Low Energy Air Conditioning for Hot Climates

A thesis submitted to The University of Manchester for the degree of Doctor of Philosophy in the Faculty of Engineering and Physical Sciences

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Abstract

Fossil fuels are the major sources of electrical power generation in the world. Among all fossil fuels, oil is considered as the most sought-after fuel. The burden on countries that provide subsidized electricity produced from oil-fired power plants is noteworthy. Kuwait is a notable example of these countries. Electricity in Kuwait is heavily consumed by residential air conditioning, which comprises 60% of the total electricity generated at peak times on a hot summer day. From this perspective, residential air conditioning in Kuwait was selected to undergo further investigation regarding low energy air conditioning choices. Three solutions to control the rapid growth of demand for electricity by residential air conditioning are examined.

The first solution investigated assesses the orientation and grouping of houses in Kuwait in order to examine their effect on cooling load and electrical energy consumption for future houses. Four residential cases were developed; each case comprises six typical houses. The cases identified are: (1) single block facing east-west, (2) single block facing north-south, (3) double block facing east-west and (4) double block facing north-south. Cooling loads are calculated using the DesignBuilder building thermal simulation software. Case (2) is found to have the smallest cooling load, and case (1) the largest. The estimated savings from applying case (2) compared to the average of the four cases for the future houses planned to be built by the government by the year 2016 (i.e. approximately 20,000 houses) are found to be approximately $US 33 million of power system capital costs, 15 GWh per year of electrical energy consumption and 11 kilotons per year of CO₂ emissions.

In the second solution, a lifecycle cost analysis is performed to evaluate the economic feasibilities of electricity driven chilled water system compared to predominant air conditioning system in Kuwaiti houses which is Packaged- Direct Expansion. The study considers the total cash paid by the consumer and the total cash paid by the government, since electricity is subsidized in Kuwait. The study finds that the chilled water system is not cost-effective for consumers due to high installation cost. However, a chilled water system would be cost-effective for the government because it consumes 40% less electrical energy than Packaged-DX. So, the study suggests subsidising the installation of chilled water systems so that the installation cost to the consumer is the same as for Packaged-DX systems.

In the third solution, the study examines the viability of a single-effect LiBr absorption chiller driven by steam extracted from the steam turbine in the configuration of a combined cycle power plant (CCPP). The analysis shows that CCPP with absorption chiller yields less net electrical power available to utility grid compared to similar CCPP giving electricity to the grid and to Direct-Expansion air conditioning systems for the same cooling requirements. The reasons for that are the reduction in steam turbine power output resulted from steam extraction, and the amount of electrical energy required to operate the configuration of CCPP with absorption chiller.
Declaration

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Nomenclature

A  Annual cash flow in LCCA
Abs  Absorption
CW  Chilled Water
COP  Coefficient of performance
DX  Direct Expansion
h  specific enthalpy, kJ/kg
i  interest rate
d  discount rate
j  inflation rate
KISR  Kuwait Institute for Scientific Researches
ff  ratio of the concentration of the strong solution to the concentration of the weak solution
LCCA  Lifecycle Cost Analysis
LiBr  Lithium Bromide
m  mass flow rate, kg/s
MEW  Ministry of Electricity and Water
PAHW  Public Authority for Housing Welfare
P  Pressure, kPa
PV  Present Value in Lifecycle Cost Analysis
Q  Heat flow, kW
rp  Pressure ratio
R_o  Gas constant (kJ/kg.K)
s  entropy, kJ/(kg °K)
T  Temperature, °C
UPV  Uniform Present Factor in LCCA
v  specific volume, m³/kg
V  Volumetric flow rate, m³/kg
W  Mechanical power, kW
x  concentration (mass percentage of LiBr)
y  Steam turbine extraction to generator
**Greek Letters**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>η</td>
<td>Efficiency</td>
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<td>ρ</td>
<td>Density, kg/m$^3$</td>
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**Subscripts**

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<td>compressor</td>
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<td>combined cycle power plant</td>
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<td>HRSG</td>
<td>Heat Recovery Steam Generator</td>
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Chapter 1  Introduction to the Thesis

1.1  Introduction

Energy resources, especially fossil fuels, are of great importance to all nations, because these resources have created a boom in the development of all aspects of life in the last century. The significant growth in populations, in addition to rapid developments in industries, lifestyle, and comfort, has led to extensive use of these nonrenewable energy resources. Buildings represent significant consumer energy, since they account for 20 to 40% of the total energy consumption; buildings’ Heating, Ventilation and Air Conditioning systems (HVAC) account for almost half of the energy consumed in buildings and around 10 to 20% of the total energy consumption in developed countries (Lombard et al, 2008). Among all equipments and devices in buildings, air conditioning was found as the major source of energy consumption in hot climates countries, as addressed by Hart and De Dear (2004). From this perspective, hot climate countries that have high dry bulb temperatures and/or high relative humidity require effective and efficient air conditioning systems.

The effectiveness of any cooling system is usually defined according to its ability to provide the desired level of comfort for its users; the efficiency of the cooling system is a measure of its ability to provide thermal comfort with low electrical energy consumption. It is important to understand that the success of a low energy cooling system in one country may not ensure its success in another country. For example, the effective use of a solar cooling system depends on the amount of solar energy received from the sun and the amount of cooling needed; both of these parameters vary from one place to another. Furthermore, other regional factors that must be considered before setting priorities and developing solutions for the electrical energy demand problem also vary from one country to another. These factors include current population, anticipated population growth, current and projected electricity consumption, power generation methods, the cost of energy, building design methods, governmental energy consumption policies, and future strategic plans.

As a case study, this work aims to explore effective solutions for the rapidly increasing demand for electrical energy associated with air conditioning needs in
Kuwait. Residential air conditioning in Kuwait was selected based on a detailed analysis which will be presented in the beginning of this research.

1.2 Aim and Objectives

The aim of this research is to investigate solutions for reducing energy consumption and emissions due to air-conditioning, selecting Kuwaiti houses as a case study. The overall objectives of this study are as follows:

- Verify energy demand factors particularly factors affecting energy consumption in hot climate countries;
- Investigate residential cooling energy demand in Kuwait;
- Study orientation and grouping style of houses in Kuwait to verify the best style for reducing the cooling load and energy consumption;
- Examine the economic feasibility of electricity driven chilled water system compared to the predominant air conditioning system in Kuwaiti houses; and
- Study the application of combined cycle power plant supplying electricity and chilled water from absorption chiller for houses in Kuwait.
1.3 Research Methodology

This research was conducted based on the major steps illustrated in Figure 1.1. The figure shows the order of major steps that were used to achieve the objectives indicated in section 1.2 of this thesis.

Step 1: Review of world energy resources and factors affecting the consumption to verify that residential sector is a significant energy consumer and air conditioning is a major factor for high electricity consumption in hot climates countries

Step 2: Selection of hot climate country (Kuwait) to determine share of electrical energy usage for air conditioning

Step 3: Detailed analysis for Kuwait in terms of electrical energy usage, significant electrical energy consumers, electrical energy policy, residential buildings types, and major studies towards resolving air conditioning energy demand in Kuwait

Step 4: Identifying three possible solutions to undergo further investigation for the significant energy consumer (i.e. Residential sector in Kuwait)

Solution (1): The impact of orientation and grouping of houses in Kuwait on electrical energy consumption

Solution (2): The selection of efficient air conditioning system to replace the common air conditioning type used in Kuwait houses

Solution (3): Absorption chiller driven by steam extraction from combined cycle power plant to form the basis of district cooling scheme for Kuwaiti houses

Step 5: Calculate cooling load of common Kuwait houses by Building thermal simulation software

Step (6): Detailed analysis for solution (1)

Step (7): Detailed analysis for solution (2)

Step (8): Detailed analysis for solution (3)

Step (9): Concluding the study and identifying recommendations and future work

Figure 1.1 Major steps of the research
From figure 1.1, the methodology used to form the basis of steps 1 to 3 was based on a literature review by reviewing scientific publications and official reports. Step (4) was identified based on the outcome of the detailed analysis presented during step (3) of this research. For steps 5 to 8, the following was done;

Methodology followed for step (5):
- Selection of building simulation software.
- Identifying the input data required for calculating the cooling load of common Kuwaiti houses.
- Interpretation of the simulation results in accordance with the relevant Kuwaiti building energy standard.

Methodology followed for step (6), Solution (1):
- Identifying how solution (1) can be useful for future houses.
- Identifying the benchmarks on how energy savings from solution (1) can be determined.
- Verifying the savings in terms of costs and CO₂ emissions.

Methodology followed for step (7), Solution (2):
- A survey in AC market in Kuwait to obtain factors affecting the selection of air conditioning systems for housing.
- Reviewing the features of the common air conditioning system that is currently in use in Kuwaiti houses and the proposed efficient air conditioning type.
- Identifying life cycle cost analysis as the analysis selection tool for the studied air conditioning alternatives
- Obtaining annual electrical energy consumption associated with the studied air condition types by the help of the used building thermal simulation software.
- Applying the life cycle cost analysis for the studied air condition types.
- Analyzing the results.
Methodology followed for step (8), Solution (3):

- Review of thermodynamics of the combined cycle power plant
- Preparing the requirements of the analysis (e.g., cooling load profile of Kuwaiti houses, input data and assumptions required, output data).
- Previewing the computer software to be used.
- Arranging the model's equations and the system’s parameters in the program.
- Modeling the combined cycle power plant (CCPP) without an absorption chiller driving packaged DX air conditioning systems.
- Modeling the CCPP with a single-effect LiBr/water absorption chiller.
- Preparing the cooling load profile of the studied Kuwaiti houses in an external file (exported from the used building simulation software).
- Acquiring and analyzing the results.

In step (9), the methodology used to accomplish this step was based on majors findings obtained from steps 1 to 8 shown in Figure 1.1.
1.4 Thesis Organization

This thesis is divided into six chapters. Figure 1.2 shows the layout of this thesis. After an introduction in Chapter 1, Chapter 2 summarizes fossil fuels and energy resources in the world and provides an overview of the major consequences of energy consumption, particularly the demand on electrical energy.

In Chapter 3, one specific hot climate country, Kuwait, is selected for further analysis. This chapter gives an overview of electrical generation in Kuwait, discusses the energy consumed by the main users, and develops the residential cases to be studied. Chapter 4 presents the background and methods for cooling load calculations, and the solutions to be verified. Chapter 5 presents the data and results. Finally, Chapter 6 concludes this work and makes recommendations for the future.
Chapter 1: Introduction to the Thesis

Chapter 2: Energy and the implication of air conditioning energy demand in hot climates

Chapter 3: Electrical energy situation in Kuwait and identifying the cases to be studied

Chapter 4: Background and Methods

Chapter 5: Results and Discussion

Chapter 6: Conclusions, recommendations and future work

Figure 1.2: Thesis structure
Chapter 2  Energy and the implication of air conditioning energy demand in hot climates

2.1 Overview
Energy resources, especially fossil fuels, are of great importance to all nations, because these resources have created a boom in the development of all aspects of life in the last century. The significant growth in populations, in addition to rapid developments in industries, life style and comfort, has led to extensive usage of these nonrenewable energy resources.

This chapter presents a summary of fossil fuels and energy resources in the world and provides an overview of the major consequences of energy consumption and ways to verify the high demand on energy, particularly electrical energy.

The chapter also presents current patterns of electrical energy consumption in the world in general, in five countries in particular, and among major domestic consumers. The study in this chapter aims to verify that residential air conditioning significantly affects energy consumption, particularly in countries with hot climate conditions, and depend on invaluable energy resources.
2.2 Global Energy Consumption

Coal, oil, gas and nuclear energy are the major sources of energy, followed by renewable sources such as wood, peat and animal waste, which are unreliably documented in terms of consumption statistics (Renewables, 2007). The global final energy consumption is shown in figure 2.1.

![Figure 2.1: Global Final Energy Consumption for 2006 (Renewables, 2007)](chart.png)

As shown in figure 2.1, 79% of the world’s energy use comes from fossil fuels. This high demand on fossil fuels can be linked to the thermal efficiency and flexibility of use of fossil fuels, which has made fossil fuels seemingly irreplaceable in terms of overall efficiency and performance for myriad technologies and important applications. Their use in automobiles, aviation, electricity generation and other services highlight the linkage between energy services and quality of life.
2.3 Energy Demand and Future Needs

The global demand for energy is projected to rise sharply over the coming years because of the expected increase in population urbanization and modernization. The current population, which is about 6.5 billion, is expected to double by the middle of the current century (Dincer and Rosen, 1999). Among all energy sources, oil represents the main source of energy. Recent statistics show that oil represents about 35% of the world energy consumption resources (IEA, 2007). Because of the extensive usage of oil, a question has arisen as whether the oil resources can be sustained. In the developing economies, the demand for oil will rise because of consumption in the industrial, residential and services sectors (IEA 2004; IEA 2005). According to (IEA 2004), the projection for oil supply will jump from 77 million barrels per day (mb/d) according to the year 2000 statistics to 121.3 mb/d in 2030. However, the remaining oil reserves contain about 1,143.355 billion barrels (IEA, 2006).

It is important to acknowledge that the demand for oil will never stop so long as nothing changes; figure 2.2 shows the history and projections for the demand on oil and other global energy resources through 2030 (IEA, 2006). From the economic point of view, the oil industry is a profitable sector for some corporations and governments, and taxes from oil are a major source of income for about 90 governments (O’Rourke and Connolly, 2003). Therefore, any interruption in oil supply and processing industries will impact the economical and social aspects of the affected countries. More specifically, any effect on large consumers, such as electricity power plants, will be enough to interrupt most of the economic activities in any country. A complicated dynamic exists between securing our communities’ reserves, economies and comfort, and responding responsibly to the consequences that will result from the further consumption of oil reserves.
The uncertainties in oil supply and reserves have brought doubt to the oil markets, and the fluctuating oil prices and political stresses in hot spots on the earth are symptomatic of these doubts. The concerns about the oil supply are reasonable given the findings of studies regarding global oil reserves. Table 2.1 shows the longevity of supply of oil for selected countries (Holditch and Chianelli, 2008).

Table 2.1: The longevity of supply of oil for selected countries.

<table>
<thead>
<tr>
<th>Country</th>
<th>Years remaining for current oil reserves producing at current oil flow rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saudi Arabia</td>
<td>75</td>
</tr>
<tr>
<td>Iran</td>
<td>87</td>
</tr>
<tr>
<td>Iraq</td>
<td>168</td>
</tr>
<tr>
<td>Kuwait</td>
<td>105</td>
</tr>
<tr>
<td>United Arab Emirates</td>
<td>70</td>
</tr>
<tr>
<td>Russia</td>
<td>20</td>
</tr>
<tr>
<td>Venezuela</td>
<td>52</td>
</tr>
<tr>
<td>United States</td>
<td>16</td>
</tr>
</tbody>
</table>
2.4 Fossil Fuels and Environment

Figure 2.2 shows that oil is the most widely used fossil fuel, followed by coal. The use of oil for modern and newly developed societies is likely to be inevitable based on rapid development and human demands for comfort and convenience. However, continuation of the extensive use of oil will consume the reserves and lead to severe economic, social, political, environmental and health consequences.

From the environmental and health point of view, fossil fuels, mainly oil and coal, contribute to severe damage to the environment. Burning oil and coal releases large quantities of carbon dioxide (CO₂) into the atmosphere, which contributes to climate change and global warming. This environmental phenomenon has resulted in an increase in the average measured temperature of the Earth's near-surface air and oceans since the mid-20th century (IPCC, 2007). Impacts on human life are definite from the side effects of climate change (Asif and Muneer, 2007). Moreover, the biological consequences of global warming resulting from greenhouse gases, especially CO₂, can have a profound effect on the physiology of some species and the life cycle of many organisms (Hughes, 2000).

In light of the environmental impacts and in an effort to move toward a global emissions-reduction scheme, Japan has sponsored the establishment of an international agreement, the Kyoto Protocol. The protocol sets targets for 37 industrialized countries and the European community for reducing greenhouse gas (GHG) emissions, and it is directly linked to the United Nations Framework Convention on Climate Change (UNFCC, 2008).
2.5 Energy and Life Needs

Excessive amounts of CO₂ are released into the atmosphere on a continual basis as a result from activities considered essential to human comfort and convenience, including electricity generation. Modernization and improvements in quality of life have caused the demand for energy to reach high levels. Energy, especially electricity, touches on almost all aspects of life in all developed and newly developed societies.

Consumption per capita is the common measure of the demand on energy. Per capita energy consumption varies from country to country and, within a country, from region to region depending on the level of urbanization. According to Suthuye and Meyers (1985), consumption per capita is influenced by the growth in household income, which growth allows people to buy devices that use more energy, like refrigerators, water heaters and air conditioning. Also, consumption of energy in productive activities enables growth in income, because workers and business makers will be able to use power driven machinery which make them more productive. Figure 2.3 shows energy consumption per capita versus gross domestic product per capita (GDP/capita); which is a good indication of income. The figure illustrates that the consumption and GDP/capita tend to increase together, although there are wide variations around the general trend.

![Energy consumption per capita versus GDP per capita](Source: IEA, 2006)
2.6 Energy Resources and Electricity Generation

2.6.1 Shares of Energy Resources Used for Electricity Generation

The electricity generation sector is an important consumer of fossil fuels and renewable resources. To verify significant factors affecting consumption, the study herein presents an overview of electrical energy consumption per capita and shares of energy sources used to generate electricity in the world as a whole and in five specific countries. The five countries were selected based on their electrical energy consumption per capita, which are related to individual incomes, and climate conditions, which can influence electricity consumption.

Figure 2.4 shows energy sources used to generate electricity in the world and in the selected countries. From the figure, it is clear that the production of electricity in the world is highly dependent on fossil fuels, mainly coal, since the consumption of coal represents about 40% from the total resources used. This high dependence on coal exists in the USA, the UK, Australia, and India, whose consumptions of coal are 55%, 34%, 80% and 70%, respectively, of their entire domestic energy resources used to generate electricity. By contrast, in Saudi Arabia, the production of electricity depends on oil (51%) and natural gas (49%).
Figure 2.4: Percentages of energy sources used to generate electricity in the world and in five selected counties (IEA, 2005)
2.6.2 Consumption by Residential Sector and Demand Factors

Electrical energy consumption for residential sectors is a critical issue for many regions in the world, especially developed countries and urbanized cities. Figure 2.5 shows the percentages of national electrical energy shares by various consumers in the world and in five selected countries. In the same context where Figure 2.4 has been analyzed, Figure 2.5 shows that the share of residential sector electrical energy consumption in Saudi Arabia is notable. The residential sector in Saudi Arabia is the highest percentage consumer of national electricity among the five selected countries because of the hot climate conditions; air conditioning systems during summer account for about 65% of the total electricity consumed in Saudi Arabia (Al-Hammad and Assaf, 1992). It is not surprising that Saudi electricity suppliers face shortages in electricity during the summer (Hasnain and Alabbadi, 2000). On this point, the high consumption of electricity as a result of climate conditions and thermal comfort applications has been addressed by several studies. Rajan and Jain (1999) indicated that weather is one of the main factors influencing energy consumption patterns. In the UK, for example, 58% of the total energy delivered to the residential sector is used for space heating (DTI, 2005), while 43% of the total energy delivered to the residential sector in the USA is used for cooling and heating (DOE, 2005). Furthermore, a study on weather sensitivity in household appliances energy end-use has been conducted in Australia by Hart and De Dear, (2004). The major outcomes of the study indicated that space cooling consumes a large amount of energy and is directly affected by outdoor wind speed, relative humidity, and air temperature. Therefore, weather is a major factor for energy consumption in residential sectors around the world, and it represents a major challenge for countries such as Saudi Arabia, which rely on electrical energy as a major energy source for cooling purposes.
Figure 2.5: Percentages of electrical energy shares by various consumers in the world and in five selected counties (IEA, 2005)
From Figure 2.5 also, the world average percentage for residential use is 28.3% and four of the selected countries, excluding India, are above this average. This can be explained due to the variation in modernization and life style between India, on one hand, and the other four countries, on the other. Accordingly, a summarized conclusion of this analysis can be obtained from Figure 2.6 which shows residential electrical energy consumption and electricity consumption per capita based on the world average and the five selected countries. From this figure, the selected countries, excluding India have residential electrical energy share and per capita electrical energy above the world average.

Figure 2.6: The percentage of residential electrical consumption nationally and per capita consumption in the world and five countries, (IEA,2005)
2.7 Significant Energy Resources and Hot Climates

It was shown in the previous section that major energy consumers such as the electricity generation and major electricity consumers such as the residential sector are of high influence on energy resources. Weather and incomes are major factors that influence consumption. Hot weather which leads to high air conditioning needs represents a considerable factor for energy consumption in countries with harsh summer, such as Saudi Arabia. Conventional air conditioning systems consume large quantities of electricity, making them expensive in resources, and contributing global warming. Along with effective electricity generation methods, low-energy appliances, particularly low-energy air conditioning systems, are attractive solutions. Countries with hot climate conditions and full dependence on fossil fuels, as is the case for Saudi Arabia, will benefit in terms of energy availability and low emissions if such low-energy systems are adopted. Based on this, it was decided to undertake a detailed analysis of one specific hot climate country to make sure that the hot weather leading to high consumption of residential electricity is a significant consumer of nonrenewable energy resources.
2.8 Specific Hot Climate Country with High Reliance on Oil: Kuwait

Kuwait has harsh outside climate conditions with average ambient temperature of around 45 °C during the summer months (Kuwait International Airport, 1983), which requires the use of air conditioning systems from April through October. Buildings in Kuwait are subject to high ambient air temperatures and to strong solar radiation, which reaches as high as 940 W/m² on a horizontal surface in the summer (Alison, 1979). Figure 2.7 shows the variation of dry bulb temperature based on the average of many hot days.

![Figure 2.7: Variation of dry-bulb temperature during summer day in Kuwait (Kuwait International Airport, 1983).](image)

Electrical energy in Kuwait is generated by conventional steam power plants, which depend primarily on fuel oil. Continued use of the current power plant technology that depends extensively on Kuwait oil will have severe adverse impacts on the country's economy, considering that oil is the major source of national income. Darwish et al (2008 a) conducted a study for the local consumption of Kuwait’s oil for power generation and water desalination which indicated that in about 30 years, the total oil production may not be enough to provide fresh drinking water for people and allow them to live in air-conditioned spaces.
In light of the facts about factors that affect energy consumption in the world in general, and in hot countries in particular, the statistics related to national annual electrical energy consumption were analysed. Figure 2.8 shows the maximum and minimum monthly electrical energy consumption in Kuwait using the annual electrical statistical book for the year 2006 (MEW, 2007).

![Figure 2.8: Maximum and minimum electrical energy demand in Kuwait during the year 2006.](image)

It can be seen that the maximum and minimum demands rise in the summer and fall in the winter. As other factors that might be expected to influence electricity consumption (daylight, holidays, etc.) do not vary much in Kuwait, the obtained conclusion is that this is due to varying cooling and heating loads. Air conditioning in the Kuwaiti residential sector is from the beginning of April to the end of October (Alajmi et al. 2006). Moreover, according to our observation, no heating is required during the second half of February and March. Now, based on the maximum and minimum electrical demands obtained from Figure 2.8, the electrical energy required for operating air-conditioning systems during peak usage days in the summer can be estimated by taking the difference between maximum and minimum demands during the year. The minimum system demand was about 2710 MW<sub>e</sub> at 14:00 hours on February 25, 2006 (MEW, 2007). In February the temperature is relatively moderate and no heating or cooling systems were required during this month. Also, most of the lighting systems in the buildings and on the streets are switched off at this hour (14:00). The maximum demand was 8900 MW<sub>e</sub>, and it occurred at 15:30 on July 26, 2006, at which time the highest outside temperature for the year also occurred.
Consequently, the difference between the minimum demand and the maximum demand was 6190 MW\textsubscript{e}, which amounts to about 70\% of the total energy generated at the time of maximum demand. The difference is expected to be due to the operation of air-conditioning systems in all buildings in Kuwait. To estimate the share of residential sector air conditioning, we must know the percentage of residential buildings among all buildings types in Kuwait. Residential buildings represent about 84\% of the total number of buildings in Kuwait (MEW, 2007). Using the percentage obtained on the national level for the energy consumption attributed to air-conditioning, i.e., 70\%, it can be said that residential air-conditioners consume 55 to 60\% of the total electrical energy delivered by power plants at peak usage time on a hot summer day in Kuwait
2.9 Conclusion

Fossil fuels, especially oil, are an important global energy resource. The extensive usage of global energy resources has negative impacts on many aspects of life and concerns about future demands on energy resources are considerable. The chapter indicated that there is an approximate relationship between energy consumption and income. Hot weather was also found to be a significant factor for energy consumption in countries that have harsh summer conditions. Kuwait was selected for additional analysis of its electrical energy usage. The findings showed that residential cooling is a significant factor for electricity consumption in Kuwait. The concerns about future demands on energy resources are considerable.
Chapter 3  Electrical Energy Situation in Kuwait and identifying the Cases to be Studied

3.1 Introduction

Kuwait is a hot-climate country in the Arabian Gulf that has harsh outside climate conditions, which require running AC systems from April through October. It was shown earlier that energy consumption attributed to air-conditioning in Kuwait is about 70% of the total electrical energy delivered by power plants at peak usage time on a hot summer day in Kuwait. The impacts of peak demand were experienced during the summer of 2006, when MEW was forced to control electrical demand by applying scheduled load reductions and power cuts in order to keep the demand within the maximum installed capacity of power stations. This intervention by MEW led to an argument between the parliament and the government. However, the building owners/users were not very concerned, because the government of Kuwait subsidizes about 93% of the cost domestic energy consumption (Al-Ragom and Al-Ghimlas, 1998).

This chapter will include information related to energy policies in Kuwait, electrical power plants, and air conditioning energy demand in the country. Moreover, the chapter will explore the common residential building in Kuwait and its features. Finally, the chapter will end up developing the cases to be studied; which will be utilized for cooling load calculations in a later stage of this work.
3.2 Electrical Energy Demand in Kuwait

Kuwait is a small country located in the northwestern corner of the Arabian Gulf. The total land area of Kuwait is 17818 km². Development in Kuwait has increased sharply during the past 40 years. Due to the abundance of job opportunities, expatriates, mostly from Asia, Egypt, and Iran, have moved to Kuwait to enhance their incomes. From 1965 to 1995, the population increased from 467,339 in 1965 to 1,575,982, in 1995 and 3,182,960 in 2006 (MEW 2007). The rise in population is apparent in increased electricity consumption shown in Figure 3.1.

![Figure 3.1: Annual electrical energy consumption in Kuwait, (MEW, 2007)](image)

In Kuwait, electricity is subsidized, the relatively low electric tariff that the consumers must pay is KD 0.002 per Kilowatt hour (0.002 Kuwaiti Dinar per kWh is equivalent to US $ 0.006 per kWh according to exchange rate in April 2010). In recent years, the Kuwaiti government has become more aware of the importance of energy conservation practices, especially after the Gulf war in 1991, when huge expenditures were paid to repair the damage that resulted from Iraq's invasion. For these reasons, the Kuwaiti government is trying to find effective solutions for the electricity supply problem. This has led to several studies, symposia, and energy conservation measure programs being conducted by the Kuwait Institute of Scientific
Research (KISR) and to MEW’s speaking out assertively about this issue, as will be shown later.

It was concluded (EIA, 2004) that Kuwait must invest around US$ 4 billion over the next ten years to finance an expansion program for an additional 3.4 GWe of electricity to meet the predicted demand. The true cost of generated electricity to the Kuwaiti government is about 16 times the price at which it is sold (Al-Awadi et al., 1989; Eltony, 1998). A conventional steam power plant costs approximately $1500/kW, including installation, transmission, power transformation, and distribution and supply, and construction takes about seven years from order to installation (Darwish, 2007). The government may well be forced to erect new fossil-fuelled power stations as the most obvious solution, although this will have a direct impact on sustainable environment and contributes to the risk of global warming if the existing technology of power generation by using carbon-intensive heavy fuel oil is continued.

The proportion of electrical energy consumed by each sector in Kuwait is shown in Figure 3.2 (MEW, 2007). The Figure shows that 47% of electricity generated by power stations in Kuwait is consumed by the residential sector.

![Figure 3.2: Sector-wise proportional load distribution during 2006 (MEW, 2007)](image-url)
3.3 Electrical Power Plants in Kuwait

Power stations in Kuwait are operated by fossil-fuel energy, mostly fuel oil. The consumption of fossil fuel (oil and natural gas) has increased in recent years due to the extensive use of electrical energy and desalinated water. In 2006, the amounts of fuel oil and natural gas consumed by power stations were 67.7 million barrels and 123.5 billion m³, respectively (MEW, 2007). The total cost to the government for fuel to generate energy was slightly more than one billion KD, which is equivalent to 3.6 billion US $ (MEW, 2007). The use of fossil fuels to run power plants is having a negative effect on the environment as the result of a variety of pollutant emissions, especially CO₂. Based on the operational conditions for Kuwait’s power plants, approximately 0.72 kg of CO₂ is emitted into the atmosphere for every kWh of electricity produced (Hajiah, 2006). Figure 3.3 shows the plume containing pollutant emissions from a steam power plant in Kuwait.

Figure 3.3: Emissions generated from steam power plant in Kuwait
3.4 Houses in Kuwait

There are two main types of houses in Kuwait. One is designed by the public authority for housing welfare (PAHW), and is made available to limited-income families through a rent-to-own public housing program (Figure 3.4). The other type is the private house, which is usually financed by the government based on a long-term loan and built by the owner of the house (Figure 3.5). Most of the houses in Kuwait are of the first type, and both types are built based on energy code requirements in terms of thermal performance of the exterior walls and roof, described later. However, the owner of a private house has the right to design and shape it the way he likes. Some private houses are designed with a large area of glass, which represents a complete disregard of climate conditions and of efficient use of air conditioning (Figure 3.6).

Figure 3.4: Typical Kuwaiti House distributed by PAHW for families with limited income based on rent to own strategy.
Figure 3.5: Private house sponsored by the government and built by the owner of the house.

Figure 3.6: Private house with large windows which represents complete disregard to weather conditions and efficient use of AC system.
3.5 Housing Projects in Kuwait

As indicated previously, the residential sector in Kuwait is a significant consumer of electrical energy produced by power plants in Kuwait. Hence, having an idea about future housing projects is imperative for planning electricity supply. The public authority for housing welfare (PAHW) has plans to build five residential cities between July 2008 and April 2016, as shown in Table 3.1 (PAHW, 2008). According to the five-year plan published by the PAHW for the years 2011-2016 (PAWH, May 2008), the housing program will include 19568 houses, while the remaining residential units will be villas and apartments.

