District Cooling for Al Hamra Village in Ras Al Khaimah-United Arab Emirates (UAE)

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Master of Science Thesis
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ABSTRACT

In this thesis, the feasibility of a solar assisted district cooling system for the Al Hamra village (phase 4) under RAK weather conditions is assessed. Utilizing solar energy is very attractive since the cooling requirements are in phase with the solar energy availability.

The research was conducted to estimate the dynamic cooling load of the Al Hamra village phase 4 using Design Builder (DB) and Transient System Simulation (TRNSYS) softwares and designing an economically feasible and environmental friendly solar assisted district cooling system which can meet the yearly cooling load demand besides maintaining thermal comfort of the village residencies.

The simulation results showed hourly peak cooling demand of about 37 MW cooling which occurs in July (Design day) when the average hourly temperature exceeds 50 °C and the annual cooling energy demand is about 123 GWhrs. After the analyzing of techno-economical feasible solar assisted district cooling system, two feasible options were found. One is environmental standpoint and other one is for economical standpoint.

The environmental standpoint solution is cooling system with solar assisted cooling system with single effect absorption chillers (with 50 % solar fraction and direct sea water condenser cooling). This system save primary energy 5,397 m³ annually and save 13,874 tons of CO₂ emission annually. The payback period of this system is 14 years and 10 months and which save the money US $ 2,501,388 in every year.

The economical standpoint solution is cooling system with water cooled vapor compression chiller system. This system saves primary energy 2,908 m³ annually and save 7,442 tons of CO₂ emission annually. The payback period of this system is just 8 years and 10 months and which save the money US $ 1,347,672 in every year.

Keywords: Cooling load, solar absorption cooling, Sea water heat rejection, TRNSYS, Design Builder.
ACKNOWLEDGEMENT

I am grateful to CSEM-UAE Innovation Center LLC for bringing forth the concept about the project and the facilitation accorded towards its successful completion. Worthy notice is the invaluable cooperation and input of Al Hamra real estate and management those who provided adequate information about Al Hamra village. I am also indebted to the expertise, supervision and guidance of Prof. Bjorn Palm and Dr. Sad Jarall from KTH and Dr. Hamid Kayal and Mr. Manoj Kumar Pokhrel from CSEM-UAE.

I also wish to express my gratitude to my parents who always support me during my life.
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NOMENCLATURE

AC  Air-Conditioning
AHU  Air Handling Unit
ALCC  Annual –life cycle cost
ASHRAE  American Society for Heating Refrigeration and Air Conditioning Engineers
ASME  American Society of Mechanical Engineers
BMS  Building Management System
CFCs  Chloro-Fluoro-Carbons
CHP  Combined Heat and Power
CO₂  Carbon Dioxide
COP  Coefficient of Performance
CPC  Compound Parabolic Concetrator
CSEM  Swiss Center for Research in Electronics and Micro techniques
CV  Capital Value
DB  Design Builder
EPA  Environmental Protection Agency
FCU  Fan Coil Unit
GMT  Greenwich Mean Time
GWh  Giga Watt hours
GWP  Global Warming Potential
HVAC  Heating Ventilation and Air Conditioning
IEA  International Energy Agency
IMF  International Monetary Fund
kWh  Kilo Watt hours
LCC  Life Cycle Cost
MWh  Mega Watt hours
MC  Maintenance Cost
NOₓ  Nitrogen Oxides
NPV  Net Present Value
OC  Operating Costs
PB  Payback period
PVF  Present Value Factor
PTC  Parabolic tough Collectors
PV  Photo Voltaic
RAK  Ras Al Khaimah
ROI  Return on investment
SO₂  Sulphur Oxides
TEWI  Total Equivalent Warming Impact
TMY  Typical Meteorological Year
TRNSYS  Transient System Simulation Program
UAE  United Arab Emirates
1. INTRODUCTION

1.1 Renewable Energy

Today, 14% of the world primary energy demand supplies by renewable energy. This renewable energy sources includes hydro, biomass and other renewable. Other renewable energy sources include solar, wind, tidal, geothermal and wave energy and are approximately 1% of the world primary energy demand. However, the utilization of these other renewable energy sources is increasing faster (5.7% annually) than other primary energy sources (International Energy Agency [IEA], 2004). Threats of the climate change, exhaustion of fossil fuels and the need for secure energy supply stimulate the utilization of renewable energies. Today's global energy system is unsustainable in the economic, social and environmental terms. In near term renewable energies may be a solution for the problem mentioned above although they have some drawbacks.

