The procedure was simply direct rating and thus did not involve any complexities or lengthy discussions. Furthermore, in addition to the panel method, the individualist, egalitarian, hierarchist and equal weighting schemes were conducted.

Table 3.8 Importance coefficients distribution based on the panel method

Dimension	Weight
Energy Impact	0.10
Exergy	0.17
Environmental Footprint	0.18
Social Impression	0.14
Economic Impact	0.12
Technology	0.15
Education	0.09
Size Factor	0.05

The purpose behind that is to investigate the effect of weighting on the results. These schemes were also considered in order to reduce subjectivity of the results as much as possible. In order to determine the relative importance coefficient of the indicators, a scale of 1 to 5 was adopted (1 – very unimportant, 2-unimportant, 3-neutral, 4-important, 5-very important) with respect to time, space and receptor criteria (Hacatoglu, 2014).

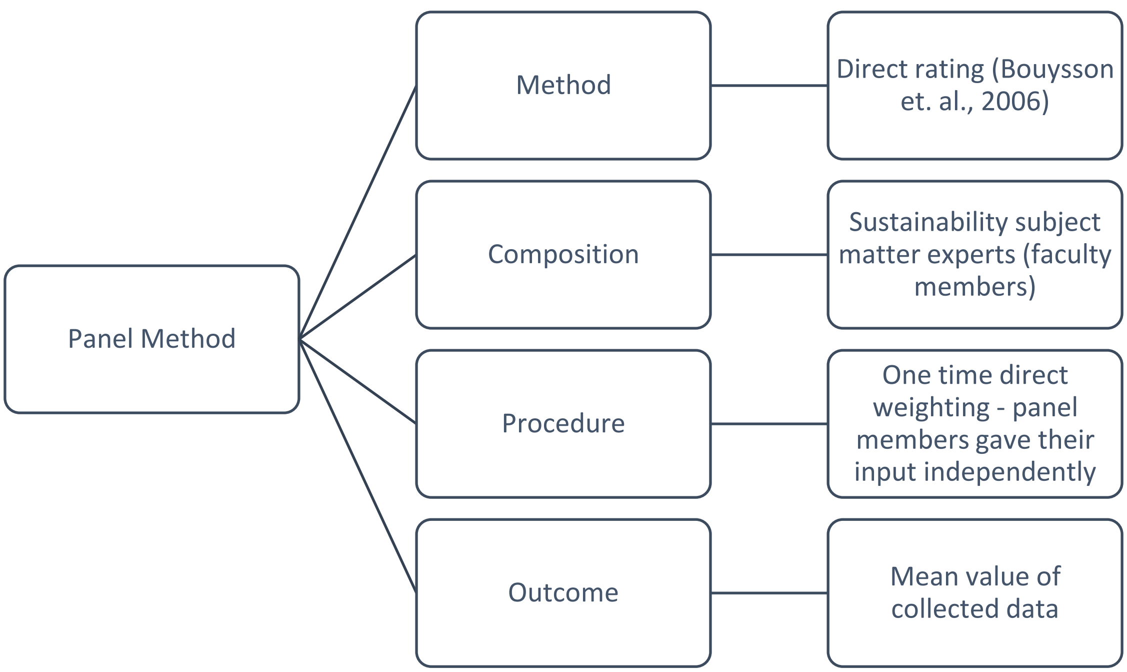

Figure 3.7 Using the panel method, various details are outlined pertaining how the panel was conducted and how the values were obtained.

Table 3.9 shows the different schemes and the organization for evaluating the indicators in order to determine the importance coefficients.

Table 3.9 Difference between schemes with respect to time, space and receptor (Source: Hacatoglu,2014)

Scheme	**Time**	**Space**	**Receptor**
Individualist	Short	Local	Humans
Egalitarian	Long	Global	Ecosystems
Hierarchist	Medium	Regional	Both

Each indicator used in this assessment was put to scale from 1 to 5 for time, space and receptor. Weights are then determined by dividing the indicator's value by the sum of all values within the same dimension. For example, the energy efficiency's value after rating is conducted based on Table 3.9 is divided by the sum of the value of the energy efficiency in addition to the production rate.

Chapter 4: Case Studies

The proposed sustainability assessment model is applied on two case studies highlighting solar energy as a renewable energy source for meeting the growing energy demand of societies today. The 3-S (Source, System, and Service) by Dincer and Acar (2015) is adopted in designing the case studies. Therefore, the objective of these case studies or the Service in this case is to provide efficient, clean and dependable energy options to meet the residential demand for electricity, heating, cooling and hot water. Figure 4.1 illustrates a summary of the characteristics of the systems used in the case studies (i.e. Solar and wind).

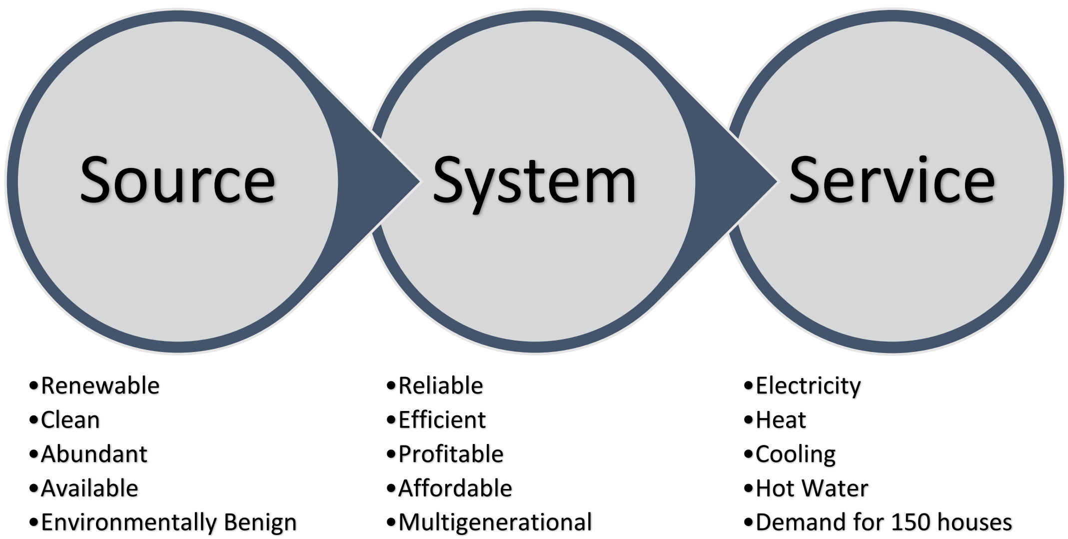

Figure 4.1 Illustration elaborating on the 3-S presentation approach for the case studies (Dincer and Acar, 2015).

Furthermore, these case studies are designed to meet the demand for 150 Ontarian households. In average, the annual electricity consumption for Ontario households is 10,000 kWh/house (Ontario Ministry of Energy, 2015). On another hand, the heating and cooling usage for an average Canadian household is 30,861.1 kWh/house (Statistics Canada, Environment Accounts and Statistics Division, 2011). The source that is selected for these case studies is solar energy primarily because it is abundant, available and clean. The system is calculated and designed to meet the demand and will be explained further.

4.1 PV Solar Energy System

4.1.1 System Description

Solar photovoltaics is used in this study. In order to meet the demand for 150 houses, the total energy production is 6.13 GWh. The total size of the system is calculated using the following equation:

$$\dot{S}S = \frac{PR}{YP_{residential}} \tag{4.1}$$

where PR is the production rate and $YP_{residential}$ is the yield production for residential purposes, which is set to be 1200 kWh/kWp as per the industrial standards. Therefore, the total size of the system is 4.38 MW with approximately 13,681 solar panels to be installed. This comes to an average of 91 panels per household with a power rate of 0.32 kW/panel. However, it is anticipated that this system would be installed on roofs of spacious warehouses and commercial buildings. The area needed to install this system is approximately 7 acres, which keeps in consideration the shading effect. The area for the system is calculated using the following equation:

$$\eta_{max} = \frac{P_{max}}{E_{S,Y}^{SW} \times A_c} \tag{4.2}$$

where η_{max} is the maximum efficiency, which is set at 20% (reference), P_{max} is maximum power output or the target energy demand, which is 1.25 MW, $E_{S,Y}^{SW}$ is the incident radiation flux, which is set at 1 kW/m2 for the purposes of this study and A_c is the area of collector in m2. Figure 4.1 shows the general layout of the solar-PV system with a heat pump. The type of silicon used to produce the solar cells has an impact on the power conversion efficiency of a PV module. As observed in Figure 4.1, the solar radiation received by the PV module is converted into electricity from the initial state of phonic energy. This way, the PV modules produce DC power, which is connected to a DC motor that is also linked with a compressor. Matching the electrical properties of the motor and the available voltage and current generated by the PV modules becomes the main concern.

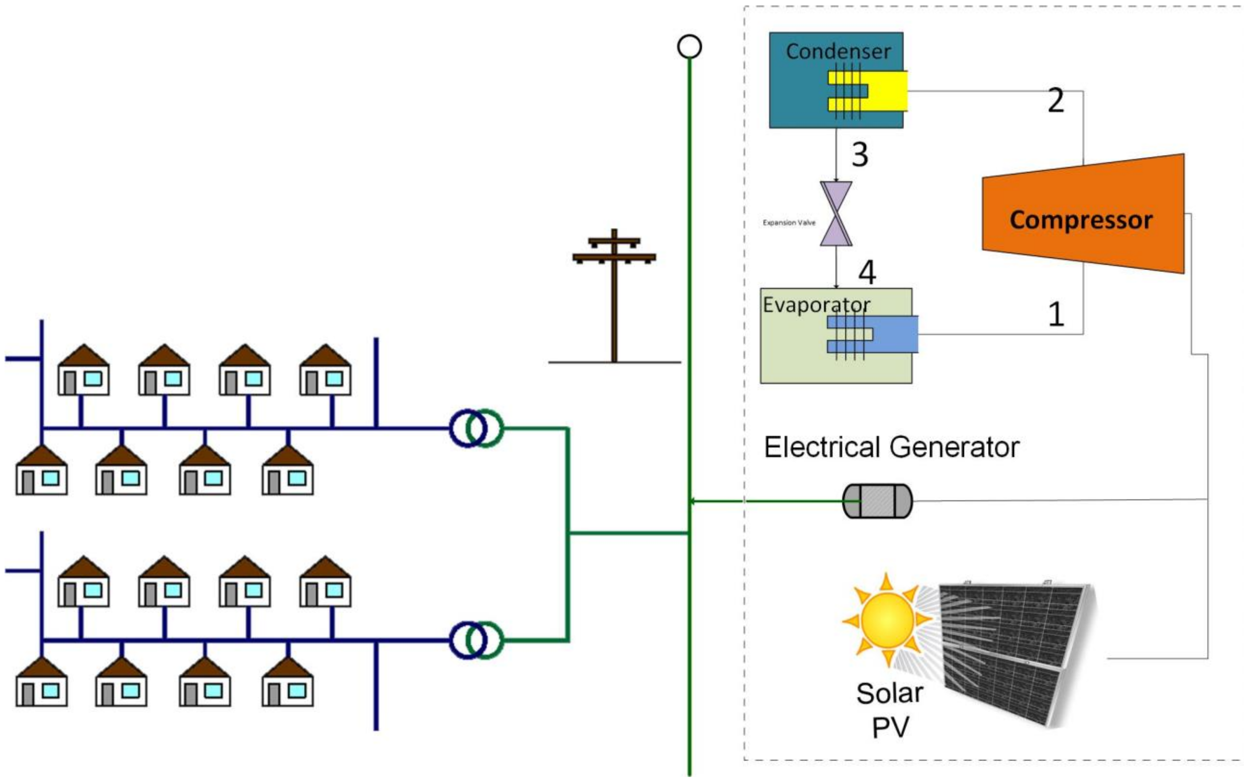

Figure 4.2 A schematic sketch illustrating the analyzed solar PV case study

4.2 System Analysis

Engineering Equation Solver is used and a model is developed for annual simulation of this system with input variables described in Table 4.1 solar irradiance is also accounted for in this system analysis.

4.2.1 Solar Irradiance

According to Natural Resources Canada (2007), the solar irradiance in Ontario is promising. Solar energy potential is measured in kWh generated per kW of the installed photovoltaic capacity. South-facing rooftops can ultimately harvest solar energy to meet the residential demand. Ontario municipalities vary greatly in their irradiance rates. For example, the annual PV potential for Toronto is 1161 kWh/kW, which is decent when compared to Cairo, Egypt at 1635 kWh/kW for example.

Table 4.1 Input parameters used to assess the photovoltaic system used in this case study (Source: Hacatoglu (2015)).

Parameter	**Value**	**Reference**
Liveable floor space	195 m2	Saldanha and Beausoleil-Morrison (2012)
Coefficient of performance of an average central air conditioning system	4	Sandler (1999)
Effectiveness of regenerator	0.75	Cengel and Boles (2010)
Efficiency of combustion	0.85	Sandler (1999)
Electric generator efficiency	0.92	Zini and Tartarini (2010)
Isentropic efficiency of a compressor	0.75	Cengel and Boles (2010)
Isentropic efficiency of a gas turbine	0.75	Cengel and Boles (2010)
Isentropic efficiency of a pump	0.75	Cengel and Boles (2010)
Number of people per household	4	Saldanha and Beausoleil-Morrison (2012)
Space heating factor	0.7 W m-2 K-1	Sørensen (2011)
Temperature of domestic hot water	60 °C	Sandler (1999)
Temperature of household	18 °C	Saldanha and Beausoleil-Morrison (2012)

4.2.2 Solar Modeling

The sequence of these equations follow the schematic sketch presented in Figure 4.2. The compressor is labelled as state number 1 followed by the condenser, the valve and finally the evaporator as state number 4.

For the adiabatic compressor, one can write the thermodynamic balance equations as follows:

Mass Balance Equation (MBE): $\dot{m}_1 = \dot{m}_2$ (4.3)

Energy Balance Equation (EBE): $\dot{m}_1 h_1 + \dot{W}_{in} = \dot{m}_2 h_2$ (4.4)

Entropy Balance Equation (EnBE): $\dot{m}_1 s_1 + \dot{S}_{gen} = \dot{m}_2 s_2$ (4.5)

Exergy Balance Equation (ExBE): $\dot{m}_1 ex_1 + \dot{W}_{in} = \dot{m}_2 ex_2 + \dot{E}x_{dest}$ (4.6)

For the condenser, one can write the thermodynamic balance equations as follows:

Mass Balance Equation (MBE): $\dot{m}_2 = \dot{m}_3$ (4.7)

Energy Balance Equation (EBE): $\dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{Q}_{out}$ (4.8)

Entropy Balance Equation (EnBE): $\dot{m}_2 s_2 + \dot{S}_{gen} = \dot{m}_3 s_3 + \frac{\dot{Q}_{out}}{T_0}$ (4.9)

Exergy Balance Equation (ExBE): $\dot{m}_2 ex_2 = \dot{m}_3 ex_3 + \dot{Q}_{out}\left(1 - \frac{T_0}{T_0}\right) + \dot{E}x_{dest}$ (4.10)

For the evaporator, one can write the thermodynamic balance equations as follows:

Mass Balance Equation (MBE): $\dot{m}_4 = \dot{m}_1$ (4.11)

Energy Balance Equation (EBE): $\dot{m}_4 h_4 + \dot{Q}_{in} = \dot{m}_1 h_1$ (4.12)

Entropy Balance Equation (EnBE): $\dot{m}_4 s_4 + \frac{\dot{Q}_{in}}{T_{space}} + \dot{S}_{gen} = \dot{m}_1 s_1$ (4.13)

Exergy Balance Equation (ExBE): $\dot{m}_4 ex_4 + \dot{Q}_{in}\left(1 - \frac{T_0}{T_{space}}\right) = \dot{m}_1 ex_1 + \dot{E}x_{dest}$ (4.14)

For the expansion valve, one can write the thermodynamic balance equations as follows:

Mass Balance Equation (MBE): $\dot{m}_3 = \dot{m}_4$ (4.15)

Energy Balance Equation (EBE): $\dot{m}_3 h_3 = \dot{m}_4 h_4$ (4.16)

Entropy Balance Equation (EnBE): $\dot{m}_3 s_3 + \dot{S}_{gen} = \dot{m}_4 s_4$ (4.17)

Exergy Balance Equation (ExBE): $\dot{m}_3 ex_3 = \dot{m}_4 ex_4 + \dot{E}x_{dest}$ (4.18)

Where the process is isenthalpic and entropy at state 4 can be found using enthalpy and pressure parameters.

The PV system analysis is modeled using the following equations:

$\dot{Q}_{Solar} Area_{PV} = \dot{W}_{PV} + \dot{Q}_{Loss,PV}$ (4.19)

$$n_{PV} = \frac{\dot{W}_{PV}}{\dot{Q}_{Solar} Area_{PV}} \quad (4.20)$$

$$\frac{\dot{Q}_{Loss,PV}}{T_{amb}} = \frac{\dot{Q}_{Solar}}{T_{Sun}} Area_{PV} + \dot{S}_{G,PV} \quad (4.21)$$

$$\dot{E}x_{Q,Solar} = \dot{W}_{PV} + \dot{E}x_{Q,Loss,PV} + \dot{E}x_{D,PV} \quad (4.22)$$

$$\dot{E}x_{Q,Loss,PV} = \dot{Q}_{Loss,PV} \left(1 - \frac{T_0}{T_{amb}}\right) \quad (4.23)$$

$$\dot{E}x_{Q,Solar} = \dot{Q}_{Solar} Area_{PV} \left[1 - \frac{4}{3} \left(\frac{T_0}{T_{amb}}\right) + \frac{1}{3} \left(\frac{T_0}{T_{amb}}\right)^4 \right] \quad (4.24)$$

4.3 Wind Energy System

4.3.1 System Description

Wind turbines are used to convert kinetic energy to useful electricity that is utilized to meet the demand of 150 households in Ontario. This wind power system is intended to meet the annual heating and cooling demand of 30,861.1 kWh/house (Statistics Canada, Environment Accounts and Statistics Division, 2011). Furthermore, the annual electricity demand, which is 10,000 kWh/household is also planned to be included in this design (Ontario Ministry of Energy, 2015). The set temperature of the household used is 18 °C (Saldanha and Beausoleil-Morrison, 2012). Furthermore, the working fluid of the heating system is R134a. The mechanical efficiency of the wind turbine is 55% based on the Betz efficiency limit. Further parameters of this wind system is presented in Table 4.2

Table 4.2 input parameters used when assessing the wind system for this case study.

Parameter	Value	Reference
Cut-in wind speed	2.5 m s^{-1}	Ashtine et al. (2016)
Cut-out wind speed	25 m s^{-1}	Ashtine et al. (2016)
Mechanical efficiency of a wind turbine	0.55	Zini and Tartarini (2010)
Power coefficient of a wind turbine	0.397	Dai et al. (2016)
Pressure ratio	8	Cengel and Boles (2010)
Rated wind speed	15 m s^{-1}	Berg (2007)

The following assumptions are considered in the analysis of this system:

- Evaporator and condenser work with 80% heat exchanger effectiveness.
- The compressor is isentropic with the given isentropic (90%) and mechanical efficiencies (85%).
- The expansion valve is isenthalpic; and the facility is well insulated with no heat losses. In addition, there are no pressure losses through piping, condenser and evaporator.
- Air density is 1.16 kg/m^3. Wind turbine generator efficiency is 90%; wind turbine transmission efficiency is 95%. Ambient temperature is 25°C.

Figure 4.3 illustrates the sketch used for this case study.

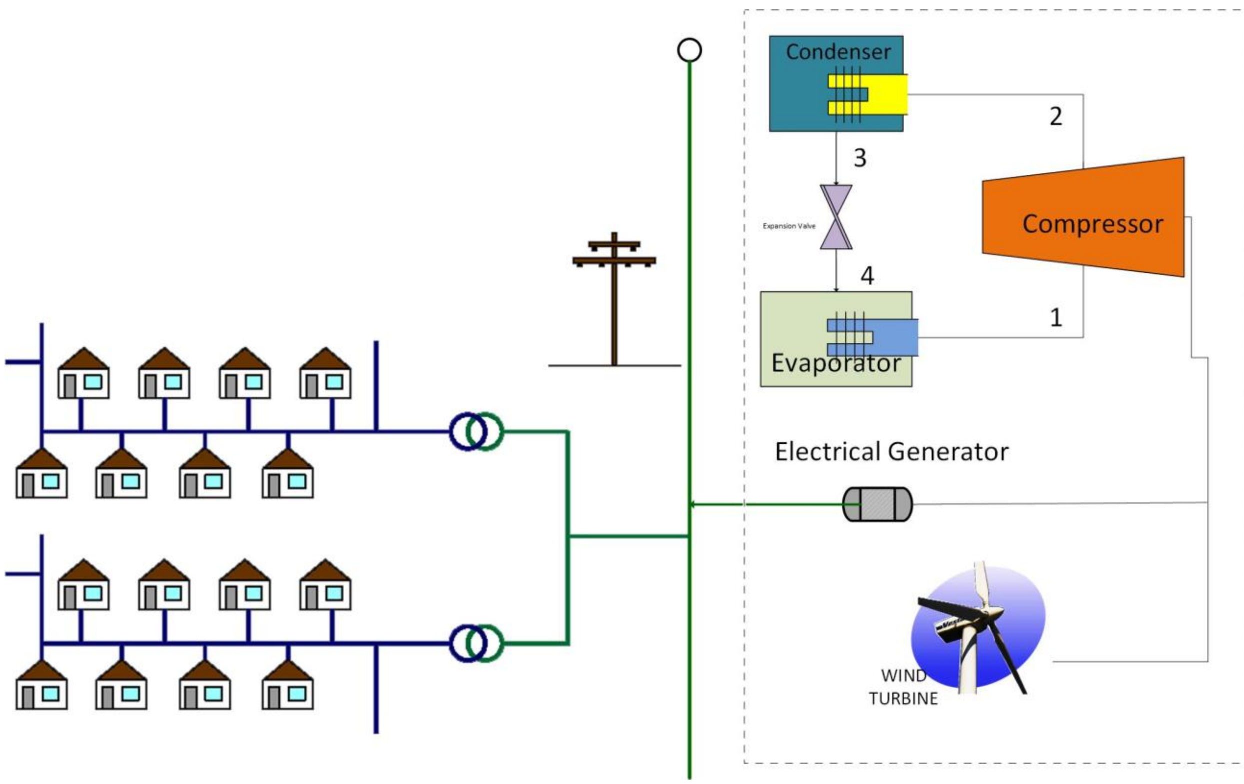

Figure 4.3 A sketch illustrating the design used for the wind energy case study.

The sequence of these equations follow the schematic sketch presented in Figure 4.3. The compressor is labelled as state number 1 followed by the condenser, the valve and finally the evaporator as state number 4.