Table 3.1: Residential Projects in Kuwait

<table>
<thead>
<tr>
<th>City</th>
<th>Construction project started</th>
<th>Construction project completed</th>
<th>Number of residential units</th>
<th>Electrical capacity required MW&lt;sub&gt;e&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sabah Al-Ahmad</td>
<td>July 2008</td>
<td>November 2011</td>
<td>9266</td>
<td>926.6</td>
</tr>
<tr>
<td>Jaber Al-Ahmad</td>
<td>February 2009</td>
<td>April 2013</td>
<td>6710</td>
<td>671</td>
</tr>
<tr>
<td>North-West Al-Sulaibikat</td>
<td>June 2009</td>
<td>February 2012</td>
<td>1736</td>
<td>173.6</td>
</tr>
<tr>
<td>Al-Khairan</td>
<td>August 2009</td>
<td>July 2014</td>
<td>35844</td>
<td>3584.4</td>
</tr>
<tr>
<td>Al-Mutlaa</td>
<td>April 2011</td>
<td>April 2016</td>
<td>18000</td>
<td>1800</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>-</td>
<td>71556</td>
<td>7155.6</td>
</tr>
</tbody>
</table>

From the above Table, the total installed electrical energy required for these residential units will be more than 7150 MW<sub>e</sub>. According to (Hamdan, 2008), estimations for electrical energy required for other buildings such as public buildings, schools, clinics, and other services is generally taken as 20% of the total installed capacity for residential units for each city. This will result in an additional amount of approximately 1430 MW<sub>e</sub>. Therefore, the total electrical energy capacities required to be installed for new residential cities by 2016 is approximately 8600 MW<sub>e</sub>. This is close to the total installed capacity of power plants in Kuwait in 2006 (10189 MW<sub>e</sub>) (MEW, 2007).
3.6 Overview of Major Energy Research and Conservation Measures in Kuwait

Oil and natural gas represent around 90% of the total revenues of Kuwait. In the mid-1970s, after the oil embargo (1973/1974), the government of Kuwait established a scientific and research institution concerned with oil, energy, water, and the environment, called Kuwait Institute of Scientific Research (KISR). Concerning KISR has two main programs for energy research, which are Energy Efficiency Enhancement and Energy Conservation Program, and Renewable Energy Application Program. KISR defined the following strategic goal for the energy sector: to evaluate and promote modern energy techniques and to develop sustainable procedures for innovative use of energy resources, achieve maximum efficiencies and cost-effectiveness, and protect the natural environment. KISR initiated serious research efforts in the late 1970s to address the energy problems in Kuwait.

3.6.1 Energy Efficiency Enhancement and Energy Conservation Program (EEE & ECP)

The doubts about sustainability of Kuwait’s oil reserves and the fluctuations in the price of crude oil encouraged the decision makers in the government to look for energy conservation measures, improving power plants efficiency, and renewable energy, especially solar energy. A symposium was held in Kuwait (KFAS, 2007) to discuss innovative solutions for desalination and power generation. At the end of the symposium, experts offered several recommendations, such as improving power plants for electricity generation and water desalination and examining the application of renewable energy technology for Kuwait.

KISR consider this program a priority among all research programs. In this program, there are three areas for research, which are in sections 3.6.1.1 to 3.6.1.3 below:
3.6.1.1 Energy Conservation Code of Practice for Buildings

The main effort that has been done by researchers at KISR is the "Energy Conservation Code of Practice for Buildings," which was afterwards enforced by MEW beginning in 1983. The code stipulates minimum thermal insulation requirements for walls and roofs, maximum glazing areas for a given type of glazing, and minimum ventilation rates; controls the performance rating of different types of AC systems; and does not permit the cooling demand or power requirement per unit area to exceed a specified value for a given building and type of AC system. The success achieved from implementing the code is evident in that any fully-complying building is estimated to need 40% less cooling than the same building constructed before the code was established (Mahshewari, 2008). Meerza and Mahsehwari, 2002, estimated that, from the time the code was implemented until 2001, the savings were over 1763 MW of peak power, and nearly 78 million barrels of fuel. The estimated cost benefits were KD 1.535 billion (US$ 5.53 billion), and there was a reduction in CO₂ emissions of more than 30 million metric tons.

The maximum permitted installed power of different standard buildings, the maximum power rating for different types of AC systems and their components, and the minimum requirement for glazing quality in relation to window-to-wall ratio are shown in Tables 3.2, 3.3, and 3.4, respectively (Hussain and Al-Mulla, 2007).
Table 3.2: Maximum permitted installed power of different standard building

<table>
<thead>
<tr>
<th>Building Type</th>
<th>Lighting (W/m²)</th>
<th>AC systems (W/m²)</th>
<th>Water-Cooled Chiller</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>DX*</td>
<td>Air-Cooled Chiller</td>
</tr>
<tr>
<td></td>
<td></td>
<td>250</td>
<td>250 &lt; RT &lt; 500</td>
</tr>
<tr>
<td>Residential</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Villa</td>
<td>10</td>
<td>60</td>
<td>71</td>
</tr>
<tr>
<td>- Apartment</td>
<td>10</td>
<td>60</td>
<td>71</td>
</tr>
<tr>
<td>Clinic</td>
<td>20</td>
<td>85</td>
<td>100</td>
</tr>
<tr>
<td>School</td>
<td>20</td>
<td>100</td>
<td>118</td>
</tr>
<tr>
<td>Mosque</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Prayer area)</td>
<td>20</td>
<td>115</td>
<td>135</td>
</tr>
<tr>
<td>Fast food restaurant</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- stand-alone</td>
<td>20</td>
<td>145</td>
<td>171</td>
</tr>
<tr>
<td>- In a mall</td>
<td>20</td>
<td>120</td>
<td>141</td>
</tr>
<tr>
<td>Office</td>
<td>20</td>
<td>70</td>
<td>82</td>
</tr>
<tr>
<td>Shopping mall</td>
<td>40</td>
<td>70</td>
<td>82</td>
</tr>
<tr>
<td>Community hall, dining</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>hall, theatre</td>
<td>20</td>
<td>115</td>
<td>135</td>
</tr>
</tbody>
</table>

(*) DX= Direct Expansion

Table 3.3: Maximum permitted power rating for different types of AC systems and their components

<table>
<thead>
<tr>
<th>System</th>
<th>Power Rating (kW/RT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>PR&lt;sub&gt;CHILL&lt;/sub&gt;</td>
</tr>
<tr>
<td>Ducted, split, and Package units</td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>-</td>
</tr>
<tr>
<td>Air-Cooled</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>1.600</td>
</tr>
<tr>
<td>100-250</td>
<td>-</td>
</tr>
<tr>
<td>250</td>
<td>-</td>
</tr>
<tr>
<td>Water-Cooled</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>0.950</td>
</tr>
<tr>
<td>250-500</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>0.750</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

RT = refrigerating ton, PR = power rating, CHILL = chiller, CTF = cooling tower fan, CW = condenser water pump, CHW = chilled water pump, AH = air handling unit, T = total
### Table 3.4: Window's glazing specifications with respect to window-wall ratio

<table>
<thead>
<tr>
<th>Glazing Type</th>
<th>SHGC*</th>
<th>TV**</th>
<th>U-Value (W/m²·K)</th>
<th>Window-to-wall Ratio maximum permitted</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-mm single-clear</td>
<td>0.721</td>
<td>0.8</td>
<td>6.21</td>
<td>≤5</td>
</tr>
<tr>
<td>6-mm single-reflective</td>
<td>0.314-0.371</td>
<td>0.16-0.27</td>
<td>6.41-6.44</td>
<td>6-10</td>
</tr>
<tr>
<td>6-mm double-tinted</td>
<td>0.36-0.40</td>
<td>0.357</td>
<td>3.42-3.44</td>
<td>11-15</td>
</tr>
<tr>
<td>6-mm double-reflective</td>
<td>0.245</td>
<td>0.228</td>
<td>3.38</td>
<td>16-50</td>
</tr>
<tr>
<td>6-mm double-spectrally selective</td>
<td>0.356</td>
<td>0.565</td>
<td>1.71</td>
<td>51-100</td>
</tr>
</tbody>
</table>

* SHGC is solar heat gain coefficient
** TV is visible light transmittance coefficient

#### 3.6.1.2 Energy Audits in Air-Conditioned Buildings

Another approach KISR has adopted is the energy auditing strategy for large buildings. The objectives of the energy auditing strategy are to reduce the expenditure on energy, conserve oil since it is the primary source of national revenue, and reduce power plant emissions of global warming gases. Since 1985, the Energy Department at KISR has conducted several studies to manage electrical energy consumed by AC systems in buildings in Kuwait, especially governmental buildings. A study of five buildings at KISR during non-occupancy periods using programmable thermostats was made, and it produced savings in the range of 33-35% of energy consumed during peak summer months (Al-Homoud et al., 1985).

KISR has also implemented two techniques to control both thermal comfort and lighting inside some buildings. Energy audits by implementing Pre-Closing Treatment (PCT) and Time-of-Day Control (TDC) were conducted at the MEW and MPW complex during the summer of 2004. The techniques helped to reduce the annual energy consumption by the buildings by over 20%, and the power demand was reduced by 5.1% between 13:00 h and 14:00 h and by more than 38% after 14:00 h (Al-Ragom et al., 2005). Researchers at KISR are encouraging the government and all building owners to look for PCT and TDC as an immediate solution to the high demand for electrical power by their buildings.


3.6.1.3 District Cooling

As illustrated earlier, the residential sector accounts for about 47% of the electrical energy consumed in Kuwait. Most of the houses in Kuwait use conventional cooling systems that consist of package DX-units. Application of District Cooling (DC) was founded to be an attractive area for further research by KISR researchers. Hajiah et al., 2006, conducted an analytical study for a newly-developed residential area south of the Doha residential area. The study outlined that power consumption could be reduced by 31.1%, if a DC system had been used. However, no attempts have been made to assess the economic viability of applying chilled water systems for houses in Kuwait.

Darwish and Maarafi, 1987, recommended in a general estimation study to use district cooling for a newly-planned university campus with a surrounding residential and commercial area. They indicated that absorption air conditioning would use only 20% of the electric power required for a conventional cooling system. But, their study was established on peak cooling load size, not on a comprehensive cooling load profile, because they did not estimate the annual cooling requirements.

Darwish (2001) recommended utilizing heat generated at the co-generation power and desalination plant (CPDP) to drive absorption water chillers for district cooling. It is worth mentioning that most power plants in Kuwait are operated by steam turbine units with oil-fired boilers. A strategic plan has been made by the Kuwaiti government to replace most of the power generation plants based on oil-fired boilers by erecting combined cycle power plant (gas turbine with heat recovery steam generator and steam turbine) (Saud, 2009). Hence, question arises of utilizing these plants to drive absorption chiller plants for district cooling applications.
3.6.2 Renewable Energy Application Program

The renewable energy program is the second major program in KISR. Renewable energy has been a questionable area for Kuwait and KISR in the last three decades. A number of theoretical and experimental studies have been conducted by KISR researchers to study the feasibility of applying renewable energy, such as solar energy. Examples include a 100-kW solar thermal power station using a parabolic dish collector which was commissioned late in 1970 (Al-Kandari et al., 1988). Also, cooling systems of small and medium cooling capacity using flat plate collectors and vapor absorption chillers, a 40-kW photovoltaic (PV) solar system for a school, and small PV units for traffic lights were installed between the mid-1970s and mid-1980s (Mahsewari, 2008). All of these studies concluded that solar energy systems are not cost-effective due to their initial cost, poor efficiency, and high maintenance cost, compared to the cost of power generated from fossil fuels. A theoretical study of the cost of electrical energy generated by a photovoltaic solar collector compared to electrical energy generated by fossil fuel at Kuwait power plants showed that the photovoltaic collector was not cost-effective for Kuwait (Al-Hasan, 1997), but it showed promise for use in peak-load shaving during the summer months.

The new developments related to the use of solar energy around the world may increase the potential of using this power source in Kuwait, despite the country’s past negative experiences with this power source. Figure 3.7 shows that Kuwait receives a great amount of solar radiation around the year, especially during summer season.
Figure 3.15: Monthly global solar radiation in Kuwait, (KISR, MTY 1999)
3.7 Identifying the Cases to be studied:

Residential buildings in Kuwait represent 84% of the total number of buildings (MEW, 2007). Al-Ragom (2003) indicated that 69% of the total number of residential houses have been built by the National Housing Authority. An example of these houses was illustrated previously in Figure 3.4. These houses are of standardised shape, size and structure. However, the government offers renovation loans for the home owners to expand and improve the structure of their houses provided they comply with the Energy Conservation Code of Practice (Al-Ragom, 2003).

In this study, a short investigation has been conducted by the author to determine the common shape of these renovated houses (April 2009). The findings indicated that there is a boom in renovation projects to add a third storey, and the renovated houses shape is typically rectangular. Figure 3.8 shows examples of renovation projects in Kuwaiti houses.

Concerning the dimensions of the typical Kuwaiti houses, the land area of each house is about 400 m² and each storey is 4 meters in height (Hamdan, 2009). The layout and orientation of the houses can be gained by the use of the program "Google earth". A satellite image (Figure 3.9) shows typical house arrangements and orientations in Kuwait. It is clear from the figure that there are four cases which need to be considered; namely single block east-west and north-south; double block east-west and north-south. Therefore, the study will consider 6 houses under the same simulation conditions to be arranged according to figure 3.9. These houses will be modelled in a computer program later in the study.
Figure 3.8: Renovation projects to add a third storey in Kuwaiti houses
Figure 3.9: Common arrangements and orientations of Kuwaiti houses
3.8 Conclusion

The chapter shows that urban development, the subsidized energy, and the reliance on AC systems for cooling during the harsh summer season have negative impacts on the electrical energy usage in Kuwait. Among all electrical energy consumers, the residential sector founded to be worthy for further investigation to look at low energy air conditioning solutions. The study also indicated that all power plants in Kuwait burn fossil fuels, mostly heavy fuel oil that is associated with high levels of various emissions, especially CO$_2$ that is known to have an adverse effect on the environment worldwide. From this perspective, the great challenge for the Kuwaiti government is that the country is almost exclusively dependent on Kuwait oil revenues that are being increasingly consumed for power generation.

Residential buildings which form about 84% of the total number of buildings require practical solutions. The rapid increase in number of residential projects in Kuwait conflicts with providing solutions like energy auditing for every house in particular. The only success in the country for residential buildings is the implementation of energy conservation code of practice. Although, the current orientation and grouping patterns of houses in Kuwait is not considered by the energy conservation code, and no efforts have been made to substantiate the best orientation and grouping style of houses.

The use of efficient air conditioning systems such as chilled water systems for new residential areas was discussed as a promising solution in terms of energy saving only. However, no attempts have been made in Kuwait to discuss the entire economical consequences for both the consumers and the governments.

Due to the need for constructing new power stations to meet the demand for electricity, the Combined Cycle Power Plant (CCPP) probably provides a feasible solution for district cooling scheme due its high thermal efficiency and low CO$_2$ emissions compared to a conventional steam power plant using heavy fuel oil.
The findings presented in this chapter support the idea that a typical Kuwait house needs to be studied to examine different air conditioning solutions. As an initial step towards looking for effective solutions, the study identified the type of house that needed to be studied. For the selected type of house, four arrangements were chosen to undergo analysis. It is therefore necessary to know the cooling load of the selected cases. This will be based on the use of building thermal simulation, as will be shown in the next chapter.
Chapter 4 Background and Methods

4.1 Introduction

In this chapter the methods needed to study the three solutions that were identified earlier are presented. Each solution has specific requirements; however, calculating the cooling load for Kuwaiti houses is necessary before verifying the solutions (Figure 4.1).

![Diagram]

Kuwaiti Houses Cooling Load

- Impact of orientation and grouping of houses on cooling load
- Lifecycle cost analysis for the best air conditioning choice
- Combined cycle power plant with absorption chiller

Figure 4.1: Three potential solutions for reducing air conditioning electrical energy demand of Kuwaiti houses.

Based on the figure above, the cooling load calculation method will be described first, followed by the methods needed for the three solutions.
4.2 Building Cooling Load Calculations

4.2.1 Theory

Cooling load is defined as the rate at which the cooling equipment would have to remove thermal energy from the air in the space in order to maintain constant temperature and humidity (Kreider et al, 2002). Obtaining cooling load of the building is a primary step to determine the appropriate size of the building air conditioning system and predict its associated energy consumption. There are two types of cooling loads, one is sensible cooling load; due to heat transfer to the indoor air; the other is latent cooling load; due to the water vapor input to the indoor air.

The design of the building has a major effect on the cooling load. According to ASHRAE Fundamentals (2005), a cooling load calculation determines total heat gains from:

1. Opaque surfaces (walls, floors, ceilings, and doors).
2. Transparent fenestration surfaces (windows, skylights, and glazed doors).
3. Infiltration
4. Heat sources in the conditioned spaces (people, lighting, equipment).

Figure 4.2 shows cooling load components.

![Cooling load components](source: Benjamin, 2011)
Heat gain through exterior opaque surfaces is derived as a function of the mass and nature of construction which affects the rate of conductive heat transfer. For the heat gains through fenestration, ASHRAE fundamentals handbook (1997) indicated that the heat admission through fenestration areas is affected by many factors including:

- Solar radiation intensity and incident angle (Figure 4.3).
- Outdoor-indoor temperature difference.
- Velocity and direction of airflow across the exterior and interior fenestration surfaces.
- Low-temperature radiation exchange between the surfaces of the fenestration and the surroundings.
- Exterior and/or interior shading.

![Diagram of incident angle and solar radiation through glazing](image)

Figure 4.3: Incident angle and solar radiation through glazing

For the infiltration, pressure differences due to wind and to inside-outside temperature difference cause outdoor air to infiltrate into cracks around doors and windows, resulting in sensible and latent heat gains. Heat sources in conditioned spaces are classified as people, lighting and equipment. Heat gains from people depend on the activity, the occupancy period, and the gender and age of people. The heat gain from people has two components: sensible and latent. The total and the proportions of sensible and latent heat vary depending on the level of activity and the surrounding temperature, humidity and air velocity. Heat gains from lighting depends on the installed lights wattage, diversity factor and operation period. Finally, heat gain from equipment such as televisions, refrigerators and printers depends (as for lighting) on installed wattage, diversity and operation period.
4.2.2 Building Energy Simulation Software

Building energy simulation software allows evaluation of each aspect of a building's energy consumption; including cooling load; before the construction stage, and during the actual operation of the building. Mohammad Al-Homoud, (2001) stated that "energy simulation models are electively used for the design and prediction of building thermal performance". This can assist buildings’ designers and operators to achieve greater optimization of the buildings’ energy consumption. Knowing the capabilities of building energy simulation programs is a major factor in the selection method. Crawley et. al. (2005) studied the capabilities of building energy simulation programs in a study sponsored by the U.S. Department of Energy. The comparison between programs was based on general features and capabilities, the features and capabilities of loads, and the features and capabilities of HVAC systems. According to this comparison, the EnergyPlus simulation program has the best features and capabilities among the programs evaluated.

EnergyPlus was initially designed based on the best features and capabilities of BLAST (Building Loads Analysis and System Thermodynamics) and DOE-2 (Department of Energy). The best features of BLAST are heat balance calculation, interior surface convection, thermal comfort, and atmospheric pollution calculation; while the best features in DOE-2 are input functions, advanced fenestration calculations, day lighting illumination control, and anisotropic sky model (Crawley et. al., 2001). EnergyPlus has passed the comparison test for ASHRAE Standard 140P and the heat exchange test for BEPAC (Building Environmental Performance Analysis Club) (Liu et al., 2007).

EnergyPlus program performs cooling load calculations by the standard ASHRAE Heat Balance Method (DesignBuilder Manual, 2009). ASHRAE Heat Balance Method depends on computing energy transferred to or generated within the air-conditioned space based on sub-hourly time steps to provide a simultaneous building and systems solution (EnergyPlus Manual, 2001). Hence the variation of cooling load with time is determined based on time-step calculations to allow for variations in ambient and inside conditions with respect to time.
EnergyPlus is written in FORTRAN, the structure and modularization of which make it easy to maintain, renovate, and extend. But the input and output data are as ASCII text (American Standard Code for Information Interchange), which maybe inconvenient for users. This encouraged the creation of user interface software such as DesignBuilder. The first version of DesignBuilder was released in December 2005. The combination of DesignBuilder and EnergyPlus successfully passed Building Thermal Envelope and Fabric Load Tests from ANSI/ASHRAE Standard (ASHRAE 140 Envelop Test, 2006). It is one of the four programs commonly used by engineering consultants (M.F. Jentsch et al, 2008).

As well as consultants, DesignBuilder has also been used by several building simulation researchers. Chowdhury et. al, (2008) used DesignBuilder for the modeling and simulation of energy consumption of a building in Central Queensland University in Australia. The authors also indicated that DesignBuilder is one of the best interfaces to model building energy performance through EnergyPlus based simulation. Valdiserri et al. (2007), used DesignBuilder to evaluate the annual heating requirements for two different buildings located in the north-centre of Italy. Piechowski and Rowe (2007), used the software to explore the link between the selection of an air conditioning system, its design and controls on the thermal comfort and the building energy efficiency for an airport terminal building in a tropical climate in northern Australia. Rilling et. al, (2007), described how the cooling load of residential buildings can be predicted by utilizing buildings simulation software. They focused on the orientation as well as set-up of the buildings construction with the help of the DesignBuilder program. Ortiz et al (2009) used DesignBuilder in the evaluation of building’s energy consumption during the operation phase of HVAC for a residential dwelling in Catalonia in Spain. Krneta et. al (2007) used DesignBuilder to examine the heat gains through windows for a classroom in a school in Serbia. Masoso and Grobler (2008) used the program to study the relation between internal heat gains, cooling set point-temperature and insulation U-value and their impact on the annual cooling energy consumption.
### 4.2.3 Cooling Load and Building Energy Calculations

In building energy simulation programs, cooling load requires the inputs as described in Figure 4.4 below:

![Simulation inputs requirements](image)

**Figure 4.4: Simulation input requirements for cooling load calculations**

The simulation inputs required for cooling load calculations are (DesignBuilder):

- **Weather data**: Comprises a set of weather parameters that includes time-step values of solar radiation, temperature, humidity, wind speed, and wind direction for a typical year.

- **Layout**: Specifying the shape, dimensions and orientation of building

- **Activity**: Specifying occupancy periods, type of people, indoor cooling set point temperature and humidity control, and appliances loads and schedules.

- **Construction**: specifying construction materials, insulations, thicknesses, thermal resistance, and infiltration.

- **Openings**: Specifying windows, dimensions, glazing, and shading.

- **Lighting**: Specifying lighting energy, lighting type, and lighting control and schedule.

- **HVAC**: If a specific HVAC has been selected, cooling load can include cooling distribution losses and heat gains through ducts and from fan motors.

It should be noted that several factors affect the accuracy of the cooling load calculation including variation in heat transmission of building materials, motivation
and skills of those who constructed the building, and variation in the building’s operation (ASHRAE, 1997). These effects will not be considered in this thesis.

4.3 Building and Orientation

The first solution to be investigated in this thesis is the impact of orientation and grouping of houses on cooling load. It is known in air conditioning and building energy technology that the shape and orientation of the building can affect the heat loss or gain through the envelope. For example, a rectangular shape building has a surface-to-volume ratio greater than a square shape building. Minimizing the surface-to-volume ratio and especially the roof area is important to minimize the summer heat gain, (Capeluto et al, 2003). The orientation is also important in energy consumption. If the largest surface of the building is positioned towards east or west, it will receive high solar radiation during summer, which will increase the cooling load, (Harvey, 2006).

The impact of solar radiation on walls and windows varies according to the measures taken by the building's architect. Designers can tailor the building to meet cooling or heating needs with respect to occupancy periods. Figure 4.5 shows an example of a house orientation with the sun's rise and set, where the largest face is positioned towards north and south. Thus, the method to be used for verifying the benefits of the best orientation and grouping of houses in Kuwait will focus on the best orientation towards north and south.

Figure 4.5: House orientations with sun (Source: Arizona Solar Center, 2008)
4.4 Air Conditioning Systems

The second solution to be investigated in the thesis is the selection of a low energy air conditioning system. The selection of suitable air conditioning system requires detailed selection criteria (i.e. energy consumption, cost, etc). For better understanding for this issue, it is important to have a general background about air conditioning types in buildings. Air conditioning systems are generally divided based on the method the cooling process uses for space cooling; as described in 4.4.1 and 4.4.2 below (Carrier, 1960).

4.4.1 Direct Expansion System

The direct expansion (DX) system, shown in Figure 4.6, is the cooling system in which the evaporator is in direct contact with the air stream, so the cooling coil of the airside loop is also the evaporator of the refrigeration loop. The term “direct” refers to the position of the evaporator with respect to the airside loop, while the term "expansion" refers to the method used to introduce the refrigerant into the cooling coil. The liquid refrigerant passes through an expansion device (usually a valve) just before entering the cooling coil (the evaporator). This expansion device reduces the pressure and temperature of the refrigerant until it is colder than the air passing through the coil. This system does not use chilled water as an intermediate cooling medium.

Figure 4.6: Direct Expansion (DX) System
In a unitary system, the complete cooling system is in one casing. Since all equipment is prepackaged, the installation cost is usually low. Window air conditioners and packaged units are typical examples of DX systems.

### 4.4.2 Central Chilled-Water System

The primary difference between a central chilled-water system and a direct expansion system is the use of a chilled-water loop to cool the incoming air. There are three major categories of central chilled-water systems, as described below: all-air, all-water and air-water.

#### 4.4.2.1 All-Air System

In the all-air system (Figure 4.7), chilled water is used to cool and dehumidify the air at a handling unit (AHU). The AHU is the primary equipment in an air system of a central chilled AC system; it conditions the air and distributes it to various conditioned spaces.

Figure 4.7: All-Air System
In the AHU, the required amounts of outdoor air and recirculation air are mixed and conditioned. The temperature and humidity of the discharge air are maintained within predetermined limits by means of control systems. After that, the conditioned supply air is distributed through ductwork to air conditioned spaces, as shown earlier in Figure 4.7.

Many air-handling units are modular so that components can be added as required. However, an AHU basically consists of an outdoor air intake and mixing box section, a fan section including a supply fan and a fan motor, a coil section with a water cooling/heating coil, and a filter section, as shown in Figure 4.8.

Figure 4.8: Components of an Air Handling Unit (Source: Wang, 2000)

All-air systems provide air conditioning by using a tempered flow of air to the air-conditioned spaces (zones). All-air systems require substantial space for ducting the air to each zone. To change the heating or cooling capacity of the air supply to one zone, the system must either adjust the supply temperature or adjust the flow of air to that zone. There are two major methods for supplying the air in this system, namely the constant-air-volume (CAV) system and the variable-air-volume (VAV) system (McDowall, 2006).
The CAV system provides a constant quantity of supply air and varies the temperature of the supply air in response to changes in the cooling load in the zone. A thermostat is installed in the zone to compare the dry-bulb temperature in the zone to the desired set-point temperature. The thermostat modulates the reheat coil until the temperature of the space matches the desired temperature, as shown in Figure 4.9.

In a VAV system, the quantity of constant temperature supply air varies in response to the changing cooling load in the zone. The duct to each zone is fitted with a control damper that can be throttled to reduce the airflow to maintain the desired temperature, as shown in Figure 4.10.

Figure 4.9: Constant air volume system with preheat coil

Figure 4.10: Variable air system with control dampers to adjust the air flow
4.4.2.2 All-Water System

In the all-water system, shown in Figure 4.11, chilled water is supplied from a remote refrigeration plant to the conditioned space.

The chilled water circulates through the coils of a fan-coil unit. The fan–coil unit conditions the air and supplies it to the conditioned space. The unit acquires air either from the outside or from the space itself through a return air system within the conditioned space. There is no need to duct the air supplied to the zone. In all-water systems, the temperature can be adjusted by the flow rate of the chilled water supplied by the water control valves in the fan-coil unit, which is controlled by the setting on the thermostat in the air-conditioned space.

Figure 4.11: All-Water System
4.4.2.3 Air-Water System

The air-water system is a combination of the previous two systems. The conditioned space is dehumidified by a flow of air that is cooled by the chilled water coil in the air-handling unit, but the cooled water that circulates through the fan-coil unit does most of the sensible cooling. The air-water system is shown in Figure 4.12. This system is called an air-water system because the air is conditioned by both air and water. The main reason for the air-water system is to supply dehumidified air to the air conditioned space so that the fan-coil units do not dehumidify, hence no drainage is required from the fan coil (as is needed in the all-water system).

Figure 4.12: Air-Water System
4.4.3 Survey of Air Conditioning Market in Kuwait

The thesis herein presents a plan for a survey to be conducted in air conditioning market in Kuwait. The objective and overall information to be obtained are as follows:

- **Objective:**

  The objective of this survey is to provide a foundation for the selection analysis of the best air conditioning choice for houses in Kuwait. The specific information required is as follows:
  - To obtain general overview of the predominant type of AC systems used in Kuwaiti houses.
  - To acquire the opinions of air conditioning engineers concerning the preferred air conditioning systems for the Kuwaiti houses considered in this study.
  - To determine the factors that affect the decision of whether to use a packaged DX system or a chilled-water system.
  - To obtain installation and maintenance prices for the investigated air conditioning types.

- **Methodology:**

  The methodology to be followed to gather the required information is presented below:

  - **General overview of predominant AC type in Kuwaiti houses:**

    The predominant AC type for houses in Kuwait is a Packaged-DX air conditioning system (Hajiah et al., 2006). Information on this type will be collected by visiting an HVAC company specialized in this type of AC in Kuwait. The information to be collected will cover the AC system components, heat rejection method, and the AC unit installation on the roof of the houses. Photos will be taken to make the presented information clearer.
- **Acquiring opinion on the preferred chilled water system for houses in Kuwait:**

There is a few number of HVAC companies in the HVAC market in Kuwait who deal with installing chilled water systems. So, the survey will focus on a well established HVAC company in the market. HVAC designers from the selected company will be interviewed to obtain a consultation about the preferred chilled water system for houses in Kuwait. The interview’s design will be in the form of asking questions from the author, and allowing the designers to answer and elaborate on the answer.

- **Determining the factors that affect the selection of AC:**

In the same interview from the point shown above, questions on the factors that affect the selection of AC systems will be raised. The author will allow the HVAC designers to elaborate about the answers with emphasis on the factors that affect the affordability of the system.

- **Obtaining capital and maintenance prices for the investigated AC types:**

There are only a few HVAC companies that deal with different systems brands. For this reason, one major company that has access to many projects and deals in the market will be selected to investigate the costs associated with the selection. The sales department is the targeted place for inquiry in the company.

It should be noted that all of the required information must be collected within one month in Kuwait. The specified period of time should cover communication with the selected companies, meetings with people, and gathering the required information. It is worth mentioning that this survey is not a paper based survey. A summary of the information required and the investigation method is shown in Table 4.1.
Table 4.1: Survey Methodology

<table>
<thead>
<tr>
<th>Information Required</th>
<th>Investigation Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>General overview of predominant AC type in Kuwaiti houses</td>
<td>Site visits, photographing</td>
</tr>
<tr>
<td>Acquiring opinion about the preferred chilled water system for houses in Kuwait</td>
<td>Meeting HVAC designers</td>
</tr>
<tr>
<td>Determining the factors that affect the selection of AC</td>
<td>Meeting HVAC designers</td>
</tr>
<tr>
<td>Obtaining installation and maintenance prices for the investigated AC types</td>
<td>Meeting Sales Representatives</td>
</tr>
</tbody>
</table>
4.5 Lifecycle Cost Analysis Methodology

4.5.1 Overview of Lifecycle Cost Analysis

Lifecycle cost analysis is an economic evaluation technique that determines the total cost of owning and operating a system over a period of time (Fuller and Petersen, 1995).