The primary source of all renewable energies except geothermal energy is solar radiation. The amount of solar energy striking the earth’s surface is \(5.4 \times 10^{24}\) J per year (Sorensen, 2004). Solar energy is mainly harvested in two ways. It can be converted into either heat or electricity. Converting solar energy into heat is possible by using solar thermal energy technologies. Converting solar energy directly to electricity is achievable by using photovoltaic (PV) cells. Energy (electricity or heat) obtained from solar energy technologies can be used for many applications such as drying, heating, cooling, desalination (Kalogirou, 1997) and generating electricity (Mills, 2004).

Solar thermal energy describes all technologies that collect sunlight and convert their electromagnetic energy into, either for directly satisfying heating/cooling needs or for producing electricity. In order to increase efficiency, high temperatures are necessary for electricity production from solar thermal processes. These high temperatures are possible to obtained through concentrating solar power (CSP) technologies (Philibert, 2005).

In solar thermal system there are several advantages (European Solar Thermal Industry Federation [ESTIF], 2006):

- Reduces the dependency on imported fuels
- Save natural resources
- Save CO\(_2\) emission
- Curbs urban air pollution
- Is immediately available
- Creates local jobs and stimulates the local company
- Inexhaustible.

In this study district cooling by using solar energy technologies are emphasized. Solar assisted district cooling can be done by using solar thermal technologies which will be considered in detail in the literature review.
1.2 Feasibility to Solar cooling in UAE

There is a rapid increase in the electricity consumption in the United Arab Emirates (UAE). Electricity consumption has increased from 5.5 billion kWh in 1980 to about 36 billion kWh in 2000 with an annual growth rate of 10% compared to the world average of 3% (Al-Iriani 2005). The demand of the electricity increase specially in the summer because of the extensive use of air conditioners.

UAE is a federation of seven emirates with the second largest economy in the Arab Middle East after Saudi Arabia and has the 17th highest GDP per capita in the world which directly transforms to high energy/electricity consumption per capita. It has a total land area of 83,600 km$^2$ and lies between latitudes 22.0°-26.5°N and longitude 51.0°-56.5° E. The country is a desert but cooler in Eastern mountains and the lowest altitude is 0m at Arabian gulf while the highest point in Jabal at 1527m. The climate in UAE can be characterized as hot, dry and humid. The period October to March is associated with relatively low temperatures (day average of about 26°C and the night average of about 15°C) but relative humidity varying between 60 RH% to 100 RH%. April to September is a hottest period having peak temperature of about 50°C relative humidity varying between 20 RH% to 50 RH% and the night time relative humidity is varying between 50 RH% to 70 RH %. Electricity production in 2007 was at 71.5 billion kWh and consumption was 66 billion kWh. In 2007, fossil fuel contributed 100% of the total energy production with natural gas taking 65% and oil accounting for 35%. Total CO$_2$ emission were 171 billion metric tons in 2007 with per capita CO$_2$ emission of 33 metric tons (http://www.cia.gov; http://www.eia.doe.gov).

Ras Al Khaimah (RAK) is a fourth biggest emirate in UAE after Abu Dhabi (Capital city), Dubai and Sharjah and is at 8m above sea level. It lies between 25°47’ N and 55°57’ E with the maximum temperature of about 59°C and the minimum temperature 10°C. The relative humidity varies between 10 RH% to 100RH %.

However, the UAE receives an abundance of solar radiation. The annual average global irradiation is 6kW h/m$^2$/day (Alnaser, Trieb, Knies, 2007). Therefore utilization of solar energy to drive the cooling process is very attractive. Since the building air conditioning load profile is in phase with the solar energy availability, utilizing solar energy to drive air conditioners would be the great interest.
1.3 Objectives and Purpose of the Thesis

Main Objective

- To theoretically model and simulate centralized district cooling system for Al Hamra village in RAK –UAE with hybrid solar thermal driven absorption chillers and water cooled vapor compression chillers by considering sea water as one possible heat sink for the both chiller type.

Specific Objective

- Considering earlier work of Al Hamra mall solar cooling, identify a district in Al Hamra village with comparable cooling needs.
- Conduct a literature review to identify the current status of district cooling technologies with hybrid electricity/waste heat and solar assisted heat driven chillers/electrically driven chillers by considering sea water as heat sink.
- To theoretically approximate and simulate the detail dynamic cooling loads profile of one district of the AL Hamra Village area.
- Conceptualize, design, simulate and optimize multiple energy inputs integrated centralized district cooling system with electricity, solar thermal as energy source and sea water as heat sink.
- Compare the potential effectiveness of proposed solution to the conventional solution.

