# A FRAMEWORK FOR BENCHMARKING THE TOTAL ENERGY EFFICIENCY OF NET ZERO ENERGY BUILDINGS

by

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## Approval Signatures

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# Abstract

The need for net zero energy buildings (NZEB) is a result of global depletion of natural fuel resources and the effects of the usage of these fuel resources on climate. For Instance, the building sector in the US alone contributes to 40% of energy use and greenhouse gas emissions as opposed to 32% in the industrial sector and 28% in the transportation sector. This large percentage reflects the need for reducing the energy consumed by buildings and using renewable energy resources. In essence, NZEB utilize renewable energy resources to offset the amount of energy used in a building over the course of a year. In the literature, there are various definitions for NZEB that relate to the energy used and the costs and emissions from that energy. Also, there is no unified benchmarking approach that can be used to compare NZEB. In this thesis, a framework for benchmarking the total energy efficiency of NZEB is introduced which indicates an overall reduction in the energy costs and emissions and utility energy use of NZEB. The total energy efficiency was computed using a network of two data envelopment analysis (DEA) models. The first DEA model benchmarks the energy efficiency of the building based on uncontrollable weather and functional factors. The second DEA model benchmarks the renewable energy system of the buildings based on the energy costs and emissions and utility energy used. Through combing both efficiencies in one benchmark, the total energy efficiency was able to indicate reductions in energy, costs and emissions as it indicated buildings with highest ratios of outputs to inputs that were included in the models. It is important to note that the models were applied on commercial office buildings and from the application; a framework was developed to benchmark all types of NZEB. It is recommended that the framework is applied to the benchmarked NZEB rather than the results of the models as the data used contained simulated data.



Search Terms: Net Zero Energy Buildings, Data Envelopment Analysis, Benchmarking Energy Efficiency, Benchmarking Total Energy Efficiency, Building Energy.

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# Chapter 1: Introduction

## 1.1 Background

The building sector has become a major contributor to the consumption of world-wide reserves of energy and a major emitter of greenhouse gases. According to Novotny et al. [1], the building sector in the US contributes to 40% of energy use and greenhouse gas emissions as opposed to 32% in the industrial sector and 28% in the transportation sector. This issue draws attention to building energy use, which can affect the current and future levels of natural fuel resources and can raise concerns regarding the emission of greenhouse gases, which have considerable impacts on the climate. To solve this problem, one of two solutions must be maintained within the building sector: either reduce building energy use or use renewable sources of energy as alternatives to fossil fuel energy. Net zero energy buildings (NZEB) combine both of the previous solutions; according to Torcellini et al. [2], these buildings are energy efficient, allowing them to rely on renewable energy sources in an economical way. Additionally, research showed that renewable energy is sufficient to satisfy energy demands, as proven in a study by Resch et. al [3]. The study estimated that the technical potential for renewable energy is 16 times the demand in 2004, whereas the current use of these resources is only approximately 13% of 2004 demand levels. Therefore, the concept of NZEB has gained popularity and is seen in many projects worldwide.

## 1.2 Problem Statement

Although there have been many projects built as NZEB, a common definition for NZEB is lacking, as indicated by several studies [2], [4] and [5]. These buildings can be defined, simply, as buildings that generate an amount of energy equal to the amount of energy used; but there is still no common agreement over the metric, which can be energy, costs or emissions, along with other features which lack consensus [4]. It was apparent that there is a need to introduce a benchmarking framework for NZEB to evaluate these buildings based on common features of NZEB, such as the energy efficiency of the buildings and the renewable energy efficiency, measured by the utility energy used and the energy costs and emissions.

## 1.3 Objectives

The research is aimed to accomplish the following objectives:

1- Develop a framework for benchmarking NZEBs that considers both energy efficiency and renewable energy efficiency.
2- Modify previously developed energy efficiency Data Envelopment Analysis (DEA) by using the reciprocal of the observed Energy Use Intensity (EUI) as an output and the reciprocal of functional and weather factors as inputs.
3- Predict the energy efficiency DEA score using ANN.
4- Develop a new methodology to benchmark NZEB renewable energy systems using DEA.
5- Introduce the concept of combining energy efficiency DEA and renewable energy efficiency DEA in a network and obtaining a total efficiency score for the two DEAs.
6- Provide a model for benchmarking commercial office buildings that utilizes renewable energy systems.

## 1.4 Research Significance

Although NZEB utilize renewable energy to offset the energy used in a building throughout a year, the use of offsite renewable energy might lead to designing less energy-efficient buildings. This is because the cost of installing the renewable energy system is not incurred by the owner and thus will not lead the owner to reduce energy use. Using site and source energy definitions for NZEB might also lead to less use of efficient renewable generation technologies in terms of energy costs and emissions. Additionally, the concept of NZEB allows for the use of grid electricity, which can lead to renewable systems with less reliability and more buildings using grid electricity, which produces more emissions. Therefore, there is a need to benchmark NZEB based on common features of these buildings, and in a way that serves the overall goal of constructing such buildings, which is to reduce the energy used, costs and emissions.

The previous drawbacks can be overcome by using the total energy efficiency of NZEB, a new benchmark introduced by the author. The total energy efficiency provides a unified approach for benchmarking NZEB that can lead to maximizing the advantages of these buildings. First of all, the energy efficiency part of the concept gives better credit to buildings that utilize active and passive systems to reduce building energy needs, which consequently leads to lower building energy costs and emissions. Second, by introducing the renewable energy efficiency part of the concept, credit is given to buildings that use less costly renewable energy systems, leading to more economic advantages of NZEB. Additionally, the renewable efficiency part gives credit to buildings that use less utility energy, leading to more reliable renewable energy systems. Focus is maintained on the building emissions, and thus credit is given to buildings with the least emissions.

### 1.5 Research Contribution

At the time of the study, there is no current benchmarking methodology for NZEB that considers both the efficiency in energy use and the efficiency of renewable energy systems. The concept of total energy efficiency for net zero energy buildings has not been introduced in literature, and presents a new approach that fits the benchmarking of NZEB. The total energy efficiency encompasses both reductions in energy use and reductions in building energy costs and emissions. An additional contribution of the research is not in the concept, but in the methodology used. Although the research used DEA to benchmark energy efficiency, which has been done before in research [6] and [7], using DEA in benchmarking building renewable energy has not been done before in research, to the author's knowledge. Moreover, the formation of the two DEAs used in a network and calculating an overall efficiency is a new methodology that fits NZEB. This indicates that the thesis work will not only present a new concept but also a new methodology for benchmarking NZEB in general. Finally, the data sources that are used in the thesis were not used, as is, to benchmark these buildings; additional parameters were added regarding the utility energy used and the cost and emissions of renewable energy systems.

### 1.6 Research Methodology

Since the thesis work is dependent on data regarding the energy consumption and energy conservation features for a large sample of buildings, which requires extensive resources and time, the commercial building energy consumption survey

(CBECS) micro data for 2003 will be used as the main source of data during research. The CBECS is a survey that is performed by the US Energy Information Administration on a sample of commercial buildings. The survey [8] 'includes approximately 5000-6000 commercial buildings from the US. These buildings are surveyed on the basis of their energy related characteristics and their energy consumption.' It is important to note that the data corresponds to traditional buildings, but additional theoretical data parameters will be added to the buildings, such as the utility energy used and costs and emissions of the renewable energy systems.

The data obtained from the CBECS and the theoretical data will be used in benchmarking NZEB in three stages. In the first stage, the energy efficiency of the building will be benchmarked using a data envelopment analysis (DEA) which will incorporate the EUI as output and uncontrollable functional and weather factors as inputs. Because the DEA contains undesirable outputs and inputs, the reciprocals of the previous inputs and outputs can be used. In addition, artificial neural networks will be used to predict the energy efficiency score using a set of controllable factors which will aid the building owner in selecting the energy conservation features. In the second stage, the renewable energy efficiency will be benchmarked using DEA which will incorporate the EUI as input and total energy costs and emissions per unit area and utility energy used per unit area as outputs. Here also the reciprocal of the inputs and outputs is used to deal with undesirability of inputs and outputs. The third and final stage is to calculate the total energy efficiency using one of the techniques for calculating the total efficiency of a network DEA. The total energy efficiency should be able to indicate the efficiency in reducing energy use and reducing the costs and emissions of energy.

# Chapter 2: Literature Review

## 2.1 Renewable Energy Sources

For the purpose of benchmarking the renewable energy systems of NZEB, the renewable energy sources are examined along with their potential and performance metrics as follows:

### 2.1.1 Overview

- Biomass Energy:

Biomass energy refers to the production of energy from biological sources, such as forest and agriculture residues and municipal solid waste. The most common approach to obtain biomass energy is through the direct combustion of the biological material using the steam Rankine cycle. In this cycle, biomass is combusted to produce a hot gas, which is then utilized to generate a steam used in developing electricity. The plants employing biomass combustion can generate 1-50 MW of electricity with 15% to 25% efficiency [9]. Due to the high capital costs associated with these plants, the cost of generating electricity is generally higher than the conventional coal-fired plant. Another approach to producing biomass is through gasification, where biomass is converted to a gaseous fuel that can be used directly in heating or in producing electricity in plants that operate on a 10-100 MW basis. The drawback of the gasification process is in the production of tar and coil, which can cause failures or problems in the system. This is countered by the integrated gasification combined cycle (IGCC), where the biomass is turned into a gaseous fuel in a thermochemical process and used to generate a steam that can be used to produce electricity. This process has higher efficiency than the steam cycle and lower costs per kW. These technologies are not commonly used on a commercial scale, but there are some projects developed using these technologies [9]. Therefore, it can be concluded that the cost of generating biomass energy and the emissions produced are some of the disadvantages of this type of renewable energy.

- Solar Energy:

1- Solar Photovoltaic (PV):

A PV system relies on PV modules composed of connected solar cells made of a semiconducting material, which can generate electricity when exposed to sunlight. These PV modules can have a capacity of 30 to 200 watts, and when connected to other modules can provide tens of megawatts. Moreover, PV systems and modules can be based on silicon semiconducting materials, or can be built based on non-silicon materials such as thin films, which are currently being employed due to their low price with respect to capacity, although they are less efficient than silicon-based semiconductors. A higher efficiency in solar PV can be achieved with newly introduced concentrated solar cells, which focus sunlight on a smaller area. The main advantage of solar PV, aside from being a clean source of energy, is that it can be scaled from tens of watts to tens of megawatts, as it has the same modular capability as wind turbines. The advantage of this is that a small increase in the required energy would not require similar installment costs, as new solar modules can be added to the system to fit the required increase. However, the major difference between wind energy and solar PV is that wind speed and wind patterns cannot be predicted beforehand, whereas sunlight can be more accurately predicted earlier on [10]. Therefore, the advantages of solar energy generated by solar PV are that it can generate energy with the lowest costs, least emissions and most reliability.

2- Concentrated Solar Thermal Power (CSP):

CSP depends on the concentration of the sun's radiation, turning the heat into mechanical and then electrical energy. This is done with the use of fields of solar receivers, collectors and a power block, as seen in CSP plants, which are complemented by heat storage and backup and cooling systems. Because CSP plants are equipped with heat storage and backup systems, these plants can provide energy after sunset, which is a substantial advantage. The main disadvantage of CSP over Solar PV is that CSP requires direct sunlight, unlike Solar PV, which can work based on solar diffusion. Another disadvantage is that CSP plants also require a substantial amount of water for cooling, which might not be available at the plant site [10].

- Wind Energy:

Wind energy is developed using wind turbines which take two forms: the horizontal axis turbine and the vertical axis turbine. The horizontal axis turbine is the most common, as it is usually taller than the vertical axis turbine and can take advantage of the higher wind speeds at higher altitudes. This wind speed is the main factor affecting the power produced from wind turbines; due to the cubic relationship between wind speed and power, doubling the amount of wind speed increases eightfold the amount of power produced by the turbine. The normal capacity for a large scale wind turbine can reach 5-6 MW, although there are small scale wind turbines below 100 kW used in rural households. To gain the economic advantage of wind energy, wind farms combine large scale wind turbines onshore or offshore, with onshore being the most economical choice. Due to land scarcity and the effect on aesthetic views at certain sites, some countries have chosen to develop offshore wind farms.

The main advantage of wind energy is that it produces no carbon emissions during electricity generation, and can therefore be considered a clean energy. Additionally, wind energy has low costs, as the costs of generating electricity from wind over the lifetime of the plant can reach a levelized cost of 3-6 cents per kWh [9]. Although wind energy has several advantages, its main disadvantage is the dependence on wind speed, which does not guarantee a constant power output. Additionally, wind energy has some environmental impacts, including the noise produced and the effects on the aesthetic aspects of the site.

- Geothermal Energy:

Geothermal energy comes from heat stored in the earth, which can be available from hydrothermal resources or hot dry rock. Hydrothermal resources represent hot water or steam stored within 100 to 3000 m of the earth’s surface within a permeable reservoir. On the other hand, hot dry rock represents heat that is stored in impermeable rock present 4000 m or more below the earth’s surface. To utilize hot dry rock, hydraulic fracturing is used to create a permeable reservoir so that water from the surface can transfer the heat from the rocks [11]. The main two technologies used to produce electricity from geothermal sources are the flash and binary technologies. In flash technology, the geothermal fluid pressure is lowered to produce a steam, which drives the turbine to generate electricity. In binary technology, heat transfer is conducted between the hot water and another fluid with a lower boiling point, after which this fluid evaporates and the vapor is used in the turbine.

- Hydropower:

Hydropower is produced from the water flow in natural rivers and in man-made reservoirs using turbines, which utilize the mechanical energy of the water flow to generate electricity. The main types of hydropower generation methodologies are storage, run-of-river and pumped storage. Storage employs the use of a dam to hold water, whereas run-of-river utilizes the natural water flow in rivers. Additionally, pumped storage utilizes a lower and upper basin, with water pumped from the lower to the upper basin when there is a low demand for electricity. When the demand increases, water is allowed to flow from the upper to the lower basin, generating electricity. Although hydropower is a clean and flexible source of energy, the drawback of hydropower is that it depends on the season and the rainfall fluctuations from one season to the next [10].

### 2.1.2 Renewable Energy Potential

Resch et al. [3] studied the potential for renewable energy sources at a global scale, and found that the theoretical potential, or the maximum amount of energy that is available, can reach 144 million EJ (Table 1). This is an advantage of renewable energy, as this amounts to 30000 times the amount of energy used in 2004. Additionally, the study found that the technical potential for renewable energy, or the maximum that can be reached with the current available technologies, is approximately 7500 EJ. Although there is a large difference between the theoretical and technical potential due to the efficiency of current technologies, the study still shows the promise of using renewable energy to satisfy the global demand. The study shows that the technical potential is approximately 16 times the global demand in 2004, and with improvements in technologies, higher values can be reached. However, as estimated in 2004, the use of renewable energy sources is still limited, representing 13.1% of the 2004 energy demand. Although energy demand increased from 2004 till the time of the study, still the capacity of renewable energy is 16 times larger than the demand in 2004 which is much more than the current demand.

**Table 1: Renewable Energy Global Potential [3]**

| Global theoretical and technical potentials (Unit: EJ) | | | |
|---|---|---|---|
| Resource | Current use (2004) | Technical potential | Theoretical potential |
| Biomass energy | 50 | 250 | 2900 |
| Geothermal energy | 2 | 5000 | 140,000,000 |
| Hydropower | 10 | 50 | 150 |
| Ocean energy | – | – | 7400 |
| Solar energy | 0.2 | 1600 | 3,900,000 |
| Wind energy | 0.2 | 600 | 6000 |
| Total | 62.4 | 7500 | 143,916,450 |

### 2.1.3 Metrics and Optimization of Hybrid Energy Systems

Due to the low reliability in using one source of renewable energy, buildings employ a hybrid system composed of multiple sources of renewable energy in addition to the grid electricity. This requires optimization methods for sizing the components of the building energy system that satisfy certain technical, economical and sometimes environmental objectives. Luna-Rubio et al. [12] reviewed the metrics and optimization methodologies of hybrid energy systems, including the following important indexes:

1- Loss of power supply probability (LPSP):

This index represents the reliability of the hybrid systems in terms of the probability of deficits occurring in a certain period, according to equation 1 that follows:

$$LPSP = \frac{\sum_{t=1}^{T} DE(t)}{\sum_{t=1}^{T} P_{load}(t).\Delta t} \quad (1)$$

where $DE(t)$ = Energy deficit at hour $t$, and

$P_{load}$ = power load required.