For the adiabatic compressor, one can write the thermodynamic balance equations as follows:

Mass Balance Equation (MBE): $\dot{m}_1 = \dot{m}_2$ (4.25)

Energy Balance Equation (EBE): $\dot{m}_1 h_1 + \dot{W}_{in} = \dot{m}_2 h_2$ (4.26)

Entropy Balance Equation (EnBE): $\dot{m}_1 s_1 + \dot{S}_{gen} = \dot{m}_2 s_2$ (4.27)

Exergy Balance Equation (ExBE): $\dot{m}_1 ex_1 + \dot{W}_{in} = \dot{m}_2 ex_2 + \dot{E}x_{dest}$ (4.28)

For the condenser, one can write the thermodynamic balance equations as follows:

Mass Balance Equation (MBE): $\dot{m}_2 = \dot{m}_3$ (4.29)

Energy Balance Equation (EBE): $\dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{Q}_{out}$ (4.30)

Entropy Balance Equation (EnBE): $\dot{m}_2 s_2 + \dot{S}_{gen} = \dot{m}_3 s_3 + \frac{\dot{Q}_{out}}{T_0}$ (4.31)

Exergy Balance Equation (ExBE): $\dot{m}_2 ex_2 = \dot{m}_3 ex_3 + \dot{Q}_{out}\left(1 - \frac{T_0}{T_0}\right) + \dot{E}x_{dest}$ (4.32)

For the evaporator, one can write the thermodynamic balance equations as follows:

Mass Balance Equation (MBE): $\dot{m}_4 = \dot{m}_1$ (4.33)

Energy Balance Equation (EBE): $\dot{m}_4 h_4 + \dot{Q}_{in} = \dot{m}_1 h_1$ (4.34)

Entropy Balance Equation (EnBE): $\dot{m}_4 s_4 + \frac{\dot{Q}_{in}}{T_{space}} + \dot{S}_{gen} = \dot{m}_1 s_1$ (4.35)

Exergy Balance Equation (ExBE): $\dot{m}_4 ex_4 + \dot{Q}_{in}\left(1 - \frac{T_0}{T_{space}}\right) = \dot{m}_1 ex_1 + \dot{E}x_{dest}$ (4.36)

For the expansion valve, one can write the thermodynamic balance equations as follows:

Mass Balance Equation (MBE): $\dot{m}_3 = \dot{m}_4$ (4.37)

Energy Balance Equation (EBE): $\dot{m}_3 h_3 = \dot{m}_4 h_4$ (4.38)

Entropy Balance Equation (EnBE): $\dot{m}_3 s_3 + \dot{S}_{gen} = \dot{m}_4 s_4$ (4.39)

Exergy Balance Equation (ExBE): $\dot{m}_3 ex_3 = \dot{m}_4 ex_4 + \dot{E}x_{dest}$ (4.40) where the process is isenthalpic and entropy at state 4 can be found using enthalpy and pressure parameters.

The wind system analysis is modeled using the following equations:

Mass Balance Equation (MBE): $\dot{m}_1 = \dot{m}_2$ (4.41)

Energy Balance Equation (EBE): $\dot{m}_1 \left(h_1 + \frac{V^2{}_1}{2}\right) = \dot{m}_2 \left(h_2 + \frac{V^2{}_2}{2}\right) + \dot{W} + \dot{Q}_{loss}$ (4.42)

Entropy Balance Equation (EnBE): $\dot{m}_1 s_1 + \dot{S}_{gen} = \dot{m}_2 s_2 + \frac{\dot{Q}_{loss}}{T_{surr}}$ (4.43)

Exergy Balance Equation (ExBE): $\dot{m}_1 ex_1 + \dot{m}_1 ex_{\mathrm{k}} = \dot{m}_2 ex_2 + \dot{m}_2 ex_{\mathrm{k}} + \dot{E}x_{dest} + \dot{E}x^W + \dot{E}x^Q$

(4.44)

Chapter 5: Results and Discussion

The results of the sustainability assessment model is presented and discussed in the chapter along with the results of the aforementioned case studies. Furthermore, the different weighting schemes (i.e. individualist, egalitarian, hierarchist and panel method) are further analyzed in this chapter. Besides, results of each dimension are also analyzed in depth and discussed further.

5.1 Weighting

The weighting schemes are explained earlier in chapter 3. Furthermore, the difference between each scheme has also been addressed previously. In this section, the weights according to these schemes are presented for all indicators used in this model.

5.1.1 Energy and Exergy Impacts

Energetic and exergetic indicators were put to scale from 1 to 5 with respect to time, space and receptor. Equal weighting has also been conducted as presented in Table 5.1, which illustrates the importance coefficients for the energy and exergy dimension.

Table 5.1 Importance coefficients with respect to various schemes for the energy and exergy indicators

Indicator	Individualist	Egalitarian	Hierarchist	Equal
Energy Efficiency	0.50	0.52	0.46	0.50
Production Rate	0.50	0.48	0.54	0.50
Exergy Efficiency	0.53	0.52	0.50	0.50
Exergy Destruction	0.47	0.48	0.50	0.50

These values are also plotted for better illustration and comparison in Figure 5.1. While equal weighting is in line with the individualist scheme for the energy dimension, the egalitarian and individualist schemes are similar in assessing the exergy dimension. Furthermore, equal weighting and the hierarchist schemes were the same in assessing the exergy dimension. However, their assessment of the energy dimension was very different from each other. Overall, the various schemes are illustrated alongside their linear trend line for better comparison and analysis between schemes.

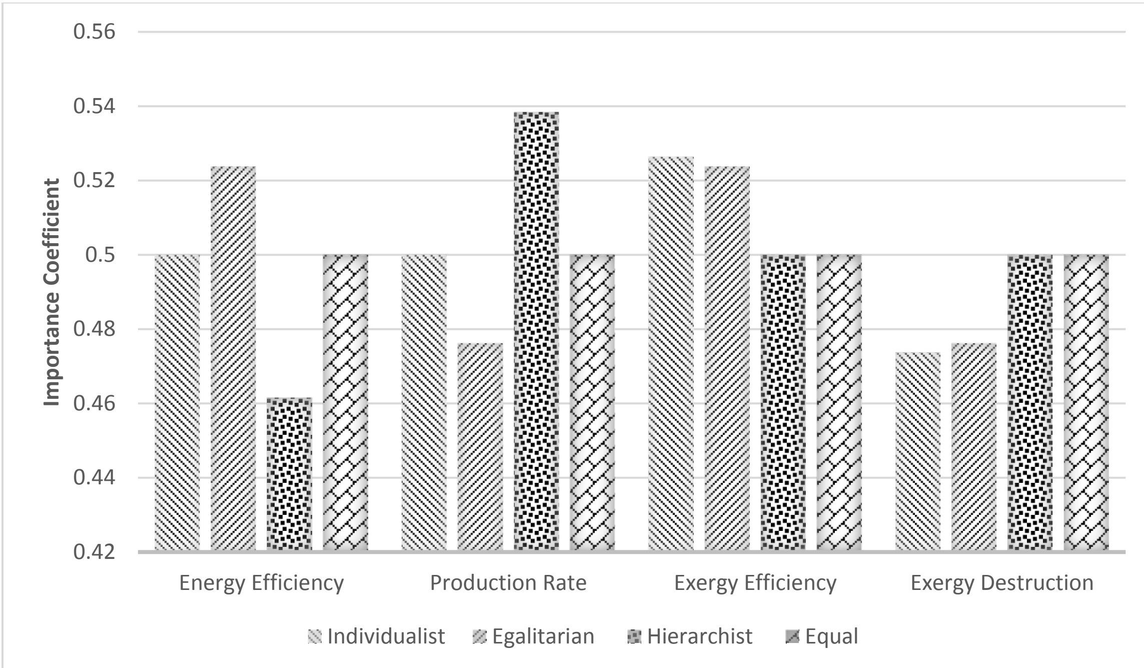

Figure 5.1 Distribution of importance coefficients and linear trend based on the four schemes for the energy and exergy indicators

5.1.2 Environmental Footprint

Environmental factors vary as they may be grouped separately. For example, impact categories related to air emissions such as GWP have a global or regional effect compared to impact categories such as water consumption and land use, which have a local influence. Furthermore, some impact categories directly related to human health such as smog air and abiotic depletion while other impact categories such as water ecotoxicity and eutrophication potential impact aquatic ecosystems more directly than their effect on humans. Table 5.2 show the importance coefficients of the environmental indicators with respect to the schemes adopted in this thesis. As discussed earlier, environmental indicators vary in their space, time horizon and receptor association. It is evident that GWP received very low importance when assessed using the individualist scheme because this scheme is considered with short term and local affairs. Rather, GWP is more long term and global. This explains the high importance given by the egalitarian scheme, which is more concerned for long-term effect and globalism of the impact.

Table 5.2 Importance coefficients with respect to various schemes for the environmental indicators

Indicator	Individualist	Egalitarian	Hierarchist	Equal
GWP	0.04	0.14	0.08	0.10
ODP	0.07	0.12	0.08	0.10
AP	0.10	0.09	0.13	0.10
EP	0.11	0.08	0.14	0.10
Air Toxicity	0.09	0.11	0.08	0.10
Water Ecotoxicity	0.11	0.11	0.13	0.10
Smog Air	0.09	0.11	0.08	0.10
Water Consumption	0.15	0.07	0.11	0.10
Land Use	0.13	0.08	0.07	0.10
Abiotic Depletion	0.12	0.11	0.08	0.10

Furthermore, land use is a local matter, which is why it received a higher importance coefficient than its assessment by the egalitarian. The hierarchist gave this indicator an importance between the two extreme schemes. Figure 5.2 illustrates the dynamicity of the schemes for each indicator.

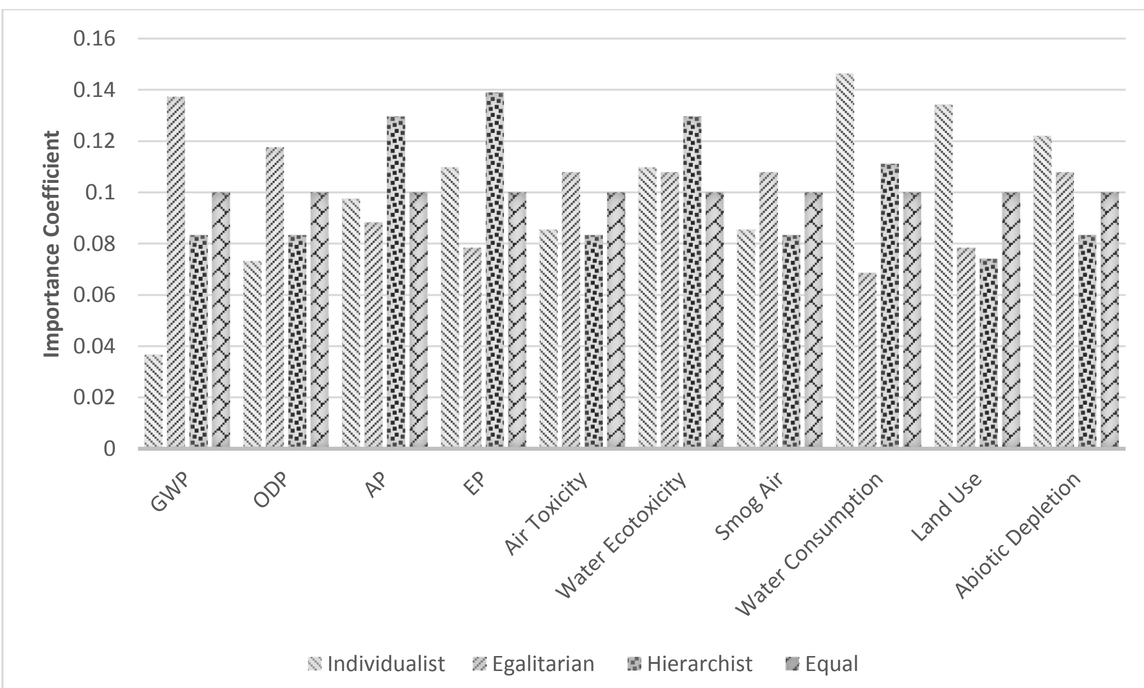

Figure 5.2 Distribution of importance coefficients based on the four schemes for the environmental indicators

5.1.3 Economic Impact and Technology

These dimensions tend to mirror the long-term outcome. For example, payback time, BCR and Commercializability are all indictors that are long term and could be global. On the other hand, LCOE is a local or regional matter where different localities may differ in their LCOE depending on the available resources, sociopolitical variations and other factors. Table 5.3 present the importance coefficients for the indicators used to assess the economic and technological dimensions of this model.

Table 5.3 Importance coefficients with respect to various schemes for the economic and technological indicators

Indicator	Individualist	Egalitarian	Hierarchist	Equal
Benefit-Cost Analysis	0.26	0.29	0.25	0.25
Payback time	0.26	0.29	0.23	0.25
Operation and Maintenance Cost	0.21	0.21	0.25	0.25
Levelized Cost of Electricity/Energy	0.26	0.21	0.28	0.25
Commercializability	0.37	0.34	0.31	0.33
Technology Readiness	0.32	0.32	0.31	0.33
Innovation	0.32	0.34	0.38	0.33

These values are further illustrated in Figure 5.3 along with the linear trend line for each scheme. Since many of these factors are associated with long-term impacts, the egalitarian scheme highlighted most of them as equally important. Thus, the values of the egalitarian scheme and the equal scheme are very similar as illustrated.

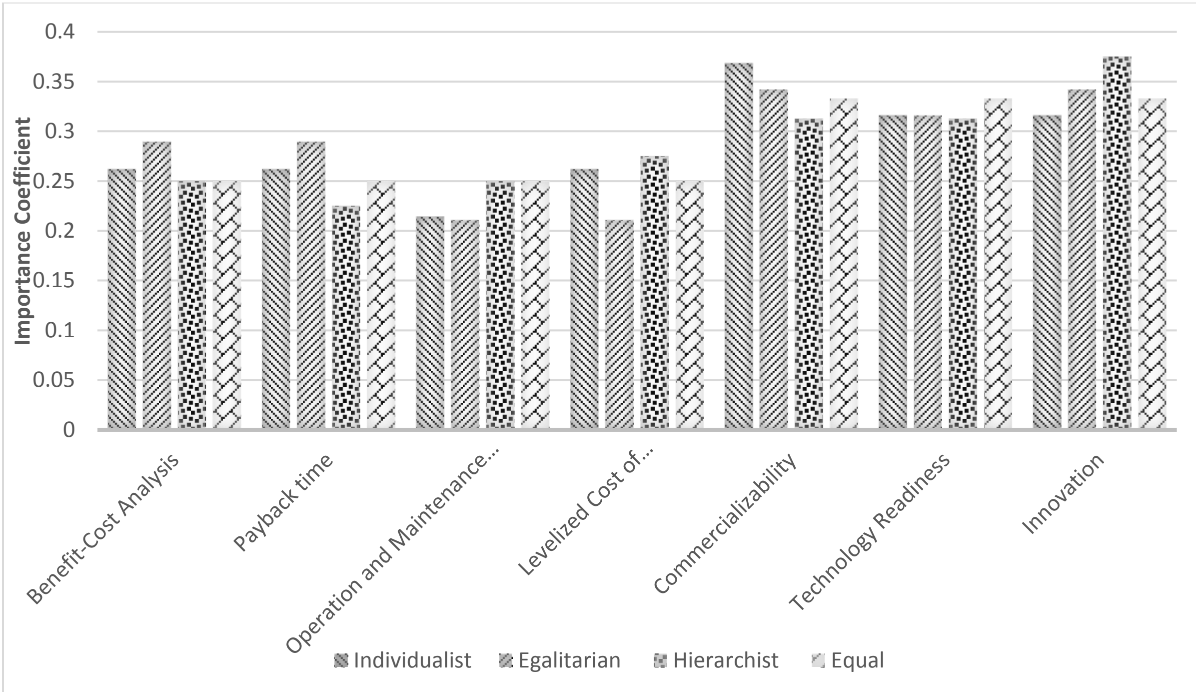

Figure 5.3 Distribution of importance coefficients based on the four schemes for the economic and technological indicators

5.1.4 Social Impression

Social indicators have a direct effect on humans and are closer towards the individualist scheme, thus the higher values presented in Table 5.4. Human welfare and human health are indicators that could be local and regional. Furthermore, job creation, public awareness and social acceptance could be local and regional as well with direct input from the population of these communities.

Table 5.4 Importance coefficients with respect to various schemes for the social indicators

Indicator	Individualist	Egalitarian	Hierarchist	Equal
Job Creation	0.18	0.14	0.17	0.17
Public Awareness	0.17	0.16	0.17	0.17
Social Acceptance	0.18	0.16	0.14	0.17
Social Cost	0.11	0.26	0.18	0.17
Human Welfare	0.17	0.14	0.15	0.17
Human Health	0.18	0.14	0.18	0.17

These social indicators are consistent with respect to association with humans as opposed to ecosystems. Thus, the individualist values this aspect, yet undermines some indicators because of their long-term nature. Figure 5.4 illustrates the various indicators and their importance coefficients.

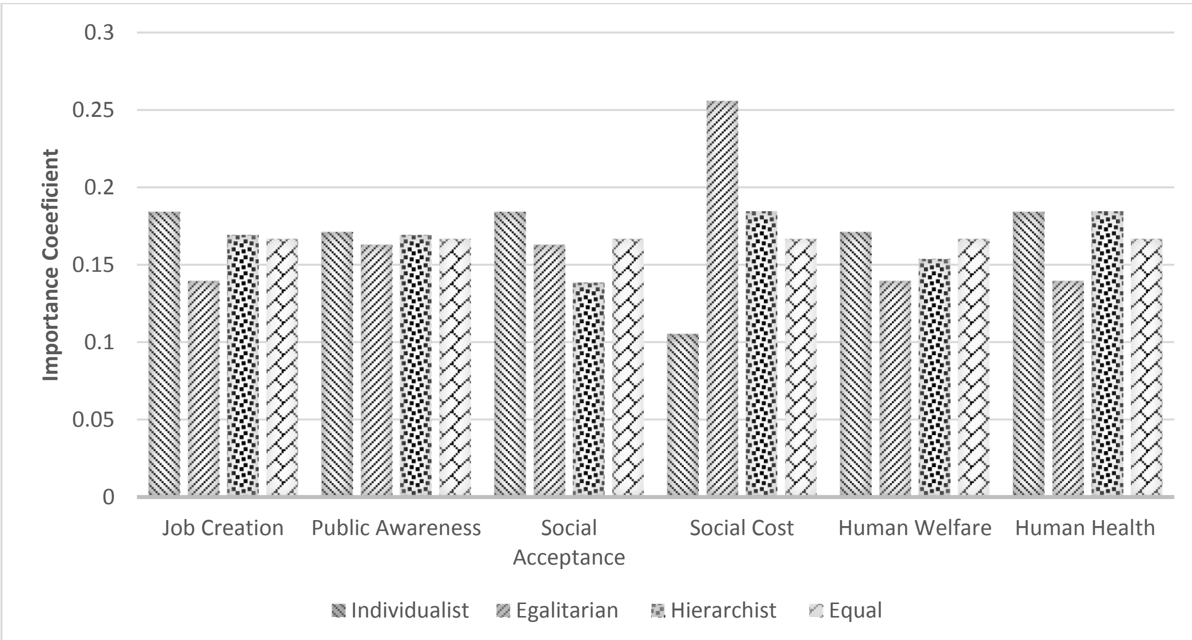

Figure 5.4 Distribution of importance coefficients based on the four schemes for the economic and technological indicators

5.1.4 Education and Size Factor

Indicators pertaining education mirror an egalitarian approach since they may be medium with respect to time horizon, regional in effect and affect both humans and ecosystems alike. On another note, the mass and volume are considered only for mobile applications such as vehicles and any other applications. Since the case studies adopted for this thesis are stationary, mass and volume are irrelative, thus the area receives the full weight to reflect the Size factor in all case studies assessed in this thesis. Table 5.5 show the importance coefficients generated for the educational indicators and the Size factor. Mass and volume are indicators associated only with mobile applications. Since the case studies are stationary energy applications, the full weight is limited to the land use. However, if these indicators were considered, their impact would be local and long-term.

Table 5.5 Importance coefficients with respect to various schemes for the educational and Size factor indicators

Indicator	Individualist	Egalitarian	Hierarchist	Equal
Number of trained people required by industry	0.44	0.26	0.32	0.33
Educational Level	0.30	0.30	0.32	0.33
Innovation and Creativity	0.26	0.43	0.36	0.33
Mass	0.35	0.37	0.30	0.33
Land Use	0.38	0.37	0.41	0.33
Volume	0.27	0.27	0.30	0.33

Thus, a mixture between the egalitarian and individualist schemes. Figure 5.5 illustrates the relationship between the importance coefficients of these indicators and the various schemes.

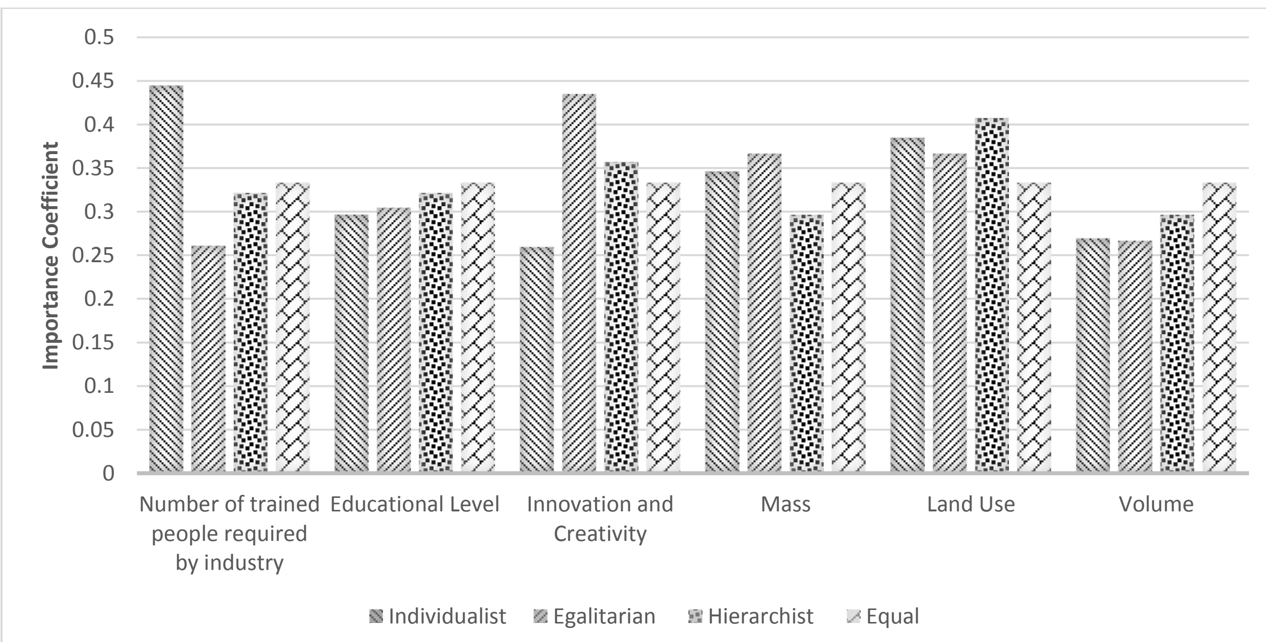

Figure 5.5 Distribution of importance coefficients based on the four schemes for the educational and Size factor indicators

5.1.5 Sustainability Dimensions and Weighting Schemes

The same schemes were used to weigh the category dimensions used in this model. The time-space-receptor method was also used in appointing appropriate values for each dimension. The dimensions used in this thesis vary as some have long-term impact such as exergy and energy while others have short-term impact. Table 5.6 shows the various dimensions and their associated weights as per the schemes used: panel method, individualist, egalitarian, hierarchist and equal weighting method.

Table 5.6 Importance coefficients of the 8 main dimensions of the sustainability mode with respect to various schemes.

