World residential sector energy consumption:
can implementing energy efficient designs save energy?

UNIVERSITY

of

OTAGO

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Master of Science (Energy Studies)
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June 2011

Abstract

This thesis has investigated if building energy efficient dwellings in the residential sector will be sufficient to allow an absolute reduction in the world residential sector energy consumption in the future. A simulation model using Microsoft Excel Spreadsheet was used to simulate and predict the future energy consumption in residential sector for the world in the 90 years until 2100 and to distinguish the energy savings potential by building energy efficient dwellings. As the 90 years period is a relatively long time frame, several scenarios regarding dwelling growth rates are considered.

The primary driver of the total number of dwellings in the world is the increasing world population. Other factors considered included a declining occupancy rate around the world as fewer people live in a single dwelling and an increasing house size as income increases. The differing energy consumption patterns between developed countries and developing countries was taken into account in terms of operating energy as was the fact that energy efficient dwellings tend to use more energy during construction (initial embodied energy) and in maintaining (recurring embodied energy) the dwellings during their life cycle.

The model results showed that the world could finally see a savings that is an absolute reduction, in the total residential sector energy consumption in 2100 against the current (2010) consumption under these very stringent conditions: a very low rate of growth of dwellings at 0.5% p.a., an extremely high rate of new built dwellings being built as energy efficient dwellings i.e. 91% p.a. or higher, 1.2% p.a. or a higher percentage of existing dwellings being retrofitted as energy efficient dwellings throughout the world and the classification for the energy efficient dwellings must give savings of over 80% compared to conventional dwellings. Such conditions are thought, highly improbable, however, to be achieved on a world scale.

Acknowledgements

I would like to acknowledge the endless time and effort which my supervisor, Bob Lloyd has dedicated to myself and this project.

My gratitude to all those supported me through this journey:

- To the government of Malaysia for the scholarship.
- To the staff of Physics Department Administration Office for all the administrative help.
- To everyone in Room 428 for the support in any respect.

Many thanks to my father (Abah), my late mother (Emak) and my siblings for their support throughout my entire academic career.

A special thanks to my wife (Afifah), my daughters (Almas & Alana) and my parent in-law for their patient and constant support over the past years of work and study here.

Finally, to the Almighty God (Thank you - Alhamdulillah).

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Abbreviations

kWh	Kilowatt hour
m^2	Square meter
kWh/m^2	Kilowatt hour per square meter
EED	Energy efficient dwelling
CD	Conventional dwelling
OE	Operating energy
IEE	Initial embodied energy
REE	Recurring embodied energy
CO_2	Carbon dioxide emissions
GHG	Greenhouse gasses
EIA	US Energy Information Agency
IEA	International Energy Agency

1 INTRODUCTION

1.1 CONTEXT

There has been considerable concern regarding how to reduce the world's carbon dioxide (CO_2) emissions. Improving the energy efficiency of the residential building industry sector is one area which has received attention as a possible candidate in which significant reductions are possible. Sylvie Lemmet, the Director of Division of Technology, Industry and Economics United Nations Environment Programme, in her foreword for a recent UNEP report, states that the decision makers must tackle emissions from the building sector to meet the target for greenhouse gas emissions reduction. Otherwise, given the massive growth in new construction and the inefficiencies of existing building stock worldwide, the greenhouse gas emissions from buildings will more than double in the next 20 years **(UNEP, 2009).**

The buildings construction industry has a very important impact on the environment and one of the biggest consumers of energy resources and raw materials **(Dimoudi et al., 2008 cited in Yan et al., 2010)**. This sector consumes large quantities of energy and emits large amounts of greenhouse gasses (GHG) from manufacturing, transportation, installation and construction activities. At present (2010), buildings are suggested to contribute to more than 40% of global energy used and may be responsible for about one third of global greenhouse gas emissions, primarily through the use of fossil fuels during their operational phase **(UNEP, 2009).** Almost 50% of CO_2 emissions in the member states of European Union are from their buildings life cycle and approximately 50% of the energy that is generated used in buildings is used mainly for space heating and cooling, lighting and other equipment (computer, washing machine etc) **(Dimoudi et al., 2008 cited in Yan et al., 2010).** In addition, the global contributions from buildings towards energy consumption, both residential and commercial, have steadily increased, reaching figures between 20% p.a. and 40% p.a. in developed countries **(Perez-Lombard et al., 2008)**. **Perez-Lombard et al.** highlights in their abstract that the energy demand for this sector will continue to grow in the future due to the growth in population, increasing demand for building services and comfort levels, together with the rise in time spent inside buildings. Therefore, they highlighted the need to put energy efficiency in buildings as a prime objective for energy policy at regional, national and international levels. Analysis by the EIA (US Energy Information Agency of the US Department of Energy) in their *2006 International Energy Outlook* suggests that building energy consumption worldwide will grow by 34% over the next 20 years at an average rate of 1.5% p.a **(EIA, 2006).** As shown in **Figure 1**, the EIA predicted that the energy use for the residential for developed and developing countries will be approximately equal by 2010 after which the main growth will be in developing countries **(see Figure 1).**

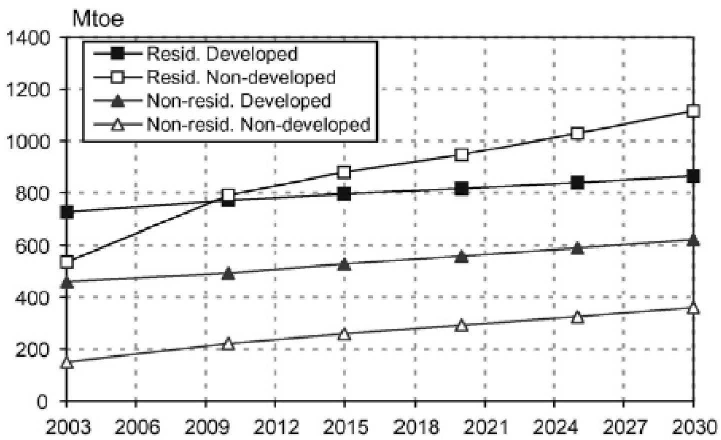

Figure 1: **Buildings energy consumption outlook**
(Source: Perez-Lombard et al., 2008 using data from EIA 2006).

The total world energy consumption for 2010 is around 12,000 Mtoe **(BP, 2011),** thus the above review by **Perez-Lombard et. al** suggests buildings around the world consume around 2.3 Btoe or 19% of the total world energy consumption in 2010. This percentage is quite low compared to that suggested by UNEP (2009) and the IEA (2008) who both claim that buildings (residential and non commercial together) are responsible for more than 40 percent of global energy consumption. It is highly like that the EIA projection does not included the embodied energy to make the dwellings.

China, the country with the most rapid economic growth in the world, is expected to construct two billion square meters of residential buildings every year through to 2020 **(Zhou et al., 2009)**. The effect of this increase in building area and build rate will be an increase in the demand for energy and, consequently, in CO_2 concentrations in the atmosphere. It has been reported that the energy consumption in the residential sector for the world between 1990 and 2005 has increased by 19% to reach 82 EJ or 2 Btoe **(IEA, 2008).**

Thus, with increasing energy consumption for the residential sector and with the awareness of the subsequent environmental issues, the world's communities have started to move towards energy efficient housing. Energy efficient housing are thought to have a huge potential to achieve large energy savings and emission reductions. For this reason an energy efficient house is a prime objective for energy policy interventions at the regional, national and international levels. According to a report released by the **UNEP** in December 2009 entitled *Buildings and Climate Change – Summary for Decision Makers*, energy efficient buildings could significantly contribute to reducing the risk engendered by climate change **(UNEP, 2009).**

1.2 ENERGY EFFICIENT HOUSING

> ***Low energy building:*** *Refers to a building built according to special design criteria aimed at minimizing the building's operating energy.*
>
> **Sartori et al. (2006).**

There is no global definition for a low energy dwelling or energy efficient house, but it is generally taken as a type of house which uses less energy than a conventional house while delivering the same or better amenity. Energy efficient housing typically uses high levels of insulation, energy efficient windows, low levels of air infiltration and heat recovery ventilation to lower heating and cooling energy. Also, energy efficient dwellings typically use passive or active solar design techniques. The energy consumption of a conventional dwelling is of course a matter of context and will depend on the ambient environment, cultural expectations etc. Such a house would also be expected to provide the occupants with healthy and comfortable living space and be less damaging to the environment by reducing the impact on climate change.

There are many different types of energy efficient house (low energy house) being built today with the terms covering a variety of concepts and also known under different names worldwide. The types which are mentioned in the literature review are passive houses, solar houses, net zero energy housing and self sufficient housing. The term passive building is a building that significantly utilizes the passive energy flows for both in heating and cooling and such that active solar technology is not expected to play a major role **(Athienitis et al., 2002).** However, the design of a solar house building is taken to make maximum exploitation of solar energy (with both passive and active technologies) **(Sartori et al., 2006).** Zero energy houses are refers to a building with a net energy consumption of zero over a typical year **(Wang et al., 2009).** In addition, a self sufficient house by definition needs no end-use energy deliveries (no grid connections and no fuel delivery) and derives its energy from natural sources (solar radiation, wind etc.) **(Feist, 1997).** Variations exist not only as regards the terms chosen, but also what energy use (standard) is included in the definition. In Austria, low energy houses have annual heating demand equal or less than 17 kWh/m^2 and passive houses suggested having annual heating demand less than 10 kWh/m^2 **(Mahdavi et al., 2010).** In Germany a passive house has an annual heating demand less than 15 kWh/m^2 **(Feist, 1997).**

The main reason to built energy efficient housing is to save energy. Often the focus is on minimizing the energy consumption during the operation phase, in terms of the final external energy consumption or the purchased energy. While the energy use for the production phase is often neglected. To incorporate the latter there is a need to take into account at the embodied energy, as the portion of the embodied energy will get proportionally bigger if the houses are designed, constructed and managed efficiently **(Thormark, 2002, Sartori and Hestnes, 2007 and Gustavsson and Joelsson, 2010).**

1.3 REBOUND EFFECT

There is general consensus that energy consumption and impact on the environment will be reduced by building energy efficient housing. However, there are questions whether such an intervention can really save absolute energy when both housing size and the number of houses are still increasing. The increase of the number of houses, the floor area, number and energy consumption of equipment in the house etc might reduce the overall energy savings achieved. In fact, some have argued that the introduction of energy efficiency measures might contribute to an increase in energy demand. This is called *rebound effect* a term which was introduced by energy economist named Daniel Khazzoom in 1980 **(Horace Herring and Steve Sorrell, 2009)** in which the energy savings are *taken back* through various mechanisms. The *rebound effect* is also known as the *Jevons effect* named after Javons who suggested in the 1800s that the increase in energy efficiency of steam engines would lead to more coal use not less **(Jevons, 1865 cited in Alcott, 2005).**

There are two type of rebound effect: direct rebound effect and indirect rebound effect:

Direct rebound effect

An example of a direct rebound effect is when cars are made more energy efficient and drivers take the benefits by driving further or more often **(Ewing et al., 2007 cited in Howden-Chapman et al., 2009).** Similarly, when houses are made more energy efficient, people can take advantage of cheaper energy bills and use more energy.

Indirect rebound effect

An example of an indirect rebound effect is when the drivers of fuel efficient cars spend the extra money from paying lower petrol bills for a holiday overseas **(Horace Herring and Steve Sorrell, 2009).** In the same way, when the embodied energy (energy in materials to install and manufacture) used to improve energy efficiency offsets some of the energy savings achieved **(Sorrell, 2007 cited in Philippa Howden-Chaman et al., 2009)** or the energy savings from energy efficient house are used to built larger house or buy more appliances that uses more energy.

This above example indicate that the complexity of human behavior might affect the gains from increased in energy efficiency in any sector including residential sector. This thesis will then address the question can energy efficient residential housing contribute to absolute reductions in energy consumption by the world community.

1.4 AIMS OF THE THESIS

This thesis will determine if building energy efficient dwellings in the residential sector will be sufficient to allow an absolute reduction in the world residential sector energy consumption in the future. To accomplish this, a number of specific research questions will be answered sequentially to identify the future energy consumption in the residential sector and the effect on building energy efficient dwellings towards future energy consumption.

1.4.1 Specific research questions

The following questions will be addressed in this thesis:

i. How many residential dwellings exist in the world and how many new built dwellings may be built in the future?

ii. What is the average operating energy and embodied energy (initial and recurrent) of a conventional dwelling per square meter (kWh/m^2) for the world?

iii. What is an estimate of the total energy consumption for the world existing dwellings and how will this increase over time?

iv. What is the average operating energy and embodied energy (initial and recurrent) of an energy efficient dwelling per square meter (kWh/m^2) for the world?

v. How much energy will the world residential sector energy consumption save by building energy efficient dwellings?

1.4.2 Structure of the thesis

The thesis is divided into **6 chapters**.

- **Chapter 1 (Introduction) -** This chapter provides an introduction to the subject, defines aims and introduces specific research questions to achieve the results.

- **Chapter 2 (Background) -** This chapter was undertaken substantially from the literature review which will gives the background on residential stock, energy consumption in the residential sector and energy efficiency measures in the residential sector.

- **Chapter 3 (Methodology) -** This chapter defines the framework to work with in achieving the thesis aim.

- **Chapter 4 (Results) -** This chapter presents the results obtained.

- **Chapter 5 (Discussion) -** This chapter presents the discussion of the results.

- **Chapter 6 (Conclusions) -** This chapter summarizes and draws relevant conclusions. Also, includes thesis limitations and recommendations for future works.

2 BACKGROUND

This chapter is divided in 5 sections; the first section provides background information about residential building stock. The second section provides information about the factors affecting residential energy sector consumption. The third section provides information about the energy consumption by end-use. The fourth section provides information about operating and embodied energy of housing stock. Finally, the fifth section provides information about energy efficiency measures in the residential sector. Information in this chapter was gained from the journal, book and website reviews.

2.1 RESIDENTIAL DWELLING STOCK

If we want to investigate possible energy savings from the existing world housing stock, we need to know how many individual dwellings there are in the world. Note the term dwellings in this thesis is used to denote all housing units, be they individual houses or combined flats or various sorts. While obtaining an exact number of dwellings for the whole world may be difficult question to answer in detail, as long as we only require a reasonable estimate the problem becomes tractable. If we do simple calculations based on population and rate of occupancy per house, the answer will be:

<u>For 2010:</u>

- World population ≈ 6.9 billion people **(World Bank, World Development Indicators – Last update 29 November 2010).**

- Assuming occupancy rate between 4 and 7 people living in a house gives a range between 1 billion and 1.7 billion individual dwellings increasing at rate of around 25 million p.a., assuming a population increase of 1.5% p.a.

Occupancy rates obviously vary between developed and developing countries, as well as, between urban and rural areas. In addition there is a largely undocumented homeless population in the world and thus getting a more accurate estimate from the literature review was not possible.

However, the United Nations Human Settlements Programme (UN-HABITAT) has projected the total number of households for each country in the world until 2030 **(Table 1) (UN-HABITAT, 2007).** UN-HABITAT is the United Nations (UN) for human settlements and it is mandated by the UN General Assembly to promote socially and environmentally sustainable towns and cities with the goal of providing adequate shelter for all **(UN-HABITAT, 2010).** The number of households estimated by UN-HABITAT can be assumed to be the number of dwellings. Thus, this data will be used in this thesis to project the number of dwellings for the world until 2100.

Total number of household in the world (`000)							
Year	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Number	1,568,621	1,746,538	1,939,110	2,123,168	2,305,787	2,481,701	2,653,637

Table 1: Projection for the total number of household in the world until 2030 (UN-HABITAT, 2007).

2.2 ENERGY USE IN THE RESIDENTIAL SECTOR

Energy use in the residential sector is defined as the energy consumed by the usual occupation of dwellings (this excludes transportation uses) **(EIA, 2010).** The EIA also stated that the type and amount of energy used by dwellings vary from country to country, depending on income levels, natural resources, climate and available energy infrastructure. Also, it is widely known that size, building envelope construction, age distribution of the existing building stock, weather conditions, age and efficiency of equipment used and occupancy are the key factors for energy consumption in the residential sector **(Perez-Lombard et al., 2008 and Balaras et al., 2007).**

Low density development, increase in dwelling area, decrease in occupancy and increasing number of energy consuming appliances has been posited to make a contribution to the observed rapid increase in residential sector energy consumption, even while efficiency standards have been tightening **(Kaza, 2010)**. According to **Mantzos et al., (2003) (cited in Balaras et al., 2007),** as a result from the rising number of dwellings, changes in age structure, lifestyles and dwellings area, in 2000 – 2030 total energy demand from dwellings is expected to increase by 0.6% per annum. However, according to **EIA (2010),** the energy consumption in the residential sector will grow at an average of 1.1% per annum from 2007 to 2035. The EIA reported that energy consumption in the residential sector accounted for about 14% of world delivered energy consumption in 2007.

The **EIA (2006),** in its *International Energy Outlook 2006* analyses and forecasts that the growth of construction in the world will boost the residential sector energy demand considerably by 2030 mainly due to growth in China and India. Therefore, it is believed that with an increase of total number of dwellings, residential energy use is very likely to continue and increase with as well. According to **Schipper & Bartlett (cited in Pereira et al., 2008),** about 45% to 55% of total energy consumption in the residential sector is influenced by the occupant's activities.

These authors also argued that besides energy prices and income, mix of personal activities and locations will drive significant changes in residential energy consumption. **Y.M. Wei (2007)** also found that occupant's lifestyles and the economic activities attribute to the energy consumption in residential sector in China. Therefore, one factor which has an impact to the increased in the residential energy consumption is occupant's behavioral activities and lifestyle **(Pereira et al., 2008).**

The **EIA (2006)** has predicted that both developed and developing countries are equally responsible for energy use in the residential sector by 2010 (Refer **Figure 1**, Chapter 1). Based on the *International Energy Outlook 2010* by the **EIA (2010)**, typical dwellings in OECD nations use more energy than those in non-OECD nations (developing countries). This difference is in part due to the higher income levels in OECD nations which support purchases or larger houses and more appliances. However, residential energy consumption shows much more growth in non-OECD countries where standard of living are improving due to higher economic growth which fuels demand **(EIA, 2010).** In addition, the **EIA (2010)** reported that non-OECD residential energy consumption is rising by 1.9% per annum as compared to the OECD residential energy consumption which increased by only 0.4% per annum in 2010.

2.2.1 Area of dwellings

The physical area of the dwelling appears to be one of the most important structural components driving energy demand in developed countries **(Unader et al., 2004 and EIA, 2010).** The relationship between the dwelling's area and energy consumption has been shown to be directly proportional i.e. larger dwelling area means more energy consumed. According to **IEA (2008),** larger dwellings area in the IEA-19 countries have led to an average annual increase of 0.7% in energy demand from 1990 to 2005. It is widely known that the dwelling's area is expected to increase around the world, in both developed and developing countries. As reported by **IEA (2004),** as shown in **Table 2** the average area of dwellings has increased from 1973 to 1998 in developed countries**.**

	House Area (m^2/dwelling)			
	1973	**1980**	**1990**	**1998**
Australia	108	115	122	129
Canada	-	117	126	127
Denmark	102	106	107	108
Finland	65	69	74	76
France	78	81	86	88
Germany	-	-	82	84
West Germany	76	82	88	-
Italy	78	85	93	98
Japan	76	83	90	93
Norway	88	98	109	124
Sweden	96	102	111	114
UK	77	81	84	85
US	136	139	143	157
IEA-11	101	104	110	117

Table 2: Trends in dwellings area in selected developed countries 1973-1998 (source: IEA, 2004).

The above data were used again in **Zhou et al. (2009)** and in addition, China data until 2004 were included **(Figure 2)**.

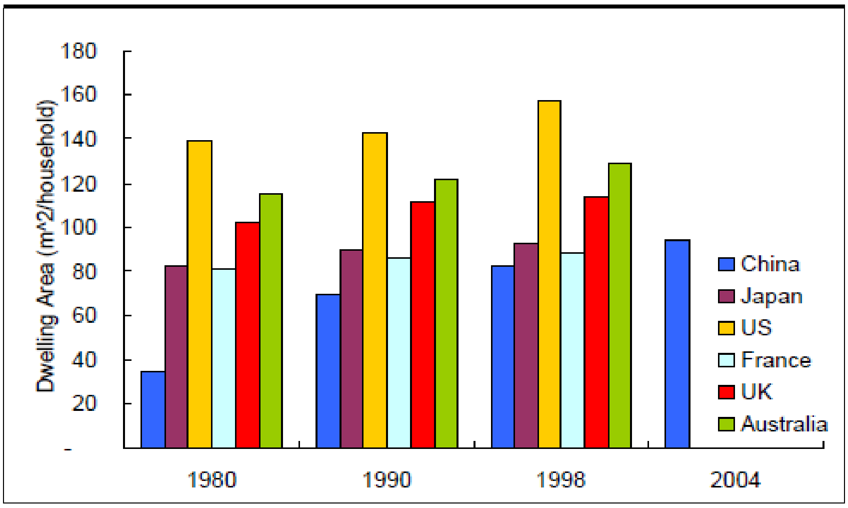

Figure 2: Trends in house area in selected developed countries but including China (source: Zhou et al., 2009).

Over the past two decades, dwelling area in China has increased significantly with an average of 4.3% increase per year, while it is only about 0.6% per year in other countries **(Zhou et al., 2009).** It is possible that in the near future, the average dwelling area in developing countries will match with the average house size in developed countries.

2.2.2 Occupancy rate

Dwelling occupancy rate (measured as persons per house) is another important structural component on residential energy consumption. However, the relationship between energy consumption and household occupancy is not strict as the relationship with dwelling area. In fact it has been shown that the energy demand is relatively independent of how many people occupy a dwelling; if dwellings occupancy declines, space heating demand in a given residence declines at much slower rate or does not declines at all **(Unader et al., 2004).** Unader et al. found that the main reason is that space heating demand and lighting levels are relatively independent of how many people occupy a given house.

According to the **IEA (2008),** larger dwellings area and fewer occupants per dwelling have tended to drive up energy demand for space heating. The demand for space heating has increased due to the reduction in the occupancy of each household because a larger number of houses are required to house a given population. Furthermore, fewer people living in a given house do not necessarily reduce the heating needs. The **IEA** also found that lower occupancy rates actually increased energy demand by 0.5% p.a. In addition, as shown in **Table 3** below, since 1970s, household occupancy has steadily declined in Denmark, Sweden and Norway, but, the ownership levels of major household appliances have increased. These increased in the use of electric appliances will definitely affect the demand for energy **(Unader et al., 2004).**

	Denmark			Sweden			Norway		
	1973	1990	1999	1973	1990	1999	1973	1990	1999
Housing Structure									
Area/dwelling	99	101	97	96	111	114	88	109	122
Persons/dwelling	2.8	2.2	2.1	2.4	2.1	2.2	2.9	2.4	2.4
Appliance ownership									
Refrigerators (%)[a]	97	97	111	97	111	118	89	130	143
Freezers (%)	42	62	65	55	81	88	57	92	91
Clothes washers (%)	41	66	78	59	83	89	72	89	89
Dish washers (%)	6	28	47	11	40	49	3	37	52
Clothes dryers (%)	1	22	42	9	40	45	15	32	38

[a] **Includes combination refrigerator-freezer devices**

Table 3: Structural components affecting house energy consumption (Source: Unader et al., 2004).

As referred to **Table 4** below, the average household occupancy has been declining in most developed countries, even though, the dwelling size increases.

	House Area (m2/dwelling)				Household Occupancy			
	1973	1980	1990	1998	1973	1980	1990	1998
Australia	108	115	122	129	3.5	3.2	3.0	2.8
Canada	-	117	126	127	-	3	2.8	2.7
Denmark	102	106	107	108	2.7	2.4	2.2	2.1
Finland	65	69	74	76	3.1	2.8	2.5	2.3
France	78	81	86	88	3.1	2.9	2.7	2.6
Germany	-	-	82	84	-	-	2.3	2.2
West Germany	76	82	88	-	2.8	2.5	2.4	-
Italy	78	85	93	98	3.4	3.2	2.9	2.7
Japan	76	83	90	93	3.8	3.4	3.2	2.9
Norway	88	98	109	124	2.9	2.7	2.4	2.4
Sweden	96	102	111	114	2.4	2.3	2.1	2.2
UK	77	81	84	85	3.0	2.8	2.5	2.4
US	136	139	143	157	3.1	2.8	2.7	2.6
IEA-11	101	104	110	117	3.2	2.9	2.7	2.6

Table 4: Trends in household occupancy and house size for selected developed countries 1973-1998 (Source: IEA, 2004).

Also, same scenario occurs in developing countries. As can be seen in **Figure 3** below that average dwelling occupancy decreases in China while the dwelling size increases **(refer Figure 3) (Zhou et al., 2009)**.

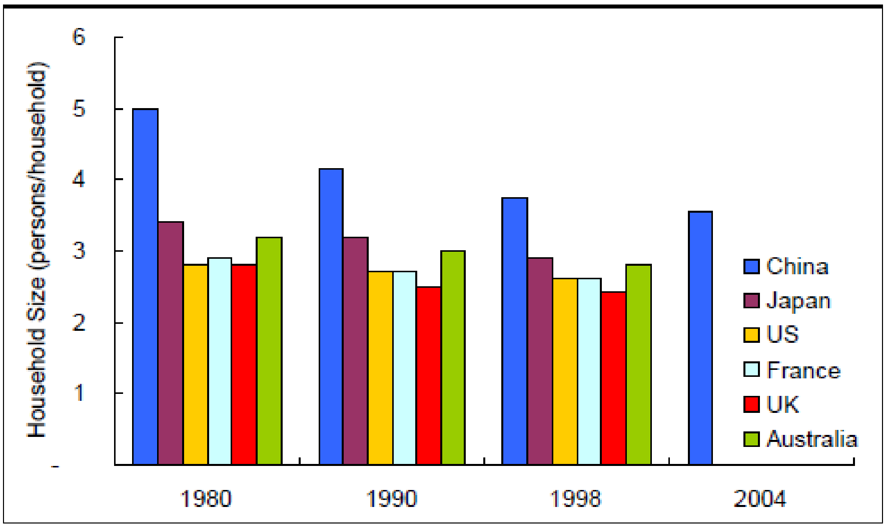

Figure 3: Trends in household occupancy in selected developed countries including China (Source: Zhou et al., 2009).

2.2.3 Income level

Household income level is another important factor which affects energy consumption in the residential sector. A report produced by The Energy Program Consortium **(EPC, 2008)** has sets out the relationship between the dwellings, income and energy consumption in the US. In the US at least it seems that higher income households consume more energy overall but less energy per square meter due to poorer building fabric. Below summarizes the findings:

- *Higher-income households represent 38 percent of U.S. households yet consume 45 percent of total energy in the residential sector. Lower-income households make up a larger 43 percent of the U.S. population yet consume only 36 percent of total energy in the residential sector.*

- *Lower-income households live in homes that average 1,480 square feet, compared to higher-income households which occupy homes that average over 2,700 square feet. However, lower-income households consume 28 percent more energy per square foot of living space than higher-income households. Lower-income households tend to be older, less well insulated and have older less-energy-efficient appliances and space heating systems. The combination of these features accounts for much of their higher per-square-foot energy use in these households.*

- *Higher-income households devote 2 percent of their annual income to paying energy bills even though their bills (at an average of $2,317) are close to 50 percent higher than those of average lower-income households (at an average of $1,542). Lower-income households devote 8 percent of their annual income to paying their energy bills.*

EPC (2008).

In New Zealand, The Building Research Association of New Zealand (BRANZ) also found that there is statistically significant relationship between income and total energy consumption **(Isaacs et al., 2010).** In addition, electricity demands for the residential sector in Malaysia also driven by the household income distribution. A study in 1999 for Malaysia has estimated that an average family in low cost house spends about RM 65 (about US$ 17) per month, while average family in medium cost house spends about RM 110 (about US$ 30) per month **(Faridah, 2003).** This study is consistent with a data from Malaysia national energy provider (TNB) which shows that higher income level households consume more electricity overall **(TNB, 1999 cited in Tang, 2005) (see Figure 4).**

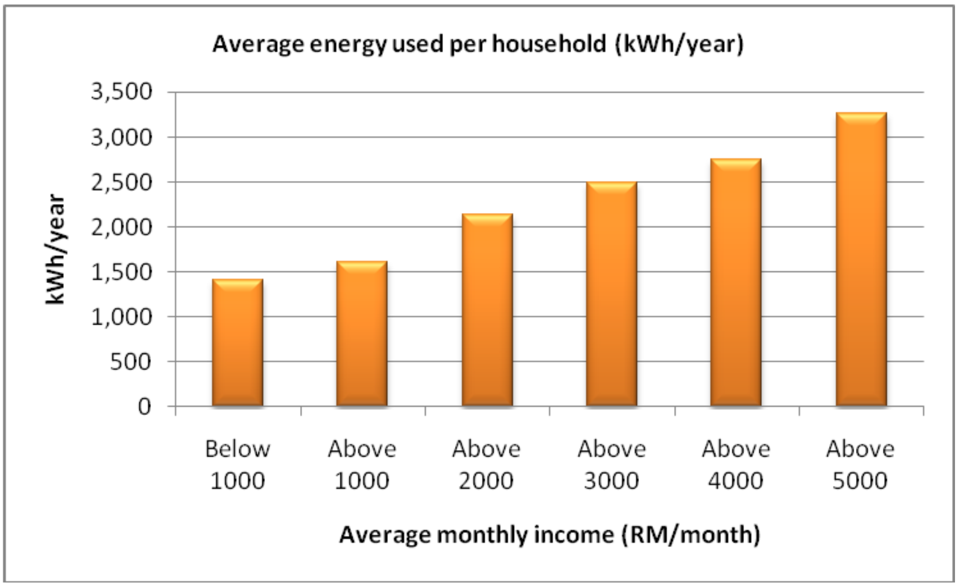

Figure 4: Estimate of average annual electricity demand by household income level in Malaysia (Tang, 2005 using data from TNB, 1999).