2- Level of Autonomy (LA)

This index is similar to the LPSP in the sense that it indicates the reliability of the system. This index is calculated as follows in equation 2:

$LA = 1 - \frac{H_{lol}}{H_{tot}}$ (2)

where $H_{lol}$ = Number of hours in which loss of load occurs, and

$H_{tot}$= Total hours of operation.

3- Expected energy not supplied (EENS):

The previous indexes were based on the actual operation of the hybrid system, whereas the EENS is based on expected energy not supplied by the hybrid system, as follows in equations 3 and 4:

$EENS = L - \int_{P_{hmin}}^{P_{hmax}} P_h . f_{ph}(P_h) dP_h \, , when\ L > P_{hmax}$ (3)

$EENS = \int_0^L (L - P_h). f_{ph}(P_h) dP_h \, , when\ 0 \leq L \leq P_{hmax}$ (4)

where $P_h$ = Power supplied by the system, $L$ = Load on the system and $f_{ph}(P_h)$ is the probability density function of this power.

4- Levelized cost of energy (LCE)

This index represents the economic efficiency of the hybrid system, which is represented as a ratio (eq. 5) between the total annualized cost and the total energy usage:

$LCE = \frac{TAC}{E_{total}}$ (5)

where $TAC$ = Total annualized costs, and

$E_{total}$ = Total annual energy.

The above indexes can be used as objectives of the optimization model for hybrid energy systems, which can be solved using genetic algorithms, artificial neural networks or other methods as indicated by [12]. As shown in the previous indexes, the focus remains on cost, reliability, and utility electricity usage of the renewable energy systems.

## 2.2 Net Zero Energy Buildings (NZEB)

To properly benchmark NZEB, the common features and design strategies for these buildings must be studied in detail.

### 2.2.1 Definition

According to Torcellini et al. [2], there is no common definition for NZEB, but the main conceptual basis is that these buildings are defined as 'residential or commercial buildings with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be satisfied with renewable technologies.' To be able to respond to energy needs, NZEB are usually connected to the utility grid, which would allow the building to use grid electricity during renewable energy shotages that mainly depend on the season. In exchange for grid electricity, the excess renewable energy can be exported to the grid to compensate for used electricity and to reach a zero balance between energy generation and usage. This is the main reason that these buildings are described as "net zero" and not zero-energy buildings. Additionally, it is difficult to rely only on renewable energy, as in off-grid buildings, to reach net zero balances because excess energy requires storage technologies that are currently not well developed.

The inconsistency in the definition of NZEB is apparent in research, and Marszal et al. [4] studied 11 definitions and calculation methodologies of NZEB proposed by researchers participating in the IEA SHC Task 40/ECBCS Annex 52, 'Towards Net Zero Energy Solar Buildings' [13] in addition to a methodology proposed by Hernandez and Kenny [14], and the authors found that there is no common agreement over definitions and calculation methodologies of NZEB, as shown in table 2 on the next page.

As can be inferred from Table 2 and from [4], [5], the differences between the definitions and methodologies used can come from the following factors:

- Metric used for the balance:

Although NZEB are more focused on energy needs, the metric that is used for defining NZEB is not always based on energy metrics. It is more dependent on the objectives of the project and the goals of the stakeholders, which could be directed towards reducing emissions, controlling energy costs or reducing energy consumption at site or at source.

**Table 2: NZEB Calculation Methodologies [4]**

| | (1) Metric of the balance | | | | (2) Period of balance | | (3) Type of energy use | | | (4) Type of balance | | (5) Renewable supply options | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Delivered energy | Primary energy | $CO_2$ emissions | Energy cost | Annual | Monthly | Operating energy | Total energy | Energy use & EE* | Generation/ Use | Grid in/out | Footprint | On-site | Off-site |
| Meth. 1 | | √ | | | √ | | | √ | | √ | | √ | √ | |
| Meth. 2 | | √ | | | √ | | | √ | | √ | | √ | √ | |
| Meth. 3 | | √ | | | √ | | | √ | | √ | | √ | √ | |
| Meth. 4 | √ | √ | √ | √ | √ | | | √ | | √ | | √ | √ | √ |
| Meth. 5 | √ | √ | √ | √ | √ | | | √ | | | √ | √ | √ | √ |
| Meth. 6 | √ | | | | | √ | √ | | | √ | | √ | √ | |
| Meth. 7 | √ | √ | √ | | √ | | | √ | | √ | | √ | √ | √ |
| Meth. 8 | | √ | | | √ | | | √ | | √ | | √ | √ | |
| Meth. 9 | √ | | | | √ | | | √ | | √ | | √ | √ | √ |
| Meth. 10 | | √ | | | √ | | √ | | | √ | | Not fully defined | | |
| Meth. 11 | | √ | | | √ | | | | √ | √ | | √ | √ | |
| Meth. 12 | | √ | | | √ | | | | √ | √ | | Not fully defined | | |

* Embodied energy.

From these objectives, it can be seen that there are four metrics for NZEB [2]:

1- Net zero site energy:

‘A site NZEB produces at least as much energy as it uses in a year, when accounted for at the site’ [2, p 5]. The site energy is usually easily measurable and does not consider conversion factors to account for transportation and conversion losses. This means that different energy sources, such as gas and electricity, are measured on a 1-to-1 basis, which leads to a more energy-efficient design than when using source energy. A result of this is that NZEB which utilize thermal energy and electricity usually need more renewable energy when accounting for site energy, and need less renewable energy when accounting for source energy. Therefore, it is seen that source energy is easily achievable than site energy.

2- Net zero source energy:

‘A source NZEB produces at least as much energy as it uses in a year, when accounted for at the source’ [2, p 5]. The source energy is usually calculated using conversion factors that account for energy losses occurring from the production of energy at the source until its importation to the site. The use of the conversion factor can lead to a lower renewable energy need in some buildings, as was mentioned earlier, and can lead to fluctuations due to the changing nature of the conversion factor according to the regional source.

3- Net zero energy costs:

‘In a cost NZEB, the amount of money that the building owner is paid for the energy the building exports to the grid is at least equal to the amount the owner pays for the energy services and energy used over the year’ [2, p 5]. The problem with utilizing energy cost in the balance is that energy cost varies frequently with time. Additionally, utilities usually do not rate generated electricity as equal to consumed electricity, which makes this definition the most difficult to achieve. However, this definition is useful in the financial evaluation of NZEB and therefore buildings which achieve the cost balance are mostly profitable.

4- Net zero energy emissions:

'A net-zero emissions building produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources' [2, p 5]. Here, conversion factors are used to account for emissions from the source, which fluctuate with time.

- Period of the balance:

It is typical to apply the balance on a yearly basis, although some calculation methodologies, as seen in Table 2, propose a monthly period. In addition, Hernandez and Kenny [14] propose using the lifetime of the building as the basis for the balance, while also including the embodied energy of the building along with the used energy. However, using the yearly period is more appropriate, as it is difficult and less accurate to calculate the total energy over the life of the building. Additionally, using the monthly period increases the difficulty of achieving the balance because of the variation between seasons in some sources of renewable energy, such as solar energy.

- Building system boundary and type of energy use:

The energy use could be specified as the operating energy that does not depend on the user, including the energy for the HVAC system, water heating and lighting. However, it is preferable to also include user-related energy and to consider the total energy of the building, as seen in most of the methods from Table 2.

- Balance type:

The net zero energy balance could be performed between energy generation and energy usage or between electricity imported from the grid and electricity exported [5]. The following equations (eq. 6 and 7) show the two types of energy balance:

$$\sum_i e_i \times w_{ei} - \sum_i d_i \times w_{di} = E - D \geq 0 \quad (6)$$

where $e_i$ = exported energy by energy carrier $i$;

$d_i$ = energy imported by energy carrier $i$;

$w_{ei}$ *and* $w_{di}$ = weighting factors for exported energy and imported energy;

$E$ = weighted exported energy; and

$D$ = weighted imported energy.

$$\sum_i g_i \times w \quad - \sum_i l_i \times w \quad = G - L \geq 0 \ (7)$$

where $g_i$ = energy generated by energy carrier $i$;

$l_i$ = energy demand for energy carrier $i$;

$w$ = weighting factor;

$G$ = weighted generated energy; and

$L$ = weighted demand energy.

As seen in Table 2, the typical balance is applied between energy generation and demand, which can be easily determined during the design stage.

- Renewable energy supply options:

Torcellini et al. [2] illustrated a hierarchy for the energy supply options which prioritizes supply options that reduce the environmental impact through energy efficiency and minimization of transportation and conversion losses; can supply the building with energy during its life time; and are common in the market. The hierarchy of these supply options is shown in Table 3.

**Table 3: Renewable Energy Supply Options Ranking for NZEB [2]**

| Option Number | ZEB Supply-Side Options | Examples |
|---|---|---|
| 0 | Reduce site energy use through low-energy building technologies | Daylighting, high-efficiency HVAC equipment, natural ventilation, evaporative cooling, etc. |
| | **On-Site Supply Options** | |
| 1 | Use renewable energy sources available within the building's footprint | PV, solar hot water, and wind located on the building. |
| 2 | Use renewable energy sources available at the site | PV, solar hot water, low-impact hydro, and wind located on-site, but not on the building. |
| | **Off-Site Supply Options** | |
| 3 | Use renewable energy sources available off site to generate energy on site | Biomass, wood pellets, ethanol, or biodiesel that can be imported from off site, or waste streams from on-site processes that can be used on-site to generate electricity and heat. |
| 4 | Purchase off-site renewable energy sources | Utility-based wind, PV, emissions credits, or other "green" purchasing options. Hydroelectric is sometimes considered. |

As seen in the table, the first priority is given to the supply option that is available within the building footprint and at the site, and lower priority is given to offsite sources. This is because offsite supply options do not provide energy efficiency incentives, as seen in the case of buildings that purchase renewable energy (option 4). In these buildings, the cost of construction and maintenance of renewable energy sources is not borne by the owner, which often leads to less energy efficiency.

- Building Requirements:

Not all definitions of NZEB emphasize the need for efficiency [4]; however, it is important to maintain an efficient design to avoid oversizing the renewable energy system and to reach economic feasibility. In addition to energy efficiency, NZEB should satisfy indoor climate requirements, which consist mainly of ensuring the health and thermal comfort of the occupants. Additionally, NZEB should have a proper interaction with the grid and have good load matching index ($f_{load}$) and grid interaction index ($f_{grid}$) values, as shown in the next equations (eq. 8 and 9).

$$f_{load,i} = \frac{1}{N} \times \sum_{year} \min(1, \frac{g_i(t)}{l_i(t)}) \quad (8)$$

where $g_i$ = energy generated by energy carrier $i$;

$l_i$ = energy demand for energy carrier $i$; and

$t$ = time interval used.

$$f_{grid,i} = STD\ (\frac{e_i(t) - d_i(t)}{Max(e_i(t) - d_i(t))}) \quad (9)$$

where $e_i$ = energy exported by energy carrier $i$;

$d_i$ = energy imported by energy carrier $i$; and

$t$ = time interval used.

- Common Features:

As explained before, the common features for NZEB are as follows in Table 4:

**Table 4: Common features of NZEB**

| Feature | Common Characteristics |
|---|---|
| Metric of the Balance | Energy, Cost, Emissions |
| Period of the Balance | Annual |
| Type of Energy Use | Total Energy |
| Renewable supply options | Onsite and Offsite |
| Type of the Balance | Generation/Load |
| Building Requirements | Energy efficiency, Comfort and Grid Interaction |

From these common features, it can be seen that the metric of the balance can be energy, costs or emissions, which should be considered when benchmarking these buildings. Additionally, the building is required to be energy efficient and use less grid electricity.

### 2.2.2 Energy Use Intensity (EUI)

When considering the energy efficiency of NZEB, it is important to note the EUI, which is basically the total annual building energy divided by the gross floor area of a building. This parameter is important when comparing the energy performance of different buildings. However, it has been found that buildings in colder climates have higher EUIs because of the energy consumed in heating. Additionally, the type of the building can have an impact on the occupancy densities, type of plug and process loads, domestic hot water and cooling loads from equipment, and lighting internal heat gain. This has a greater impact on the EUI than climate alone. Because of these effects on the EUI, it is necessary to compare the EUI for buildings of the same type and climate so that sound judgment can be made with regards to energy performance. In general, the EUI can be helpful in setting baseline targets for the energy usage of the building. These can be established using baselines developed by ASHRAE 90.1, which are used by LEED, or CBECS, which are used by the 2030 challenge; or using data from similar buildings, in which case the EUI usage is necessary during the design phase. If ASHRAE 90.1 and CBECS are used, it is recommended to reduce the ASHRAE 90.1-2007 baseline by 40% and the CBECS baseline by 60% or more in order to establish a baseline for NZEB [15]. Other than utilizing ASHRAE 90.1 and CBECS, the lowest feasible energy usage can be determined from peer buildings, which also can aid in establishing the NZEB target. The actual energy usage targets and the energy generated from renewable energy sources should be kept separate here. After deciding on the energy targets for the building, renewable energy targets are chosen so that they offset the energy used.

### 2.2.3 Passive Design of NZEB

Net zero energy buildings incorporate an envelope design with a low thermal transmittance (U-factor) for all of its assemblies, including floors and slabs, roof, glazing, doors and openings. This reduction in the thermal transmittance will aid in neutralizing the building envelope and creating what is called a super-insulated building. Not only should the U-factor be reduced, but thermal bridges that connect the exterior and interior environments should also be minimized or eliminated. Another concern for building envelopes is air infiltration, where air can pass from the exterior of the building through gaps in the envelope. For that, an air barrier should be designed to continuously extend over the whole building envelope while giving special attention at the joints of the different assemblies. This air barrier should have very low air permeability and should be tested by fan pressurization according to ASTM E799.

In addition to the previous strategies, NZEB should employ passive strategies which utilize the building design and external climate to provide heating, cooling, ventilation and lighting. Examples of these strategies are shown in the following techniques [15]:

1- Thermal mass: The use of a thermal mass like concrete in the external envelope can lessen temperature swings through the envelope.
2- Superinsulation: The use of thermal insulation through a lower U-factor and reduction of thermal bridging can reduce the effect of the external climate on the internal environment.
3- Earth coupling: Coupling the building to the earth can reduce thermal transmission to the building.

4- Airtightness: Airtightness achieved by using a low-permeability air barrier can reduce the effect of the external climate on the internal environment.
5- Shading: Providing shading in the glazing system can aid in reducing the cooling loads in high temperatures.
6- Passive solar: If the glazing system allows for direct sunlight, this can aid in heating the internal environment.
7- Natural ventilation: The use of operable windows can provide a cooling effect to decrease the internal temperature.
8- Fan ventilation: Through evaporation, fan ventilation can provide a cooling effect.
9- Solar collectors: Solar collectors can aid in heating air before it is used in the ventilation or heating system.
10- Evaporative cooling: Introducing water to air in a cooling tower lowers the air temperature before it falls from the cooling tower.
11- Daylighting: Incorporating daylight into the building through top and side lighting and by using control systems to change the internal lights in response to daylight can save energy.

### 2.2.4 Energy-Efficient Active Systems for NZEB

In addition to utilizing passive strategies, net zero energy buildings also have active systems that are energy efficient [15]. For that, net zero energy buildings require a non-conventional HVAC system that reduces energy consumption both in the distribution system and the primary equipment. To consume less energy during distribution, it is recommended to use water instead of air for heat transfer, as water has a high volumetric heat capacity relative to air and this would save energy when pumping the heat transfer medium. The main drawback of using water for temperature control is that water cannot be used to ventilate or dehumidify air, which is why air should be used separately from temperature control water to dehumidify and ventilate. This separation should only be used in buildings that are dominated by heating and cooling. Additionally, it is recommended that modest heating and cooling temperatures are used for hot and chilled water, which would allow for using natural sources for heating and cooling. In addition to the previous recommendations, there are some systems available that can reduce the energy usage. One of these systems is the radiant heating and cooling system with a dedicated outside air supply. This system employs surfaces such as ceilings, floors and attached metal panels for heating and cooling. Along with the radiant heating and cooling is a dedicated outside air supply system that is used for ventilation and dehumidification. The benefit of this approach is that the dedicated air system consumes less energy than the traditional HVAC system. Another system that can be employed is called displacement ventilation with perimeter heat, in which cool air is introduced at the bottom of the room. This air moves gradually to the top due to the stacking effect of heat sources, such as heat produced by people, and is then removed after becoming warmer and picking up contaminants. This system uses less air volume than the traditional mixing system and operates on less extreme temperatures, which can save more energy. Because displacement ventilation is insufficient in heating, it must be coupled with radiant heat panels.