The first task of an LCCA is to determine the costs that affect building systems, quantify these costs, and express them in cash amounts. According to (Fuller, 2007), building-related costs usually fall into the following categories:

- Initial Costs—Purchase, Acquisition, Construction Costs
- Fuel Costs
- Operation, Maintenance, and Repair Costs
- Replacement Costs
- Residual Values - Resale or Salvage Values or Disposal Costs
- Financial Charges - Interest Payments on Loans
- Non-Monetary Benefits or Costs

4.5.2 Overview of Lifecycle Cost Calculation Method for Air Conditioning Selection

The great value of lifecycle cost analysis is the consideration of costs over the life of the air-conditioning system, because the analysis provides a better indicator of total costs rather than just considering the initial installation costs. Studies in which the goal is establish a reliable comparison between two or more AC alternatives will benefit from using LCC techniques because 1) LCCA depends on the development of a detailed cooling load profile to obtain initial and operation costs and 2) LCCA requires real values for other costs associated with AC selection, such as maintenance costs. For these reasons, LCCA was a preferable choice for many studies to compare alternative air-conditioning systems, as in the examples found in the studies conducted by (Aktacir et al., 2006) and (Elsafty and Al-Daini, 2002).
In this thesis, detailed cooling load profile for Kuwaiti houses will be used to obtain initial, operational, and maintenance costs that will help to evaluate the economic feasibilities of air conditioning system to be selected, compared to the current air conditioning system in Kuwaiti houses. The calculation of lifecycle cost for each AC system requires that all costs be identified by year and by amount. The requirements addressed for studying the cost-effectiveness of air conditioners fall into the following categories:

- Installation Cost
- Operation Cost
- Maintenance Cost

Based on the above categories, the following expression will be used to calculate the LCC:

\[ \text{LCC} = I + \text{Ope} + \text{M}, \]  
(4.1)

where:
- \( I \) = Capital Installation Cost
- \( M \) = Maintenance Cost
- \( \text{Ope} \) = Operation Cost

It should be mentioned that the LCC requires consideration of future prices and values, because the study period is more than a few years long. For that reason, future costs associated with the lifespan of the two AC alternatives, must be calculated according to the expected changes in prices. Based on that, the study will use "present value method", which can be used to estimate the lifecycle cost in present value.

The present value (PV) is defined as the time equivalent value of past, present, or future cash flows as of the beginning of the base year (Fuller and Petersen, 1995). The Uniform Present Value (UPV) factor is used to calculate the PV of a series of cash amounts (A) over a period of (n) years. The present value (PV), which will be used for all expenses given in equation (4.1), is determined using the following formula:
PV = A\cdot UPV, \quad (4.2)

where A represents expenses from equation 4.1, and UPV represents the uniform present worth factor, which can be calculated as shown in expression 4.3 (Fuller and Petersen, 1995):

\[
UPV = \frac{\left[ (1+d)^n - 1 \right]}{d \left( 1 + d \right)^n} \quad (4.3)
\]

Therefore, a uniform discount rate (d) must be applied to the cost stream to calculate the net present value. The discount rate is a function of interest rate (i) and inflation rate (j). The exact relationship between the interest rate and the inflation rate is shown in equation (4.4) (Fuller and Petersen, 1995):

\[
d = \frac{i - j}{1 + j} \quad (4.4)
\]

The purpose of calculating the LCC based on the discount rate is because investors in general prefer to receive or save money earlier than later for two primary reasons, firstly, because money generally loses purchasing power over time due to inflation, secondly, cash amounts received earlier can be reinvested so earning additional returns which generally depends on interest rate.
4.6 Combined Cycle Power plant and Absorption Cooling

4.6.1 Overview

In combined cycle power plant, combined means a gas turbine combined with a heat recovery steam generator and steam turbine. The hot exhaust from the gas turbine is used to produce steam that drives the steam turbine. In combined heat and power (CHP), the plant produces power and heat or combined cooling, heat and power (CCHP) where the plant produces power, heat and cooling. The power plant may be a combined cycle plant, conventional gas or steam turbine plant, diesel plant or other type. The third solution to be investigated in the thesis is a combined cycle power plant with absorption chiller.

The power plant model is proposed to drive a single-effect water/Lithium Bromide (LiBr) absorption chiller. The motivation for this is Kuwait’s strategic plan to erect more combined cycle power plants for electrical power generation. The combined heat and power technology is preferred for power generation and heating applications or to drive absorption chillers for cooling (U.S. EPA, 2002).

4.6.2 Major Combined Cooling, Heat and Power Systems Applications

A combined cooling, heat and power (CCHP) system is defined according to its ability to provide electricity and heat simultaneously. Figure 4.13 shows a typical CCHP system comprises of a prime mover (gas turbine), an electrical generator, a heat recovery steam generator, and an absorption chiller.
Figure 4.13: Typical combined, heat, power and cooling system (CCHP)

The CCHP system, with its enhanced energy supply efficiency and utilisation of waste heat, is highly recommended for cooling and heating purposes, because it is an important part of national and regional strategies for the reduction of greenhouse gas (GHG) emissions, as indicated by IEA (IEA, 2008). CCHP systems are classified based on their scale of usage, i.e., small-scale and large-scale systems. More information about each type is provided next.

4.6.2.1 Small-scale CCHP Applications

Small-scale CCHP are always designed for limited residential, commercial, or industrial demand (Zakopoulos, 2010). The term 'small-scale CCHP' is used commonly for electrical power demand of less than 200 kW (Alanne and Saari, 2004). This CCHP type is generally preferred for buildings in isolated areas and or in areas with high electrical tariffs, because it allows the heating and cooling buildings without full dependence on electricity grid utilities.

Small-scale CCHP systems represent a promising, practical solution due to their ability to generate electricity near where it is needed, which can also reduce transmission losses, and their ability to provide waste heat that can be put to good use. However, discussing how to locate such facilities must be based on a feasibility analysis to confirm the practicality of the decision. According to Fumo et al., (2009), the feasibility of a combined heat and power system has a significant relationship
with the amount of energy savings compared to the use of conventional technologies, and this relationship is strongly influenced by the primary energy resource being used for the primary mover.

Combined heat and power systems are usually classified according to the prime mover component (Zakopoulos, 2010). The prime mover in a typical CCHP system can be a steam turbine, a gas turbine, internal combustion engines, or fuel cells (Bloomquist, 2010). Because CCHP systems classified according to the prime mover type, careful consideration about the location where they operate must be taken into account to avoid any inconvenience resulting from the operation of the prime mover.

To understand how CCHP can serve an individual building, regardless of the type of the prime mover, Figure 4.14 shows a sketch of a typical, small-scale CCHP system to supply the demands for electricity, cooling, and heating (if required).

Figure 4.14: Typical, small CCHP system for an individual building

The common feature of such applications is that the goal is to reduce energy usage and, as a result, reduce the cost and the emissions that are associated with conventional systems. Yet, the type and availability of fuel play important roles in deciding whether to apply a small CCHP system or not. This factor is important, in view of the fact that small CCHP systems are generally preferred for isolated building (far from utilities grid) or if energy tariff is high, as explained earlier.

Small-scale combined heat and power systems are attractive for consumers only if they can save money compared to the cost of electricity with its high tariffs from the power company’s grid (Alanne and Saari, 2004). Yet, if the tariff on the electricity
from the grid is influenced by fluctuating operating expenses associated with the
generation of electrical power, the savings here can be further justified. But, for
countries that provide high subsidies for electricity, such as Kuwait that depends
totally on its oil, tangible savings from applying small CHP systems for consumers
seem to be impossible. However, this scenario may not continue if the nations of the
world continue to use non-renewable energy resources, predominantly oil, in the
future, because oil, as indicated previously in this study, is the most sought-after,
global energy resource. It should be noted that the economic savings may vary from
one place to another. However, this should not be used as an excuse to ignore the
fact that small-scale CCHP systems can give satisfactory achievements in terms of
energy savings and environmental benefits. The next subsection presents more
detailed information concerning large-scale applications of CCHP systems.

4.6.2.2 Large-Scale CCHP Applications

Large-scale CCHP applications are applied where there are large energy and heat
demands. For this reason, the primary mover in a large scale CCHP system must
efficiently utilize the primary fuel to generate electricity. The amount of power
required, the availability of fuel, and other factors, such as environmental impact,
noise, and location, are the general factors affecting the selection of CCHP systems,
particularly the type of the primary mover of the system.

Similarly to the process illustrated earlier in Figure 4.13, the large-scale CCHP
system drives a generator that produces the electricity, and the exhaust gases pass
through a recovery unit that provides heat in the form required by the site (e.g.,
steam). Although all CCHP systems have the same concept of power generation and
waste heat utilization, the significant difference with large-scale CCHP systems is
the quantity of power and heat produced. For this reason, large-scale CCHP plants
are considered as a favored choice for huge waste heat utilization schemes, such as
district cooling and heating (Babus’Haq et al., 1986). The advantage herein is that
large-scale CCHP plant is able to serve larger numbers of end users through district
network pipelines. Because the concept of district cooling is to cover the maximum
number of end-users, further energy savings and reduction of emissions could be
obtained if efficient technology is applied. In view of the fact that weather conditions
are a significant cause for immoderate energy use, particularly in the residential sector in hot climates, as proved earlier by this work, utilizing the waste heat from the combined heat and power plant to meet the cooling demand for multiple buildings could be a very attractive choice. Figure 4.15 shows a schematic of a large-scale CCHP plant for district cooling/heating for a number of buildings.

Figure 4.15: Schematic of a large-scale CCHP plant for electrical power supply and district cooling and heating

Absorption chillers are preferred for utilizing heat in an integrated chilled water production system for a district cooling network due to their ability to utilize waste or surplus heat (Skagestad and Midenstein, 2010). According to Ditchtl (2005), the combined cycle power plant represents the best available large-scale combined heat and power technology. This is compatible the main aim of the study in this stage which is about investigating the configuration of a combined cycle power plant driving a single-effect absorption chiller; as a third solution to be investigated for residential air conditioning in Kuwait.
4.6.3 Combined Cycle Power Plant

The selection of the type of power plant is based on thermal efficiency, cost effectiveness, and environmental impact, where thermal efficiency and heat rate are the most important factors in evaluating various types of power plants (Kehlhofer, 1997). Combined heat and power technology is recommended as the best power generation method, and, among all possible types, the combined cycle power plant (CCPP) is the best due its high thermal efficiency. The combined cycle power plant is a combination of a gas turbine cycle (the Brayton Cycle), a heat recovery steam generator (HRSG), and a steam turbine cycle (the Rankin Cycle). For better understanding of the components of the CCPP, more details about each component of the system are provided below. It is worth noting that the explanations about the components are done step by step, including elucidation of the thermodynamics background. The theoretical background of each of the components of a CCPP can be obtained from Khartchenko (1997), and Kehlhofer (1997).

4.6.3.1 Gas Turbine Cycle (Brayton Cycle)

Gas turbine power plants are classified into two types, open cycle and closed cycle (Cohen et al., 1987). Figure 4.16 shows the flow diagram of an open-cycle gas turbine power plant. As shown in the figure, the open-cycle gas turbine system consists of a compressor, a combustor, and a gas turbine with a generator.

Figure 4.16: Schematic diagram of open-cycle gas turbine

As shown in Figure 4.16, fresh air at ambient conditions is drawn into the compressor, where its temperature and pressure are increased. The high-pressure air proceeds into the combustion chamber, where the fuel is burned at constant pressure.
The resulting high-temperature gases then enter the gas turbine to rotate the shaft that connects the turbine with a magnetic coil in the generator. When the shaft is rotating inside the magnetic coil, electrical current is produced. The exhaust gases leaving the turbine in the open-cycle configuration are not recirculated.

Figure 4.17 shows the flow diagrams of the ideal Brayton Cycle, i.e., the T-s diagram (4.17a) and the p-v diagram (4.17b). These diagrams will be used to explain the energy and heat equations associated with the system.

Based on Figure 4.17, the ideal gas-turbine cycle (Brayton Cycle) is made up of four internally reversible processes, as follows:

1-2 Isentropic compression (in a compressor)
2-3 Constant pressure heat addition
3-4 Isentropic expansion (in a turbine)
4-1 Constant pressure heat rejection (for closed cycle).

The term “isentropic”, it refers to a process at constant entropy (Sears and Salinger, 1986).

The energy balance of a steady-flow process can be expressed, on a unit-mass basis, as follows:

\[(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_{out} - h_{inlet}\]  \hspace{1cm} (4.5)

Therefore, heat transfer to and from the working fluid (gas) are:

\[q_{in} = h_3 - h_2 = C_p(T_3 - T_2)\]  \hspace{1cm} (4.6)
84

and

\[ q_{\text{out}} = h_4 - h_1 = C_p (T_4 - T_1) \]  \hspace{1cm} (4.7)

where \( C_p \) is the specific heat of the working fluid (gas).

The thermal efficiency of the ideal Brayton Cycle is:

\[ \eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{C_p (T_4 - T_1)}{C_p (T_5 - T_2)} \]  \hspace{1cm} (4.8)

Because of the processes 1-2 and 3-4 are isentropic, \( P_2 = P_3 \) and \( P_4 = P_1 \), it may be shown that:

\[
\frac{T_3}{T_1} = \left( \frac{P_3}{P_1} \right)^{\frac{(k-1)}{k}} = \left( \frac{P_3}{P_4} \right)^{\frac{(k-1)}{k}} = \frac{T_1}{T_4},
\]  \hspace{1cm} (4.9)

where \( k \) is the specific heat ratio \((c_p/c_v)\)

Substituting these equations into the thermal efficiency relationship and simplifying give

\[ \eta_{\text{th}} = 1 - \frac{1}{r_p^{\frac{(k-1)}{k}}} \]  \hspace{1cm} (4.10)

where \( r_p = \frac{P_3}{P_1} = \frac{P_4}{P_4} \), which is the pressure ratio.  \hspace{1cm} (4.11)

other important expressions are:

Density of air:

\[ \rho_a = \frac{P_{\text{atm}}}{R_a T_a} \]  \hspace{1cm} (4.12)

Mass flow rate of air:

\[ m_a = V_a \rho_a \]  \hspace{1cm} (4.13)

Mass flow rate of fuel:

\[ m_f = V_f \rho_f \]  \hspace{1cm} (4.14)

Mass flow rate of gas:

\[ m_g = m_a + m_f \]  \hspace{1cm} (4.15)
4.6.3.2 Heat Recovery Steam Generator

The Second Law of thermodynamics indicated that the higher the maximum fluid temperature in a heat engine, the more of the heat input can be converted to work (Nag, 2005). In a conventional steam power plant, most of the heat cannot be converted to work because the maximum steam temperature that is economically possible is about 800 K, while the combustion temperature in the boiler is about 2000 °K (Kehlhofer, 1997). However, gas turbines can work on maximum gas temperatures above 800 K because the temperature of blades, shaft, casing etc. can be kept below the gas temperature by a cooling system. For that reason, the advantage of the combined cycle power plant is its utilization of the waste heat from the gas turbine by means of heat recovery steam generator (HRSG) to heat the steam that enters the steam turbine. Figure 4.18 shows the connection between the gas-turbine cycle and the heat recovery steam generator.

\[ m_s (h_f - h_g) = m_g (h_f - h_g) \]

where \( m_s \) is the mass flow rate of steam, and \( m_g \) is the mass flow rate of the hot gases.

Figure 4.18: Configuration of HRSG with Gas-Turbine Cycle
4.6.3.3 Steam Turbine Cycle (Rankin Cycle)

The configuration of the steam turbine cycle (Rankin cycle) is shown in Figure 4.19 as part of the combined cycle power plant. The waste heat from the hot gases exhausted from the gas turbine shown in Figure 4.19 is used to provide steam for the steam turbine. The steam turbine cycle here is slightly different from the conventional steam power plant, which uses a fired boiler to generate steam to drive the turbine for power generation.

As shown in Figure 4.19, the steam turbine has two exits, one that conducts steam to the condenser and another that goes to another application. The general application for the second discharged steam (state 8 on Figure 4.19), which is known as extraction, is for process purposes in a CHP facility. According to Ziegler and Riesch, (1993), this low/medium pressure extracted steam may be used to drive absorption chillers in a CHP plant.

Figure 4.19: The configuration of the steam turbine cycle and steam extraction as part of the combined cycle power plant
Figure 20 shows the T-s diagram of the steam cycle.

Figure 4.20: T-s diagram of the steam cycle in the CCPP configuration with steam extraction used in an absorption chiller

According to Figures 4.19 and 4.20, the steam cycle process is as follows:

9-10 Isentropic pressure increase of condenser outlet to feed water pressure
10-11 Pumped condensates mixed in feed water heater
15-11 Return of steam extraction mixed in feed water
11-6 Isentropic pressure increase (in a pump)
6-7 Constant pressure heat addition (by the HRSG)
7-8s Isentropic expansion from high pressure to intermediate pressure turbine (works for absorption chiller generator).
8-14s Isentropic expansion from intermediate pressure to low pressure turbine (condenser pressure)
14-9 Constant pressure heat rejection (by cooling water through a condenser)

It should be noted that the state 8 and 8s, 14 and 14s are mentioned in Figure 4.20 to explain the difference between actual and isentropic work of the steam turbine. Actual work does less work because of friction losses and leakage of the high pressure steam entering the turbine; while the isentropic work represents the idealized work. The difference between actual and isentropic process is measured by isentropic efficiency. It involves a comparison between the actual performance of a device and the performance that would be achieved under idealized circumstances for the same inlet and exit states (Nag, 2005).
Based on the explanation for the process in the steam cycle, the heat and energy balances are as follows:

First, the energy balance for the steam turbine work is:

\[ W_{\text{Steam Turbine}} = m_s \ y (h_7 - h_8) + m_s (1 - y) (h_8 - h_{14}) \]  

(4.17)

Where the subscript “s” refers to steam and “y” represents the fraction extracted from the turbine exit to the absorption chiller.

Second, heat transfer in the steam condenser (Condenser 1) is:

\[ Q_{\text{Cond}} = m_s (1 - y) (h_{14} - h_y) \]  

(4.18)

where the subscript “w” refers to water.

High pressure feed water pump (pump 1):

\[ W_{\text{pump1}} = m_s \nu_w (P_6 - P_{11})/\eta_{\text{pump}} \]  

(4.19)

Condensate pump (pump 2):

\[ W_{\text{pump2}} = m_s (1 - y) \nu_w (P_{10} - P_y)/\eta_{\text{pump}} \]  

(4.20)

Where \( \nu_w \) = specific volume of water

Heat balance for the mixing chamber:

\[ h_{11} = (1 - y) h_{10} + y h_{15} \]  

(4.21)
4.6.4 Absorption Cooling System

4.6.4.1 Overview

Absorption cycles are used for refrigeration and cooling applications because they are capable of utilizing waste heat and renewable energy, such as solar energy (Srikhirin et al., 2001).

LiBr/Water is the preferred solution in absorption chillers that are used primarily for air-conditioning applications (Carrier AC Division, 1974). The basic absorption cycle is the single-effect cycle. There are also other absorption cycles, which are called multi-effect absorption cycles. The main objective of a higher-effect absorption cycle is to increase system performance when a high-temperature heat source is available (Srikhirin et al., 2001). This study will consider only the configuration of the single-effect absorption chiller driven by steam that is extracted from steam turbine of a combined cycle power plant.
4.6.4.2 Energy, Heat, and Mass Balances for a Single-Effect LiBr/Water Absorption Chiller

The study herein illustrates the basic principles of the energy, heat, and mass balance equations for a single-effect absorption cycle. Information about the fundamentals of the single-effect absorption chiller can be obtained from Howell et al. (1998). Figure 4.21 shows a schematic of a single-effect absorption chiller, with the states in the cycle numbered. It is worth mentioning that the absorption cycle's condenser, expansion valve and evaporator are equivalent to the ones in the vapour compression cycle, while the generator, heat exchanger, absorber and solution pump replace the compressor.

Figure 4.21: Schematic of the single-effect absorption chiller

An important issue before starting the development of the energy, heat, and mass balance equations is the assumptions associated with this cycle. The following assumptions are made for the ideal, single-effect absorption cycle (Tozer and James, 1997):

- Constant pressure in absorber and evaporator (negligible pressure drop)
- Constant pressure in generator and condenser (negligible pressure drop)

In addition to these two assumptions, the following additional points of explanation are offered before developing the equations:
• (Process 8-15) Steam to heat the strong solution in the generator for refrigerant removal. The heat is equal to the sum of the heat of vaporization and the heat of solution.

• (Process 22-23) Cooling of the weak solution in the heat exchanger.

• (Process 23-24) Throttling of the weak solution to evaporation pressure.

• (Process 25-26) Heat removal from the absorber to cool the solution at constant pressure.

• (Process 16-17) Cooling of the refrigerant vapor produced in the generator at constant pressure down to the saturation temperature (Condensation) \( (T_{17}) \).

• (Process 29-30) Heat removal from the condenser.

• (Process 17-18) Throttling of the refrigerant from condensation to evaporation pressure.

• (Process 18-19) Evaporating the refrigerant in the evaporator.

• (Process 27-28) Heat addition to the evaporator by the chilled water cycle from cooling demand side.

• (Process 31-20) Pumping the strong solution to the generator.

The energy, heat, and mass balance equations are as follows:

**Generator:**

\[
Q_{gen} = m_w y (h_m - h_{16}) = m_{ws} h_{22} + m_R h_{16} - m_{ss} h_{21},
\]

(4.22)

where the subscript “ws” refers to weak solution, the subscript “R” refers to refrigerant, and the subscript “ss” refers to strong solution.

For the mass balance

\[
m_{ss} = m_{ws} + m_R,
\]

(4.23)

Where,

\[
m_{ws} = m_R \left( \frac{x_{ws}}{x_{ws} - x_{ss}} \right) \quad \text{and} \quad m_{ss} = m_R \left( \frac{x_{ws}}{x_{ws} - x_{ss}} \right)
\]

For the LiBr balance

\[
m_{ws} (1 - x_{ws}) = m_{ws} (1 - x_{ss}),
\]

(4.24)

where “x” refers to the concentration of water which is the refrigerant (R) in the solution.
Solution Heat Exchanger:

The energy balance equations are:
\[ m_{ss} h_{20} + m_{ws} h_{22} = m_{ss} h_{21} + m_{ws} h_{23} \]  \hspace{1cm} (4.25)

Absorber:

\[ Q_{\text{abs}} = m_{25} (h_{26} - h_{25}) = (m_R h_{19} + m_{WS} h_{24}) - m_{SS} h_{31} \]  \hspace{1cm} (4.26)

Evaporator:

\[ Q_{\text{evap}} = m_{27} (h_{27} - h_{28}) = m_R h_{19} - m_R h_{18} \]  \hspace{1cm} (4.27)

Condenser (cond2):

\[ Q_{\text{cond2}} = m_{29} (h_{30} - h_{29}) = m_R (h_{16} - h_{17}) \]  \hspace{1cm} (4.28)

Solution pump (pump 3):

\[ W_{\text{pump3}} = m_{ss} \nu (P_{20} - P_{31}) / \eta_{\text{pump}} \]  \hspace{1cm} (4.29)

Chilled water pump (pump 4):

\[ W_{\text{pump4}} = m_{27} \nu \Delta P_{\text{district network}} / \eta_{\text{pump}} \]  \hspace{1cm} (4.30)
4.6.5 Computer Model of Combined Cycle Power Plant with Absorption Cooling

Figure 4.22 shows the flow chart for the major steps in the modeling of the power plant and absorption chiller.

![Flow Chart]

Figure 4.22: Major steps in the modeling of CCPP with Absorption Cooling

For the energy consumption associated with absorption cooling, the whole system (CCPP with absorption cooling) will be controlled based on the variation of cooling load, which will be presented as a function of the variation in steam extraction (y), as explained earlier. The fuel input to the plant will be held constant, so that the power output will vary according to the steam extraction. The net power \( W_{\text{net(Abs)}} \) output of the system and the thermal efficiency \( \eta_{\text{th(Abs)}} \) of the plant will be calculated.

For the energy consumption of the packaged-DX system, the CCPP power output without steam extraction \( (y = 0) \) will be used to meet the electrical energy required by the cooling load. This will be based on the assumption that electricity will be supplied by the plant electrical power supplied to the utility grid. Again, the fuel input will be held constant, and the net power \( W_{\text{net(Pack-DX)}} \) of the whole system and the thermal efficiency \( \eta_{\text{th(Pack-DX)}} \) of the plant will be calculated.
The computer model will be prepared in Engineering Equation Solver (EES) which is a comprehensive engineering thermodynamics and heat transfer problem solving software program that was developed in the Mechanical Engineering Department at the University of Wisconsin-Madison (Klein and Alvarado, 2002). EES provides many built-in mathematical and thermo-physical property functions useful for engineering calculations. This feature simplifies the process for the user and ensures that the solver will always operate at optimum effectiveness. In the past, most programmers of thermodynamics models wrote the equations and identified the thermodynamic parameters (e.g., enthalpy (h) and entropy (s)), and then they made a separate file for the list of the values of the state properties in another program (EES Manual). When they are ready to run the program, they make a call command to import the file into the program. Although this may lead to the same results as EES produces, the main obstacle is the effort required for the programmer to look at the thermodynamics properties from tables and charts and then prepare them in a special table, which are very time-consuming efforts. EES has been used successfully in many published research works around the world including (Bruno et al., (2005) and Hwang (2004)). In this study, the method of modeling will be based on the steps described in Figure 4.23 below.

![Figure 4.23: Sequence of the major steps in the modeling](image-url)
Chapter 5: Results and Discussion

5.1 Simulation Inputs for Cooling Load Calculations

5.1.1 General

Building thermal simulation requires many items of input data. The DesignBuilder program categorizes the inputs as shown in Figure 5.1 below:

![Diagram showing DesignBuilder Inputs: Layout, Activities, Constructions, Openings, Lighting, HVAC]

Figure 5.1: Building input data in DesignBuilder program

The input data is based on typical Kuwaiti conditions, construction practice and the Energy Conservation Code of Practice for Buildings, as described in sections 3.4 to 3.7. The input data is summarised in Table 5.1.

It was necessary to make assumptions for many items of data. These will be discussed below.
### Table 5.1: Building simulation input data

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Description of the Studied Case</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Kuwait (29.22° N latitude, 47.98° E longitude, and 55m above sea level)</td>
<td>DesignBuilder</td>
</tr>
<tr>
<td>Weather file</td>
<td>Kuwait International Airport</td>
<td>DesignBuilder</td>
</tr>
<tr>
<td>Orientation and arrangement</td>
<td>• Single &amp; double blocks North South.</td>
<td>See figure 5.2</td>
</tr>
<tr>
<td></td>
<td>• Single &amp; Double blocks East-West</td>
<td></td>
</tr>
<tr>
<td>Plan shape</td>
<td>Rectangular</td>
<td>See figure 5.2</td>
</tr>
<tr>
<td>Number of floors</td>
<td>3</td>
<td>See figure 5.2</td>
</tr>
<tr>
<td>Floor to floor height</td>
<td>4m</td>
<td>Kuwaiti construction common practice</td>
</tr>
<tr>
<td>House Dimensions</td>
<td>Length= 22 m, width= 18.2 m</td>
<td>National Housing Authority</td>
</tr>
<tr>
<td>Space between houses</td>
<td>3 m</td>
<td>National Housing Authority</td>
</tr>
<tr>
<td>Floor occupancy area</td>
<td>383.7 m²</td>
<td>Calculated in DesignBuilder</td>
</tr>
<tr>
<td>Wall area of one floor</td>
<td>315.4 m²</td>
<td>Calculated in DesignBuilder</td>
</tr>
<tr>
<td>Window area</td>
<td>30% of the wall area, uniformly distributed</td>
<td>Energy Code of Practice</td>
</tr>
<tr>
<td>Type of window glass</td>
<td>• 6mm Double glazing, clear and reflective</td>
<td>Energy Code of Practice</td>
</tr>
<tr>
<td></td>
<td>• U-value (3.38 W/m².K)</td>
<td></td>
</tr>
<tr>
<td>Window Blinds</td>
<td>Internal blind operated between 12 pm- 11 pm</td>
<td>Assumed, see explanation in section 5.1.6</td>
</tr>
<tr>
<td>Wall U-value</td>
<td>0.568 W/m².°K</td>
<td>Energy Code of Practice</td>
</tr>
<tr>
<td>Roof U-value</td>
<td>0.397 W/m².°K</td>
<td>Energy Code of Practice</td>
</tr>
<tr>
<td>Ground Temperature</td>
<td>Monthly Average Data</td>
<td>See Table 5.2</td>
</tr>
<tr>
<td>Occupancy density</td>
<td>0.01 people/m²</td>
<td>Estimated, see section 5.1.5</td>
</tr>
<tr>
<td>Occupancy schedule</td>
<td>Occupied all the day</td>
<td>Assumed, see explanation in section 5.1.5</td>
</tr>
<tr>
<td>Lighting load</td>
<td>10w/m²</td>
<td>Energy Code of Practice</td>
</tr>
<tr>
<td>Lighting schedule</td>
<td>12 pm- 11 pm with diversity factor of 70%</td>
<td>Estimated, see section 5.1.7</td>
</tr>
<tr>
<td>Equipment load</td>
<td>12 W/m² (Ground floor), 5 W/m² upper floors</td>
<td>(Al-Saadi S. &amp; Budaiwi I., 2007)</td>
</tr>
<tr>
<td>Equipment schedule</td>
<td>• Ground floor:</td>
<td>Assumed, see explanation in section 5.1.5</td>
</tr>
<tr>
<td></td>
<td>- Weekdays: 7am-9am , 4pm-11pm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Weekends: 7am-11pm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Upper Floor: 4pm-11pm daily</td>
<td></td>
</tr>
<tr>
<td>Infiltration</td>
<td>0.5 ACH (air change/hour)</td>
<td>Common HVAC Design Practice in Kuwait</td>
</tr>
<tr>
<td>Thermostat setting</td>
<td>24°C &amp; 50% RH</td>
<td>Energy Code of Practice</td>
</tr>
<tr>
<td>Cooling load Calculation</td>
<td>ASHRAE Heat Balance Method</td>
<td>DesignBuilder</td>
</tr>
</tbody>
</table>
5.1.2 External Conditions

The DesignBuilder / EnergyPlus software system includes typical hourly weather data for Kuwait, which is required for the simulation. The ground temperature is also required, in order to calculate heat gains from the ground floor. This was set using data from Sebzali (2009), as shown in Table 5.2.

Table 5.2: Monthly average ground temperature at 1 m depth for Kuwait (Sebzali, 2009)

<table>
<thead>
<tr>
<th>Month</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>19.5</td>
</tr>
<tr>
<td>February</td>
<td>19.2</td>
</tr>
<tr>
<td>March</td>
<td>20.7</td>
</tr>
<tr>
<td>April</td>
<td>24.6</td>
</tr>
<tr>
<td>May</td>
<td>28.3</td>
</tr>
<tr>
<td>June</td>
<td>32.4</td>
</tr>
<tr>
<td>July</td>
<td>34.4</td>
</tr>
<tr>
<td>August</td>
<td>35.7</td>
</tr>
<tr>
<td>September</td>
<td>34.8</td>
</tr>
<tr>
<td>October</td>
<td>32.3</td>
</tr>
<tr>
<td>November</td>
<td>28.2</td>
</tr>
<tr>
<td>December</td>
<td>22.5</td>
</tr>
</tbody>
</table>
5.1.3 Layout

Four models were created in DesignBuilder, as shown in Figure 5.2. Each model comprised six identical houses, and the models were identical apart from the arrangement of the houses. The dimensions of the models are given in Table 5.1.