2.3 ENERGY CONSUMPTION IN DWELLINGS BY END USES

As mentioned previously, households in developed countries consume more energy than household in developing countries. Also mentioned previously, larger sizes of house, higher expected levels of comfort and more household appliances in developed countries reflects this scenario. However, Japan's energy consumption is significantly lower due to their common practice of heating one room rather than the whole house **(WBCSD, 2009)**. WBCSD reported that in Europe and Northern China energy consumption are dominated by space heating, while Japan is dominated by water heating. In developing countries, like in rural India, the main energy consumption is cooking which typically uses biomass, as many people do not have access to electricity **(Figure 5)**. However, it is believed that rising wealth in developing countries will lead to higher energy consumption for basic equipment, appliances and electronics goods.

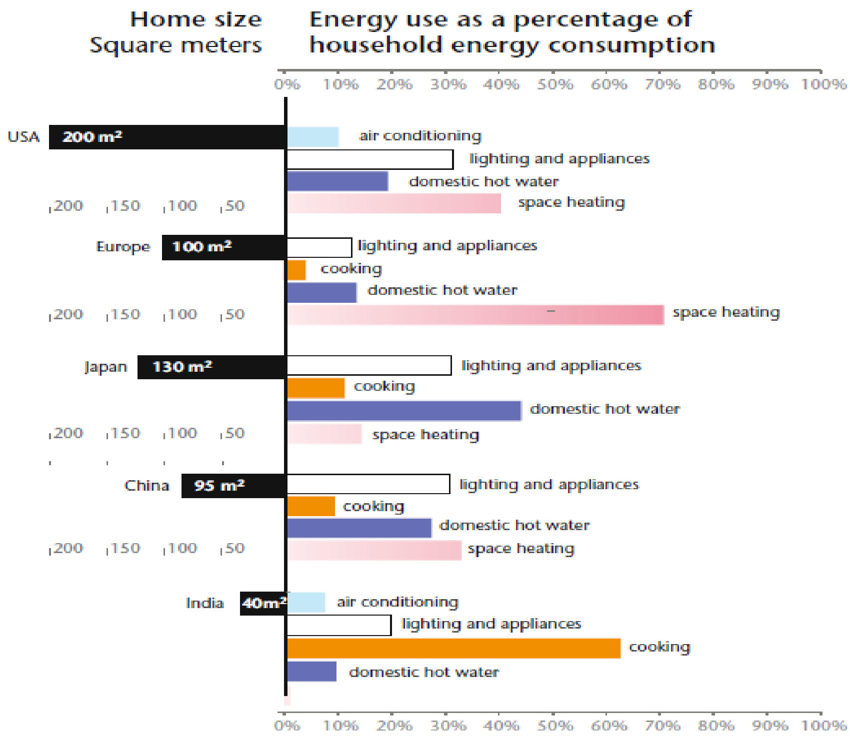

Figure 5: Wide differences in home size and residential energy consumption in few countries (Source: WBCSD, 2009).

According to **Perez-Lombard et al. (2008),** HVAC (Heating, Ventilation and Air Conditioning) is the largest energy end use in the residential sector in developed countries and it often represents about half of the energy consumption as compared to other end uses. **Table 5** below shows the percentage energy consumption by end uses in the residential sector in Spain, EU countries, USA and the UK for year 2003 as indicated in **Perez-Lombard et al. (2008).**

End uses in the residential sector (%)	Spain	UE	USA	UK
Space conditioning	42	68	53	62
Domestic hot water (DHW)	26	14	17	22
Lighting and appliances	32	18	30	16

Table 5: Energy consumption by end uses in the residential sector (Source: Perez-Lombard et al., 2008 using data from EIA, IDEA and BRE, 2003).

The above data for EU-15 countries also concurs with a report which stated 70% of energy consumption by end-use in EU-15 member is dominated by space heating, 14% by water heating and 12% by electric appliances and lighting **(ENERDATA cited in Balaras et al., 2007).** A survey project by The Building Research Association of New Zealand (BRANZ) entitled *Household Energy End-use Project (HEEP)* found that the largest portion of the residential sector energy consumption by end-use in New Zealand was space heating which accounted for 34%, followed by water heating with 29%, 13% for other appliances, 10% for refrigeration, 8% for lighting and the remaining 6% for range **(Isaacs et al., 2010).** In addition, **Unader et al. (2004)** also indicates that Scandinavian residential energy use is dominated by space heating. **Figure 6** shows per capita residential energy use by end-use for three Scandinavian countries and selected IEA countries as stated in **Unader et al.**, with space heating adjusted to 2700 degree days (18°C base) to correct for differences in climate among the countries

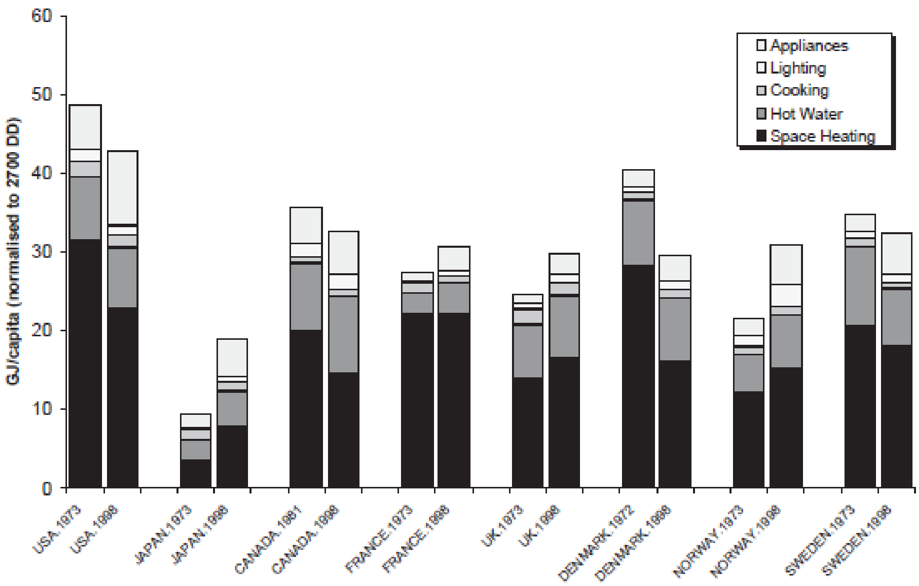

Figure 6: Residential final energy use per capita by end use (Unader et al., 2004).

As can be seen, since space heating is the largest energy use by end-use in the residential sector for developed countries, any significant reduction in residential energy consumption thus needs to take account of a combination of higher efficiency of space heating equipment and improved thermal performance of new and existing dwellings.

However, in terms of increases, according to **IEA (2009)** space heating energy use has only increased by 0.3% per annum from 1990 to 2006 (corrected for yearly climate variations) even though it is still the most important energy consumption category by end uses in the residential sector of the IEA-19. Whereas, the most rapidly growing household demand for energy come from appliances, with consumption increasing by 52% from 1990 to 2006. It is recorded that appliances overtook water heating as the second most energy-consuming end-use. In New Zealand, it is interesting to note that there has been no increase in electricity use per household since 1974 **(MED, 2009).**

The **IEA (2009)** also indicates, in 2006, that 52% of total household electricity consumption comes from appliance use in the IEA countries (developed). It has been recorded that electricity consumption for household appliances in the IEA-19 grew 57% from 1990 to 2005 which has been driving the overall increase in household electricity demand **(IEA, 2008).** According to **IEA (2009),** the proportion of the major appliances i.e. refrigerators, freezers, washing machines, dishwashers and televisions in the total household energy consumption dropped from 47% in 1990 to only 28% in 2006. However, as these five majors appliances share has declined, a wide range of mostly small appliances (e.g. personal computers, mobile phones, personal audio equipment and other home electronics) has shown the most rapid increase in appliances energy consumption up by 41%. Therefore, more concern to energy efficiency measures for small appliances is likely to help to reduce energy consumption in residential sector.

2.4 OPERATING ENERGY AND EMBODIED ENERGY

Energy is one of the most important resources used in buildings (both in the production of the buildings and during its operation)

(Winter and Hestnes, 1999).

The energy consumption over the lifetime of a building can be divided into the operating energy (used during the building's occupancy) and the embodied energy (used during the production of construction materials and during the on-site construction). In addition, there are other parts of the life cycle of buildings which use energy, which are disassembly (demolition), renovation and waste management **(L. Gustavsson and A. Joelsson, 2009).** This thesis focuses only on the operating energy and embodied energy. Any other energy used in the residential sector is expected to be small **(Gustavsson and Joelsson, 2010, Sartori and Hestnes, 2007, Cole and Kernan, 1996, A. Dodoo et al., 2009).**

In the words of the IPCC 4th assessment report:

The embodied energy in building materials needs to be considered along with operating energy in order to reduce total lifecycle energy use by buildings. For typical standards of building construction, the embodied energy is equivalent to only a few years of operating energy, although there are cases in which the embodied energy can be much higher (Lippke et al., 2004). Thus, over a 50-year time span, reducing the operating energy is normally more important than reducing the embodied energy. However, for traditional buildings in developing countries, the embodied energy can be large compared to the operating energy, as the latter is quite low. In most circumstances, the choice that minimizes operating energy use also minimizes total lifecycle energy use. In some cases, the high embodied energy in high-performance building envelope elements (such as krypton-filled double- or triple-glazed windows) can be largely offset from savings in the embodied energy of heating and/or cooling equipment (Harvey, 2006, Chapter 3), so a truly holistic approach is needed in analyzing the lifecycle energy use of buildings

(IPCC Fourth Assessment Report: Climate Change, 2007).

2.4.1 Operating energy

Operating energy is the energy use in keeping the indoor environment within the desired range **(Chen et al., 2001).**

A house requires energy for its day to day operation, keeping warm in winter, keeping cold in summer or watching television in the living area uses energy which typically comes from the oil, gas, solid fuels or electricity. **Winter and Hestnes (1999)** indicates that 90% of energy consumption over the lifespan of the building consumed during operation and this definitely overshadows the energy consumed during construction. In addition **Winter and Hestnes** reported, in 1991, that the energy used for operation of houses in Norway was as much as 25% the total energy use in the country. They stated that a reduction in energy use in buildings will thus have a significant impact on the national energy use. Therefore, as can be seen much research has been focused on means to reduce recurrent energy consumption for house and water heating. **Adalberth (1997a)** stated that operating energy is consumed during the period of use for buildings and this period is also known as the building management phase of a building.

Figure 7: Phases of a building during its life cycle (Adalberth, 1997a).

According to **Adalberth (1997b),** energy required during the years when the house is actually inhabited (operation) is for space heating, hot water and electricity. In addition, **Adalberth (1997b)** also stated that the people who live in the house are able to influence the utilization of energy (e.g. indoor temperature, hot water use and electricity). In the 1990s, the annual total energy consumption in residential buildings averaged around 150-230 kWh/m^2 **(Rasmussen, 1994 cited in Balaras et al., 2007)** for developed countries**.** However, in Scandinavia, well insulated residential buildings were documented to have an annual consumption of only 120-150 kWh/m^2, while so-called low-energy buildings may even be as low as 60-80 kWh/m2 **(Balaras, 2007)**. **Perez-Lombard et al. (2008)** reported that houses in developed countries use more energy/m^2 than developing countries and this is due to the installation of new appliances (air conditioners, computers, etc.). They also stated that the average energy use intensity by the residential in the US was about 147kWh/m^2 per annum in 2006.

Since most of the energy consumption is over the operational lifespan of the building, achieving significant reductions in energy consumption can assist significantly in reducing the resource consumption and improving comfort.

2.4.2 Embodied energy

Embodied energy is the total energy required for the extraction, processing, manufacture and delivery of building materials to the building site. Energy consumption produces CO_2, which contributes to greenhouse gas emissions, so embodied energy is considered an indicator of the overall environmental impact of building materials and systems

(Level NZ, 2010).

For the past several decades, the embodied energy in building materials has been studied by researchers interested in the relationship between building materials, construction processes and their environmental impacts. Many people are familiar with the concept of improving house energy efficiency by reducing its operating energy. However, little attention has been focused on recognizing that reducing the embodied energy of the house structure will improve the lifetime energy efficiency of the house. Every residential building is a complex combination of many processed materials, each of which contributes to the house's total embodied energy. Basically, there are two types of embodied energy in buildings; initial embodied energy and recurring embodied energy.

The initial embodied energy of a building is the energy used in producing a building whereas the recurring embodied energy is the energy used in maintaining and repairing of the building over its effective life

(Chen et al., 2001).

Embodied energy can contribute up to 40% of the life cycle energy use in residential buildings **(Cole and Kernan, 1996 and Chen et al., 2001)** and also represents a high percentage of the overall life cycle energy use of a building **(Hernandez and Kenny, 2011)**. This is quite a large portion of energy and as mentioned in Chapter 1 (Introduction) and this portion will gets proportionally bigger if the building is designed, constructed and managed efficiently **(Thormark, 2002, Sartori and Hestnes, 2007 and Gustavsson and Joelsson, 2010).**

It can be concluded that the embodied energy of housing construction materials and associated adjunct energy systems may become more important as we move towards more energy efficient housing. It has been found by some researchers that as the operating energy for residential building decreases, the relative importance of the energy used in production phase increases and thus the effort to minimize the life cycle energy use will be effected **(Gustavsson & Joelsson, 2010). Gustavsson and Joelsson** also found that the primary energy use for production can be 45% or 60% of the total lifetime energy use for a conventional and low energy residential building respectively.

Since the embodied energy in buildings appears significant especially so for energy efficient buildings, so reducing it can also significantly reduce the overall environment impact of the building.

2.5 ENERGY EFFICIENCY IN RESIDENTIAL SECTOR

It is likely that energy consumption in the residential sector will grow dramatically if no action taken to substantially improve energy efficiency. Many governments around the world have set energy efficiency targets in the residential sector as their main goal to reduce energy consumption. The main purpose of energy efficiency measures in residential buildings is to reduce the environmental impact from CO_2 emissions. However, it will not succeed if the implementation is unrealistic and ineffective.

Balaras et al. (2007) presented the most effective energy conservation measures in Hellenic residential buildings in Greece as: the insulation of external walls (33% - 60% energy savings), weather proofing of opening (16% - 21%), the installation of double-glazed windows (14% - 20%), regular maintenance of central heating boilers (10% - 12%) and the installation of solar collectors for sanitary hot water production (50% - 80%). They also stated **(cited from ENERDATA, 2003)** that on an average, new European houses are about 60% more energy efficient as compared to ones constructed before the 1970s, when the first oil crisis happened and 28% consume less than houses built in 1985.

Research carried out by the European Commission's Joint Research Centre – Institute for Prospective Technological Studies (JRC-IPTS) found between 25% and 40% of energy for room heating and associated greenhouse gas emissions can be saved from the renovation and refurbishment of windows, wall insulation and roof insulation independently of major renovations of whole buildings (outside the major renovation cycles) compared to the savings expected from existing and already formally proposed EU policies, which focus on energy efficiency of new buildings and major renovation **(Uihlein and Eder, 2009).** The research shows that there is always a potential for additional energy efficiency policies to lead to further reductions in the environmental impacts. **Levine et al. (2007)** stated that by having effective residential energy efficiency policies is increasingly important as building operation, as well as construction, contributes significantly to emissions of carbon dioxide and contributes to the enhanced greenhouse effects.

Retrofitting existing houses not just save the energy and associated greenhouse gas emissions, this measure also improved houses occupants' health. It has been found that by insulating existing houses has led to a significantly warmer, drier environment, thus resulted in improved self rated health, self reported wheezing, days off school and work, and visits to general practitioners as well as a trend for fewer hospital admissions for respiratory conditions **(Howden-Chapmen et al., 2007).** However, a study has shown that in New Zealand, occupants could be exposed to indoor temperature below WHO recommendations despite the residential energy efficiency upgrade program **(Lloyd et al., 2008).**

According to the **IEA (2008),** energy efficiency programmes implemented in many IEA countries has been significantly helped decrease the share in total electricity demand of major appliances. The programmes include minimum energy performance standards, appliances labeling and voluntary agreements with industry **(IEA, 2008). Figure 8** shows the impacts of these energy efficiency programmes in EU-15.

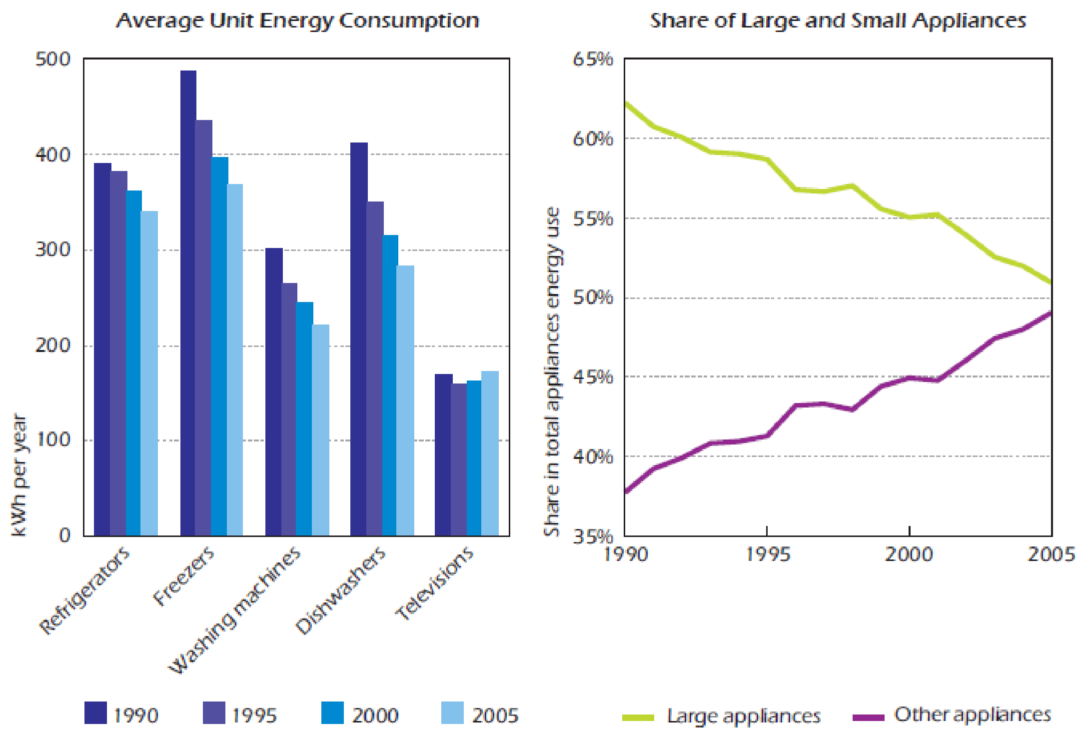

Figure 8: Energy consumption of appliances for EU-15 (Source: IEA, 2008).

Since 1990, all these appliances have shown significant decreases in average unit energy consumption, except televisions. In recent time, consumer trends towards larger screens which use more energy, have offset the energy efficiency gains (a good example of the direct rebound effect). On the other hand even though the size of refrigerators and freezers has become larger, the average unit energy consumption has been shown to decline **(IEA, 2008).** Analysis done by the **IEA (2008)** for IEA-11 shows that improved energy efficiency in the residential sector continues to play major role in shaping energy consumption and the pattern of CO_2 emissions, but the rate of improvement has slowed substantially **(Figure 9).**

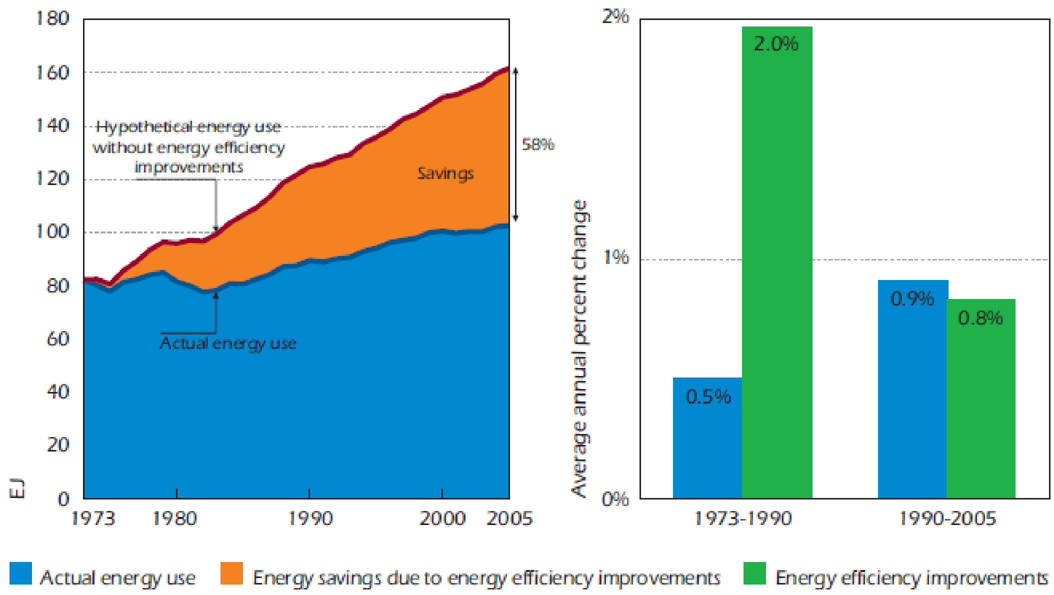

Figure 9: Savings from improved energy efficiency for IEA-11 (Source: IEA, 2008).

The biggest problem with energy efficiency which the world will face in the future is continuing economic growth (even at slower rate) will definitely trump energy efficiency gains at some point in the future. In the words of **William R. Catton, Jr.** in his book entitled *Overshoot: the Ecological Basis of Revolutionary Change*:

... our lifestyles, mores, institutions, patterns of interaction, values, and expectations are shaped by a cultural heritage that was formed in a time when carrying capacity exceeded the human load. A cultural heritage can outlast the conditions that produced it. That carrying capacity surplus is gone now, eroded both by population increase and immense technological enlargement of per capita resource appetites and environmental impacts. Human life is now being lived in an era of deepening carrying capacity deficit. All of the familiar aspects of human societal life are under compelling pressure to change in this new era when the load increasingly exceeds the carrying capacities of many local regions and of a finite planet. Social disorganization, friction, demoralization, and conflict will escalate.

Catton (1982).

3 METHODOLOGY

3.1 OVERVIEW

The objective of this thesis is to determine the total world energy consumption for the residential sector and potential energy savings by buildings energy efficient dwelling. Microsoft Excel simulation models were built to estimate and project the total world residential energy consumption from 2010 to 2100. As this is a relatively long time frame, several scenarios regarding dwelling growth rates were made.

In selecting the criteria for several scenarios, the following four (4) factors were considered directly related to the dwelling stock:

I. **Number of dwellings as a function of time:** The UN-HABITAT data, which is used in this thesis **(see later),** is originally on the total number of households in the world. In this thesis, the total number of residential dwellings was assumed to be equivalent to the total number of households.

II. **The number of new builds being energy efficient dwellings:** There are various possibilities that the percentage of new built dwellings will be built as energy efficient dwellings and the remainder will be built as status quo (conventional dwelling) every year. Therefore, the percentage of new built dwellings being built every year was considered as a variable in the simulation models.

III. **Existing dwelling retrofits:** There is also the possibility that a number of existing dwellings (conventional dwellings) could be retrofitted or rebuilt as energy efficient dwellings. Therefore, the percentage of existing dwellings retrofitted each year was taken as a variable.

IV. **Energy efficient dwelling energy savings:** In order to distinguish the energy savings potential, energy efficient dwelling in this thesis were classified in three types:

a. Energy efficient dwelling 1 (EED 1) with 20% operating energy reductions over the conventional dwellings.

b. Energy efficient dwelling 2 (EED 2) with 50% operating energy reductions over the conventional dwellings.

c. Energy efficient dwelling 3 (EED 3) with 80% operating energy reductions over the conventional dwellings.

Based on the above four (4) factors, four (4) scenarios were then selected to analyze the residential energy consumption of the world. Scenarios for calculating the total world residential energy consumption over the 90 year period were as follows:

i. **Scenario 1: Business as Usual (BAU)**

- All (100%) new built dwellings being built as status quo (conventional dwelling).
- Existing dwellings being treated as conventional dwellings (i.e. no retrofits).

ii. **Scenario 2: Energy Efficient Dwelling 1 (EED 1)**

- A set percentage of new built dwellings being built as EED 1 each year.
- The remainder new built dwellings being built as status quo.
- A set percentage of existing dwellings being retrofitted as EED 1 each year.

iii. **Scenario 3: Energy Efficient Dwelling 2 (EED 2)**

- A set percentage of new built dwellings being built as EED 2 each year.
- The remainder new built dwellings being built as status quo.
- A set percentage of existing dwellings being retrofitted as EED 2 each year.

iv. **Scenario 4: Energy Efficient Dwelling 3 (EED 3)**

- A set percentage of new built dwellings being built as EED 3 each year.
- The remainder new built dwellings being built as status quo.
- A set percentage of existing dwellings being retrofitted as EED 3 each year.

According to **Callau (2009)**, state dwellings in New Zealand can be classified as single-detached unit, single-twin unit, double-twin unit, single-storey flat, double-storey flat and multi-storey flat. A single-detached dwelling is a free standing or stand alone residential building which usually resides by single family. Single-twin unit and double-twin unit which also called semi-detached housing consists of pairs of dwellings built side by side as unit sharing the same structure in such a way that each dwelling's floor plan is a mirror image of its twin. However, single-storey flat, double-storey flat and multi-storey flat classified as where multiple separate housing units for residential residents are contained within one building. In addition, a multi-storey flat cal also called an apartment **(Callau, 2009).** Although dwellings around the world appear to be many different types which can be built in large variety of configurations, it can be assumed that every country in the world have similar types of dwellings as in New Zealand since many of variations of dwellings exist in the world are purely matters of style rather than spatial arrangement or scale. In this thesis, however, it is important to note that types of dwelling were not considered relevant as the thesis only uses the energy consumption of the individual residences in term of energy (kWh) per square meter.

The analysis in this thesis has been carried out in **4 stages**:

Stage 1: Estimating the **total number of existing dwellings and the rate of new builds per annum** for each country in the world and thus estimating the total number of residential dwellings in the world as a function of time.

Stage 2: Estimating the **average dwelling area (m^2/dwelling)** for each country in the world and projecting the increase over time thus calculating the total residential floor area for the world as a function of time.

Stage 3: Estimating the average value of **operating energy (OE), initial embodied energy (IEE), and recurring embodied energy (REE) (maintenance) in kWh/m^2** for conventional dwelling and energy efficient dwelling.

Stage 4: Calculating the **total energy consumption in the residential sector** as a function of time according to the 4 scenarios as mentioned above.

3.2 STAGE 1: TOTAL NUMBER OF EXISTING AND NEW DWELLING IN THE WORLD

The estimation of total number of existing dwellings and the projection new built dwellings were made for each country in the world. The projection of dwelling growth was calculated based on data from The United Nations Human Settlements Programme (UN-HABITAT) report entitled *Enhancing Urban Safety and Security: Global Report on Human Settlements 2007* **(UN-HABITAT, 2007)**.

The UN-HABITAT projection growth data was used with the world population growth data to construct three (3) dwelling growth i.e. high, medium and low growth. The original UN-HABITAT data was taken as the high growth scenario. The world population growth data used was from the United Nations (UN) Department of Economic and Social Affairs/Population Division, which indicated in their report titled *World Population to 2300* **(UN, 2003).** With these assumptions, the number of existing and new built dwellings in the world was calculated as a function of time in 5-year intervals from 2010 to 2100. The 5-year interval was selected on the basis of 5-year interval was used in the UN-HABITAT data.

As mentioned previously in **Section 3.1**, the UN-HABITAT data was originally for the total number of households. However, in this thesis it was assumed that the total number of households in the world to be equivalent to the total number of individual residential dwellings in the world.

3.3 STAGE 2: TOTAL RESIDENTIAL FLOOR AREA FOR THE WORLD

Prior to calculating the total residential floor area for the world, an average floor area per dwelling (m^2/dwelling) for each country in the world first must be obtained. In this stage 2, a comprehensive literature review was completed to find out the information for many countries as possible. Complete geographical coverage was not available; therefore, assumptions had to be made for the countries where the data on average floor area per dwelling could not be found.

To make these assumptions, the data on existing dwellings average floor area for all countries found in the literature review were plotted against the GDP/capita at the time of the data point. It was found that the existing dwellings average floor area found in the literature review correlated with the GDP/capita data. Based on the weighted averaged calculations on the data found, it was estimated average floor area per dwelling for developed countries was estimated to be 120 m^2/dwelling in 1998 and 63 m^2/dwelling in 2002 for developing countries.