The previous systems mentioned save energy during distribution, but there are other systems that can save energy in the primary equipment itself [15]. One of these systems is the economizer, which is also known as free cooling, in which outside air of convenient temperature and humidity is utilized without using compressor-based cooling. There are two types of economizers: air-side economizers which work well with displacement ventilation and water-side economizers which work well with radiant cooling. A second approach that can be utilized is heat recovery from exiting air. This approach can aid in heating or cooling entering air using exiting air before using primary equipment, which can lead to energy savings. To use such an approach, heat exchangers are deployed, which can take the form of heat wheels, heat pipes and cross-flow heat exchangers. A third approach that can be used to reduce energy consumed in cooling is called evaporative cooling, in which water moisture is added to the entering air. This moisture adds humidity to the air and attracts the heat within the air, producing a cooling effect. Adding moisture directly is called direct evaporative cooling, whereas there is another indirect approach in which moisture is added to an external air stream to create a cooling effect. This cooling effect is then transferred to the air entering the building using a heat exchanger. Another approach that can be utilized is ground source thermal storage, in which soil or earth is used in thermal storage, and heat can be removed from the building and stored in the ground to produce a cooling effect, or heat stored in the ground can be moved to the building to produce a heating effect. This system is usually comprised of a ground source loop, a heat pump and the distribution system of the building. Additionally, the size of the system or the ground source loop usually depends on soil characteristics, which should be studied for each site.

Other than reducing energy in heating and cooling the building, there are some approaches that can be utilized in water heating and in lighting [1] and [15]. There are two energy-saving approaches that can be used for heating the water: using solar thermal energy to heat the water or using heat pumps supplied with energy from solar cells. The first approach utilizes glass tubes containing the heating fluid, which are heated by solar radiation and are then transferred to heat the water tank. In the second approach, where heat pumps are utilized, a refrigerant is vaporized in the heat pump evaporator and is then moved to the compressor, where it is compressed and its temperature rises, after which it moves to the water tank to heat the water. Using solar thermal heating might require backup energy to heat the water, whereas using heat pumps can be based entirely on solar cells, which is in fact the most effective approach. For lighting, which consumes the most energy within a building, there are some effective approaches to reduce energy. One of these approaches is to integrate daylighting in the building and use artificial lighting as a supplement for natural lighting sources. This can be done by utilizing controls to assure that lighting is used only when needed. These controls should be both manual and automatic, with the automatic control being sensitive to the occupancy, daylight and time of day. Ambient lighting should also be separated from task lighting. This can result in lower lighting levels for ambient light and an ability to optimize task light as much as needed by the occupants through, for example, the use of controlled low-energy LED lights. Additionally, the lighting system used should be energy efficient, such that it has a low light EUI. An example of energy-efficient lighting would be high-intensity-discharge light, linear fluorescent, compact fluorescent and light-emitting diodes.

### 2.3 Benchmarking Energy Efficiency

The current methodologies for benchmarking NZEB are examined as follows:

### 2.3.1 Methodologies Used

Chung [16] illustrated various methodologies that were used in research for benchmarking the energy efficiency of buildings. These methodologies are as follows:

1- Simple normalization:

In this approach, a ratio between the energy use and a single input that determines the amount of energy is used for benchmarking. The input employed is a main driver of energy use and could be the floor area of the building, the number of occupants or the building operation hours. In most cases, the building floor area is used as an input and the ratio is called energy use intensity (EUI). To account for climatic differences, the EUI can be normalized using information about the degree days at the building site. The main drawback of using this simple normalization is that the use of one input results in a less accurate benchmark. This is mainly due to the presence of other inputs that may be ignored, such as the building age or occupant behavior.

2- Ordinary least squares

This method depends on determining a multiple linear regression model for energy use, which shows the relationship between the normalized energy use intensity and several inputs that affect it. The general form of the multiple regression model is shown in the following equation (eq. 10):

$$EUI = a + b_1x_1 + b_2x_2 + \cdots + b_nx_n \quad (10)$$

where $EUI$ = The climate adjusted energy use intensity;

$a$ = Regression intercept;

$b$ = Regression slope for factor $x_n$; and

$x_n$ = Standardized factor based on mean level.

After determining the standardized factor for a certain building, the EUI can be predicted using the regression line, and this can be compared with the measured EUI. The residual between the predicted and measured EUI can be used to determine if the building is energy efficient or not. A benchmark table can also be constructed from the sample by utilizing the distribution of the residuals from these samples. The drawbacks of this approach are that it depends on an average value and that the residuals do not represent energy inefficiency, as they might be due to data collection errors or other factors that are not considered in the regression model. A modification of this approach was presented by Chung et al. [17], and in this method the regression model is modified such that the intercept of the regression model is on the left side of the equation (eq. 11), as seen below:

$$EUI_{norm} = EUI_0 - b_1 x_1 - b_2 x_2 - \cdots - b_n x_n \quad (11)$$

where $EUI_{norm}$ = The normalized energy use intensity after removing the effect of factors $x_1$ to $x_n$. The normalized energy use intensity corresponds to the regression slope $a$ in Equation 13;

$EUI_0$ = The climate adjusted energy use intensity;

$b_n$ = Regression slope for factor $x_n$; and

$x_n$ = Standardized factor based on mean level.

The benchmarking table can be constructed later from the sample $EUI_{norm}$, which can be used to determine the rank of a specific building. Another modification of the procedure in Equation 1 was also presented by Sharp [18], who used another method to determine the benchmarking table. In this method, the standard error and t-distribution were utilized to determine the ranking of each building. This was done by calculating the difference between actual and predicted EUI, and a t-value can be determined by using the standard error.

3- Stochastic frontier analysis:

The drawback of the ordinary least squares method is that the residuals might not represent efficiencies, but could instead be related to errors in the data collected and other factors not mentioned in the model. This can be overcome using stochastic frontier analysis, which determines the amount of inefficiency. Amsler et al. [19] reviewed the procedure for stochastic frontier analysis and the latest developments from recent research. According to Amsler's review, stochastic frontier models are used to determine technical efficiency, which could be based on the input or output efficiencies. The input efficiency is basically the comparison of the actual inputs to the minimum possible inputs, whereas output efficiency is based on the comparison between the actual output and the maximum possible output. Because the stochastic models are commonly used to determine production efficiency, or in this case, the energy efficiency, the model used will be based on output efficiency (eq. 12).

$$Technical\ Inefficiency = 1 - \frac{y_0}{y_1} \quad (12)$$

where $y_0$ = the actual output, and

$y_1$ = the maximum output.

According to Amsler et al. [19], the introduction of the stochastic model was initially deterministic. The next equations show the calculation of the technical inefficiency (eq. 13 to 17) along with the deterministic form (eq. 18) as follows:

$$y \leq f(x) \quad (13)$$

$$y = f(x) + u,\ u \geq 0 \quad (14)$$

$$Y = e^{f(x)} \times e^{-u} \quad (15)$$

$$Technical\ efficiency = \frac{Y}{e^{f(x)}} = e^{-u} \quad (16)$$

$$Technical\ inefficiency = 1 - e^{-u} \approx u\ for\ small\ u\ values \quad (17)$$

where $y$ = $\log_{10}$ of the output for unit $i$;

$Y$ = level of output;

$f(x)$ = frontier for $y$; and

$u$ = error.

$$yi = \alpha + x_i \times \beta - u_i, u_i \geq 0, i = 1,2, \ldots, N \quad (18)$$

where $yi$ = $\log_{10}$ of the output for unit $i$;

$\alpha$ = regression slope;

$x_i$ = $K \times 1$ vector of inputs;

$\beta$ = vector of coefficients; and

$u_i$ = technical inefficiency.

The deterministic form can be solved by linear or quadratic programming which is shown in the following equations (eq. 19 and 20):

$$Min \sum_{i=1}^{N}(y_i - \alpha - x_i \times \beta) \; subject \; to \; y_i \leq \alpha + x_i \times \beta \; for \; all \; i \quad (19)$$

$$Min \sum_{i=1}^{N}( y_i - \alpha - x_i \times \beta)^2 \; subject \; to \; y_i \leq \alpha + x_i \times \beta \; for \; all \; i \quad (20)$$

While the previous equations for the deterministic form consider the total error to be due to inefficiency, it is better to use the stochastic frontier model (eq. 21), which considers the total error $\varepsilon_i$ to consist of the technical inefficiency $u_i$ and the statistical noise $v_i$ as follows:

$$yi = \alpha + x_i \times \beta + v_i - u_i \quad (21)$$

In the case of energy efficiency, the term $y_i$ represents the log of the EUI and the distribution for $v_i$ is usually considered normal, while $u_i$ is considered half normal. The solution for the stochastic frontier model is determined from the maximization of the likelihood function (eq. 22) shown below:

$$\ln L = \sum_{i=1}^{N}(\ln K \; (y_i - \alpha - x_i \times \beta)) \quad (22)$$

Where $k(\varepsilon)=\int_0^\infty h(u, \varepsilon + u)du$, $h(u,v) = f(v)g(u)$, and $f(v)$ and $g(u)$ are the probability density functions for $u$ and $v$.

It's worth noting that the inefficiency cannot be estimated directly by comparing the actual log of EUI with the frontier, but rather by calculating the expected value for $u_i$ given $\varepsilon_i$. It can also be seen from the previous equations that stochastic frontier analysis corrects for statistical errors, but specifies a certain form of the frontier, which is its main disadvantage.

4- Data envelopment analysis (DEA):

Data envelopment analysis (DEA) is applied to a wide array of problems, due to the nature of the analysis, which does not specify a relationship between the input and maximum output or, in other words, the production function. This is contrary to other techniques that are employed in determining the production function, such as stochastic frontier analysis (SFA), which specifies a form for the relationship between inputs and outputs. The reason behind that is due to the nature of the DEA, which connects the most efficient points in terms of the ratio of outputs to inputs. In the case of multiple outputs or inputs, DEA uses a set of weights to convert all output into one virtual output and all inputs into one virtual input. This allows for using DEA when there are multiple outputs, which gives it an extra advantage over SFA. It is important to note that the ratio of output to input is the focal point of DEA and represents a combination of the effects of the efficiency and the returns to scale [20]. It can also be seen that DEA and SFA are both frontier methods which determine the efficiency with respect to the most efficient instead of the average regression line, as is used in statistical analysis.

- DEA Concepts:

1- Basic efficiency ratio: Data envelopment analysis depends on measuring the efficiency of production units, which can be simplified to a simple ratio (eq. 23) between output and input. The more efficient the unit, the less input it requires for the same level of output.

$$efficiency = \frac{Output}{Input} \quad (23)$$

Using this ratio, production units which turn inputs into outputs can be benchmarked or compared with the unit with the maximum efficiency. According to Cooper et al. [20], there are two approaches to constructing the efficiency ratio: considering the efficiency as a partial productivity measure or as a total factor productivity measure. The partial productivity measure can take the example of output per worker-hour or employee, which is basically a measure of productivity as it is formally known. While this might be valid in some cases, the more discernable approach is to use the total factor productivity measure that includes all the inputs that enter the decision-making unit and all of the outputs that result. This will enable an accurate measurement of the efficiency because the missing input or outputs can lead to misleading results regarding the efficiency of the production unit.

2- Decision-making units: Using the ratio mentioned earlier, the set of production units which turn inputs into outputs can be benchmarked or compared with the production unit with the maximum efficiency. The benefit of this approach is that the units are compared with an actual optimum unit, and thus lessons learned from the optimum unit can be investigated and transferred to other, less-efficient units. The production units that are involved in the data envelopment analysis are called decision-making units, as they represent entities with separate decisions that affect their efficiency.

3-Relative efficiency: Data envelopment analysis is based on measuring the relative efficiency balance (eq. 24) of the decision-making units by comparing the efficiency of each point in the set to the maximum efficiency. Thus, this method is based on measuring relative efficiency, rather than the actual efficiency of the decision-making units involved. The relative efficiency for the decision-making unit can range from 0 to 1.

$$Relative\ efficiency = \frac{DMU\ Efficiency}{Maximum\ DMU\ Efficency} \quad (24)$$

- Graphical Explanation (One Input - One Output):

Table 5 shows a hypothetical set of decision-making units (A to H) and is an altered example based on Cooper et al. [20]:

**Table 5: DEA One Input-One Output Example**

| **Point** | **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** |
|---|---|---|---|---|---|---|---|---|
| **Input** | 2 | 3 | 3 | 4 | 5 | 7 | 2 | 3 |
| **Output** | 1 | 2.5 | 1 | 1 | 2 | 4 | 2 | 2 |
| **Efficiency (Out/In)** | 0.50 | 0.83 | 0.33 | 0.25 | 0.40 | 0.57 | 1.00 | 0.67 |
| **Relative Efficiency** | 0.50 | 0.83 | 0.33 | 0.25 | 0.40 | 0.57 | 1.00 | 0.67 |

As seen from Table 5, point G has the highest output to input ratio with respect to the other points, and this ratio results from a combination of the efficiency of the decision-making units and the returns to scale at the current level of input. Because point G is achieving the maximum ratio possible between the decision-making units, it can be considered to be operating at (100%) or (1) relative efficiency at its level of input or scale, and the production function corresponding to 100% efficiency can pass through this point, but it can deviate in slope according to the returns to scale. An example of this can be seen in the following graph:

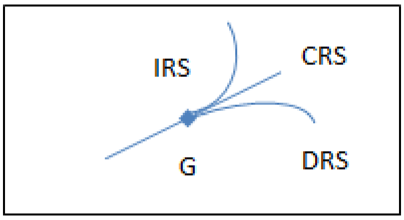


**Figure 1: Various Types of Returns to Scale in DEA**

As seen from Figure 1, the 100% level of efficiency can decrease after point G because of decreasing returns to scale, increase because of increasing returns to scale or remain the same under constant returns to scale. Additionally, the concept of DEA can be illustrated as shown:

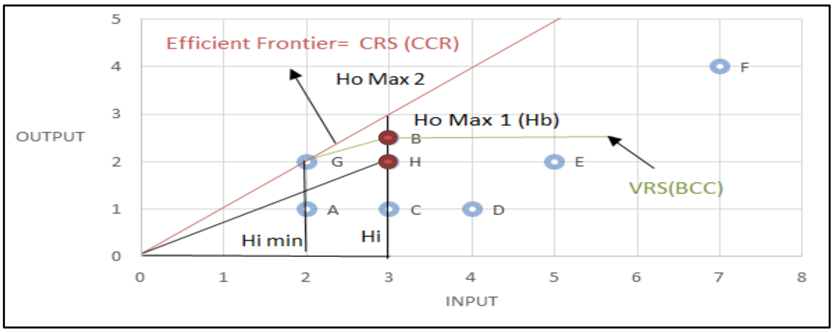


**Figure 2: DEA Basic Graphical Example**

As seen from Figure 2, the basic idea of data envelopment analysis is to create a graphical plot or frontier between the input and the maximum output, called the production frontier, which starts from zero input and moves along the points with the maximum output/input ratios. This is different from benchmarking using a regression line, which follows a central tendency behavior in the data rather than the most efficient frontier. Because DEA measures the efficiency from the most efficient frontier, this can lead to a more accurate calculation of the efficiency if the data regarding the most efficient points do not resemble outliers. If constant returns to scale are assumed, the maximum efficiency cannot be altered with the production level or scale, and thus the slope of the data envelop will not change [20]. The assumption of constant returns to scale (CRS) along with the variable return to scale

(VRS) can be seen in the above graph with the lines of fixed and variable slope that pass through point *G* from the 0 input, 0 output point. Additionally, it can be seen that the slope of the line represents the efficiency of the point *G*. The maximum output for each input can also be obtained by linking the decision-making unit with the envelope line by a vertical link. An example of that would be for point *H*, which has the input *Hi* and can reach the maximum output of *Ho max2* under CRS and *Ho max1* under VRS (*Ho max1* and *Ho max2* are shown in enclosed red circles). Another way of interpreting the graph would be to determine the least input that can be achieved with the determined level of output for point *H*, which can be seen in the graph in the distance *Hi min* under CRS. Therefore, point *H* can improve its efficiency by increasing output to either *Ho max2* or *Ho max1* or reducing its input to *Hi min*.