![Figure 5.2: Houses arrangements and orientations used in this study](image)

5.1.4 Constructions

Constructions commonly used in Kuwait were selected for the models, based on information received from an expert at the National Housing Authority (NHA) (Hamadan, 2009). The constructions are shown in Figures 5.3 and 5.4.

![Figure 5.3: Common (a) wall and (b) roof constructions in Kuwaiti houses (Hamdan, 2009)](image)
In Figures 5.3 and 5.4 (a) the inner surface is the surface adjacent to the cooled space, while the outer surface is adjacent to the outside air or ground. In Figure 5.4 (b) the inner and the outer surfaces are both adjacent to the cooled space, as this represents the internal floors.

The colour of the external surfaces was assigned as light gray in Design Builder, to represent "medium-light" colour in Kuwait’s Energy Code of Practice as commonly used in Kuwait (Hamdan 2009).

The U-values of the selected constructions were calculated using Design Builder. As expected, they were found to comply with Kuwait’s Energy Code of Practice, which specifies maximum allowable U-values for external walls and roofs.

5.1.5 Activities

According to recent statistics, the population in Kuwait has reached 3,182,960 and the total number of residential buildings in the country is 320890 (MEW, 2007),
which gives an average occupancy of about 10 people per house. As the simulated houses are intended to be typical, the occupancy was set to 10 people per house.

The total occupancy area of each house is approximately 1151\text{m}^2, so the occupation density is about 0.01 persons/\text{m}^2. This low density is in accordance with the Kuwaiti custom of keeping generous living spaces to allow sons to live with their parents when they get married. Kuwaiti houses tend to utilize the whole plot area due to the hot climate conditions during summer, in contrast to European houses which have outdoor spaces for use in good weather.

An average metabolic heat output (110 W per adult male) was calculated using the database of activities (e.g. eating, sleeping, cooking, reading etc.) in DesignBuilder. Two or three generations of people, including elderly people and small children, are expected to occupy each house. DesignBuilder recommends a heat output adjustment factor of 0.87 for a typical mixture of men, women and children. This was therefore applied to the metabolic heat output. DesignBuilder uses a polynomial function to divide the heat gain into sensible and latent portions (DesignBuilder Manual, 2009).

Due to the presence of small children and old people, it was assumed that the houses would be occupied all day and all night. Al-Mumin et al. (2003) conducted a survey analyzing the energy consumption of 30 Kuwaiti houses selected randomly from various areas in Kuwait. The study indicated that all houses from the sample have central AC systems and most of the rooms are air-conditioned all day long and throughout the summer.

It is difficult to estimate heat gains from equipment. This study could not find any data specifically for Kuwait. According to a study sponsored by ASHRAE (Hosni et al., 1999) “Accurate information on the total heat gain from equipment is lacking in current handbooks. Some equipment includes a nameplate rating showing total power consumption, while other equipment does not have this”. Al-Saadi and Budaawi (2007) used a dynamic thermal simulation program to evaluate the thermal characteristics of a two storey Saudi house; they assumed equipment loads of 12 W/\text{m}^2 for the ground floor (living area) and 5 W/\text{m}^2 for the first floor (sleeping area).
of a typical Saudi single-family house. Climate and lifestyle in Saudi Arabia and
Kuwait are similar, therefore equipment heat gains for this study were set to 12W/m²
for the ground floor and 5 W/m² for the first and the second floors.

Three operation profiles for equipment heat gains were generated, based on the
author's experience of living habits in Kuwait. Two profiles were applied to the
ground floor equipment gain, "Family weekday" (Sunday to Thursday, 7.00-9.00 and
16.00-23.00) and "Family weekend" (Friday and Saturday, 7.00-23.00). One profile,
"Upper floor" (every day, 16.00-23.00), was applied to the first and second floor
equipment gain.

5.1.6 Openings

Common practice in Kuwait is for a window-to-wall ratio of about 30% for all
façades, as it is widely preferred by building owners (Hamdan, 2009). A window-to-
wall ratio of 30% was therefore selected for this study.

The Energy Conservation Code of Practice permits various types of windows for this
window-to-wall ratio, depending on orientation. Double/reflective-glazed windows
with aluminium frames, dividers with thermal break, and internal blinds were
selected as typical.

Based on the author's experience from Kuwait, the window blinds were assumed to
be closed from 12.00-23.00 to exclude solar heat gains in the afternoons and provide
privacy in the evening when lights are on.

External doors were neglected as they are normally only a very small fraction of the
wall area of Kuwaiti houses.
5.1.7 Lighting

The lighting heat gain was set to 10W/m² in accordance with the Energy Code of Practice. A diversity factor of 70% was applied to the lighting heat gain since it is unlikely that all the lights will be on simultaneously.

The operating schedule for the lighting was set to be daily from 12.00-23.00, because in Kuwait window blinds are generally closed in the afternoon to limit heat gains through the windows.

5.1.8 HVAC

A typical Kuwaiti house has a central mechanical air-conditioning system that provides cooling during the hot season (Al-Temeemi, 1995). Since this study is concerned with the entire cooling load of the house rather than a specific zone, the cooling load for each house will be computed as a single zone. This is accepted by ASHRAE fundamentals (2005) for single-family houses.

The simulation set point for cooling was chosen in accordance with the Kuwait Energy Code of Practice (24° C, relative humidity 50%). The operation period will be 24 hours thought summer.
5.2 Performance Criteria for the Simulation

The simulation was conducted for four cases that represent the actual arrangement and orientation of typical Kuwaiti houses. These cases are single and double blocks N-S and single and double blocks E-W. Each house was given an identification number in the results as shown in Figure 5.5. The same simulation inputs illustrated in Table 5.1 were used for all of the houses to measure their sensitivity to any solution to be verified later in this study. Joseph and Sam (1996) indicated that fixing all the input data except the one parameter to be analyzed is referred to as sensitivity analysis; this technique can help building designers and decision makers evaluate the thermal design of a building. The differences in simulation results can be attributed to the studied parameter, as suggested by Spitler et al. (1989). The simulation process considered each case individually to determine any significant effects on the total cooling requirements between the cases. The results were compared to identify the differences and relate them to the Energy Code of Practice.

It was illustrated previously in Chapter 3, Table 3.2 (which shows the energy conservation requirements of the air conditioning system) that residential electrical energy consumption should be no more than 60 W/m² for the peak cooling design. Table 3.3 indicated that the power rating for residential air conditioning in Kuwait is 1.7 kW/RT (electricity/refrigeration ton, where 1RT = 3.517 kW). Therefore, the resulting peak cooling design for the cases studied in this chapter will be calculated with reference to these limits. The calculation in this regard is:

\[
\text{Peak A/C electrical load} = \left( \frac{\text{Cooling design load resulted in the simulation \, kWc}}{3.517\, \text{kWc} / \text{1RT}} \right) \times \frac{1.7\, \text{kWc}}{\text{RT}} \quad (5.1)
\]

All cases should not exceed a peak A/C (air conditioning) electrical load per area of 60 W/m², which is the target maximum for the design.
Figure 5.5: The six houses in the four arrangement and orientation cases created in DesignBuilder.
5.3 Simulation Results

5.3.1 Peak Cooling Design and Compliance with the Standard

The peak cooling load obtained for each case was compared to the Energy Code of Practice. The analysis was based on the block load from each case. According to (Al-Ragom, 2003), low peak electrical load for A/C is compatible with the core objectives of the Energy Code of Practice. In the same study, Al-Ragom assessed a two-storey Kuwaiti house built before the implementation of the Energy Code of Practice (1983). She investigated 15 parametrical cases concerning various types of wall and roof insulation and glazing commonly used in renovation projects in Kuwait. The results indicated that the peak electrical loads of A/C per area for the 15 cases ranged between 35 W/m² and 89 W/m². The study recommended the parametrical options that led to the lowest value. Darwish (2007) indicated that the total cooling load for a Kuwaiti house is about 70 kW.

The results from each simulated case show excellent agreement with the Energy Code of Practice. The variations in the results for various building simulation studies are generally due to the different assumptions (Hui and Cheung, 1998). For instance, in the study conducted by Al-Ragom (2003) mentioned above, the power rating used in the analysis was 2 kW/RT, while in the Code of Practice it is 1.7 kW/RT. Figure 5.6 shows the peak electrical load obtained for each case with respect to the Code. The results show satisfactory agreement between the two studies, as the slight difference can be attributed to variations in the input data.
Figure 5.6: Peak A/C electrical load for the studied cases compared to the Energy Code of Practice and F.Al-Ragom (2003)

Figure 5.7 shows the peak cooling load in each house in this study. It is clear that the single block E-W has the highest cooling load, which is about 71 kW for each house. The effect of shading from neighboring houses in this case is almost negligible, because the largest surface of the block is positioned in the east-west direction, whereas the shading effect is apparent for other cases. Houses facing east-west are warmer than other blocks. To confirm this, the single N-S case, which has the largest surface area positioned in the north-south direction, must be analyzed. Houses 1 and 6 have the greatest cooling loads. It is also apparent that house 1 has a greater cooling load than house 6. The peak time and thereafter, the west facing house has higher cooling load since the peak solar radiation coincides with the high outside air temperature. For houses facing east, the cooling load is lower, because prior the peak time the solar radiation coincides with the outside temperature, which is relatively low in the morning. The findings for the double block cases are similar to those for the single block. Hence, it is evidentiary from Figure 5.7 that houses facing west have the largest cooling load.
Figure 5.7: Peak cooling design for the houses identified previously in Figure 4.5
5.3.2 Breakdown of Peak Cooling Load

The design cooling load for each case in this study can be found in Figure 5.8 below.

![Design Cooling Load Chart](image)

Figure 5.8: Design cooling load for the four studied cases

The single block E-W arrangement carries the largest cooling load, about 425 kW. This is followed by the double block E-W arrangement, which has a cooling load of 405.46 kW as shown in Figure 5.8. The N-S arrangements have lower cooling load values compared to E-W arrangements, the lowest among them being the cooling load in single block arrangements as indicated in the same figure. The difference between the largest cooling load and the smallest one is about 6.6%; which is reasonable small. However, it is important to analyse the components of peak cooling load to provide greater detail about each case.

Shares in percentage of cooling load components for each case are illustrated in Figure 5.9. The similarities in the loads among the four cases result from equipment, lighting, occupancy, and external infiltration, which can all be related to the unified input data applied in the simulation. Figure 5.9 also illustrates the slight variations in the loads that result from the building envelope. The variations are reasonable as all houses were constructed based on the uniform requirements specified for Kuwaiti houses. Nevertheless, clear differences exist in loads that result from a glazing load. The order of glazing loads from higher to lower value indicates first the single block...
E-W followed by double block E-W, double block N-S, and finally single block N-S. The order is compatible with the cooling load for each case presented in Figure 5.8. This shows that heat gains through glazing, which vary during the daytime, have a significant impact on building load with respect to the arrangements and directional orientations of the houses.
Figure 5.9: Percentages of Cooling Load components in each case.
5.3.3 Cooling Load Profiles

5.3.3.1 Peak Day Cooling Load

Based on the weather data in DesignBuilder, the hottest summer day's temperature begins to increase substantially from 11 am until it reaches its maximum of 49.2°C at 4 pm, as illustrated in Figure 5.10. It can also be seen that the temperature is almost steady between 3 pm and 5 pm.

![Figure 5.10: Dry-Bulb temperature during the peak summer day based on weather data used in the Simulation](image)

It is necessary to obtain the hourly cooling load for the day and analyse it according to the temperature profile during the same day. The hourly cooling load for each case studied is shown in Figure 5.11.

![Figure 5.11: Peak Day hourly cooling load profile for the four cases studied](image)
From Figure 5.11, the cooling loads increase steadily from the early hours of the morning, and there is a clear dissimilarity for the single block E-W compared to the other cases. This was explained previously as resulting from the tendency of this arrangement to be affected by solar radiation that coincides with the increase in outside temperature mainly on the west facing side. It is also apparent from the figure that all cooling loads increase sharply at 12 pm due to the increase in outside temperature and since the operation schedule for the lighting system commences at that time. The cooling loads continue to increase steadily with a significant increase noted for the single block E-W case until they reach their peak time interval between 4 pm and 5 pm. Figure 5.10 illustrated that the maximum temperature for the day occurred at 4 pm and remained constant until 5 pm. It may also be seen based on the input data that the operation schedule for the equipment located on the ground floor, which represents the living area, begins after 4 pm. The cooling loads begin to decrease after 5 pm owing to the decrease in outside temperature. This decline in cooling loads continues until a sharp decline occurs at 11 pm when the lighting system is switched off for the sleeping period. It is clear from Figure 5.11 that harsh climate conditions that occur during the afternoon period have a substantial impact on the building load, especially in the single block E-W case. Although the other cases do not match in terms of peak cooling load values, they indeed produce the same cooling profile during the day.
5.3.3.2 Daily Cooling Load

The single block E-W case has the dominant daily cooling load curve over the other cases throughout the entire summer period (Figure 5.12). The largest cooling load day occurred on day 126.

![Daily Cooling Load Profile](image)

Figure 5.12: Daily cooling load profile for the four cases studied

The findings reflected in Figure 5.12 match well with the previous findings which indicate that the single block E-W case has the largest cooling load. It is also worth noting from the same figure that the single block N-S case generates the smallest daily cooling profile as the curve inclines upward, which indicates the increase in outside temperature and solar radiation. This is because the single block N-S arrangement has the smallest surface of the block positioned in the east-west compared to the other cases.

5.3.3.3 Monthly Cooling Load

The last cooling profile is the monthly cooling load. As illustrated in Figure 5.10, the maximum dry-bulb temperature occurred in August. However, this data alone is insufficient to assume that August is the hottest month during the summer period. Therefore, it is necessary to review the monthly average dry-bulb temperatures shown in Figure 5.13. In that figure, it is apparent that August has the greatest average dry-bulb temperature. Returning to Figure 3.7 in chapter 3, which shows Kuwait’s monthly global solar radiation, August has the highest value of about 960 MJ/m².
Figure 5.13: Monthly average dry-bulb temperature during summer season in Kuwait as per DesignBuilder

The monthly cooling load for each case studied can be seen in Figure 5.14. The increase in cooling load for each case runs from April until August with priority for the single block E-W case owing to the same reasons specified previously. The cooling loads decline until they reach approximately the same level in October, which is the last month for operating AC systems in Kuwaiti houses.

Figure 5.14: Monthly cooling load profile for the four cases.
5.3.4 Parametrical and Sensitivity Analysis

The models studied were simulated according to the specific requirements of the Energy Code of Practice in Kuwait. The Energy Code of Practice mandates that the electrical energy requirements for residential AC systems should be no more than 60W/m².

Figure 5.9 depicts the breakdown of the cooling load components in the models. The loads that result from glazing significantly affect the total cooling load. The selected window-to-wall ratio (WWR) was assumed to be 30% for double reflective glazing. The Code of Practice offers some freedom for this type of window to use a WWR of up to 50%; however, the selection for this study was made according to the common practice noted previously. Therefore, it was necessary to ensure that the simulated blocks can use a WWR of 50% and still comply with Code of Practice relative to the power rating for AC.

Regarding the lighting system, lighting with a power density of 10W/m² of the fluorescent type was used. It was seen that a diversity factor of 70% was assumed for the use of lighting systems during the day for the simulated blocks. Thus, to determine whether the blocks still fulfil the requirements of the code, it is essential that the simulated blocks can indeed use fluorescent lighting with a power density of 10W/m² at 100% usage.

A good choice for the required analysis mentioned above is to conduct the analysis on the single block E-W case, because it achieved the highest AC power rating as illustrated in Figure 5.6.
5.3.4.1 50% Window-to-Wall ratio (WWR)

The analysis was made using the single block E-W case and focusing on the same input data specified in Table 5.1. The only change is the window-to-wall ratio was 50% rather than the 30% used in the simulation. The resulting cooling load for this block and the new AC power rating are shown in Figure 5.15.

From the figure, a 50% WWR resulted in an AC power rating of about 36W/m², which is below the maximum value specified by the Code of Practice (60W/m²).

5.3.4.2 Lighting (100% Usage)

Another analysis focused on the lighting system, and was accomplished using the same input data specified in Table 5.1. The only difference was the lighting system usage was at 100% rather than the diversity factor of 70% used in the previous simulation. The resultant cooling load for this block and the new AC power rating are shown in Figure 5.16.
Figure 5.16: Design Cooling Load and AC Power rating for single block E-W at different WWR and Lighting usage percentages

Based on the figure, the lighting use at the full percentage is permitted by the Code of Practice, because the obtained AC power rating is less than 60W/m². The figure also indicates that when the lighting is fully used and WWR is set at 50%, the maximum according to the code, the block still complies with the Code of Practice. These changes would indeed add a greater level of confidence to the simulation data.
5.4 Solution (1): Grouping and Orientation of Houses

5.4.1 Background:

This work deals with the current directional orientation and grouping styles of Kuwaiti houses. It determined the impact of these arrangements of the houses on the future residential energy demand, in terms of energy savings and positive environmental effects. Thus, it can be considered as a zero-cost alternative for reducing residential energy demand. No previous attempts have been made to assess and substantiate the energy-saving benefits of appropriate grouping of houses.

The thesis work considered the Kuwaiti government's plan which indicated the construction of new residential areas with approximately 71,000 residential units by 2016, as pointed out in Table 3.1. It was mentioned earlier that the housing program will include 19568 houses. The type of house was considered as the baseline of the analysis in this work, because it represents the majority of houses in Kuwait. It was also indicated in Chapter 3 that the Kuwaiti government is providing loans to owners of existing PAHW houses to renovate and expand their houses. It should be noted at this point that a long-term strategy must be established to verify whether Kuwait should continue making renovation and expansion loans, considering the new, planned residential projects. In addition to the budget required for this strategy, the energy demand associated with the strategy is a major challenge.
5.4.2 Analysis Criteria for the Four Residential Cases

Figure 5.17 shows the flowchart diagram of the steps to fully estimate AC energy costs.

![Flowchart](chart.png)

**Figure 5.17: Flowchart to determine energy costs.**

To accomplish the energy estimation process, the annual cooling load \( Q_{\text{annual}} \) should be multiplied by the allowable power rating (PR) for residential air conditioning from the Energy Code of Practice, i.e. 1.7 kW/RT or 0.4834 kWe/kWr (1 RT = refrigeration ton, 1 RT = 3.517 kW refrigeration). This power rating is for the direct-expansion of air conditioning systems common in the residential sector.

Annual electrical energy consumption can be obtained from the following equation:

\[
E_{\text{annual}} = Q_{\text{annual}} \times \text{PR} \tag{5.2}
\]

Conventional power plants in Kuwait emit 0.72 kg of CO\(_2\) per kWh of electricity produced (Hajiiah 2006). The amount of annual electrical energy can be used to estimate the associated CO\(_2\) as follows:

\[
\text{CO}_2 \text{ Emissions} = E_{\text{annual}} \times 0.72 \tag{5.3}
\]

Estimation of electrical energy production cost is based on the net cost to the government, which is $ US 0.09/kWh (Saud, 2009).

\[
\text{Electrical Energy Production Cost} = E_{\text{annual}} \times $0.09/\text{kWh} \tag{5.4}
\]

Electrical supply capital cost can be estimated based on the peak cooling load (PL) for each case. The peak cooling load should be multiplied by the allowed power
rating (PR) to convert it to electrical load, then this should be multiplied by the capital cost of conventional power plant in Kuwait, which is $ US 1500/kWe (Darwish 2007). It includes the costs of installation, transmission, power transformation, and distribution.

The calculation is performed as follows:

\[
\text{Electrical Supply Capital Cost} = PL \times PR \times $\text{US 1500/kWe} \tag{5.5}
\]

The 19568 planned PAHW houses are equivalent to approximately 3621 blocks of six houses. The results from each simulated case were multiplied by 3261 to estimate the results for the planned houses.

### 5.4.3 Analysis and Results

#### 5.4.3.1 Annual Cooling Load

The annual cooling loads (April-October) for the simulated cases (multiplied by 3261 to represent the future houses) are shown in Figure 5.18.

![Figure 5.18: Annual cooling load for future PAHW houses.](image)

Figure 5.18: Annual cooling load for future PAHW houses.
5.4.3.2 Annual Electrical Consumption

As given in Expression 5.2, the Energy Code of Practice specifies a power rating of 1.7 kW/RT for commonly-used, residential AC (Direct-Expansion Technology). The annual electrical consumption for cooling (April-October) for the future houses can be estimated (Figure 5.19).

![Diagram showing annual total electrical consumption for air conditioning of the future houses.](image)

Figure 5.19: Annual total electrical consumption for air conditioning of the future houses.

5.4.3.3 Annual CO₂ Emitted

As addressed in Expression 5.3, conventional power plants in Kuwait emit 0.72 kg of CO₂ per kWh of electricity. Incorporating this into the simulated blocks, Figure 5.20 shows the annual CO₂ emissions generated from the electrical energy consumption associated with the cooling requirements for the buildings during the summer season (April-October).
Figure 5.20: Annual CO$_2$ emissions associated with air conditioning of the future houses.

5.4.3.4 Electrical Power Installation

Peak cooling load value is important for estimating the required electrical power installation. In accordance to the peak cooling loads presented in Figure 5.8, the estimate for the new power installation for air conditioning can be made for the four cases studied. Using equation 5.4, the calculated amount and cost of power installation required for the air conditioning of future houses to be built by the year 2016 are shown in Figure 5.21.

Figure 5.21: Amount and cost of electrical power installation required for the air conditioning of future PAHW houses.
5.4.3.5 Comparison between the Four Residential Cases

Table 5.3 shows a summary of the results obtained for the future 19568 houses. In the table, case 1 represents the single block east-west arrangement, case 2 the single block north-south arrangement, case 3 the double block east-west arrangement, and finally case 4 the double block north-south arrangement.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Units</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak electrical load</td>
<td>MW</td>
<td>693</td>
<td>645</td>
<td>670</td>
<td>659</td>
<td>667</td>
</tr>
<tr>
<td>Electrical supply</td>
<td>$ US million</td>
<td>1040</td>
<td>967</td>
<td>1004</td>
<td>988</td>
<td>1000</td>
</tr>
<tr>
<td>capital cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual electrical</td>
<td>GWh</td>
<td>1593</td>
<td>1554</td>
<td>1565</td>
<td>1563</td>
<td>1568.7</td>
</tr>
<tr>
<td>energy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual generation</td>
<td>$US million</td>
<td>143.4</td>
<td>139.8</td>
<td>140.7</td>
<td>140.6</td>
<td>141.2</td>
</tr>
<tr>
<td>cost to government</td>
<td>per year</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual CO₂ emissions</td>
<td>kilotons per year</td>
<td>1150</td>
<td>1120</td>
<td>1130</td>
<td>1125</td>
<td>1131</td>
</tr>
</tbody>
</table>

Based on the above table, the single block E-W case consumed the largest quantity of electrical energy and produced the most CO₂ emissions associated with electrical energy consumption. Hence, it will be assumed that this case will be excluded as a potential alternative. In contrast, case 2 has the smallest cooling load, and the smallest values among the entire cases, when compared to the average. For a better understanding of the comparison between the cases, Table 5.4 shows the anticipated savings from each case. The savings are shown both compared to Case 1, which has the highest values, and also compared to the average of the four cases (equivalent to assuming that the future houses will be distributed equally between the four orientations and grouping arrangements).
Table 5.4: Anticipated savings for the future 19568 houses based on the results provided in Table 5.3

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Units</th>
<th>As compared to Case 1</th>
<th>As compared to the average of the four cases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Case 1</td>
<td>Case 2</td>
</tr>
<tr>
<td>Savings in Electrical Supply Capital Cost</td>
<td>$ US million</td>
<td>------</td>
<td>71</td>
</tr>
<tr>
<td>Savings in annual electrical energy</td>
<td>GWh/year</td>
<td>------</td>
<td>39.1</td>
</tr>
<tr>
<td>Savings in annual electrical generation cost</td>
<td>$US million/year</td>
<td>------</td>
<td>3.52</td>
</tr>
<tr>
<td>Reduction in annual CO₂ emissions</td>
<td>kilotons per year</td>
<td>------</td>
<td>28.1</td>
</tr>
</tbody>
</table>

Note: the (-) sign indicates increased costs and emissions

Table 5.5 shows twenty-year projected savings for each case, excluding the single block east-west case. The estimated savings presented in Table 5.5 are based on the savings from the average of the four cases presented in Table 5.4.

Table 5.5: Twenty-year projection of the expected savings for the future 19568 houses

<table>
<thead>
<tr>
<th>Case</th>
<th>Savings in Electrical Supply Capital Cost (million $ US)</th>
<th>Savings in Electricity Production Cost (million $ US)</th>
<th>Total Savings (million $ US)</th>
<th>CO₂ Equivalently Annual Electricity Savings (kiloton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 2</td>
<td>33</td>
<td>27</td>
<td>60</td>
<td>222</td>
</tr>
<tr>
<td>Case 3</td>
<td>-4</td>
<td>6.6</td>
<td>2.6</td>
<td>35.2</td>
</tr>
<tr>
<td>Case 4</td>
<td>12</td>
<td>10.2</td>
<td>22.2</td>
<td>82</td>
</tr>
</tbody>
</table>

Note: the (-) sign indicates increased costs

It was preferred to rely on the savings from comparison with respect to average to estimate the future savings, because it is more likely that future houses will be distributed equally between the four arrangements styles. From Table 5.5, the single block north-south case would achieve significant savings among other cases.
5.5 Solution (2): Economic comparison between packaged direct-expansion and chilled-water air conditioning systems

5.5.1 Background

This solution aimed to assess the viability of using a chilled water system as compared to a packaged direct expansion (DX) system, which is the air conditioning (AC) technology currently used in Kuwaiti houses. The study carried out a survey including information about the factors that affect the decision concerning which type of AC system to use, information about the packaged DX units used in Kuwaiti houses, and a description of the proposed chilled-water system. Estimation of energy consumption associated with the AC systems studied was done using DesignBuilder software. The estimated energy consumptions obtained were evaluated from both economic and environmental perspectives.

For the economic evaluation the study used lifecycle cost analysis. The procedure for computing the total lifecycle cost for two different AC systems that fulfill the cooling requirements of the four residential cases is presented. The results of the lifecycle cost were used to evaluate the total cost of each system over its lifetime, allowing a comparison of the two systems to select the most economical alternative. The study also presents the environmental evaluation used to determine the quantity of CO₂ emissions eliminated by the system that required the lesser quantity of electrical energy to operate.
5.5.2 Survey Results

This section presents the results of the survey into the Kuwaiti HVAC market, which provides the necessary data for the LCCA.

5.5.2.1 Predominant Type of AC Used in Kuwaiti Houses

As mentioned in Chapter 3, packaged DX air conditioners (Figure 5.24) are widely used for houses in Kuwait, dominantly the rooftop type for central cooling. The photo was taken by the author during a site visit to a Kuwaiti house (April, 2010).

Thus, the first type of AC system investigated was the packaged DX system. The components of the packaged DX system’s refrigeration loop (evaporator, compressor, condenser, expansion device, and even some unit controls) may be packaged together, providing for factory assembly and testing of all components, including the electrical wiring, the refrigerant piping, and the controls (Figure 5.23). Heat rejection in this AC type is accomplished by the air-cooled condenser, which contains propeller-type fans that draw outdoor air across the finned-tube condenser coils, where heat is transferred from the hot refrigerant vapour directly to the outdoor air without the use of a separate condenser-water loop. The fan is shown in Figure
5.24. The photos were taken by the author during a site visit to Coolex company, an HVAC company in Kuwait (April, 2010).

Figure 5.23: Packaged Direct-Expansion Unit. (a) Side view. (b) Top view.

Figure 5.24: Fan in packaged Direct Expansion rooftop air conditioning system.
5.5.2.2 The Preferred Chilled-Water Air Conditioning System in Kuwait

The author met two HVAC designers from Trane company which is a major HVAC company in Kuwait (April, 2010). The author began the meeting by identifying the objectives of the project, identifying the residential cases studied, and clarifying what his needs for the study. In this context, the first question raised was as follows:

**Question:** What is the preferred chilled water system?

**Answer:** There are three central chilled-water systems, namely all-air, all-water, and air-water systems. In Kuwait, the all-air chilled-water system is preferred. This preference is due to the relative ease in which this system can be centralized and controlled. The chiller is centralized allowing the conditioned air to be supplied to the zones through ducts. For purposes of control, the temperature settings can be maintained by adjusting the flow rate and/or the temperature of the air that is supplied to the zones through the ducts. Since cooled air is supplied from a central source and distributed through ducts, the installation of the all-air system requires close coordination between the architectural, mechanical and construction engineers to determine the appropriate locations for the ducts (Figure 5.25) during the construction phase.

![Distribution of ducts for central cooling](image)

Figure 5.25: Distribution of ducts for central cooling.
5.5.2.3 Factors in the Selection of an Air Conditioning System:

In the same meeting with the designers, the author of this thesis raised the second question which is as follows:

**Question:** What are the factors that affect the selection of an AC system?

**Answer:** There are various factors that must be considered that may affect the final decision (Figure 5.26). However, there are only three factors which affect the affordability of the system, and are the capital cost, maintenance cost, and energy consumption.

![Factors that Affect the Decision](image)

Figure 5.26: Factors that affect the choice of an AC system.
5.5.2.4 Capital and Maintenance Costs for the Predominant AC and the Preferred Chilled Water System:

The author met one sales representative from Alkhurafi company, a multi business and projects company in Kuwait (April, 2010). The author showed the sales representative the shape and design of the houses and the intended distribution of chilled water system to the houses. The sales representative required only schematic diagrams for the houses and the distribution of chilled water system; while a schematic diagram of a Packaged-DX type was not required as he could estimate the prices from the cooling load (already estimated by the author with the help of simulation). Based on this, the estimation for chilled water system was made in accordance to the schematic diagrams shown in Figures 5.27 and 5.28.

Figure 5.27: Schematic of chilled-water distribution to each AHU in the houses.

Figure 5.28: Schematic of CAV air-conditioning and the air supply ductwork for each floor.
**Capital Cost:**

For the two types of AC systems under consideration, the packaged DX rooftop system and the air-cooled all-air, chilled-water, constant-volume system, the capital cost is about $ US 880/RT for the packaged DX type, and $ US 2,800/RT for the constant-air-volume, chilled-water system, and includes the costs of cooling production, air distribution in zones, and water distribution from chillers to the AHU. The sales representative estimated these costs based on a wide range of potential suppliers, and although there may be some variation in the precise costs, the large (approximately three-to-one) ratio between the capital costs for chilled water compared to Packaged DX system is not very sensitive to these variations.

**Maintenance Cost:**

The annual cost of maintenance in the HVAC market in Kuwait for the rooftop packaged DX unit and all-air system with air-cooled chiller averages $ US 11/RT and $ US 16/RT, respectively. The costs include the recommended cleaning and preventive maintenance procedures typically associated with the units based on a 15-year lifespan. Other contingent costs cannot be predicted.
5.5.2.5 Summary:

It was shown that the installation cost of a package DX air conditioner is lower than the cost for an air-cooled chiller. Also, a DX system does not require the use of energy to run pumps, as shown in the comparison presented in Table 5.6.