From the literature review, the changes in residential average floor area over time were also investigated. Existing dwellings average floor area data for each country found in the literature review was plotted against their GDP/capita data to observe if there any correlation between these two data. Since the existing dwellings average floor area data and GDP/capita data for each selected countries were determined to be correlated, the residential average floor area rate of change against the GDP/capita rate of change was determined.

The residential average floor area for each country in the world and thus the total residential average floor area for the world were then calculated as a function of time in 5-year intervals from 2010 to 2100.

3.4 STAGE 3: OPERATING ENERGY (OE), INITIAL EMBODIED ENERGY (IEE) AND RECURRING EMBODIED ENERGY (REE)

In stage 3, a comprehensive literature review was conducted to find an **average value of operating energy (OE), initial embodied energy (IEE) and recurring embodied energy (REE)** for conventional dwelling and energy efficient dwelling in the world in terms of **kWh/m^2**. Here the same problem was found as in Section 3.3 since it was unfeasible to find these data for every country in the world. Hence, a set of different assumptions for maximum and minimum value of OE for conventional dwelling in developed and developing countries was made considering the range of values obtained from the literature review. However, assumptions for IEE was made only for the world since the embodied energy to construct a dwelling anywhere in the world would be approximately the same per square meter.

The OE for the three types of energy efficient dwelling used in this these was computed according to the classifications which were mentioned in Section 3.1:

a. Energy efficient dwelling 1 (EED 1) with 20% operating energy reductions over the conventional dwelling.

b. Energy efficient dwelling 2 (EED 2) with 50% operating energy reductions over the conventional dwelling.

c. Energy efficient dwelling 3 (EED 3) with 80% operating energy reductions over the conventional dwelling.

IEE to build an energy efficient dwelling was found to be higher than for conventional dwelling. This finding was discussed in Chapter 2 (Background) where the energy used in the production phase increases as the operating energy decreases **(Gustavsson and Joelsson, 2010).** With this finding, the rate of change of IEE against rate of change of OE was calculated. In economic terms this would be the elasticity of OE against IEE. However, IEE of an energy efficient dwelling being retrofitted from conventional dwelling would not be equal to the IEE to build a new energy efficient dwelling. Thus, the different between IEE of a conventional dwelling and IEE of an energy efficient dwelling was considered as the IEE for the works of a conventional dwelling to be retrofitted as an energy efficient dwelling.

In the case of REE, the rate of usage was calculated against the value of IEE for conventional and energy efficient dwelling.

3.5 STAGE 4: TOTAL RESIDENTIAL ENERGY CONSUMPTION

In this stage 4, the total residential energy consumption for the world was calculated. Previously mentioned in Section 3.1, the total energy consumption for the world was calculated according to these four (4) scenarios **(Table 6)** as a function of time from 2010 to 2100 (90 year period):

Scenario	Description
1: Business as Usual (BAU) (Conventional Dwelling)	• All new built dwellings being built as status quo (conventional dwelling). • Existing dwellings being treated as conventional dwellings (i.e. no retrofits).
2: Energy Efficient Dwelling 1 (EED 1)	• A set percentage of new built dwellings being built as EED 1 each year. • The remainder new built dwellings being built as status quo. • A set percentage of existing dwellings being retrofitted as EED 1 each year.
3: Energy Efficient Dwelling 2 (EED 2)	• A set percentage of new built dwellings being built as EED 2 each year. • The remainder new built dwellings being built as status quo. • A set percentage of existing dwellings being retrofitted as EED 2 each year.
4: Energy Efficient Dwelling 3 (EED 3)	• A set percentage of new built dwellings being built as EED 3 each year. • The remainder new built dwellings being built as status quo. • A set percentage of existing dwellings being retrofitted as EED 3 each year.

Table 6: Selected scenarios to analyze the residential total energy consumption for the world.

For the Business as Usual scenario analysis, 100% of new built dwellings were considered being built as status quo (conventional dwellings). As for scenario 2, 3 and 4 analyses, a set of percentage of new built dwellings were considered being built as energy efficient dwellings and the remainder was considered being built as status quo (conventional dwelling). Additionally, a set of percentage of existing dwellings were considered to being retrofitted as energy efficient dwelling every year for scenario 2, 3 and 4.

Finally, in order to calculate the total energy consumption for the residential of the world, **equations 1(i) to 2(iii)** were used.

Equation 1: Scenario 1 - Business as Usual (BAU) (Conventional Dwelling)

i. **OE**

$$= \text{OE (CD)} \times \left\{ \begin{array}{c}\text{Accumulative total floor area of} \\ \text{new built dwellings}\end{array} + \begin{array}{c}\text{Total floor areas of} \\ \text{existing dwellings}\end{array} \right\}$$

ii. **IEE**

$$= \text{IEE (CD)} \times \left\{ \begin{array}{c}\text{Total floor area of new built} \\ \text{dwellings every year}\end{array} \right\}$$

iii. **REE**

$$= \text{REE (CD)} \times \left\{ \begin{array}{c}\text{Accumulative total floor area of} \\ \text{new built dwellings}\end{array} + \begin{array}{c}\text{Total floor area of} \\ \text{existing dwellings}\end{array} \right\}$$

Equation 2: Scenario 2, 3 & 4 - EED 1, EED 2 & EED 3

i. OE

$$= \left\{ \begin{array}{c}\text{OE}\\ \text{(EED)}\end{array} \text{ X } \begin{array}{c}\text{Accumulative total floor area of}\\ \text{new built dwellings being}\\ \text{built as EED}\end{array} \right\} + \left\{ \begin{array}{c}\text{OE}\\ \text{(CD)}\end{array} \text{ X } \begin{array}{c}\text{Accumulative total floor area of}\\ \text{new built dwellings}\\ \text{being built as CD}\end{array} \right\}$$

$$+ \left\{ \begin{array}{c}\text{OE}\\ \text{(EED)}\end{array} \text{ X } \begin{array}{c}\text{Accumulative total floor}\\ \text{area of existing}\\ \text{dwellings being}\\ \text{retrofitted as EED}\end{array} \right\} + \left\{ \begin{array}{c}\text{OE}\\ \text{(CD)}\end{array} \text{ X } \begin{array}{c}\text{Accumulative remaining total}\\ \text{floor area of existing dwellings}\\ \text{not yet being retrofitted as EED}\end{array} \right\}$$

ii. IEE

$$= \left\{ \begin{array}{c}\text{IEE}\\ \text{(EED)}\end{array} \text{ X } \begin{array}{c}\text{Total floor area of new built}\\ \text{dwellings being built as EED}\\ \text{each year}\end{array} \right\} + \left\{ \begin{array}{c}\text{IEE}\\ \text{(CD)}\end{array} \text{ X } \begin{array}{c}\text{Total floor area of new built}\\ \text{dwellings being built as EED}\\ \text{each year}\end{array} \right\}$$

$$+ \left\{ \begin{array}{c}\text{IEE}\\ \text{(Retrofit works)}\end{array} \text{ X } \begin{array}{c}\text{Total floor area of existing dwellings}\\ \text{being retrofitted as EED each year}\end{array} \right\}$$

iii. REE

$$= \left\{ \begin{array}{c}\text{REE}\\ \text{(EED)}\end{array} \text{ X } \begin{array}{c}\text{Accumulative total floor area of}\\ \text{new built dwellings being}\\ \text{built as EED}\end{array} \right\} + \left\{ \begin{array}{c}\text{REE}\\ \text{(CD)}\end{array} \text{ X } \begin{array}{c}\text{Accumulative total floor area of}\\ \text{new built dwellings being}\\ \text{built as CH}\end{array} \right\}$$

$$+ \left\{ \begin{array}{c}\text{REE}\\ \text{(EED)}\end{array} \text{ X } \begin{array}{c}\text{Accumulative total floor}\\ \text{area of existing wellings}\\ \text{being retrofitted as EED}\end{array} \right\} + \left\{ \begin{array}{c}\text{REE}\\ \text{(CD)}\end{array} \text{ X } \begin{array}{c}\text{Accumulative remaining total}\\ \text{floor area of existing dwellings}\\ \text{not yet being retrofitted as EED}\end{array} \right\}$$

Equations 1 (i) (ii) (iii) and 2 (i) (ii) (iii) were then set into the Excel Spreadsheet simulation models to simulate the total world energy consumption for the residential sector as a function of time and to determine the potential energy savings by buildings energy efficient dwellings with considering the previously mentioned scenarios.

Based on the methods used in this thesis as explained in Section 3.2, 3.3, 3.4 and in this section (Section 3.5), **Table 7** is the summarize table to show all the inputs needed in analyzing the result of the total residential energy consumption of the world.

	INPUT DESCRIPTION	INPUT DATA
1	Projection growth (high, medium or low).	%
2	Average floor area rate of change against the GDP/capita rate of change.	%
3	Rate of new built dwellings being built as energy efficient dwellings each year	%
4	Rate of existing dwellings being retrofitted to be energy efficient dwellings each year.	%
5	OE and IEE of conventional dwelling.	kWh/m^2
6	REE rate of usage of conventional dwelling against the value of IEE.	%
7	REE of conventional dwelling	kWh/m^2
8	OE reduction rate of energy efficient dwelling over the OE of conventional dwelling.	%

9	OE of energy efficient dwelling.	kWh/m^2
10	IEE energy efficient dwelling rate of change against the OE reduction rate.	%
11	IEE of energy efficient dwelling.	kWh/m^2
12	IEE of retrofit works for a conventional dwelling to be retrofitted as an energy efficient dwelling.	kWh/m^2
13	REE energy efficient dwelling rate of usage against the value of IEE.	%
14	REE of energy efficient dwelling.	kWh/m^2

Table 7: Inputs needed to analyze the residential total energy consumption for the world.

4 RESULTS

4.1 OVERVIEW

This section presents the result for:

1. The total number of existing dwellings and the rate of new builds per annum in the world and the total number of dwellings in the world as a function of time.

2. Estimates or actual data for the average dwelling area (m^2/dwelling) for each country in the world as a function of time and the total dwellings floor area for the world as a function of time.

3. Estimates for the operating energy (OE), initial embodied energy (IEE), and recurring embodied energy (REE) (maintenance) in kWh/m^2 for both conventional dwelling (some actual data) and energy efficient dwelling.

4. The total energy consumption for the residential dwelling sector in the world as a function of time, for 4 scenarios.

4.2 STAGE ONE: TOTAL NUMBERS OF EXISTING DWELLINGS AND NEW BUILT DWELLINGS AS A FUNCTION OF TIME.

This section presents the results for the total number of existing dwellings and rates of new built dwellings for the world as a function of time (2010 to 2100). As mentioned in Chapter 3 (Methodology), the projected growth of the total number of dwellings in the world has been based on data from UN-HABITAT, which is an existing, projection from the year 2000 to 2030 for each country in the world. Also mentioned in Chapter 3, this data was originally based on the total number of households and has been assumed to be the total number of residential dwellings (i.e. a flat in an apartment block has been taken as a residential dwelling). Based on this original data, the annual rate of change of total number of dwellings in the world from the year 2000 to 2030 will be about 1.75% p.a. **Table 8** shows the natural logarithm value, computed from the UN-HABITAT data, of total number of dwellings in the world and **Figure 10** presents a linear best fit to this data (black line) giving the average annual rate of change calculation for the world over this time period.

Total number of dwellings in the world based on the UN-HABITAT original data (`000)

Year	2000	2005	2010	2015	2020	2025	2030
Actual value	1,568,621	1,746,538	1,939,110	2,123,168	2,305,787	2,481,701	2,653,637
LN value	14.27	14.37	14.48	14.57	14.65	14.72	14.79

Table 8: Total number of dwellings in the world based on the UN-HABITAT original data (UN-HABITAT, 2007).

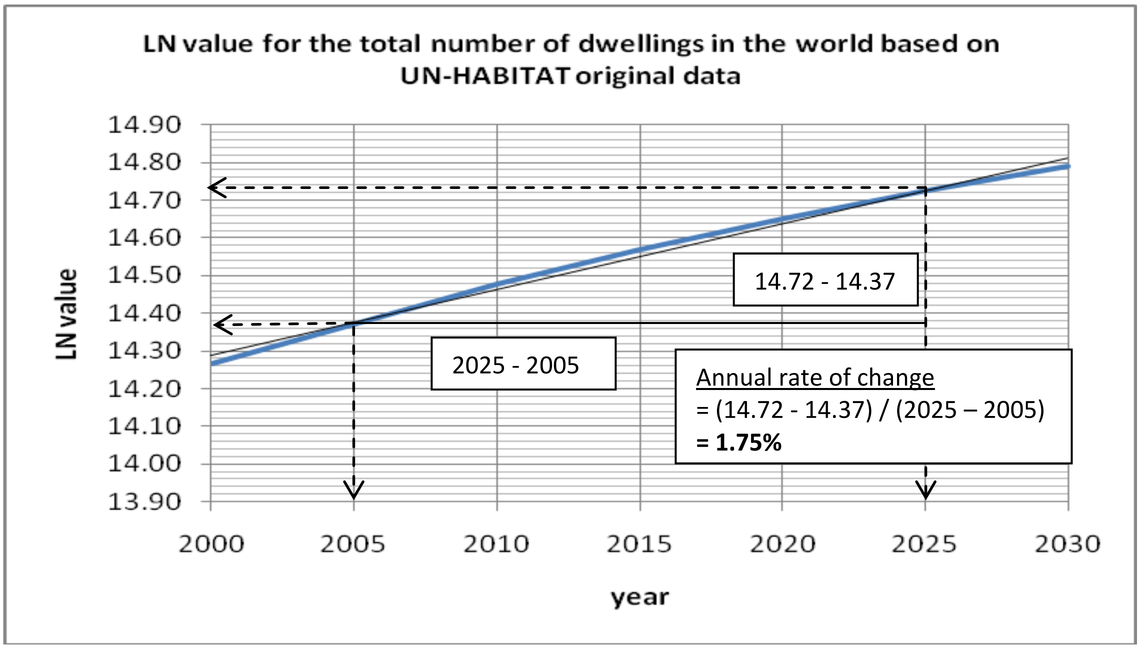

Figure 10: Linear best fit for data in Table 4.2a and the average annual rate of change of total number of dwellings in the world.

With this average annual rate of change, the UN-HABITAT data was recalculated from the year 2010 to 2100 in 5-year intervals. The 5-year interval was selected on the basis of 5-year intervals was used in the UN-HABITAT original. Note that the UN-HABITAT data shows a slight slowing in growth rate to 2030. Extending this data to 2100 is of course problematic as various factors (i.e. natural calamities, wars etc) could intervene over this long time period but such events can be handled by using various scenarios for future growth rates **(see Table 10).**

Year	original value	recalculated value	Error (%)
2000	1,568,621	1,568,621	0.00%
2005	1,746,538	1,698,372	-2.84%
2010	1,939,110	1,841,407	-5.31%
2015	2,123,168	1,999,269	-6.20%
2020	2,305,787	2,173,700	-6.08%
2025	2,481,701	2,366,675	-4.86%
2030	2,653,637	2,580,432	-2.84%
2035		2,817,517	
2040		3,080,824	
2045		3,373,657	
2050		**3,699,784**	
2055		4,063,520	
2060		4,469,809	
2065		4,924,328	
2070		5,433,605	
2075		6,005,162	
2080		6,647,682	
2085		7,371,204	
2090		8,187,355	
2095		9,109,627	
2100		10,153,701	

Table 9: Recalculated value of the original UN-HABITAT data and the percentage error.

It is of course probable that the number of dwellings in the world will be strongly related to the number of people in the world. According to the United Nations Department of Economics and Social Affairs (Population Division), the world population could reach 8.9 billion by 2050 if medium growth is considered **(UN, 2004).** Then, assuming an average occupancy rate is 4 persons per dwelling, the total number of dwellings in the world in 2050 could be only around 2.23 billion dwellings. As can be seen from the **Table 9,** the total number of dwellings in 2050 from the UN-HABITAT data would be around 3.7 billion dwellings. Therefore, it can be assumed that UN-HABITAT growth rate assumption of 1.75% p.a. would be a high growth scenario.

Following the consideration of UN-HABITAT data as extrapolated at 1.75% p.a. being high growth, medium growth and low growth scenarios for the total number of dwellings in the world were made by subtracting 0.75% and 1.50% respectively from the calculated annual rate of change above. **Table 6** shows the calculated linear projection growth rates for UN-HABITAT data (high growth) and for medium and low growth rates for the world.

Growth Rate	World projection growth (%)
High	**1.75 (extrapolated UN-HABITAT)**
Medium	1.00
Low	0.25

Table 10: Calculated linear projection growth rates for dwellings in the world.

Following these growth rates, the number of existing dwellings in the world was then calculated from the year 2010 to 2100 in 5-year intervals. For rates of new built dwellings, the difference between the intervals has been taken as the total number of new built dwellings in each five year interval. **Table 11 and Figure 11** shows the projection of the total number of dwellings in the world. Whereas, **Table 12 and Figure 12** shows the projection of the total number of new built dwellings in the world.

The number of existing dwellings in 2010 was set to be the value from the calculated medium growth (1.72 billion dwellings). This value is considered reasonable when comparing with the total number of population in 2010 and assumed average occupancy rate in the world.

→ 2010 population = 6.9 billion people

→ Assuming occupancy rate = 4 persons per dwelling

→ Total number of existing dwellings in 2010 = 6.9 billion / 4

= 1.73 billion dwellings.

Projection for the total number of dwellings per 5 years in the world ('000s)			
year	**low growth**	**medium growth**	**high growth**
2010		1,716,235	
2015	1,612,951	1,799,193	1,999,269
2020	1,633,251	1,888,992	2,173,700
2025	1,656,493	1,986,266	2,366,675
2030	1,682,816	2,091,727	2,580,432
2035	1,712,382	2,206,168	2,817,517
2040	1,745,377	2,330,478	3,080,824
2045	1,782,017	2,465,654	3,373,657
2050	1,822,547	2,612,820	3,699,784
2055	1,867,244	2,773,237	4,063,520
2060	1,916,426	2,948,329	4,469,809
2065	1,970,449	3,139,702	4,924,328
2070	2,029,718	3,349,176	5,433,605
2075	2,094,687	3,578,808	6,005,162
2080	2,165,872	3,830,934	6,647,682
2085	2,243,848	4,108,206	7,371,204
2090	2,329,267	4,413,642	8,187,355
2095	2,422,861	4,750,680	9,109,627
2100	2,525,453	5,123,240	10,153,701

Table 11: Projection for the total number of dwellings per 5 years in the world.

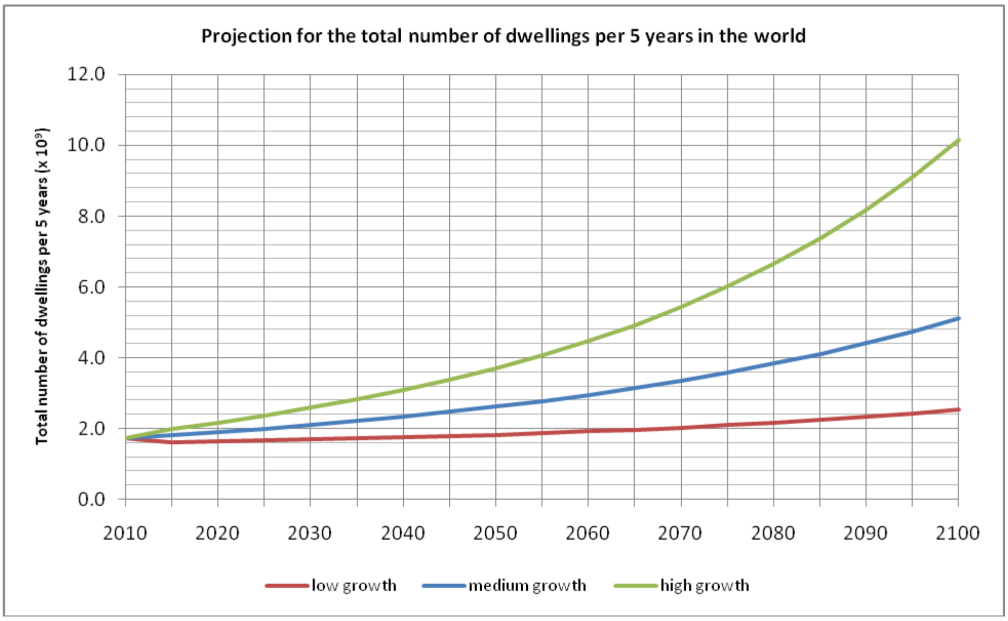

Figure 11: Projection for the total number of dwellings per 5 years in the world.

Projection for the total number of new built dwellings per 5 years in the world ('000s)			
	low growth	medium growth	high growth
2015	17,476	82,958	157,862
2020	20,300	89,799	174,431
2025	23,242	97,275	192,975
2030	26,323	105,461	213,757
2035	29,566	114,441	237,085
2040	32,996	124,310	263,308
2045	36,640	135,177	292,832
2050	40,529	147,166	326,127
2055	44,697	160,417	363,736
2060	49,182	175,092	406,289
2065	54,023	191,374	454,519
2070	59,269	209,474	509,277
2075	64,970	229,632	571,557
2080	71,184	252,126	642,520
2085	77,976	277,272	723,522
2090	85,419	305,436	816,151
2095	93,594	337,038	922,272
2100	102,592	372,560	1,044,074

Table 12: Projection for the total number of new built dwellings per 5 years in the world.

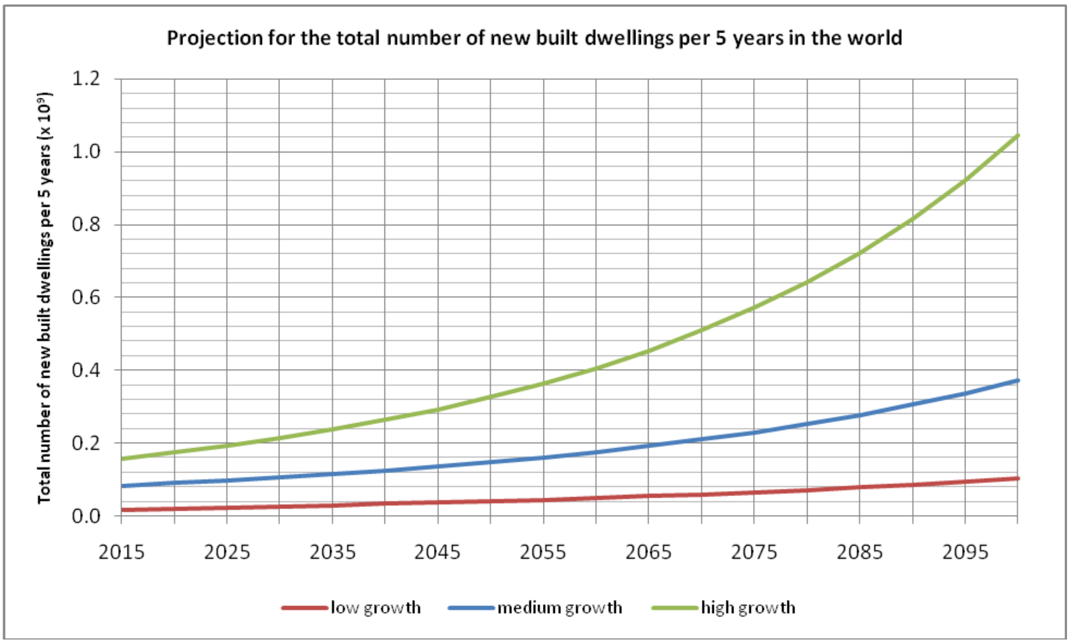

Figure 12: Projection for the total number of new built dwellings per 5 years in the world.

4.3 STAGE TWO: TOTAL DWELLINGS FLOOR AREA FOR THE WORLD AS A FUNCTION OF TIME.

This section presents the result for the total dwellings floor area for the world as a function of time (2010 to 2100). Prior to calculating the total dwelling area in the world, an average floor area per dwelling (m^2/dwelling) for each country in the world first must be obtained.

Table 13 below summarizes all data gathered from literature review on the average floor area of all dwellings and new dwellings respectively for selected countries in the world.

Country	Average floor area for all dwellings (m^2/dwelling)										Source
	1973	1980	1990	1998	2002	2004	2005	2006	2007	2008	
Australia	108.00	115.00	122.00	129.00							IEA (2004)
Canada		117.00	126.00	127.00							
Denmark	102.00	106.00	107.00	108.00							
France	78.00	81.00	86.00	88.00							
Germany			82.00	84.00							
West Germany	76.00	82.00	88.00								
Italy	78.00	85.00	93.00	98.00							
Norway	88.00	98.00	109.00	124.00							
Sweden	96.00	102.00	111.00	114.00							
UK	77.00	81.00	84.00	85.00							
US	136.00	139.00	143.00	157.00							
Japan	76.00	83.00	90.00	93.00							IEA (2004) & Japan Housing and Land Survey (2008)
Finland	65.00	69.00	74.00	76.00							IEA (2004) & Finland Statistics (2009)
Lithuania						61.30	61.80	62.10	62.90	65.70	Lithuania Dept. of Statistics (2008)
China		35.00	70.00	80.00		90.00					Zhou et al. (2009)
India					38.00						India Household Survey (2002)

Table 13: Average floor area for all dwellings for selected countries in the world.

Based on the **Table 13**, all the data were plotted against the GDP/capita at the time of the data point **(see Figure 13**). As referred to a Table of Probabilities for Correlation Coefficients **(see Appendix A),** it was found that (number of data, N=60 and R = $\sqrt{0.1545}$ = 0.39 ≈ 0.4) the correlation between the average floor area per dwelling and GDP/capita is significant with 87% probability that data are correlated at 5% level.

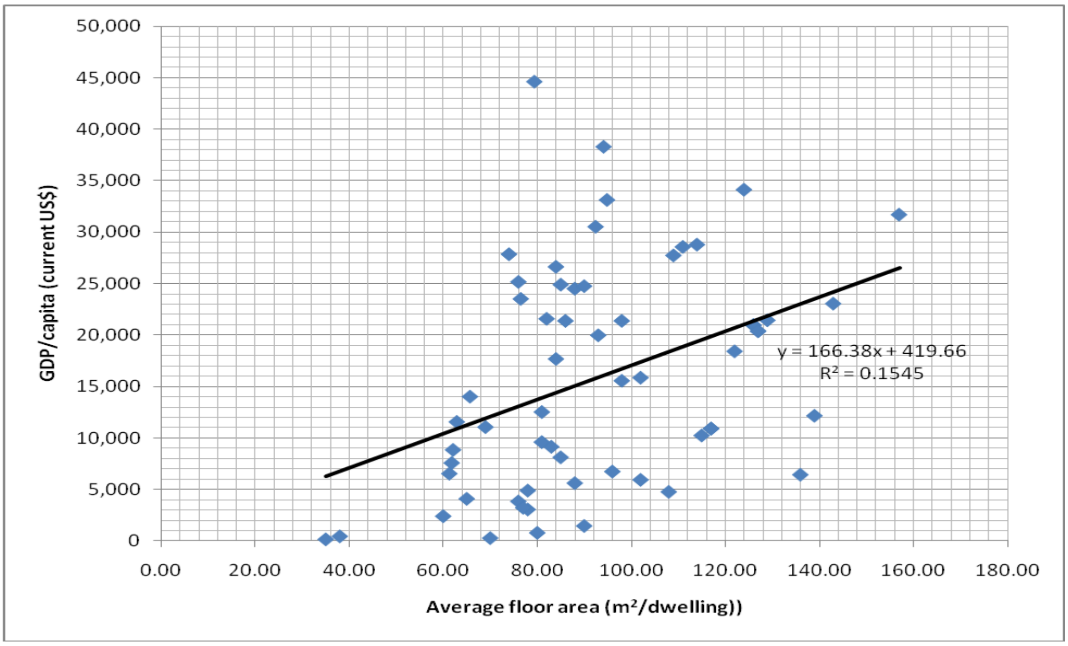

Figure 13: Probabilities for correlation between the average dwelling floor area (m²/dwelling) and GDP/capita.

Following this finding, the average floor area per dwelling for developed and developing countries were calculated according to their population (weighted average using 2010 population). As can be seen in the **Table 14** and **Table 15**, the average floor area per dwelling was estimated to be close to 120 m²/dwelling in 1998 for developed countries and 63 m²/dwelling in 2002 for developing countries.

Country	average floor area (m2/dwelling)	population	(population X floor area)
	1998	2010	
Australia	129.00	22,421,417	2,892,362,793
Canada	127.00	34,207,000	4,344,289,000
Denmark	108.00	5,540,241	598,346,028
France	88.00	65,447,374	5,759,368,912
Germany	84.00	81,757,600	6,867,638,400
Italy	98.00	60,340,328	5,913,352,144
Norway	124.00	4,896,700	607,190,800
Sweden	114.00	9,366,092	1,067,734,488
UK	85.00	62,041,708	5,273,545,180
US	157.00	309,975,000	48,666,075,000
Japan	93.00	127,380,000	11,846,340,000
Finland	76.00	5,366,100	407,823,600
TOTAL		**788,739,560**	**94,244,066,345**
weighted average (average floor area in 1998) m^2/dwelling	**120**		

Table 14: Average floor area per dwelling for selected developed countries in 1998.