- CCR Model

To solve the problem of having multiple inputs and outputs, the inputs can be turned into one single virtual input by using a set of weights that translate the set of inputs in terms of one of these inputs. The outputs can also be translated into one single output, which can be seen in the following equation (eq. 25):

$$\text{Efficiency} = \frac{Virtual\ Output}{Virtual\ Input} = \frac{u_1 y_{10} + u_2 y_{20+} \ldots\ldots + u_s y_{s0}}{v_1 x_{10} + v_2 x_{20+} \ldots\ldots + v_m x_{m0}} \quad (25)$$

Using fixed weights u,v for all DMUs will affect the efficiency of each DMU, and therefore a preferred approach would be to maximize the efficiency for each DMU while keeping the efficiency for other DMUs less than one. This will remove the effect of the choice of the weights because each point will be able to maximize its efficiency with its own set of weights. The following equation (eq. 26) correspond to the fractional portion of the DEA model:

$$Max\ \theta = \frac{u_1 y_{10} + u_2 y_{20+} \ldots\ldots + u_s y_{s0}}{v_1 x_{10} + v_2 x_{20+} \ldots\ldots + v_m x_{m0}} \quad (26)$$

Subject to:

$$\frac{u_1 y_{1j} + u_2 y_{2j+} \ldots \ldots . + u_s y_{sj}}{v_1 x_{1j} + v_2 x_{2j+} \ldots \ldots . + v_m x_{mj}} \leq 1 \ (j = 1, \ldots \ldots, n)$$

$$v_1, v_2, \ldots \ldots, v_m \geq 0$$

$u_1, u_2, \ldots\ldots, u_m \geq 0$

This equation (eq. 27) can be modified into the following form for output-oriented DEA:

$Max\ \sum_{i=1}^{m} u_i y_{io}$ (27)

Subject to:

$$\sum_{j=1}^{n} v_j x_{j0} = 1$$

$$\sum_{i=1}^{m} u_i y_{ik} - \sum_{j=1}^{n} v_j x_{jk} \leq 0\ for\ k = 1,2,\ldots,h$$

For input-oriented DEA, equation 28 takes the following form:

$Min\ \sum_{j=1}^{n} v_j x_{j0}$ (28)

Subject to:

$\sum_{i=1}^{m} u_i y_{io}$=1

$$\sum_{i=1}^{m} u_i y_{ik} - \sum_{j=1}^{n} v_j x_{jk} \leq 0\ for\ k = 1,2,\ldots,h$$

- BCC Model

The BCC model takes into account the change in efficiency when varying the scale, and the corresponding equation (eq. 29) for the output-oriented BCC model is as follows:

$Max\ \sum_{i=1}^{m} u_i y_{io} + w$ (29)

Subject to:

$$\sum_{j=1}^{n} v_j x_{j0} = 1$$

$$\sum_{i=1}^{m} u_i y_{ik} - \sum_{j=1}^{n} v_j x_{jk} + w \leq 0 \;\; for\; k = 1,2,\dots,h$$

For input-oriented BCC, the equation (eq. 30) takes the following form:

$Min\ \sum_{j=1}^{n} v_j x_{j0} - w$ (30)

Subject to:

$\sum_{i=1}^{m} u_i y_{io}$=1

$$\sum_{i=1}^{m} u_i y_{ik} - \sum_{j=1}^{n} v_j x_{jk} + w \leq 0 \;\; for\; k = 1,2,\dots,h$$

It is important to note that the advantage of data envelopment analysis is that it does not assume a certain form of the envelopment; however, it is deterministic and not stochastic.

5- Artificial neural networks (ANN):

The most common used type of network for ANN is the back propagation (BP) which was demonstrated in a research review on ANN by Basheer and Hajmeer [21]. This type of network employs an input node layer which contains input variables, one or multiple hidden layers corresponding to weights, biases and transfer functions, which are used to account for nonlinearity; and an output node layer which is composed of dependent variables (shown in Figure 3). The methodology of BP is to propagate errors calculated at the output layer to the hidden layer and then to the input layer. The BP method starts with a forward step to calculate the solution, followed by a backward step of propagating errors to correct the weights used.

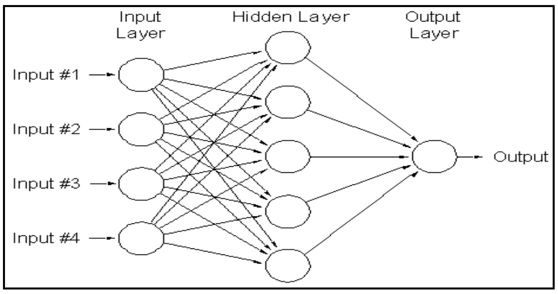


**Figure 3: Network Map of ANN [22]**

Yalcintas [23] presented the earliest research to use ANNs for energy benchmarking. In his research, the author used ANN with a backward algorithm to determine the predicted EUI for a building in a tropical climate, based on an ANN model for input factors consisting mainly of the plug load, lighting demand and air conditioning demand. These factors consisted of ten inputs to the ANN, with the inputs determined from survey questionnaires of 60 buildings in Hawaii. To ensure the validity of the survey, the author used ANN sub-models for the combined input factors and compared those models to the survey results, which appeared to be consistent. One fourth of the data was not used in determining the ANN model, but was rather used in verifying the model. It appeared that there is an 85% correlation with test data, which indicates the sufficiency of ANN in predicting energy efficiency. As a benchmarking technique, ANN would be similar to regression in that it considers the difference between the actual and predicted value to be due to inefficiency.

# Chapter 3: Research Methodology

## 3.1 Research Background

The research background covers the following stages (Figure 4):

1- Problem Statement: At the initial stage of the thesis work, a problem statement is identified. Here, the problem would be the need to benchmark NZEB, as there are various definitions for these buildings in research.

2- Literature Review: A literature review is performed to determine the nature and the common features of NZEB, along with the current benchmarking methodologies.

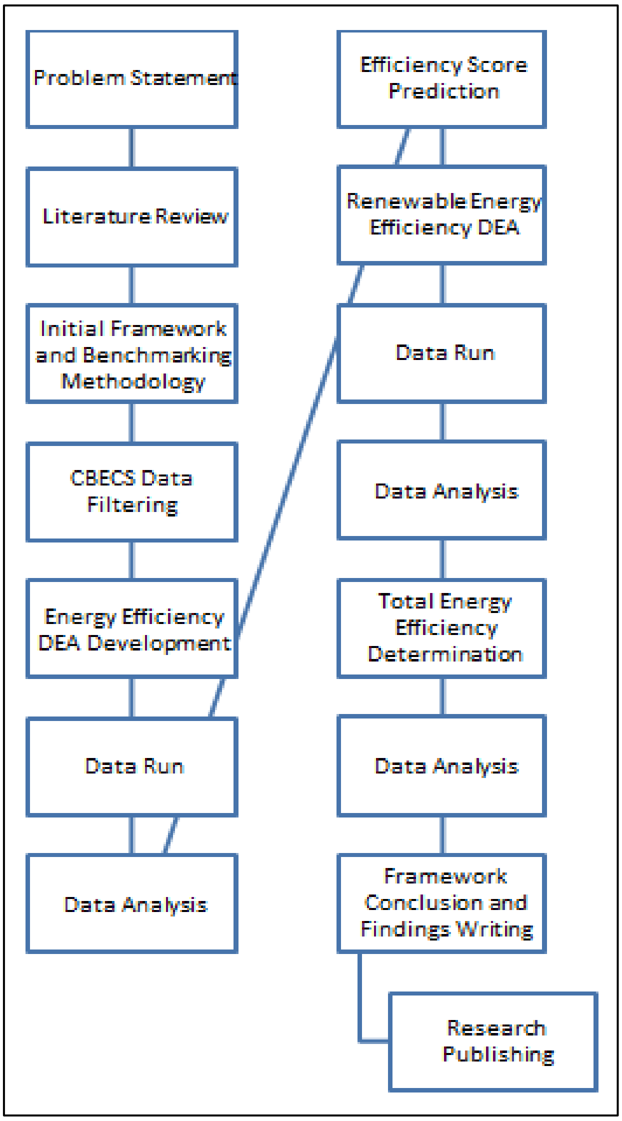


**Figure 4: Research Mechanism**

### 3.2 Framework Development

The framework development covers the following stages (Figure 4):

1- Initial Framework and Benchmarking Methodology: An initial framework is identified based on common features of NZEB, which will consist of benchmarking the energy efficiency and benchmarking the renewable energy efficiency. The benchmarking methodology is selected according to suitability, and DEA is selected as the benchmarking methodology for this case. This methodology is chosen because it does not specify a specific form of the frontier, which is an accurate approach in the case of NZEB.

2- CBECS Data Filtering: Because acquiring data about NZEB requires extensive work and resources, the CBECS 2003 micro data are selected as the source data for the benchmarked buildings and additional data are simulated regarding the cost, emissions and utility energy of NZEB.

3- Energy Efficiency DEA Development: This requires using a set of uncontrollable input factors affecting energy use intensity, which are beyond the control of the owner and designer.

These uncontrollable factors can be:

1- Climate:

- Cooling degree days.
- Heating degree days.

2- General building characteristics:

- Building age.

3- Building functional characteristics:

- Weekly operating hours.
- Number of occupants per unit area.

Using inputs similar to those previously mentioned, the energy use efficiency can be benchmarked using DEA with one output, which is the EUI. Because the DEA contains undesirable outputs and inputs, the reciprocals of the previous inputs and outputs can be used. The selection of this method is mainly based on the fact that this method does not assume any specific shape for the relationship between inputs and outputs, which can be beneficial in modeling complex relationships, especially in the case of buildings.

4- Data Run: Using the configuration of the DEA model and the assumptions made regarding the model, a data run is completed using selected commercial software.

5- Data Analysis: Benchmarking samples covering the whole range of efficiency values are examined to determine whether the efficiency score is correlated with the ratios between outputs and inputs.

6- Efficiency Score Prediction: After the energy efficiency is calculated, an extra stage is to identify the sources of efficiency by applying an Artificial Neural Network (ANN) between the efficiency obtained from the DEA model and a set of controllable factors that affect the efficiency. The use of an ANN is more suitable than regression because there are many input factors, some of them binary.

These controllable factors are as follows:

1- Lighting System and Passive Lighting:

- Percentage of area daylighted.
- Whether auto control or sensors on lighting are used
- Whether skylights are used.
- Percent lit by specified lighting type.

2- HVAC System and Passive Heating and Cooling:

- Whether variable air volume is used.
- Whether an economizer is used.
- Whether external overhangs are used.
- Whether maintenance is performed regularly.
- Percentage area cooled by specific cooling equipment.
- Percentage area heated by specific heating equipment.

7- Renewable Energy Efficiency DEA Development: This stage involves benchmarking the renewable energy system used in the building, which will also be based on DEA. The method applied belongs to the author, and in this approach a DEA will be used with the following inputs and output:

1- Energy use intensity. (Input)
2- Total yearly building energy costs per unit area. (Output)
3- Total yearly utility energy used per unit area. (Output)
4- Total yearly building energy emissions per unit area. (Output)

To use the previous inputs and outputs, the reciprocal of these factors can be used because the outputs and inputs are undesirable.

8- Data Run: Using the configuration of the DEA model and the assumptions made regarding the model, a data run is completed using selected commercial software.

9- Data Analysis: Benchmarking samples covering the whole range of efficiency values are examined to determine whether the efficiency score is correlated with the ratios between outputs and inputs.

10- Total Energy Efficiency Determination: Based on the accuracy of the data and the configuration of the two models, the calculation methodology for the total energy efficiency is determined. The total benchmark for the network composed of the two DEAs would be the total energy efficiency, which can be calculated from equation 31:

$$Total\ energy\ efficiency = Energy\ use\ efficiency \times Renewable\ efficiency \quad (31)$$

A possible alternative to the previous equation is to average both efficiencies to avoid overriding a efficiency score with the other, as seen from equation 32:

$$Total\ energy\ efficiency = (Energy\ use\ efficiency + Renewable\ efficiency)/2 \quad (32)$$

As seen from the equation, the total energy efficiency can indicate a reduction in the energy used, in the carbon emissions and in the costs of energy of the NZEB.

11- Data Analysis: Benchmarking samples covering the whole range of efficiency values are examined to determine whether the efficiency score is correlated with the ratios between outputs and inputs. If the results are satisfactory, the methodology is finalized and the study can proceed to the next stage.

### 3.3 Concluding and Publishing

1- Framework conclusion and documentation of findings: Based on the lessons learned from the methodology and data analysis, a final framework is determined and the conclusions are documented for the study.

2- Publication of Research: After completion of the thesis work and review of the study, the research will be submitted for publication

# Chapter 4: Framework Development

## 4.1 Introduction

In this Chapter, the framework introduced benchmarking NZEB will be outlined in detail. The framework applied in the next sections will consist of the following three parts:

1- Benchmarking the energy efficiency of NZEB.
2- Benchmarking the renewable energy efficiency of NZEB
3- Benchmarking the total energy efficiency of NZEB.

In the first part, data envelopment analysis is used as the method of choice for benchmarking NZEB in terms of the energy efficiency, due to the nature of DEA, which does not specify a certain frontier form. In this part, the DEA model will consist of several uncontrollable input factors which result in an increase in the EUI of the building. The efficiency of the building will be judged in terms of the weighted ratio between the output, which is the reciprocal of the EUI, and the input factors included in the DEA model. The input factors and the properties of the DEA model will be discussed in further detail in this chapter. In addition to the DEA, ANNs are used to predict the efficiency score of the building. The efficiency score will be predicted using controllable input factors that affect the energy efficiency of the building, such as the use of economizers. The details of the ANN network used and the factors involved will be discussed in proceeding sections. In the second part, the renewable energy generation will be assessed in terms of its efficiency. The efficiency will be evaluated based on the total emissions, total costs and utility energy use incorporated in a DEA model that allows for multiple outputs. The properties of the DEA model will be discussed in further detail in this chapter. The third and final part will involve combining the efficiency scores obtained from the first and second parts to find the total energy efficiency of the NZEB. Details of the total energy efficiency calculation will also be discussed in this chapter.

## 4.2 Benchmarking The Energy Efficiency of NZEB

In the suggested framework, the benchmarking of NZEB according to energy efficiency or EUI performance will include creating both a DEA model to determine the efficiency score of the buildings and an additional ANN model to predict the efficiency score of the buildings determined in the DEA. Using the ANN will provide the building owners with the ability to measure the building efficiency from controllable factors that can be determined during design. It is important to note that the energy efficiency part of the methodology was applied to commercial buildings for which the principal building activity is to lease offices. Therefore, variation in the factors involved can be determined based on the functional characteristics of the building, or on functional drivers of energy usage and weather characteristics such as heating degree days and cooling degree days, which were used in the study.

### 4.2.1 DEA Model

To benchmark the energy efficiency of NZEB, a DEA model will be used to determine the actual efficiency scores of the included buildings. In the following sections, the various aspects of the DEA model are introduced.

#### 4.2.1.1 Data Used and Data Caveats

The data used in constructing the DEA model correspond to 432 office buildings included in the 2003 micro data published online by the CBECS. The buildings were selected from 5216 buildings available in the CBECS database. The selection was based on the following factors:

1-Principal building activity: The buildings were chosen to have a principal building activity of leasing offices. This can reduce the variation in the EUI of the buildings based on the function. In case the model is applied to another types of functions, separation according to function is preferred, as it will allow the EUI performance to be measured more accurately.

2-Free-standing building: To reduce the errors due to the inaccurate calculations for buildings in complexes, the buildings were filtered to include only free-standing buildings.

3-Used in the last 12 months: Only buildings used in the last 12 months were chosen, to avoid reductions in the EUI due to unoccupied buildings.

4-Less than 100,000 Sq. ft.: Because NZEB are not yet implemented on a large scale, only areas less than 100,000 Sq. ft. were chosen. Although NZEB did not reach an area of 100,000 Sq. ft., this filter was still kept to allow for more data in the sample.

5-Year of construction: To reduce error due to different building technologies, only buildings built in the forty years before the year of the CBECS study were chosen. Although forty years is a substantial period in terms of building technology, this filter was kept to allow for additional sample data.

6-Complete data record: To avoid replacing missing data, only buildings with a complete data record were chosen for the study.