Dimension	**Individualist**	**Egalitarian**	**Hierarchist**	**Panel**	**Equal**
Energy	0.13	0.12	0.13	0.10	0.13
Exergy	0.13	0.12	0.13	0.17	0.13
Environment	0.13	0.13	0.15	0.18	0.13
Economy	0.13	0.15	0.13	0.14	0.13
Technology	0.09	0.12	0.12	0.12	0.13
Social	0.17	0.12	0.12	0.15	0.13
Education	0.13	0.12	0.12	0.09	0.13
Size Factor	0.10	0.10	0.12	0.05	0.13

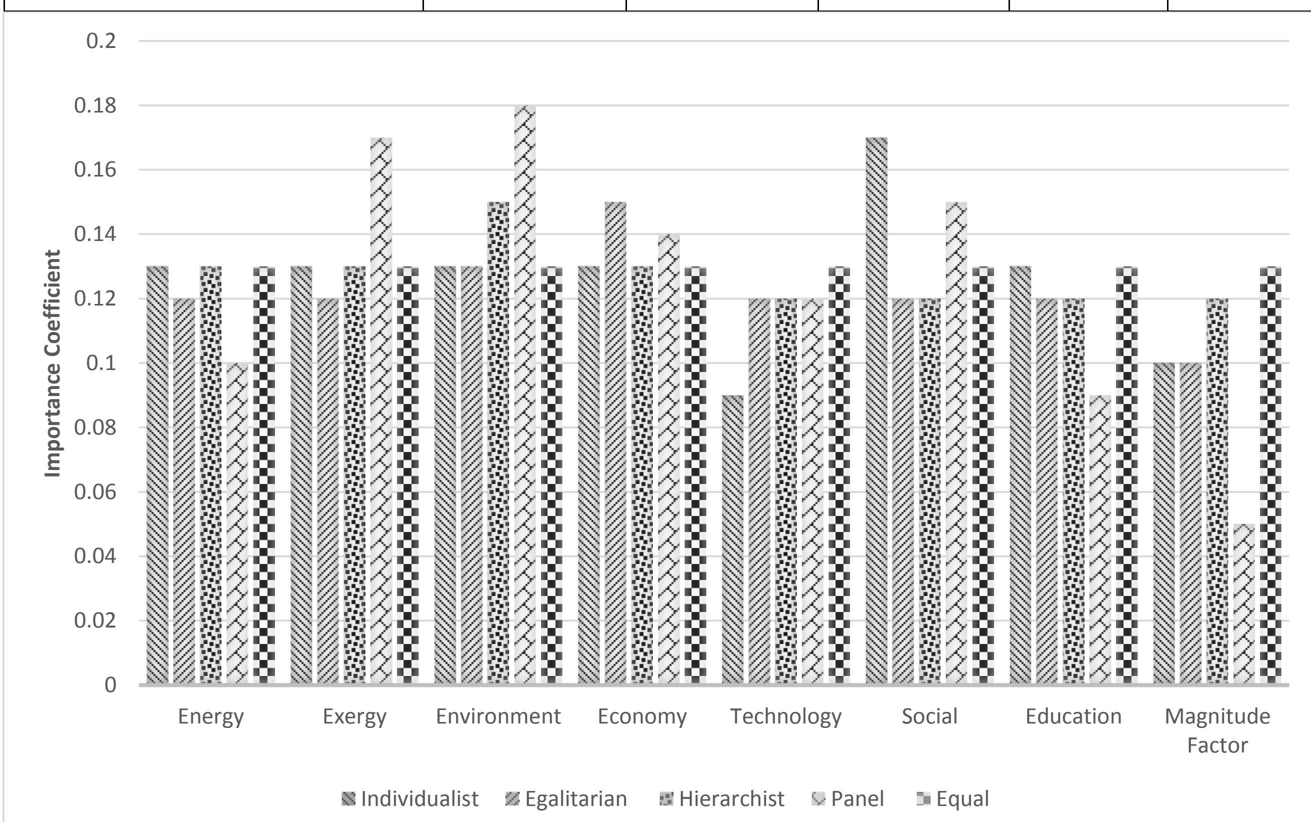

Figure 5.6 Distribution of importance coefficients based on the four schemes for the main dimensions used for the sustainability assessment model

There are slight variations between the different schemes in prioritizing specific dimensions over the other. For example, the panel method prioritized exergy, neglected the Size factor while the individualist method prioritized the social dimension, and neglected technology. Furthermore, the panel gave less priority for education whereas all the other schemes placed it at a higher priority compared to the panel scheme.

5.2 Solar PV System

While solar PV is considered an intermittent source of energy, technological advances in this discipline with respect to efficiency, performance, reliability and economic attraction are well underway. Furthermore, the system is designed to meet the heating, cooling, electricity and hot water load for 150 Ontario households, which is approximately three subdivisions. In Ontario, solar irradiance vary between cities. For example, Brampton and Barrie have a relatively lower annual irradiance compared to Windsor and St. Catharine's. The variation between the electricity demand per household (kW) and the solar irradiance is presented in Figure 5.7

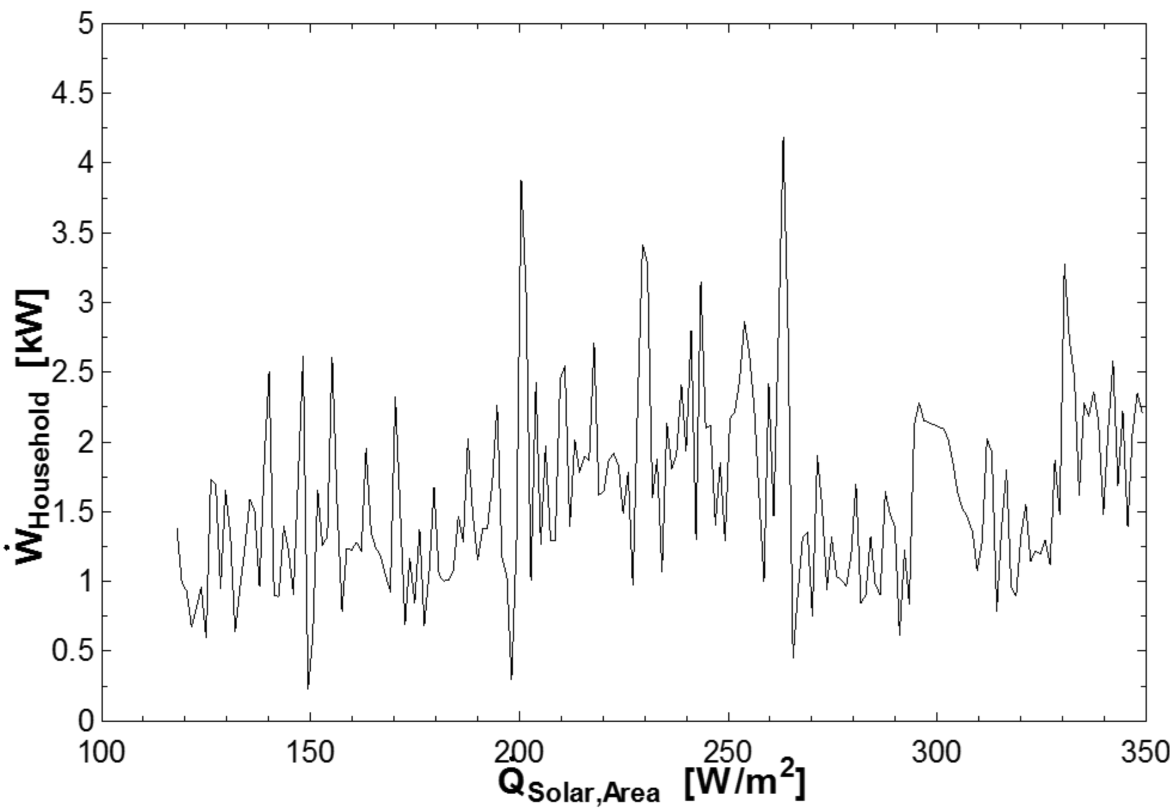

Figure 5.7 Distribution of the household electricity demand as the solar irradiance changes

5.2.1 Sustainability Assessment

Because weighting and aggregation are subjective concepts, various weighting schemes and aggregation methods have been used in order to minimize any noise and in order to present results objectively as much as possible. Therefore, there are two aggregation schemes used, which are weighting arithmetic mean and weighting geometric mean as explained in chapter 3. Table 5.7 shows the final sustainability index for the PV system with respect to the characterization schemes applied and the aggregation method used.

Table 5.7 Final sustainability index of PV system using various weighting and aggregation methods

Scheme	Sustainability Index (WGM)	Sustainability Index (WAM)
Panel	0.56	0.59
Individualist	0.56	0.54
Egalitarian	0.58	0.55
Hierarchist	0.59	0.55
Equal	0.59	0.63

From Table 5.7, it evident that there is a slight difference between the uses of weighted geometric mean and the weighted arithmetic mean for calculating the sustainability index of the PV system. Using WAM, the sustainability index derived from the equal weighting and panel schemes was higher than the derived values using WGM. Figure 5.8 shows the plot, which compares all values from various methods. The difference of values between the WGM and the WAM for the hierarchist and equal weighting schemes double the difference in values for the panel, individualist and egalitarian schemes.

On the contrary, it is apparent that the sustainability index derived from the other weighting schemes when using WAM were less than the values obtained when using WGM. Moreover, the graph illustrates the weak points of the WAM and highlights the advantage of using the WGM over the WAM when assessing sustainability of PV systems. Moreover, the final sustainability index using the WGM varied by a factor of 0.03 between the different weighting schemes as illustrated in Figure 5.9

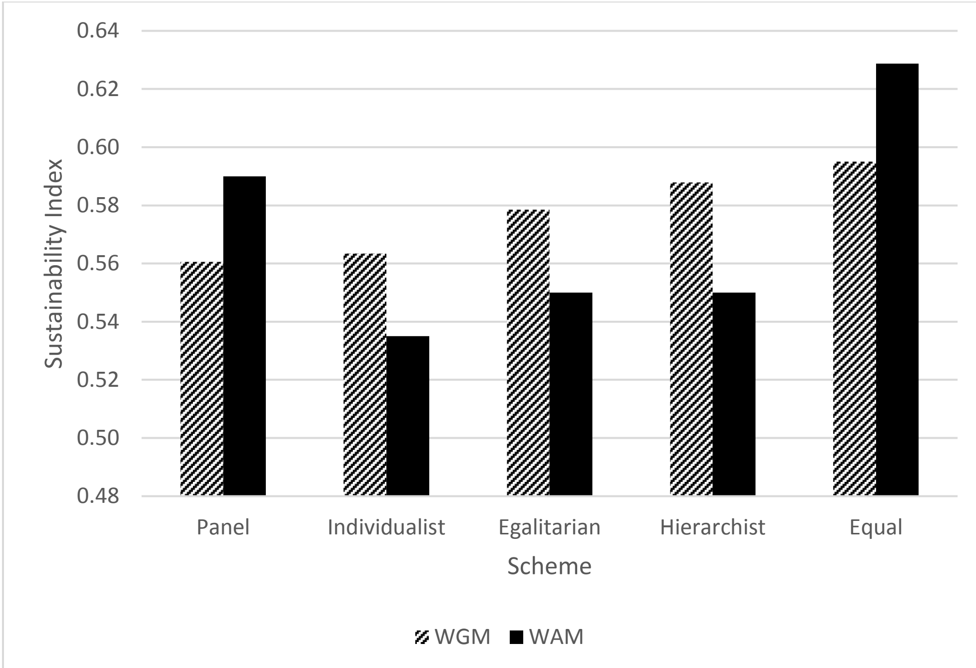

Figure 5.8 Distribution of the sustainability index results based on the various aggregation method and characterization scheme for the solar PV energy system

The individualist and panel methods yielded in a similar score while equal weighting suggested the highest sustainability score for the PV system in this case study. The minimum variation that

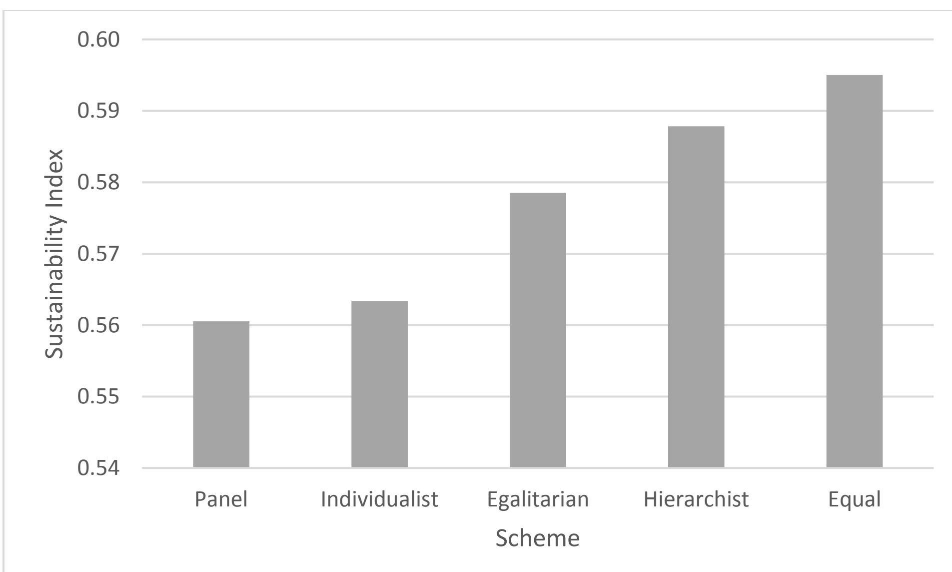

Figure 5.9 Distribution of the sustainability index results based on WGM and characterization schemes for the solar PV system

exists in these results suggest its robustness and strength over the results extracted using the WAM as observed in Figure 5.10.

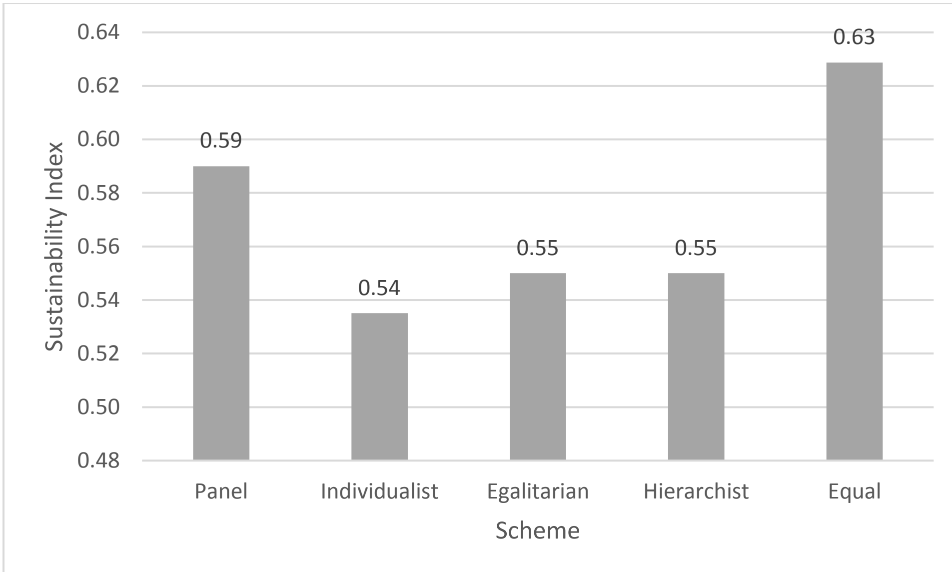

Figure 5.10 Distribution of the sustainability index results based on WAM and characterization schemes for the solar PV system

In this illustration, the panel method is similar to the equal weighting method, which differs from WGM where the panel method was parallel to the individualist method. On the other hand, the individualist, egalitarian and hierarchist schemes resulted in very similar sustainability index values, which are relatively lower than the other two schemes. Furthermore, the variation in data in the WAM is triple times the variation in the WGM. This suggests that the WAM is less preferable when aggregating values for the sustainability assessment. On another note, it is critical to know how changes in the inputs affects the final sustainability index. As observed earlier in Table 5.5, each characterization scheme highlights a number of selected dimensions. For example, using the individualist scheme, the technology and social dimensions are the first two dimensions that catch attention. This is because the social dimension received the highest importance coefficient while the technology dimension received the lowest. Therefore, using this methodology, the following figures will help us analyze the influence of these selected dimensions on the final sustainability index of the solar PV system. When conducting this, values of all other dimensions were kept as is in order to account only for the effect of the dimension of interest on the sustainability index score. Furthermore, the results were extracted using the WGM. Figure 5.11 shows the various schemes and the influence of the energy dimension as its dimensionless value increases from 0.2 to one (one being the most favorable).

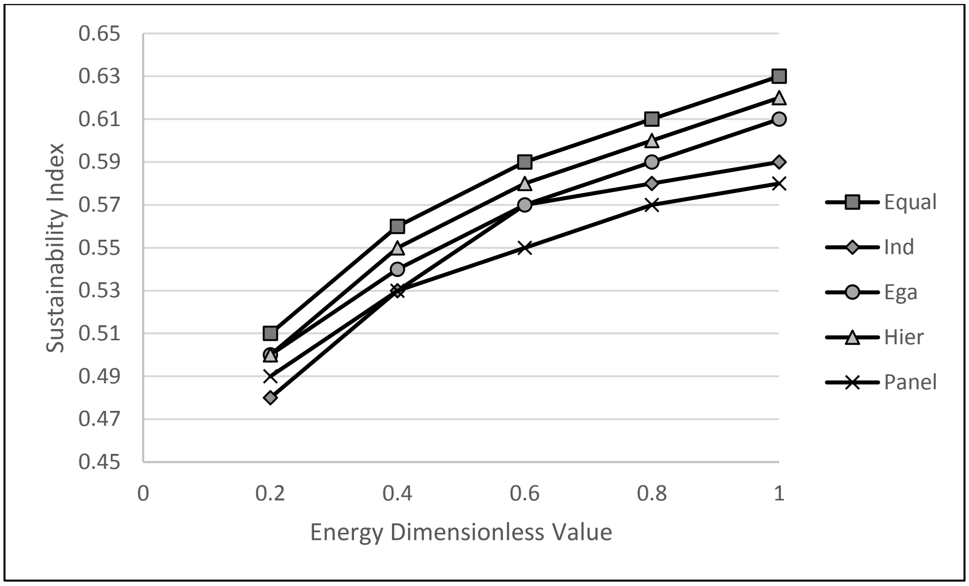

Figure 5.11 Variation of the solar PV sustainability index with respect to the energy dimension

Equal weighting and hierarchist schemes show a similar trend for the energy dimension characterized by steady increase of the sustainability index as the energy value increases. This also goes with the egalitarian scheme. However, the panel method and the individualist scheme present slightly different dynamics. As for the individualist scheme, the energy dimension is most impactful on the sustainability index when the value is between 0.2 and 0.6, after which the increase results in a less steeper and more steadily increase in the sustainability index value. Similarly, the panel method shows that the energy dimension is most impactful on the index when the values increases from 0.2 to 0.4. After, as the value of the energy dimension increases, its effect is steady. Figure 5.12 presents the exergy dimension and its impact on the sustainability index. Similar to the energy dimension, the equal weighting scheme suggests the highest sustainability index scores as the exergy dimensionless value increases. The sustainability index score changes between 0.65 and 0.48 depending on the exergy performance. This accounts for 17% increase or decrease on the sustainability index all due to the exergy performance.

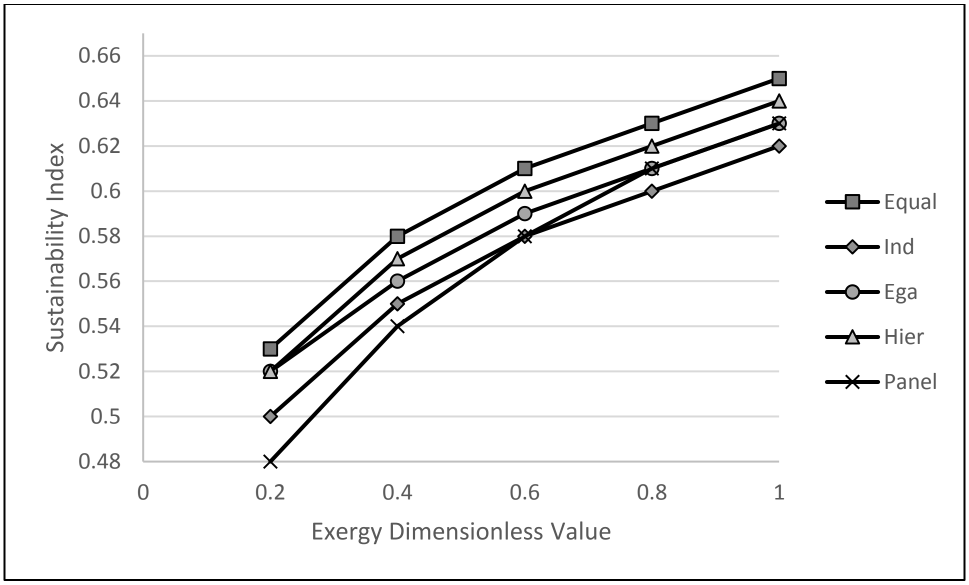

Figure 5.12 Variation of the solar PV sustainability index with respect to the exergy dimension

Similar dynamics on the impact of the panel and individualist method for the energy dimension are also observed for the exergy dimension as well. Figure 5.13 displays the environment dimension and its influence on the sustainability index.

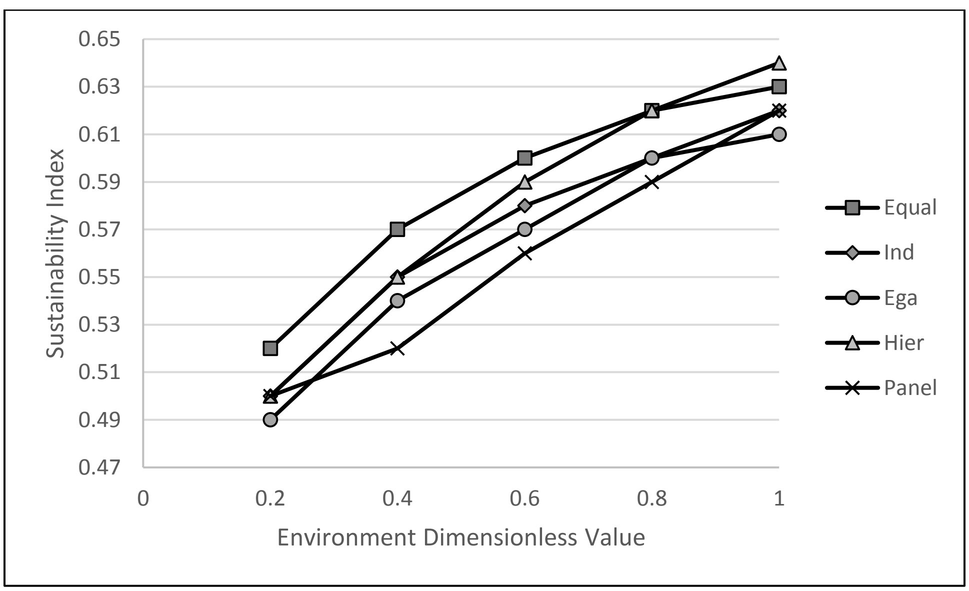

Figure 5.13 Variation of the solar PV sustainability index with respect to the environment dimension

According to the panel method, environmental score changes between 0.2 and 0.4 have a minimal effect. As the score move between 0.4 and 1, its impact on the sustainability index is much higher. In fact, this increase alone accounts for 10% increase on the sustainability index with scores varying from 0.52 to 0.62. Figure 5.14 illustrates the impact of the economy dimension on the sustainability index.