Country	average floor area (m2/dwelling)	population	(population X floor area)
	2002	2010	
China	85.00	1,339,190,000	113,831,150,000
India	38.00	1,184,639,000	45,016,282,000
TOTAL		**2,523,829,000**	**158,847,432,000**
weighted average (average floor area in 2002) m^2/dwelling	**63**		

Table 15: Average floor area per dwelling for China and India (developing countries) in 2002.

Similarly the average floor area per dwelling for the world was calculated using a population weighted average give result 78 m²/dwelling in 2010 **(see Figure 27).** As mentioned in Chapter 2 (Background), an average floor area per dwelling is increasing over time. The reason for this is likely to be increasing wealth, thus existing average floor area per dwelling data for each countries indicated in **Table 13** were plotted against its GDP/capita data **(World Bank, 2010**) to investigate the correlation between these data. **Figure 14 to Figure 26** show the probabilities for correlation between an average floor area per dwelling and GDP/capita for selected countries in the world as indicated in **Table 13**. Note that the data for West Germany was not plotted due to data unavailability on GDP/capita in World Bank. Germany and India were also not plotted due to insufficient data on an average dwellings floor area.

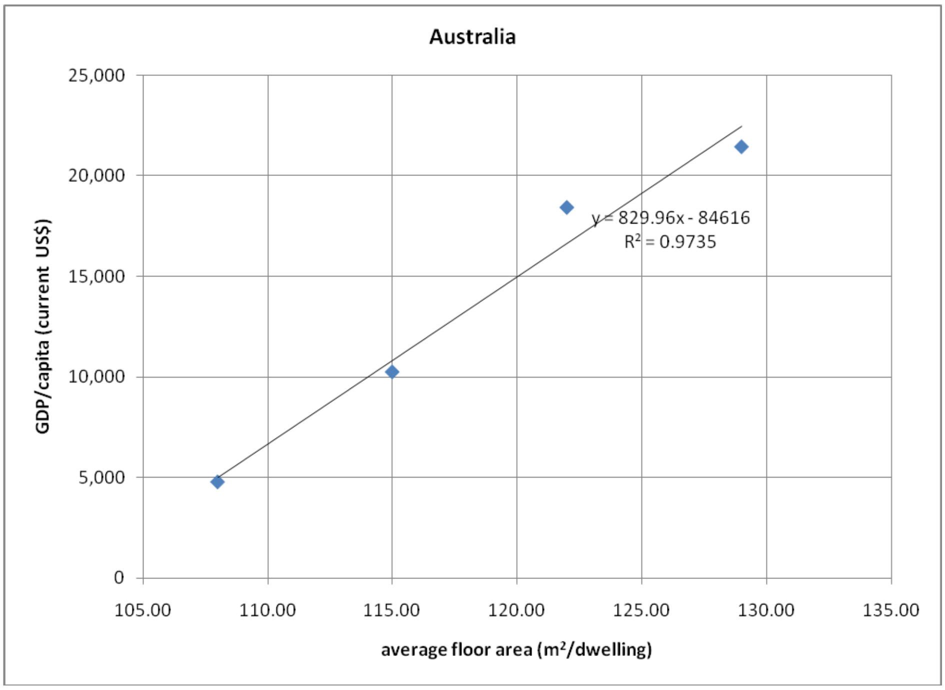

Figure 14: Probabilities for correlation between an average floor area per dwelling and GDP/capita (Australia).

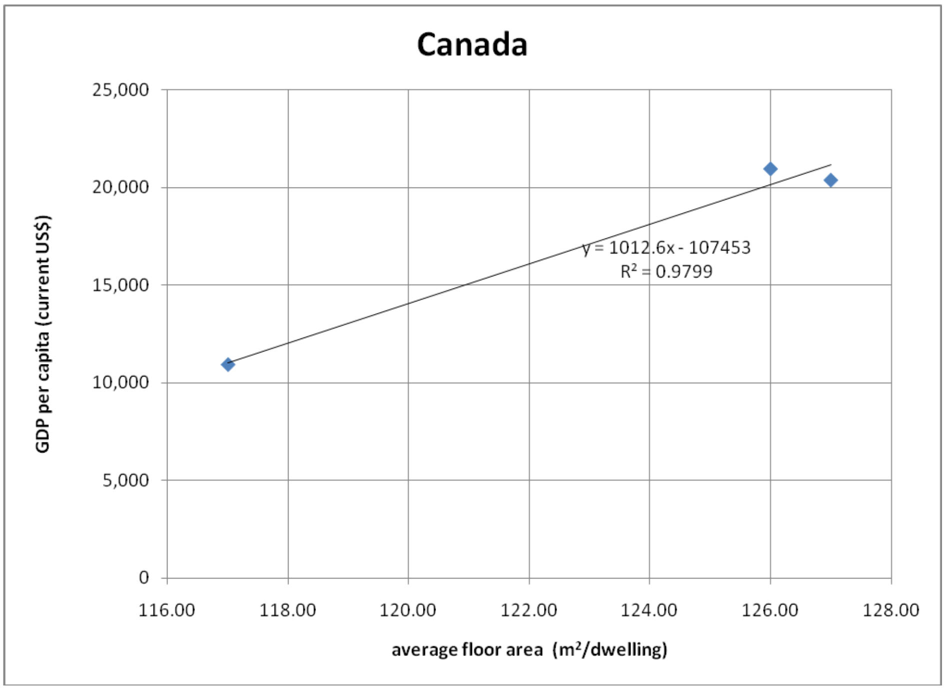

Figure 15: Probabilities for correlation between an average floor area per dwelling and GDP/capita (Canada).

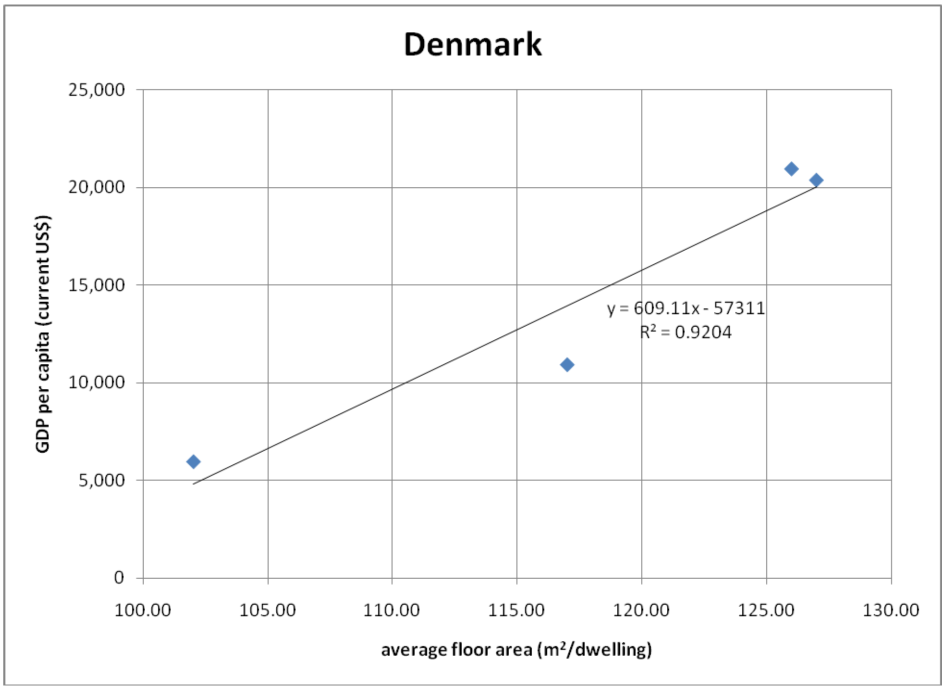

Figure 16: Probabilities for correlation between an average floor area per dwelling and GDP/capita (Denmark).

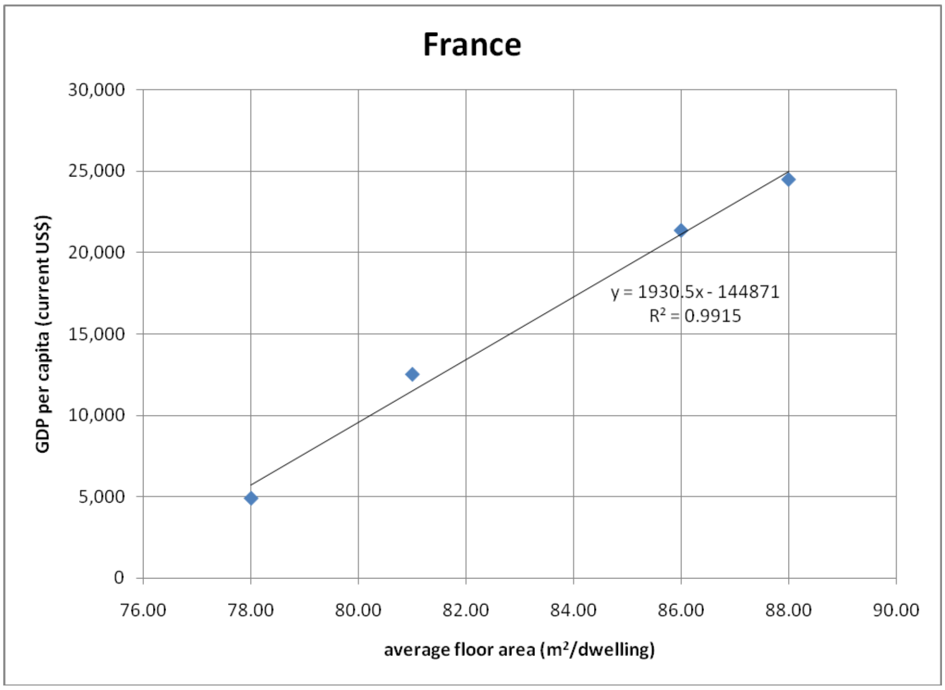

Figure 17: Probabilities for correlation between an average floor area per dwelling and GDP/capita (France).

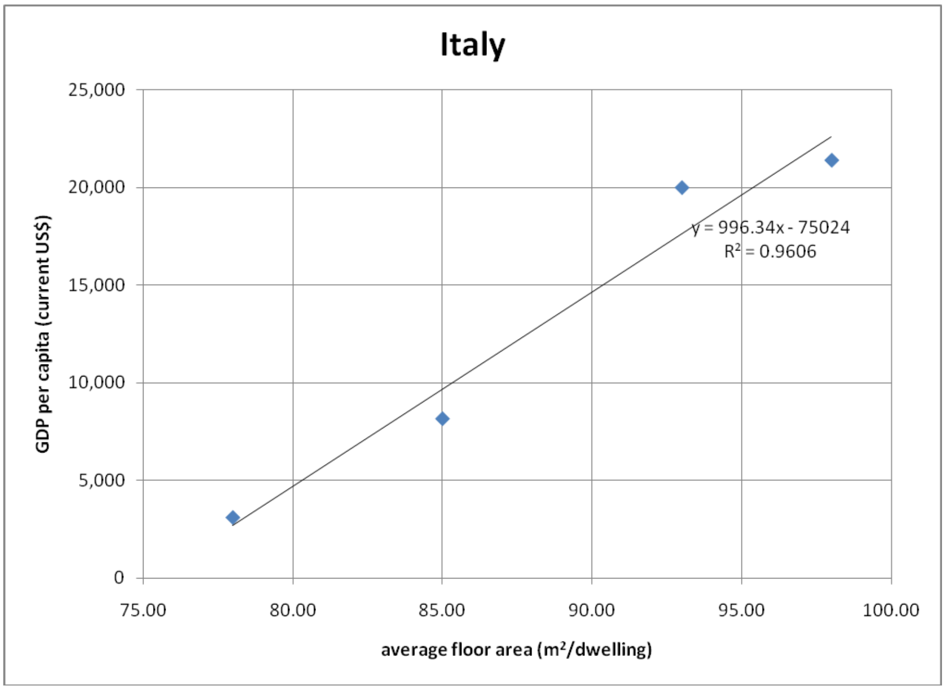

Figure 18: Probabilities for correlation between an average floor area per dwelling and GDP/capita (Italy).

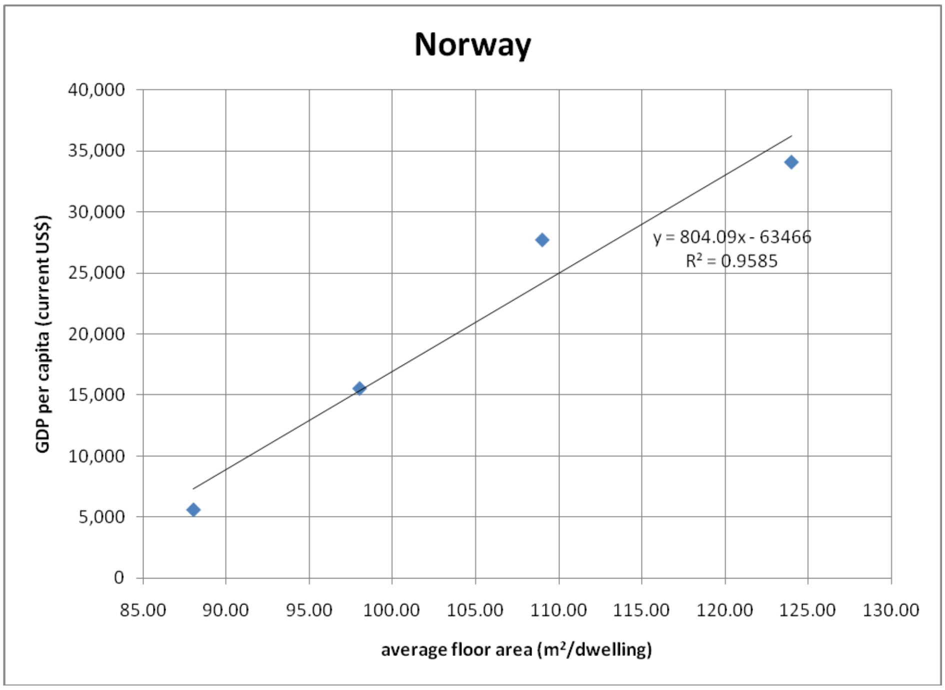

Figure 19: Probabilities for correlation between an average floor area per dwelling and GDP/capita (Norway).

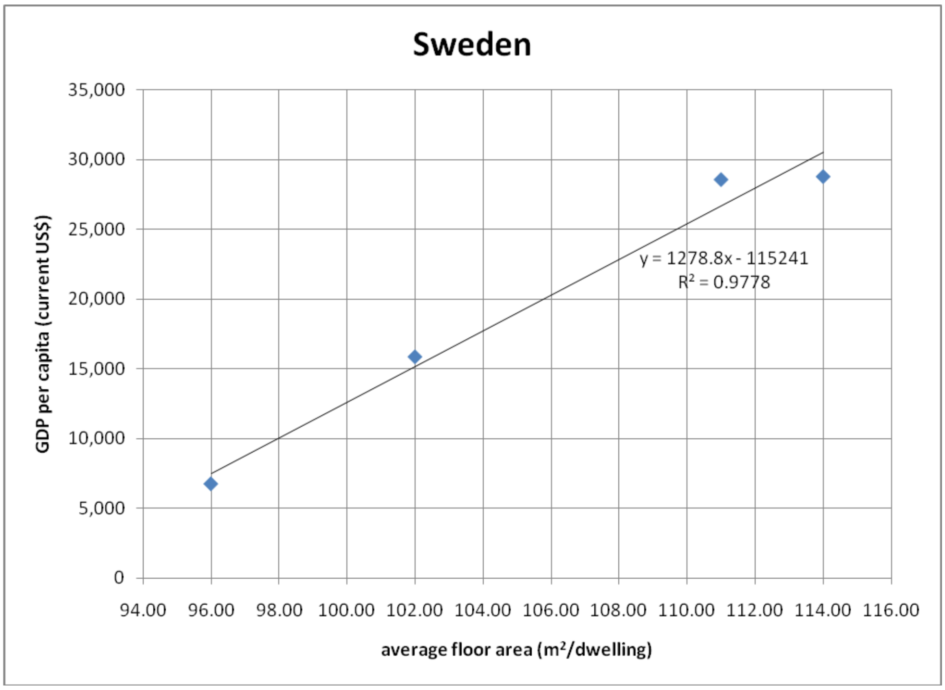

Figure 20: Probabilities for correlation between an average floor area per dwelling and GDP/capita (Sweden).

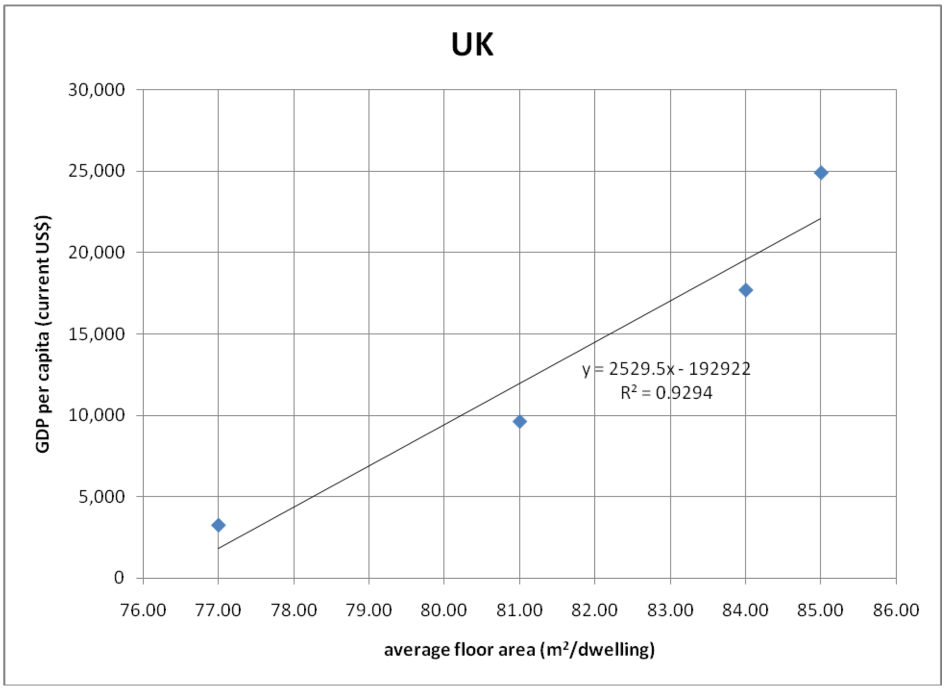

Figure 21: Probabilities for correlation between an average floor area per dwelling and GDP/capita (UK).

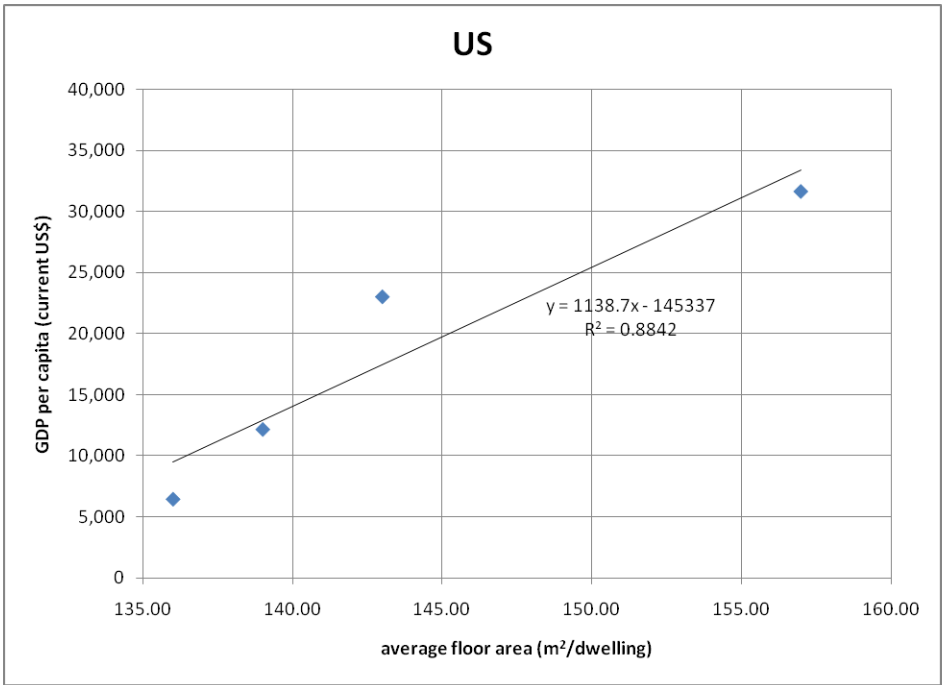

Figure 22: Probabilities for correlation between an average floor area per dwelling and GDP/capita (US).

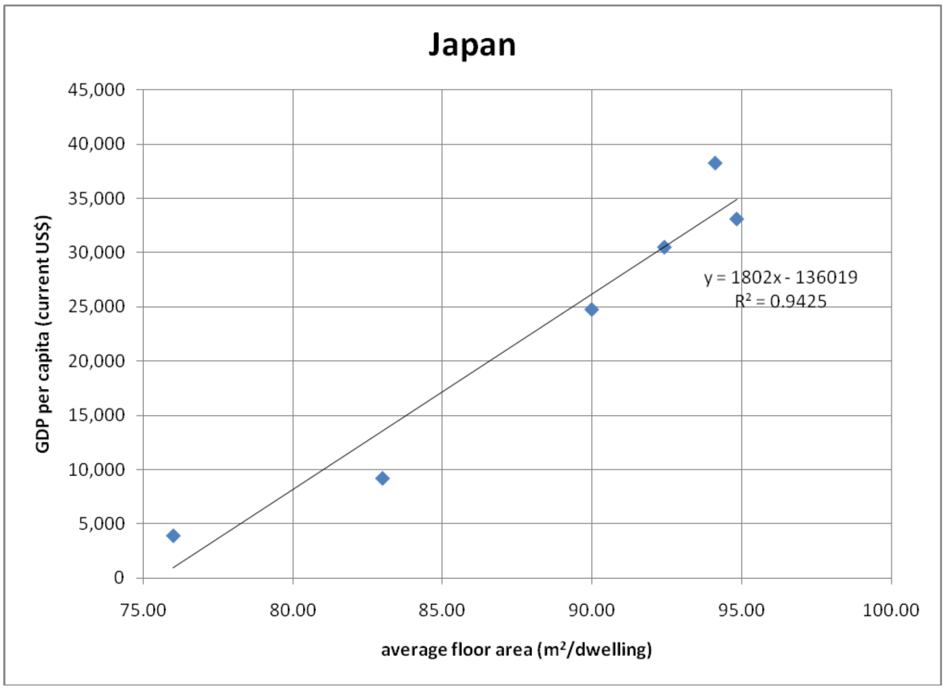

Figure 23: Probabilities for correlation between an average floor area per dwelling and GDP/capita (Japan).

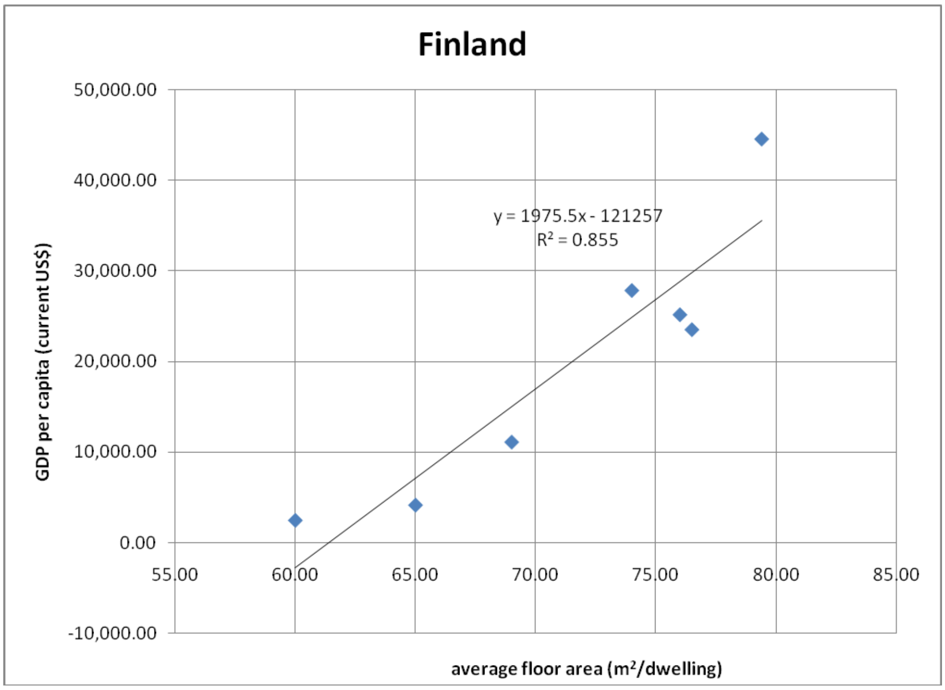

Figure 24: Probabilities for correlation between an average floor area per dwelling and GDP/capita (Finland).

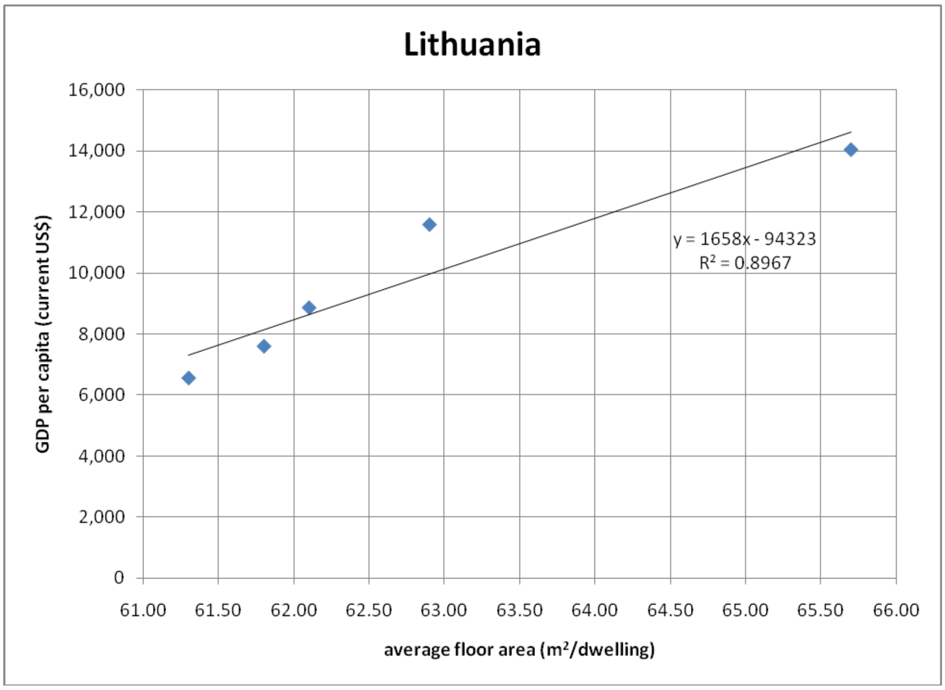

Figure 25: Probabilities for correlation between an average floor area per dwelling and GDP/capita (Lithuania).

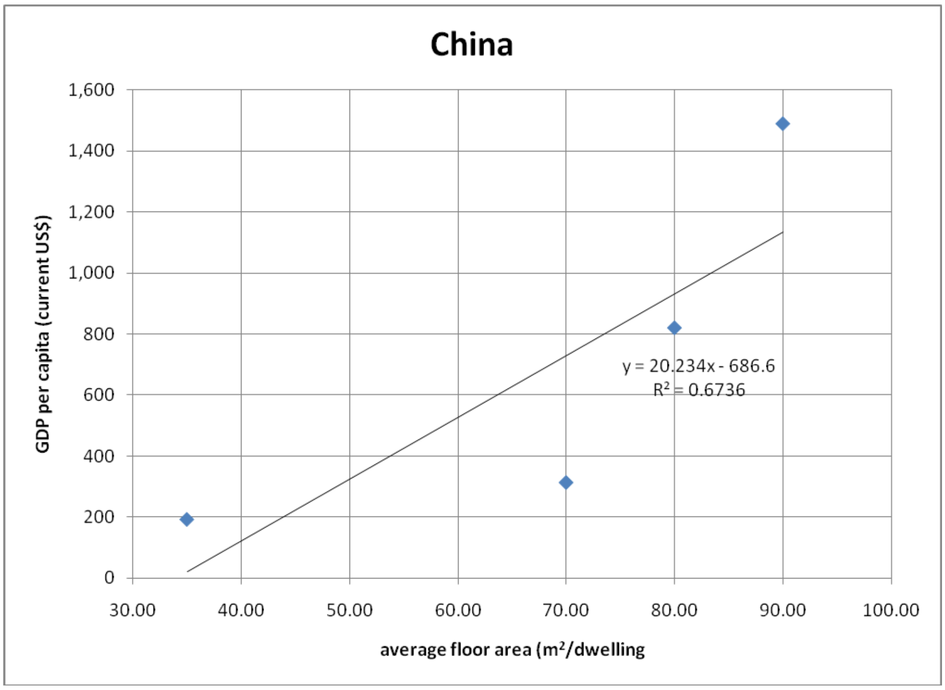

Figure 26: Probabilities for correlation between an average floor area per dwelling and GDP/capita (China).