Although the data are original data, some important considerations have to be made concerning the data caveats. One of these data caveats is the square footage of the building, which has been rounded to provide confidentiality of the building identity. The square footage for buildings less than 1,000,000 Sq. ft. was rounded to within 5% of the upper limit of the building square footage category. Therefore, if the building is 11,400 Sq.ft. in the 500-12000 sq. ft. category, then the building is rounded to the nearest 5% of the upper limit, which is approximately 500 Sq. ft., so the building area is rounded to 11,500 Sq. ft. .If the rounding is beyond the upper and lower limit, the building is rounded to the limits of the category in which it is placed. Another data caveat is in the number of workers during main shift, which was rounded to the nearest 250 for worker populations between 2500 and 4999. For worker populations equal to 5000 or more, the number of workers was replaced by a weighted average for buildings with worker populations greater than 5000. A final consideration in the data used is that the heating degree days and the cooling degree days were masked to prevent identification of the building's weather station. These data caveats will affect the accuracy of the DEA model and the ANN model used in this stage.

#### 4.2.1.2 Factors Involved

To determine the efficiency score for the buildings, one output was chosen along with several inputs that include weather and function uncontrollable external factors. These factors are as follows:

1-Reciprocal of Heating degree days (1/F):

A ‘heating degree day’ refers to the positive difference between the outside temperature on a given day and a base temperature (65 F) for which the building would require no heating. This difference will be summed across the whole year to determine the heating degree days for a building, based on the Fahrenheit system. With the increase in heating degree days, the heating demand for the building increases and thus the energy use intensity increases. The efficiency in this case can be apparent in a building that has high heating degree days and low energy use intensity.

2-Reciprocal of Cooling degree days (1/F):

A ‘cooling degree day’ refers to the negative difference between the outside temperature on a given day on which the building requires cooling and a base temperature (65F), which will be summed across the whole year. With an increase in cooling degree days, the energy use intensity in a building is expected to increase. The efficiency in this case can be apparent in buildings that have high cooling degree days and low energy use intensity.

3-Reciprocal of Total weekly operating hours (1/Hrs):

The total weekly operating hours is a major predictor of the energy use intensity of the building, as the building is expected to use more energy with the increase in operating hours. Therefore, efficient buildings are the ones that have more weekly operating hours with low energy use intensity.

4-Reciprocal of Number of employees during main shift per unit area (Sq. ft. /No.):

This factor can be a major predictor of the energy use and the energy use intensity, and buildings with many employees per unit area during the main shift and lower energy use intensity are considered to be the most efficient buildings. The previous factors will be used with one output: the reciprocal of the energy use intensity. The reciprocal of the energy use intensity is used because higher efficiency scores should be given to buildings that have higher reciprocals of the energy use intensity with the current input levels. Table 6 summarizes the inputs and output of Energy Efficiency DEA.

**Table 6: Energy Efficiency DEA Factors**

| Factor | Input/Output | Unit |
|---|---|---|
| 1/Heating degree days | Input | 1/F |
| 1/Cooling degree days | Input | 1/F |
| 1/Total Weekly operating hours | Input | 1/No. |
| Area/Number of employees during main shift | Input | Sq. ft./No. |
| 1/EUI | Output | Sq. ft/ kBtu |

#### 4.2.1.3 Data Envelopment Analysis Methodology

The previous factors for the 432 building data sets were inserted into MaxDEA software Version 6.1, which is free for non-commercial use. The DEA will be calculated for both the 300 data out of the sample and for all 432 data sets. This will be beneficial because it will allow for the use of the whole sample for calculating total energy efficiency, and for the use of part of the sample to validate the ANN results, with 300 data sets for training and 132 data sets for determining the efficiency score and comparing these to the DEA data for all 432 data sets. The DEA methodology involved a CCR model with constant returns to scale, meaning that the maximum efficiency ratio may not increase or decrease with the increase in scale. The CCR model was used because most of the buildings were efficient under the BCC model, and the CCR model is therefore a more rigid benchmarking technique. The model also assumes radial distance, and the slack is computed in one stage. Additionally, the DEA that is used is output oriented, meaning that the maximum output will be determined for some level of input; and for this study, the output is the reciprocal of the EUI. Finally, no weight restrictions were input to the model. The following equation (eq. 33) is for the output-oriented CCR model and is the one followed in this methodology.

$Max\ \sum_{i=1}^{m} u_i y_{io}$ (33)

Subject to:

$$\sum_{j=1}^{n} v_j x_{j0} = 1$$

$$\sum_{i=1}^{m} u_i y_{ik} - \sum_{j=1}^{n} v_j x_{jk} \leq 0\ for\ k = 1,2, \dots, h$$

MaxDEA was chosen as the DEA software because it will reduce the time spent determining constraints, as only the inputs, outputs and the desired model must be entered into the software. Additionally, the calculation methodology uses the equations mentioned above and, more specifically, follows the output-oriented CCR model. In addition, the results of the software for the both the CCR and BCC DEA were verified, and follows is table 7 which shows the BCC output-oriented DEA score verified for a sample of 9 data points:

**Table 7: Inputs of MaxDEA Software Verification**

| DMU | X1 | X2 | Output |
|---|---|---|---|
| **101** | 2965 | 1367 | 0.02138387 |
| **102** | 4722 | 1294 | 0.00499431 |
| **103** | 6582 | 575 | 0.00890676 |
| **104** | 851 | 3537 | 0.00471374 |
| **105** | 2970 | 1505 | 0.00473993 |
| **106** | 6470 | 715 | 0.0080052 |
| **107** | 4351 | 1293 | 0.00791337 |
| **108** | 7780 | 667 | 0.00225024 |
| **109** | 5372 | 825 | 0.0117166 |

The results for the calculation and the software scores are presented on Table 8:

**Table 8: Verification Score of MaxDEA Software**

| DMU | v1 | v2 | u | w | 1/Z | Score Max DEA |
|---|---|---|---|---|---|---|
| **101** | 0.000158 | 0.000388 | 46.764261 | 2.46E-11 | 0.999999 | 1 |
| **102** | 7.57E-06 | 0.003189 | 200.228027 | 0.100075 | 0.246175 | 0.24683 |
| **103** | 0 | 0.001913 | 112.274428 | 0.100174 | 0.999999 | 1 |
| **104** | 0.001673 | 0 | 212.146067 | 0.423634 | 0.999999 | 1 |
| **105** | 7.39E-06 | 0.003357 | 210.973911 | 0.100064 | 0.201013 | 0.221659 |
| **106** | 8.82E-06 | 0.002008 | 124.918855 | 0.100137 | 0.717985 | 0.720391 |
| **107** | 8.79E-06 | 0.002031 | 126.36846 | 0.100076 | 0.389995 | 0.391401 |
| **108** | 0 | 0.007058 | 444.396694 | 0.10015 | 0.217039 | 0.217286 |
| **109** | 0.002336 | 0.011966 | 85.34907 | 21.42218 | 0.999999 | 1 |

#### 4.2.1.4 Sample Results

Tables 9 and 10 show the data for 16 buildings out of 432 inserted in the DEA, which were selected for having scores close to 100, 80, 60, 40, 20 and 5 percent. The data for the ratios between the output and the inputs are shown to indicate a reduction in the ratios with the lower benchmarks.

**Table 9: Energy Efficiency Benchmarking Samples**

| DMU Name | 1/HDD | 1/CDD | 1/Worker Hr. | Area/No. Workers | 1/EUI |
|---|---|---|---|---|---|
| **505** | 0.000407 | 0.000572 | 0.02 | 233.3333 | 0.102537 |
| **167** | 0.000157 | 0.006135 | 0.025 | 4625 | 0.231042 |
| **251** | 0.002703 | 0.000235 | 0.02 | 1666.667 | 0.148903 |
| **231** | 0.000569 | 0.000511 | 0.025 | 5000 | 0.114129 |
| **380** | 0.006757 | 0.000184 | 0.016667 | 1083.333 | 0.085104 |
| **459** | 0.000298 | 0.000562 | 0.025 | 2000 | 0.060427 |
| **188** | 0.000138 | 0.002075 | 0.025 | 200 | 0.024134 |
| **384** | 0.000805 | 0.00141 | 0.005952 | 507.6923 | 0.026792 |
| **110** | 0.000152 | 0.000991 | 0.018182 | 4000 | 0.026277 |
| **172** | 0.000183 | 0.00085 | 0.005952 | 1350 | 0.018628 |
| **453** | 0.000208 | 0.00086 | 0.025 | 300 | 0.023477 |
| **109** | 0.000339 | 0.000434 | 0.02 | 560.3448 | 0.016164 |
| **193** | 0.00059 | 0.00052 | 0.016667 | 264.7059 | 0.017554 |
| **285** | 0.000148 | 0.001145 | 0.025 | 383.3333 | 0.00991 |
| **290** | 0.000249 | 0.00059 | 0.025 | 325.5814 | 0.003597 |
| **392** | 0.001017 | 0.000588 | 0.02 | 288 | 0.005191 |

**Table 10: Energy Efficiency Benchmarking Sample Results**

| DMU Name | Ratio 1 | Ratio 2 | Ratio 3 | Ratio 4 | Score CCR | Times as BM |
|---|---|---|---|---|---|---|
| **505** | 252.1386 | 179.1322 | 5.126853 | 0.000439 | 1 | 424 |
| **167** | 1469.196 | 37.65986 | 9.241682 | 5E-05 | 1 | 307 |
| **251** | 55.09396 | 634.4739 | 7.445129 | 8.93E-05 | 1 | 171 |
| **231** | 200.525 | 223.465 | 4.565168 | 2.28E-05 | 1 | 39 |
| **380** | 12.59541 | 463.4772 | 5.106249 | 7.86E-05 | 0.838535 | 0 |
| **459** | 202.55 | 107.4989 | 2.417064 | 3.02E-05 | 0.757012 | 0 |
| **188** | 174.681 | 11.63253 | 0.965355 | 0.000121 | 0.604393 | 0 |
| **384** | 33.27601 | 18.99573 | 4.501103 | 5.28E-05 | 0.601772 | 0 |
| **110** | 172.3771 | 26.51349 | 1.445235 | 6.57E-06 | 0.413373 | 0 |
| **172** | 101.8566 | 21.92487 | 3.129463 | 1.38E-05 | 0.406126 | 0 |
| **453** | 113.0423 | 27.30389 | 0.939085 | 7.83E-05 | 0.391301 | 0 |
| **109** | 47.66805 | 37.20985 | 0.808207 | 2.88E-05 | 0.201573 | 0 |
| **193** | 29.75441 | 33.75677 | 1.053253 | 6.63E-05 | 0.200116 | 0 |
| **285** | 67.1399 | 8.651385 | 0.396398 | 2.59E-05 | 0.198913 | 0 |
| **290** | 14.45971 | 6.093223 | 0.143878 | 1.1E-05 | 0.051065 | 0 |
| **392** | 5.102817 | 8.82481 | 0.259553 | 1.8E-05 | 0.049768 | 0 |

Additionally, Figures 5 to 8 show graphs of the ratios for each of the previous points, and indicate a reduction in the ratios with the reduction in the benchmarking score. It is notable that not all of the efficient points performed well for all ratios, but they perform well in most ratios.

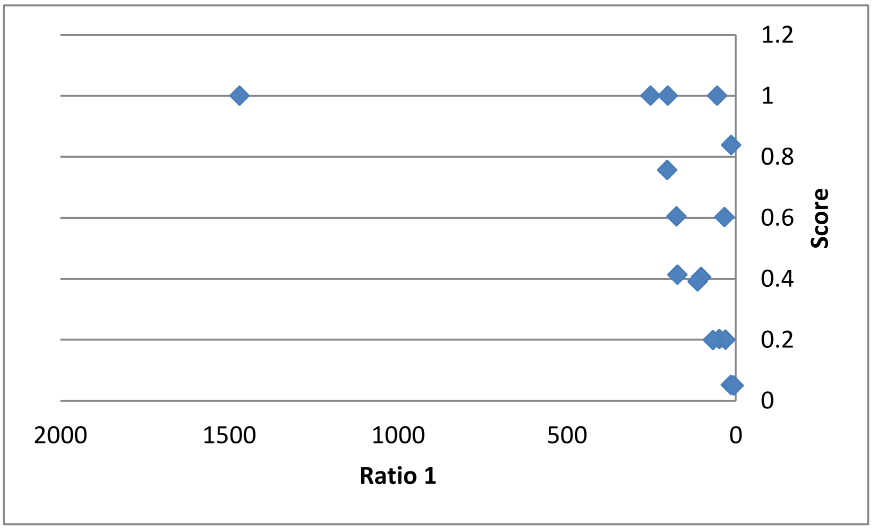


**Figure 5: Energy Efficiency Score Vs. Ratio 1**

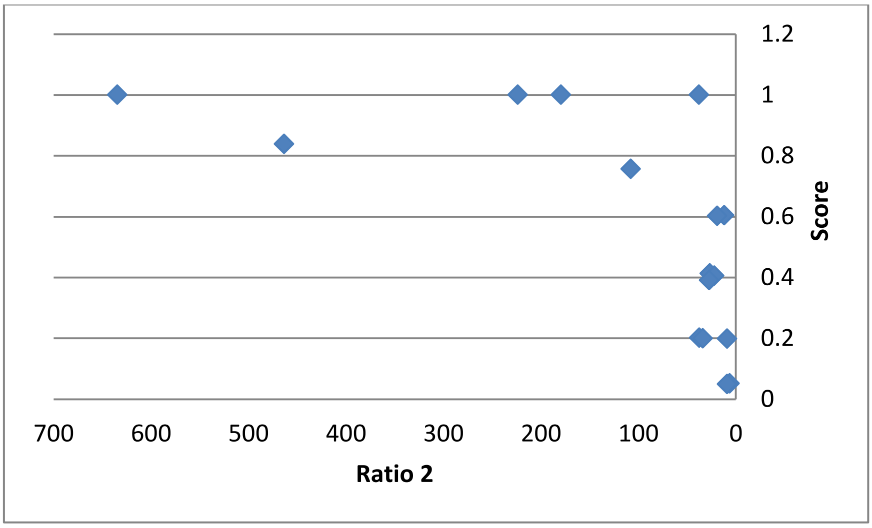


**Figure 6: Energy Efficiency Score Vs. Ratio 2**

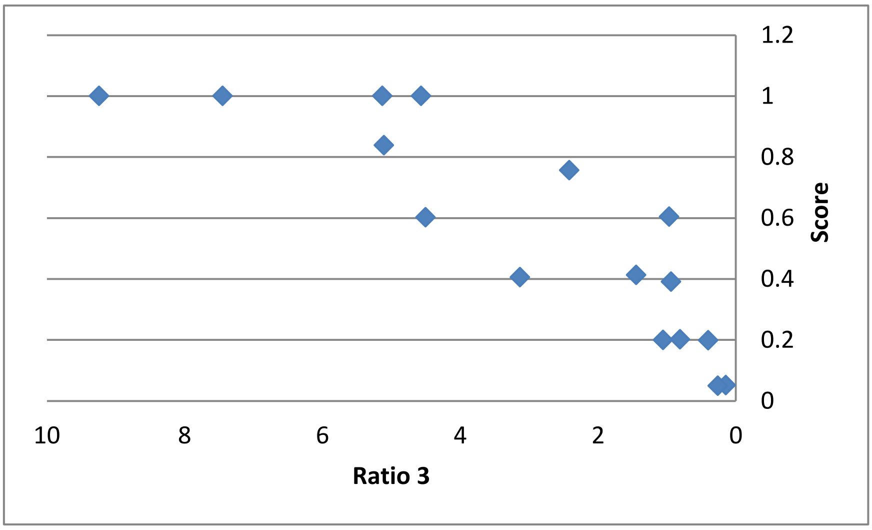


**Figure 7: Energy Efficiency Score Vs. Ratio 3**

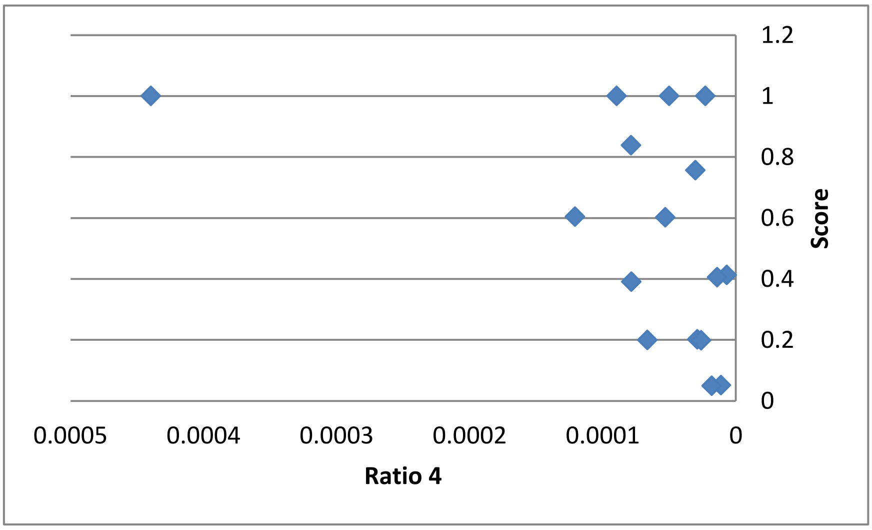


**Figure 8: Energy Efficiency Score Vs. Ratio 4**

For the framework to be used again, only the benchmarks should be used in the DEA calculation, which will save the evaluator time. Table 11 of the benchmarks follows:

**Table 11: Energy Efficiency Benchmarks**

| DMU Name | 1/HDD | 1/CDD | 1/Worker Hr. | Area/No. Workers | 1/EUI | Score CCR | Times as BM |
|---|---|---|---|---|---|---|---|
| **167** | 0.000157 | 0.006135 | 0.025 | 4625 | 0.231042 | 1 | 307 |
| **231** | 0.000569 | 0.000511 | 0.025 | 5000 | 0.114129 | 1 | 39 |
| **251** | 0.002703 | 0.000235 | 0.02 | 1666.667 | 0.148903 | 1 | 171 |
| **505** | 0.000407 | 0.000572 | 0.02 | 233.3333 | 0.102537 | 1 | 424 |

### 4.2.2 Predicting the Efficiency Score using ANN

#### 4.2.2.1 Data Used and Factors Involved

The data used for the ANN are for 432 buildings, out of which 300 are used for training a DEA, and the remaining 132 data samples are for querying. The predicted efficiency scores will be compared with the DEA scores for the whole 432-building sample. The factors used in the ANN to predict the efficiency score are as follows:

1- The percentage heated by a specific type of heating equipment:

This item consists of seven factors corresponding to the percentage of the floor area of the building that is being heated by specific heating equipment. The specific heating equipment are as follows:

A- Furnaces.
B- Boilers.
C- Packaged Heating.
D- Individual Space Heaters.
E- Heat Pumps.
F- District Steam/Hot Water.
G- Other Heating Equipment.