Table 5.6: Comparison between DX and Chilled-Water System.

<table>
<thead>
<tr>
<th>Component</th>
<th>DX</th>
<th>Chilled Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Supply and exhaust (or return) fans</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Condenser fans</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Pumps</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Another common reason for selecting a DX system is the limited space available for indoor equipment rooms. Chilled-water systems frequently require indoor equipment rooms to house the chillers and pumps. In Kuwaiti houses, the preferred DX type, as indicated earlier, is the packaged, air-cooled rooftop condenser type, which can be located on the roofs of houses, as shown in Figure 5.22. On the other hand, the size and shape of the building may also play an important role in deciding between a chilled-water system and a DX system. High-rise buildings are often not well suited for packaged DX rooftop systems, due to the long transport distances of supply air. The physical size of the equipment and ductwork and the static-pressure requirements of the long duct often limit the use of packaged DX rooftop units to short buildings, such as houses. In contrast, chilled-water systems are ideal for applications in which the refrigeration equipment is centrally located within a building or within a campus of buildings. The chilled water can be transported long distances to the air-conditioned rooms, regardless of the building height.

The required cooling capacity of the system can also influence the decision. In large buildings, a chilled-water system generally consists of fewer pieces of refrigeration equipment than a DX system. For example, a school with design capacity of 200 tons (704 kW) can use a single, 200-ton water chiller, whereas a DX system serving
the same school could use five 40-ton or forty 5-ton packaged rooftop units. Hence, the number of pieces of equipment impacts the maintenance requirements. A chilled-water system generally offers more stable control than a DX system. Temperature may fluctuate as a result of step-control characteristic of DX systems since their compressors have either one part load condition or none; this creates difficulty in dealing with load variations. However, in a chilled-water system, the control is better due to the large volume of water inside the chilled-water loop, which can provide a thermal buffer that dampens any changes to the cooling load. In addition, chillers can run in a different capacity control mode at part-load conditions.
5.5.3 Input Data Used for the Simulation

In DesignBuilder, the user can enter details in the HVAC templates, such as mechanical ventilation, heating systems, cooling systems, natural ventilation, air-temperature distribution, and domestic hot water requirements. The selected HVAC template is then modeled in detail in EnergyPlus (DesignBuilder Manual, 2009). With respect to the system of interest in this part of the study, i.e., the all-air chilled-water system, DesignBuilder contains a comprehensive, compact, all-air system template. Figure 5.29 shows the required input data for chilled water system with constant air volume configuration. Explanation of input data used is as follows:

- **Mechanical Ventilation (Cooling)**
  
  In this part of the simulation input, the natural ventilation option was not used, because the outside temperature during summer is much higher than the desired internal temperature. The mechanical ventilation rate (mechanical cooling) was assumed to be 3 ac/h (Abdulrazaq, 2010).

- **Night Cycle Control**
  
  The night cycle control remains off because the outside temperature during the whole summer season is above the internal desired set-point temperature, both during the day and at night. Therefore, there is no reason to keep this option on during the simulation.

- **Fan Placement**

  The AHU can work with either a blow-through fan or a draw-through fan. It is recommended that a blow-through fan be used because it effectively creates a uniform velocity profile across the downstream cooling coil (Abdulrazaq, 2010).

- **Pressure Increase**

  As stated previously, DesignBuilder analyses building energy requirements with the help of the popular DOE EnergyPlus simulation engine. DesignBuilder estimates the
pressure increase by fans based on an auto-sizing feature that links the simulated building with the detailed, compact HVAC system in the EnergyPlus simulation engine (DesignBuilder, 2009).

- **Fan Total Efficiency**

Efficiency varies with the type and size of motor. Available fans in the AHUs of chilled-water systems in Kuwait are mostly in the range of 90% total efficiency, and that is the preference of HVAC designers in Kuwait for systems with cooling capacity above 100 RT (Abdulrazaq, 2010).

- **Fan in Air**

The supply and return air fans and their electric driven motors in the AHUs dissipate heat to the air stream. The amount of heat dissipation depends on the static pressure of the duct system and on the efficiencies and locations of the fans and motors. The heat increase due to the inefficiency of the motor is significant; therefore, it must be calculated and added to the cooling load of the building. Fan heat gains range from 4 to 12.5%, and generally taken 8% on average (Adnot et al, 2003).

- **Temperature and Humidity of the Supply Air**

The temperature and humidity of the supply air are parameters that ensure suitable thermal comfort conditions in Kuwait's climate. These parameters are generally used to maintain internal room conditions at a DB temperature of 24 °C and an RH of 50% (Kuwait Energy Code of Practice, 1983). DesignBuilder will automatically design the chilled water supply temperature in the EnergyPlus simulation engine to guarantee the conditions of the supply air temperature to the air-conditioned zone from the AHU.

- **Chiller COP**

The Energy Code of Practice allows for air-cooled chillers with a power rating of 1.6 kWe/RT or less (Energy Code of Practice, 1983). To enter this value as a COP value, 1.6 kWe/RT is equivalent to 2.2. However, this value represents the minimum allowed value of the COP for the air-cooled chiller. It should be noted that the price
obtained earlier for chiller installation in the survey was for a chiller with a COP of 4.5, and this value was used in the simulation.

- **Cooling Distribution Loss**

  Cooling distribution loss is generally between 2% and 5% as per Chilled-Water designers in Kuwait (Abdulrazaq, 2010). Therefore, it will be assumed that a loss of 3% will occur in the simulation of the total load of the system.

- **Cooling Coil Setpoint Reset Type**

  DesignBuilder recommends using the 'warmest' cooling coil set-point type, because it is more efficient in handling variations in cooling load of the building during the day (DesignBuilder manual, 2009).

- **Central Cooling Coil Type**

  As this is a chilled-water system for cooling, a chilled-water coil type is selected.

- **Cooling Coil Setpoint**

  The cooling coil set point was 14 °C, as recommended for HVAC design in Kuwait (Abdulrazaq, 2010).

- **Air Temperature Distribution Mode**

  As all simulation inputs will be processed by the EnergyPlus simulation engine, the air temperature distribution mode will be assumed to be completely uniform (i.e., the air is fully mixed), because this is what EnergyPlus assumes by default.

- **Operation Schedule**

  The air conditioning will be assumed to be ON throughout the summer (from April 1 through October 31).
Figure 5.29: Input data for chilled water system with constant air volume configuration.
Summary of the inputs data used in the simulated models in DesignBuilder as per constant-air-volume chilled water system are shown in Table 5.7.

Table 5.7: Inputs Required by DesignBuilder for Chilled-Water System.

<table>
<thead>
<tr>
<th>Input Type</th>
<th>Input Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical Ventilation (ac/h)</td>
<td>3 ac/h, constant-air-volume</td>
</tr>
<tr>
<td>Night cycle control</td>
<td>Off</td>
</tr>
<tr>
<td>Fan Placement</td>
<td>Blow-through (AHU)</td>
</tr>
<tr>
<td>Pressure rise (Pa)</td>
<td>Auto-sized in EnergyPlus</td>
</tr>
<tr>
<td>Total efficiency (%)</td>
<td>90%</td>
</tr>
<tr>
<td>Fan in air</td>
<td>Inside the air stream</td>
</tr>
<tr>
<td>Economizer type</td>
<td>None</td>
</tr>
<tr>
<td>Air temperature (°C)</td>
<td>Indoor Temp=24 °C</td>
</tr>
<tr>
<td>Air humidity (%)</td>
<td>RH=50%</td>
</tr>
<tr>
<td>Chiller COP</td>
<td>COP=4.5</td>
</tr>
<tr>
<td>Cooling distribution loss (%)</td>
<td>3%</td>
</tr>
<tr>
<td>Central cooling coil type</td>
<td>Chilled water</td>
</tr>
<tr>
<td>Cooling coil setpoint</td>
<td>Off coil=14 °C</td>
</tr>
<tr>
<td>Air Temperature Distribution Mode</td>
<td>Mixed</td>
</tr>
<tr>
<td>Operation Schedule</td>
<td>Auto, 24 hours/7 days, based on mixed mode temperature control</td>
</tr>
</tbody>
</table>

To acquire a reliable energy consumption comparison for the cases studied, each was simulated using the packaged DX compact template available in the program to be simulated in detail in EnergyPlus. The simulation for this type was based on a COP of 2.1, which is a general value for this AC type in Kuwait, and this was also considered in the pricing in the survey. Moreover, the simulation for the packaged-DX type was based on the same air distribution, ventilation and thermal comfort requirements applied to the simulation for the chilled-water type shown in Table 5.7. However, a loss of 5% was assumed because the distribution of the conditioned air will be from a rooftop unit that supplies air through ducts to the three floors. Fans in packaged units are generally less efficient than those available for chilled-water systems. Hence, a fan with an efficiency of 75% was applied to the simulation (Gopal, 2010).
Table 5.8 summarizes the inputs applied to the Packaged-DX-type simulation.

Table 5.8: Inputs Required by DesignBuilder for Packaged-DX System

<table>
<thead>
<tr>
<th>Input Type</th>
<th>Input Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical Ventilation (ac/h)</td>
<td>3 ac/h</td>
</tr>
<tr>
<td>Pressure Drop (Pa)</td>
<td>Auto-sized in EnergyPlus</td>
</tr>
<tr>
<td>Fan Total efficiency (%)</td>
<td>75%</td>
</tr>
<tr>
<td>Fan in air</td>
<td>Inside the air stream</td>
</tr>
<tr>
<td>Air temperature (°C)</td>
<td>Indoor Temp=24 °C</td>
</tr>
<tr>
<td>Air humidity (%)</td>
<td>RH=50%</td>
</tr>
<tr>
<td>AC Unit COP</td>
<td>2.1</td>
</tr>
<tr>
<td>Cooling distribution loss (%)</td>
<td>5%</td>
</tr>
</tbody>
</table>

5.5.4 Analysis Criteria

The first step in the analysis should consider annual energy consumption associated with the operation of air-conditioning systems. The annual energy consumption by both the packaged DX system and the preferred chilled-water system was determined by using DesignBuilder and the EnergyPlus simulation engine. Then, the result was compared with respect to each AC type for the cases studied. The comparison between the studied AC will be presented based on lifecycle cost analysis.

5.5.5 Simulation Preparation

Compact HVAC data templates were used to organise the simulation data at the building and zone levels for both chilled water and Packaged-DX systems. The schedule of AC system availability was used at the building level to be operating in the entire summer season. The simulation was conducted on detailed HVAC component models automatically generated from the compact description that links all of the data to be processed in the EnergyPlus simulation through its interface with DesignBuilder.
The AC option selected for modeling was the all-air chilled-water system. In this system, central cooling coils are used to condition air, which is subsequently delivered to each of the zones in the system through an air handling unit (AHU) in each zone. Air delivery is set up to minimize the requirements for fresh air supply. The thermostat is located in the control zone as set out by the thermostatic control zone at zone level. The thermostat is set up in each zone in such that it ensures the desired internal temperature for the air-conditioned zone. The cooling capacity is automatically sized using the cooling design calculations for the simulated cases prepared earlier. The coefficient of performance of the chiller is used to calculate the annual electrical energy required to meet the cooling demand during the AC operating season. The chiller's energy consumption includes all energy consumed by such ancillary devices within the chiller. However, other auxiliary equipment (fans and pumps) are simultaneously sized by the autosized feature available in the compact HVAC template that interlinks the simulated model with the EnergyPlus simulation engine to enhance the accuracy of the electrical energy calculation (DesignBuilder Manual, 2009). For the packaged direct-expansion template, the simulation was based on the same air distribution, ventilation and thermal comfort requirements applied to the simulation for the chilled-water type, however, other inputs indicated earlier in Table 5.8 were considered.

The cooling distribution loss to be considered in the simulation is the loss of cooling energy due to the distribution of cold water/air around a building. The losses here were computed to increase the cooling load prior to calculating the energy consumption of the selected AC type. According to (DesignBuilder Manual, 2009), the formula for electricity and chiller energy consumption is:

\[
\text{Chiller Energy} = \text{Chiller COP} \times (\text{EnergyPlus cooling loads} + \text{Cooling distribution loss}).
\]

Hence, the total energy consumption required by the chilled water system comprises of the chiller, fans and distribution pumps. For the packaged-DX system, the total energy consumption consists of the electrical energy required by the cooling unit in the system and fans only, as there are no pumps in this system.
5.5.6 Simulation Results

The program gives the entire electrical energy consumption for the whole system which includes chiller, pumps and fans for the chilled water system (CW) and only chiller and fans for the packaged-DX. Table 5.9 shows the simulation results for the annual energy consumption obtained for the all air- air-cooled chiller compared to the packaged-DX system.

Table 5.9: Simulation Results for Packaged-DX and Chilled Water (CW) Systems.

<table>
<thead>
<tr>
<th>Case</th>
<th>Packaged-DX</th>
<th>CW</th>
<th>Savings of CW Compared with Packaged-DX</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annual Electrical Load (MW_e_h)</td>
<td>Annual Electrical Load (MW_e_h)</td>
<td>Annual Electrical Load (MW_e_h)</td>
</tr>
<tr>
<td>Single Block E-W</td>
<td>786.3</td>
<td>484.7</td>
<td>301.6</td>
</tr>
<tr>
<td>Single Block N-S</td>
<td>757.8</td>
<td>462.0</td>
<td>295.8</td>
</tr>
<tr>
<td>Double Block E-W</td>
<td>767.1</td>
<td>469.4</td>
<td>297.7</td>
</tr>
<tr>
<td>Double Block N-S</td>
<td>764.8</td>
<td>467.6</td>
<td>297.2</td>
</tr>
<tr>
<td>Average of the four cases</td>
<td>769</td>
<td>479.9</td>
<td>298</td>
</tr>
</tbody>
</table>

Table 5.9 shows that CW can provide promising electrical energy savings, especially if the number of houses is large. The savings here represent the difference between the two AC types for each case studied, not between the cases. The CW system can lead to about 40% savings in electrical energy as compared to Packaged-DX system, and the single block east-west case has the largest electrical energy consumption associated with air-conditioning systems, followed by the double block east-west case, then the double block north-south case, and finally the single block north-south case. The order of the case results here are compatible with earlier conclusions in the study that indicate that the east-west cases require more cooling, because they have the largest solar gains on their west facades in the afternoon.
5.5.7 Lifecycle Cost Analysis

5.5.7.1 LCCA Requirements for Air-Conditioning Systems in Kuwaiti Houses

An important step in the evaluation of the lifecycle cost is to prepare all the requirements for the analysis. Figure 5.30 shows the requirements of LCCA for the cases studied.

![Diagram](image)

**Capital Cost:**

Capital cost is the initial cost that depends on the market price of the investigated air conditioning system. The study in this regard considered the market price for each AC type to be analysed. The common prices for the two AC types considered are about $880/RT for the packaged DX –rooftop unit and about $2800/RT for the air-cooled water chiller in the constant-air-volume configuration. They are considered as the initial capital cost for each AC type, as considered in the LCCA calculation. Table 6.6 shows the base date capital cost for each case studied based on the two selected AC systems and based on the design cooling load obtained for each studied case. One Refrigerating Ton is equivalent to 3.517 kW cooling.
Table 5.10: Base date capital cost for each case with both AC types

<table>
<thead>
<tr>
<th>Case</th>
<th>Packaged DX Capital Cost (US $)</th>
<th>CW Capital Cost (US $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Block E-W (425 kW)</td>
<td>106,340.60</td>
<td>338,356.50</td>
</tr>
<tr>
<td>Single Block N-S (395kW)</td>
<td>99,084.440</td>
<td>315,268.69</td>
</tr>
<tr>
<td>Double Block E-W (405kW)</td>
<td>101,336.36</td>
<td>322,433.89</td>
</tr>
<tr>
<td>Double Block N-S (404kW)</td>
<td>101,086.15</td>
<td>321,637.75</td>
</tr>
<tr>
<td>Average of the four cases</td>
<td>101,961</td>
<td>325,000</td>
</tr>
</tbody>
</table>

**Maintenance Cost:**

Maintenance costs depend on many parameters, such as labor expenses, the experience of the workers, the age of the system, and the length of time of operation (Aktacir et al. 2006). The price of annual maintenance for packaged DX rooftop units and air-cooled chiller with constant-air-volume configuration is about $11/RT and $16/RT, respectively. It is expected that the annual maintenance cost will increase due to the probable increase in service cost and wages of workers during the lifespan of these AC systems. Table 5.11 shows the base date annual maintenance cost (without considering the discount rate) for the four studied cases and based on the annual maintenance price for each AC type.

Table 5.11: Base date annual maintenance cost for each case with both AC types

<table>
<thead>
<tr>
<th>Case</th>
<th>Packaged DX Annual Maintenance Cost (US $)</th>
<th>CW Annual Maintenance Cost (US $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Block E-W (425 kW)</td>
<td>1,329</td>
<td>1,933</td>
</tr>
<tr>
<td>Single Block N-S (395kW)</td>
<td>1,238</td>
<td>1,801</td>
</tr>
<tr>
<td>Double Block E-W (405kW)</td>
<td>1,266</td>
<td>1,842</td>
</tr>
<tr>
<td>Double Block N-S (404kW)</td>
<td>1,263</td>
<td>1,837</td>
</tr>
<tr>
<td>Average of the four cases</td>
<td>1,274</td>
<td>1,853</td>
</tr>
</tbody>
</table>
**Operation Cost:**

The operating costs are those incurred for the operation of the AC system, and include the cost of electricity, wages of labors, and any other costs incurred for the actual operation of the system. It was assumed that all air conditioning systems are operated automatically; therefore, estimation of labor cost was ignored in the LCCA, as suggested by Elsafi and Al-Daini (2002).

The annual electrical energy requirement for the operation of an AC system is an important technical and economic parameter for the selection of a cost-effective AC system. The annual electrical energy was estimated as the summation of the hourly electrical energy demand over the complete running period of the AC system. The annual electricity cost was calculated based on the estimated electricity costs to the consumer and government, which are US$0.006/kW·h and US$0.09/kW·h respectively. Table 5.12 shows the annual operation cost based on consumer’s tariff and operation’s cost to government.

<table>
<thead>
<tr>
<th>Case</th>
<th>Packaged DX Annual Electrical Energy Consumption (kWh)</th>
<th>Packaged DX Annual Operation Cost (US $)</th>
<th>CW Annual Electrical Energy Consumption (MWh)</th>
<th>CW Annual Operation Cost (US $)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Consumer</td>
<td>Government</td>
<td></td>
<td>Consumer</td>
</tr>
<tr>
<td>Single Block E-W</td>
<td>786.3</td>
<td>4,717</td>
<td>70,755</td>
<td>484.7</td>
</tr>
<tr>
<td>Single Block N-S</td>
<td>757.8</td>
<td>4,546</td>
<td>68,190</td>
<td>462.0</td>
</tr>
<tr>
<td>Double Block E-W</td>
<td>767.1</td>
<td>4,602</td>
<td>69,027</td>
<td>469.4</td>
</tr>
<tr>
<td>Double Block N-S</td>
<td>764.8</td>
<td>4,588</td>
<td>68,820</td>
<td>467.6</td>
</tr>
<tr>
<td>Average of the four cases</td>
<td>769</td>
<td>4,613</td>
<td>69,198</td>
<td>479.9</td>
</tr>
</tbody>
</table>
5.5.7.2 Financial Inputs and Discounting the Annual Recurring Costs

The present value (PV) was used to calculate the cash flows as of the beginning of the base year. The capital costs for the studied AC systems were considered in present year values. However, the annual recurring costs, i.e. the operations and maintenance costs, are uniform dollar amounts to be paid on an annual basis. Consequently, the uniform present value (UPV) method was selected to calculate these two uniform annual recurring costs.

The UPV requires that all annual recurring costs be discounted to present values. As the study depended on actual data from Kuwait, it was preferred to use the actual financial inputs required to discount all annual recurring costs to present values. By reviewing the last two financial years in Kuwait (CBK, 2007/8 and 2008/9), there was an average interest rate of 3.2%; while the inflation was 2.1% based on the increase in the consumer price index between the two financial years. The recent available discount rate determined by the Central Bank of Kuwait is 3.75% (CBK, 2008/9). The study considered these obtained values, as it is difficult to make future predictions of its value.

It should be noted that the annual operating cost is not affected by inflation for two reasons: the subsidization policy in Kuwait for electricity consumers and the fact that electricity is produced by power plants using national oil in Kuwait, hence the government does not buy the primary fuel for electrical power plants. However, the government provides an annual average production cost for each kWh of electricity produced based on the national oil price/barrel to be included in the annual financial statement of the country. Therefore, the discount rate for the annual operating costs is the same as the interest rate, which is 3.2% since the inflation rate was assumed to be 0%. However, the annual maintenance cost is expected to increase in the future due to expected increases in the costs of the consumable parts required for maintenance, as well as increases in the wages of the workers. Hence, the annual maintenance cost was discounted to present value based on the discount rate of 3.75%, which is a function of both interest and inflation rates.
It should be noted that the prices presented in US dollars depend on the currency exchange rate of 0.275 Kuwaiti Dinar versus US dollars (April 2010). The most recent exchange rate is 0.276 Kuwaiti Dinar versus US dollar (October 2011). The variation herein is insignificant and will not make any tangible difference in the results.

5.5.7.4 LCCA Results

Based on the values presented in Tables 5.10, 5.11 and 5.12 for the four cases, the LCCA was conducted based on the averages. The analysis depended on the average of the four residential case studied to compare the two studied AC alternatives, not the residential cases. The present value method with a uniform present value was used to perform a 15-year LCC analysis based on an operator-subsidized tariff. Conducting the LCC calculations using the subsidized electricity tariff was logical because, in reality, consumers are purchasing the AC systems, and they pay the operation and maintenance costs. Hence, it was expected that the analyses of LCC based on the subsidized tariff would be beneficial for determining feasible selection scenarios. The economic analyses also show the present value for the government’s production cost for each kWh of electricity during the 15-year period. The results of the LCC are shown in Table 5.13.

It was shown earlier that the use of the Chilled Water system (CW) can reduce annual electricity consumption by 40%. Looking at it from an economic point of view based on LCCA, the results based on the operator-subsidized tariff indicate that the Packaged-DX system has an LCC that is 54% lower, due to the low cost of the subsidized tariff and the higher capital and maintenance costs of the CW system compared to the Packaged-DX system.

From the total cash paid nationally to own, operate, and maintain AC systems, the consumers’ financial contributions represent approximately 17% and 43% for Packaged-DX and CW systems, respectively. Although the government has no role in purchasing the AC systems or maintaining them, the cash paid by the government represents about 82% and 56% of the total cash paid for Packaged-DX and CW systems, respectively. These results show that the total LCC based on the
consumers’ tariff, which includes the total expenses of AC, is less than the government's production cost, and is expensive for the government. Consumers in the residential sector will not consider the use of a chilled water system to replace the air conditioning that they currently use as the LCCA results indicate; this change would not be cost effective for them.

In addition to the environmental benefits that can be obtained from energy savings, there is a significant difference between the government’s total operational costs for the two AC systems, amounting to approximately $300,000. In this context, one possible scenario for utilizing the cash savings would be the government subsidizing the capital cost of the chilled water system to encourage consumers to choose this alternative. Also, the government could use part of the savings to install more electrical power which costs $1500/kWe.

As the analysis shows, the government pays most of the costs associated with the operation of air conditioning systems. Subsidization of chilled water systems would help conserve Kuwait’s oil reserves, which are a major source of national income.
Table 5.13: LCC Results Based on the Average of the Four Orientation and Houses Grouping Cases.

<table>
<thead>
<tr>
<th></th>
<th>Base Date Cost in US $</th>
<th>Year of Occurrence</th>
<th>Uniform Present Value Factor</th>
<th>Present Value in US $</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Packaged-DX</td>
<td>CW</td>
<td></td>
<td>Packaged-DX</td>
</tr>
<tr>
<td>AC Capital Cost</td>
<td>101,961</td>
<td>325,000</td>
<td>Initial</td>
<td>101,961</td>
</tr>
<tr>
<td>Operation Cost (Consumer Tariff)</td>
<td>4,613</td>
<td>2,825</td>
<td>Annual</td>
<td>52,173</td>
</tr>
<tr>
<td>Maintenance Cost</td>
<td>1,274</td>
<td>1,853</td>
<td>Annual</td>
<td>14,982</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>169,116</td>
</tr>
<tr>
<td>Total LCC to Consumer US $</td>
<td></td>
<td></td>
<td></td>
<td>169,116</td>
</tr>
<tr>
<td>Operation Cost (Government Production Cost)</td>
<td>69,198</td>
<td>42,382</td>
<td>Annual</td>
<td>782,629</td>
</tr>
<tr>
<td></td>
<td>951,745</td>
<td>858,081</td>
<td></td>
<td>951,745</td>
</tr>
</tbody>
</table>
5.5.7.5 Sensitivity Analysis

LCCA results can also be analyzed by subjecting them to sensitivity tests to determine the influence of the uncertain input variables. Although it is preferable to use reliable input data for LCCA, some inputs are based on assumptions and estimates, the variability and inaccuracies associated of which can have a major influence on the results.

Among the input data used in the cost effectiveness analyses, the government's production cost for the electricity produced by power plants was the most uncertain inputs. This uncertainty is due to the strong relationship between production cost and the cost of oil, which is influenced significantly by the unpredictable global market price. In addition, the findings obtained in Chapter 2 showed that, in spite of the uncertainty associated with the amounts of the remaining oil reserves, oil is likely to remain the most sought after energy resource in the foreseeable future, which is certain to make prices fluctuate unpredictably. Accordingly, this study focused on the production cost of electricity as an important, but uncertain, input that required sensitivity analyses. It was assumed that the future increase in operation cost (cash paid by the government) will be between 10-30% greater than the original price considered earlier which is US$0.09/kWh. The results of the sensitivity analyses were compared with the LCC results obtained based on the total cash paid by consumers. Figure 5.31 shows the present value of different government production costs.
Figure 5.31: Increase in government's operation cost (in present value) for electricity production compared to the LCC based total cash paid by consumers.

As Figure 5.31 shows, the Packaged-DX system is an attractive AC system for consumers, in spite of its burden on the government, which has assumed the responsibility for supplying electricity to consumers based on a subsidized tariff. The results shown in Figure 5.31 represent the total cost for consumers and the cost of electricity production for the government in 15 years. The costs are discounted to present values and are significant because they indicate the deleterious effect of the continued use of Packaged-DX AC systems on the government's costs. Also, the results provide insight concerning the proposed use of chilled water AC systems to replace the Packaged-DX AC systems currently in use.

According to the findings obtained from the LCCA conducted and according to the projection of the future increase in government's electricity operation cost shown in Figure 5.31, it is apparent that chilled water AC systems are not a cost effective alternative for consumers, based on the current market prices obtained from the AC market in Kuwait, even though chilled water AC systems use 40% less electricity than Packaged-DX AC systems. However, the continued use of Packaged-DX systems was not found to be cost effective for the government,
because of the subsidized tariff. The barriers to converting to chilled water systems should be evaluated with respect to all of the benefits, which include economic, environmental, social, and practical benefits, to prepare the residential sector to shift to chilled water AC systems.

5.5.8 Environmental Benefits of Using Chilled Water Systems for the Cases Studied

The study also demonstrated the environmental benefits obtained from using chilled water systems as an alternative to the Packaged-DC systems currently used in Kuwaiti houses. An important benefit is the significant reduction of the annual CO₂ emissions associated with electricity production. The approach followed here is multiplying the amount of CO₂ produced per kWhₑ of electricity produced by power plants in Kuwait (0.72kg/kWhₑ) by the annual electrical energy consumption (Eₐnnual in kWhₑ) associated with operating air-conditioning systems. The results in Table 5.14 show that CW systems can lead to a reduction in annual CO₂ emissions of approximately 40% compared to Packaged-DX systems for each case studied. This is a significant CO₂ emission reduction that any energy conservation method can offer.

Table 5.14: CO₂ emissions eliminated by chilled water system.

<table>
<thead>
<tr>
<th>Case</th>
<th>Packaged-DX</th>
<th>CW</th>
<th>Reduction of CO₂ by CW Compared with Packaged-DX (Ton/Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annual</td>
<td>Annual</td>
<td>Annual CO₂ Emissions (Ton)</td>
</tr>
<tr>
<td></td>
<td>Electrical</td>
<td>CO₂</td>
<td>Load (MWₗh)</td>
</tr>
<tr>
<td>Single Block E-W</td>
<td>786.3</td>
<td>56.60</td>
<td>484.7</td>
</tr>
<tr>
<td>Single Block N-S</td>
<td>757.8</td>
<td>54.56</td>
<td>462.0</td>
</tr>
<tr>
<td>Double Block E-W</td>
<td>767.1</td>
<td>55.20</td>
<td>469.4</td>
</tr>
<tr>
<td>Double Block N-S</td>
<td>764.8</td>
<td>55.06</td>
<td>467.6</td>
</tr>
<tr>
<td>Average of the four cases</td>
<td>769</td>
<td>55.36</td>
<td>479.9</td>
</tr>
</tbody>
</table>
5.6 Solution (3): The Integrated Combined Cycle-with Absorption Chiller System

5.6.1 Background

An integration of each component of the combined cycle power plant driving a single-effect LiBr/water absorption chiller was made. The objective was to verify how the packaged-DX AC, which is the current air-conditioning in use in Kuwaiti house; can be compared to other promising solution in terms of energy usage.

There are many publications that address CHP with cooling applications. In addition, the combined cycle power plant configuration, which is the preferred CHP choice, has received significant attention in research. However, to our knowledge, no previous attempts have been made regarding this complete configuration (CCPP with absorption chiller) to be modeled with full cooling load profile, and then compared to another alternative. The idea of using steam extraction to drive an absorption chiller is not new (Ziegler and Riesch, 1993). However, the study here will examine CCPP with absorption chiller as an alternative for residential cooling. The inspiration of this general idea came from the work conducted by Darwish et al. (2008 b), when they suggested better utilization choices for CCPP in which they recommended an absorption chiller driven by steam extraction as a promising choice. Figure 5.32 shows the suggested integrated CCPP with absorption chiller for residential cooling.
Figure 5.32: The integrated combined cycle power plant driving a single-effect absorption chiller.
5.6.2 Step-by-Step Modeling Criteria

The purpose of this section is to present the modeling steps. The intended work involves the following major steps:

- Preparing the requirements of the analysis (e.g., cooling load profile of Kuwaiti houses, input data, output data, and assumptions)
- Arranging the model's equations and the system’s parameters in EES.
- Modeling the combined cycle power plant (CCPP) without an absorption chiller driving packaged DX air conditioning systems
- Preparing the cooling load profile in an external file (exported from DesignBuilder).
- Modeling the CCPP with a single-effect LiBr/water absorption chiller.
- Acquiring and analyzing the outcomes.

5.6.3 Preparation of the Input Data

5.6.3.1 Parameters of the Combined Cycle Power Plant

The main concern addressed along with the proposed configuration was the influence of the cooling load on the performance of the integrated system, i.e., specifically its relationship with the amount of steam extraction and its impact on power generation. Hence, it was important first to have the data related to the CCPP to model the plant in EES.