Using the Table of Probabilities for Correlation Coefficients **(see Appendix A),** the probability of correlation between an average floor area per dwelling and GDP/capita data was determined and **Table 16** below summarizes the results obtained for every country as plotted in **Figures 14 to Figure 26.**

Country	Number of data (N)	R^2	R (Ro)	Probability correlated (%)
Australia	4	0.9735	0.99	**99.0**
Canada	3	0.9799	0.99	**97.1**
Denmark	4	0.9204	0.96	**96.0**
France	4	0.9915	0.99	**99.0**
Italy	4	0.9606	0.98	**98.0**
Norway	4	0.9585	0.98	**98.0**
Sweden	4	0.9778	0.99	**99.0**
UK	4	0.9294	0.96	**96.0**
US	4	0.8842	0.94	**94.0**
Japan	6	0.9425	0.97	**99.6**
Finland	7	0.855	0.92	**99.5**
Lithuania	5	0.8967	0.95	**98.2**
China	4	0.6736	0.82	**82.0**

Table 16: Probability of correlation between an average floor area per dwelling and GDP/capita data for selected countries in the world.

From **Table 16**, it can be seen that country with the highest percentage of correlation was Japan with 99.6% and the lowest was China with 82%. Overall, however, it can be seen that the correlation between existing dwellings average floor area data and GDP/capita data is highly significant. Following this finding, an average floor area per dwelling rate of change p.a. to 1% change in GDP/capita was then calculated. **Table 17** shows the result for average floor area per dwelling rate of change p.a. to 1% change in GDP/capita.

Country	Average dwellings floor area rate of change p.a. to 1% change in GDP/Capita (%)
Australia	0.06
Canada	0.10
Denmark	0.08
France	0.04
Italy	0.06
Norway	0.11
Sweden	0.08
UK	0.03
US	0.08
Japan	0.07
Finland	0.11
Lithuania	0.08
China	0.15

Table 17: Average floor area per dwelling rate of change p.a. to 1% change in GDP/capita.

It can be seen that the minimum and maximum value of an average floor area per dwelling rate of change p.a. to 1% change in GDP/capita were around 0.03% and 0.15% respectively. Thus, the best estimate of an average floor area per dwelling rate of change p.a. to 1% change of GDP/capita was around 0.09%.

Range	Average floor area per dwelling rate of change p.a. to 1% change in GDP/capita
Maximum	0.15%
Best estimate	0.09%
Minimum	0.03%

Table 18: Values range on an average floor area per dwelling rate of change p.a. to 1% change in GDP/capita.

In order to identify the changes in average floor area per dwelling over time, the GDP/capita rate of change p.a. was calculated for each country in the world. With GDP/capita rate of change p.a. data, an average floor area per dwelling rate of change p.a. for each country in the world was computed. Once an average floor area per dwelling rate of change p.a. for each country in the world was obtained, the changes of an average floor area per dwelling over time was calculated. **Figure 27** below shows the changes of dwellings average floor area for the world as a function of time according to a maximum, best estimate and minimum average floor area per dwelling rate of change to 1% change in GDP/capita as indicated in **Table 18.**

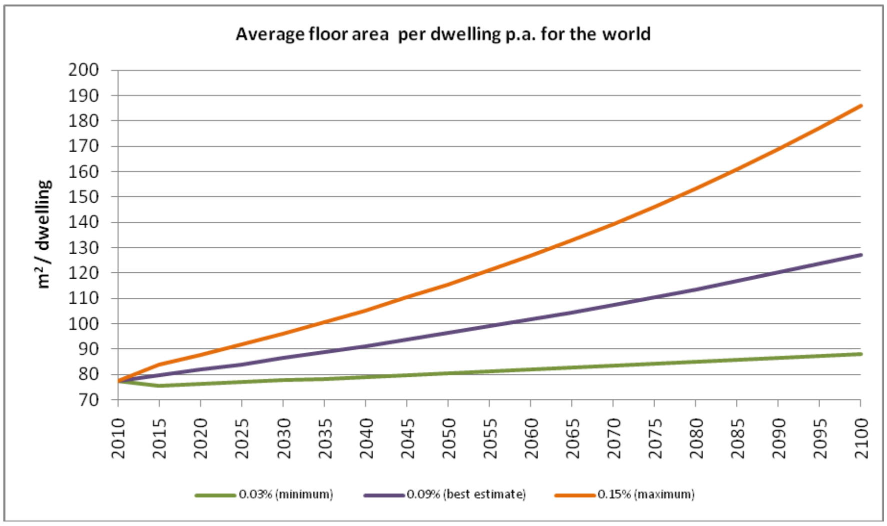

Figure 27: Average floor area per dwelling for 0.15% (maximum), 0.09% (best estimate) and 0.03% (minimum) average floor area per dwelling rate of change to 1% change in GDP/capita.

Note that, the result for the world average change in floor area per dwelling p.a., for the best estimate value (0.09% change in an average floor area per dwelling to 1% change in GDP/capita) will be used to estimate the total dwelling floor area for the world. Thus, from the result on the average floor area per dwelling (based on the best estimate value) and the result on the projection of the total number of dwelling in the world as obtained in Section 4.2, the projection for the total dwellings floor area for the world was estimated.

4.3.1 Total dwellings floor area for the world (2010 to 2100)

Data for the total dwelling floor area for the world from the year 2010 to 2100 are displayed in **Figure 28** for 0.09% (best estimate) change in dwellings average floor area to 1% change in GDP/capita.

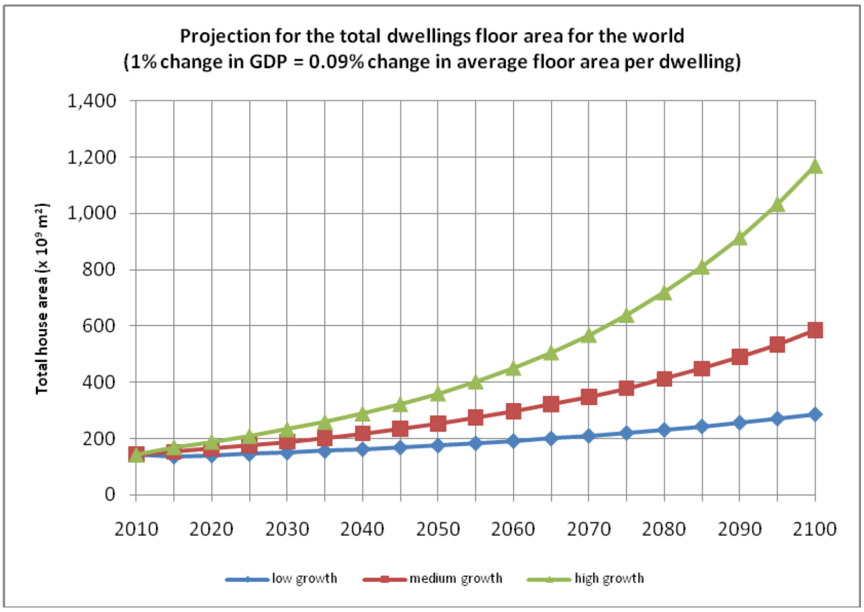

Figure 28: Projection for the total dwellings floor area for the world for 0.09% (best estimate) change in dwellings average floor area to 1% change in GDP/capita.

4.3.2 Total new dwellings floor area for the world (2010 to 2100)

Data for the total new dwellings floor area for the world from the year 2010 to 2100 are displayed in **Figure 29** for 0.09% (best estimate) change in dwellings average floor area to 1% change in GDP/capita accordingly.

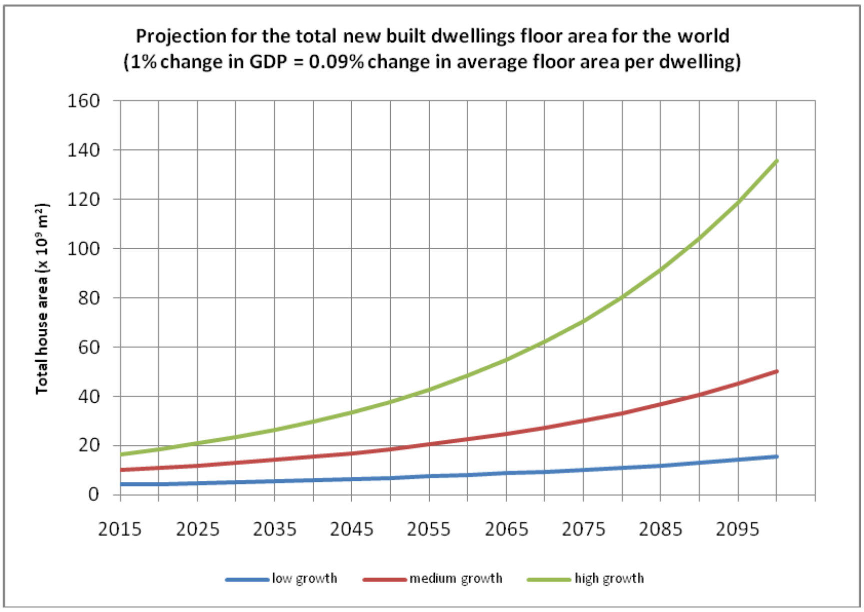

Figure 29: Projection for the total new built dwellings floor area for the world for 0.09% (best estimate) change in dwellings average floor area to 1% change in GDP/capita.

4.4 STAGE THREE: OPERATING ENERGY (OE), INITIAL EMBODIED ENERGY (IEE), AND RECURRING EMBODIED ENERGY (REE).

This section presents an **average value of operating energy (OE) per annum, initial embodied energy (IEE) and recurring embodied energy (REE) per annum** for conventional residential dwelling and energy efficient residential dwelling in terms of kWh/m^2. The recurring embodied energy per annum (REE) is taken as the energy cost per annum of maintaining the initial embodied energy (i.e. maintenance on the dwelling).

<u>Conventional dwelling</u>

As mentioned in Chapter 3 (Methodology), it was not feasible to find these data for every country in the world; a set of assumptions for the maximum and minimum values for the of OE for conventional dwelling in developed and developing countries was made considering the range of values obtained from the literature review **(Table 19).** However, assumptions for IEE was made only for the world since the embodied energy to construct a dwelling anywhere in the world would be approximately the same per square meter.

In the case of REE, the rate of its usage was calculated as a percentage of the value of IEE. **Table 19** below shows the gathered data from the literature review for OE, IEE and REE for conventional dwellings. In addition, the table also shows the REE rate of usage (%) to the value of IEE.

country	operating energy (OE)		initial embodied energy (IEE)	recurring embodied energy (REE)	% of REE to IEE	source
	kWh/dwelling/yr	kWh/m^2/yr	kWh/m^2	kWh/m^2/yr		
New Zealand	11,406.00	80.00				BRANZ (2010)
New Zealand			500.00	7.29	1.46%	Mithraratne & Vale (2004)
Malaysia	6,980.10	38.78 (only electricity)				Tang (2005)
US		147.00				Perez-Lombard et al. (2008)
China	8,389.00	94.00				Tonooka et al. (2003)
Germany		182.00	1,171.00	4.96	0.42%	Feist (1997)
Norway	18,500.00	168.00	333.75	2.23	0.67%	Winther & Hestnes (1999)
Sweden		141.00	1,020.00	7.80	0.76%	Adalberth (1997b)
		148.00	980.00	7.40	0.76%	
		128.00	810.00	6.60	0.81%	
Sweden			775.00			Gustavsson & Joelsson (2010)
		54.00 (only space heating)	647.00			
Sweden		160.00				Wall (2006)
Indonesia			230.00			Utama & Gheewala (2008)
Scotland			450.00			Asif et al. (2007)
Japan		233.00				Saitoh & Fujino (2001)
Canada		123.00				Leckner & Zmeureanu (2011)
Canada			1,397.00			Canadian Wood Council (2004)
			1,764.00			
			2,189.00			
OECD		150-230				Balaras et al. (2007)
Central & Eastern Europe		250-400				
Scandinavia		120-150				
Switzerland		137.00				Pfeiffer et al. (2005)
India		93.50	555.00			Chel & Tiwari (2009)
-			1,529.00			Dixit et al. (2010)
Hong Kong			1,819.00	3.33	0.18%	Chen et al. (2001)
			1,756.00	3.96	0.23%	

Table 19: OE, IEE and REE of conventional housing for selected countries.

Table 20 shows the assumptions for maximum, minimum and best estimate value of OE and IEE for conventional dwellings in developed countries. However, for developing countries 90 kWh/m^2 is given as the best estimate value based from **Table 19**. Besides, the REE for conventional dwellings was ascertained to be around 0.6% p.a. of its IEE value.

Conventional Dwelling	kWh/m^2			
	OE p.a. (developed)	OE p.a. (developing)	IEE	REE
Max	250	-	1000	0.6% p.a. of IEE
Best estimate	175	90	750	
Min	100	-	500	

Table 20: OE, IEE and REE for conventional dwelling.

Energy efficient dwelling

An OE for an energy efficient dwelling was computed according to the classifications as listed in Chapter 3 (Section 3.1). As for the value of IEE for energy efficient dwelling, the rate of change of IEE to the rate of change of OE from converting conventional dwelling to energy efficient dwelling was considered. **Table 21** shows the result of percentage increase in IEE to 1% decrease in OE. From these findings in the literature, it was deduced that the operating energy of an energy efficient dwelling will increase by about 1% for an increase of about 0.5% in IEE.

country	conventional dwelling		energy efficient dwelling		% increase in IEE to 1% decrease in OE	source
	OE	IEE	OE	IEE		
	$kWh/m^2/yr$	kWh/m^2	$kWh/m^2/yr$	kWh/m^2		
NZ	22.86 **(space heating)**	500.00	12.33 **(space heating)**	667.00	0.72%	Mithraratne & Vale (2004)
Germany	182.00	1,171.00	120.00	1,220.00	0.11%	Feist (1997)
			30.00	1,391.00	0.23%	
Norway	168.00	333.75	125.00	441.00	1.25%	Winther & Hestnes (1999)
			131.82	406.00	1.00%	
Sweden	54.00	647.00	26.00	656.00	0.03%	Gustavsson & Joelsson (2009)
Canada	123.00	992.00	67.00	1,238.00	0.54%	Leckner & Zmeureanu (2011)
India	93.50	555.00	58.50	639.00	0.40%	Chel & Tiwari (2009)

Table 21: Percentage increase in IEE for a 1% decrease in OE for energy efficient dwellings.

In the case of REE, the rate of its usage was calculated as a percentage of the value of IEE for energy efficient dwellings, the same case for conventional dwellings. Thus, **Table 22** summarizes the percentage rate of the OE, IEE and REE for 3 types of energy efficient dwellings used in this thesis.

Energy Efficient Dwelling	kWh/m^2		
	OE	IEE	REE
1	20% reductions from conventional dwelling	1% decreased in OE = 0.5% increase in IEE	0.6% of IEE
2	50% reductions from conventional dwelling		
3	80% reductions from conventional dwelling		

Table 22: Summary of percentage rate for the OE, IEE and REE for 3 types of energy efficient dwellings.

However, the IEE of a conventional dwelling being retrofitted to be an energy efficient dwelling would not be equal to the IEE to build a new energy efficient dwelling. Therefore, the difference between IEE for a conventional dwelling and IEE for an energy efficient dwelling was considered to be the IEE for the change of a conventional dwelling to be retrofitted as an energy efficient dwelling.

Table 23 below shows the set of OE, IEE and REE for conventional dwelling and 3 types of energy efficient dwelling used in this thesis according to the best estimate value obtained for conventional dwelling (shaded boxes). These values will be used to analyze the total energy consumption in the residential sector for the world in the next section.

	kWh/m^2				
	OE (developed)	**OE (developing)**	**IEE**	**IEE (retrofits)**	**REE**
Conventional dwelling	175	90	750	-	4.50
Energy efficient dwelling 1 (EED 1) - 20% reductions in OE	140	72	825	75	4.95
Energy efficient dwelling 2 (EED 2) - 50% reductions in OE	88	45	938	188	5.63
Energy efficient dwelling 3 (EED 3) - 80% reductions in OE	35	18	1050	300	6.30

Table 23: A set of OE, IEE and REE for conventional and energy efficient dwelling based on the Best Estimate Value obtained for conventional dwellings.

4.5 STAGE FOUR: TOTAL ENERGY CONSUMPTION IN THE RESIDENTIAL SECTOR AS A FUNCTION OF TIME.

This section presents the total residential energy consumption for the world as a function of time and the potential energy savings by building energy efficient dwellings. A simulation model built using Excel Spreadsheet was used to simulate the future growth of world energy consumption in residential sector according to the four (4) scenarios as outlined in Chapter 3 (Section 3.5). Best Estimate values obtained in Section 4.3 and Section 4.4 were considered in order to analyze the total residential energy consumption for the world. The future growth of the total energy consumption in the residential sector according to the Business as Usual (BAU) scenario (Scenario 1) considering high, medium and low growth rate of the total number dwellings in the world is shown in **Figure 30.**

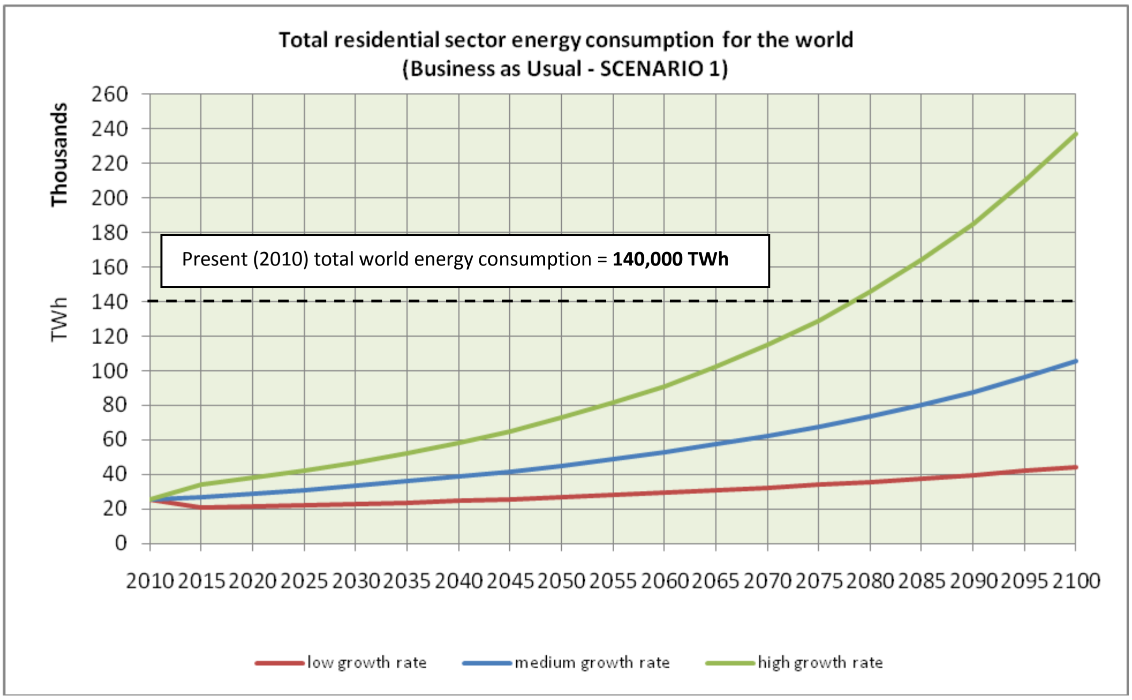

Figure 30: Residential sector total energy consumption future growth as a function of time according for BAU and for high, medium and low growth rates.

This total energy consumption for residential sector as shown in **Figure 30** above includes operating energy, initial embodied energy and recurring embodied energy, this will the same case as the result on the total energy in the following sections. It was estimated that the total present (2010) total energy consumption for the residential sector for the world to be around 25,100 TWh (90 EJ). According to BP (British Petroleum) Statistical Review of World Energy 2011 **(BP, 2011),** total world energy consumption in 2010 was around 12,000 Million tonnes oil equivalent (Mtoe) which is equivalent to 140,000 TWh (marked with black dotted line in **Figure 30**) or 504 EJ (using conversion factor of 1 toe = 42 GJ). Thus, the world residential energy consumption was estimated to around 18% of total world energy consumption in 2010.

In the following results, a set percentage of new built dwellings being built as energy efficient dwellings every year and a set percentage of existing dwellings being retrofitted as energy efficient dwellings every year have been considered for scenarios 2, 3 and 4.

4.5.1 Best estimate values, 10% new built dwellings being built as energy efficient dwelling each year and 0.5% existing dwellings being retrofitted as energy efficient dwelling each year.

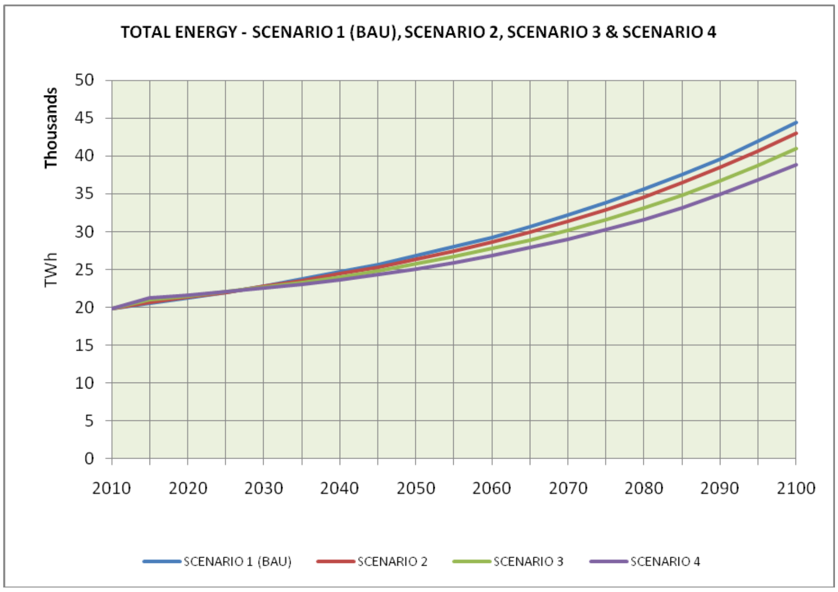

Figure 31: Total energy (low growth rate, 10% energy efficient for new builts p.a. & 0.5% retrofits for existing p.a.).

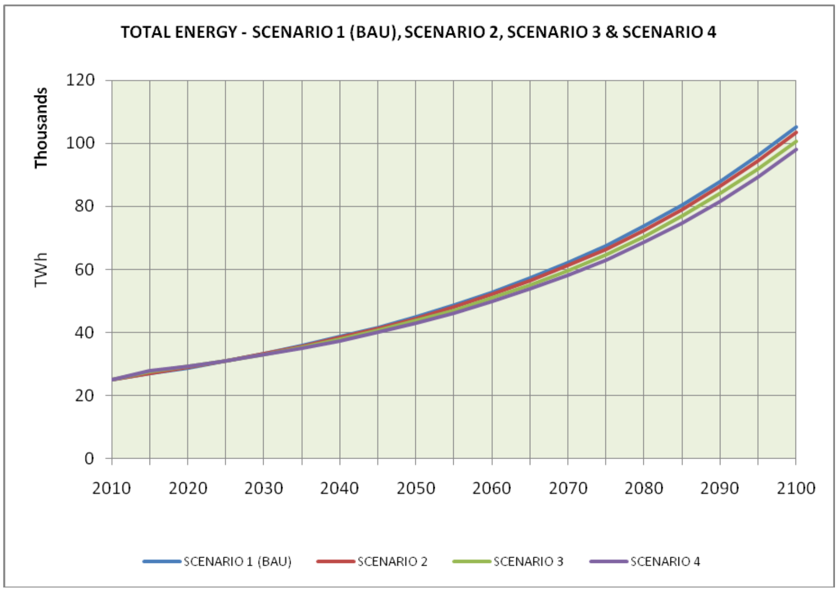

Figure 32: Total energy (medium growth rate, 10% energy efficient for new builts p.a. & 0.5% retrofits for existing p.a.).

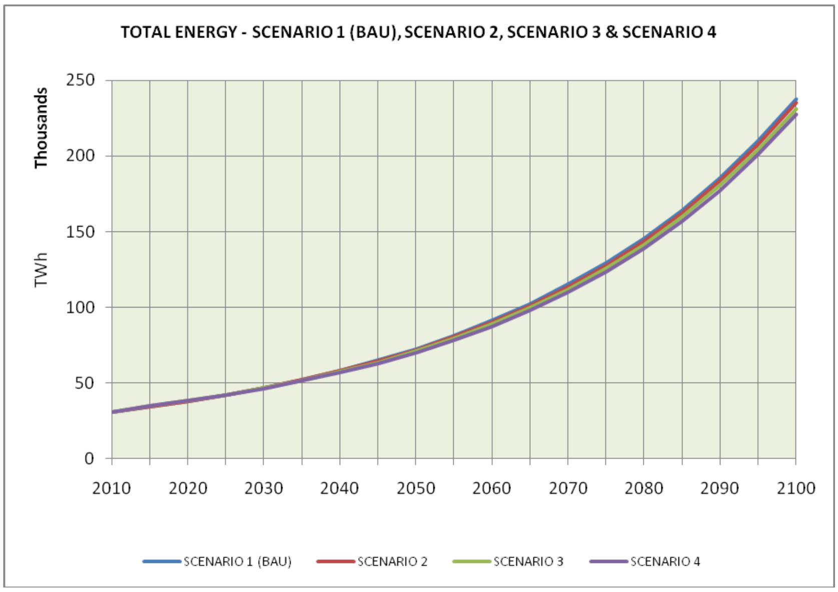

Figure 33: Total energy (high growth rate, 10% energy efficient for new builts p.a. & 0.5% retrofits for existing p.a.).

Based on the **Figures 31, 32 and 33** for low, medium and high growth rates respectively, the difference (savings) between the total energy for scenarios 2, 3 and 4 against the total energy for BAU scenario were not significant, if 10% new built dwellings being built as energy efficient dwelling and 0.5% existing dwellings being retrofitted as energy efficient dwellings were considered. Therefore, higher penetration rates for both new built and existing dwellings would be considered and these cases will be presented in the following sections.

4.5.2 Best estimate values, 50% new built dwellings being built as energy efficient dwelling each year and 1% existing dwellings being retrofitted as energy efficient dwelling each year.

As can be seen from **Figure 34**, the operating energy for scenarios 2, 3 and 4 was lower than BAU scenario and the difference increased over time. This means the savings in the operating energy for scenarios 2, 3 and 4 against BAU scenario inceased over time. This result would be expected since the operating energy of energy efficient dwellings considered in scenarios 2, 3 and 4 were 20%, 50% and 80% respecively less than the operating energy of conventional dwelling considered in BAU scenario.

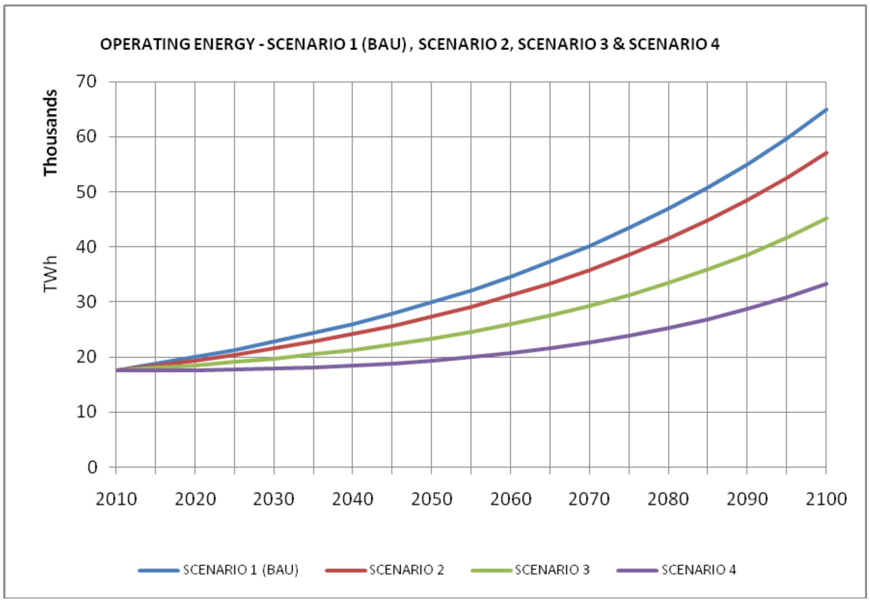

Figure 34: Operating energy (medium growth rate, 50% energy efficient for new builts p.a. & 1% retrofits for existing p.a.).

From **Figure 35 and Figure 36**, the initial embodied energy and recurring embodied energy for scenarios 2, 3 and 4 is seen to be higher than BAU scenario. Over time, the differences slightly increased for both type of energy. These results also might be expected as when operating energy is decreased due to improved energy efficiency, the initial embodied energy is increased (see Chapter 2 – section 2.2.2), and in addition, the upkeep of the energy efficient dwellings will incur a slightly higher recurring energy.