Knowing the percentage floor area heated by each of these systems can help to more accurately determine the efficiency score.

2- The percentage cooled by a specific type of cooling equipment:

This item consists of eight factors corresponding to the percentage of the floor area of the building that is being cooled by specific cooling equipment. The specific cooling equipment are as follows:

A- Packaged A/C.
B- Central A/C.
C- Individual Room A/C.
D- Heat Pumps.
E- District Chilled Water.
F- Central Chillers.
G- Swamp Coolers.
H- Other Cooling Equipment.

Knowing the percentage floor area cooled by each of these systems can help to more accurately determine the efficiency score.

3- Whether variable air volume is used:

Variable air volume is a system installed in the building that allows the HVAC system to reduce energy by varying the volume of the entering air. This system can result in a lower EUI.

4- Whether an economizer cycle is used:

Economizers help reduce the energy used by an HVAC system, which can reduce the EUI of a building.

5- Whether regular HVAC maintenance is performed:

Regular HVAC maintenance can aid in lowering the EUI of the building, and thus can be beneficial in predicting the efficiency score.

6- Whether external overhangs are used:

External overhangs can help predict the efficiency score, as these overhangs can reduce the energy used by providing shading.

7- The percentage area lit by specific lighting equipment:

The percentage of the floor area lit by specific lighting equipment can aid in predicting the efficiency score because the type of light used can determine the energy conservation. The percentages for the following light types are included:

A- Florescent.
B- Compact Florescent.
C- Incandescent.
D- Halogen.
E- HID.

8- Whether skylights are used for lighting:

Skylights use natural passive lighting techniques to reduce the energy used in lighting and the building EUI.

9- Whether auto controls for lighting are used:

Auto control for lighting utilizes sensors to automatically adjust the lighting in the room, which reduces the energy usage and the EUI.

10- Percentage of daylight:

The higher the percentage of daylight incorporated in a building, the lower the use of the lighting system and thus the lower the EUI of the building.

The previous factors will be used to predict the efficiency scores of a building and are summarized in table 12 that follows:

**Table 12: ANN Model Factors**

| Factor |
|---|
| The percentage heated by a specific type of heating equipment (7 factors) |
| The percentage cooled by a specific type of cooling equipment (8 factors) |
| Whether variable air volume is used |
| Whether the economizer cycle is used |
| Whether regular HVAC maintenance is performed |
| Whether external overhangs are used |
| The percentage lit by specific lighting equipment (5 factors) |
| Whether skylights are used for lighting |
| Whether auto controls for lighting are used |
| Percentage of daylight |

#### 4.2.2.2 ANN Methodology

The ANN was applied using JustNN, which is commercially available for free, and the ANN methodology involved a network which has six hidden nodes in two layers, as shown in Figure 9:

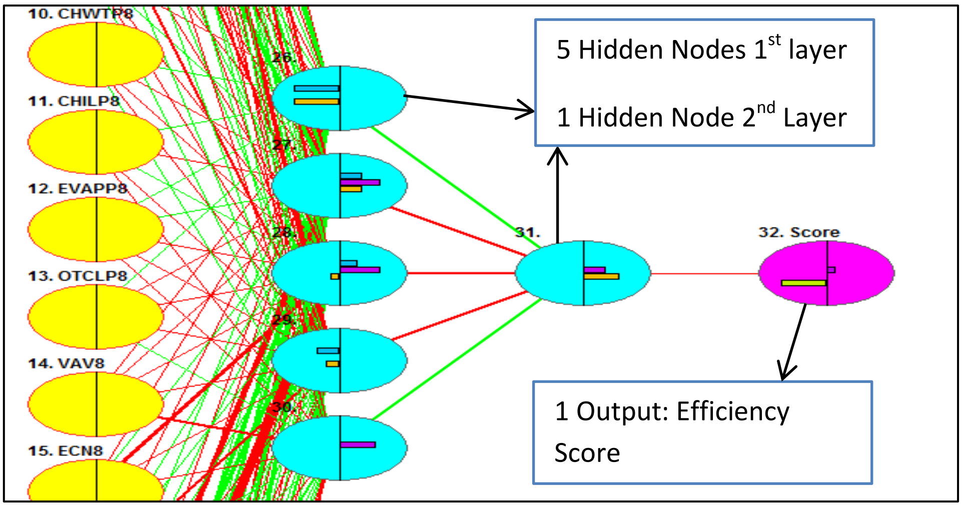


**Figure 9: ANN Model Network Layers**

Figure 10 shows that the learning rate is 0.7, the momentum is 0.8, the average error after 5000 cycles is approximately 0.024, and the maximum error is approximately 0.514, which is adequate.

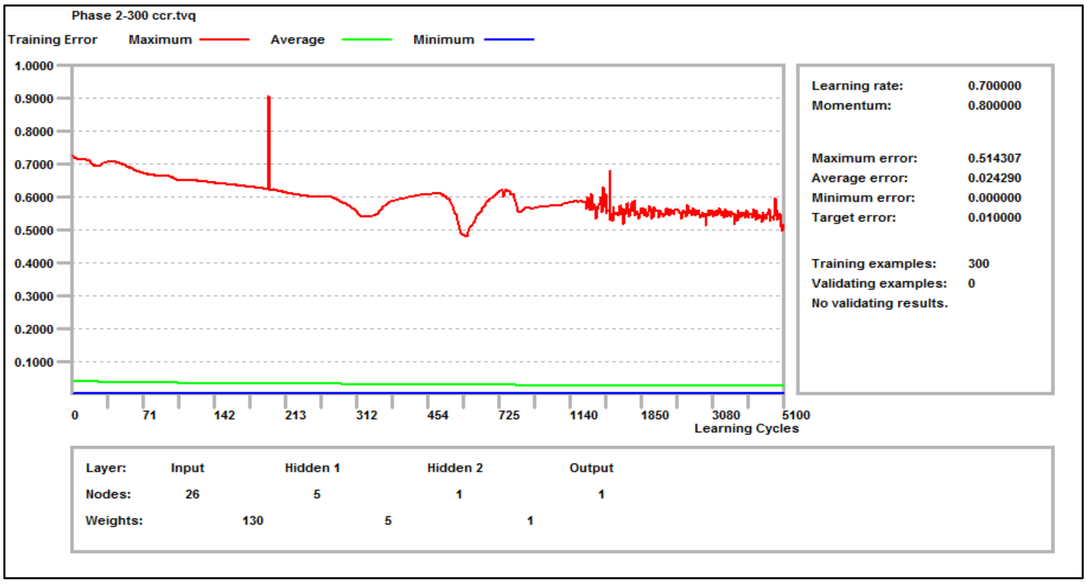


**Figure 10: ANN Model Error Evaluation**

Figure 11 shows the relative importance for each of the used factors and that the type of lighting area percentages (BULBP8-CFLRP8) and the daylight percentage (DAYLTP8) are the most important factors. This is acceptable, because the principal building activity is to lease offices.

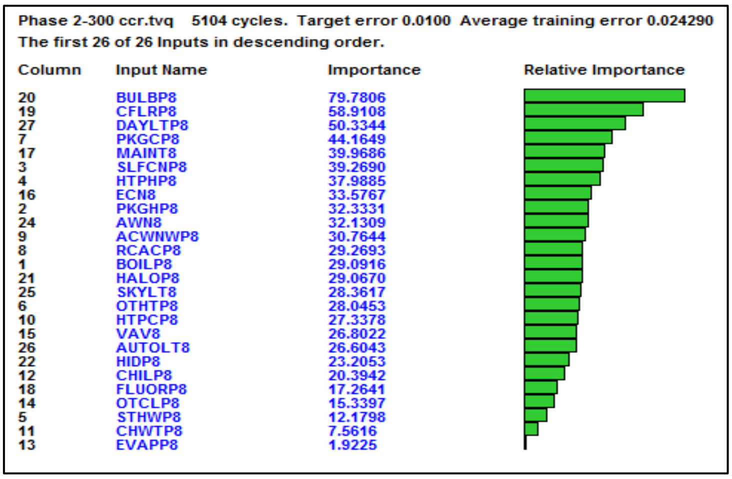


**Figure 11: ANN Model Relative Importance of Factors**

### 4.2.2.3 Sample Results

Table 13 shows the actual and predicted scores for a sample of 132 buildings, and shows that the average difference between DEA scores (1) and ANN scores (2) is 55.7%. This percentage difference is high, which requires improving the methodology with accurate data and with a more thorough selection of inputs.

**Table 13: ANN Model Sample Results**

| Score DEA | Score ANN | % Diff | Score DEA | Score ANN | % Diff | Score DEA | Score ANN | % Diff |
|---|---|---|---|---|---|---|---|---|
| 0.156582 | 0.561781 | 1.128 | 0.114321 | 0.111915 | 0.021 | 0.073134 | 0.186754 | 0.874 |
| 0.126413 | 0.186799 | 0.386 | 0.156325 | 0.111915 | 0.331 | 0.193712 | 0.111915 | 0.535 |
| 0.042604 | 0.111916 | 0.897 | 0.149425 | 0.232019 | 0.433 | 0.108866 | 0.166455 | 0.418 |
| 0.137146 | 0.116269 | 0.165 | 0.091085 | 0.21778 | 0.820 | 0.12362 | 0.111915 | 0.099 |
| 0.106956 | 0.186933 | 0.544 | 0.204273 | 0.561781 | 0.933 | 0.319985 | 0.186193 | 0.529 |
| 0.125195 | 0.169232 | 0.299 | 0.095567 | 0.311224 | 1.060 | 0.214149 | 0.186935 | 0.136 |
| 0.040436 | 0.137244 | 1.090 | 0.1395 | 0.15907 | 0.131 | 0.034129 | 0.240385 | 1.503 |
| 0.176715 | 0.186797 | 0.055 | 0.177007 | 0.334439 | 0.616 | 0.07784 | 0.114319 | 0.380 |
| 0.245691 | 0.111915 | 0.748 | 0.391301 | 0.186934 | 0.707 | 0.190984 | 0.186934 | 0.021 |
| 0.051947 | 0.186911 | 1.130 | 0.34303 | 0.111927 | 1.016 | 0.087864 | 0.167508 | 0.624 |
| 0.07707 | 0.111915 | 0.369 | 0.163295 | 0.186428 | 0.132 | 0.075699 | 0.111918 | 0.386 |
| 0.197736 | 0.189056 | 0.045 | 0.132376 | 0.186369 | 0.339 | 0.055137 | 0.173805 | 1.037 |
| 0.250919 | 0.186938 | 0.292 | 0.106273 | 0.186842 | 0.550 | 0.211161 | 0.192286 | 0.094 |
| 0.109243 | 0.564765 | 1.352 | 0.140437 | 0.306547 | 0.743 | 0.084668 | 0.186932 | 0.753 |
| 0.107995 | 0.113304 | 0.048 | 0.757012 | 0.186921 | 1.208 | 0.074909 | 0.111915 | 0.396 |
| 0.116196 | 0.564428 | 1.317 | 0.117112 | 0.12834 | 0.091 | 0.040959 | 0.186935 | 1.281 |
| 0.303958 | 0.112413 | 0.920 | 0.065618 | 0.186934 | 0.961 | 1 | 0.111915 | 1.597 |
| 0.269116 | 0.111915 | 0.825 | 0.080056 | 0.111915 | 0.332 | 0.072014 | 0.145804 | 0.678 |
| 0.124414 | 0.11886 | 0.046 | 0.133987 | 0.187075 | 0.331 | 0.112473 | 0.519549 | 1.288 |
| 0.183439 | 0.478706 | 0.892 | 0.158097 | 0.298186 | 0.614 | 0.059963 | 0.561907 | 1.614 |
| 0.136517 | 0.112101 | 0.196 | 0.032237 | 0.186934 | 1.412 | 0.123255 | 0.244827 | 0.661 |
| 0.220434 | 0.189493 | 0.151 | 0.106315 | 0.119337 | 0.115 | 0.232874 | 0.113135 | 0.692 |
| 0.135241 | 0.224158 | 0.495 | 0.077575 | 0.115526 | 0.393 | 0.112432 | 0.185905 | 0.493 |
| 0.629875 | 0.296493 | 0.720 | 0.118806 | 0.407698 | 1.097 | 0.146494 | 0.311224 | 0.720 |
| 0.159793 | 0.561781 | 1.114 | 0.225968 | 0.547784 | 0.832 | 0.034101 | 0.552223 | 1.767 |
| 0.127278 | 0.174879 | 0.315 | 0.273418 | 0.111916 | 0.838 | 0.075054 | 0.143906 | 0.629 |
| 0.122298 | 0.118807 | 0.029 | 0.116887 | 0.11449 | 0.021 | 0.119557 | 0.187056 | 0.440 |
| 0.162169 | 0.208603 | 0.250 | 0.103133 | 0.307009 | 0.994 | 0.146501 | 0.186935 | 0.243 |
| 0.123386 | 0.286701 | 0.796 | 0.042885 | 0.111915 | 0.892 | 0.087196 | 0.111915 | 0.248 |
| 0.234195 | 0.311224 | 0.282 | 0.122658 | 0.56475 | 1.286 | 0.164017 | 0.235432 | 0.358 |
| 0.126299 | 0.177038 | 0.335 | 0.081607 | 0.129667 | 0.455 | 0.065463 | 0.187017 | 0.963 |
| 0.034516 | 0.112 | 1.058 | 0.208755 | 0.112179 | 0.602 | 0.15158 | 0.186879 | 0.209 |
| 0.168872 | 0.564769 | 1.079 | 0.120487 | 0.18644 | 0.430 | 0.204511 | 0.185213 | 0.099 |
| 0.144028 | 0.15907 | 0.099 | 0.123126 | 0.234795 | 0.624 | 0.07281 | 0.222306 | 1.013 |
| 0.117284 | 0.111922 | 0.047 | 0.049765 | 0.112455 | 0.773 | 0.128059 | 0.190674 | 0.393 |
| 0.134909 | 0.216944 | 0.466 | 0.088486 | 0.310736 | 1.113 | 0.154516 | 0.564754 | 1.141 |
| 0.066795 | 0.111915 | 0.505 | 0.048762 | 0.154001 | 1.038 | 0.110093 | 0.206794 | 0.610 |
| 0.077248 | 0.11342 | 0.379 | 0.2165 | 0.111928 | 0.637 | 0.06248 | 0.111915 | 0.567 |
| 0.121138 | 0.161483 | 0.286 | 0.847779 | 0.304513 | 0.943 | 0.183004 | 0.112154 | 0.480 |
| 0.097262 | 0.233364 | 0.823 | 0.104786 | 0.111915 | 0.066 | 0.198336 | 0.111915 | 0.557 |
| 0.048533 | 0.216944 | 1.269 | 0.198294 | 0.148361 | 0.288 | 0.146131 | 0.186932 | 0.245 |
| 0.204337 | 0.186934 | 0.089 | 0.089461 | 0.172854 | 0.636 | 0.448245 | 0.186934 | 0.823 |
| 0.171128 | 0.241247 | 0.340 | 0.170086 | 0.123444 | 0.318 | 0.132612 | 0.111917 | 0.169 |
| 0.07755 | 0.165368 | 0.723 | 0.158031 | 0.193718 | 0.203 | 0.113242 | 0.237445 | 0.708 |
| | | | | | | | Average | 0.557 |

### 4.3 Benchmarking The Renewable Efficiency of NZEB

In this section, the efficiency of renewable energy will be evaluated in terms of total costs, total emissions and amount of utility energy used. As the data does not contain NZEB, data for NZEB will be simulated using software. After that, a DEA will evaluate the efficiency of NZEB with the outputs mentioned earlier.