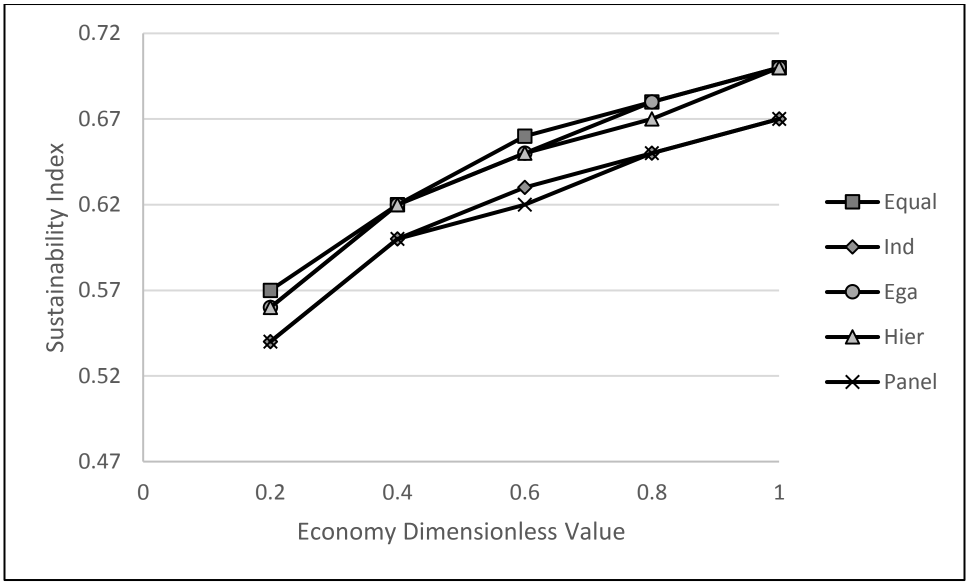

Figure 5.14 Variation of the solar PV sustainability index with respect to the economy dimension

Changes in the economy dimensionless value from 0.2 to 0.4 are presented on a steeper line compared to value changes from 0.4 to 1. While the panel method and individualist scheme show a similar relationship, the other three schemes also present a steady increase of sustainability index due to steady increase of the economy dimensionless value. Figure 5.15 illustrates the variation of sustainability index with respect to the changes in the technology dimensionless value. Most schemes show that technology dimensionless value changes between 0.2 and 0.4 yield in the highest rate of change on the sustainability index, which translates in larger increase segment. After that, steady increase is observed except for the values resulting from the individualist scheme as they line becomes less steep as the dimensionless value increases from 0.8 to 1. Furthermore, the equal weighting scheme followed by the hierarchist, egalitarian yield in the highest sustainability index scores for the technology dimension’s increase in value. Figure 5.16 presents the results of the social dimension.

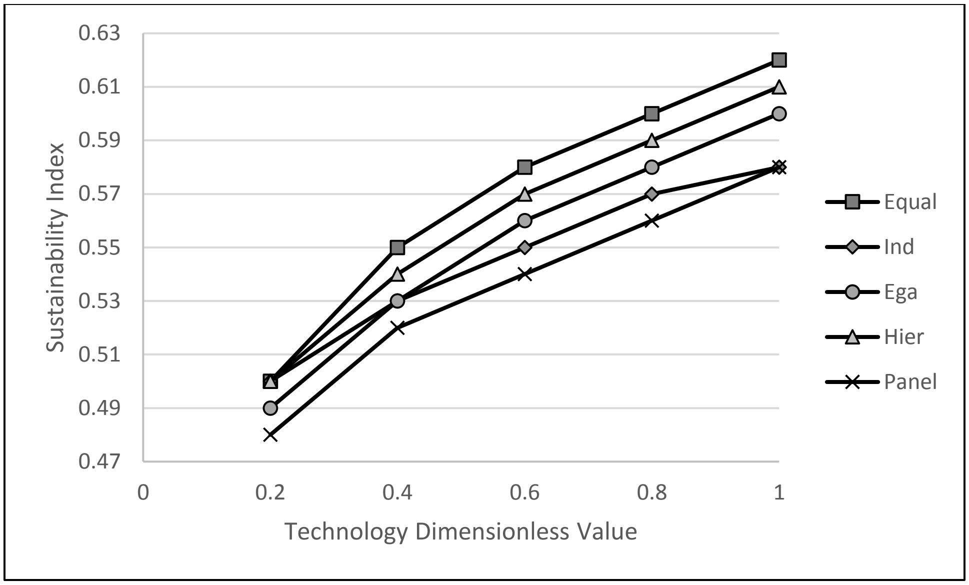

Figure 5.15 Variation of the solar PV sustainability index with respect to the economy dimension

Figure 5.16 shows that the sustainability index scores are more variable among schemes with the social dimensionless value is low. As the dimensionless value reaches towards 0.8 and 1, variability among schemes on the sustainability index score is reduced. This means that consensus is achieved in the decision-making criteria between all schemes for that value range. Figure 5.17 shows the education dimension and its effect on the sustainability index.

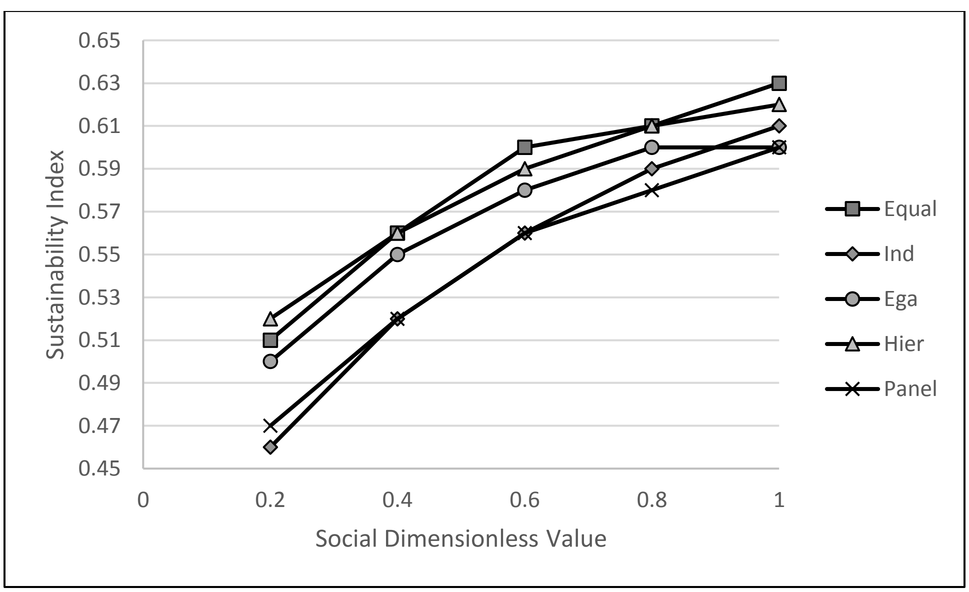

Figure 5.16 Variation of the solar PV sustainability index with respect to the social dimension

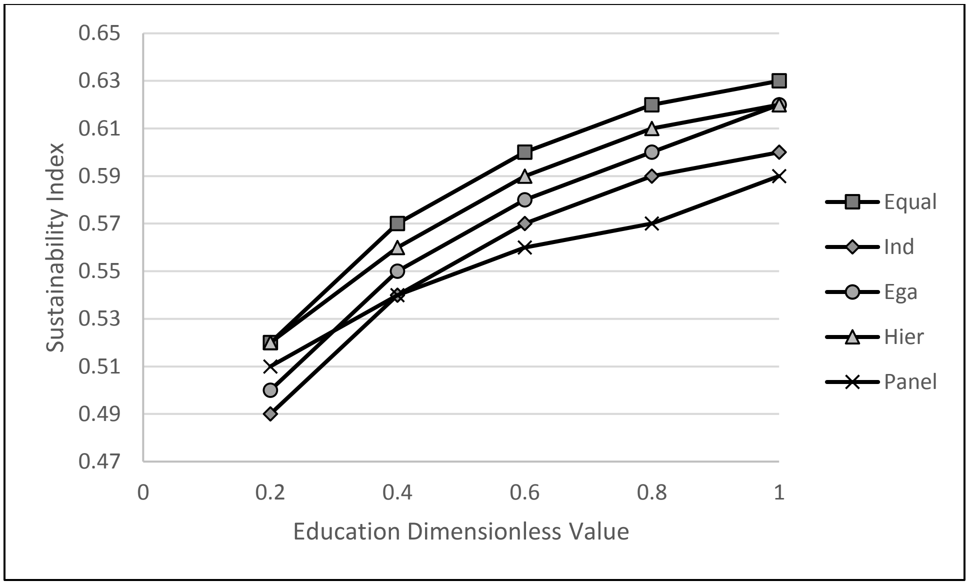

Figure 5.17 Variation of the solar PV sustainability index with respect to the education dimension

The lowest sustainability index score resulting from this dimension's poor performance is 0.49 according to the individualist scheme while the highest score is 0.63 according to the equal weighting scheme. Figure 5.18 shows the impact of the Size factor and its variation on the sustainability index.

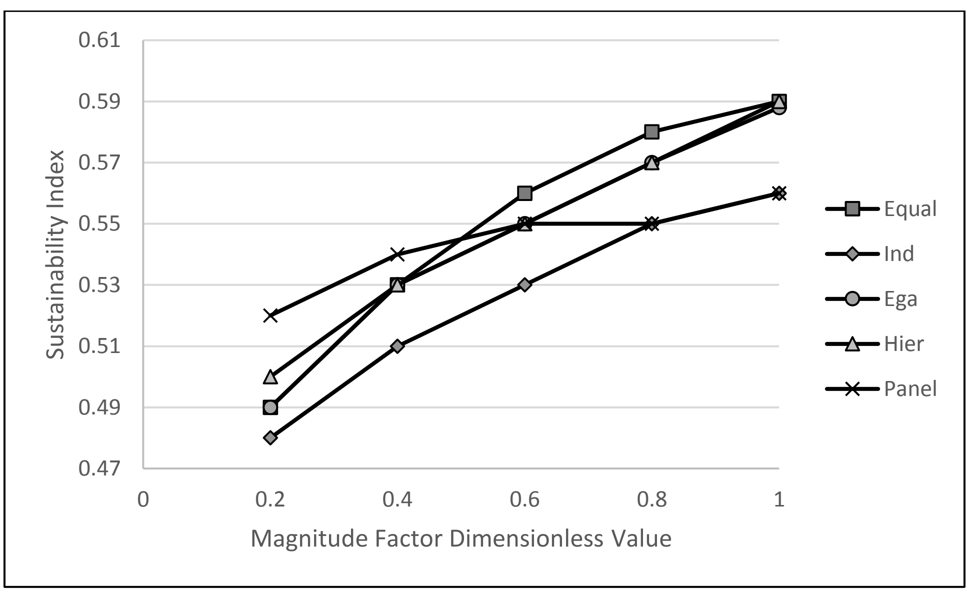

Figure 5.18 Variation of the solar PV sustainability index with respect to the Size factor dimension

Interestingly, according to the panel method, increases of performance of the Size factor from 0.6 to 0.8 results in the same sustainability index score. Furthermore, equal weighting method results in the second lowest sustainability index score when the dimensionless value is low. However, when it surpasses 0.6, the equal weighting method results in the highest sustainability index score.

According to Table 5.5, social, technology and environment dimensions were the most prominent and had unique importance coefficients with respect to the individualist-weighting scheme. Their impact on the sustainability index is presented in Figure 5.19

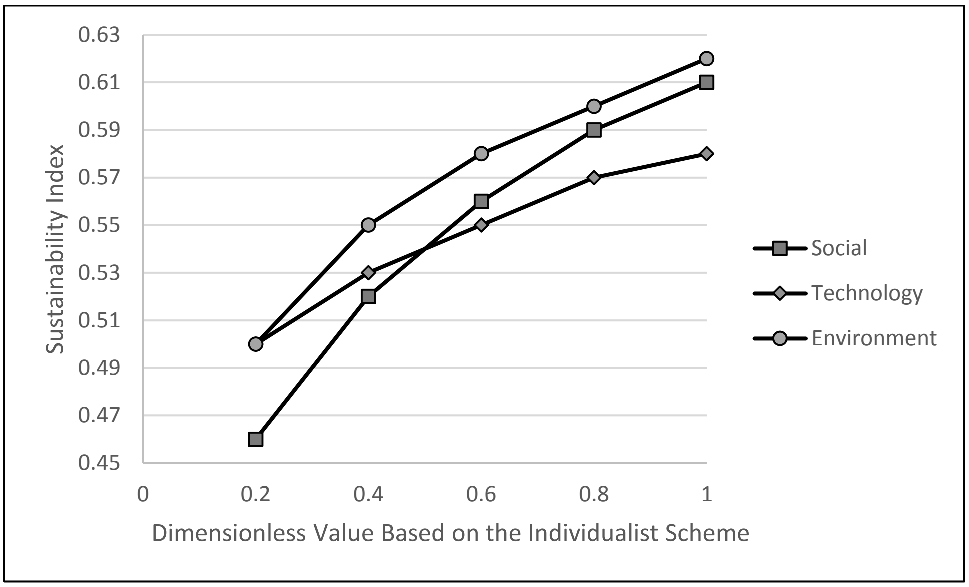

Figure 5.19 Variation of the solar PV sustainability index with respect to various dimensions based on the individualist scheme

According to the individualist scheme, social dimension is the most important among all other dimensions. However, it is observed that social dimensionless values lower than 0.4 result in the lowest sustainability index scores with respect to the other dimensions. Social dimensionless values higher than 0.4 cause steady increase in sustainability index. However, it is evident that the environment dimension, which considered less important result in higher sustainability index scores for this scheme than the social dimension. Furthermore, as the environment dimensionless value increased, sustainability index also steadily increases with the environment dimension being the one which yields the highest sustainability index among the other two dimensions. Lastly, technology dimension was rated the lowest according to the individualist scheme and thus its effect on the sustainability index is observed through a less steep and linear graph. Figure 5.20 highlights key dimensions to reflect the egalitarian scheme and the sustainability index variations.

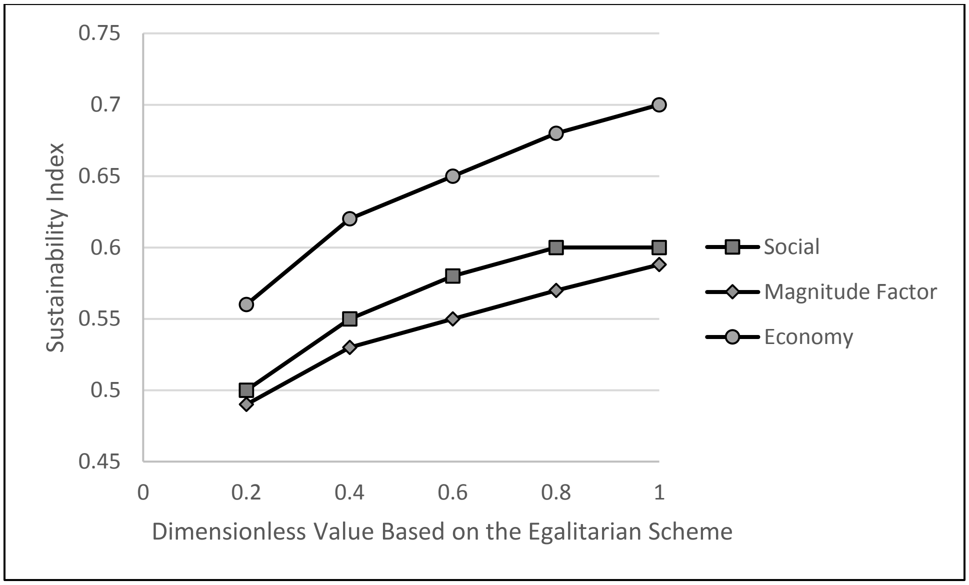

Figure 5.20 Variation of the solar PV sustainability index with respect to various dimensions based on the egalitarian scheme

According to the egalitarian scheme, economy dimension was considered the most important dimension followed by other dimensions such as social dimension while the Size factor was considered the least important dimension effecting sustainability of solar PV. Figure 5.20 clearly resembles this categorization and the relationship of each dimension to the sustainability index score. In this figure, economy dimension yields the highest sustainability index scores followed by social dimension and lastly the Size factor dimension. Figure 5.21 highlights the hierarchist scheme and the key dimensions with respect to the sustainability index. The hierarchist scheme considers the environment dimension to be the most important followed by economy and social dimensions. In Figure 5.21, it is obvious that the changes in economy dimension result in higher sustainability index score as opposed to social or environment dimensions. The economy dimension line is steeper, and then becomes steadier followed by another steepness as values approach 1.

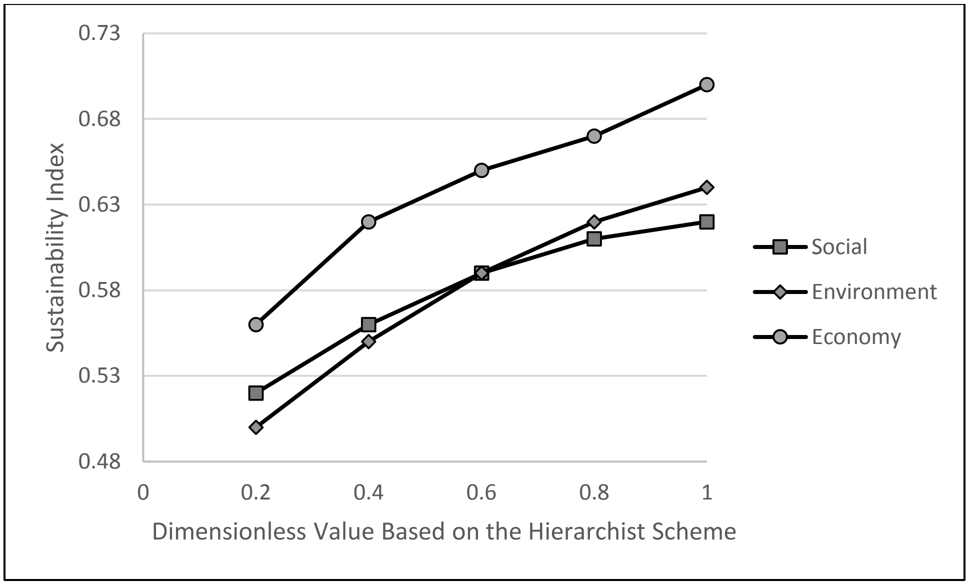

Figure 5.21 Variation of the solar PV sustainability index with respect to various dimensions based on the hierarchist scheme

Moreover, environment dimension is ranked second in yielding higher sustainability index score, however, that is only true when the environment dimensionless value is higher than 0.4. If not, the social dimension becomes the second in the ranking. Figure 5.22 presents the panel method and the variation of sustainability index scores with respect to key dimensions.

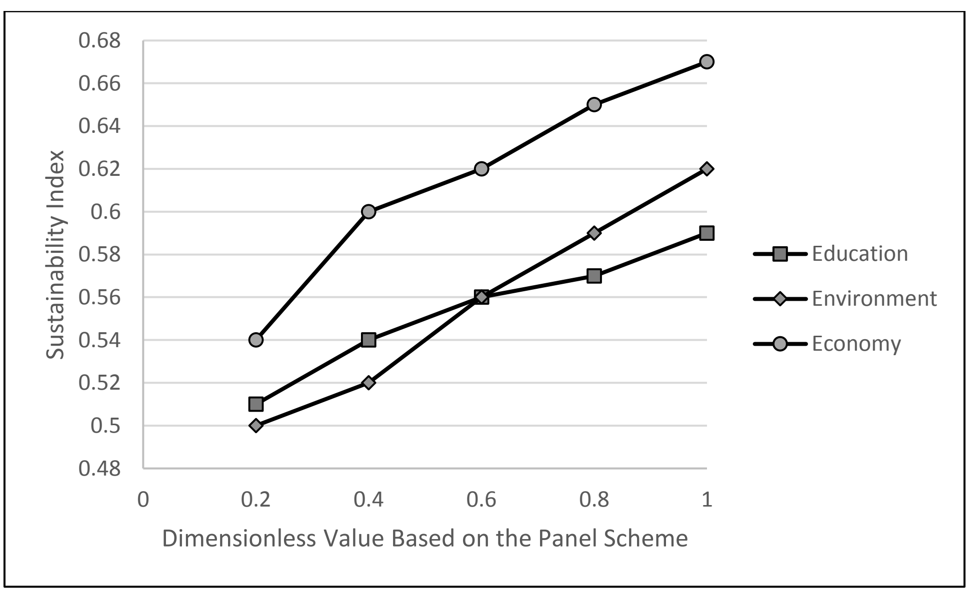

Figure 5.22 Variation of the solar PV sustainability index with respect to various dimensions based on the panel scheme

The panel method rated the environment dimension to be the most important of all dimensions with importance coefficient of 0.18 while the economy dimension was 0.14 and the education dimension was 0.09. Figure 5.22 shows conflicting results compared to the importance ranking. While the environment dimension has the highest importance coefficient, the economy dimension is the one that yields higher sustainability index scores with steeper effect when the dimensionless value is between 0.2 and 0.4. On the other hand, the environment performance is only effective when its dimensionless value is higher than 0.4, otherwise, it yields in the lowest sustainability index out of these dimension presented in the figure. Figure 5.23 shows the equal weighting method and key dimensions with their impact on the sustainability index score.

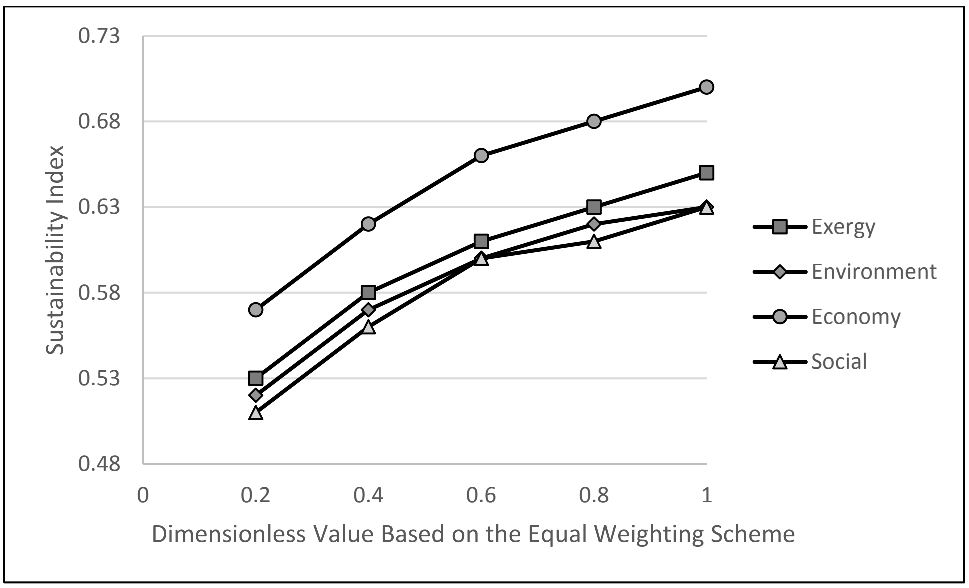

Figure 5.23 Variation of the solar PV sustainability index with respect to various dimensions based on the equal-weighting scheme

Although theoretically, these dimensions presented in Figure 5.23 have equal weights, they vary in their impact on the sustainability index. Repetitively and similar to previous schemes, the economy dimension turns to be the dimension that yields the highest sustainability index scores. The other dimensions show very similar values throughout the changes of the dimensionless values, which reflects the equal weighting phenomena.

5.2.2 Energy & Exergy Performance

Using EES, the solar PV system was designed and simulated to obtain system parameters such as energy and exergy efficiency with respect to various inputs and factors such as irradiance, ambient temperature, and the days of the year. These parameters and their dynamics relationships with energy and exergy efficiencies are important as they project the performance of the system and could shed light on ideas for enhancements of the system and thus the growth of its sustainability in the long term. Figure 5.24 illustrates the relationship of the energy and exergy efficiencies over the course of the year with day 1 being August 1 of a given year.