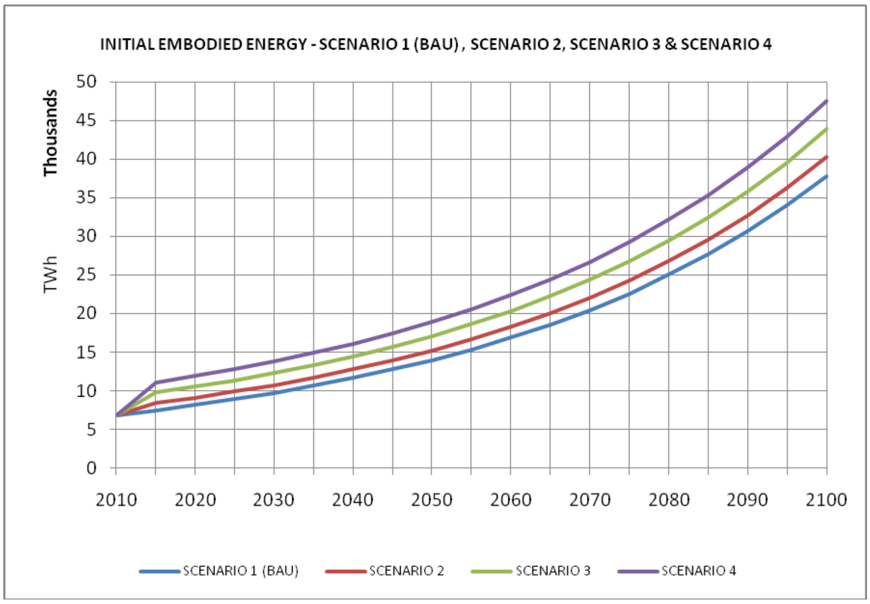

Figure 35: Initial embodied energy (medium growth rate, 50% energy efficient for new builts p.a. & 1% retrofits for existing p.a.).

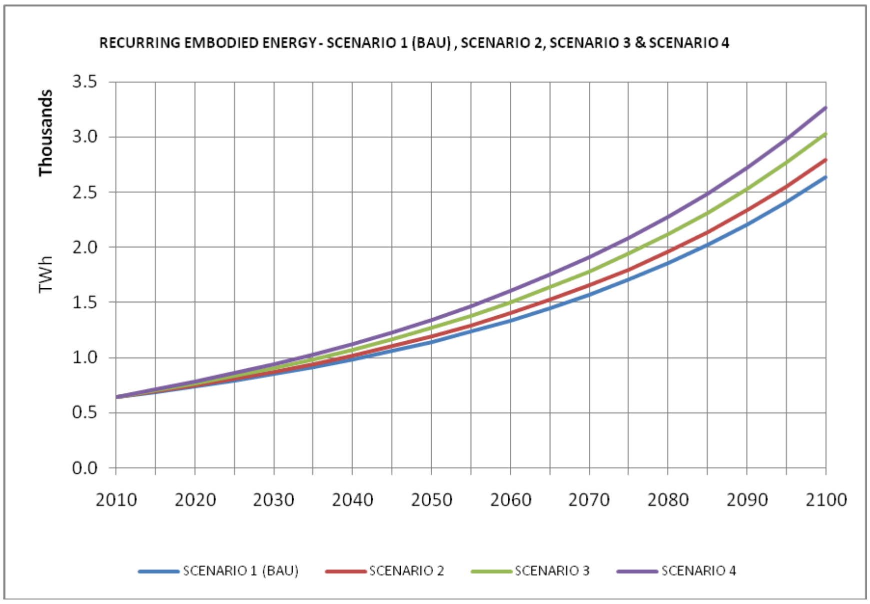

Figure 36: Recurring embodied energy (medium growth rate, 50% energy efficient for new builts p.a. & 1% retrofits for existing p.a.).

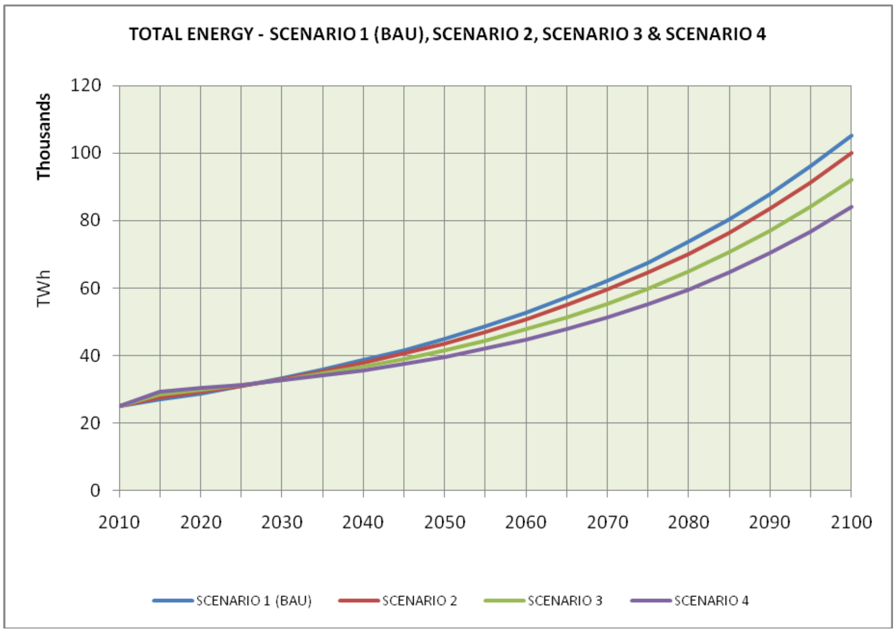

Figure 37: Total energy (medium growth rate, 50% energy efficient for new builts p.a. & 1% retrofits for existing p.a.).

Adding the above componets together, it can be seen in **Figure 37** that over time the total energy consumption for the residential sector for scenarios 2, 3 and 4 are lower than the BAU scenario. The savings in the operating energy overcome their higher value in the initial embodied energy and recurring embodied energy. This savings is clearly shown in **Figure 38** which shows the percentage total energy savings for scenrios 2, 3 and 4 against BAU scenario. However, it is interesting to note that there are no savings for the total energy for scenarios 2, 3 and 4 against BAU scenario until sometime the year of 2022.

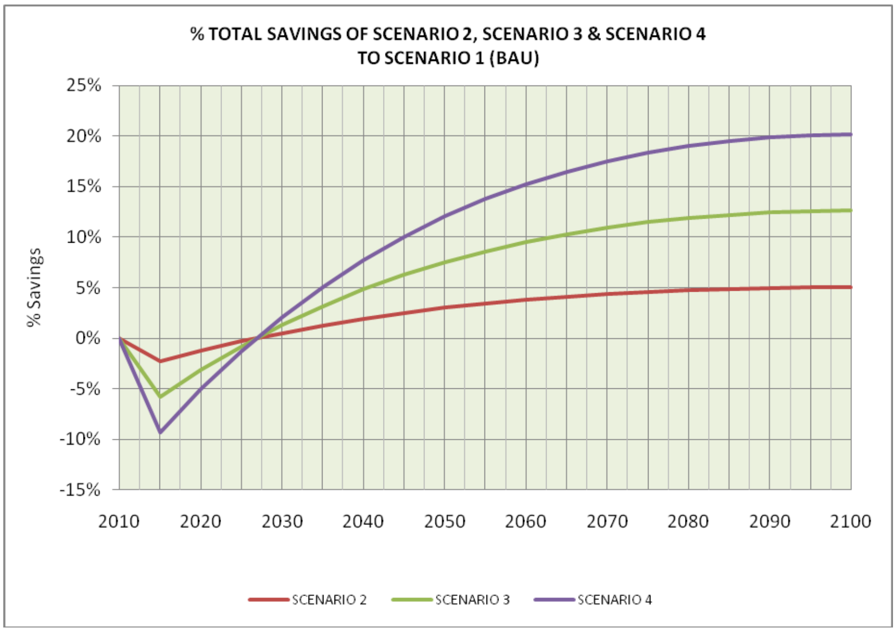

Figure 38: Percentage of total energy savings for scenarios 2, 3 and 4 against BAU scenario (medium growth rate, 50% energy efficient for new builts p.a. & 1% retrofits for existing p.a.).

Table 24 shows the percentage total energy savings for scenarios 2, 3 and 4 against the BAU scenario in 2050 and 2100 considering low, medium and high growth rates. It is clearly seen that the percentage savings are greater if a low growth rate of dwellings is used for each of scenarios 2, 3 and 4.

Growth rate	% of new built dwellings being built as EED each year	% of existing dwellings being retrofitted as EED each year	percentage savings in 2050 against BAU (Scenario 1)			percentage savings in 2100 against BAU (Scenario 1)		
			Scenario 2	Scenario 3	Scenario 4	Scenario 2	Scenario 3	Scenario 4
Low	50%	1%	3.56%	8.91%	14.26%	7.44%	18.59%	29.74%
Medium			3.01%	7.52%	12.04%	5.05%	12.62%	20.20%
High			2.50%	6.25%	8.46%	3.61%	9.04%	14.46%

Table 24: Percentage of total energy savings for scenarios 2, 3 and 4 against BAU scenario in 2050 and 2100 (50% energy efficient for new builts p.a. & 1% retrofits for existing p.a.).

Table 25 shows the percentage total energy increase for scenarios 2, 3 and 4 against against the present (2010) total world energy consumption and present (2010) total world residential sector energy consumption in 2100 considering low, medium and high growth rates. It is clearly seen that from **Table 21** that at no time do we get a decrease in world residential sector energy consumption in 2100 for scenarios 2, 3 and 4 against the present (2010) world residential sector energy consumption for low, medium and high growth rates. However, for low and medium growth rates for scenario 2, 3 and 4 the total world residential sector energy consumption in 2100 is below the present (2010) total world energy consumption.

Growth rate	% of new built dwellings being built as EED each year	% of existing dwellings being retrofitted as EED each year	percentage increase in 2100 against present (2010) total world energy consumption			percentage increase in 2100 against present (2010) total world residential sector energy consumption		
			Scenario 2	Scenario 3	Scenario 4	Scenario 2	Scenario 3	Scenario 4
Low	50%	1%	-71%	-74%	-78%	+64%	+44%	+24%
Medium			-29%	-34%	-40%	+298%	+266%	+234%
High			+64%	+54%	+45%	+811%	+760%	+709%

Table 25: Percentage increase of total energy for scenarios 2, 3 and 4 against the present (2010) total world energy consumption and present (2010) total world residential sector energy consumption in 2100 (50% energy efficient for new builts p.a. & 1% retrofits for existing p.a.).

4.5.3 Best estimate values, 100% new built dwellings being built as energy efficient dwelling each year and 1% existing dwellings being retrofitted as energy efficient dwelling each year.

It is apparent from **Figure 39 and Table 26** that by increasing the percentage of new built dwellings being built as energy efficient dwelling each year (in this case 100%), scenarios 2, 3 and 4 will have a greater total energy savings against the BAU scenario. Similar to the finding in the Section 4.5.2, the percentage savings is greater if the low growth rate for dwellings is being considered for each of scenarios 2, 3 and 4.

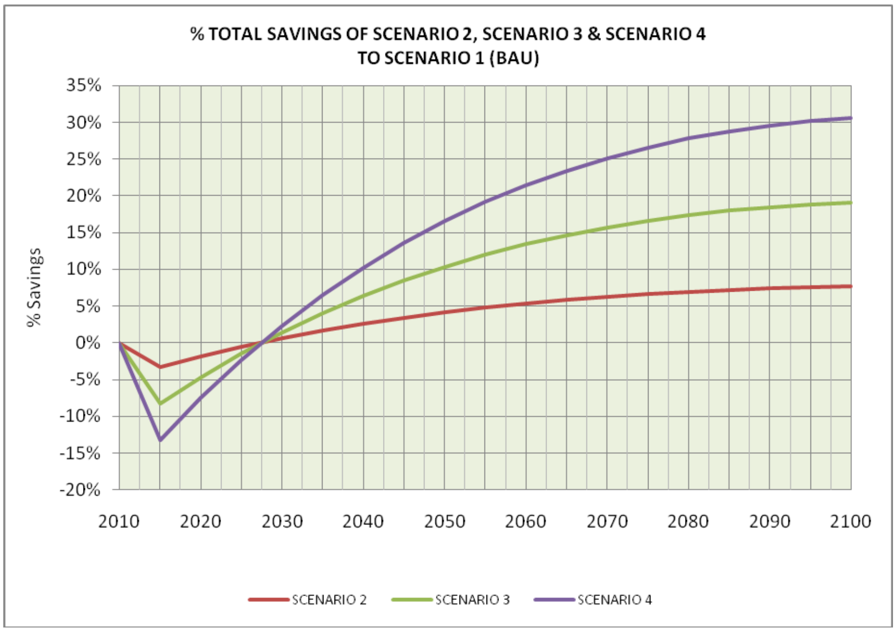

Figure 39: Percentage of total energy savings for scenarios 2, 3 and 4 against BAU scenario (medium growth rate, 100% energy efficient for new builts p.a. & 1% retrofits for existing p.a.).

Growth rate	% of new built dwellings being built as EED each year	% of existing dwellings being retrofitted as EED each year	percentage savings in 2050 against BAU (Scenario 1)			percentage savings in 2100 against BAU (Scenario 1)		
			Scenario 2	Scenario 3	Scenario 4	Scenario 2	Scenario 3	Scenario 4
Low	100%	1%	4.19%	10.47%	16.75%	9.47%	23.69%	37.90%
Medium			4.13%	10.34%	16.54%	7.65%	19.13%	30.60%
High			3.74%	9.36%	12.45%	6.06%	15.16%	24.25%

Table 26: Percentage of total energy savings for scenarios 2, 3 and 4 against BAU scenario in 2050 and 2100 (100% energy efficient for new builts p.a. & 1% retrofits for existing p.a.).

Table 27 shows the percentage total energy increase for scenarios 2, 3 and 4 against against the present (2010) total world energy consumption and present (2010) total world residential sector energy consumption in 2100 considering low, medium and high growth rates. It is clearly seen that from **Table 27** that at no time do we get a decrease in world residential sector energy consumption in 2100 for scenarios 2, 3 and 4 against the present (2010) world residential sector energy consumption for low, medium and high growth rates. However, for low and medium growth rates for scenario 2, 3 and 4 the total world residential sector energy consumption in 2100 is below the present (2010) total world energy consumption. These conditions is similar to results in Section 4.5.2.

Growth rate	% of new built dwellings being built as EED each year	% of existing dwellings being retrofitted as EED each year	percentage increase in 2100 against present (2010) total world energy consumption			percentage increase in 2100 against present (2010) total world residential sector energy consumption		
			Scenario 2	Scenario 3	Scenario 4	Scenario 2	Scenario 3	Scenario 4
Low	100%	1%	-71%	-76%	-80%	+60%	+35%	+10%
Medium			-31%	-39%	-48%	+287%	+239%	+191%
High			+59%	+44%	+29%	+788%	+702%	+616%

Table 27: Percentage increase of total energy for scenarios 2, 3 and 4 against present (2010) total world energy consumption and present (2010) total world residential sector energy consumption in 2100 (100% energy efficient for new builts p.a. & 1% retrofits for existing p.a.).

4.5.4 Best estimate values, 50% new built dwellings being built as energy efficient dwelling each year and 2% existing dwellings being retrofitted as energy efficient dwelling each year.

By increasing existing dwellings being retrofitted as energy efficient dwelling each year to 2% and keeping new built dwellings being built as energy efficient dwelling each year to 50% similar to that in Section 4.5.2, the operating energy for scenarios 2, 3 and 4 was found to be even lower than BAU scenario and the savings in their operating energy against BAU scenario was still increasing over time **(see Figure 40).** In scenario 4, it seen for the first time that there is a net reduction in total operating energy until 2060 by which time all existing dwellings have been upgraded and then the operating energy starts to increase again.

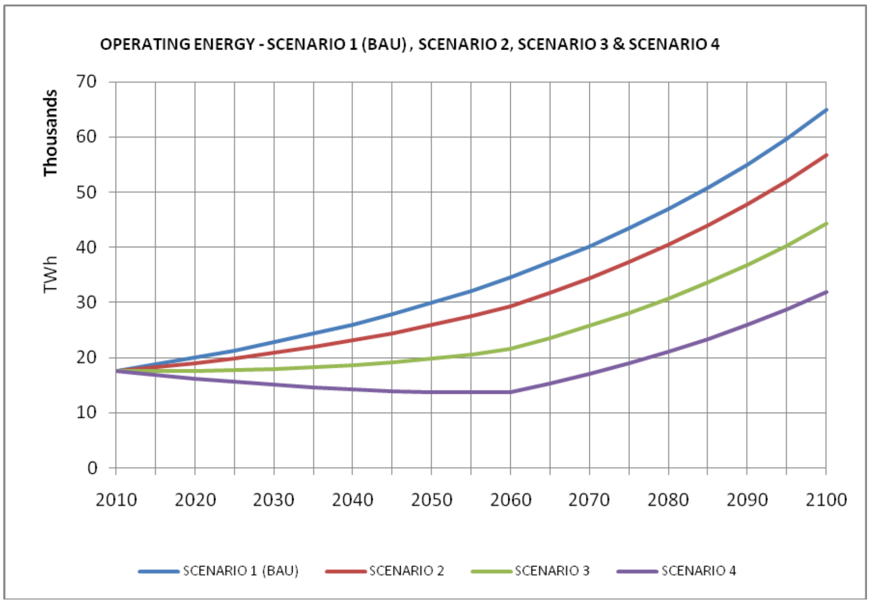

Figure 40: Operating energy (medium growth rate, 50% energy efficient for new builts p.a. & 2% retrofits for existing p.a.).

Based on the **Figure 41 and Figure 42**, as might be expected, the initial embodied energy and recurring embodied energy for scenarios 2, 3 and 4 was found to be higher than the BAU scenario. What is interesting in the result shown in **Figure 41** is that the difference between initial embodied energy for scenarios 2, 3, 4 and BAU scenario decreased starting from the year of 2060 to 2065. This is due to, with 2% p.a. existing dwellings being retrofitted as energy efficient dwellings, the retrofits work on existing dwellings will be completed in 2065. However, the initial embodied energy for scenarios 2, 3 and 4 in 2065 and beyond was still higher than the BAU scenario as expected.

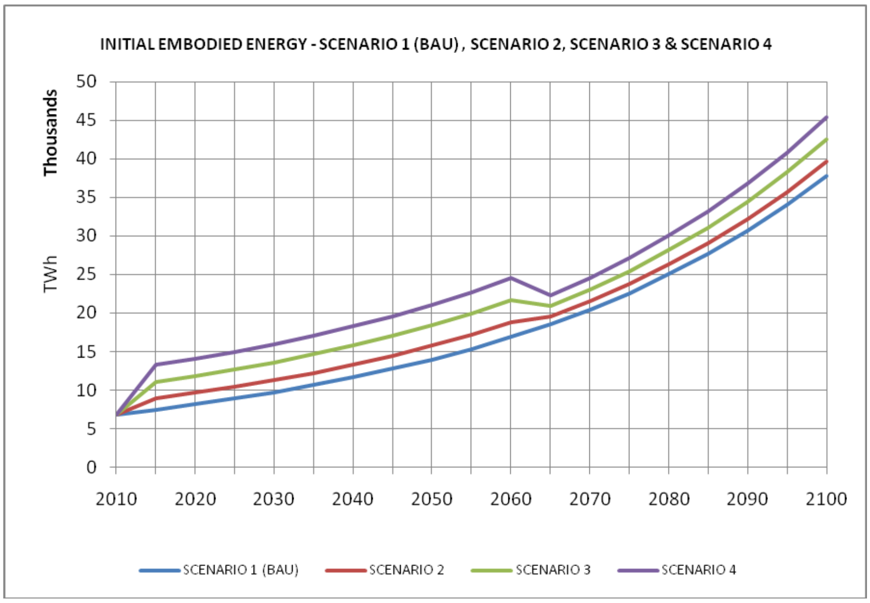

Figure 41: Initial embodied energy (medium growth rate, 50% energy efficient for new builts p.a. & 2% retrofits for existing p.a.).

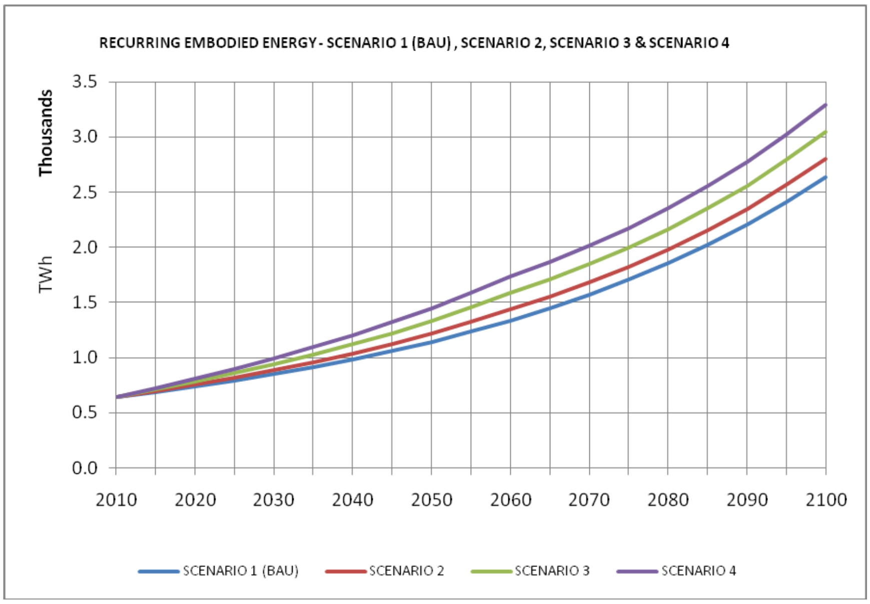

Figure 42: Recurring embodied energy (medium growth rate, 50% energy efficient for new builts p.a. & 2% retrofits for existing p.a.).

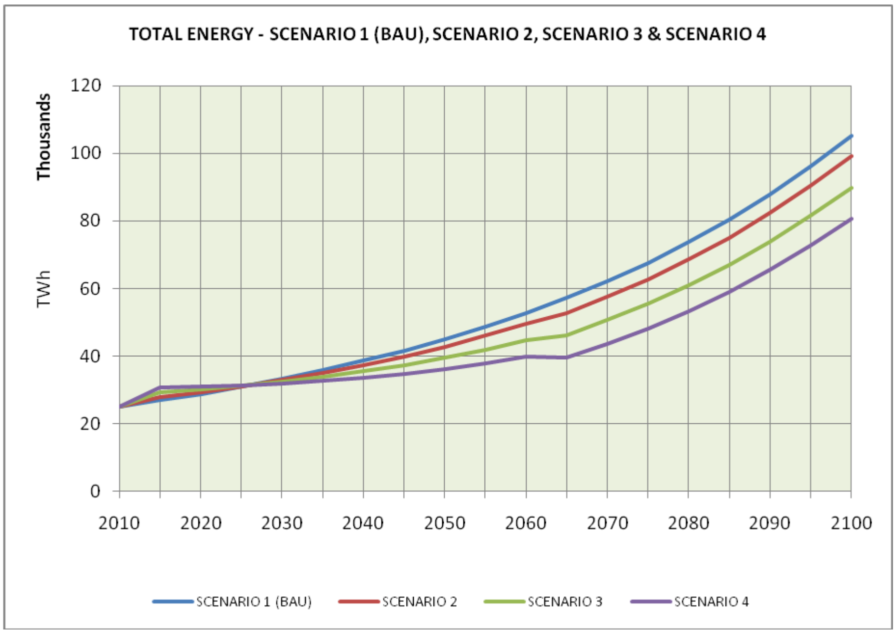

Figure 43: Total energy (medium growth rate, 50% energy efficient for new builts p.a. & 2% retrofits for existing p.a.).

Figure 43 (the same case as in Section 4.5.2) shows that over time the total energy consumption in the residential sector for scenarios 2, 3 and 4 were lower than the BAU scenario. The savings in the operating energy has overcome their higher values in the initial embodied energy and recurring embodied energy. **Figure 44** shows the percentage total energy savings for scenarios 2, 3 and 4 against BAU scenario. The total energy for scenarios 2, 3 and 4 was higher than the BAU scenario until sometime around the year 2022, which means no savings in total energy during that year. This condition is also similar to the case in Section 4.5.2. It can also be seen that although the operating energy was seen to decrease for scenario 4 **(Figure 40),** the total energy still increases modestly until 2065, after which it increases more steeply. In **Figure 44,** the percentage total energy savings for scenarios 2, 3 and 4 against BAU scenario peaked in 2065 and then started to decrease until 2100.

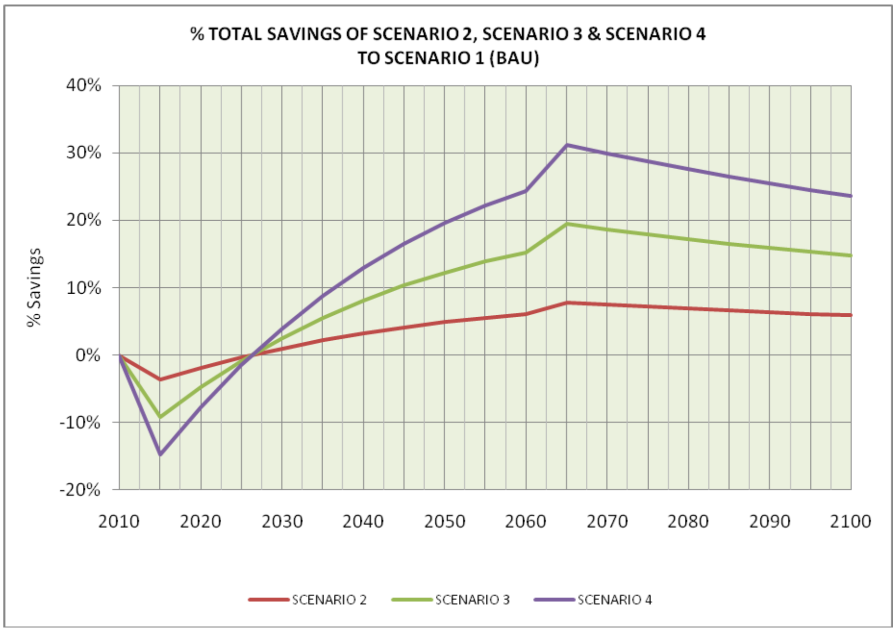

Figure 44: Percentage of total energy savings for scenarios 2, 3 and 4 against BAU scenario (medium growth rate, 50% energy efficient for new builts p.a. & 2% retrofits for existing p.a.).

Table 28 shows the percentage total energy savings for scenarios 2, 3 and 4 against BAU scenario in 2050 and 2100 considering low, medium and high dwellings growth rate. Also, it is clearly seen that the percentage savings is greater if low growth rate of dwellings is being considered for each scenarios 2, 3 and 4. However, as mentioned before, the percentage savings peaked in 2065 and then start to decrease in the same year.

Growth rate	% of new built dwellings being built as EED each year	% of existing dwellings being retrofitted as EED each year	percentage savings in 2065 against BAU (Scenario 1)			percentage savings in 2100 against BAU (Scenario 1)		
			Scenario 2	Scenario 3	Scenario 4	Scenario 2	Scenario 3	Scenario 4
Low	50%	2%	11.58%	28.96%	46.34%	9.28%	23.20%	37.12%
Medium			7.78%	19.44%	31.11%	5.89%	14.72%	23.55%
High			5.45%	13.63%	21.81%	4.01%	10.03%	16.05%

Table 28: Percentage of total energy savings for scenarios 2, 3 and 4 against BAU scenario in 2065 and 2100 (50% energy efficient for new builts p.a. & 2% retrofits for existing p.a.).

Table 29 shows that at no time do we get a decrease in the total world residential sector energy consumption in 2100 for scenarios 2, 3 and 4 against present (2010) total residential sector energy consumption for low, medium and high growth rates. However, for low and medium growth rates for scenarios 2, 3 and 4, the total world residential sector energy consumption is below the present (2010) total world energy consumption.

Growth rate	% of new built dwellings being built as EED each year	% of existing dwellings being retrofitted as EED each year	percentage increase in 2100 against present (2010) total world energy consumption			percentage increase in 2100 against present (2010) total world residential sector energy consumption		
			Scenario 2	Scenario 3	Scenario 4	Scenario 2	Scenario 3	Scenario 4
Low	50%	2%	-71%	-76%	-80%	+60%	+36%	+11%
Medium			-29%	-36%	-42%	+294%	+257%	+220%
High			+63%	+53%	+42%	+807%	+750%	+694%

Table 29: Percentage increase of total energy for scenarios 2, 3 and 4 against present (2010) total world energy consumption and present (2010) total world residential sector energy consumption in 2100 (50% energy efficient for new builts p.a. & 2% retrofits for existing p.a.).

4.5.5 Best estimate values, 50% new built dwellings being built as energy efficient dwelling each year and 3% existing dwellings being retrofitted as energy efficient dwelling each year.

By increasing existing dwellings being retrofitted as energy efficient dwelling each year to 3% and keeping new built dwellings being built as energy efficient dwelling each year to 50% similar in Section 4.5.2 and Section 4.5.4, the percentage savings on the total energy for Scenario 2, 3 and 4 against BAU scenario were started to peak and decrease earlier **(see Figure 45),** in this case was in the year of 2050.