#### 4.3.1 Simulation

The data for NZEB (Table 14) were simulated using software, by making the following assumptions regarding the distribution of the data:

**Table 14: Renewable Energy Simulation Assumptions**

| Factor | Unit | Average | Std. dev. |
|---|---|---|---|
| **Utility energy used percentage of total energy** | None | 0.10 | 0.015 |
| **Total cost percentage of actual cost** | None | 1.9 | 0.2 |
| **Emission/Energy Factor** | Kg/ kBtu | 0.0234 | 0.000967 |

The assumptions were made based on common statistics and entered into commercial software to develop random values from a normal distribution for each building. By using actual energy usage and actual cost values for the outputs of the efficiency calculation, mentioned later on, are developed for all 432 buildings.

#### 4.3.2 DEA Model

To benchmark the renewable efficiency of NZEB, a DEA model will be used to determine the efficiency score of these buildings. In the following sections, the various aspects of the DEA model are introduced.

##### 4.3.2.1 Data Used and Data Caveats

The data obtained from simulation will be used in the DEA model, though this may limit the data to within a certain range, as will be seen later on.

##### 4.3.2.2 Factors Involved

To determine the efficiency score for the renewable energy system of NZEB, one input was chosen, which is the output of the previous process. This is along with three outputs (Table 15) that cover the cost, emissions and utility energy used and these outputs are:

1-Reciprocal of total Yearly Building Energy Costs per unit area (Sq. ft./$):

This output refers to the area that one dollar can supply with energy. Instead of using the cost per sq. ft., this value was chosen to avoid the use of undesirable outputs. The ratio between this output and the reciprocal of the EUI is in units of J/$, which is an accurate representation of the financial efficiency of NZEB. The total yearly building energy cost per unit area (eq. 34) is calculated as follows:

$$\text{Total Yearly Building Energy Costs/Area} = EUI \times \text{LCE} \quad (34)$$

where *EUI* = energy use intensity, and

*LCE* = levelized life-cycle cost of renewable energy.

2-Reciprocal of utility energy used per unit area (sq.ft/J):

This output refers to the area that uses one Joule of utility energy at site. The ratio between this output and the reciprocal of the EUI is a ratio between energy used and utility energy used, which is a measure of the efficiency.

3- Reciprocal of total yearly building energy emissions per unit area (sq.ft/Kg CO2):

This output is the area that one kg of $CO_2$ equivalent can supply with energy. Instead of using the emissions per sq. ft., this value was chosen to avoid the use of undesirable outputs. The ratio between this output and the reciprocal of the EUI is in units of J/kg $CO_2$, which is an accurate representation of the environmental efficiency of NZEB. The total yearly energy emissions per unit area (eq. 35) is calculated as follows:

$$\text{Total Yearly Building Energy Emissions/Area} = \left(1 - \frac{Used\ Utitlity\ Energy}{Total\ Used\ Energy}\right) \times EUI \times REF + \frac{Used\ Utitlity\ Energy}{Total\ Used\ Energy} \times EUI \times UEF \quad (35)$$

where *EUI* = energy use intensity;

*REF* = renewable energy emission factor, which is the amount of carbon-equivalent emissions per unit of renewable energy; and

*UEF* = utility energy emission factor, which is the amount of carbon-equivalent emissions per unit of utility energy.

**Table 15: Renewable Energy Efficiency DEA Factors**

| Factor | Input/Output | Unit |
|---|---|---|
| Reciprocal of the EUI | Input | Sq.ft./Kbtu |
| Area/Total Yearly Building Energy Costs | Output | Sq.ft./ $ |
| Area/ Yearly Utility Energy Used | Output | Sq.ft./Kbtu |
| Area/ Total Yearly Building Energy Emissions | Output | Sq.ft./ Kg |

**4.3.2.3 Data Envelopment Analysis Methodology**

The previous factors for the 432 building data sets were entered into MaxDEA software Version 6.1, which is free for non-commercial use. The DEA methodology involved a CCR model with constant returns to scale, meaning that the maximum efficiency ratio may not increase or decrease with the increase in scale. The CCR model was used because most of the buildings were efficient under the BCC model and the simulated data might not show the effect of scale; the CCR model is therefore a more rigid benchmarking technique. Additionally, the model assumes radial distance and the slack is computed in one stage. The DEA that is used is output-oriented, meaning that the maximum output for a given input level will be determined, and for this study, the output is the reciprocal of the EUI. Finally, no weight restrictions were entered into the model. The following equation (eq. 36) is for the output-oriented CCR model and is the one followed in this methodology.

$$Max\ \sum_{i=1}^{m} u_i y_{io} \quad (36)$$

Subject to:

$$\sum_{j=1}^{n} v_j x_{j0} = 1,$$

$$\sum_{i=1}^{m} u_i y_{ik} - \sum_{j=1}^{n} v_j x_{jk} \leq 0 \ \ for\ k = 1,2, \dots, h$$

**4.2.1.4 Sample Results**

Table 16 and 17 shows the data for 14 buildings out of 432 used in the DEA, which were selected for having scores close to 100, 95, 90, 85 and 80 percent. The data for the ratios between outputs and inputs are also presented, to show a reduction in most of the ratios with the lower benchmarks.

**Table 16: Renewable Energy Efficiency Benchmarking Samples**

| DMU Name | 1/EUI | Area/Total Cost | Area/ Utility Energy Used | Area/ Emissions |
|---|---|---|---|---|
| 259 | 0.006825 | 0.115854952 | 0.080867247 | 0.321451515 |
| 238 | 0.001108 | 0.154922229 | 0.011736465 | 0.046384837 |
| 354 | 0.007888 | 0.165506811 | 0.068076198 | 0.379221454 |
| 136 | 0.009587 | 0.246297761 | 0.105039781 | 0.425889776 |
| 166 | 0.007118 | 0.141992339 | 0.06284407 | 0.323500812 |
| 290 | 0.003597 | 0.129549742 | 0.04115753 | 0.157067347 |
| 148 | 0.004335 | 0.112060522 | 0.04901692 | 0.18024163 |
| 173 | 0.006512 | 0.258032825 | 0.066857404 | 0.26963828 |
| 143 | 0.007371 | 0.107392514 | 0.076450844 | 0.313013433 |
| 181 | 0.045112 | 0.900576404 | 0.432686821 | 1.807461079 |
| 265 | 0.01556 | 0.33909125 | 0.142697892 | 0.622971792 |
| 453 | 0.023477 | 0.576003521 | 0.212562574 | 0.936696642 |
| 485 | 0.009989 | 0.259053653 | 0.100093879 | 0.383303833 |
| 497 | 0.008414 | 0.190322351 | 0.083870555 | 0.320318688 |

**Table 17: Renewable Energy Efficiency Benchmarking Samples Results**

| DMU Name | Ratio 1 | Ratio 2 | Ratio 3 | Score CCR | Times as BM |
|---|---|---|---|---|---|
| **259** | 16.97549 | 11.84896 | 47.10024 | 1.00000 | 390 |
| **238** | 139.81307 | 10.59184 | 41.86105 | 1.00000 | 333 |
| **354** | 20.98336 | 8.63087 | 48.07862 | 1.00000 | 285 |
| **136** | 25.69035 | 10.95629 | 44.42288 | 0.95024 | 0 |
| **166** | 19.94811 | 8.82879 | 45.44772 | 0.95003 | 0 |
| **290** | 36.01662 | 11.44236 | 43.66689 | 0.94972 | 0 |
| **148** | 25.84727 | 11.30597 | 41.57355 | 0.90087 | 0 |
| **173** | 39.62343 | 10.26660 | 41.40556 | 0.90000 | 0 |
| **143** | 14.57037 | 10.37239 | 42.46779 | 0.89978 | 0 |
| **181** | 19.96330 | 9.59147 | 40.06643 | 0.85219 | 0 |
| **265** | 21.79204 | 9.17062 | 40.03591 | 0.85031 | 0 |
| **453** | 24.53468 | 9.05403 | 39.89828 | 0.84930 | 0 |
| **485** | 25.93411 | 10.02049 | 38.37291 | 0.82916 | 0 |
| **497** | 22.61975 | 9.96799 | 38.06978 | 0.82012 | 0 |

Additionally, Figures 12 to 14 graph the ratios for each of the previous points, and show a reduction in the ratios with the reduction in the benchmarking score. Note that not all of the efficient points should have high values for each ratio.

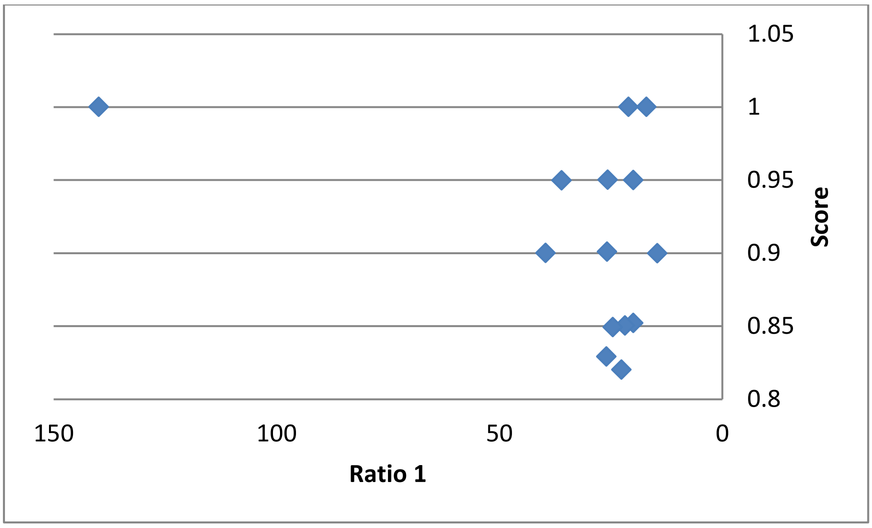


**Figure 12: Renewable Energy Efficiency Score Vs. Ratio 1**

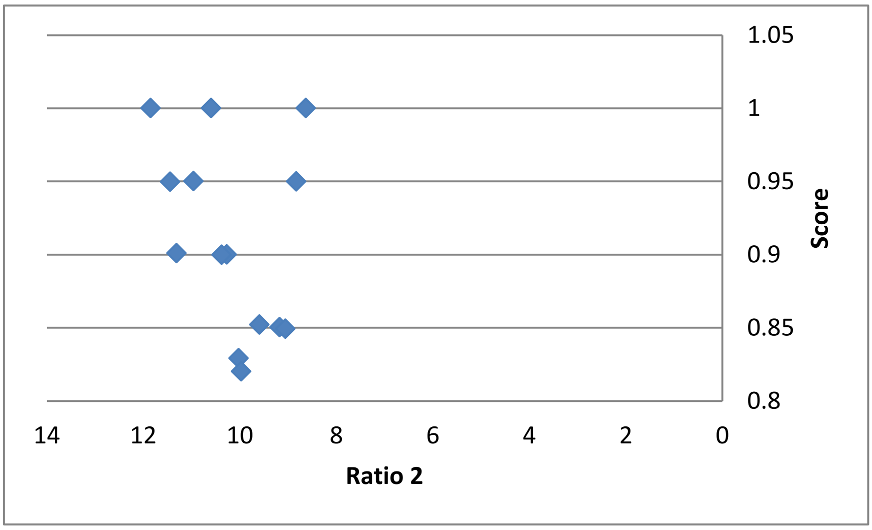


**Figure 13: Renewable Energy Efficiency Score Vs. Ratio 2**

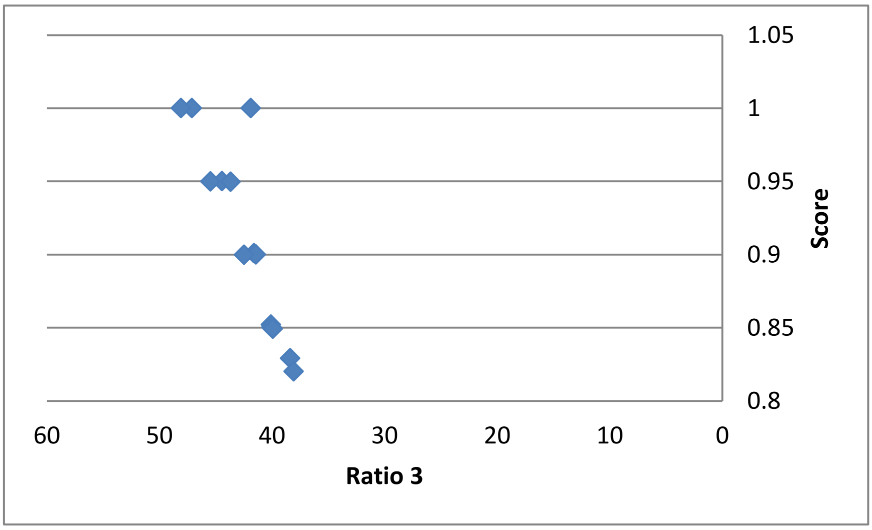


**Figure 14: Renewable Energy Efficiency Score Vs. Ratio 3**

For the framework to be used again, only the benchmarks should be used in the DEA calculation, which saves the evaluator time. Table 18 of the benchmarks follows:

**Table 18: Renewable Energy Efficiency Benchmarks**

| DMU Name | 1/EUI | Area/ Total Cost | Area/ Utility Used | Area/ Emissions | Score CCR | Times as BM |
|---|---|---|---|---|---|---|
| **123** | 0.005128 | 0.11632 | 0.098568 | 1 | 22.68235 | 17 |
| **238** | 0.001108 | 0.154922 | 0.011736 | 1 | 139.8131 | 333 |
| **240** | 0.006942 | 0.160338 | 0.103748 | 1 | 23.09826 | 142 |
| **259** | 0.006825 | 0.115855 | 0.080867 | 1 | 16.97549 | 390 |
| **354** | 0.007888 | 0.165507 | 0.068076 | 1 | 20.98336 | 285 |

### 4.4 Benchmarking the Total Energy Efficiency of NZEB

Because the previous two DEA models have the reciprocal of the EUI as a common link, they can be treated as a network DEA, where the total energy efficiency is the multiplicative product or average of the two efficiencies. In this case, it was chosen to average the two efficiencies because the data are not completely accurate. The data shown in Table 19 and 20 correspond to values of approximately 99, 70 and 50 percent. It can be noted that most of the input and output ratios are maximized for the efficient data points. However, to apply the methodology, the benchmarks of the previous DEAs should be used and the two efficiencies averaged to determine the total energy efficiency.