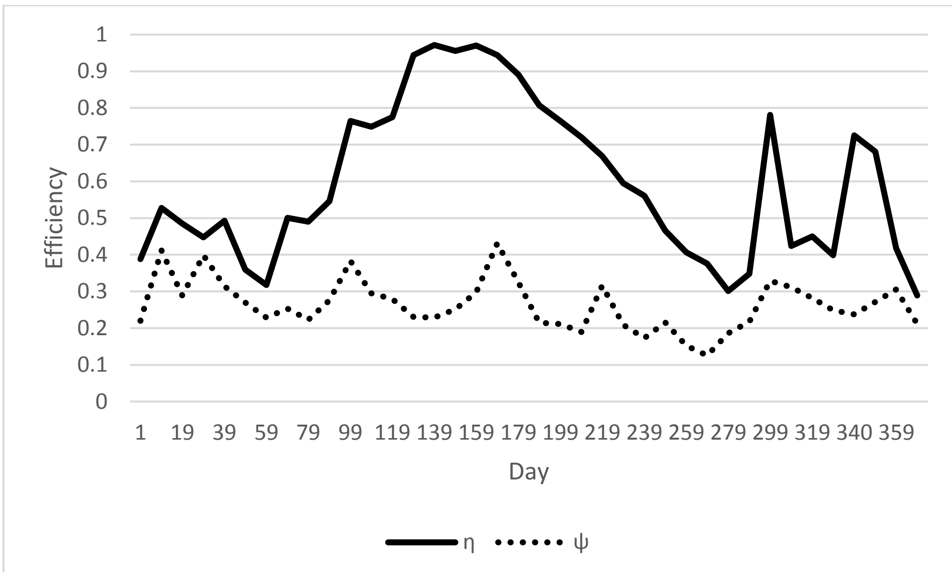

Figure 5.24 Energy and exergy efficiencies for the solar PV system with respect to the days of the year

It is evident that the efficiencies are fluctuating significantly throughout the year. Higher energy efficiencies are obtained in a segment where the efficiency suggests continuous growth between days 59 and peaks at 159. This period represents the months between October and January or the fall season. Thereafter, the efficiency gradually declines in a linear fashion until day 270 where it peaks up again for a shorter term and continuous the fluctuation paradigm. This refer to the beginning of the summer. In summary, the fall season suggests energy efficiency increases while the winter season suggests the opposite. The summer season hosts these significant fluctuations in efficiencies. Furthermore, the relationship between these efficiencies and the power demand per household is presented in Figure 5.25

Energy and exergy fluctuate regularly in response to various household power demand. The energy efficiency approaches 100% on a number of instances while the exergy efficiency is limited between 10% and 40%.

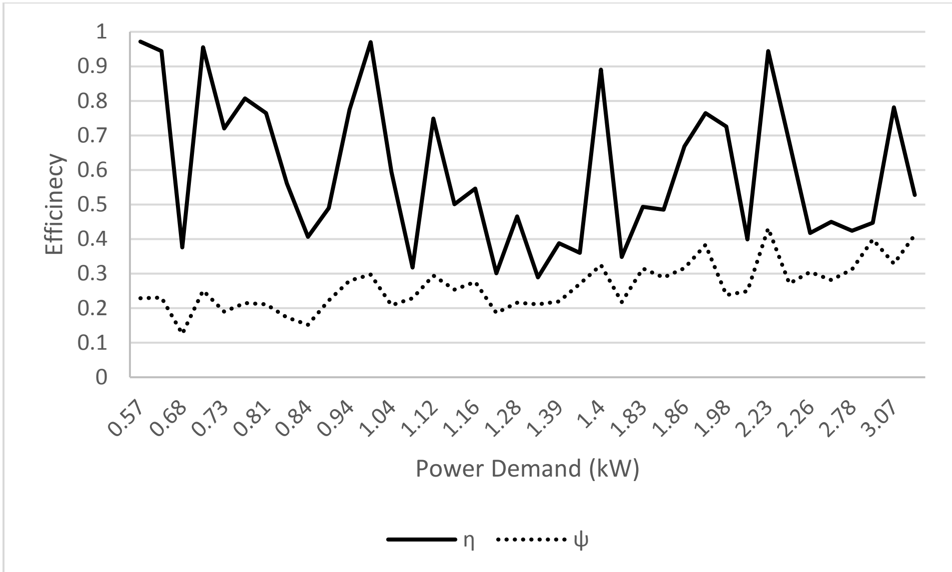

Figure 5.25 Energy and exergy efficiencies for the solar PV system with respect to the household power demand ($\dot{W}$) in kW

The exergy efficiency subtly increases as the power demand increases while the same cannot be observed for energy efficiency. Therefore, it could be speculated that higher power demand in households will gradually and eventually yield in rising exergy efficiencies. Figure 5.26 illustrates the efficiencies performance as the ambient temperature varies from negative to positive values.

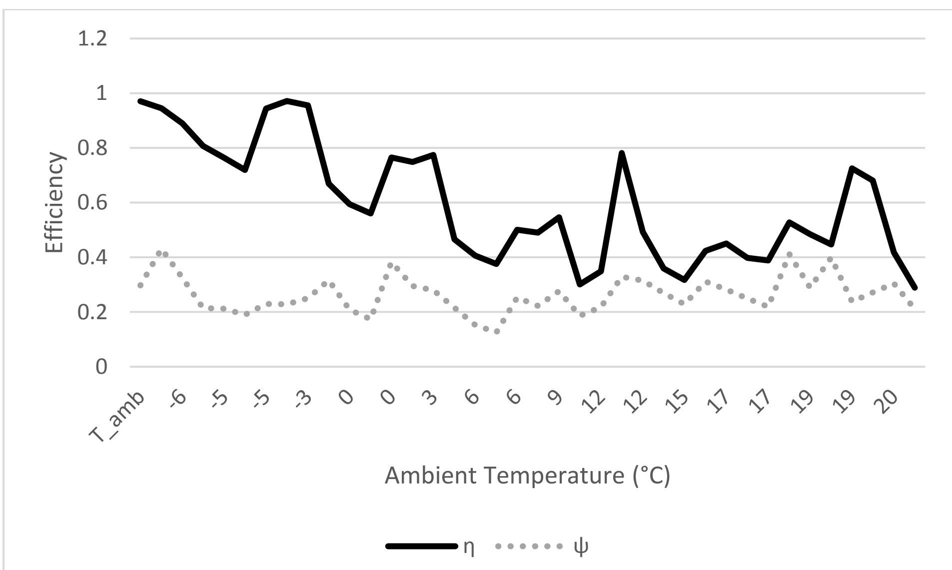

Figure 5.26 Energy and exergy efficiencies for the solar PV system with respect to the ambient temperature (°C)

Energy efficiency fluctuates throughout the range of the ambient temperature; however, its trend suggests a graduate decrease as the ambient temperature rises. It is evident that 100% energy efficiency is only achieved in two instances when the ambient temperature was negative. The energy efficiency fluctuates from 100% to approximately 30% depending on the ambient temperature. As for the exergy efficiency, minimal fluctuations are occurring, with values between 15% and 40%. Figure 5.27 illustrates the relationship between the energy and exergy efficiencies with respect to the changes in solar irradiance.

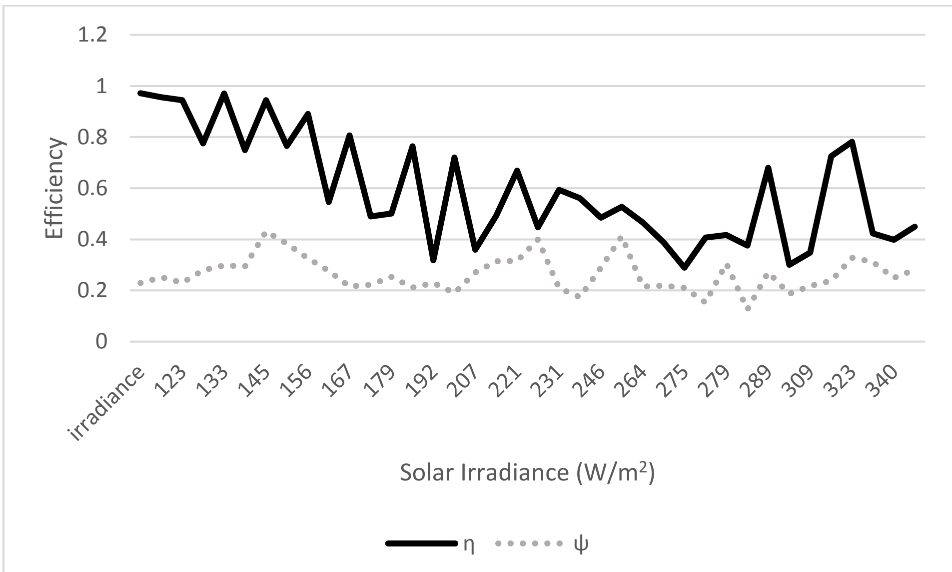

Figure 5.27 Energy and exergy efficiencies for the solar PV system with respect to the solar irradiance (W/m^2).

The energy efficiency is gradually decreasing in a zigzag fashion as the solar irradiance increases from 123 (W/m^2) to 275 (W/m^2). After that, it picks up again and starts to gradually increase as the solar irradiance increases towards 323 (W/m^2). The exergy efficiency's response towards solar irradiance is less radical than that of the energy efficiency. The exergy efficiency is limited to the fluctuation between 15% and 40% throughout the changes of the solar irradiance. Therefore, solar irradiance increase negatively influences the energy efficiency until a certain point, where it becomes beneficial. The range of the solar irradiance presented in Figure 5.27 demonstrates the solar irradiance rates in Ontario.

5.3 Wind System

Wind is a renewable energy source, which relies on the speed of the wind to produce useful energy that could be used for the daily energy demand of the household. Figure 5.28 demonstrates various cut-in wind speeds and the system efficiency from an energy and exergy perspectives.

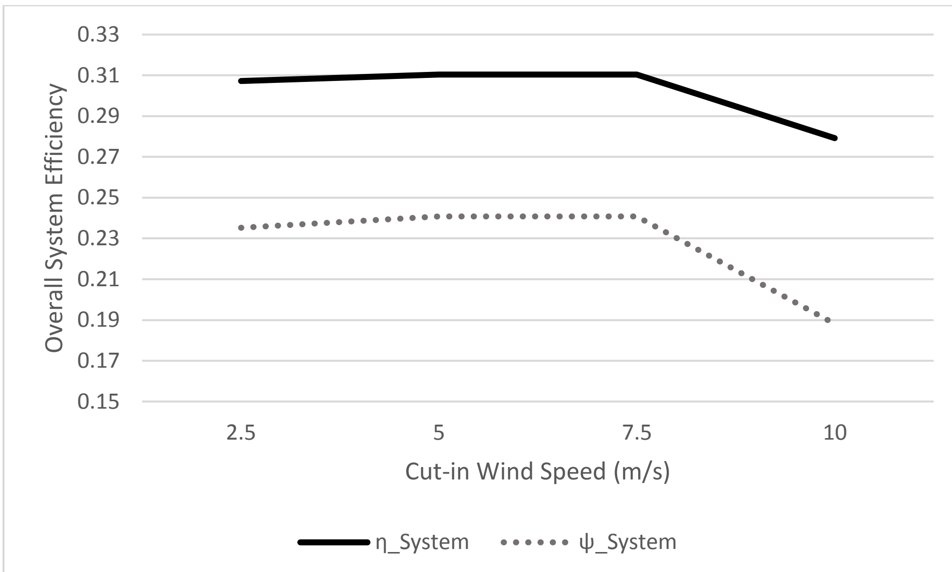

Figure 5.28 Overall system energy and exergy performance with respect to various cut-in wind speeds

The cut-in wind speed has limited impact on the system's energy and exergy efficiencies. That is, as the cut-in wind speed changes from 2.5 m s^{-1} to 7.5 m s^{-1}, both the energy and exergy efficiencies remain constant. These efficiencies start to decline as the cut-in wind speed approaches 10 m s^{-1}. Furthermore, it is evident that the energy and exergy efficiencies behavior with respect to the cut-in wind speed is identical. Figure 5.29 illustrates the relationship of these efficiencies with respect to the cut-out wind speeds. Similar to the cut-in wind speed, the behavior of the energy and exergy efficiencies with respect to the cut-out wind speed is identical. Furthermore, as the cut-out wind speed increases from 15 m s^{-1} to 25 m s^{-1}, system energy and exergy efficiencies increase gradually. However, these efficiencies remain unchanged with further increases to the cut-out wind speed as observed in Figure 5.29. Besides, the energy efficiency fluctuates between 25% and 30% while the exergy efficiency fluctuates between 12% and 24% with respect to changing cut-out wind speeds.

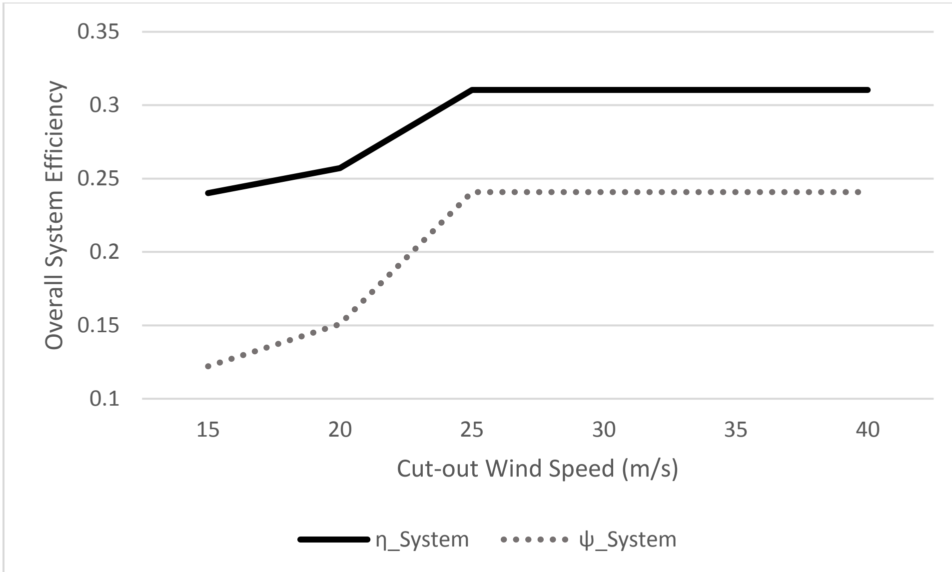

Figure 5.29 Overall system energy and exergy performance with respect to various cut-out wind speeds

The relationship between the rated wind speeds and their effect on the system's energy and exergy efficiencies is presented in Figure 5.30.

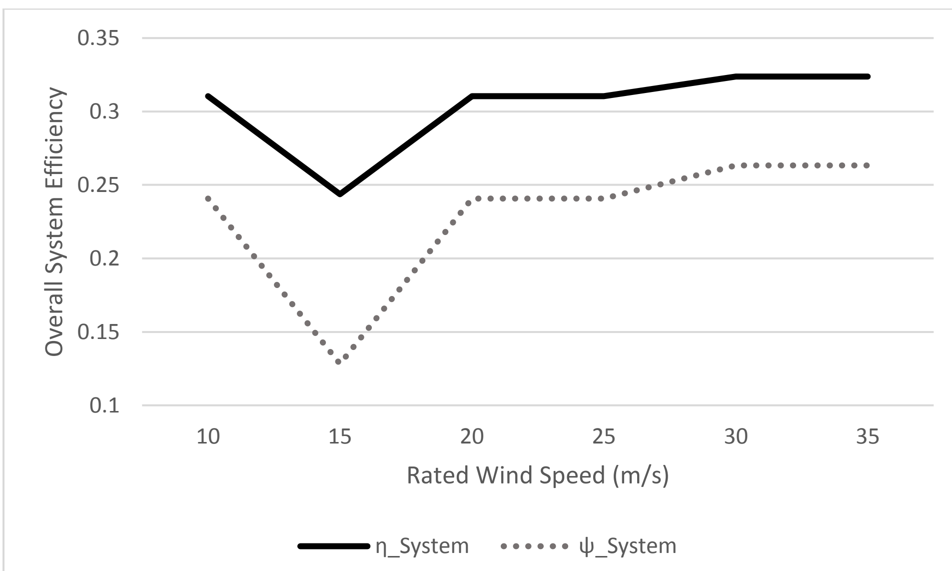

Figure 5.30 Overall system energy and exergy performance with respect to various rated wind speeds

As observed, as the rated wind speeds increase from 10 m s^{-1} to 15 m s^{-1}, the efficiencies decline. However, as the rated speeds increases once more from 15 m s^{-1} to 20 m s^{-1}, the efficiencies move back to their initial values. As the rates speed increases beyond 20 m s^{-1}, the increase in energy and exergy efficiencies of the system is very subtle and almost negligible. The trend can be categorized as constant. Another input parameter that can be adjusted when it comes to wind energy is the wind turbine mechanical efficiency. Figure 5.31 demonstrates the relationship between the changes in wind turbine mechanical efficiency and their impact on the system's energy and exergy efficiencies.

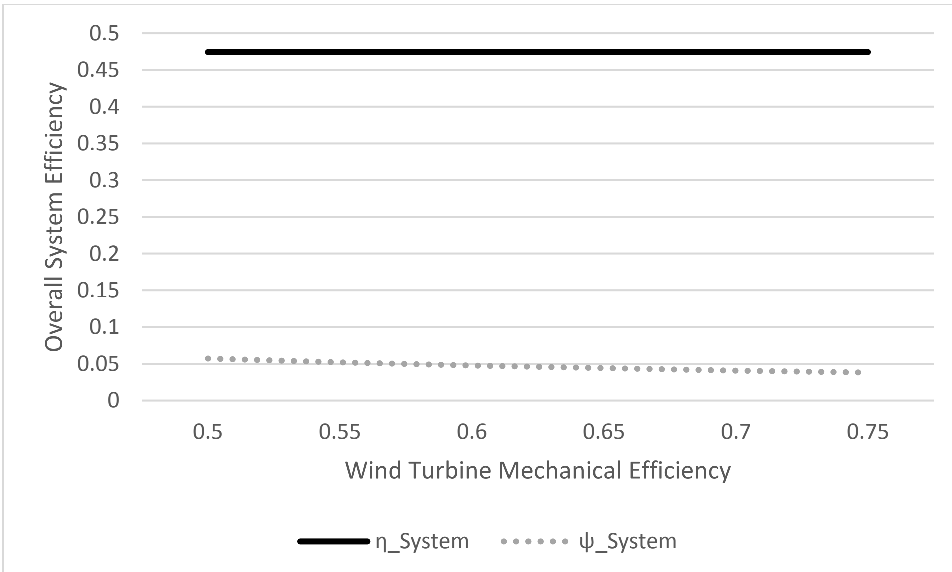

Figure 5.31 Overall system energy and exergy performance with respect to various wind turbine mechanical efficiencies

Changes in the wind turbine mechanical efficiency has no effect whatsoever on the overall system's energy efficiency. However, it influences the system's exergy efficiency as shown in Figure 5.32. Exergetic efficiency decreases as the wind turbine mechanical efficiency is increased. Values fluctuate between 4% and 6%.

5.3.1 Sustainability Assessment

The final sustainability index for the wind energy system proposed in this thesis is presented in this section with further discussion and analysis of the results and the methods used to obtain these results. At first, since wind and solar PV energy systems are both renewable and share some similarities concerning environmental performance and other factors, the sustainability index may be similar. Table 5.8 indicate the sustainability index using both aggregation methods as discussed earlier with respect to each weighting scheme.

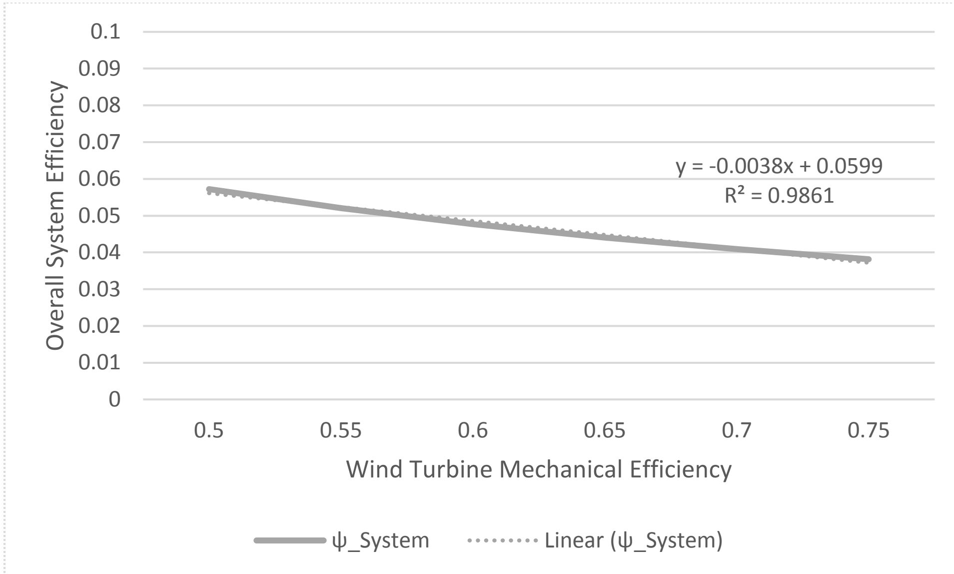

Figure 5.32 Overall system exergy performance with respect to various wind turbine mechanical efficiencies

Similar to the solar PV results, the dynamics between the WAM and the WGM in deriving the sustainability index for this case study are evident. The WAM present values that are spread out with the lowest index being 0.51, which is the individualist assessment while the highest index is 0.60, which is the assessment using equal weighting.

Table 5.8 Final sustainability index of Wind system using various weighting and aggregation methods

Scheme	Sustainability Index (WGM)	Sustainability Index (WAM)
Panel	0.56	0.57
Individualist	0.55	0.51
Egalitarian	0.57	0.53
Hierarchist	0.58	0.53
Equal	0.58	0.60

Furthermore, the equal weighting scheme and the panel scheme both result in higher result values; whereas the other three schemes yield in a very similar sustainability index for this system. Figure 5.33 shows the various outcomes resulting from the WAM and the WGM aggregation from the perspective of various schemes.

On the other hand, the WGM is a better illustration of the sustainability results, which was also the case when assessing solar PV. It is evident that values resulting from the use of WGM are more precise and accurate than the values of the WAM.

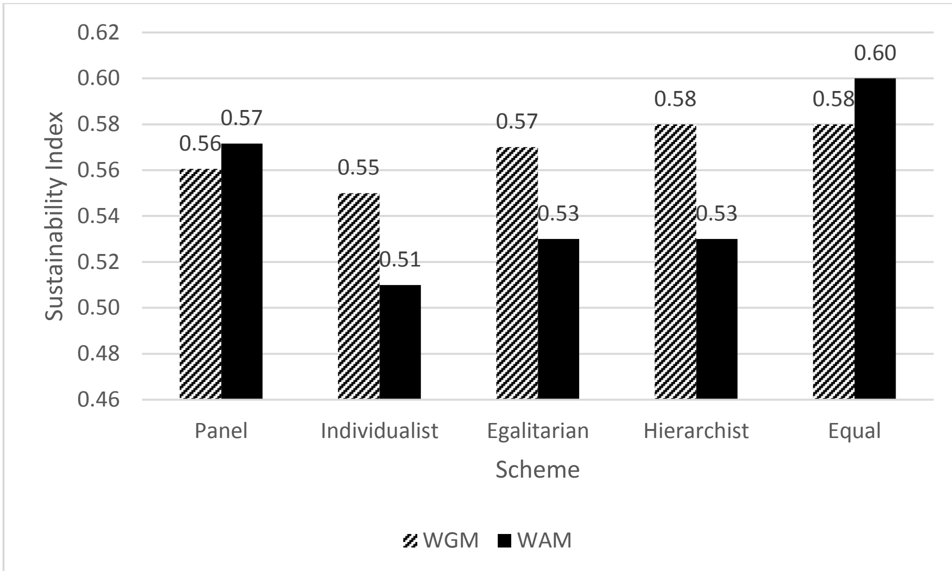

Figure 5.33 Distribution of the sustainability index results based on the various aggregation method and characterization scheme for the wind energy system

Furthermore, the variation factor of the sustainability index for the wind energy system is only 0.03, which is favorable as it reflects accuracy, consistency and good performance. Additionally, the sustainability index for the wind energy system from the various schemes using the WGM are presented in Figure 5.34. The panel method and the individualist scheme also share some similarities in their values while the hierarchist and the equal weighting methods resulted with the same value of 0.58 for the sustainability of the wind energy system. On the other hand, the results from the WAM are presented in Figure 5.35, illustrating the variety of values between 0.51 and 0.60 for the sustainability index of the wind energy system in this case study. Once again, a similar trend to the solar PV results can be observed with the results presented in Figure 5.35, where the panel and equal weighting schemes yield in higher sustainability index values while the other three schemes yield in similar values. In fact, the hierarchist and egalitarian schemes both resulted in the value of 0.53 for the sustainability assessment of the wind energy system in this case study. Moreover, the impact of various dimensions on the sustainability index is further analyzed by extracting the WGM of each dimension when they are at a dimensionless value between 0.2 and 1.