Since the performance of CHP systems depends mainly on the prime mover (i.e. gas turbine in CCPP), it was preferred to make a visit to a newly commissioned power plant in Kuwait. The purpose of this visit was to obtain reliable combined cycle
specifications. The visited power plant was the Shuaiba power plant located south of Kuwait. Figure 5.33 shows an external view of the plant.

Figure 5.33: Shuaiba Power Plant South of Kuwait.

During the visit, more details were obtained about the actual operating parameters that could be used in the computer model. Based on the process provided with the configuration presented in Figure 5.32, Table 5.15 shows the actual operating parameters of the plant. It should be noted that the study relied on these parameters assuming no changes will occur to the operation conditions of the plant. This condition is known as “Base Load" operating parameters, which is an assumption that the plant is producing its maximum gross power output directly to the utility grid.
### Table 5.15: Specifications of Shuaiba combined cycle power plant

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pressure ratio ($r_p$)</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>Air compressor volumetric flow rate ($V$)</td>
<td>600 m³/s</td>
</tr>
<tr>
<td>3</td>
<td>Compressor isentropic efficiency ($\eta_{\text{comp}}$)</td>
<td>90%</td>
</tr>
<tr>
<td>4</td>
<td>Fuel volumetric flow rate ($V_{\text{fuel}}$)</td>
<td>0.021 m³/s</td>
</tr>
<tr>
<td>5</td>
<td>Fuel specific gravity</td>
<td>0.6</td>
</tr>
<tr>
<td>6</td>
<td>Gas Turbine isentropic efficiency ($\eta_{\text{gt}}$)</td>
<td>88%</td>
</tr>
<tr>
<td>7</td>
<td>Gas turbine design inlet temperature ($T_3$)</td>
<td>1010 °C</td>
</tr>
<tr>
<td>8</td>
<td>Gas turbine design exit temperature ($T_4$)</td>
<td>630 °C</td>
</tr>
<tr>
<td>9</td>
<td>Flue gas design temperature (from HRSG) ($T_5$)</td>
<td>150 °C</td>
</tr>
<tr>
<td>10</td>
<td>Heat recovery steam generator effectiveness</td>
<td>50%</td>
</tr>
<tr>
<td>11</td>
<td>Pressure loss inside heat recovery steam generator</td>
<td>30%</td>
</tr>
<tr>
<td>12</td>
<td>Steam turbine isentropic efficiency ($\eta_{\text{st}}$)</td>
<td>84%</td>
</tr>
<tr>
<td>13</td>
<td>Condenser pressure (absolute pressure)</td>
<td>6 kPa</td>
</tr>
<tr>
<td>14</td>
<td>High pressure steam cycle ($P_6$)</td>
<td>14,182 kPa</td>
</tr>
<tr>
<td>15</td>
<td>Temperature of feedwater ($T_6$)</td>
<td>130 °C</td>
</tr>
<tr>
<td>16</td>
<td>Sea water temperature ($T_{12}$)</td>
<td>32 °C</td>
</tr>
<tr>
<td>17</td>
<td>Steam turbine design inlet temperature ($T_7$)</td>
<td>530 °C</td>
</tr>
<tr>
<td>18</td>
<td>Pumps mechanical efficiency</td>
<td>75%</td>
</tr>
</tbody>
</table>

The parameters shown in Table 5.15 were entered in the model. Steam turbine inlet pressure can be calculated by multiplying $P_6$ by the HRSG pressure loss. Sea water temperature is assumed to be 32 °C which is the daily average sea water temperature during summer in Kuwait, according to Albanaa and Rakha (2009). Other inputs were considered from hourly cooling load profiles (i.e. $T_1$ is the temperature of the ambient air and houses cooling load).
5.6.3.2 Parameters of the Single-Effect Absorption Cycle

The second set of parameters required for the system is those of the single-effect LiBr/water absorption chiller. An important input parameter for a cooling system is the coefficient of performance. The efficiency of the absorption chiller is described in terms of coefficient of performance (COP), i.e., the refrigeration effect divided by the net heat input. For single-effect absorption chillers, values of the COP are generally in the range of 0.6 - 0.8 (Howell et al., 1998). An absorption chiller’s COP cannot be compared to the COP of other cooling cycles, such as an electrically-driven chiller, because the input energy for an absorption chiller can be essentially free if, for example, it is provided by solar energy or by the waste heat from an energy process, such as the generation of electricity. In this regard, the amount of heat is an important parameter in the absorption system. In absorption chillers, heat is required to vapourize the refrigerant in the generator. The single-effect LiBr/water absorption chiller operates on low-pressure steam at a generation temperature (Tg) of 90°C (Howell et al., 1998). The thermal energy input to the generator in the absorption chiller was obtained by multiplying the mass flow rate of the steam by the enthalpy difference between the steam entering the generator and the condensate at the outlet. The amount of energy required for the generator was determined based on the amount of cooling required, and the design COP of the chiller was determined from the equation:

\[
COP = \frac{Q_{\text{cooling}}}{Q_{\text{gen}} + W_{\text{Solution Pump}}} 
\]

(5.6)

Another parameter was the concentration of the LiBr/water solution. As indicated earlier, water is the refrigerant in this cooling system. When the vaporization occurs in the generator, the solution is divided into three parts, i.e., weak solution (ws), strong solution (ss), and refrigerant (R). The refrigerant (R) is water vapor, however, the concentrations of the weak and strong solutions must be identified as input parameters in the cycle. According to the analysis of a single-effect water/LiBr absorption cycle presented by Thomas et al. (1998), the concentration of the strong
LiBr solution is 57.5%, whereas the concentration of the weak LiBr solution is 64%. The concentrations here represent the presence of LiBr in the mixture. On the other hand, the temperatures of the other components in the chiller must be defined in the model. Kayanki and Kilic (2007) indicated that the system's evaporator for the selected chiller type cannot operate at temperatures well below 5 °C, because the refrigerant is water vapour, while the condenser and absorber temperatures are in the range of 35 °C. Table 5.16 lists the salient input parameters for the single-effect LiBr/water absorption chiller.

Table 5.16: Parameters for the single-effect LiBr/water absorption chiller.

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator Temperature</td>
<td>$T_{gen} = T_{16} = 90 , ^\circ\text{C}$</td>
</tr>
<tr>
<td>COP</td>
<td>0.7</td>
</tr>
<tr>
<td>Weak solution concentration</td>
<td>$x_{ws} = 0.64 , \text{kg LiBr/kg mix}$</td>
</tr>
<tr>
<td>Strong solution concentration</td>
<td>$x_{ss} = 0.575 , \text{kg LiBr/kg mix}$</td>
</tr>
<tr>
<td>Evaporator Temperature</td>
<td>Not less than 5 °C</td>
</tr>
<tr>
<td>Condenser Temperature</td>
<td>35 °C</td>
</tr>
<tr>
<td>Absorber Temperature</td>
<td>35 °C</td>
</tr>
</tbody>
</table>

5.6.3.3 Cooling Side Demand (Houses)

In modeling the process, cooling load data were supplied as the calculated hourly cooling load of the buildings obtained from DesignBuilder software through its interface EnergyPlus program. The cooling load was assumed to include an additional 10% of cooling energy to cover the cooling losses in the supply line and the buildings. Including the cooling losses is essential in the design of the district cooling plant (Shimoda et al., 2008). On the other hand, the cooling loads of the DX air conditioning were obtained from DesignBuilder including 5% losses (i.e. cooling loss inside houses). Both cooling load profiles are based on the average cooling loads of the four cases considered earlier in this work. In this context, the study in this part has considered a number of 1000 houses, which is equivalent to 167 blocks of six houses. Therefore, the cooling loads that represent the 6 houses were multiplied by 167. The calculation of pressure loss in district cooling network requires a detailed
engineering calculation which is beyond the scope of this study. A typical pressure drop for a district cooling system is approximately 240 kPa (Kazmah, 2007).

It is worth mentioning that the variation in the cooling load will serve as a control sequence to simulate the chiller performance. Krishnamurthy (2010) indicated that running steam driven absorption chillers directly to the load without an intermediate thermal energy storage plant for district cooling (DC) is a logical design option that can be provided by DC suppliers. Darwish (2001) discussed the idea of varying the constant temperature process heat to the absorption chiller according to cooling load variations, and emphasized that this should be considered in the design stage of the plant. Consequently, and based on equation (4.22) from chapter 4 and equation (5.6), the whole system runs according to the variation in steam extraction (y), as shown in equation (5.7):

\[
COP = \frac{Q_{\text{cooling}}}{Q_{\text{gen}} + W_{\text{pump}}}
\]

\[
Q_{\text{km}} = m_s y (h_8 - h_{15}) \Rightarrow COP = \frac{Q_{\text{cooling}}}{m_s y (h_8 - h_{15}) + W_{\text{pump}}}
\]

\[
y = \frac{Q_{\text{cooling}} - COP * W_{\text{pump}}}{m_s (h_8 - h_{15}) COP}
\]

On the other hand, the temperatures of the chilled water leaving the evaporator to the buildings and the return chilled water are important parameters to be verified for the modeling. According to Kalogirou (2008), the single effect absorption chiller is mainly used for building cooling loads, where chilled water is required at 6-7 °C. It was assumed that the temperature of the chilled water returning from the building is about 12.5°C. The temperature herein includes the cooling loss (i.e., heat gain) in the buried pipes that could not be mitigated by thermal insulation around the pipes. Therefore, the control of chilled water from the chiller to the terminal unit in the building (i.e., AHU’s cooling coil) is also based on the variation in the generator heat input (steam extraction from the power plant) and the cooling load from the demand side. Table 5.17 shows input parameters from the cooling demand side.
Table 5.17: Input parameters from the cooling demand side (houses).

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hourly cooling load</td>
<td>To be exported from DesignBuilder</td>
</tr>
<tr>
<td>Cooling distribution loss</td>
<td>10%</td>
</tr>
<tr>
<td>Temperature of the chilled water supply</td>
<td>7 °C</td>
</tr>
<tr>
<td>Temperature of the chilled water return</td>
<td>12.5 °C</td>
</tr>
<tr>
<td>Chilled water pressure loss</td>
<td>240 kPa</td>
</tr>
</tbody>
</table>

5.6.3.4 Overall Assumptions in the Model

- The gas cycle is an open cycle
- Electrical generator magnetic coil efficiency is neglected, because the study depends on the energy saving between the two studied configurations.
- No pressure losses in the plant excluding the HRSG.
- Plant is running at full throughput of power generation (gas and steam turbine).
- No additional firing in the HRSG.
- Energy consumption associated with the circulated cooling water to the CCPP condenser and the absorption chiller's condenser and absorber are neglected (i.e., plant is assumed near sea, pressure difference is very low).
- No heat loss from the envelope of the system's components and pipelines (adiabatic).
- Steam leaving the CCPP's condenser is a saturated liquid.
- Steam extraction is intermediate-pressure steam at $T_{gen} + 10$ °C (i.e. 100 °C)
- Weak solution and refrigerant leaving the generator have the same generation temperature.
- Strong solution leaving the absorber has a temperature equal to the absorber temperature.
- Constant pressure in the absorber and the evaporator (negligible pressure drop).
• Constant pressure in the generator and the condenser (negligible pressure drop).
• Chilled water temperature leaving and entering the evaporator represent the temperature of the flow coming to and from the terminal units in the cooling demand side (i.e., AHU).
• Cooling demand is met by the variation of chilled water mass flow rate from the chilled water pump.

5.6.4 Plant Energy Calculations

Plant net power output is the main parameter in the CCPP configured with absorption chillers and Direct-Expansion air conditioning. Explanation of the net power from the plant for each type ($W_{net}$) is as follows:

For the CCPP with absorption chiller, the net power is:

$$W_{net,Abs} = W_{Tot} - (W_c + W_{pump1} + W_{pump2} + W_{pump3} + W_{pump4})$$

(5.8)

For the CCPP with DX cooling, the electrical power required for operating this type was assumed to be taken from the gross power produced by the plant to the utility grid, therefore the net power is:

$$W_{net,DX} = W_{Tot} - (W_c + W_{pump1} + \frac{Q_{cooling}}{COP_{DX}})$$

(5.9)

Where the $Q_{cooling}$ represents the cooling load data taken from the Building simulation files later on, while the COP represents the coefficient of performance of DX air conditioner. It should be noted that equation (5.8) does not include terms for cooling, because absorption chiller depends mainly on heat energy. However, expression 5.8 differs from equation 5.9 in the inclusion of electrical power required to operate pump 2 in the steam cycle, pumps 3 and 4, which are required to operate the absorption chiller.
5.6.5 Results

5.6.5.1 Combined Cycle Model

A parametrical analysis was conducted for the system to ensure the computer model was accurate and did not conflict with the thermodynamics principles of the plant. The first parameter demonstrates the impact of ambient temperature variations on the system. It is known that cooling load varies significantly with variations in ambient temperature. Hence, it is important to make sure that the system responds to ambient temperature variations. The second analysis to be verified is to ensure the system is able to vary in response to the amount of steam extracted from the exit of the steam turbine exit and sent to the generator in the absorption chiller. Thus, as demonstrated in equation 5.7, ensuring the ability of the whole system to interact with variations in the fraction of steam used to drive the generator is a significant step in this analysis.

Figure 5.34 shows variation of net power output with varying (a) ambient air temperature and (b) steam extraction.

Figure 5.34: Variation of net power of the power plant versus; (a) ambient air temperature, (b) steam extraction (y).
From Figure 5.34 (a), an increase in ambient temperature causes a decrease in the net power of the plant. This is due to the effect on the mass flow rate of air entering the compressor, as is explained in the following expressions:

Decrease in the density of air,

\[ \rho_a = \frac{P_{am}}{R \cdot T_a} \]

leads to a decrease in the mass flow rate of air

\[ m_a = V_a \rho_a \]

Since the output of the plant power depends on the total power produced by the gas turbine \( W_{gt} \) and the steam turbine \( W_{st} \), the decrease in the mass flow rate of air mainly leads to a decrease in the mass flow rate of gas entering the gas turbine, as is explained in the equation below:

\[ m_g = m_a + m_f \]

Hence, the power of the gas turbine is affected by this decrease in the mass flow rate of the gas, as shown in the equation below:

\[ W_{gt} = m_g (h_3 - h_4) \]
Figures 5.35 (a) and (b) confirm the fact that air temperature has affects the power output of the gas turbine. These Figures can be linked to the explanation for Figure 5.34 (a).

![Figure 5.35](image)

Figure 5.35: (a) mass flow rate of ambient air with ambient temperature; (b) output of the gas turbine with ambient temperature

To explain why the net power output decreases with the increase in steam extraction (Figure 5.34 b), it is necessary first to understand the fundamental aspects of steam turbine power generation by recalling the steam turbine energy balance:

\[
W_{st} = m_s y (h_7 - h_8) + m_s (1 - y) (h_8 - h_{14})
\]

It is also necessary to understand the process explained in Figure 4.20 in Chapter 4, which shows three pressure levels on the Temperature-Entropy diagram for the steam entering and leaving the steam turbine. In Figure, 4.20, point (7) has the highest thermal energy, followed by point (8) and then point (14). When calculating the power of the steam turbine, part (1) in the equation above, i.e., \((h_7-h_8)\), which represents the steam turbine expansion to extraction pressure, has a lower enthalpy difference than part (2), i.e., \((h_8-h_{14})\), which represents the steam turbine expansion to condensation. When the amount of steam extraction \((y)\) increases, the effect of part (2), i.e., the highest enthalpy difference, is minimized since the amount of steam \([m_s (1-y)]\) will decrease and approach zero, since \([0 < y < 1]\); meanwhile, part (1), which
has less enthalpy difference, will be multiplied by the maximum amount of steam ($m_y$). In total, the power output of the steam turbine decreases as the quantity of steam extracted increases, as shown in Figure 5.36. This is in accordance with one of the outcomes in the study conducted by Al-Hawaj and Al-Mutairi (2007).

![Figure 5.36: The effect of steam extraction ($y$) on the power output of the steam turbine](image)

Figure 5.37 shows the final step that must be verified in the parametrical analysis. This step is to ensure that the thermal energy of the generator can cope with the variation in the amount of steam extracted to drive the absorption chiller. It is clear that the relationship is proportional, because the absorption chiller’s cooling capacity depends mainly on the amount of steam delivered to drive the generator, as shown in equation 5.7.
Figure 5.37: Absorption chiller generator heat versus the fraction of steam extraction ($y$)
5.6.5.2 Electrical Energy Savings

When modeling a combined cycle power plant with a single-effect absorption chiller, three major parameters will vary with respect to time, 1) ambient temperature, because ambient conditions vary frequently during the period when air-conditioning systems must operate in Kuwait (i.e., April 1 - October 31); 2) the hourly values of cooling load ($Q_{\text{cooling}}$) in the cases that were studied; and 3) the amount of steam extracted ($y$) to operate the generator for the absorption chiller. In this context, the amount of steam extracted ($y$) was addressed in equation 5.7. The steam extraction parameter ($y$) was calculated to get the exact amount of steam that must be extracted to meet the cooling required by the demand side (i.e., houses). Accordingly, hourly values of all three of the parameters (i.e., $T_a$, $Q_{\text{cooling}}$, and $y$) were imported into the computer model in EES as input data during the air-conditioning operation period.

For the analysis of the Direct-Expansion type of air conditioning system, no steam extraction is needed in the computer model and the power needed to meet the electrical demand associated with the cooling load was subtracted from the power output of the combined cycle.

The calculation of the average net electrical energy savings in the CCPP from both options, i.e., CCPP with absorption chiller (CCPP$_{\text{Abs}}$) and CCPP with Direct-Expansion (CCPP$_{\text{DX}}$) is:

$$W_{\text{net-Saving}} = \frac{\sum_{i=1}^{n} \left[ W_{\text{net,CCPP DX}} - W_{\text{net,CCPP Abs}} \right]}{n}$$

(5.10)

where 'n' is the number of hours that the air-conditioning system was operated. The result from equation 5.10 will be positive (+ve) if $W_{\text{net,DX}} > W_{\text{net,Abs}}$.  

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Based on the case in which 1000 houses were studied, Table 5.18 shows the average net electrical power from CCPP\textsubscript{Abs} and CCPP\textsubscript{DX} during the summer season (MW\textsubscript{e}, expression 5.10), the percentage of the average electrical energy savings from both configurations (MW\textsubscript{e}, equation 5.10), and the total annual savings in gigawatt hours (GW\textsubscript{e}hr).

Table 5.18: Net electrical power from the CCPP for both configurations

<table>
<thead>
<tr>
<th>Number of houses</th>
<th>( W_{\text{net,CCPP,Abs}} ) (MW\textsubscript{e})</th>
<th>( W_{\text{net,CCPP,DX}} ) (MW\textsubscript{e})</th>
<th>( W_{\text{average-savings}} ) (MW\textsubscript{e})</th>
<th>( W_{\text{annual-savings}} ) (GW\textsubscript{e}hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>417</td>
<td>419</td>
<td>2</td>
<td>10.2</td>
</tr>
</tbody>
</table>

The values presented in Table 5.18 do not represent the electrical energy savings associated with the operation of the two types of air-conditioning systems studied; instead, they represent the average electrical power available in the grid from the CCPP based on unified operating parameters for the CCPP for the two studied configurations (CCPP\textsubscript{Abs} and CCPP\textsubscript{DX}). As seen in Table 5.18, when the CCPP was configured with the cooling load of DX air conditioning systems, it produced more electrical power output to be sold to the grid. The reason for this is the effect of steam extraction on the performance of steam turbine power.

The analysis of the two possible air conditioning systems was made based on unified inputs for the CCPP, which include gas cycle, HRSG, and steam cycle configurations. This is based on the main idea of CCHP systems which is the ability to supply electrical energy and cooling from a primary mover, i.e., the gas cycle of the CCPP in this study. The savings reported in this study were based only a consideration of the energy factor, and other factors associated with the capital, operation, and maintenance of the systems must still be addressed. Figures 5.38 and 5.19 show the energy flow in CCPP\textsubscript{Abs} and CCPP\textsubscript{DX}, respectively.
Figure 5.38: Energy flow diagram for CCPP with absorption chiller based on cooling load for 1000 houses.
Based on the average of all results generated in EES, energy flows in Figures 5.38 and 5.39 show energy streams in the plant (work and heat). Based on same fuel quantities and unified CCPP operating parameters, the CCPP,Abs produces net electrical power (E1) by 55%; while the CCPP,DX produces net electrical power (E1+E2) about 59% from the total fuel input. This is due two reasons, first, the steam turbine power declines with steam extraction rate and, second, the CCPP,Abs has more electrical power consumed inside the plant. From the same figures, heat from flue gas leaving the HRSG for both configurations is almost the same, because exhaust gas and HRSG conditions for both studied configurations are the same. Share of heat flow from the main condenser in the CCPP,Abs is lower than the same heat flow in the CCPP,DX, because the CCPP,Abs, part of the steam leaving the turbine does not enter the condenser (i.e. to absorption chiller generator). Rejected heat from
absorption chiller’s condenser and absorber (Q5) is applicable only for the CCPP,Abs and represents about 10% from the total heat input. To understand the relationship between the cooling needed by absorption chiller driven by steam extraction in the CCPP with the amount of electrical produced by the plant. Figure 5.40 shows the relationship between CCPP net electrical power, and absorption chiller cooling measured based on the number of houses. It is clear from the figure that the CCPP net electrical power decreases with the increase in number of houses (i.e. more steam extraction). The cooling load in CCPP,Abs computer model is presented in terms of steam extraction (y), hence, due to the small variation in extraction rate as shown in Figure 5.40, the effect on the net electrical power is small. The extraction rate here is for the annual cooling load divided by the number of hours (hours of AC operation).

![Graph showing the relationship between CCPP net electrical power and number of houses](image)

Figure 5.40: Average net electrical power in MW from CCPP,Abs based on number of houses receiving chilled water.

Finally, plant thermal efficiency was calculated. Thermal efficiency is calculated based on the amount of work and/or heat obtained from the fuel burned. In reality, energy (work or heat) cannot be obtained ideally (i.e., without any losses) from burned fuel. In any system, losses, such as friction, heat loss, and equipment efficiency, will preclude the ideal conversion of the burned fuel to useful heat and/or
work. The theoretical thermal efficiency can be calculated based on the lower temperature in the studied CCPP which is the condensation temperature ($T_9$), and the maximum temperature is the temperature at the inlet of the gas turbine ($T_3$):

$$\eta_{th} = 1 - \frac{T_9}{T_3} \quad (5.11)$$

The actual thermal efficiency of the plant is based on the ratio between the net electrical power and the heat input in the combustion chamber as follows:

$$\eta_{in} = \frac{W_{net}}{Q_{comb}} \quad (5.12)$$

A comparison between the actual thermal efficiency obtained from the plant and the theoretical efficiency is shown in Table 5.19.

**Table 5.19: Thermal efficiency of the plant**

<table>
<thead>
<tr>
<th>CCPP Configuration Type</th>
<th>$\eta_{ccpp}$</th>
<th>$\eta_{th}$ based on the second law of thermodynamics</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCPP$_{Abs}$</td>
<td>56%</td>
<td>76.2%</td>
</tr>
<tr>
<td>CCPP$_{DX}$</td>
<td>57.3%</td>
<td>76.2%</td>
</tr>
</tbody>
</table>

The thermal efficiency of the CCPP is slightly higher when no extraction is applied. This is due to the ability of CCPP$_{DX}$ to offer more net power than the CCPP$_{Abs}$. 
5.7 Conclusions:

5.7.1 Cooling Load

This calculation of Kuwaiti house cooling loads was conducted using the DesignBuilder simulation program. The simulation was conducted for four cases, namely single block east-west, single block north-south, double block east-west and double block north-south. Each block consisted of 6 houses to allow for the occurrence of the internal shading that results from neighbouring houses. Every simulated case was analyzed and compared to the other cases. Among all simulated cases, the single block east-west case achieved the largest cooling load. Additionally, the analysis indicated that the single north-south orientation had the smallest cooling load. The findings are explained such that if the largest surface of the block is facing east-west, it will receive more solar radiation than the block with the largest surface facing north-south. The breakdown of cooling load components also indicated that load resulting from glazing significantly affects the cooling load, especially in single block E-W arrangement, as it represents 32% of the peak cooling load. At this point, and based on the comprehensive analysis of the Kuwaiti houses cooling load presented in this chapter, the study can make the following conclusions:

- The simulated cases complied with the Energy Code of Practice and other relevant studies in terms of houses peak cooling load values and AC power rating. The cooling load of one house is about 70 KW.
- The simulated cases show that houses facing east-west have the largest cooling loads, significantly increased by glazing which contributes to about 30% of the cooling load.
- Shading resulted from neighboring houses is almost negligible in the single block E-W case, while it is apparent for other simulated cases.
- The breakdown of cooling load components show that the load resulted from glazing significantly varies with the directional orientation.
5.7.2 Orientation and Grouping of Houses

This study estimated the effect of directional orientation and grouping arrangements of future Kuwaiti houses on cooling load and electrical energy consumption. The study considered the governmental plan to build 19568 houses by 2016, shown earlier in Table 3.1. A detailed energy analysis was conducted for the studied cases which represent the common directional orientations and groupings of houses in Kuwait. Each case was assumed to consist of six houses. The methodology followed to conduct the verifications was based on detailed energy analysis (i.e. consumption cost based on consumer's tariff, operation cost based on electricity production cost, and electrical energy installation capital cost), using the cooling load profiles obtained by DesignBuilder simulation software. The results obtained were compared with respect to two benchmarks.

The results obtained were compared with respect to two benchmarks. The first benchmark was the single block east-west arrangement, since it had the largest cooling load among the four simulated cases. The second benchmark was the average of all four cases; because it is expected that the future houses will be built based on these four arrangements styles. Based on the first benchmark, the single block east-west case was found to have greater peak cooling load and annual electrical energy consumption by 6.6% compared to the single block north-west case; which has the smallest cooling load; that resulted in no savings. Based on the second benchmark; which is the average of the four cases; the single block north-south case achieved notable savings. In accordance to a number of 19568 houses used in the analysis and 20 years period, the single block north-south case can achieve savings in electricity supply and production of $US 3066/house and 11.3 ton of CO$_2$/house. These values are based on the supply cost of oil-fired power plant in Kuwait which is $US 1500/KWe, the production cost paid by the government which is $US 0.09/KW$_e$h, and the CO$_2$ emissions from oil-fired power plant which is 0.72 Kg CO$_2$/KWe.
The study suggested that the single block north-south case is a zero-cost energy conservation measure that can significantly improve the thermal performance of the future houses and thus reduce their consumption of electrical energy.

5.7.3 Selection of Efficient Air Conditioning Based on Lifecycle Cost Analysis

The work described in this part related to the evaluation of the cost effectiveness of current air-conditioning systems in use in Kuwaiti houses, i.e., Packaged-DX systems, compared to chilled water systems. Information was presented about all chilled water system types and about direct-expansion systems. To provide a satisfactory starting point, a survey of the AC market in Kuwait was conducted. This survey determined the factors that affect the selection of air-conditioning systems. Seven factors were identified, with only three factors related to economics, i.e., capital cost, operation cost, and maintenance cost. The studied residential cases were prepared to simulate the cases with the two air-conditioning systems that were included in the analysis. The annual energy consumption profile associated with the operation of the evaluated air-conditioning systems was obtained from DesignBuilder Simulation Software using the EnergyPlus simulation engine, which simulated the residential cases with the selected air-conditioning alternatives each time. The use of chilled water systems can produce up to 40% savings of electricity usage. Chilled water system has lower energy consumption, because the chilled water chillers have higher COP than small DX equipment.

A lifecycle cost analysis (LCCA) was conducted based on the costs of the studied air conditioning systems, the electricity production cost to the government, and the electricity tariff for the consumers. LCCA depends on initial and future costs to be discounted to present values. The annual operation cost based on the government production cost per kWh of electricity was also discounted to present value for the
entire study period, which is 15 years. The analysis depended on the average of the four residential case studied, to compare the two studied AC alternatives, not the residential cases.

The study encouraged the selection of chilled water system although it achieved the highest LCC, because of the significant energy savings. The cost effectiveness based on the cash paid by the consumers is unreliable, because it depended on the current situation in Kuwait in which the subsidization policy covers 92% of the current total production cost of electricity. From the total cash paid in the country to own, operate, and maintain AC systems, consumers’ cash represents about 17% and 43% for Packaged-DX and chilled water systems, respectively. Although the government has no hand in purchasing the AC systems or maintaining them, the cash paid by the government amounts to about 82% and 56% of the total cash paid for Packaged-DX and chilled water systems, respectively. Based on this, the government’s can save approximately $US 300,000 of the operational costs associated with operating DX air conditioning systems for 6 houses within 15 years. More clearly, the government can save about $US 50,000/house if the government stipulates a system to shift from using DX air conditioning system to chilled water system.

Chilled water systems are not cost effective for consumers in spite of their ability to conserve 40% of the energy currently used for air conditioning. The limitation here is the high capital cost for chilled water systems, compared to the capital cost of Packaged-DX systems. In this context, the study recommended to use part of the cash savings the government will incur if chilled water systems replace Packaged-DX systems to encourage the consumers to shift to this AC type.
5.7.4 The Integrated Combined Cycle Power Plant with Absorption System

The study discussed the viability of a new alternative for residential air conditioning, i.e., a single-effect LiBr absorption chiller driven by steam extracted from the steam turbine in the configuration of a combined cycle power plant (CCPP). The motivation for this alternative came from the ability of CCPP to generate electricity efficiently and from the ability of the absorption chiller to utilize heat energy from the plant. The idea for accomplishing the integrated CCPP with an absorption chiller is a verification stage for any potential district-cooling analysis to be based on the same configuration proposed in this study. The examination was based on the annual cooling load profile that represents the average cooling load for the four residential cases obtained from DesignBuilder simulation software. A computer model that represented the CCPP with absorption chiller and the CCPP with the DX air conditioning system was developed in Engineering Equation Solver software (EES). A step-by-step explanation of the system, with all input and output data was presented. A parametric study was conducted to ensure the accuracy of the model. Then, the computer model interacted with the cooling load profiles obtained from DesignBuilder software. Based on the analyses of the parametrical and performance parameters, the following conclusions are presented:

- The net power of the plant is at its maximum value at low ambient temperature and low steam extraction rate.
- The power output of the steam turbine is at its minimum value at a high steam extraction rate.
- Both configurations (CCPP\textsubscript{Abs} and CCPP\textsubscript{DX}) can meet the cooling demand required by both air conditioning types, but the net electrical power available to be sold to the utility grid is higher for the case of CCPP supplying electricity for DX systems.
- The integrated CCPP\textsubscript{Abs} produced less net electrical power by 2\% compared to a CCPP\textsubscript{DX} for the same number of houses.
• The excess annual electrical energy available to utility grid from the CCPP,DX is about 10 GW/hr.

• The CCPP,Abs uses annually about 25% of the steam leaving the steam turbine to drive the absorption chiller that is connected to the cooling load of 1000 houses.

• Annual heat rejected from the main condenser in the CCPP,Abs is 6% less than the heat rejected from the main condenser in the CCPP,DX as a result of steam extraction used to drive absorption chiller.