**Table 19: Total Energy Efficiency Benchmarking Samples**

| DMU Name | Ratio 1 | Ratio 2 | Ratio 3 | Ratio 4 | Score CCR | Times as BM |
|---|---|---|---|---|---|---|
| **505** | 252.1386 | 179.1322 | 5.126853 | 0.000439 | 1 | 424 |
| **214** | 9.463334 | 118.2325 | 1.656083 | 0.000419 | 0.953362 | 0 |
| **251** | 55.09396 | 634.4739 | 7.445129 | 8.93E-05 | 1 | 171 |
| **154** | 135.4788 | 82.27224 | 1.931273 | 0.000133 | 0.521315 | 0 |
| **387** | 36.45756 | 202.3605 | 1.867225 | 1.56E-05 | 0.507484 | 0 |
| **347** | 147.1184 | 23.96265 | 4.128949 | 2.59E-05 | 0.500495 | 0 |
| **288** | 17.58373 | 6.202115 | 0.664038 | 2.12E-05 | 0.116723 | 0 |
| **290** | 14.45971 | 6.093223 | 0.143878 | 1.1E-05 | 0.051065 | 0 |
| **386** | 17.03629 | 8.308706 | 0.212092 | 5E-06 | 0.062417 | 0 |

**Table 20: Total Energy Efficiency Benchmarking Samples Results**

| DMU Name | Ratio 5 | Ratio 6 | Ratio 7 | Score | Times as BM | TE |
|---|---|---|---|---|---|---|
| **505** | 20.74611 | 8.256298 | 44.09867 | 0.920909 | 0 | 0.960455 |
| **214** | 15.77516 | 14.49462 | 43.44993 | 0.964588 | 0 | 0.958975 |
| **251** | 19.05837 | 12.35315 | 41.82321 | 0.910035 | 0 | 0.955018 |
| **154** | 4.280622 | 7.643195 | 45.10272 | 0.938103 | 0 | 0.729709 |
| **387** | 16.17634 | 10.58588 | 44.25769 | 0.936363 | 0 | 0.721924 |
| **347** | 14.26885 | 8.660561 | 42.33164 | 0.886831 | 0 | 0.693663 |
| **288** | 12.97912 | 13.8619 | 39.44691 | 0.884085 | 0 | 0.500404 |
| **290** | 36.01662 | 11.44236 | 43.66689 | 0.949717 | 0 | 0.500391 |
| **386** | 23.02638 | 10.0366 | 44.20196 | 0.937259 | 0 | 0.499838 |

Figures 15-21 show the ratios for these points. The ratios are lower for lower scores, which validates the calculation methodology. This cannot be seen clearly in the second set of ratios (Ratios 5-7) because most of the simulated buildings were efficient.

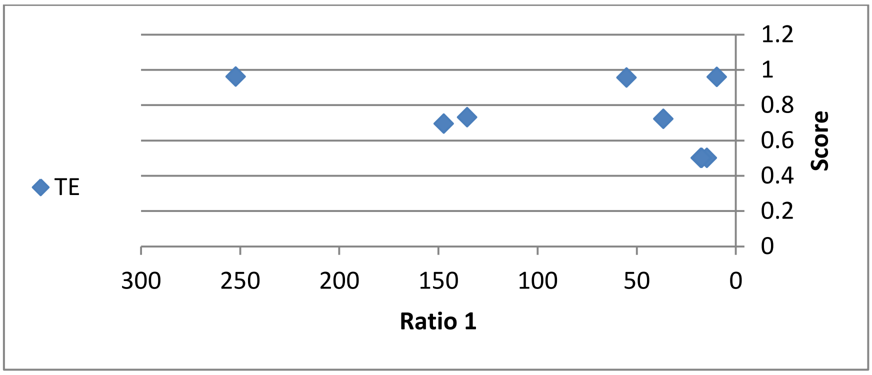


**Figure 15: Total Energy Efficiency Vs. Ratio 1**

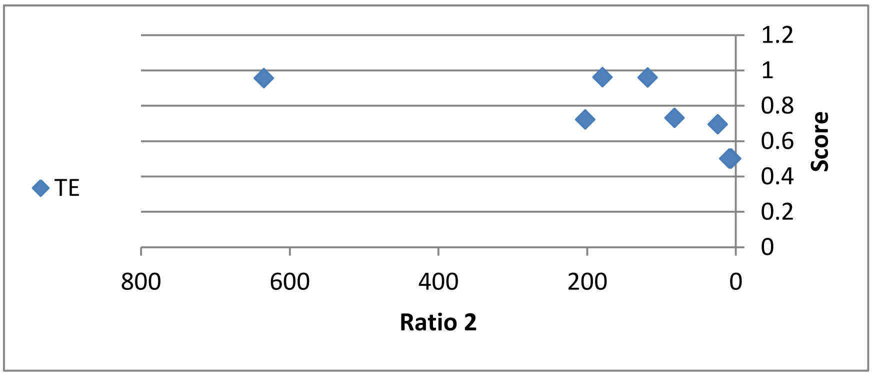


**Figure 16: Total Energy Efficiency Vs. Ratio 2**

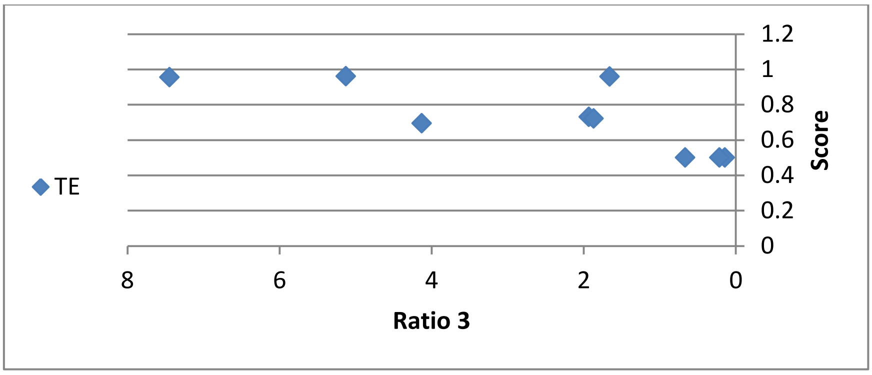


**Figure 17: Total Energy Efficiency Vs. Ratio 3**

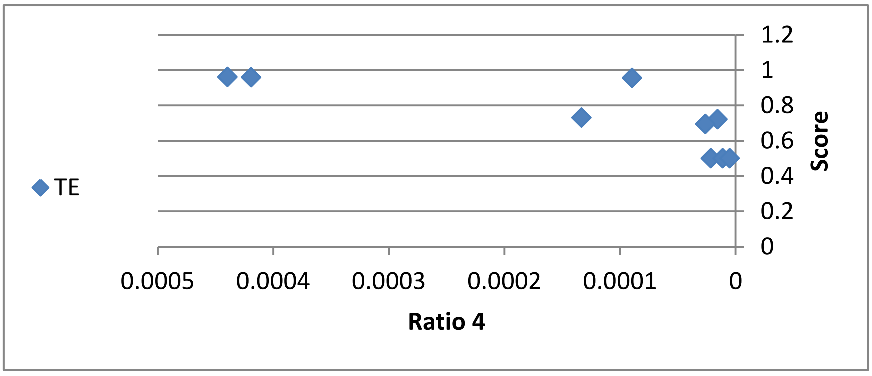


**Figure 18: Total Energy Efficiency Vs. Ratio 4**

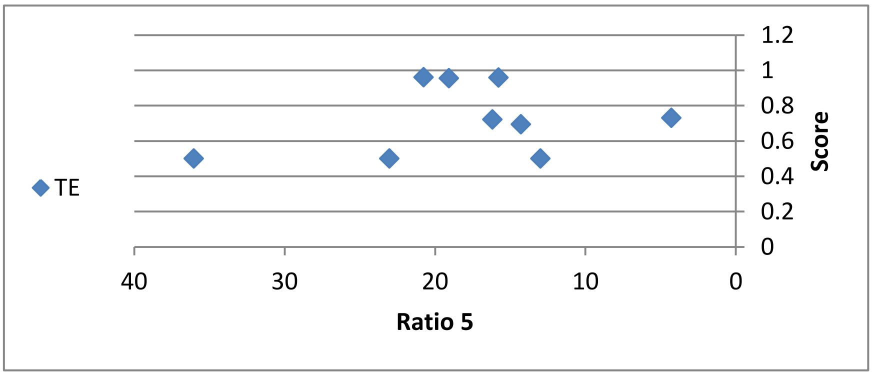


**Figure 19: Total Energy Efficiency Vs. Ratio 5**

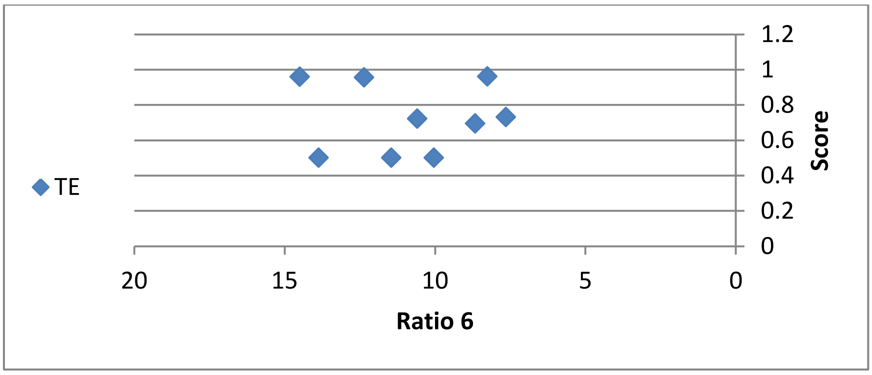


**Figure 20: Total Energy Efficiency Vs. Ratio 6**

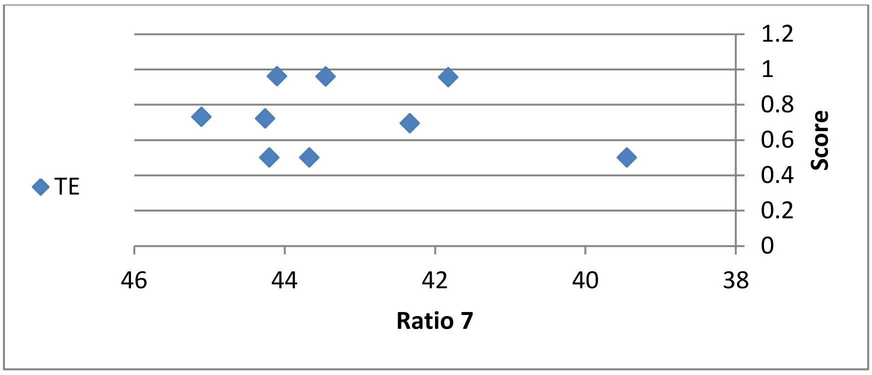


**Figure 21: Total Energy Efficiency Vs. Ratio 7**

### 4.5 Suggested Framework

The framework for benchmarking NZEB (Table 21) is constituted of 5 stages that were developed according the procedures mentioned in this chapter. The first stage is to filter the buildings according to definite characteristics that are related to function, building age and vacancy. The second stage is to benchmark the energy efficiency using DEA based on uncontrollable weather and functional factors. Moreover, the third stage is to benchmark the renewable energy efficiency using DEA based on the total energy costs, total energy emissions and total utility energy used. In addition, the fourth stage is to benchmark the total energy efficiency of the building and decide over the calculation methodology. Finally, the last stage is to use the model on buildings with similar filtering characteristics.

**Table 21: Framework Stages and Steps**

| Stage | Step |
|---|---|
| **Filtering** | 1- Include buildings with the same function; for example, buildings which have the principal building activity of leasing offices, or a hotel.<br>2- Compare buildings of the same age (within a 10-20 year range).<br>3- Exclude buildings that have been vacant during any month in the comparison year. |
| **Benchmarking Energy Efficiency** | 1- Calculate the EUIs of the buildings.<br>2- Select weather factors that result in an increase in the EUI of buildings, such as heating degree days and cooling degree days.<br>3- Select functional factors that are correlated and lead to an increase in the EUI, such as the operating hours, number of employees per unit area and number of beds per unit area.<br>4- Select proper weight restrictions based on the correlation or importance of the input factors.<br>5- Apply DEA analysis with the reciprocal of the EUI as the output and the reciprocals of previous factors as inputs.<br>6- As an extra step, use ANN with a number of efficiency measures to predict the efficiency score without using the calculation. This will aid the owner in choosing the efficiency measures before the building is constructed. |
| **Benchmarking Renewable Efficiency** | 1- Calculate total building energy emissions and costs and total fossil fuel energy used, and calculate these values per unit area.<br>2- Select proper weight restrictions for the outputs based on importance.<br>3- Apply a DEA analysis with the reciprocal of the EUI as input and the reciprocal of the total building energy emissions, costs and utility energy used divided by the area as output. |
| **Total Energy Efficiency** | 1- Average or multiply both efficiencies based on the accuracy of the calculation and data. If the data are not accurate, and to avoid overriding one efficiency calculation with the other, averaging may provide a better result. |
| **A New Building with Same Filtering Characteristics** | 1- Use the benchmarks of stages B and C to calculate efficiency scores for both stages individually, and then apply the same technique in stage D to calculate the total energy efficiency. |

# Chapter 5: Conclusion and Recommendations

## 5.1 Conclusion

In this thesis, a framework for benchmarking NZEB and a total energy efficiency benchmarking approach for buildings were introduced. These provide a complete perspective on building efficiency and allow for emphasis on the overall goals of building benchmarking, which are to reduce energy usage, energy emissions and costs. The thesis work provides continuity between efficiencies resulting from reductions in energy use and generation efficiencies resulting from the reductions in cost and emissions.

In the first part of the framework, a DEA model was used with the reciprocal of the EUI as the only output. The inputs to the DEA model are functional and weather input factors that are chosen for the specific types of buildings under consideration. In this study, the benchmark was applied to office buildings to reduce the bias in the EUI comparison of buildings with different functions. Functional factors, such as the number of workers per area and operating hours, were added to accurately benchmark the EUI. Heating degree days and cooling degree days were also added to the input factors to represent weather conditions. It is important to note that the application of the DEA on energy benchmarking using uncontrollable factors was based on Lee and Lee [6] and Lee [7], but with a different configuration of the model, which considers the reciprocal of the EUI as an output; this was necessary because the EUI is a major design factor for NZEB and is a major indicator of building efficiency, to the author's knowledge. The previous authors also applied regression along with the DEA, which was not applied here to keep the efficiency scores controlled by the DEA alone and to keep the methodology general to all NZEB. Additionally, a prediction methodology such as the ANN is used to predict the efficiency score before the analysis, but is still a complementary part of the framework. The ANN did not produce satisfactory results, but this can be improved with accurate data and careful selection of inputs.

The second part of the benchmark is also a DEA model, but with the reciprocal of the EUI as the only input. Output factors of this model were factors related to the cost, emissions and fossil fuel energy usage for buildings. These factors were chosen such that the efficiency calculated in the DEA model would accurately represent the efficiency of renewable energy sources. Additionally, using the DEA in this configuration is more accurate due to the presence of multiple outputs in the study. The configuration of the model is not found in previous research regarding renewable energy benchmarking for buildings.

The final part, calculating the total energy efficiency, is not found elsewhere in research. This part includes the configuration of the two DEA models in a network, and averaging the efficiencies of both models to give a final benchmark for NZEB. Additionally, the study showed that the benchmark provided a holistic perspective of the efficiency of NZEB and satisfied several ratios of outputs to inputs. Therefore, it can be concluded that calculating total energy efficiency provides a complete and accurate approach for building energy benchmarking.

### 5.2 Recommendations

Although the method was carefully designed, some recommendations can still be applied in future research:

1- Selecting proper weight restrictions for the inputs of the energy efficiency DEA to account for inputs with a larger impact on the building's EUI than other inputs.
2- Selecting proper weight restrictions for the outputs of the renewable energy efficiency DEA to compensate for problems with choosing to use renewable energy, such as giving more weight to energy costs.
3- When applying the energy efficiency DEA methodology to other types of buildings, such as hotels, different functional factors shall be considered for the functional characteristics of the buildings, such as the number of beds.
4- Other weather factors can be included in the energy efficiency DEA to add to the accuracy of the model.
5- Caution should be used for the number of factors involved in the DEA, which should be kept to a minimum to ensure a good benchmark.
6- It is important to note that the previous model does not fit every type of building, and thus special considerations should be made, as mentioned earlier in this paper.

7- Other studies may use different methods of calculating the total energy efficiency, such as multiplying efficiencies if the data are more accurate.
8- In case the BCC DEA model is selected, other method for dealing with undesirable outputs and inputs should be used, such as turning outputs into inputs and vice versa and not using the reciprocal.
9- The data in this study were masked and rounded, and some of the data were simulated, so the results are not the most accurate. Therefore, it is recommended that the framework is applied to the benchmarked NZEB rather than the results of the models.

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# Vita

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