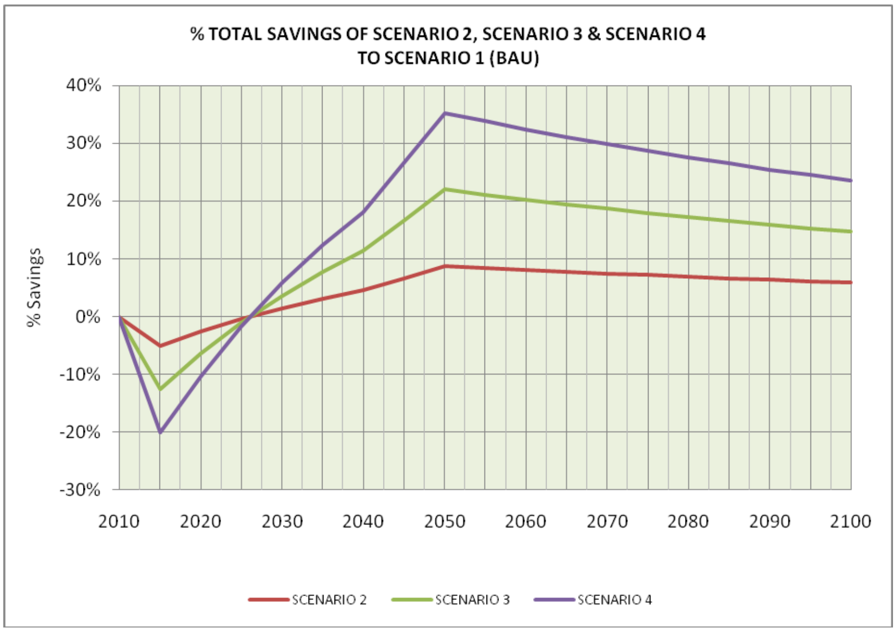

Figure 45: Percentage of total energy savings for scenarios 2, 3 and 4 against BAU scenario (medium growth rate, 50% energy efficient for new builts p.a. & 3% retrofits for existing p.a.).

In addition, the result in **Table 30** shows the percentage savings against the BAU scenario in 2100 was found to be similar to the result shown in **Table 24** in Section 4.5.4, but as stated above, the percentage savings on the total energy for Scenario 2, 3 and 4 against BAU scenario were started to peak and decrease earlier (2050).

Growth rate	% of new built dwellings being built as EED each year	% of existing dwellings being retrofitted as EED each year	percentage savings in 2050 against BAU (Scenario 1)			percentage savings in 2100 against BAU (Scenario 1)		
			Scenario 2	Scenario 3	Scenario 4	Scenario 2	Scenario 3	Scenario 4
Low	50%	3%	12.62%	31.56%	50.49%	9.28%	23.20%	37.12%
Medium			8.81%	22.02%	35.24%	5.89%	14.72%	23.55%
High			6.36%	15.91%	19.80%	4.01%	10.03%	16.05%

Table 30: Percentage of total energy savings for scenarios 2, 3 and 4 against BAU scenario in 2050 and 2100 (50% energy efficient for new builts p.a. & 3% retrofits for existing p.a.).

The result in **Table 31** was found to be identical to the result shown in **Table 25** (Section 4.5.4). This is due to the same percentage was chosen for new built dwellings being built as energy efficient dwellings (50%) and despite 2% or 3% p.a. were considered for existing dwellings being retrofitted as energy efficient dwellings, by 2100 all upgrading works for existing dwellings will be completed.

Growth rate	% of new built dwellings being built as EED each year	% of existing dwellings being retrofitted as EED each year	percentage increase in 2100 against present (2010) total world energy consumption			percentage increase in 2100 against present (2010) total world residential sector energy consumption		
			Scenario 2	Scenario 3	Scenario 4	Scenario 2	Scenario 3	Scenario 4
Low	50%	3%	-71%	-76%	-80%	+60%	+36%	+11%
Medium			-29%	-36%	-42%	+294%	+257%	+220%
High			+63%	+53%	+42%	+807%	+750%	+694%

Table 31: Percentage increase of total energy for scenarios 2, 3 and 4 against present (2010) total world energy consumption and present (2010) total world residential sector energy consumption in 2100 (50% energy efficient for new builts p.a. & 3% retrofits for existing p.a.).

4.5.6 Best estimate values, 100% new built dwellings being built as energy efficient dwelling each year and 3% existing dwellings being retrofitted as energy efficient dwelling each year.

By keeping existing dwellings being retrofitted as energy efficient dwelling each year to 3%, similar in Section 4.5.5, and increasing new built dwellings being built as energy efficient dwelling each year to 100%, the percentage savings on the total energy for scenarios 2, 3 and 4 still peaked in 2050 and then started to decrease (same case as in Section 4.5.5) **(see Figure 46).** However, the percentage savings, as shown in **Table 32,** is higher than as in **Table 30** (Section 4.5.5).

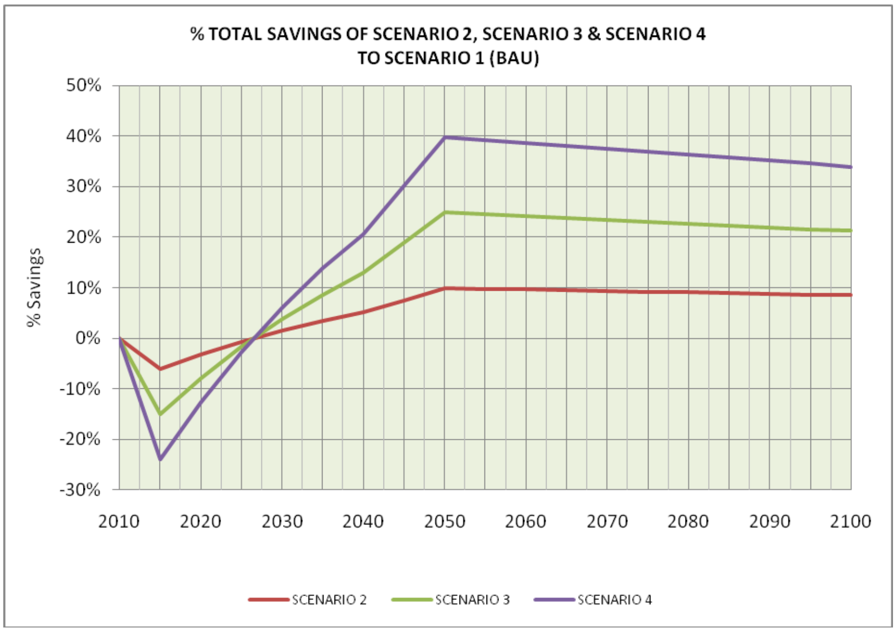

Figure 46: Percentage of total energy savings for scenarios 2, 3 and 4 against BAU scenario (medium growth rate, 100% energy efficient for new builts p.a. & 3% retrofits for existing p.a.).

Growth rate	% of new built dwellings being built as EED each year	% of existing dwellings being retrofitted as EED each year	percentage savings in 2050 against BAU (Scenario 1)			percentage savings in 2100 against BAU (Scenario 1)		
			Scenario 2	Scenario 3	Scenario 4	Scenario 2	Scenario 3	Scenario 4
Low	100%	3%	13.25%	33.11%	52.98%	11.32%	28.30%	45.28%
Medium			9.93%	24.83%	39.74%	8.49%	21.22%	33.95%
High			7.61%	19.02%	23.79%	6.46%	16.15%	25.84%

Table 32: Percentage of total energy savings for scenarios 2, 3 and 4 against BAU scenario in 2050 and 2100 (100% energy efficient for new builts p.a. & 3% retrofits for existing p.a.).

Also, the results shown in **Table 33** are not similar to the result shown in **Table 31** (section 4.5.5) (red shaded box). The difference might be due to the different percentage was chosen for new built dwellings being built as energy efficient dwelling. Result in **Table 33** shows savings in the total world residential sector energy consumption in 2100 for scenario 4 for low growth rate against the present (2010) total world energy consumption with 3% savings. Thus, it is significant to highlight that in the case of low growth, 100% p.a. new built dwellings being built as energy efficient dwellings and 3% p.a. existing dwellings being retrofitted as energy efficient dwellings, world finally get a saving in the total energy consumption for residential sector in 2100 against the present (2010) total world residential sector energy consumption.

Growth rate	% of new built dwellings being built as EED each year	% of existing dwellings being retrofitted as EED each year	percentage increase in 2100 against present (2010) total world energy consumption			percentage increase in 2100 against present (2010) total world residential sector energy consumption		
			Scenario 2	Scenario 3	Scenario 4	Scenario 2	Scenario 3	Scenario 4
Low	100%	3%	-72%	-77%	-83%	+57%	+27%	-3%
Medium			-31%	-41%	-50%	+284%	+230%	+177%
High			+59%	+42%	+26%	+784%	+693%	+601%

Table 33: Percentage increase of total energy for scenarios 2, 3 and 4 against present (2010) total world energy consumption and present (2010) total world residential sector energy consumption in 2100 (100% energy efficient for new builts p.a. & 3% retrofits for existing p.a.).

4.5.7 Best estimate values, 100% new built dwellings being built as energy efficient dwelling each year and 100% existing dwellings being retrofitted as energy efficient dwelling in the first 5 year.

100% new built dwellings being built as energy efficient dwelling each year and 100% existing dwellings being retrofitted as energy efficient dwelling in the first 5 years is totally unrealistic and impossible. However, the simulation according to these conditions was done to observe if there any savings in the total energy consumption for the residential sector in the future for scenarios 2, 3 and 4 against the BAU scenario. It is apparent from **Figure 47** the savings on the total energy for scenarios 2, 3 and 4 against BAU scenario were peak in the year 2020 and then started to decrease. **Table 34** clearly shows the decreased in the total energy savings for medium growth rate. With the decreased in percentage savings, in future we might see be no savings for scenarios 2, 3 and 4 against BAU scenario in the future.

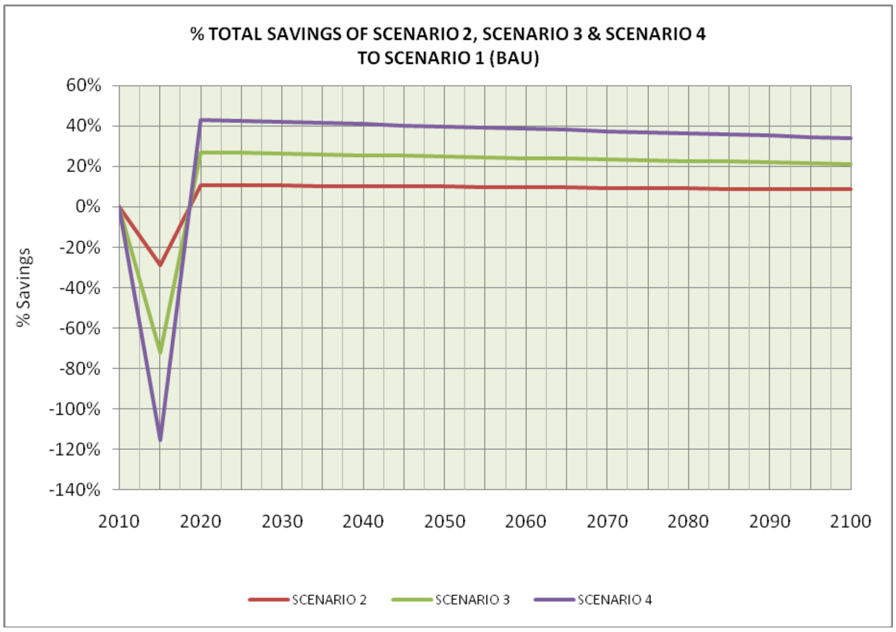

Figure 47: Percentage of total energy savings for scenarios 2, 3 and 4 against BAU scenario (medium growth rate, 100% energy efficient for new builts p.a. & 100% retrofits for existing p.a.).

MEDIUM GROWTH							
year	Scenario 1 (BAU)	Scenario 2		Scenario 3		Scenario 4	
	Total (TWh)	Total (TWh)	% savings	Total (TWh)	% savings	Total (TWh)	% savings
2010	25,131.60	25,131.60	0.00%	25,131.60	0.00%	25,131.60	0.00%
2015	26,919.90	34,697.97	-28.89%	46,365.08	-72.23%	58,032.15	-115.57%
2020	28,869.71	25,760.31	10.77%	21,096.21	26.93%	16,432.08	43.08%
2025	30,997.84	27,702.34	10.63%	22,759.10	26.58%	17,815.81	42.53%
2030	33,323.12	29,826.76	10.49%	24,582.23	26.23%	19,337.66	41.97%
2035	35,866.66	32,153.36	10.35%	26,583.40	25.88%	21,013.40	41.41%
2040	38,652.19	34,704.37	10.21%	28,782.64	25.53%	22,860.87	40.85%
2045	41,706.37	37,504.86	10.07%	31,202.60	25.19%	24,900.28	40.30%
2050	45,059.28	40,583.11	9.93%	33,868.86	24.83%	27,154.54	39.74%
2055	48,744.88	43,971.10	9.79%	36,810.43	24.48%	29,649.70	39.17%
2060	52,801.57	47,705.04	9.65%	40,060.24	24.13%	32,415.39	38.61%
2065	57,272.87	51,826.02	9.51%	43,655.75	23.78%	35,485.41	38.04%
2070	62,208.22	56,380.79	9.37%	47,639.64	23.42%	38,898.41	37.47%
2075	67,663.84	61,422.55	9.22%	52,060.62	23.06%	42,698.61	36.90%
2080	73,703.80	67,012.06	9.08%	56,974.44	22.70%	46,936.74	36.32%
2085	80,401.31	73,218.77	8.93%	62,444.98	22.33%	51,671.09	35.73%
2090	87,840.11	80,122.30	8.79%	68,545.60	21.97%	56,968.80	35.14%
2095	96,116.24	87,814.03	8.64%	75,360.71	21.59%	62,907.28	34.55%
2100	105,340.04	96,399.07	8.49%	82,987.62	21.22%	69,576.05	33.95%

Table 34: Percentage of total energy savings for scenarios 2, 3 and 4 against BAU scenario as a function of time (medium growth rate, 100% energy efficient for new builts p.a. & 100% retrofits for existing p.a.).

Growth rate	% of new built dwellings being built as EED each year	% of existing dwellings being retrofitted as EED each year	percentage savings in 2050 against BAU (Scenario 1)			percentage savings in 2100 against BAU (Scenario 1)		
			Scenario 2	Scenario 3	Scenario 4	Scenario 2	Scenario 3	Scenario 4
Low	100%	100%	13.25%	33.11%	52.98%	11.32%	28.30%	45.28%
Medium			9.93%	24.83%	39.74%	8.49%	21.22%	33.95%
High			7.61%	19.02%	30.87%	6.46%	16.15%	25.84%

Table 35: Percentage of total energy savings for scenarios 2, 3 and 4 against BAU scenario in 2050 and 2100 (100% energy efficient for new builts p.a. & 100% retrofits for existing p.a.).

It can be seen that form **Table 35** as compared to the **Table 32** (section 4.5.6) the percentage savings in the year 2100 were found to be identical. This is due to the same percentage (100%) of new built dwellings being built as energy efficient dwellings each year was considered and existing dwellings being retrofitted as energy efficient dwellings will be completed before the year 2100 despite 3% or 100% were considered as percentage p.a. for existing dwellings being retrofitted as energy efficient dwellings.

Result from **Table 36** concurred the findings in Section 4.5.6 which stated with 100% p.a. new built dwellings being built as energy efficient dwelling, world might see savings in the total residential sector energy consumption in 2100 against the present (2010) total world residential sector energy consumption for the case of low growth rate (red shaded box).

Growth rate	% of new built dwellings being built as EED each year	% of existing dwellings being retrofitted as EED each year	percentage increase in 2100 against present (2010) total world energy consumption			percentage increase in 2100 against present (2010) total world residential sector energy consumption		
			Scenario 2	Scenario 3	Scenario 4	Scenario 2	Scenario 3	Scenario 4
Low	**100%**	**100%**	-72%	-77%	-83%	57%	27%	-3%
Medium			-31%	-41%	-50%	284%	230%	177%
High			59%	42%	26%	784%	693%	601%

Table 36: Percentage increase of total energy for scenarios 2, 3 and 4 against present (2010) total world energy consumption and present (2010) total world residential sector energy consumption in 2100 (100% energy efficient for new builts p.a. & 100% retrofits for existing p.a.).

5 DISCUSSION

This chapter includes discussion of the issues found in the Chapter 4 (Results). It provides an overview of future energy consumption in residential sector for the world followed by a discussion on the thesis aims and specific research questions including the limitations of the analysis. Also, this chapter focuses on comparing the results with other studies in the Chapter 1 (Introduction) and Chapter 2 (Background).

5.1 OVERVIEW

Three specific research questions were addressed in order to predict the future residential sector energy consumption:

i. How many residential dwellings exist in the world and how many new built dwellings may be built in the future?

ii. What is the average operating energy and embodied energy (initial and recurrent) of a conventional dwelling per square meter (kWh/m^2) for the world?

iii. What is an estimate of the total energy consumption for the world existing dwellings and how will this increase over time?

In addition, additional two specific research questions were addressed in order to answer the thesis aim:

iv. What is the average operating energy and embodied energy of an energy efficient dwelling per square meter (kWh/m^2) for the world?

v. How much energy will the world residential sector energy consumption save by building energy efficient dwellings?

Thus, the results in Chapter 4 have been obtained to answer these specific research questions, and now the results will be discussed in turn.

5.1.1 Total number and area of existing dwellings and new built dwelling in the world.

The discussion in this section is based on the result found in Chapter 4 (Section 4.2 and Section 4.3).

The present (2010) total number of dwellings in the world has been estimated to be around 1.7 billion, of which about 62% exist in only ten countries: China (24%), India (12%), US (7%), Russia (4%), Indonesia (3%), Brazil (3%), Japan (3%), Nigeria (2%), Germany (2%) and Bangladesh (2%) **(Figure 48).**

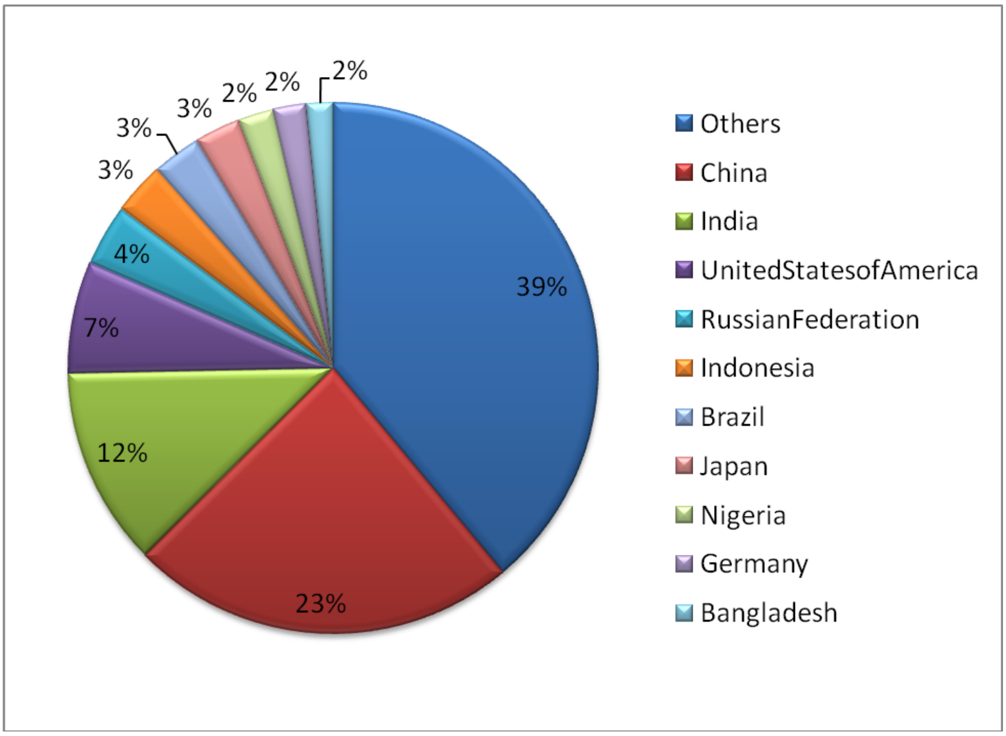

Figure 48: Top ten countries in 2010 with the highest percentage of total number of dwellings.

It can be seen that China, India and US dominate the total number of dwellings for the world in 2010. There is no surprise here since China, India and US were the top three most populated countries in 2010 **(Figure 49).**

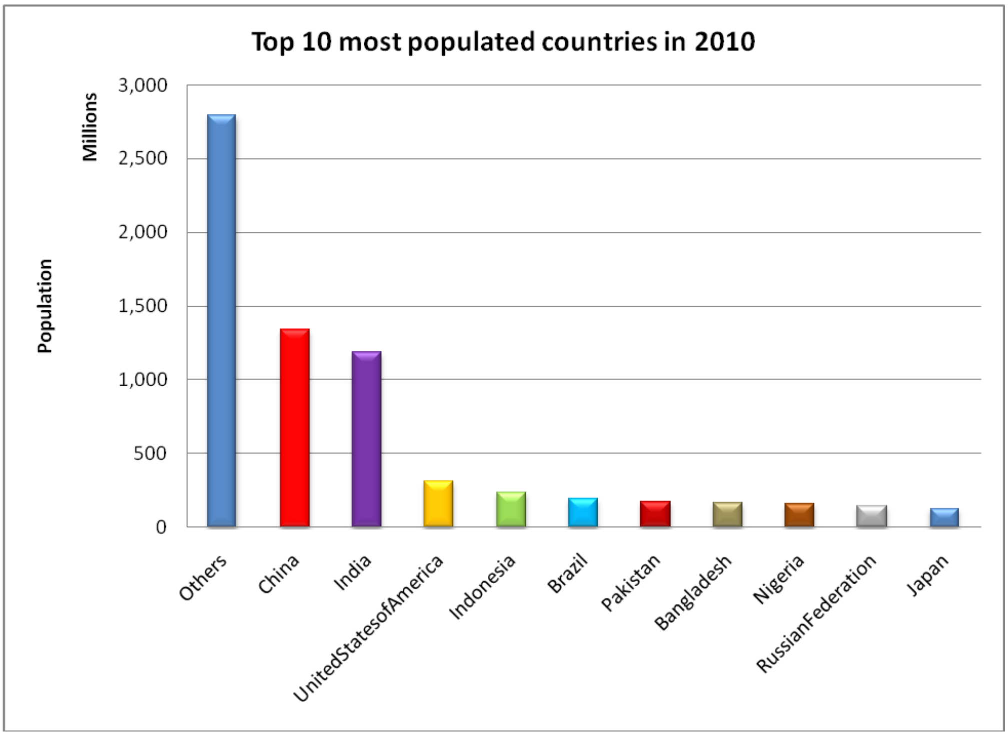

Figure 49: Top 10 most populated countries in 2010 (CIA, 2010).

It is obviously that the number of dwellings in the world will be strongly related to the number of people in the world. The rise in population will produce a rise household numbers, which consequently will increase the demand for dwellings. Thus, increase in population will increased the total number of dwellings in the world.

A limitation of this study is that, as mentioned in Chapter 4, the population growth and hence the future dwelling growth rate is subjected to many (i.e. economic collapse, natural calamities, wars etc.) which could intervene over the time period of this study (90 years). Such events have not been individually considered in the projection, however, in general they have been handled by using various scenarios for future growth. In this thesis, low (0.25% p.a.), medium (1.00% p.a.) and high (1.75% p.a.) growth rate have been considered for the projection of total number of dwellings. With these growth rates, the total number of dwellings in the year 2100 can be calculated to be about 2.5 billion for the low growth rate (an increase of 0.8 billion), 5 billion for the medium growth rate (an increase of 3.3 billion) and 10 billion for the high growth rate (an increase of 8.3 billion).

According to the United Nations Department of Economics and Social Affairs (Population Division), in 2100 the world population could reach 5.5 billion for the low growth rate (a decrease of 1.4 billion), 9.1 billion for the medium growth rate (an increase of 2.2 billion) and 14 billion for the high growth rate (an increase of 7.1 billion) **(UN, 2004).**

These numbers of dwellings will have an implication on the total world energy consumption for residential sector. As mentioned in Chapter 2 (Background), the number of people per dwelling (occupancy rate) is one of the important factors affecting residential sector energy consumption. Also, as has been found in the Chapter 2 that the world occupancy rate (numbers of persons per dwelling) has been steadily declining. Therefore, with an increased population and a decline in occupancy rate, the total number of dwellings in the world may rise faster than the population rate.

In addition, also as mentioned in Chapter 2 (Background), residential sector energy consumption is also related to the size of dwellings. It has been found in the literature review that the average area per dwelling has increased around the world. A possible explanation for this might be that the increase in dwelling size is related to increased wealth or for countries in increased GDP/capita. The result of this study has shown that average dwelling size (m^2/dwelling) per individual nation and the national GDP/capita has a strong relationship. It seems highly likely that this result is due to people building or buying larger dwellings and or expanding their existing dwellings if they gain more money. This explanation is consistent with the finding that developed countries have been found to have larger average dwelling floor areas as compared to the developing countries. It was estimated that the average area per dwelling in developed countries was around 120 m^2/dwelling in 1998, while, developing countries the corresponding estimate was around 63 m^2/dwelling in 2002. There will of course be a good deal of variation both between individual countries within countries. This finding also suggests that economic growth will affect the energy consumption in the residential sector. With the above values of average area per dwelling, the total dwellings floor area in the world was calculated as a function of time. It was thus estimated that the total dwellings floor area in 2010 was around 143 billion square meters (approximately 20 m^2 per person). Similar to the total number of dwellings in the world, China, US and India dominates the top three countries having the largest dwellings area in the world. However, this time, US outpace India with 10.5% and 9.5% respectively, due to the much higher GDP/capita in the US. While, China still has top place as the country which has the largest total dwelling floor area, as per the total number of dwellings in 2010 **(see Figure 50).**

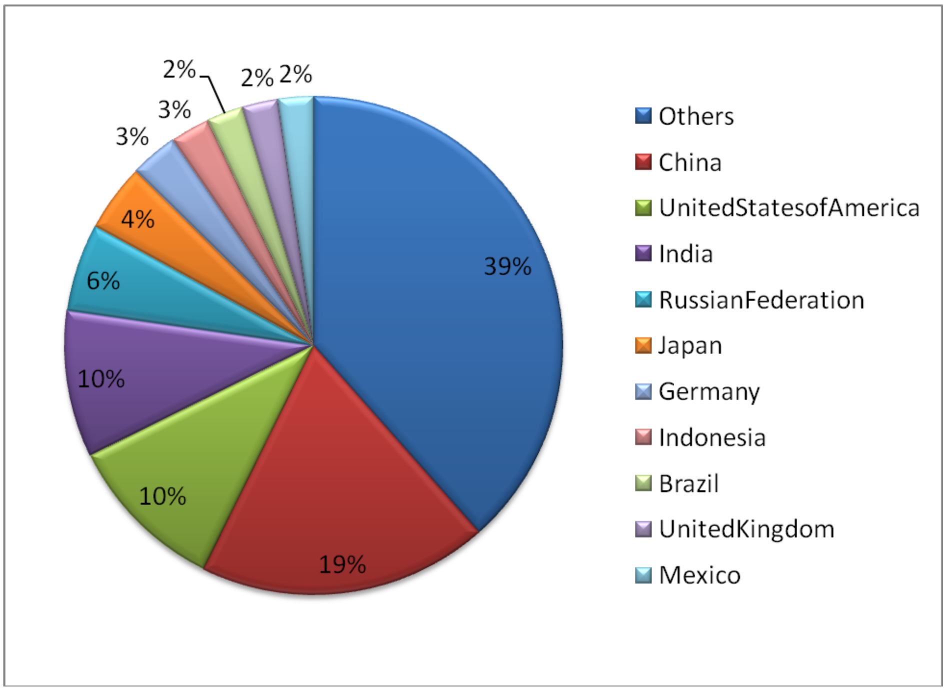

Figure 50: Top ten country in 2010 with the highet total dwellings floor area.

5.1.2 Operating energy (OE), initial embodied energy (IEE), and recurring embodied energy (REE) (maintenance).

The discussion in this section is based on the results found in Chapter 4 (Section 4.4).

i. Conventional dwelling.

It important to note that the findings in this section has been constrained by the limited sample data found in the Chapter 4 (Section 4.4) as residential energy data (both consumption and embodied energy) was not available for any but a small selection of countries. Thus, based on the available data found (refer **Table 19**, Chapter 4, Section 4.4) a set of values were chosen for developed and developing countries in the world. **Table 37** summarizes the values used in the simulations to project the future growth for the total energy consumption in the residential sector for the world. The best estimate values have been chosen from the ranges of values found in the literature review.

Conventional Dwelling	kWh/m^2			
	OE p.a. (developed)	OE p.a. (developing)	IEE	REE p.a.
Best estimate	175	90	750	4.50

Table 37: OE, IEE and REE values used in the simulations for conventional dwellings.

The value used for the OE for developed countries in this thesis is consistent with **C.A Balaras et al. (2000**) et which stated the annual total residential buildings energy consumption for OECD countries averaged between 150-230 kWh/m^2 (refer Chapter 4, **Table 19**, Section 4.4). However, there were no data found for the OE for most developing countries for comparison, so estimates based on India and China only were used for all other developing countries (refer Chapter 4, **Table 19**, Section 4.4). The values for the IEE and REE, for developing countries were taken as the same values as for rest of the world. This was thought reasonable since the dwelling floor area implies a proportionate amount of material and energy use in general, and it was not thought that such estimates would be too far out when averaged across the whole world.

ii. Energy efficient dwellings.