• The savings presented in this study were acquired by considering only the energy factor, and other factors associated with the operation of the CCPP with central absorption chiller and individual DX air conditioning system for houses, such as installation and maintenance, should be addressed in future studies.
Chapter 6 Conclusions, Recommendations and Future Work

6.1 Conclusions

Fossil fuels, especially oil, are an important global energy resource. The extensive usage of global energy resources has negative impacts on all aspects of life. This work indicated that hot weather is a significant factor for energy consumption in countries that have harsh summer conditions and are totally dependent on valuable energy resources to generate electricity. Residential cooling is also a major consumer of electricity due to conventional air conditioning systems. In conjunction with these facts, Kuwait was selected for additional analysis of its electrical energy usage. The findings showed that residential cooling is the significant factor for electricity consumption in Kuwait and consumes to about 60% of the electrical power produced by power plants at peak time on a hot summer day. The study aimed to investigate solutions for reducing energy consumption and emissions due to residential air-conditioning. To form the background for the investigation, the study presented information about electricity generations and energy policies, major studies towards electrical energy associated with air conditioning applications, and an overview of typical Kuwaiti houses. All relevant information required to obtain the cooling load of typical Kuwaiti houses were acquired and computer models represent the studied cases were prepared in DesignBuilder program which is an interface for the EnergyPlus building thermal simulation program. Three different alternatives to resolve air conditioning energy demand were nominated to undergo further verification. These alternatives are:

1. Proper orientation and grouping of future houses,
2. Electrical driven chilled water system for houses, and
3. Combined cycle power plant driving a single effect absorption chiller.
A summary of the work and the conclusions obtained from the verifications conducted for the three studied alternatives are as follows:

6.1.1 Alternative 1: Orientation and Grouping of Houses in Kuwait

In this alternative, the study aimed to estimate the effect of directional orientation and grouping arrangements of Kuwaiti houses on cooling load and electrical energy consumption. The study considered the governmental plan to build 19568 houses by 2016, shown earlier in Table 3.1. A detailed energy analysis was conducted for common directional orientations and groupings of houses in Kuwait, i.e., single block east-west, single block north-south, double block east-west, and double block north-south (Figure 6.1). Each case was assumed to consist of six houses. Cooling loads for each case were obtained using the EnergyPlus simulation software.

Figure 6.1: Typical orientation and grouping of houses created in the simulation.
The cooling loads were used to calculate the electricity consumption cost based on consumer's tariff, operation cost based on electricity production cost, and electrical energy installation capital cost. The results obtained were compared with respect to two benchmarks. The first benchmark was the single block east-west arrangement, since it had the largest cooling load among the four simulated cases. The second benchmark was the average of all four cases; because it is expected that the future houses will be built based on these four arrangements styles.

Based on the first benchmark, the single block east-west case was found to have greater peak cooling load, and the annual electrical energy consumption associated with air conditioning is 6.6% greater than the single block north-west case; which has the smallest cooling load. This showed that that the single block east-west is not a promising solution to arrange future houses.

Based on the second benchmark, which is the average of the four cases, the single block north-south case had a peak cooling load 3.3 % less and an annual electrical energy consumption for cooling 1 % less than the benchmark. The resulting financial and carbon dioxide emissions savings are shown below.

Table 6.1: Savings from single block north-south case compared to average of four cases, over 20 years

<table>
<thead>
<tr>
<th>Saving</th>
<th>For 1 house</th>
<th>For 19568 houses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity supply capital cost ($USD)</td>
<td>1,686</td>
<td>33 million</td>
</tr>
<tr>
<td>Electricity supply operating cost for government ($USD)</td>
<td>1,379</td>
<td>27 million</td>
</tr>
<tr>
<td>Electricity cost for householders ($USD)</td>
<td>91</td>
<td>1.8 million</td>
</tr>
<tr>
<td>CO₂ emissions (tons)</td>
<td>11.3</td>
<td>222 thousand</td>
</tr>
</tbody>
</table>
The values above are based on the capital cost of electricity from oil-fired power plant in Kuwait which is $US 1500/kWₑ, the production cost paid by the government which is $US 0.09/kWₑh, the price of electricity to householders which is $US0.006/kWₑh and the CO₂ emissions from oil-fired power plant which is 0.72 Kg CO₂/kWe.

The study suggested that the single block north-south case is a zero-cost energy conservation measure that can significantly improve the thermal performance of the future houses and thus reduce their consumption of electrical energy.
6.1.2 Alternative 2: Electricity Driven Chilled Water System

In this alternative, the study described the evaluation of the cost effectiveness based on lifecycle cost analysis method for the current air-conditioning systems in use in Kuwaiti houses, i.e., Packaged-DX system, compared to electricity driven air cooled chilled water system. The procedure started with a survey of the AC market in Kuwait to obtain specifications, capital and annual maintenance costs, for the two alternatives. Then, the houses that were prepared earlier were simulated in EnergyPlus with the two air-conditioning systems.

From the simulation, annual energy consumption profiles associated with the operation of the evaluated air-conditioning systems were obtained. Then, financial inputs such as capital and maintenance costs were prepared based on information obtained from the conducted survey in AC market. The costs obtained from the market are based on the unit of cooling (kW). The capital cost are $ US 250/kW for the packaged DX –rooftop unit and $ US796/KW for the air-cooled water chiller; where the average price of annual maintenance for packaged DX rooftop units and air-cooled chiller is $ US 3/kW and $ US 4.5/kW, respectively. All annual recurring costs were discounted to present values for the entire study period, which is 15 years. The discount rate was set to 3.2% for operating and 3.75% for maintenance costs. The analysis considered both the consumer's tariff and the government production cost of electricity which are US$0.006/kW\text{-}h and US$0.09/kW\text{-}h respectively. The cooling load used in this analysis is for a number of six houses that represents the average of the studied four cases.

According to the results obtained from the simulation, chilled water system can conserve 40% of the energy used for DX air conditioning. The LCCA results showed that from the total cash paid in the country to own, operate, and maintain AC systems, consumers’ cash amounts to about 17% and 43% for Packaged-DX and chilled water systems, respectively. Moreover, the cash paid by the
government amounts to about 82% and 56% of the total cash paid for Packaged-DX and chilled water systems, respectively. It was also found that the government can save about $US 50,000/house within 15 years if the government stipulates a system to shift from using DX air conditioning system to chilled water system. Summary of the LCCA was illustrated earlier in Table 5.13.

The comparatively high capital cost for chilled water systems, which may not be affordable for consumers, is a considerable limitation. For this, the study recommended that the government use part of the expected cash saving that it will acquire from applying chilled water system to subsidize the capital cost of chilled water AC systems for consumers.
6.1.3 Alternative 3: CCPP with Absorption Cooling

In this alternative, the study discussed the viability of a new alternative for residential air conditioning, i.e., a single-effect LiBr absorption chiller driven by steam extracted from the steam turbine in the configuration of a combined cycle power plant (CCPP). The motivation for this alternative came from the ability of CCPP to generate electricity efficiently and from the ability of the absorption chillers to utilize heat energy from the plant. The idea for accomplishing the integrated CCPP with an absorption chiller is a verification stage for any potential district-cooling analysis to be based on the same configuration proposed in this study. The procedure that has been followed to verify this alternative was made based on a comparison of the net electrical power available to utility grid after meeting the cooling requirements of the same number of houses. For this, the study examined the configuration of a CCPP with an absorption chiller (Figure 6.2) and CCPP with a DX air conditioning system (Figure 6.3). The total electrical output of the plant with no steam extraction is about 430 MW at 30 °C ambient air temperature.

![Diagram of Combined Cycle Power Plant with Absorption Chiller](image)

Figure 6.2: Combined cycle power plant with absorption chiller driven by steam extraction, for electricity generation and chilled water production for houses
The verification of these two CCPP configurations was based on the annual cooling load profile of 1000 houses that represents the average cooling load for the four residential cases that were obtained from EnergyPlus simulation software. In this context, a computer model that represented the CCPP with absorption chiller and the CCPP with the DX air conditioning system was developed in Engineering Equation Solver software (EES). A step-by-step explanation of the system, with all input and output data as well as the procedure for linking the cooling load profile from EnergyPlus software to the computer model prepared in EES, was presented to make the whole system, including its preparation requirements, as clear and understandable as possible.

A parametric study was conducted first to determine the effect of different operating parameters on the performance parameters of the system. Then, the computer model interacted with the cooling load profiles obtained from
EnergyPlus software. Based on the analyses of the parametrical and performance parameters, the following conclusions are presented:

- The net power of the plant is at its maximum value at low ambient temperature and low steam extraction rate.
- The power output of the steam turbine is at its minimum value at a high steam extraction rate.
- Both configurations (CCPP_{Abs} and CCPP_{DX}) can meet the cooling demand required by both air conditioning types, but the net electrical power available to be sold to the utility grid is higher for the case of CCPP supplying electricity for DX systems.
- The integrated CCPP_{Abs} produced less annual net electrical power by 2% compared to a CCPP_{DX} for the same number of houses.
- The excess annual electrical energy available to utility grid from the CCPP_{DX} is about 10 GW_hr.
- The CCPP_{Abs} uses annually about 25% of the steam leaving the steam turbine to drive the absorption chiller that is connected to the cooling load of 1000 houses.
- Annual heat rejected from the main condenser in the CCPP_{Abs} is 6% less than the annual heat rejected from the main condenser in the CCPP_{DX} as a result of steam extraction used to drive absorption chiller.
- The savings presented in this study were acquired by considering only the energy factor, and other factors associated with the operation of the CCPP with central absorption chiller and individual DX air conditioning system for houses, such as installation and maintenance, should be addressed in future studies.
6.2 Recommendations

6.2.1 Energy Policy (Subsidization of Electricity)

Energy policy in Kuwait is ineffective in conserving energy or reducing CO₂ emissions due to high subsidization of the electricity tariff. The study could not examined different tariffs due to limitations in resources about economical evaluation of tariffs. Therefore, it is recommended for decision makers in Kuwait to make projections about the best estimation of economic savings of new tariffs that can be implemented based on alternatives 1 and 2 presented in this work.

6.2.2 Windows Distribution and Glazing

The current practice in Kuwait allows for windows to be uniformly distributed on each façade (window-to-wall ratio) without any special care for the direction of solar radiation that strikes the houses. Based on the results of this study, the number of windows facing east or west should be minimized. The study used values of thermal resistance accepted by the energy code of buildings in Kuwait. Latest glazing thermal resistance values available in the market should be examined. Moreover, the number of housing blocks facing east-west should also be minimized.

6.2.3 Efficient Air Conditioning and Power Rating

Current air conditioning use in Kuwaiti houses is of low coefficient of performance (COP). For this reason, concerned authorities in Kuwait should stipulate more restricted rules for HVAC companies to avoid importing low efficiency air condition equipments. Because of this, the study used the common power rating of DX air conditioning systems in Kuwait for the analysis of alternatives 1, 2 and 3. For future attempts to use the alternatives presented by this work, it is recommended to use different COP for DX air conditioning systems to
determine possible savings with more efficient DX air conditioning systems. Efficient air conditioning systems such as electricity driven chilled water systems must be affordable for consumers by subsidizing the capital cost.

6.2.4 Combined Cycle Power Plant

The combined cycle power plant is a good choice for power generation due its ability to generate electrical power by utilizing waste heat from gas cycle to produce steam for steam turbine. However, based on the analysis presented for the configurations of combined cycle with different air conditioning choices, it can be said that the configuration of combined cycle power plant with absorption cooling for central cooling distribution (district cooling) is not efficient in terms of energy savings or energy availability compared to the same plant delivering electricity for individual DX air conditioners for the same number of houses. However, other factors associated with the operation of the examined air conditioning systems that were configured with CCPP, such as installation and maintenance, should be addressed in future studies to have a comprehensive view about the subject.
6.3 Future work

The outcomes of the presented thesis research encouraged the author to suggest the following future work:

- **Lifecycle Cost Analysis for Enhanced Window Glazing**
  This work could consider various window glazing types with modified thermal resistance characteristics. A systematic approach for optimizing the thickness and type of the examined insulation materials for a particular thermal resistance could be made. The optimization could be made based on the lifecycle cost analysis of the studied glazing using a typical Kuwaiti house as a baseline case. The savings acquired from different window's glazing could be benchmarked with the current glazing type in Kuwaiti houses. The payback period of the selected window's glazing should be evaluated.

- **Lifecycle Cost Analysis for Enhanced Wall Insulation**
  This work could examine different insulation types with enhanced thermal resistance characteristics. A systematic approach for optimizing the thickness and type of the examined insulation materials for a particular thermal resistance should be made. The optimization could be made based on the lifecycle cost analysis of the studied insulation materials using a typical Kuwaiti house as a baseline case. The savings acquired from different insulations materials should be benchmarked with the insulation materials currently in use. The payback period of the selected insulation type could be presented.

- **Economic Comparison between CCPP and Oil-Fired Steam Plant for Electrical Power Supply Required for Residential Air Conditioning: Case Study from Kuwait**
  This work could conduct a detailed economic comparison between combined cycle power plants and oil-fired steam power plants for the electrical power
installation and hourly generation of electricity needed for residential air conditioning in Kuwait. The aim of this work is to determine the benefits that Kuwait could acquire from shifting to combined heat and power technology for electrical power generation using the demand of residential cooling electrical power as a baseline for the comparisons.

**The Effect of Changing Energy Prices on Kuwait's Expenditure Allocated for Electricity Generation from Power Plants**

This study would aim to project the impact of changing energy resource prices on the Kuwait's expenditure allocated for electricity generation. The study also could suggest ways to manage the consumer tariff with respect to changes in energy prices.

**Combined Cycles-Solar Hybrid Plant Integrated With Single-Effect Absorption Chiller Plant**

This study could consider the combination of CCPP and solar plant to drive a single-effect absorption chiller for air conditioning applications. For a certain cooling load, the study could consider solar energy to supply heat to absorption chiller during peak hours only; for the rest of the day, a steam extraction from the CCPP would be supplied to the chiller. Then, a similar CCPP supplying electricity only could be introduced in the analysis, assuming that this plant is delivering electricity to meet the certain cooling load that was applied for the hybrid CCPP and solar plant. Finally, a detailed energy analysis should be made to verify the best alternative. The simulation could be employed with a computer program.
References

- Al-Ragom, F; Maheshwari G.P.; Al-Nakib D.; Alghimlas, F.; H. Al-Taqi; A.Merza; Ben Nakhi; A.M. Ali; Nouf Al-Hasem; R. Alasseri and A. Al-Farhan,. Implementation energy and power saving scheme in air-conditioned buildings, Final report, KISR, 2005
- Al-Ragom, F; G.P. Maheshwari; D.Al-Nakib; F.Alghimlas; R. Al-Murad and A. Meerza; Energy auditing for KISR's main building. Kuwait Institute for Scientific Research, KISR 6287, Kuwait, 2002
• Abdulrazaq M., HVAC Design Senior Engineer, Member of Standards and Codes Committee at American Society of Heating Refrigerating and Air-Conditioning Engineering (ASHRAE) Kuwait Chapter, P.O.Box 5969, Safat 13060 Kuwait, Private Communication (2009).


• Al-Ajmi, F, Loveday, LD, Hanby, V. The cooling potential of earth–air heat exchangers for domestic buildings in a desert climate, Building and Environment 2006; 41, 235-244.


• Al-Hassan A.; "Electricity generation cost between proposed Photovoltaic station and conventional units in Kuwait"; Renewable energy, vol.12 No. 3 PP 291-301, 1997


• Arizona Solar Center, www.azsolarcenter.com ; 2nd December 2008


- ASHRAE Handbook- Fundamentals, Residential Cooling and Heating load Calculations, 2005
- Al-Saadi S. and Budaiwi I., Performance-Based Envelope Design for Residential Buildings in Hot Climates, 10th International Building Performance Association Conference and Exhibition September, Beijing 2007

• Carrier AC Division, Absorption Refrigeration Technology, Annual Report , pp.3-7, 1974


• Darwish M., Professor of Air-Conditioning and Power Generation Systems, Kuwait Foundation for the Advancement of Science (KFAS), POB 25263, 13113 Safat Kuwait, Private Communication (2009).
• Darwish M. and Maarafi A.; Cogeneration plant for electric power and district air-conditioning in Kuwait, Journal of science, University of Kuwait, volume 14, pp.293-307, 1987
• DTI, Department of Trade and Industry; UK energy in brief, annual statistics 2005
• DOE, U.S. Department of Energy; Energy Data Book, 2005
• Eltony, M. N.; "The future of Kuwait domestic energy demand”; Energy studies review, vol. 8 no. 3 pp 269-275, 1998
• Energy Conservation Code of Practice, Kuwait, Ministry of Electricity and Water, 1983


• Hamdan S., Personal Communication, Civil Engineering Department, Public Authority for Housing Care, P.O.Box 1212 Farwania, Kuwait, 2009


• Hughes L.; Biological consequences of global warming: is the signal already apparent? Trends in Ecology & Evolution, Volume 15, Issue 2, pp. 56-61, 2000

• Hajiah A., Alghimlas F., Maheswar G.P.i; Sutability of District Cooling in Kuwait. Tenth International Symposium on District Heating and Cooling Proceedings, Germany, 2006

• Hajiah A., Energy conservation program in Kuwait, a local prospective, proceedings of fifteenth symposium on improving building systems in hot and humid climates, Orlando, FL, July 24-26, 2006

• Hussain A. and Al-Mulla A.; Impact of energy policies and the role of renewable energy for the state of Kuwait. Symposium "towards innovative desalination and power generation in Kuwait", 2007


• Hosni, M.H., Jones, B.W., Hanminq Xu, Experimental results for heat gain and radiant/convective split from equipment in buildings, ASHRAE Transactions, 1999, pp.527-539


IPCC, Intergovernmental Panel on Climate Change; Working group III, fourth assessment report, 2007


Krneta R., Bbjeki M., Peuli A. and Dragievi S., Dynamic analysis of temperature and heat gains in classrooms with different type of windows, 5th “Energy,
climate and indoor comfort in Mediterranean countries” 5-7 september 2007, GENOVA, Italy

- KFAS, Kazmah Engineering Projects, District Cooling Study, Kuwait, a Presentation to Kuwait Institute for Scientific Research (KISR), October 2007, Kuwait.
- Liu J., Li W. and Zhou X. The Study on the Simple HVAC Interface of EnergyPlus in Chinese, School of Environmental Science and Technology, Tianjin University, Tianjin 300072, China, Proceeding building simulation 2007, pp.1551-1556
- Maheshwari G., Energy and Building Department, Kuwait Institute of Scientific Researches, Personal communication, September 2008
- Ministry of Electricity and Water (MEW); Statistical year book, 2007


• Ortiz O., Bonnet C., Bruno J. and Castells F., Sustainability based on LCM of residential dwellings: A case study in Catalonia, Spain, Building and Environment 44 (2009) pp.584– 594


• Rilling D., Han Siang S. and Siang S.H., Thermal simulation as design tool for residential buildings in South Asia, University of Malaysia Journal Alam Bina, (9-3) 2007

• Renewables; Renewable Energy Network for the first twenty one century, Global Status Report, 2007

• Rajan M, Jain VK; Modeling of electrical energy consumption in Delhi. Energy, volume 24, pp.351–361, 1999
• Shimoda Y., Nagota T., Isayama N. and Mizuno M., Verification of energy efficiency of district heating and cooling system by simulation considering design and operation parameters, Build. Environ. 43 (2008), pp. 569–577
• Sebzali M., Energy and Building Department, Kuwait Institute if Scientific Research (KISR), Personal Communication, December 2009
• Soteris Kalogirou (2008). Recent Patents in Absorption Cooling Systems Recent Patents on Mechanical Engineering, volume 1,pp. 58-64
• Saud, A., Manager Technical Office in Ministry of Electricity and Water, Private Communication, October 2009
• DOE, U.S. Department of Energy; Energy Data Book, 2005


Appendix (A): Computer Model of CCPP in EES program

1. CCPP with Single-Effect LiBr/Water Absorption Chiller

"Input: Based on specifications of Cogeneration Power Plant in Kuwait (data obtained during several sites visits by the author to Shuaiba Power Plant South of Kuwait)"

"Gas Cycle (Bryaton Cycle):"

\[ \text{rp=11} \]
\[ T_{\text{a}}=46 \{\text{C}\} \]
\[ \eta_{c}=0.9 \]
\[ \eta_{gt}=0.88 \]
\[ k=1.4 \]
\[ cp_{a}=1.005 \{\text{kJ/kg.k}\} \]
\[ P_{1}=101.3 \{\text{kPa}\} \]
\[ R_{a}=0.287 \{\text{kJ/kg.k}\} \]
\[ V_{\text{dot}_{1}}=600 \{\text{m}^{3}/\text{s}\} \]
\[ T_{3}=1010 \{\text{C}\} \]
\[ T_{4}=610 \{\text{C}\} \]
\[ T_{5}=150 \{\text{C}\} \]
\[ \eta_{HRSG}=0.5 \]
\[ HRSG_{PL}=0.3 \]
\[ cp_{g}=1.7 \{\text{kJ/kg.k}\} \]

"Steam Cycle (Rankin Cycle):"

\[ T_{7}=530 \{\text{C}\} \]
\[ T_{6}=130 \{\text{C}\} \]
\[ \eta_{st}=0.84 \]
\[ cp_{w}=4.2 \{\text{kJ/kg.K}\} \]
\[ P_{H}=14182 \{\text{kpa}\} \]
\[ \{y=0.001\} \]
\[ T_{12}=32 \{\text{C}\} \]
\[ T_{8}=100 \{\text{C}\} \]
\[ \eta_{pump}=0.75 \]
\[ V_{\text{dot}_{\text{fuel}}}=0.021 \{\text{m}^{3}/\text{s}\} \]
\[ \text{row}_{\text{fuel}}=600 \{\text{kg/m}^{3}\} \]

"(4) Absorption cycle model:"

"input"

\[ T_{\text{gen}}=90 \{\text{C}\} \]
\[ T_{16}=T_{\text{gen}} \]
T_cond=35 {°C} " Condenser temperature"
T_[17]= T_cond
T_abs=35 {°C} " Absorber temperature"
T_[31]= T_abs
P_evap=0.9 {kPa} " Evaporator pressure"
x_ws=0.64 " water lithium bromide weak solution concentration"
x_sss=0.575 " water lithium bromide strong solution concentration"
T_[27]=12.5 {°C}
T_[28]=7 {°C}
COP= 0.7

"Modelling"

" (1) Gas Cycle Model: "
T_s[2]=(rp^((k-1)/k))*T_[1] " Isentropic temperature of air leaving the compressor"
\( \eta_c= \frac{T_s[2]-T_1}{T_2-T_1} \) " Compressor isentropic efficiency"
T_[2]=(T_[1]+(T_s[2]-T_[1])/\eta_c) " Temperature of air leaving the compressor"
row_a= P_[1]/(R_a*T_[1]) " Air density"
m_dot_[1]=V_dot_[1]*row_a "Mass flow rate of air"
m_dot_[2]=m_dot_[1] "Mass flow rate of air"
\( W_c= m_dot_[2]* cp_a*(T_[2]-T_[1])* \eta_c \) " Compressor work"
P_[2]= P_[1]* rp " Pressure of air leaving the compressor"
P_[3]=P_[2] " Pressure of gas leaving the combustion chamber"
P_[4]=P_[3]/rp " Pressure of gas leaving the gas turbine after the isentropic expansion in gas turbine"
P_[5]=P_[4] " Pressure of gas leaving the HRSG "

" Combustion Chamber"

m_dot_fuel= V_dot_fuel* row_fuel " Mass flow rate of fuel added to the combustion chamber"
m_dot_g= m_dot_[1]+m_dot_fuel " Gas mass flow rate"

" (2) Steam cycle model:"
\( \{ \text{mst} (h_7-h_6)= \text{mg} (h_4-h_5) \}
\text{mst cp_w} (T_7-T_6) = \text{mg cp_g} (T_4-T_5) * \eta_HRSG \) " Energy balance for HRSG"

m_dot_st=m_dot_g* cp_g*(T_[4]-T_[5])/(cp_w* (T_[7]-T_[6])) *\eta_HRSG " Mass flow rate of steam"

" , Pump(2) suction, thermodynamics properties"
P_[14]= P_[9] "no pressure loss in main condesner"

T_[9]=Temperature(steam,P=P_[9],x=0) Temperature of steam condensed by the sea water in steam condenser
v_[9]=volume(Steam,P=P_[9],x=0) "Specific volume of condensate"
h_[9]=enthalpy(Steam,P=P_[9],x=0) " Enthalpy of condensate"
T_[14]=Temperature(steam,P=P_[14],x=1) 'Temperature of low pressure steam’
P_[7]=P_[6]*0.7 'Turbin inlet pressure including pressure loss"
s_[7]=entropy(steam,P=P_[7], T=T_[7])
h_[7]=enthalpy(Steam,P=P_[7],T=T_[7])
\[ s_s[8] = s[7] \]
\[ h_s[8] = \text{enthalpy(Steam, } P=P[8], \ s=s_s[8]) \]
\[ P[8] = \text{Pressure (Steam, } T=100, \ x=1) \quad \text{" Steam extraction pressure"} \]
\[ h[8] = h[7] - (\text{eta_st} \cdot (h[7] - h_s[8])) \]
\[ s[8] = \text{entropy(Steam, } P=P[8], h=h[8]) \]
\[ s_s[14] = s[8] \]
\[ h_s[14] = \text{enthalpy(Steam, } P=P[14], s=s_s[14]) \]
\[ h[14] = h[8] - (\text{eta_st} \cdot (h[8] - h_s[14])) \]
\[ P[15] = P[8] \quad \text{" No pressure loss at points 15, 10 and 11"} \]
\[ h[10] = h[9] + v[9] \cdot (P[10] - P[9]) \quad \text{" Based on condesnate pump energy (pump 2)"} \]
\[ T[10] = \text{Temperature(steam, } P=P[10], h=h[10]) \]
\[ h[15] = \text{enthalpy(Steam, } P=P[15], x=0) \quad \text{" steam return from generator to mixing chamber"} \]
\[ T[15] = \text{Temperature(Steam, } P=P[15], x=0) \]
\[ h[11] = y \cdot h[15] + (1-y) \cdot h[10] \quad \text{" Enthalpy at point 11 considering the amount of steam extraction } y \"} \]
\[ v[11] = \text{volume(Steam, } h=h[11], x=0) \]
\[ T[11] = \text{Temperature(steam, } P=P[11], h=h[11]) \]

"Absorption Cycle"
\[ P[16] = \text{Pressure (Steam, } T=T[16], x=1) \]
\[ P[17] = P[16] \]
\[ h[16] = \text{enthalpy(Steam, } P=P[16], x=1) \]
\[ h[17] = \text{enthalpy(Steam, } P=P[17], x=0) \]
\[ h[18] = h[17] \]
\[ h[22] = h_{\text{LiBrH2O}}(T[16], x_{\text{ws}}) \]
\[ ff = x_{\text{ss}} / x_{\text{ws}} \]
\[ h[19] = \text{enthalpy(Steam, } P=P_{\text{evap}}, x=1) \]
\[ T[19] = \text{Temperature(Steam, } P=P_{\text{evap}}, x=1) \]
\[ h[20] = h_{\text{LiBrH2O}}(P[16], x_{\text{ss}}) \]

"Refrigerant mass flow rate, it can be seen that it depends on the amount of steam extraction [y]"
\[ m_R = \text{COP} \cdot (m_{\text{dot_st}} \cdot y \cdot (h[8] - h[15]) + W_{\text{pump3}}) / (h[19] - h[18]) \]
\[ m_{\text{ss}} = m_R / (1 - ff) \]
\[ m_{\text{ws}} = m_{\text{ss}} - m_R \]

" Enthalpy at state 21 based on energy balance for the absorption chiller generator"
\[ h[21] = (m_R \cdot h[16] + m_{\text{ws}} \cdot h[22] - m_{\text{dot_st}} \cdot y \cdot (h[8] - h[15])) / m_{\text{ss}} \]

" Enthalpy at state 23 based on energy balance for the solution heat exchanger in the absorption chiller"
\[ h[23] = (m_{\text{ss}} \cdot h[20] + m_{\text{ws}} \cdot h[22] - m_{\text{ss}} \cdot h[21]) / m_{\text{ws}} \]
\[ h[24] = h[23] \]

" Temperature of the strong solution leaving the absorber"
\[ h[31] = h_{\text{LiBrH2O}}(T[31], x_{\text{ss}}) \]

" Energy"
\[ W_c = m_{\text{dot}} \cdot \text{cp}_a \cdot (T[2] - T[11]) \quad \text{" Compressor energy"} \]
\[ W_{\text{gt}} = m_{\text{dot}} \cdot \text{cp}_g \cdot (T[3] - T[4]) \quad \text{" Gas turbine energy"} \]

" Steam turbine energy"
\[ W_{\text{st}} = (m_{\text{dot}} \cdot y \cdot (h[7] - h[8]) + m_{\text{dot}} \cdot (1-y) \cdot (h[8] - h[14])) \]
\[ W_{\text{Tot}} = W_{\text{gt}} + W_{\text{st}} \quad \text{" Total energy from turbines"} \]
\( W_{\text{pump}1} = \dot{m}_{\text{st}} \cdot v_{[1]} \cdot (P_{[6]} - P_{[11]})/\eta_{\text{pump}} \)  
" Feddwater pump energy"

\( W_{\text{pump}2} = \dot{m}_{\text{st}} \cdot v_{[9]} \cdot (h_{[10]} - h_{[9]})/\eta_{\text{pump}} \)  
" Condensate pump energy"

\( Q_{\text{cond}1} = \dot{m}_{\text{st}} \cdot (1 - y) \cdot (h_{[14]} - h_{[9]}) \)  
" Steam condenser energy"

\( Q_{\text{cond}2} = \dot{m}_{\text{R}} \cdot (h_{[16]} - h_{[17]}) \)  
" Condenser energy"

\( Q_{\text{abs}} = (\dot{m}_{\text{R}} \cdot h_{[19]} + \dot{m}_{\text{ws}} \cdot h_{[24]} - \dot{m}_{\text{ss}} \cdot h_{[31]}) \)  
" Absorber energy"

\( Q_{\text{comb}} = \dot{m}_{\text{g}} \cdot c_p_{\text{g}} \cdot (T_{[3]} - (T_{[2]} - 273)) / \eta_{\text{comb}} \)  
" Actual combustion energy"

\( \eta_{\text{ccpp}} = W_{\text{net}} / (Q_{\text{comb}}) \)  
" Combined cycle efficiency"

\( W_{\text{pump}3} = \dot{m}_{\text{ss}} \cdot (h_{[20]} - h_{[31]}) / \eta_{\text{pump}} \)  
" Strong solution pump"

\( Q_{\text{gen}} = \dot{m}_{\text{st}} \cdot y \cdot (h_{[8]} - h_{[15]}) \)  
" Generator energy"

\( \{ \dot{m}_{27} = Q_{\text{evap}} / (c_p_{\text{w}} \cdot (T_{[27]} - 28)) \} \)  
" Chilled water mass flow rate to and from the cooling demand side"

\( \dot{m}_{27} = Q_{\text{cooling}} / (c_p_{\text{w}} \cdot (T_{[27]} - T_{[28]})) \)  
" Chilled water pump* from the plant to cooling demand side"

\( W_{\text{pump}4} = (\dot{m}_{\text{st}} / 1000) \cdot (\Delta P) / \eta_{\text{pump}} \)  
" Plant net energy"