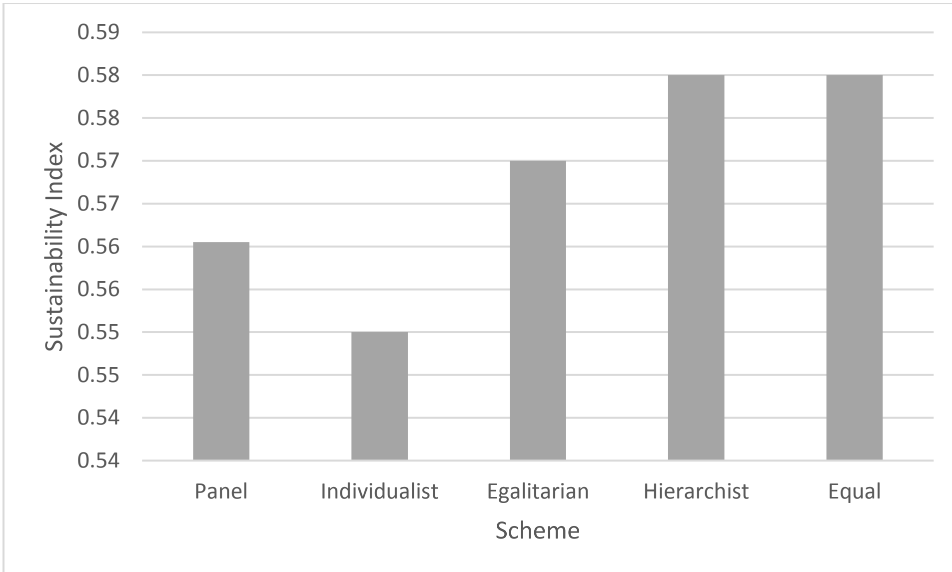

Figure 5.34 Distribution of the sustainability index results based on WGM and characterization schemes for the wind energy system

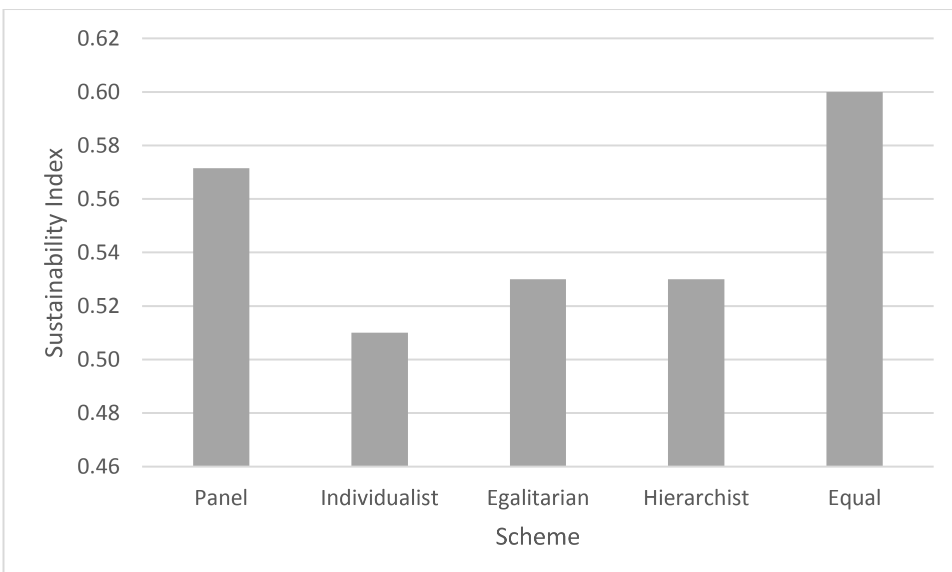

Figure 5.35 Distribution of the sustainability index results based on WAM and characterization schemes for the wind energy system

Overall, the steady and linear relationship between sustainability index score and changes to the energy dimensionless value highlights that higher value for the energy dimension results in higher sustainability index and vice versa in approximately a linear fashion.

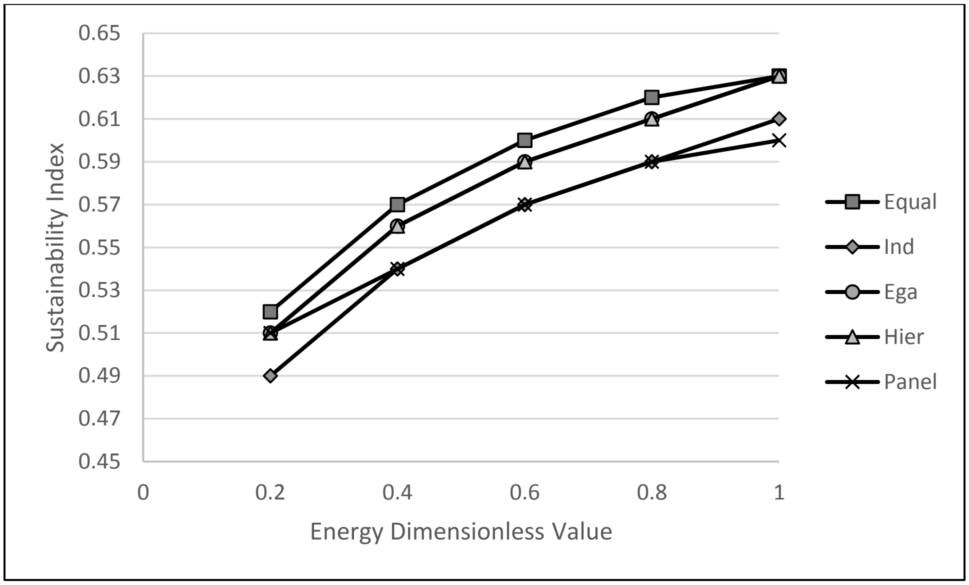

Figure 5.36 Variation of the wind system sustainability index with respect to the energy dimension

On the other hand, Figure 5.37 illustrates the variation of sustainability index score with respect to the exergy dimension. Similar to the energy dimension, the dynamics of the egalitarian and hierarchist schemes with respect to sustainability index score are the same. The equal weighting method yields the highest sustainability score for this dimension. The panel method has a steeper slope with increase in value from 0.2 to 0.4 and then is steadier afterwards. This reflects that in exergy dimension, dimensionless value increase from 0.2 to 0.4 are more critical than other variable increases when assessing the sustainability index score. Furthermore, the relationship of the environment dimension and the sustainability index is shown in Figure 5.38. For the environment dimension, the individualist and egalitarian schemes have almost exactly the same relationship with sustainability index score. Moreover, the panel method yields the lowest sustainability index scores as the environment dimensionless value increases between 0.2 and 0.6. All in all, the general trend is positive linear relationship, which translates to the importance of having a higher dimensionless value for the environment dimension in order to obtain the higher sustainability index of 0.62 for this wind system. In addition, the economy dimension's relationship with sustainability index is illustrated in Figure 5.39. Similar to the exergy dimension, all schemes demonstrate a steady linear relationship between the economy dimensionless value and the sustainability index score.

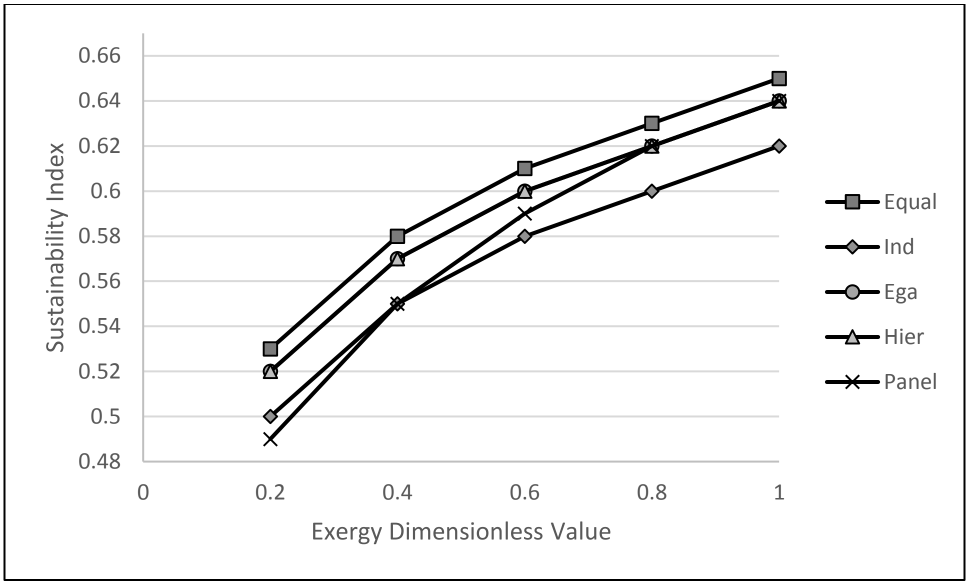

Figure 5.37 Variation of the wind system sustainability index with respect to the exergy dimension

Throughout the values, different scheme meet to suggest the same effect on the sustainability index at that value. For example, the equal weighting method and the hierarchist scheme both result in a sustainability index score of 0.57 when their dimensionless value is at 0.4. Besides, the highest sustainability index score due to the economy dimension for this case study is 0.64, which is suggested by the equal weighting method, egalitarian and hierarchist schemes alike.

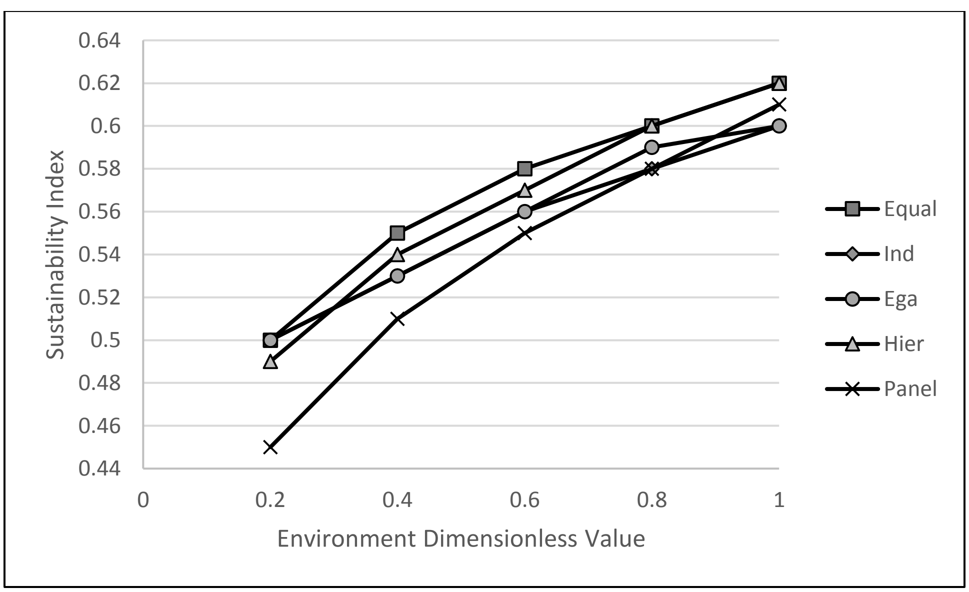

Figure 5.38 Variation of the wind system sustainability index with respect to the environment dimension

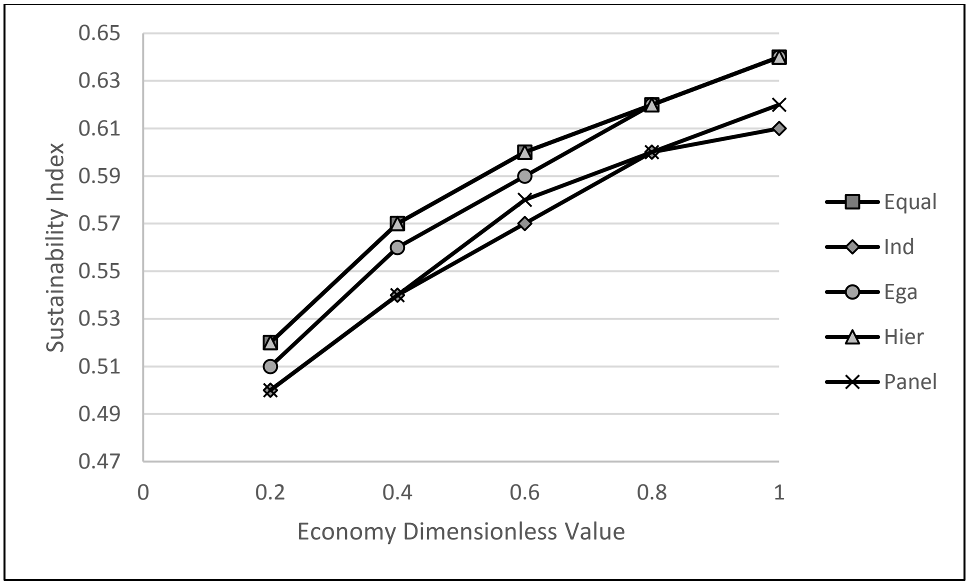

Figure 5.39 Variation of the wind system sustainability index with respect to the economy dimension

The technology dimension also shares similarities with its relationship with the sustainability index score like the exergy dimension. Figure 5.40 presents this relationship in detail. The individualist scheme and the panel method suggest a similar relationship between this dimension and the sustainability index score. On the other hand, the egalitarian and hierarchist demonstrate almost an identical relationship. Overall, the lowest sustainability index score that could result from the poor performance of this dimension is 0.48 while the highest is 0.61. The relationship between the social dimension and the sustainability index score is obtained from Figure 5.41

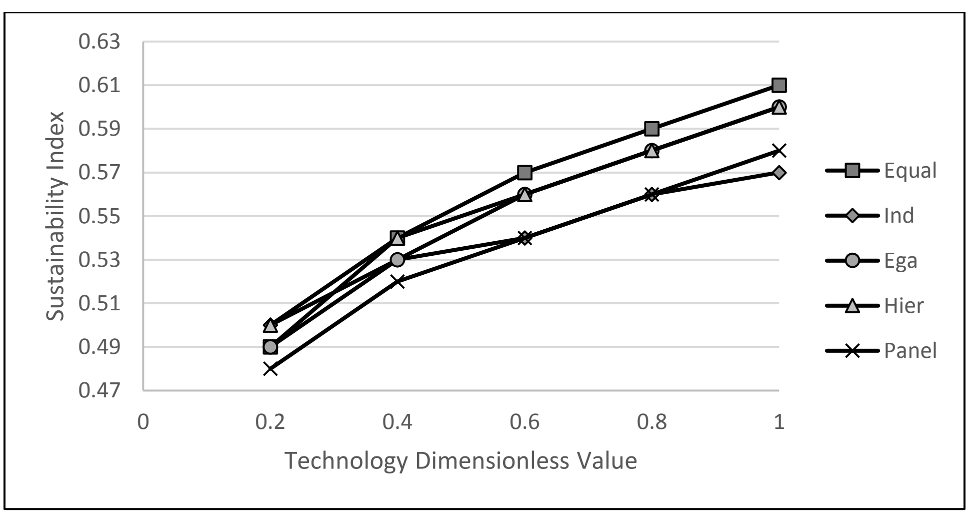

Figure 5.40 Variation of the wind system sustainability index with respect to the technology dimension

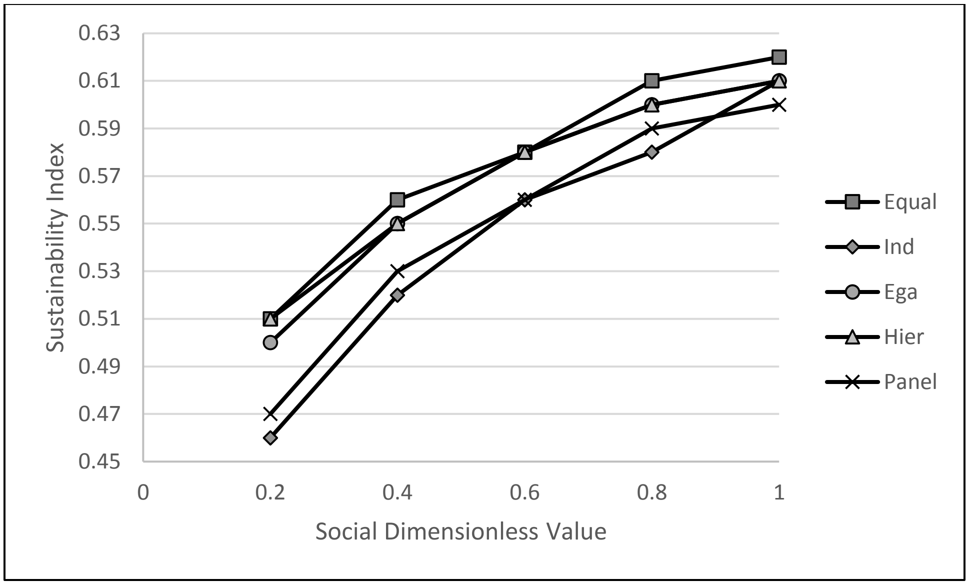

Figure 5.41 Variation of the wind system sustainability index with respect to the social dimension

All schemes suggest that increases in the social dimensionless value from 0.2 to 0.4 has the highest segmental impact on the sustainability index score, that is a jumpy from a score of 0.46 to 0.52 according to the individualist scheme. All schemes also suggest approximately an exact value for the sustainability index score when the social dimensionless value is 0.6, which is 0.57. Besides, the variation in sustainability index score and the education dimension is shown in Figure 5.42. The education dimension also joins exergy and technology in their relationship variations with respect to the sustainability index score. The egalitarian and hierarchist method produce identical estimates and the general trend is a linearly positive relationship, indicating that higher education dimensionless value results in higher sustainability index score. Furthermore, according to the panel method, increases in dimensionless values from 0.6 to 0.8 has very little impact on the sustainability index score whereas increase from 0.2 to 0.4 has a higher impact. Lastly, the Size factor dimension and its relationship with the sustainability index is presented in Figure 5.43. It is important to notice the linear relationship between the panel method and the sustainability index score. This suggests that increase in this dimensionless value results in a linear and predictable increase on the sustainability index score.

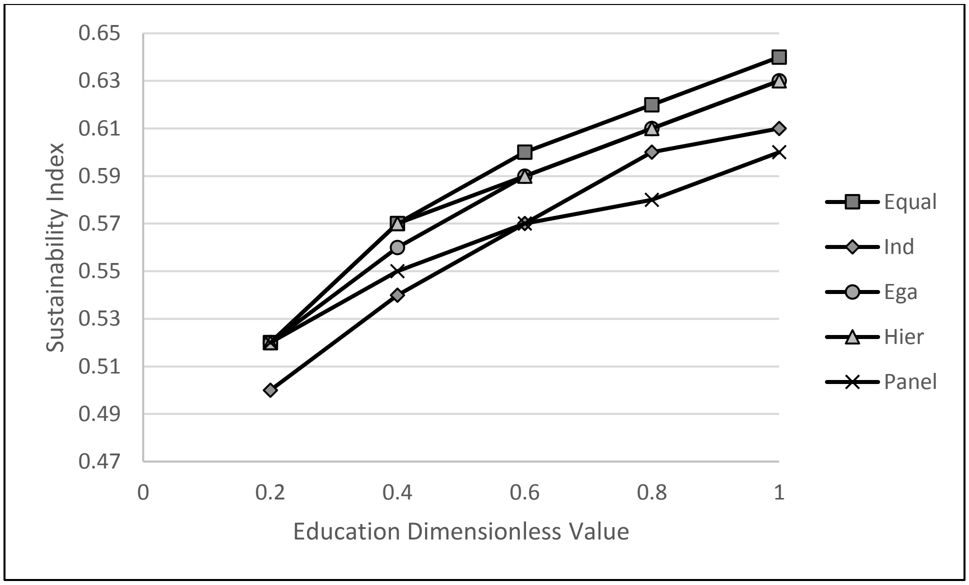

Figure 5.42 Variation of the wind system sustainability index with respect to the education dimension

Moreover, the sustainability index score due to this dimension varies between 0.47 and 0.58, which signifies little importance of this dimension according to other dimensions, which achieved higher sustainability index score. All schemes suggest that value increase from 0.2 and 0.4 yield in larger increase for the sustainability index score.

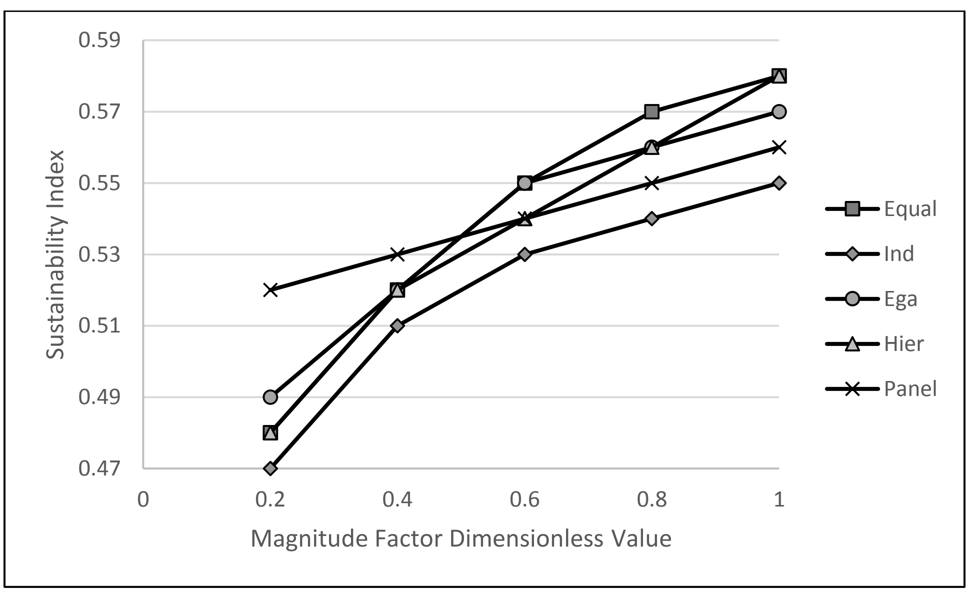

Figure 5.43 Variation of the wind system sustainability index with respect to the Size factor dimension

Moving forward, each characterization scheme is assessed using key dimensions based on Table 5.6 with respect to the sustainability index score. Figure 5.44 shows the impact of the social, technology and environment dimensions on the sustainability index.