For energy efficient dwellings, an OE was computed according to the classifications as outlined in Chapter 3 (Section 3.1). As for the value of IEE, the rate of change on IEE to the rate of change of OE from converting conventional dwelling to energy efficient dwelling was considered. However, as mentioned in Chapter 3 (Section 3.4), the IEE of an energy efficient dwelling being retrofitted from conventional dwelling would not be equal to the IEE to build a new energy efficient dwelling. Thus, the different between IEE of a conventional dwelling and IEE of an energy efficient dwelling has been considered as the IEE for the work to retrofit a conventional dwelling as an energy efficient dwelling. In the case of REE, the rate of its usage has been estimated as a percentage of the value of IEE for energy efficient dwellings, the same case as for conventional dwellings. **Table 38** summarizes the values used in the simulations to project the future growth for the total energy consumption in the residential sector for the world.

	kWh/m^2				
	OE p.a. (developed)	OE p.a. (developing)	IEE	IEE retrofits	REE p.a.
Energy efficient dwelling 1 (EED 1) - 20% reductions in OE	140	90	825	75	4.95
Energy efficient dwelling 2 (EED 2) - 50% reductions in OE	88	72	938	188	5.63
Energy efficient dwelling 3 (EED 3) - 80% reductions in OE	35	18	1050	300	6.30

Table 38: OE, IEE and REE values used in the simulations for energy efficient dwellings.

Although the classification of OE for EED 3 (developed countries) as in **Table 38** might be considered very small (35 kWh/m^2), the findings of **Feist (1997)** and **Gustavsson and Joelsson (2010)** corroborates with the classification, which indicated that energy efficient dwellings could have an OE of between 30 kWh/m^2 and 26 kWh/m^2 respectively.

For the IEE for EED 3 (developed countries), the value estimated was in the ranges of Feist and Gustavsson & Joelsson findings, which were 1,391 kWh/m^2 and 656 kWh/m^2 respectively. Based on the data found in the literature review (refer **Table 21,** Chapter 4, Section 4.5), the results on the IEE of each classified energy efficient dwellings used in this thesis indicate that the IEE of an energy efficient dwelling is usually higher than conventional dwellings. This result is consistent with that of other studies and suggests that energy used in the construction phase (embodied energy) increases as the operating energy decreases. Also, the REE for energy efficient dwellings has found to be higher than conventional dwellings, since the rate of its usage has been calculated against the value of IEE. This finding indicates that the capital upkeep of the energy efficient dwellings will incur a slightly higher recurring energy.

5.1.3 Total energy consumption for the residential sector in the world.

The discussion in this section is based on the results found in Chapter 4 (Section 4.5) and also will answer the thesis aim: To determine if building energy efficient dwellings will be sufficient to allow an absolute reduction in the world residential sector energy consumption.

As mentioned in Chapter 3 (Section 3.4), the total energy consumption for the world has been simulated using Excel Spreadsheet simulation models according to the four (4) scenarios as outlined in Chapter 3 (Section 3.1). Before proceeding with the discussion on the results, it is noteworthy to mention here that the Excel Spreadsheet simulation models has been checked for scenarios 2, 3 and 4, that the total residential energy consumption for these scenarios give the same result to BAU scenario (Scenario 1) if no (0%) new built dwellings being built as energy efficient dwelling (100% being built as status quo - conventional dwelling) and no (0%) existing dwellings being retrofitted to be energy efficient dwelling. These conditions are shown in **Figure 51** for medium growth rate.

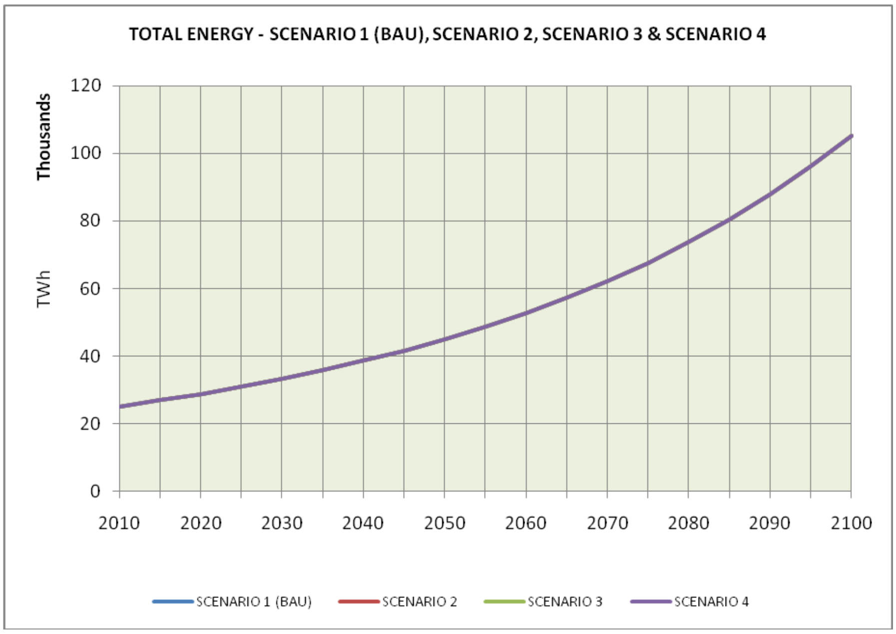

Figure 51: Total energy (medium growth rate, 0% energy efficient for new builts p.a. & 0% retrofits for existing p.a.).

As mentioned in Chapter 4 (Section 4.5), total world energy consumption in 2010 was around 140,000 TWh or 504 EJ **(BP, 2011).** Thus, it has been found that at medium growth rate the total world energy consumption in 2010 will be needed just for the residential sector in 2100. The high growth rate case **(see Figure 52**) shows that the residential sector would use over twice the 2010 world energy consumption and as such is thought unlikely.

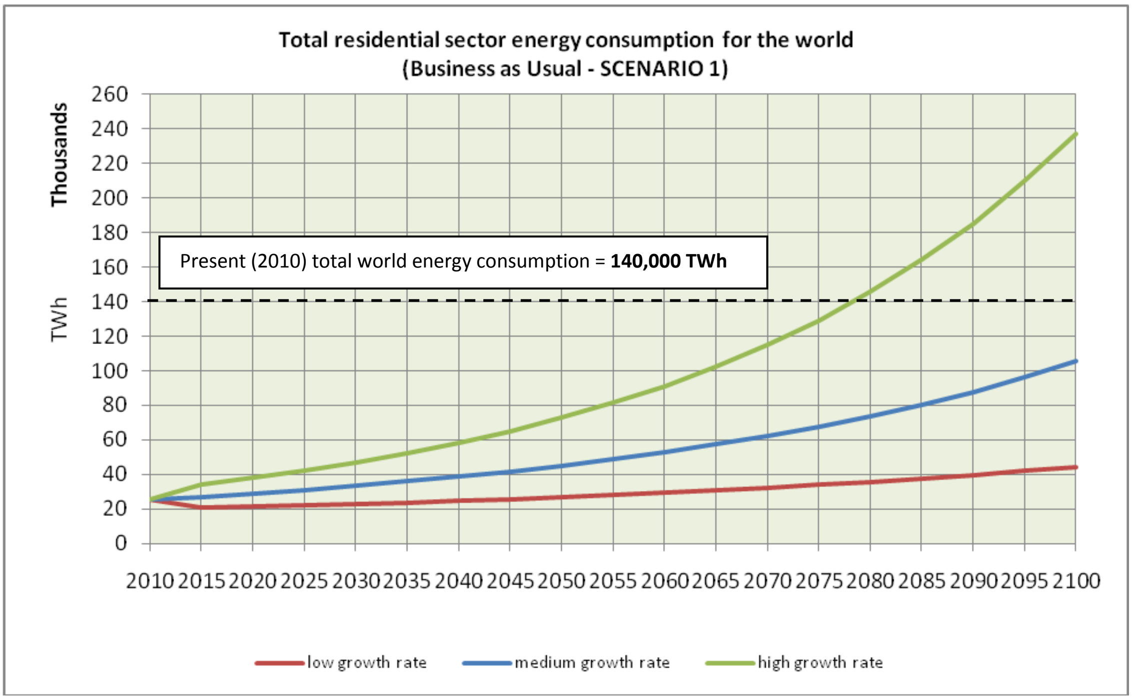

Figure 52: Comparison between the present (2010) total world energy consumption and the future growth of the total residential energy consumption for the world for BAU scenario.

Also, it has been estimated that the present (2010) world residential sector energy consumption to be around 25,100 TWh (90 EJ). This would mean that the present (2010) total residential energy sector energy consumption for the world is approximately 18% of the total world energy consumption. This is somewhat higher than what that suggested by the **EIA (2006)** that energy consumption for residential sector for all countries in 2010 will be around 13% (1,530 Mtoe or 64 EJ or 17,850 TWh) of total world energy consumption.

While, the **IEA (2008)** has reported that the world residential sector energy consumption in 2005 was 82EJ, which was 17% of the total world energy at that time and consistent with the results in this thesis. However, the percentage of the total world energy consumption as given by the EIA and IEA are highly likely not to have included the embodied energy to make the dwellings, thus the suggested percentage and value of the total energy consumption by both organizations could be higher.

Savings for scenarios 2, 3 and 4 against BAU scenario.

The first investigation was to see when increasing the penetration of energy efficient dwellings would decrease the total world BAU energy consumption. Note of course that such does not imply any absolute decrease in energy.

Table 39 summarize the results found in Chapter 4 (Section 4.5).

Num	Growth rate	% of new built dwellings being built as EED each year	% of existing dwellings being retrofitted as EED each year	No savings until the year of: Scenario 2 | 3 | 4	Savings peaked in the year of: Scenario 2 | 3 | 4	percentage savings in 2100 against BAU (Scenario 1)		
						Scenario 2	Scenario 3	Scenario 4
1	Low	50%	1%	Around the year 2022	after 2100	7.44%	18.59%	29.74%
	Medium					5.05%	12.62%	20.20%
	High					3.61%	9.04%	14.46%
2	Low	100%	1%	Around the year 2022	after 2100	9.47%	23.69%	37.90%
	Medium					7.65%	19.13%	30.60%
	High					6.06%	15.16%	24.25%
3	Low	50%	2%	Around the year 2022	2065	9.28%	23.20%	37.12%
	Medium					5.89%	14.72%	23.55%
	High					4.01%	10.03%	16.05%
4	Low	50%	3%	Around the year 2022	2050	9.28%	23.20%	37.12%
	Medium					5.89%	14.72%	23.55%
	High					4.01%	10.03%	16.05%
5	Low	100%	3%	Around the year 2022	2050	11.32%	28.30%	45.28%
	Medium					8.49%	21.22%	33.95%
	High					6.46%	16.15%	25.84%
6	Low	100%	100%	Around the year 2017	2020	11.32%	28.30%	45.28%
	Medium					8.49%	21.22%	33.95%
	High					6.46%	16.15%	25.84%

Table 39: Summary results 1.

Table 39 shows that regardless of what percentages have been used for new built and retrofit existing dwellings, the percentage savings for scenarios 2, 3 and 4 against BAU scenario were greater if low growth is considered. In addition, it seen that for any percentage of new built dwellings being built as energy efficient dwellings and for any percentage of existing dwellings being retrofitted as energy efficient dwellings, there will be a no savings period. It seems possible that these results are due to the higher embodied energy to built new dwellings and retrofit existing dwellings as energy efficient dwellings. Furthermore, the savings in operating energy at the early stage is seen not to be very high, since on balance, at this time, there were many existing dwellings not yet being retrofitted. Also, it seen that the savings will be peaked at some point and then decreases thereafter.

Therefore, to further investigate this decreased in savings, 100% p.a. of new built dwellings being built as energy efficient dwellings and 100% in 5-years of existing dwellings being retrofitted as energy efficient dwelling was considered even it is unrealistic (the maximum percentage for new built and existing dwellings can be chosen in the simulation model). Thus, the result has shown that, for any percentage of new built dwellings being built as energy efficient dwellings and for any percentage of existing dwellings being retrofitted as energy efficient dwellings, the percentage will be decreased and it seems possible at some point there will be no savings for scenario 2, 3 and 4 against BAU scenario at one period after 2100 **(refer Table 34,** Chapter 4). Note again, of course these findings does not imply any absolute decrease in energy.

Increase of the total residential sector energy consumption in 2100 against: the present (2010) consumption

The second investigation was to look at when increasing the penetration of energy efficient dwellings would decreased the absolute use for the residential sector.

Table 40 summarize the results found in Chapter 4 (Section 4.5).

Num	Growth rate	% of new built dwellings being built as EED each year	% of existing dwellings being retrofitted as EED each year	percentage increase in 2100 against the present (2010) total world residential sector energy consumption		
				Scenario		
				2	3	4
1	Low	50%	1%	+64%	+44%	+24%
	Medium			+298%	+266%	+234%
	High			+811%	+760%	+709%
2	Low	100%	1%	+60%	+35%	+10%
	Medium			+287%	+239%	+191%
	High			+788%	+702%	+616%
3	Low	50%	2%	+60%	+36%	+11%
	Medium			+294%	+257%	+220%
	High			+807%	+750%	+694%
4	Low	50%	3%	+60%	+36%	+11%
	Medium			+294%	+257%	+220%
	High			+807%	+750%	+694%
5	Low	100%	3%	+57%	+27%	-3%
	Medium			+284%	+230%	+177%
	High			+784%	+693%	+601%
6	Low	100%	100%	+57%	+27%	-3%
	Medium			+284%	+230%	+177%
	High			+784%	+693%	+601%

Table 40: Summary results 2.

Table 40 shows that we would need a low growth rate, around 100% of new built as scenario 4 energy dwellings (operating energy of 35 kWh/m² and 18 kWh/m² for developed and developing countries respectively) and around 3% to 100% energy efficient retrofits p.a. to achieve a 3% decrease in world residential energy consumption. The model was then run with alternate percentages for new built dwellings and percentages retrofits to investigate the threshold percentages of these variables to see when the world would get an absolute savings **(see Table 41).**

Num	Growth rate	% of new built dwellings being built as EED each year	% of existing dwellings being retrofitted as EED each year	% of increase in 2100 against the present (2010) total residential sector energy consumption		
				Scenario 2	Scenario 3	Scenario 4
1	Low	85%	0%	+71%	+61%	+52%
	Medium			+301%	+273%	+245%
	High			+806%	+747%	+688%
2	Low	85%	100%	+58%	+29%	+1%
	Medium			+287%	+238%	+190%
	High			+791%	+710%	+629%
4	Low	90%	100%	+57%	+28%	0%
	Medium			+286%	+236%	+186%
	High			+789%	+704%	+619%
5	Low	91%	0%	+70%	+60%	+50%
	Medium			+299%	+270%	+240%
	High			+803%	+740%	+677%
6	Low	91%	1%	+61%	+36%	+12%
	Medium			+289%	+244%	+199%
	High			+792%	+712%	+633%
7	Low	91%	1.15%	+58%	+31%	+3%
	Medium			+286%	+238%	+189%
	High			+789%	+706%	+622%
8	Low	91%	1.2%	+57%	+28%	-1%
	Medium			+286%	+235%	+185%
	High			+788%	+703%	+618%
9	Low	91%	2%	+57%	+28%	-1%
	Medium			+286%	+235%	+185%
	High			+788%	+703%	+618%
10	Low	91%	3%	+57%	+28%	-1%
	Medium			+286%	+235%	+185%
	High			+788%	+703%	+618%
11	Low	100%	100%	+57%	+27%	-3%
	Medium			+284%	+230%	+177%
	High			+784%	+693%	+601%

Table 41: Threshold of when energy consumption in residential sector will get absolute savings against the present (2010) consumption.

From **Table 41**, it is seen that with a low growth rate, 91% p.a. or higher percentage of new built dwellings being built as energy efficient dwellings and 1.2% p.a. or higher percentage of existing dwellings being retrofitted as energy efficient dwellings, the world will finally see a savings in the total residential sector energy consumption in 2100 against the current (2010) consumption **(see Figure 53).** The 1.2% of existing dwellings being retrofitted as energy efficient dwellings, is needed to ensure that the entire world dwelling stock is retrofit is completed before 2100. Using the 1.2%., of the retrofits the total number exisiting dwelling that must be retrofitted p.a. would be 21 million dwellings

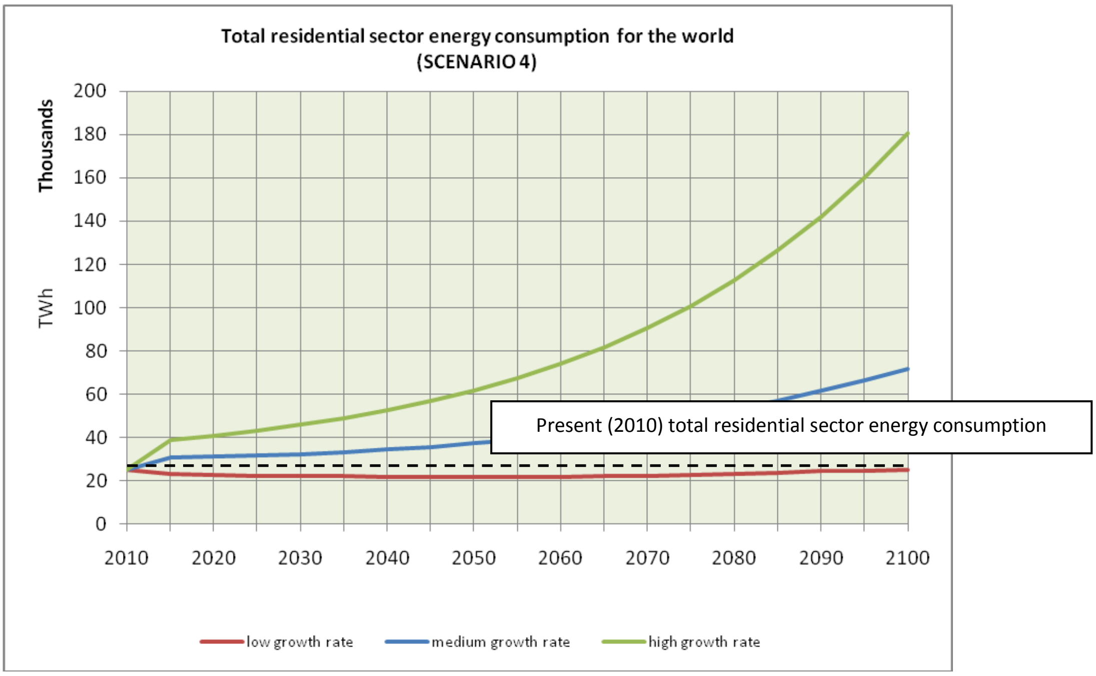

Figure 53: Scenario 4 total energy consumption (low growth, 91% p.a. energy efficient for new built, 1.2% p.a. retrofits for exisitng).

It is interesting to note that, based on **Figure 54,** that when the retrofit rate is 3% and the new build rate is 91% then the total residential sector energy consumption for scenario 4 (low growth) shows a minimum around 2050 (when the entire existing dwelling stock has been upgraded) and then increases thereafter.

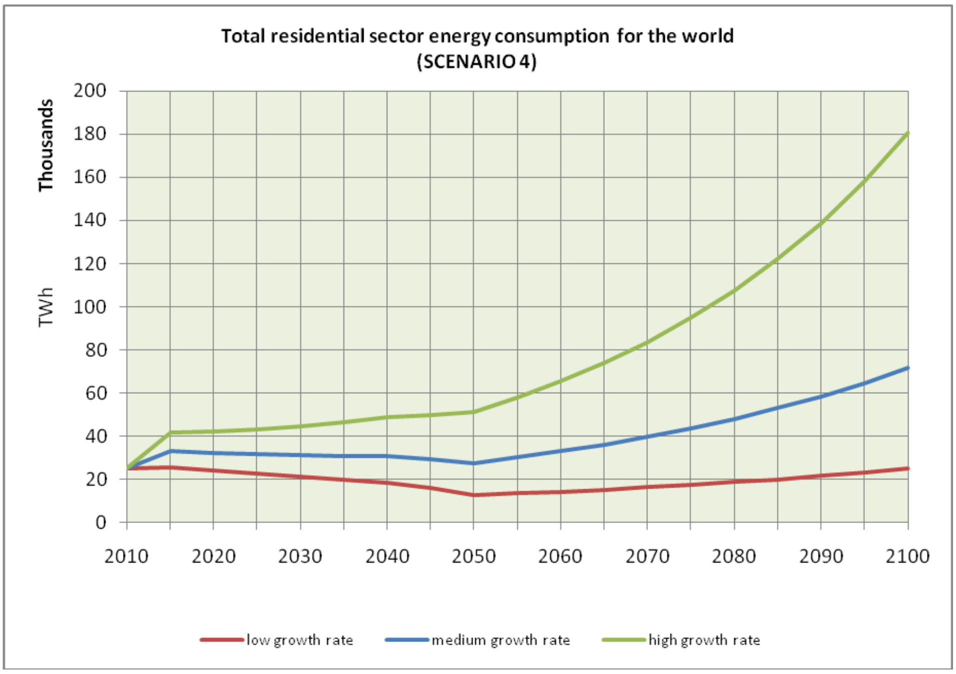

Figure 54: Scenario 4 total energy consumption (low growth, 80% p.a. energy efficient for new built, 3% p.a. retrofits for exisitng).

6 CONCLUSIONS

Improving the penetration of energy efficient buildings into the residential sector is thought to be one way the world can reduce carbon emissions and minimize resource usage. It is important, however, to consider the growth in that sector and to investigate, on a systematic basis, what total energy savings are possible. As discussed in Chapter 2 (Background), to investigate the future growth of energy consumption and possible energy savings in the residential sector we need to know how many dwellings there are in the world and how fast they are increasing. Following that, by knowing the total dwellings area (m^2) in the world and the energy consumption per square meter (kWh/m^2), we can generate the future growth curves for energy consumption in the residential sector and investigate alternative paths to reduce the growth by building energy efficient dwellings.

This thesis set out to determine if building energy efficient dwellings will be sufficient to allow an absolute reduction in the world residential sector energy consumption in the future. This aim was achieved by developing a simulation model using to simulate and predict the future energy consumption in residential sector for the world in the period of 90 years (until 2100).

In the first part of this thesis, which was to find how many residential dwellings exist in the world and how many new built dwellings may be built in the future, the results show, as might be expected, that total number of dwellings in the world is strongly related to the world population. Increase in population will increase the demand for dwellings. In addition, with a declining occupancy rate around the world, the total number of dwellings in the world may rise faster than the population rate. It was also shown that the increase in dwelling size was found to have strong relationship with economic growth (GDP/capita). The demand for more and bigger dwellings as world GDP grows will then further increase residential energy consumption.

In the second part of this thesis, which was to estimate the average operating energy and embodied energy (initial and recurrent) for conventional dwellings and energy efficient dwellings per square meter (kWh/m^2), the results showed again, as might be expected, that in general developed countries consume more than developing countries in terms of operating energy. Also, it was shown that energy efficient dwellings use more energy during construction (initial embodied energy) and in maintaining (recurring embodied energy) the dwellings during their life cycle.

Finally, in the last part of this thesis, which was to determine how much energy the world residential sector energy consumption will save by building energy efficient dwellings, the results showed that the world could finally see a savings, that is an absolute reduction, in the total residential sector energy consumption by 2100 against the current (2010) consumption but only under very stringent conditions. These conditions were:

- ✓ A very low rate of growth of dwellings at 0.5%.
- ✓ An extremely high rate of new built dwellings being built as energy efficient dwellings i.e. 91% p.a. or higher.
- ✓ 1.2% p.a. or a higher percentage of existing dwellings being retrofitted as energy efficient dwellings throughout the world and;
- ✓ The classification for the energy efficient dwellings must give savings of over 80% compared to conventional dwellings (i.e. type EED 3, refer **Table 38,** Chapter 5),

Such conditions are thought, highly improbable to be achieved on a world scale. Considering more probable scenarios for the world i.e. 10% p.a. of new built dwellings being built as energy efficient dwellings and 1.2% p.a. of existing dwellings being retrofitted as energy efficient dwellings, the world could not see savings in the total residential sector energy consumption by 2100 against the current (2010) consumption (see **Table 42**). The best outlook under this scenario would be for a 23% increase in world residential energy consumption if the number of dwellings increased by 0.5% p.a. and the very best energy efficient dwellings were used (i.e. 80% savings over conventional dwellings). High growth scenario suggests very high increases in residential energy consumption of around a factor of eight times by 2100.

Growth rate	% of new built dwellings being built as EED each year	% of existing dwellings being retrofitted as EED each year	% of increase against 2010 total residential sector energy consumption		
			Scenario 2	Scenario 3	Scenario 4
Low	**10%**	**1.2%**	+63%	+43%	+23%
Medium			+303%	+279%	+255%
High			+826%	+797%	+768%

Table 42: Percentage increase of total energy for scenarios 2, 3 and 4 against present (2010) total world energy consumption and present (2010) total world residential sector energy consumption in 2100 (100% energy efficient for new builts p.a. & 1.2% retrofits for existing p.a.).

However, the above results do not mean that people should run this world as business as usual as this would give a 77% increase in world residential energy consumption if the number of dwellings increased by 0.25% p.a. and around a factor of eight times increase if the number of dwellings increased by 1.75% p.a.

There were some limitations that were encountered in carrying out this study which have been discussed in Chapter 5 (Discussion). Again, as an overall conclusion, these limitations are addressed and acknowledged here. The most important limitation lies in the fact that the dwelling growth rates considered in this study have not, for obvious reasons, considered all the possible uncertainties in the future, for example, the imminent arrival of peak oil and climate change may engender economic and then population collapse. In addition, natural calamities, wars, new scientific discoveries including energy breakthroughs etc could intervene over the very long period of this study. Thus, further research might explore and investigate these uncertainties in projecting the dwelling growth rates. Another limitation found in this study was that the investigation with regards to the average value of an operating energy and embodied energy was limited by the sparse data found in the literature review, especially for the developing countries. It was not feasible to find such data for every country in the world. The ameliorating factor was that the world population is dominated by only few countries.

Finally, a comprehensive energy conservation policy should be introduced as it was known that an energy policy plays an important role in any country's sustainable development and improving energy efficiency in buildings. A comprehensive energy conservation policy also was found to one of the most cost-effective measures for reducing CO_2 emission which is known as the main causes of global warming **(Perez-Lombard et al., 2008).** However, as mentioned in Chapter 2 (Background), the biggest problem with energy efficiency, which the world will face in the future, will be increasing population and affluence growth rates which will always trump energy efficiency gains at some point in the future **(Catton, 1982).**

7 APPENDIX

Appendix A

Appendix C. Probabilities for Correlation Coefficients 249

Table C. The percentage probability $P_N(|r| \geqslant r_o)$ that N measurements of two uncorrelated variables give a correlation coefficient with $|r| \geqslant r_o$, as a function of N and r_o. (Blanks indicate probabilities less than 0.05 percent.)

	r_o										
N	0	.1	.2	.3	.4	.5	.6	.7	.8	.9	1
3	100	94	87	81	74	67	59	51	41	29	0
4	100	90	80	70	60	50	40	30	20	10	0
5	100	87	75	62	50	39	28	19	10	3.7	0
6	100	85	70	56	43	31	21	12	5.6	1.4	0
7	100	83	67	51	37	25	15	8.0	3.1	0.6	0
8	100	81	63	47	33	21	12	5.3	1.7	0.2	0
9	100	80	61	43	29	17	8.8	3.6	1.0	0.1	0
10	100	78	58	40	25	14	6.7	2.4	0.5	—	0
11	100	77	56	37	22	12	5.1	1.6	0.3	—	0
12	100	76	53	34	20	9.8	3.9	1.1	0.2	—	0
13	100	75	51	32	18	8.2	3.0	0.8	0.1	—	0
14	100	73	49	30	16	6.9	2.3	0.5	0.1	—	0
15	100	72	47	28	14	5.8	1.8	0.4	—	—	0
16	100	71	46	26	12	4.9	1.4	0.3	—	—	0
17	100	70	44	24	11	4.1	1.1	0.2	—	—	0
18	100	69	43	23	10	3.5	0.8	0.1	—	—	0
19	100	68	41	21	9.0	2.9	0.7	0.1	—	—	0
20	100	67	40	20	8.1	2.5	0.5	0.1	—	—	0
25	100	63	34	15	4.8	1.1	0.2	—	—	—	0
30	100	60	29	11	2.9	0.5	—	—	—	—	0
35	100	57	25	8.0	1.7	0.2	—	—	—	—	0
40	100	54	22	6.0	1.1	0.1	—	—	—	—	0
45	100	51	19	4.5	0.6	—	—	—	—	—	0

	0	.05	.1	.15	.2	.25	.3	.35	.4	.45
50	100	73	49	30	16	8.0	3.4	1.3	0.4	0.1
60	100	70	45	25	13	5.4	2.0	0.6	0.2	—
70	100	68	41	22	9.7	3.7	1.2	0.3	0.1	—
80	100	66	38	18	7.5	2.5	0.7	0.1	—	—
90	100	64	35	16	5.9	1.7	0.4	0.1	—	—
100	100	62	32	14	4.6	1.2	0.2	—	—	—

Source: John R. Tylor (1982) *An introduction to error analysis: the study of uncertainties in physical measurements*

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