\( W_{\text{net}} = (W_{\text{Tot}} - (W_c + W_{\text{pump}1} + W_{\text{pump}2} + W_{\text{pump}3} + W_{\text{pump}4})) \)  
" Heat recovery steam generator energy"

\( Q_{\text{HRSG}} = \dot{m}_{\text{g}} \cdot c_p_{\text{g}} \cdot (T_{[4]} - T_{[5]}) \cdot \eta_{\text{HRSG}} \)  
" Energy consumption inside the plant"

\( W_{\text{plant}} = W_c + W_{\text{pump}1} + W_{\text{pump}2} + W_{\text{pump}3} + W_{\text{pump}4} \)  
" The integrated combined cycle-absorption plant thermal efficiency"

\( \eta_{\text{total}} = (W_{\text{net}}) / (Q_{\text{comb}} / \eta_{\text{comb}}) \)  
" Plant heat input"

\( \text{Heatinput} = Q_{\text{comb}} / \eta_{\text{comb}} \)  
" Plant heat input"

\( \text{Heatfluegas} = \dot{m}_{\text{g}} \cdot c_p_{\text{g}} \cdot (T_{[5]} - T_{a}) \)  
" Flue gas heat"
2. CCPP Supplying Electricity to DX air conditioning System

"Input: Based on specifications of Cogeneration Power Plant in Kuwait (data obtained during several sites visits by the author to Shuaiba Power Plant South of Kuwait)"

"Gas Cycle (Bryaton Cycle):"

\[
\begin{align*}
\text{Pressure Ratio} & = \text{rp} \\
T_{(1)} &= T_a + 273 \text{ (k)} \\
\{T_a\} &= 46 \text{ (C)} \\
\text{eta}_c &= 0.9 \\
\text{eta}_\text{comb} &= 0.88 \\
k &= 1.4 \\
cp_a &= 1.005 \text{ (kJ/kg k)} \\
P_{(1)} &= 101.3 \text{ (kPa)} \\
\text{R}_a &= 0.287 \text{ (kJ/kg.k)} \\
V_{dot\_1} &= 600 \text{ (m3/s)} \\
T_{(3)} &= 1010 \text{ (C)} \\
T_{(4)} &= 610 \text{ (C)} \\
T_{(5)} &= 150 \text{ (C)} \\
\text{eta}_{HRSG} &= 0.5 \\
\text{HRSG\_PL} &= 0.3 \\
cp_g &= 1.7 \text{ (kJ/kg.k)}
\end{align*}
\]

"Steam Cycle (Rankin Cycle):"

\[
\begin{align*}
\text{Steam turbine inlet temperature} & = T_{(7)} \\
T_{(6)} &= 130 \text{ (C)} \\
\text{eta}_s &= 0.84 \\
cp_w &= 4.2 \text{ (kJ/kg.K)} \\
P_H &= 14182 \text{ (kpa)} \\
P_{(6)} &= P_H \\
y &= 0 \\
T_{(12)} &= 32 \text{ (C)} \\
T_{(8)} &= 100 \text{ (C)} \\
\text{eta}_\text{pump} &= 0.75
\end{align*}
\]

\[
\begin{align*}
V_{\text{dot\_fuel}} &= 0.021 \text{ (m3/s)} \\
\text{row\_fuel} &= 600 \text{ (kg/m3)}
\end{align*}
\]

"Modelling"

"(1) Gas Cycle Model:"

\[
\begin{align*}
T_s[2] &= \text{rp}^{(k-1)/k}\*T_{(1)} \\
\{\text{eta}_c\} &= (T_s2-T1)/(T2-T1)
\end{align*}
\]

"Isentropic temperature of air leaving the compressor" \\
"Compressor isentropic efficiency"
\[ T_{[2]} = (T_{[1]} + (T_s_{[2]} - T_{[1]})/\eta_c) \]

"Temperature of air leaving the compressor"

\[ \text{row}_a = P_{[1]}/(R_a * T_{[1]}) \]

"Air density"

\[ m_{\text{dot},[1]} = V_{\text{dot},[1]} * \text{row}_a \]

"Mass flow rate of air"

\[ m_{\text{dot},[2]} = m_{\text{dot},[1]} \]

"Compressor work"

\[ W_c = m_{\text{dot},[2]} * c_p_a * (T_{[2]} - T_{[1]})/\eta_c \]

"Pressure of air leaving the compressor"

\[ P_{[2]} = P_{[1]} * \text{rp} \]

"Pressure of gas leaving the combustion chamber"

\[ P_{[3]} = P_{[2]} \]

"Pressure of gas leaving the gas turbine after the isentropic expansion in gas turbine"

\[ P_{[4]} = P_{[3]} / \text{rp} \]

"Pressure of gas leaving the HRSG"

"Combustion Chamber"

\[ m_{\text{dot,\ fuel}} = V_{\text{dot,\ fuel}} * \text{row,\ fuel} \]

"Mass flow rate of fuel added to the combustion chamber"

\[ m_{\text{dot,\ g}} = m_{\text{dot},[1]} + m_{\text{dot,\ fuel}} \]

"Gas mass flow rate"

"(2) Steam cycle model:"

\[ \{ \text{mst} (h_7-h_6) = mg (h_4-h_5) \]

"Energy balance for HRSG"

\[ \text{mst cp}_w (T_7-T_6) = mg \text{cp}_g (T_4-T_5) * \eta_{\text{HRSG}} \]

"Mass flow rate of steam"

"Pump(2) suction, thermodynamics properties"

\[ P_{[14]} = P_{[9]} \]

"No pressure loss in main condenser"

\[ T_{[9]} = \text{Temperature(steam,P=P_{[9]},x=0)} \]

"Temperature of steam condensed by the sea water in steam condenser"

\[ \text{v}_{[9]} = \text{volume(Steam,P=P_{[9]},x=0)} \]

"Specific volume of condensate"

\[ h_{[9]} = \text{enthalpy(Steam,P=P_{[9]},x=0)} \]

"Enthalpy of condensate"

\[ T_{[14]} = \text{Temperature(steam,P=P_{[14]},x=1)} \]

"Temperature of low pressure steam"

\[ P_{[7]} = P_{[6]} * 0.7 \]

"Turbine inlet pressure including pressure loss"

\[ s_{[7]} = \text{entropy(steam,P=P_{[7]}, T=T_{[7]})} \]

\[ h_{[7]} = \text{enthalpy(Steam,P=P_{[7]},T=T_{[7]})} \]

\[ s_{[8]} = s_{[7]} \]

\[ h_{[s][8]} = \text{enthalpy(Steam,P=P_{[8]}, ss=s_{[8]})} \]

\[ P_{[8]} = \text{Pressure (Steam, T=100, x=1)} \]

"Steam extraction pressure"

\[ h_{[8]} = h_{[7]} - (\text{eta_st} * (h_{[7]} - h_{[s][8]})) \]

\[ s_{[8]} = \text{entropy(Steam,P=P_{[8]}, h=h_{[8]})} \]

\[ s_{[14]} = s_{[8]} \]

\[ h_{[s][14]} = \text{enthalpy(Steam,P=P_{[14]}, ss=s_{[14]})} \]

\[ h_{[14]} = h_{[8]} - (\text{eta_st} * (h_{[8]} - h_{[s][14]})) \]

\[ P_{[15]} = P_{[8]} \]

"No pressure loss at points 15, 10 and 11"
\[ h_{[10]} = h_{[9]} + v_{[9]}(P_{[10]} - P_{[9]}) \]  
Based on condensate pump energy (pump 2)

\[ T_{[10]} = \text{Temperature}(\text{steam}, P=P_{[10]}, h=h_{[10]}) \]

\[ h_{[15]} = \text{enthalpy}(\text{Steam}, P=P_{[15]}, x=0) \]  
steam return from generator to mixing chamber

\[ T_{[15]} = \text{Temperature}(\text{Steam}, P=P_{[15]}, x=0) \]

\[ h_{[11]} = y \cdot h_{[15]} + (1-y) \cdot h_{[10]} \]  
Enthalpy at point 11 considering the amount of steam extraction y

\[ v_{[11]} = \text{volume}(\text{Steam}, h=h_{[11]}, x=0) \]

\[ T_{[11]} = \text{Temperature}(\text{steam}, P=P_{[11]}, h=h_{[11]}) \]

" Energy"

\[ W_c = \text{m}_\text{dot}_{[2]} \cdot c_p \cdot (T_{[2]} - T_{[1]}) \]  
Compressor energy

\[ W_{gt} = \text{m}_\text{dot}_{[g]} \cdot c_p \cdot (T_{[3]} - T_{[4]}) \]  
Gas turbine energy

\[ W_{st} = (\text{m}_\text{dot}_{st} \cdot y \cdot (h_{[7]} - h_{[8]}) + \text{m}_\text{dot}_{st} \cdot (1-y) \cdot (h_{[8]} - h_{[14]})) \]  
Steam turbine energy

\[ W_{Tot} = W_{gt} + W_{st} \]  
Total energy from turbines

\[ W_{pump1} = \text{m}_\text{dot}_{st} \cdot v \cdot (P_{[6]} - P_{[11]}) / \eta_{pump} \]  
Feddwater pump energy

\[ Q_{cond1} = \text{m}_\text{dot}_{st} \cdot (1-y) \cdot (h_{[14]} - h_{[9]}) \]  
Steam condenser energy

\[ Q_{comb} = \text{m}_\text{dot}_{g} \cdot c_p \cdot (T_{[3]} - (T_{[2]} - 273)) \]  
Actual combustion energy

\[ \eta_{ccpp} = W_{\text{net}} / (Q_{comb}) \]  
Combined cycle efficiency

\[ Q_{HRSG} = \text{m}_\text{dot}_{g} \cdot c_p \cdot (T_{[4]} - T_{[5]}) \]  
eta_{HRSG}

\[ \text{Heatinput} = Q_{comb} / \eta_{comb} \]  
plant heat input

\[ \text{Heatfluegas} = \text{m}_\text{dot}_{g} \cdot c_p \cdot (T_{[5]} - T_a) \]  
flue gas heat

\[ W_{\text{net}} = (W_{Tot} - (W_c + W_{pump1} + Q_{cooling}/\text{COP})) \]  
Plant net energy

\[ W_{DX} = Q_{cooling}/\text{COP} \]  
electrical energy required for cooling

\[ \text{COP} = 2.1 \]  
for DX AC in Kuwait

\[ \eta_{\text{total}} = (W_{\text{net}}) / (Q_{comb} / \eta_{comb}) \]  
The integrated combined cycle-absorption plant thermal efficiency

\[ W_{\text{plant}} = W_c + W_{pump1} \]  
(power consumed in the plant)
Example of CCPP<sub>Abs</sub> run from EES (based on cooling load for 1000 house)

<table>
<thead>
<tr>
<th>T&lt;sub&gt;a&lt;/sub&gt; C</th>
<th>y</th>
<th>W&lt;sub&gt;net&lt;/sub&gt; kW</th>
<th>W&lt;sub&gt;plant&lt;/sub&gt; kW</th>
<th>eta&lt;sub&gt;total&lt;/sub&gt;</th>
<th>Heatinput kW</th>
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Appendix (B): Published Paper

This is to certify that Mr. Hamad Almutairi presented the article "Energy and the implication of residential cooling in hot climates: Case study for developing effective solution for residential cooling energy demand in Kuwait" by Hamad Al-Mutairi, Jonathan Dewsbury & Gregory F. Lane-Serff at the Energy and Sustainability 2011 Conference which took place from 11 to 13 April 2011 in Alicante, Spain. This paper will be published in the book Sustainable Development and Planning (ISBN: 978-1-84564-544-1) and will be permanently archived in electronic format in the WIT Press e-library (see http://library.witpress.com).

All papers published in the Wessex Institute of Technology conference proceedings are subject to peer review. This review process is mainly carried out by the conference chairman and members of the International Scientific Advisory Committee (ISAC). The names of the ISAC are published in the front of each conference book and the names and affiliations of the Committee for each conference are published on our website, www.wessex.ac.uk. The review process takes place at the abstract stage and again at the final paper stage. At either stage the author may be required to alter his/her paper in accordance with the reviewers' comments and any alterations are also subject to review.

Irene Moreno  
Conference Coordinator  
Southampton, 10th May 2011
Energy and the implication of residential cooling in hot climates: Case study for developing effective solution for residential cooling energy demand in Kuwait

H. Al-Mutairi, J. Dewsbury & G. F. Lane-Serff
School of Mechanical, Aerospace and Civil Engineering,
University of Manchester, United Kingdom

Abstract

Global energy statistics showed that oil is the most sought after energy source in the world. The economic burden on countries that are dependent on oil to produce electricity is noteworthy. Residential cooling is a significant consumer of electricity produced by oil in major oil producing countries with hot climates conditions. For this, Kuwait was selected for further analysis. By analysing official annual electricity statistics in Kuwait, residential cooling consumes 58.4% of total delivered electrical energy at peak time on a hot summer day. Accordingly, the paper investigated orientation and grouping patterns of future houses in Kuwait to determine their impact on cooling load and electrical energy consumption. The popular DOE EnergyPlus simulation engine, through its interface with DesignBuilder Software, was used to obtain the cooling loads of the future houses. It was found that efficient orientation and grouping of houses, which is a zero cost energy conservation measure, can lead to tangible savings for future houses with approximately $US 33 million of power system capital costs, 15 GWh per year of electrical energy consumption and 11 kilotons per year of CO₂ emissions.

Keywords: energy demand, oil, residential cooling, building simulation, houses orientation and grouping.

World energy situation and consumption consequences

The rapidly increasing use of energy in the world has caused concern about supply difficulties and serious environmental impacts. Fossil fuels (i.e., coal, oil, and gas) and
nuclear energy are the major sources of energy, followed by renewable sources. Global energy consumption is shown in Fig. 1.

Figure 1: Global Energy Consumption, based on official statistics [1]

The global demand for energy generally increases as the human population, urbanization, and modernization increase. However, the high reliance on oil is notable. Official statistics show that oil is used to produce about 35% of the world energy demand [2]. It is important to acknowledge that the demand for oil will continue to increase unless drastic changes are made. Fig. 2 shows the history and projections for the demand for oil and other global energy resources in million ton [3]. From an economic point of view, the oil industry is a profitable sector for some corporations and governments, and taxes from oil are a major source of income for about 90 governments [4].

Figure 2: The history and projections for global energy resources through 2030[3]
Energy and life needs

Modernization and improvements in the quality of life have caused the demand for energy to reach high levels. Energy, especially electricity, touches on almost all aspects of life in all developed and developing societies. For this reason, the paper herein gives an overview of electrical energy consumption per capita, residential electrical energy consumption in the world as a whole, and residential electrical energy consumption in five specific countries, as shown in Fig. 3. The five countries were selected based on their shares of electrical energy per capita, which is directly related to individual incomes and climate conditions, which can influence electricity consumption. Consumption per capita is the common measure of the energy demand. Per capita energy consumption varies from country to country, and, within a country, it varies from region to region, depending on the level of urbanization. Suthuye and Meyers [5] showed that the per capita energy consumption is influenced by the growth in household income, which allows people to buy devices that use more energy, such as refrigerators, water heaters, and air conditioning. Also, the consumption of energy in productive activities enables growth in income, because workers and businesses are able to use power-driven machinery, which makes them more productive.

Figure 3: The percentage of residential electrical consumption nationally and per capita consumption in the world and five countries, based on official annual statistics [6]

It is clear from Fig. 4 that four countries, excluding India, are above the world average in both per capita electrical consumption and the percentage of the consumption used by
the residential sector. This can be explained as being due to the variation in modernization and lifestyle between India and the other four countries. However, the residential sector share from the total electricity consumed in Saudi Arabia is significant. This is because Saudi Arabia is totally dependent on its major national income energy resources (oil and gas) to produce electricity [6]. Air conditioning is the suspected factor for the immoderate electricity consumption by the residential sector in Saudi Arabia [7]. To prove how the residential sector is contributing to the extensive use of electricity for air conditioning applications, one such country, Kuwait, was selected to undergo further analysis.

**Hot climate country with high reliance on oil: case study of Kuwait**

Kuwait has harsh outside climate conditions with average ambient temperature of around 45 °C during the summer months [8], which requires the use of air conditioning systems from April through October. Buildings in Kuwait are subject to high ambient air temperatures and to strong solar radiation, which reaches as high as 940 W/m² on a horizontal surface in the summer [9]. Fig. 4 shows the variation of dry bulb temperature on a hot summer day.

![Figure 4: Variation of dry-bulb temperature on a hot summer day in Kuwait [8]](image)

Electrical energy in Kuwait is generated by conventional steam power plants, which depend primarily on fuel oil. Continued use of the current power plant technology that depends extensively on Kuwait oil will have severe adverse impacts on the country's economy, considering that oil is the major source of national income. Darwish et al [10]
conducted a study for the local consumption of Kuwait’s oil for power generation and water desalination which indicated that in about 30 years, the total oil production may not be enough to provide fresh drinking water for people and allow them to live in air-conditioned spaces.

In light of the facts about factors that affect energy consumption in the world in general, and in hot countries in particular, in this paper we have proposed a simple technique to determine the significant factor that affects electrical energy consumption in hot climates. Using Kuwait as an example, the proposed technique was used to analyze the statistics related to national annual electrical energy consumption. The first step was to obtain the maximum and minimum monthly electrical energy consumption in Kuwait using the annual electrical statistical book for the year 2006 [11], as shown in Fig. 5.

Air conditioning in the Kuwaiti residential sector is from the beginning of April to the end of October [12]. Moreover, according to our observation, no heating is required during the second half of February and March. Now, based on the maximum and minimum electrical demands obtained from Fig.5, the estimation of the suspected electrical energy required for operating air-conditioning systems during peak usage days in the summer can be made by taking the difference between maximum and minimum demands during the year. According to Fig. 5, the minimum system demand was about 2710 MW<sub>e</sub> at 14:00 hours on February 25, 2006 [11]. As we mentioned earlier, the
lowest demand was in February because the temperature was relatively moderate and no heating or cooling systems were required during this month. Also, most of the lighting systems in the buildings and on the streets are switched off at this hour (14:00). The maximum demand was 8900 MW\textsubscript{e}, and it occurred at 15:30 on July 26, 2006, at which time the highest outside temperature for the year occurred [11]. Consequently, the difference between the minimum demand and the maximum demand was 6190 MW\textsubscript{e}, which amounts to 69.5% of the total energy generated at the maximum demand in the year. The difference herein is expected due to the operation of air-conditioning systems in all buildings in Kuwait. Yet, to verify the share of residential sector air conditioning, we must know the percentage of residential buildings among all buildings types in Kuwait. Residential buildings represent about 84% of all buildings in Kuwait [11]. Using the percentage obtained on the national level for the energy consumption attributed to air-conditioning, i.e., 69.5%, it can be said that residential air-conditioners consume 58.4 % of the total electrical energy delivered by power plants at peak usage time on a hot summer day in Kuwait.

Proposing efficient solution for residential cooling: Proper directional orientation and grouping of houses

Directional orientation of buildings is a low or zero-cost measure that can reduce the cooling load due to solar radiation, as indicated by Harvey [13]. Several studies have suggested measures to control the energy demand resulting from residential air conditioning in Kuwait. Examples include sinking buildings into the ground by Ben Nakh and Elshiaty [14], retrofitting energy conservation measures to old buildings by Al-Ragom [15], and exploring the cooling potential of earth-air heat exchangers by Al-Ajmi et al. [12]. But, no previous attempts have been made to assess the energy-saving benefits of appropriate directional orientation and grouping of houses in Kuwait. The work presented here estimates the effect on cooling load of four different arrangements for new houses, and the implications for electricity supply and CO\textsubscript{2} emissions.
The government’s Public Authority for Housing Welfare (PAHW) in Kuwait has planned to build 19568 houses during the years 2011 to 2016 [16]. The houses to be constructed are all two-storey houses with floor area of 400 m². For this type of house, government policy allows renovation loans for owners to expand and improve their houses. The energy demand associated with the consequences of this policy is a major challenge for the country. We assume that the prevailing renovation and expansion practices associated with the government’s residential loans policy will continue for future houses. These houses are built according to the Energy Code of Practice in terms of building envelope thermal resistance, the sizes of windows, the type of glazing, the power density of lighting, and the power rating for air conditioners [17]. One of the present authors conducted a short survey of renovated PAHW houses. It was found that it is normal for the occupiers to add a third storey, that the renovated houses are typically rectangular in shape, and that they are fully air conditioned using a central air-conditioning system with electrically powered direct expansion chiller. Fig. 6 shows a typical renovated house. This renovated house type is used to predict the cooling load and electrical energy requirements of future houses.

Figure 6: Example of a renovated house in Kuwait

Typical orientation and grouping of the houses was obtained from images published on Google Earth [18]. Fig. 7 shows four cases of directional orientations and grouping: (1) single block facing east-west; (2) single block north-south; (3) double block east-west; and (4) double block north-south.
Based on Fig. 7, this study considers blocks of six houses arranged in the four common directional orientation and grouping cases, as shown in Fig. 8.

The calculation of cooling loads was done using the DesignBuilder simulation program which has an interface with the popular DOE EnergyPlus simulation engine [19]. DesignBuilder successfully passed the Building Thermal Envelope and Fabric Load Tests established by an ANSI/ASHRAE Standard [20]. A key input in cooling load calculations is the climate data for the area where the building is or will be built. DesignBuilder building simulation software provides ready access to official hourly weather files for 4429 locations in the world, including Kuwait [19]. The characteristics of the typical renovated house in Kuwait and the input data pertinent to the simulation are listed in Table 1.
Table 1: Simulation input data for each house

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plan shape</td>
<td>Rectangular</td>
</tr>
<tr>
<td>Number of storeys</td>
<td>3</td>
</tr>
<tr>
<td>Floor-to-floor height</td>
<td>4 m</td>
</tr>
<tr>
<td>Floor dimensions</td>
<td>18 m x 22 m (approximately 400 m$^2$)</td>
</tr>
<tr>
<td>Wall area of one floor</td>
<td>315.4 m$^2$, internal wall area</td>
</tr>
<tr>
<td>Window area</td>
<td>30% of the wall area, uniformly distributed</td>
</tr>
<tr>
<td>Type of window glass</td>
<td>• 6-mm thick, double glazed, clear and reflective glass</td>
</tr>
<tr>
<td></td>
<td>• U-value (3.38 W/m$^2$·°K)</td>
</tr>
<tr>
<td>Window Blinds</td>
<td>Internal blind closed daily between 12 noon - 11 p.m.</td>
</tr>
<tr>
<td>Wall U-value</td>
<td>0.568 W/m$^2$·°K</td>
</tr>
<tr>
<td>Roof U-value</td>
<td>0.397 W/m$^2$·°K</td>
</tr>
<tr>
<td>People Load</td>
<td>10 persons; 110 Watt/person</td>
</tr>
<tr>
<td>Lighting load</td>
<td>10 W/m$^2$, fluorescent lights</td>
</tr>
<tr>
<td>Lighting schedule</td>
<td>12 noon - 11 p.m. daily with a diversity factor of 70%</td>
</tr>
<tr>
<td>Equipment load</td>
<td>12 W/m$^2$ for ground floor and 5 W/m$^2$ for upper floors</td>
</tr>
<tr>
<td>Equipment schedule</td>
<td>• Ground floor: Weekdays: 7 a.m. – 9 a.m. and 4 p.m. – 11 p.m.; Weekends: 7 a.m. – 11 p.m.</td>
</tr>
<tr>
<td></td>
<td>• Upper Floor: 4 p.m. – 11 p.m. daily</td>
</tr>
<tr>
<td>Infiltration</td>
<td>0.5 air change per hour</td>
</tr>
<tr>
<td>Thermostat setting</td>
<td>24 °C and 50% RH</td>
</tr>
</tbody>
</table>
The specifications presented in Table 1 were taken from the Energy Code of Practice for houses in Kuwait, and the operation schedules for the lighting, internal blinds and equipment loads were based on our observations of a number of typical Kuwaiti houses. The same simulation input data was used for all the houses in order to measure the sensitivity of the cooling load to their directional orientation and grouping. Joseph and Sam [21] indicated that fixing all the input data except the one parameter to be analyzed is referred to as sensitivity analysis; this technique can help building designers and decision makers evaluate the thermal design of a building. The differences in simulation results can be attributed to changing the studied parameter, as recommended by Spitler et al [22].

To estimate the annual electrical energy consumption \( E_{\text{annual}} \), the annual cooling load \( Q_{\text{annual}} \) was multiplied by the allowable power rating \( PR \) for residential air conditioning from the Energy Code of Practice, i.e. 1.7 kW/RT or 0.4834 kWe/kWr (1 RT = refrigeration ton, 1 RT = 3.517 kW refrigeration). This power rating is for the direct-expansion air conditioning systems that are commonly used in the residential sector in Kuwait. Annual electrical energy consumption was obtained from the following expression:

\[
E_{\text{annual}} = Q_{\text{annual}} \times PR
\]  

(1)

Hajiah [23] indicated that conventional power plants in Kuwait emit 0.72 kg of CO\(_2\) for every kWh of electricity produced. The amount of annual electrical energy was used to estimate the associated CO\(_2\) as follows:

\[
\text{CO}_2 \text{ Emissions} = E_{\text{annual}} \times 0.72
\]  

(2)

Estimated savings in electrical energy production cost was based on the net cost to the government, which is $ US 0.09/kWh [24]:

\[
\text{Electricity Production Cost} = E_{\text{annual}} \times $US 0.09/kWh
\]  

(3)

Electrical supply capital cost was estimated based on the peak cooling load (PL) for each case. The peak cooling load was multiplied by the allowed power rating (PR) to convert it to electrical load, then this was multiplied by the capital cost of conventional
power plant in Kuwait, which is $ US 1500/kW_e [25]. The calculation was performed as shown:

Electrical Supply Capital Cost = PL* PR * $ US 1500/kW_e  \hspace{1cm} (4)

The 19568 future PAHW houses are equivalent to approximately 3621 blocks of six houses. The results from each simulation case were multiplied by 3261 to estimate the results for the future houses.

The peak cooling load would give the first indication about any promising alternative for the four cases studied. The simulation results for the four simulated blocks showed that the single block east-west case, case (1), has the largest peak cooling load of the four cases. The cooling-load profile for the four simulated cases during the peak day, as a percentage of the peak cooling load for the single block east-west case, case (1), is shown in Fig. 9.

Figure 9: Peak day cooling load profile for the four simulated cases as a percentage of peak load that resulted for case (1)

As can be seen in Fig. 9, the single block east-west case has the largest peak cooling load. This is followed by the double block east-west case, i.e., case (3). The north-south cases have lower cooling load values compared to the east-west cases, and the lowest among the four cases is the single block north-south case, i.e., case (2). The largest peak cooling load is 6.6% greater than the lowest, which is a fairly small difference. The peak
cooling load is highest for the single block facing east-west, because it has a large solar gain on its west facade in the afternoon, when the outside air temperature is high.

The results obtained by equations (1) to (4) for the four cases are listed in Table 2. For better understanding for the comparison, Table 3 shows the anticipated savings from each case. The savings shown compared to the average of the four cases (this is equivalent to assuming that the future houses will be distributed equally between the four orientations and grouping arrangements).

Table 2: Results for the 19568 houses

<table>
<thead>
<tr>
<th>Type</th>
<th>Unit</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak electrical load</td>
<td>MWₑ</td>
<td>693</td>
<td>645</td>
<td>670</td>
<td>659</td>
<td>667</td>
</tr>
<tr>
<td>Electrical supply capital</td>
<td>$ US million</td>
<td>1,040</td>
<td>967</td>
<td>1,004</td>
<td>988</td>
<td>1,000</td>
</tr>
<tr>
<td>Annual electrical energy</td>
<td>GWhₑ</td>
<td>1,593</td>
<td>1,554</td>
<td>1,565</td>
<td>1,563</td>
<td>1,568.7</td>
</tr>
<tr>
<td>Annual generation cost to</td>
<td>$US million</td>
<td>143.4</td>
<td>139.8</td>
<td>140.7</td>
<td>140.6</td>
<td>141.2</td>
</tr>
<tr>
<td>Annual CO₂ emissions</td>
<td>kilotons per year</td>
<td>1,150</td>
<td>1,120</td>
<td>1,130</td>
<td>1,125</td>
<td>1,131</td>
</tr>
</tbody>
</table>
Table 3: Anticipated savings for the future 19568 houses based on the results obtained from Table 2

<table>
<thead>
<tr>
<th>Saving</th>
<th>Unit</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Supply Capital Cost</td>
<td>$ US million</td>
<td>-40</td>
<td>33</td>
<td>-4</td>
<td>12</td>
</tr>
<tr>
<td>Annual Electrical Energy</td>
<td>GWh_e/Year</td>
<td>-24.3</td>
<td>15</td>
<td>3.7</td>
<td>5.7</td>
</tr>
<tr>
<td>Annual electrical generation cost to government</td>
<td>$US million/year</td>
<td>-2.2</td>
<td>1.35</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Reduction in annual CO₂ emissions</td>
<td>kilotons per year</td>
<td>-19</td>
<td>11</td>
<td>1.76</td>
<td>4.1</td>
</tr>
</tbody>
</table>

Note: the (-) sign indicates increased costs and emissions

Table 4 shows twenty-year projected savings for each case, excluding the single block east-west case due to the reasons specified earlier. The estimated savings presented in Table 4 are based on the savings resulted from the average of the four cases presented earlier in Table 3.

Table 4: Twenty-year projection of the expected savings for the future 19568 houses

<table>
<thead>
<tr>
<th>Case</th>
<th>Savings in Electrical Supply Capital Cost (million $ US)</th>
<th>Savings in Electricity Production Cost in (million $ US)</th>
<th>Total Savings (million $ US)</th>
<th>CO₂ Equivalent to Seasonal Electricity Savings (kiloton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 2</td>
<td>33</td>
<td>27</td>
<td>60</td>
<td>222</td>
</tr>
<tr>
<td>Case 3</td>
<td>-4</td>
<td>10</td>
<td>6</td>
<td>35.2</td>
</tr>
<tr>
<td>Case 4</td>
<td>12</td>
<td>12</td>
<td>24</td>
<td>82</td>
</tr>
</tbody>
</table>

Note: the (-) sign indicates increased costs
As can be seen from Table 4, the single block north-south case would achieve significant savings among other cases. Although case 3 did not achieve saving in the electrical energy capital cost, it was introduced in the projected savings because it achieved savings in the annual electrical energy consumption.

Conclusion

Fossil fuels, especially oil, are an important global energy resource. The extensive usage of global energy resources has negative impacts on all aspects of life. The paper indicated that there is a direct relationship between residential energy consumption and consumption per capita. Hot weather was also found to be a significant factor for energy consumption in countries that have harsh summer conditions and totally dependent on valuable energy resources to generate electricity. In conjunction with these facts, Kuwait was selected for additional analysis of its electrical energy usage. The findings proved that residential cooling is the significant factor for electricity in Kuwait. The authors proposed a unified orientation and grouping style for future houses as a zero cost energy conservation measure. The proposed orientation and grouping style of houses can reduce solar gain; which therefore and can lead to significant savings in energy and CO\textsubscript{2} emissions.
References:

[2] International Energy Administration (IEA); Key World Energy Statitics, 2007


[23] Hajiah, A. Energy conservation program in Kuwait, a local prospective, proceedings of fifteenth symposium on improving building systems in hot and humid climates, Orlando, FL, July 24-26, 2006