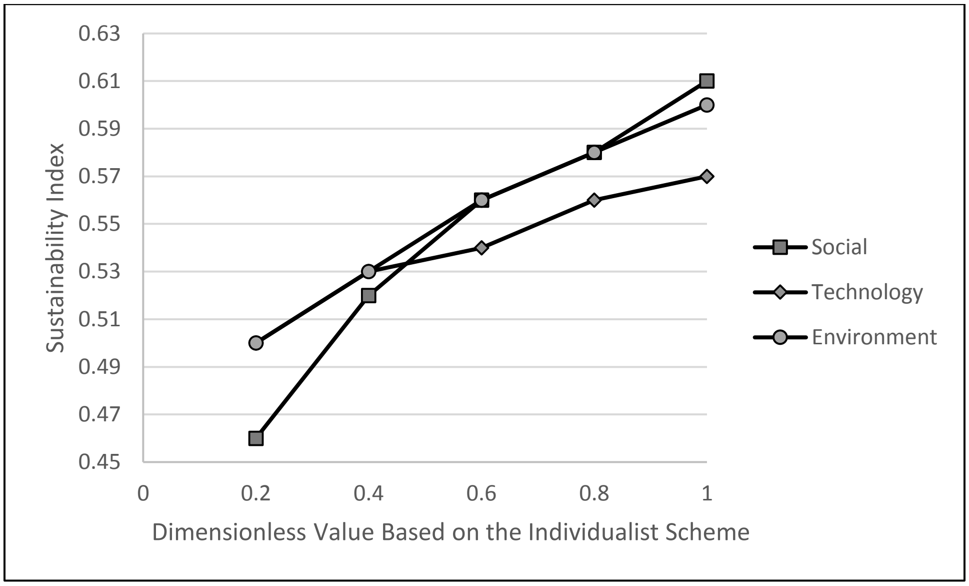

Figure 5.44 Variation of the wind system sustainability index with respect to various dimensions based on the individualist scheme

The variation of sustainability index with respect to the technology and environment dimensions from values 0.2 to 0.4 is identical. It is evident that the social dimension has a higher impact for this scheme on the sustainability index score followed by environment and lastly technology dimensions. Indeed, this scheme gave higher importance to the social dimension followed by environment and lastly the technology dimension. Therefore, the results from Figure 5.44 is consistent with the prioritization of the individualist scheme. Furthermore, social, economy and Size factor dimensions are selected to evaluate the relationship from an egalitarian scheme perspective as illustrated in Figure 5.45. Once again, the results go in line with the prioritization of this scheme. Economy was given the highest importance in this scheme while the Size factor received the lowest. From this figure, it is clear that the impact of these dimensions on the sustainability index score is relative to their importance. Moreover, all of these dimensions have steeper slopes as values increase from 0.2 to 0.6 and they start to become less steep after 0.6. Besides, as the dimensionless value for these dimensions increase, the impact on the sustainability index is more variable from one dimension to another.

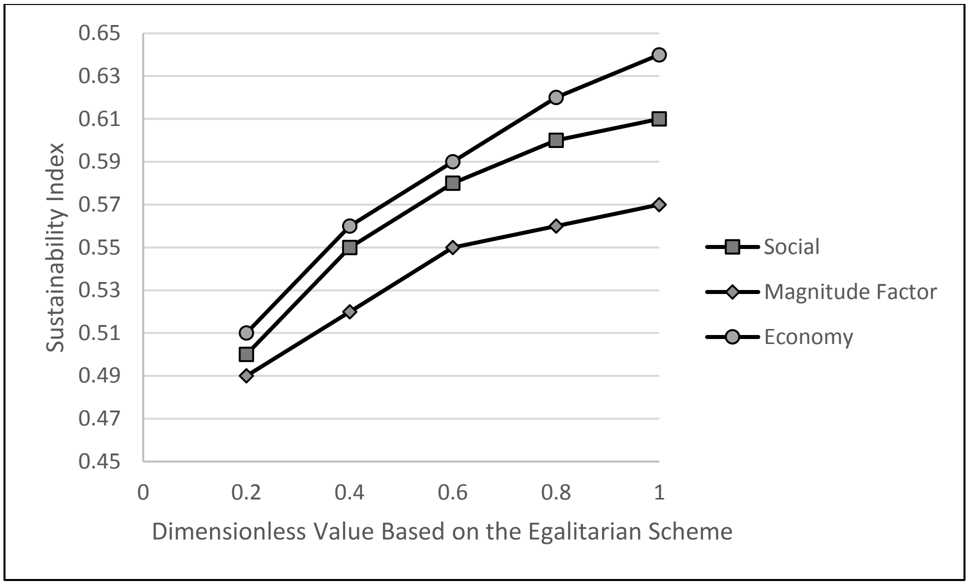

Figure 5.45 Variation of the wind system sustainability index with respect to various dimensions based on the egalitarian scheme

From a hierarchist scheme perspective, social, environment and economy dimensions are analyzed to determine their influence on the sustainability index score. Figure 5.46 demonstrates these relationships in more detail.

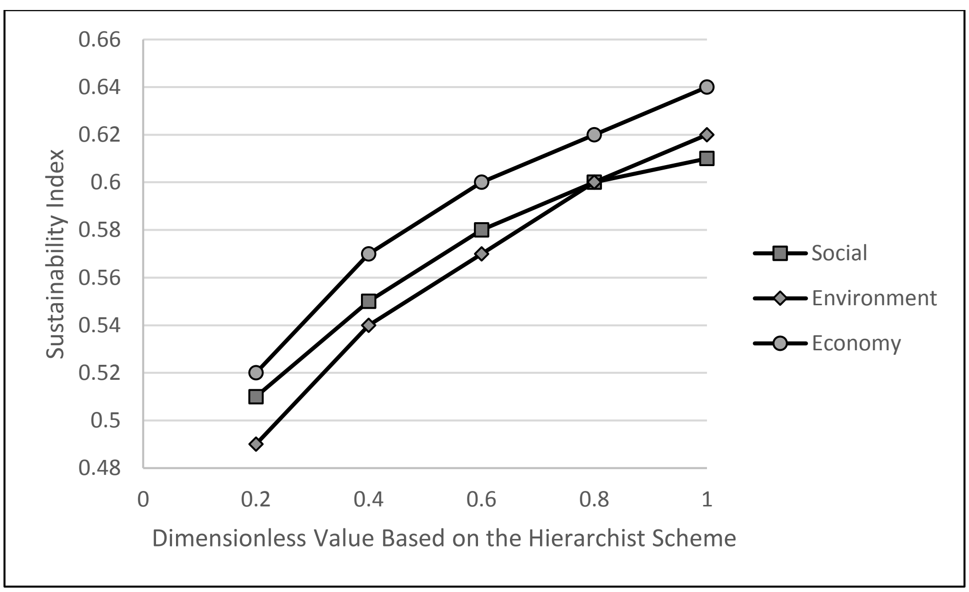

Figure 5.46 Variation of the wind system sustainability index with respect to various dimensions based on the hierarchist scheme

The results from this graph conflicts with the prioritization of the hierarchist scheme. For example, the hierarchist scheme gave highest importance coefficient for the environment dimension, yet its impact on the sustainability index score is the lowest for values between 0.2 and 0.8 when compared to other dimensions. It seems that the economy dimension yields the highest sustainability index scores followed by the social dimension and lastly the environment dimension throughout most of the trend. On the other hand, the panel method demonstrates different dynamics for the environment, economy and education dimensions with respect to their impact on the sustainability index score as presented in Figure 5.50. Moreover, the prioritization of the panel method gave more importance to the environment dimension followed by economy and education dimensions. The dynamics from this figure demonstrate conflicting results with this prioritization as the economy yields the highest sustainability index score when the dimensionless value is higher than 0.6. Furthermore, the education dimension yields the highest sustainability index for values between 0.2 and 0.4. The environment dimension yields in the lower sustainability index score for the values between 0.2 and 0.8. The highest sustainability index in this scheme due to the economy dimension is 0.62 while the lowest due to the environment dimension is 0.45. Lastly, the variation of the sustainability index score in relation to the equal weighting method and selected dimensions is presented in Figure 5.48.

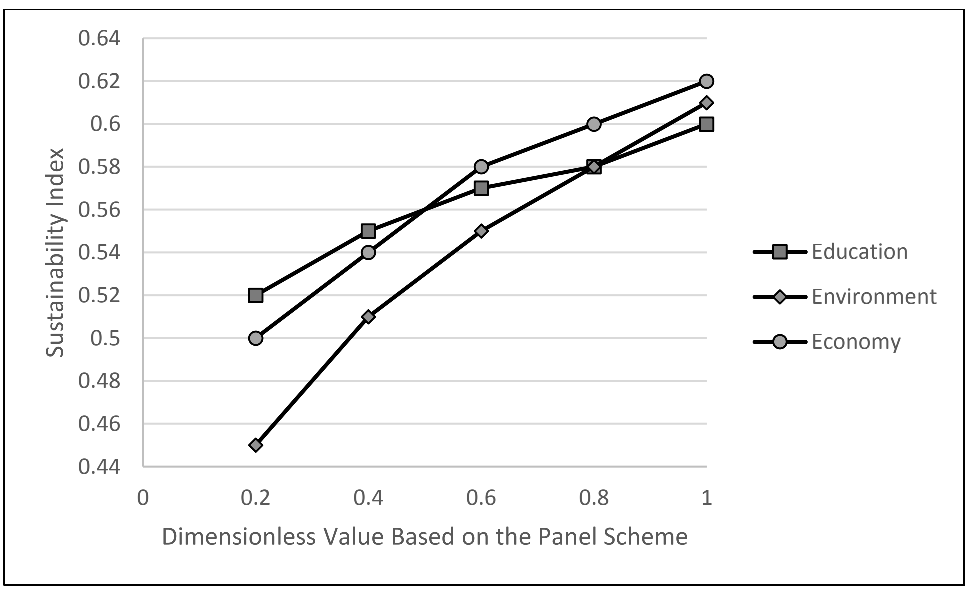

Figure 5.47 Variation of the wind system sustainability index with respect to various dimensions based on the panel method scheme

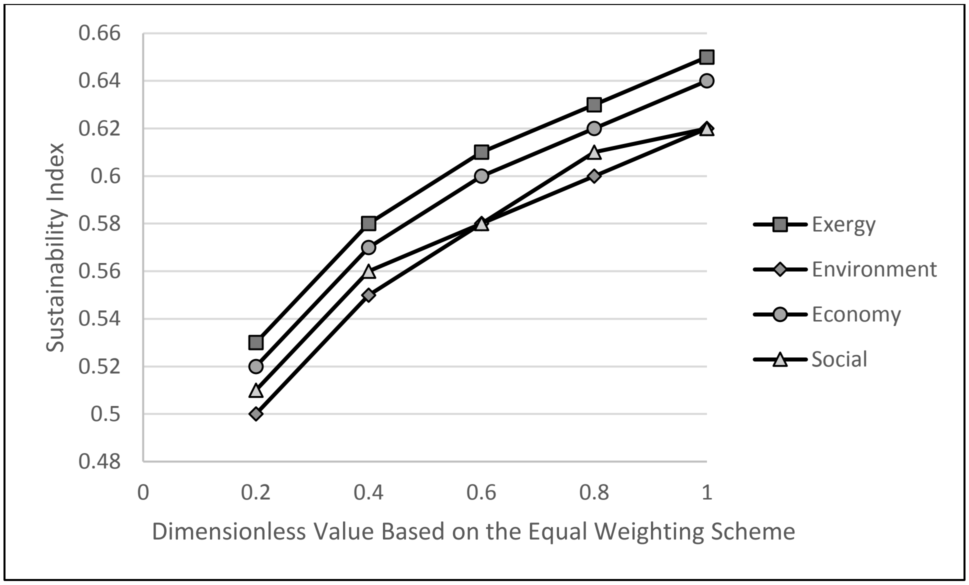

Figure 5.48 Variation of the wind system sustainability index with respect to various dimensions based on the panel method scheme

The results from the figure is in line with the distribution of the importance coefficients using the equal weighting method. The exergy, environment, economy and social dimensions all yield in approximately similar sustainability index scores as the dimensionless value increases for each dimension. Furthermore, the variation in impact is minimal at each dimensionless value, with a difference factor of 0.03 between these dimensions.

5.3.2 Energy & Exergy Performance

Over the course of the year, energetic and exergetic performance of this case study vary. Figure 5.49 illustrates the relationship between these two variables. The fluctuation of the energy and exergy efficiencies with respect to the days are due to seasonal differences. For example, efficiencies are very high between day 45 and 113, which resemble the fall season, considering that day 1 is August 1 of a given year. The beginning of the winter season demonstrates a rapid decrease in efficiencies until day 159. However, as the season continues, the efficiencies increase. Figure 5.50 shows the relationship between the energy and exergy efficiencies with respect to the household power demand.

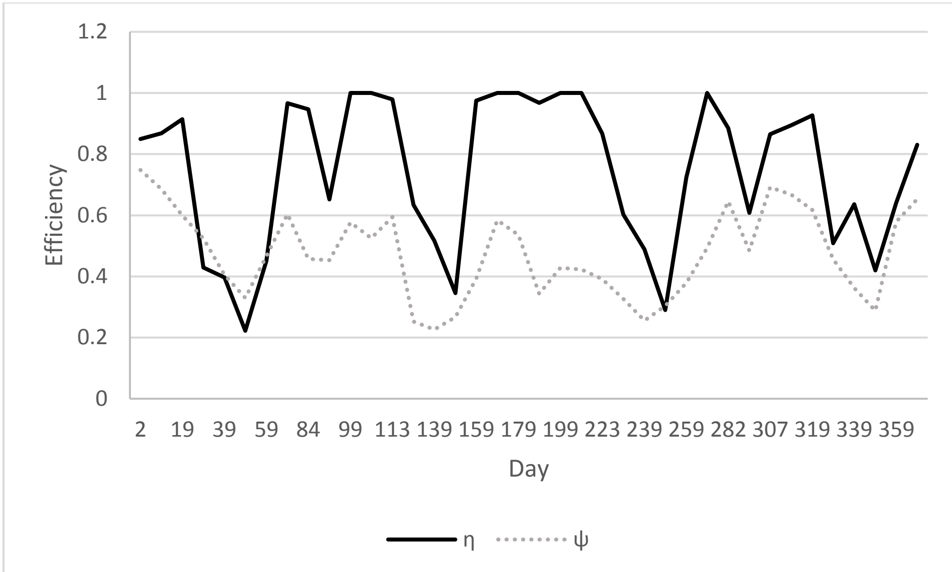

Figure 5.49 Energy and exergy efficiencies for the wind system with respect to the days of the year

Energy and exergy efficiencies fluctuate significantly in response to different household power demands. The energy efficiency changes from 20% to 100% depending on the power demand whereas the exergy efficiency changes between 20% and 70%. Figure 5.51 shows the relationship between the ambient temperature and its influence on the energy and exergy efficiencies.

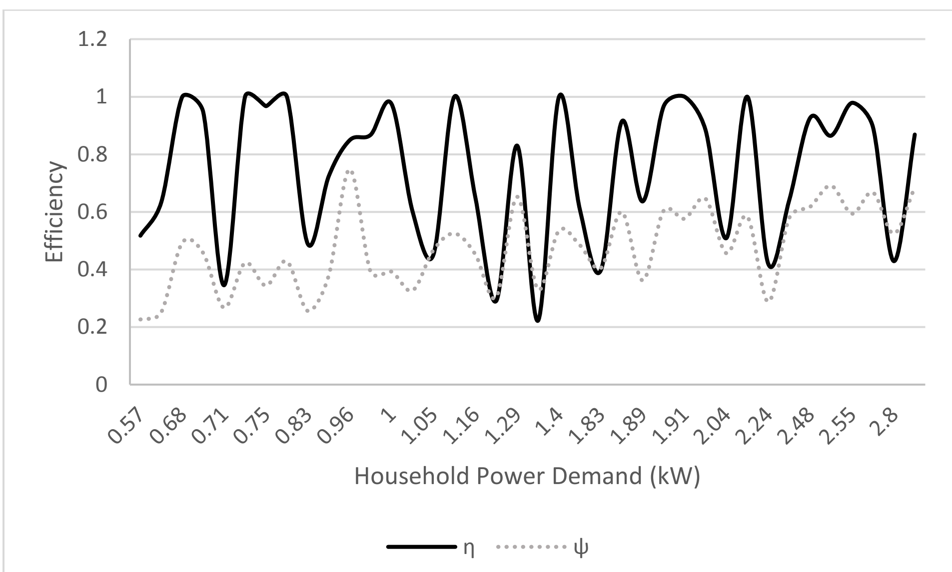

Figure 5.50 Energy and exergy efficiencies for the wind system with respect to household power demand

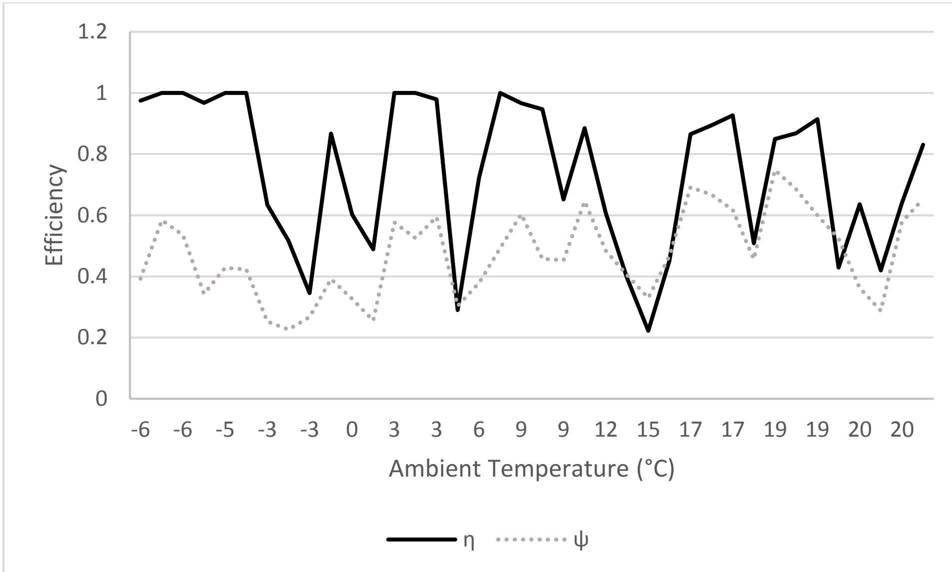

Figure 5.51 Energy and exergy efficiencies for the wind system with respect to the ambient temperature

The ambient temperature does not seem to be parameter that has a clear relationship with energy and exergy efficiencies. Furthermore, the efficiencies oscillate in values as the ambient temperature increases with no clear trend or pattern that can be extracted. Figure 5.52 illustrates the influence of the wind speed over the energy and exergy performance.

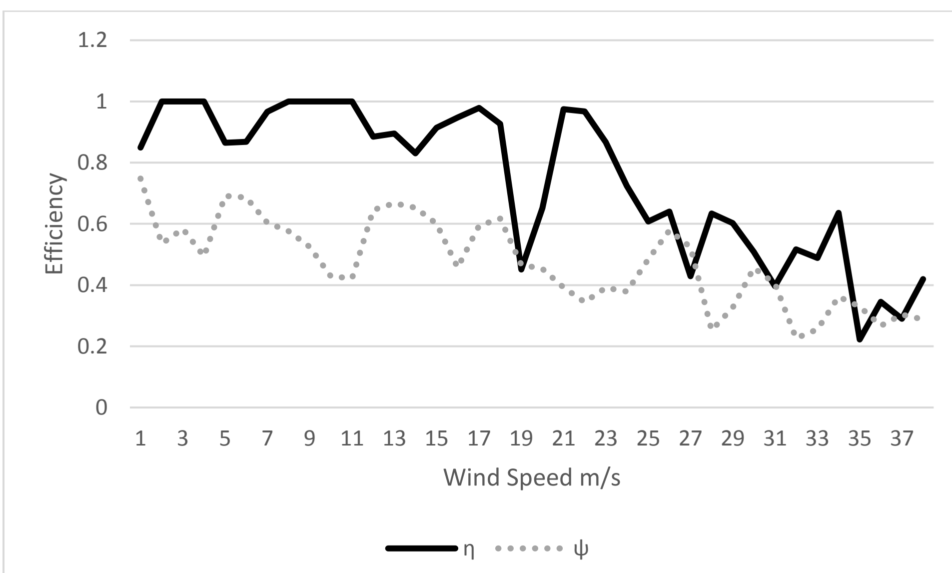

Figure 5.52 Energy and exergy efficiencies for the wind system with respect to the wind speed

The wind speed's relationship with energy and exergy efficiencies varies depending on the speed. As the wind speed increases, the general trend for the energy and exergy efficiencies is to decrease. Wind speeds less than 22 m s^{-1} are characterized with the highest energy and exergy efficiencies. On the other hand, as the wind speed surpasses 22 m s^{-1}, both efficiencies decline rapidly.

5.4 Environmental Performance of Case Studies

In this section, the Lifecycle assessment data is presented for the case studies in relation to a conventional gas-fired system. SimaPro was used to simulate the environmental impacts of these case studies. The systems were assumed to have a lifetime of 20 years and thus the impact presented is reflective of this timeframe. CML 2001 impact method is used along with its accompanying impact categories. Furthermore, these simulations of each energy system were consistent with the size proposed (150 Ontario households) and their annual energy demands including electricity, hot water, cooling and heating. Therefore, the results of this LCA represent the environmental impacts of 150 Ontario households for the period of 20 years using either conventional, solar PV or wind energy systems. Table 5.9 shows the various environmental impacts that each system imposes. It is evident that conventional systems are detrimental to freshwater aquatic ecosystems, air contamination and global warming.

Table 5.9 Environmental impacts for meeting the demand of 150 houses for 20 years of each case study

Impact Category	Unit	Conventional	Solar PV	Wind
Land competition	m2a	1.E+06	4.E+05	2.E+05
Terrestrial ecotoxicity 100a	kg 1,4-DB eq	2.E+04	3.E+03	2.E+03
Freshwater aquatic ecotox. 100a	kg 1,4-DB eq	3.E+07	6.E+06	3.E+06
Human toxicity 100a	kg 1,4-DB eq	2.E+07	1.E+07	1.E+07
Global warming 100a	kg CO2 eq	5.E+07	9.E+06	2.E+06
Ozone layer depletion steady state	kg CFC-11 eq	5.E+00	4.E+00	3.E+00
Abiotic depletion	kg Sb eq	4.E+05	6.E+04	1.E+04
Acidification	kg SO2 eq	3.E+05	4.E+04	9.E+03

Furthermore, if all these values were placed on a 100% stack bar graph, conventional system accounts for more than 80% of acidification, abiotic depletion, global warming, freshwater and terrestrial ecotoxicity. Figure 5.53 presents these values using the 100% stack bar.

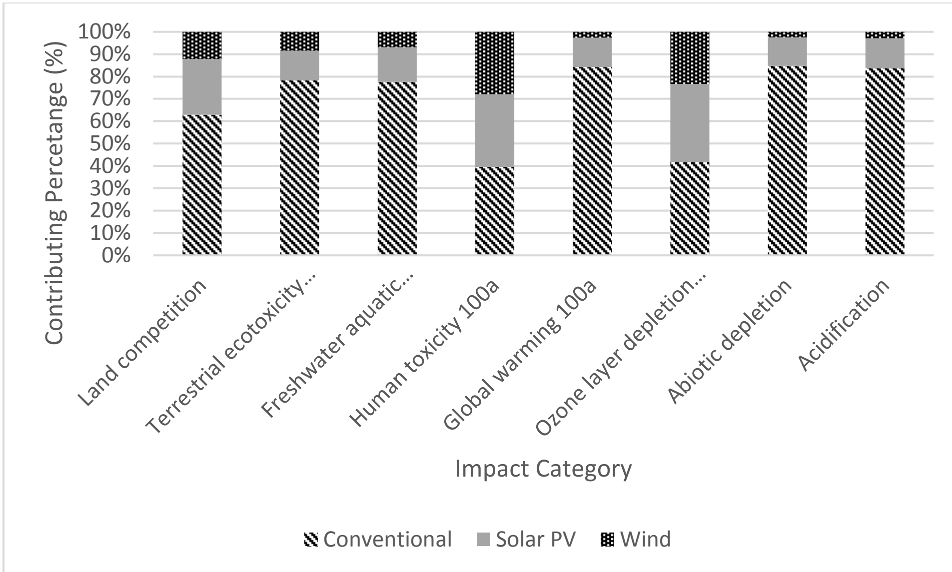

Figure 5.53 Comparison between different case studies and their environmental impact

Solar PV comes after the conventional system in its environmental pollution impact. It also seems that the wind system is the most environmentally friendly option among the three alternatives. This is based on its lowest impact on global warming, acidification, abiotic depletion, freshwater and terrestrial ecotoxicity and the rest of the impact categories. This trend of the conventional system performing worst environmentally followed by solar PV and wind will reoccur in the following graphs for each impact category. Figure 5.54 shows the eutrophication of the solar PV and wind case studies in relation to the conventional system.

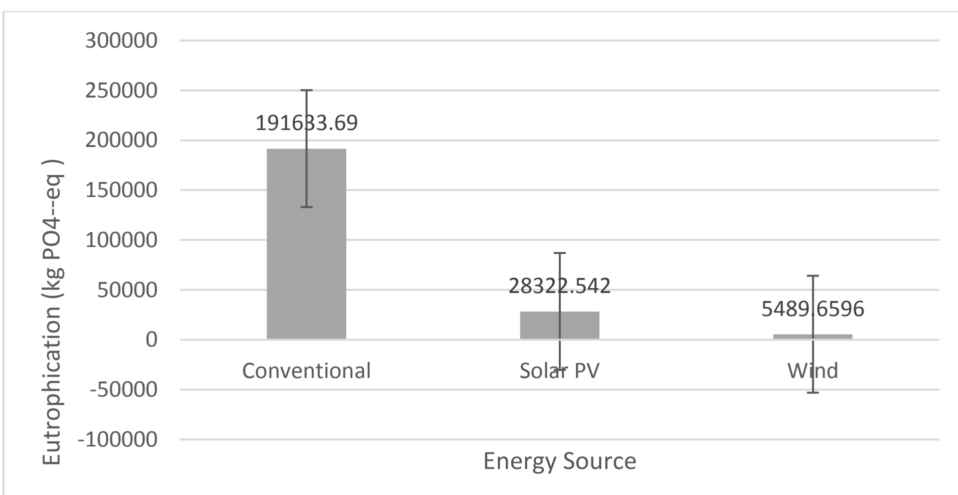

Figure 5.54 Eutrophication of solar PV, wind and conventional energy systems for the duration of 20 years

There is no doubt the renewable energy sources such as solar PV and wind are far better than gas-fired and other conventional energy systems. The difference in Size among the three system is clearly observed in Figure 5.54. Moreover, to supply electricity, heating, cooling and hot water for 150 houses in Ontario, land use is an issue. With this regards, wind systems perform much more efficiently, thus requiring less land area compared to solar and conventional energy systems as illustrated in Figure 5.55.

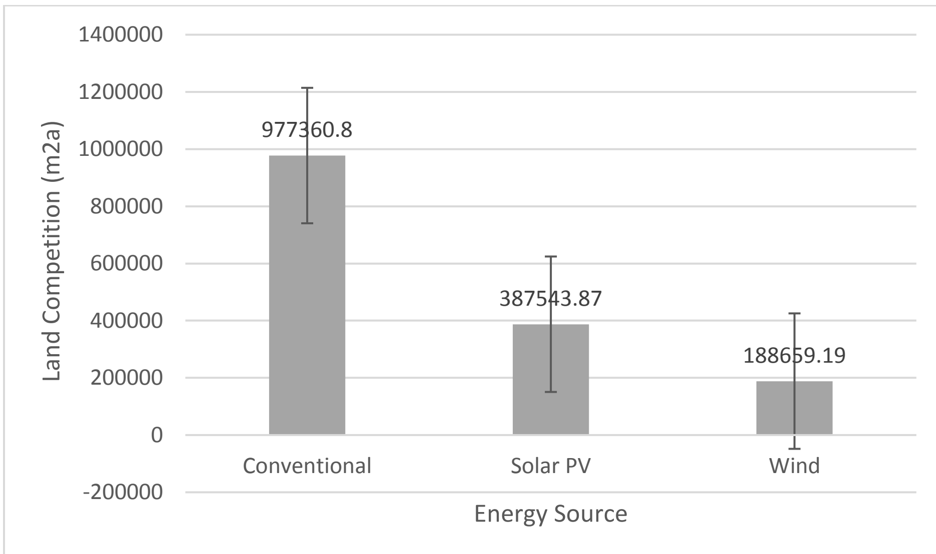

Figure 5.55 Land use of solar PV, wind and conventional energy systems

In addition, air toxicity is another environmental impact, which is considered in this LCA. The impact of wind and solar PV on air toxicity is relatively similar while the conventional system is damaging when it comes to this category. Figure 5.56 illustrates the impact of the three energy systems on air toxicity per 100 years. Water ecotoxicity is another impact category that refers to the biological aquatic ecosystems as well as the quality of aquatic species. The same trend is repetitive here, with the conventional system being the most disadvantageous followed by solar PV and wind. Figure 5.57 shows the relationship between these variables in detail. On another note, human health is effected by these energy systems and thus human toxicity is considered in the LCA with the results illustrated in Figure 5.58.

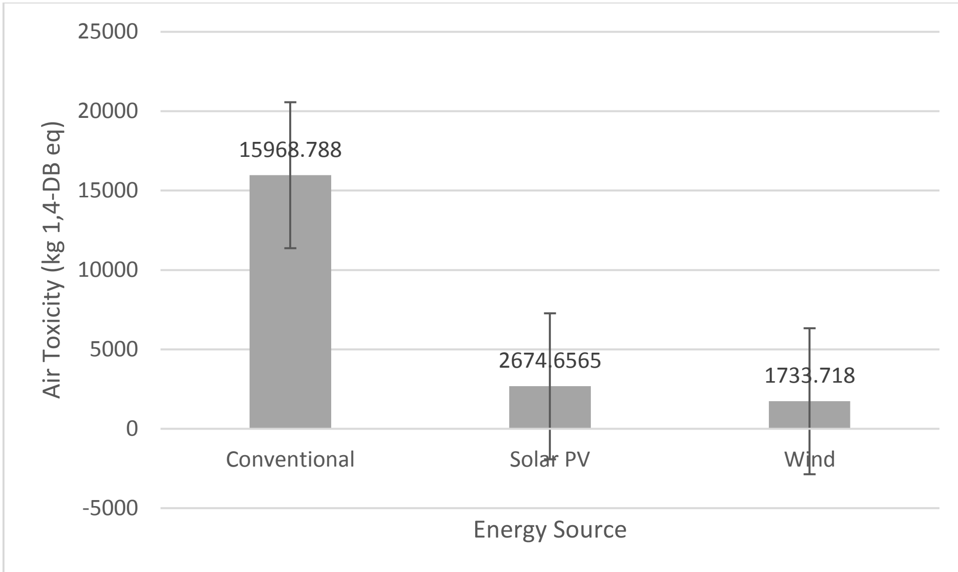

Figure 5.56 Air toxicity of solar PV, wind and conventional energy systems per 100 years

Global warming potential is another important environmental indicator, which is considered a global impact indicator as opposed to other impacts, which are local indicators. The GWP impact of each system vary greatly from the other two alternatives as presented in Figure 5.59.

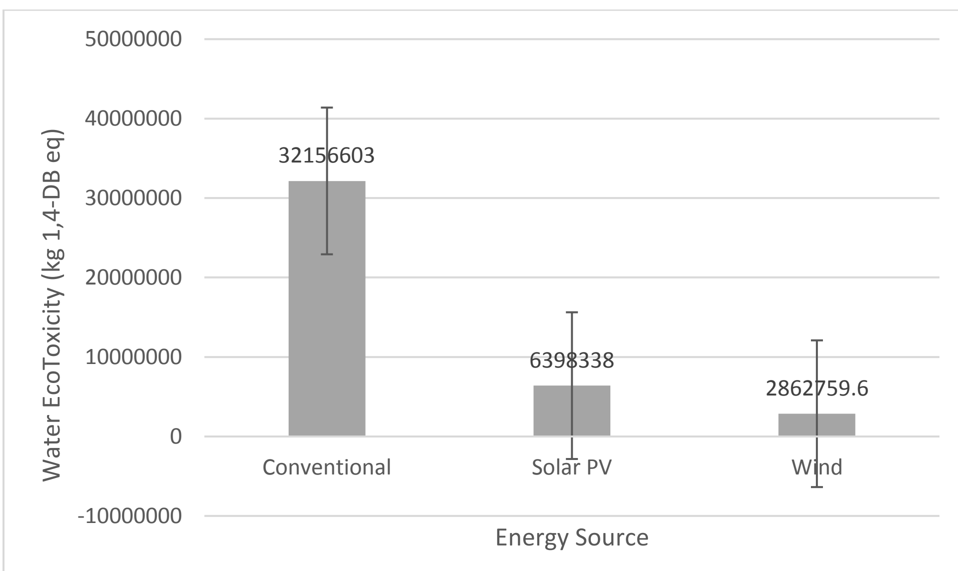

Figure 5.57 Water EcoToxicity of solar PV, wind and conventional energy systems per 100 years

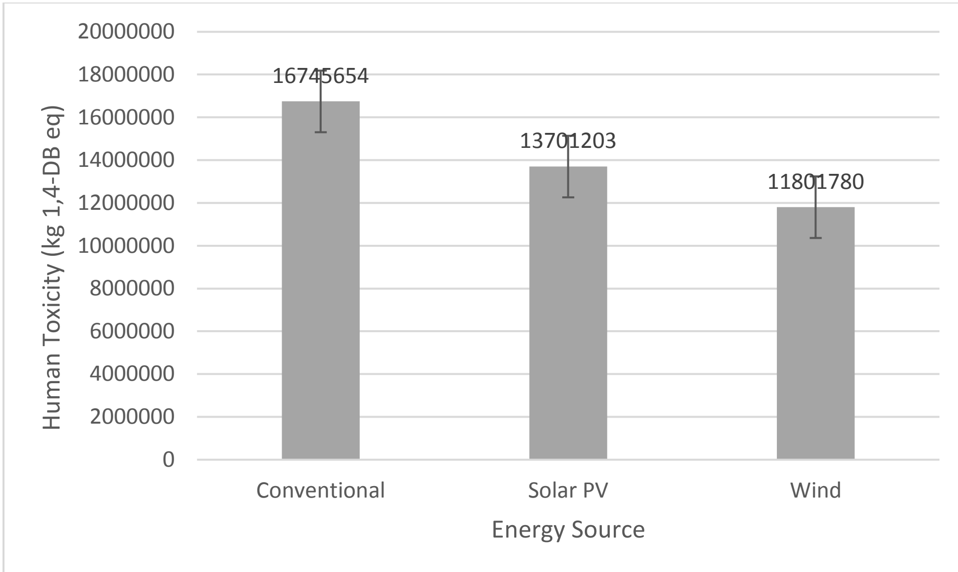

Figure 5.58 Human toxicity of solar PV, wind and conventional energy systems per 100 years

Another global indicator is the ozone depletion. Figure 5.60 presents the steady state of the ozone depletion potential for the different case studies.

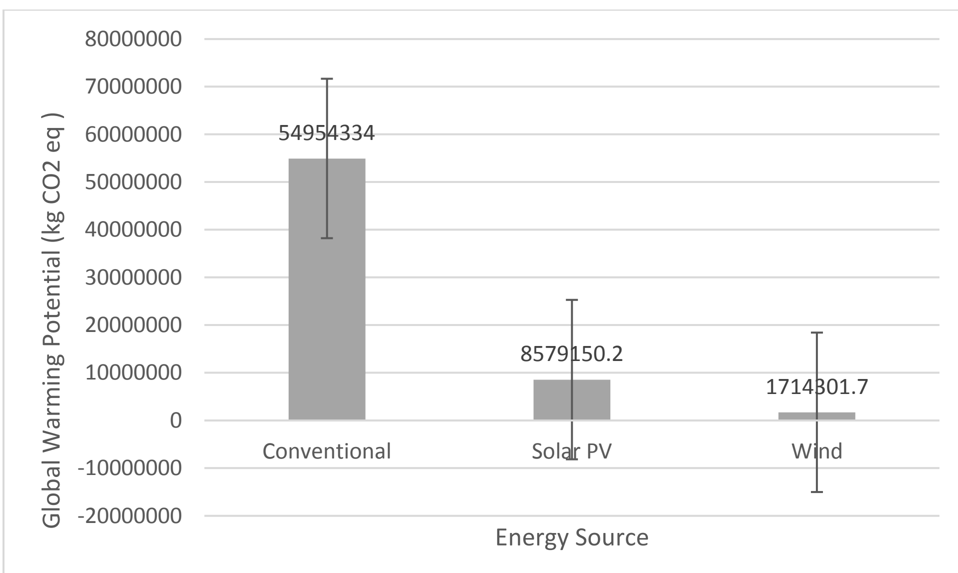

Figure 5.59 Global warming potential of solar PV, wind and conventional energy systems per 100 years

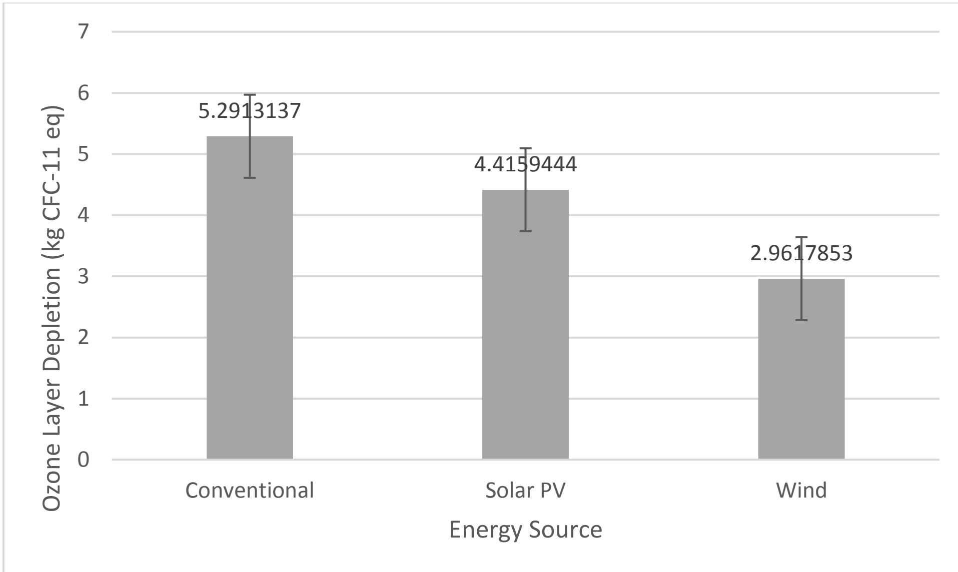

Figure 5.60 Steady state of ozone layer depletion of solar PV, wind and conventional energy systems per 100 years

Moreover, abiotic depletion potential and the impact of conventional, solar PV and wind energy systems on this category is illustrated in Figure 5.61.

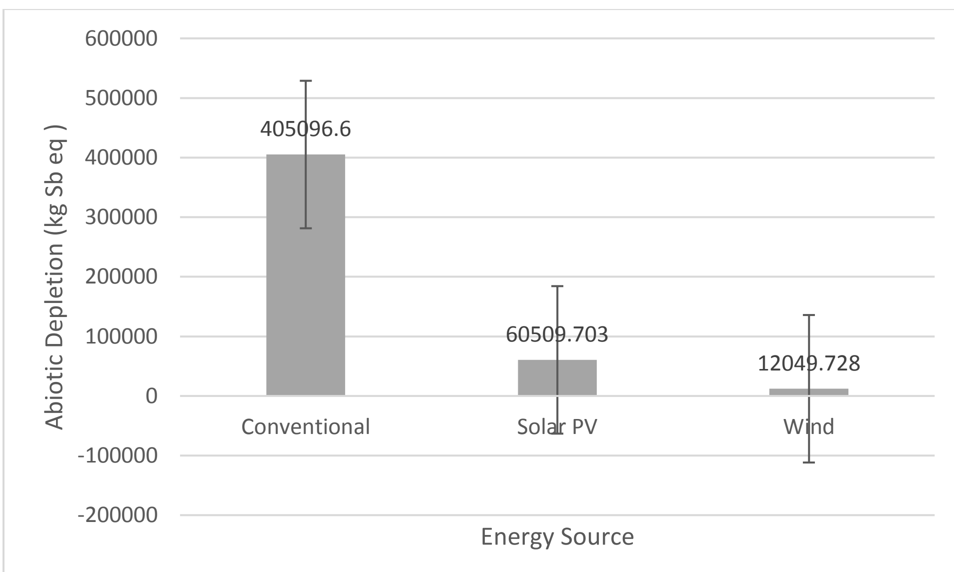

Figure 5.61 Abiotic depletion potential of solar PV, wind and conventional energy systems per 100 years

Finally, the acidification impact of the case studies is presented in Figure 5.62

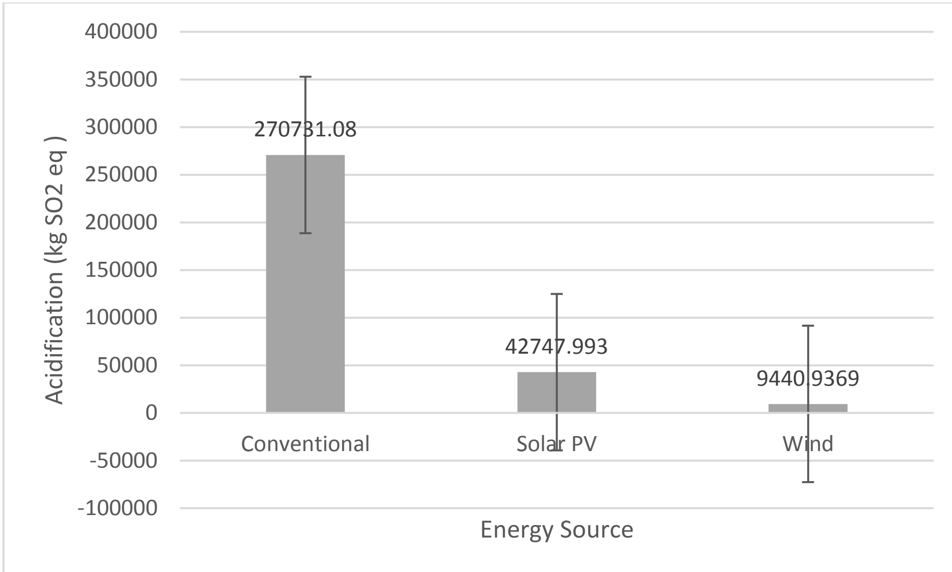

Figure 5.62 Acidification of solar PV, wind and conventional energy systems per 100 years

In summary, renewable energy sources such as solar PV and wind, which are the proposed case studies, are significantly better environmentally than the conventional energy systems. Furthermore, solar PV has a larger environmental footprint on many impact categories than the wind energy system, which suggests that wind energy system is the most suitable option from an environmental-performance perspective.

Chapter 6: Conclusions and Recommendations

This thesis investigates the concept of sustainable energy systems in close detail. This is achieved by analyzing the underlying parameters behind this topic and critically thinking in order to build an assessment model that is comprehensive and accurate. Sustainability is a complex and multi-disciplinary concept, which explains the absence of a universally adopted sustainability assessment model until today. The novelty of this thesis lies in the introduction of a comprehensive collection of indicators including thermodynamic, environmental, economic, social and technological in order to evaluate the sustainability of energy systems. Furthermore, these indicators are non-dimensionalized using target values, which reflect the preferred values under optimal conditions. The idea of using target values to normalize the data is also novel. Moreover, data collected from various indicators is further processed using a variety of aggregation and weighting schemes in order to minimize the subjectivity associated with the model as much as possible. Using the weighted geometric mean and weighted arithmetic mean along with the panel method, hierarchist, egalitarian, individualist and equal weighting schemes is novel as the results unveil important information about the behavior and influence of each method on the different categories of data. In addition, the proposed model has been validated using two case studies designed to meet the residential demand of 150 households for their annual electricity, hot water, heating and cooling. Using EES and SimaPro, the case studies are modeled to explore the thermodynamic and environmental impression performance.

5.1 Conclusions

The sustainability of solar PV and wind energy for the case studies presented in this thesis are very similar. Furthermore, the results from the various methods also follow similar patterns for both case studies. Wind energy has a better environmental footprint than solar PV, however both of their environmental performance is not comparable with the environmental impression of the conventional gas-fired system. In summary, the specific conclusions derived from this thesis are as follows:

- The solar PV system has a low sustainability score of 0.56 using the panel method and a high score of 0.59 using the hierarchist and equal weighting methods based on the weighted geometric mean.
- The solar PV system has a low sustainability score of 0.54 using the individualist method and a high score of 0.63 using the equal weighting method based on the weighted arithmetic mean.
- The dimension with the lowest importance coefficient according to the panel method is the size factor with a weight of 0.05. The dimension with the highest importance coefficient according to panel method is the environmental impression with a weight of 0.18.
- The fall season observes a heightened increase in the energy efficiency of the solar PV system reaching close to 100% efficiency. On the other hand, the winter season observes the opposite phenomenon with efficiency dropping to as low as 30%.
- Increased ambient temperature leads to the gradual decrease of the energy efficiency of the solar PV system to as low as 30%.
- Energy efficiency gradually decreases in a zigzag fashion as the solar irradiance increases from 123 (W/m^2) to 275 (W/m^2). After that, it picks up again and starts to gradually increase as the solar irradiance increases towards 323 (W/m^2).
- Cut-in wind speeds below 7.5 m/s have negligible effect on the overall system's energy or exergy efficiencies for the wind energy system.
- Cut-out wind speeds more than 25 m/s have negligible effect on the overall system's energy or exergy efficiencies for the wind energy system.
- Increased wind turbine mechanical efficiency has no impact on the wind system's energy efficiency, yet it decreases the exergy efficiency in a linear fashion.
- The wind energy system has a low sustainability score of 0.56 using the panel method and a high score of 0.58 using the hierarchist and equal weighting methods based on the weighted geometric mean.

- The wind energy system has a low sustainability score of 0.51 using the individualist method and a high score of 0.6 using the equal weighting method based on the weighted arithmetic mean.
- As the wind speed increases, the general trend for the energy and exergy efficiencies is to decrease. Wind speeds less than 22 m s^{-1} are characterized with the highest energy and exergy efficiencies.
- Environmentally, wind energy has the lowest impact on all categories whereas the solar PV system is rated second.

5.2 Recommendations

Although this model introduces novel dimensions related to the sustainability of energy systems, there is more to do in order to ensure the maturity of the assessment methodology. I propose the following recommendations for future sustainability research pertaining to this topic:

- Social impression could be measured in a better way. Indicators such as human welfare, human health, social cost and ethical responsibility can be better assessed to accurately reflect the social impression dimension.
- Inclusion of more experienced stakeholders in the panel and incorporating other methods of assigning weights such as discussion.
- Acknowledging the subjectivity of the assessment methodology and the weak parameters such as social indicators and the education indicators, which are hard to qualify; and build on it to minimize errors and weakness of the model.
- Validating this sustainability assessment model on energy systems outside of Ontario. Changing the geographical location may change economic, environmental and social impacts as well as technical parameters such as wind speed, solar irradiance or annual household energy demand.
- Carrying out an optimization analysis for the proposed systems and identifying how the system can be enhanced to achieve a better sustainability score.

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