Scope

The research focused on estimation of dynamic cooling load of a district of an Al Hamra village and design of an economically and environmentally feasible solar assisted district cooling system which can meet the yearly cooling load and maintain thermal comfort conditions of the occupants.

Purpose of research:-

Due to hot, dry and humid climate condition of UAE, there is a high demand for cooling throughout the year and this has been met largely by use of conventional totally electrical driven vapor compression air conditioning systems, which are associated with high energy cost, Ozone Depletion Potential (ODP) and Global Warming Potential (GWP). However the abundant solar energy in the region and proximity of the residential area to the sea could be advantageous to make use of sustainable air conditioning system. The proposed research has been conceived to fill the gap in research such that utilization of solar thermal energy could be use as a base energy source and the sea water as the heat sink for the air conditioning system in UAE. This research will aim at designing a techno-economical and environmental friendly hybrid district cooling system for a district of Al Hamra –RAK-UAE, which utilizes the vast solar energy resources and sea water resources in Al Hamra Village area –RAK-UAE, to meet the cooling demand.
2. LITERATURE SURVEY

Refrigeration is a process of removing heat from an enclosed space or from a substance for the purpose of lowering the temperature. Generally solar cooling or solar air conditioning terms are used for the systems which are used for obtaining thermal comfort conditions in buildings or vehicles, whereas solar refrigeration term is more likely to be used for the systems which used for the food preservation, vaccine storage or ice production. Chiller term is also used for air conditioners which are working on absorption or adsorption refrigeration cycle (i.e. Absorption Chiller).

As stated in the introduction solar energy can be converted into either thermal energy or electricity. In theoretically all the refrigeration technologies can be driven by heat or electricity, but not all of them are feasible to be driven by solar energy. As an example solar thermal driven cooling techniques cannot compete with grid electrically driven room air conditioners which are working on vapor compression cycle, because solar thermally driven techniques are more expensive per unit cooling power, bulkier (it need separate place for installation) and heavier than normal room air conditioners[1]. As well as electricity generated by PV cells is not economically competitive with grid electricity due to high investment cost of PV cells. But these fields have promising future. For instance in 1970s PV cells had efficiency 5%, today PV cells with 15% efficiency are commercially available [1]

2.1 Refrigeration system

Basically refrigeration system can be categorized into two types according to the energy type which are use as energy input.

- Electrically driven refrigeration system
- Solar thermally driven refrigeration system

2.1.1 Electrically driven refrigeration system

In this refrigeration system direct electricity is given to the refrigeration cycle as an energy input. This energy input could be either from grid or from PV. But in this study grid electricity powered refrigeration system will be explained in detail. Grid electricity powered refrigeration system also can be categorized in to two types according to way (method) which are rejecting the condenser heat.

- Air cooled vapor compression refrigeration system
- Water cooled vapor compression refrigeration system

2.1.1.1 Air cooled vapor compression refrigeration cycle.

Air cooled vapor compression refrigeration systems are most widely used countries having hot dry and humid climates. This is because this type of system can be operated in high ambient temperature conditions. The following Figure 1 shows basic components of the vapor compression refrigeration. The vapor compression refrigeration system basically consists of five components. Which are compressor, expansion valve, condenser, evaporator and refrigerant.
Compressor is a heart of the system, which lifts the pressure of the refrigerant and maintains the refrigerant circulation throughout the system. Evaporator is a device which absorbs the heat from the condition space. In chillers, water circulates through the evaporator to absorb the heat. Expansion valve or control valve is a device which reduces or drops the pressure of the refrigerant in order to maintain the evaporative temperature of the evaporator. Condenser is a device which rejects the heat which is absorbed from the evaporator from the conditioned space. In air cooled vapor compression refrigeration system heat rejects to the environment. This is accomplished by using fans. The following Figure 2 shows how it is operating.

2.1.1.2 Water cooled vapor compression refrigeration cycle

Water cooled vapor compression refrigeration cycle is also almost like air cooled vapor compression cycle. The only difference in between these two cycles is the way which rejects the heat from condenser. In water cooled vapor compression cycle used water to reject heat from the condenser. The Figure 3 shows how it operates. The cooled water passes through the condenser and absorbs the heat. Cooling tower is used to cool down the water temperature which is coming out from the condenser and maintain the water circulation. This water cooled vapor compression cycle has higher COP (approximately 5) than the air cooled vapor compression cycle (approximately 2.5)\[2\]

In this study cooling tower is not proposed to be used as it needs fresh water. Therefore instead of cooling tower, sea water is used to reject the heat from the condenser.

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1 Condensing pressure. This is the pressure required for the condenser in order to reject heat
2.1.2 Solar thermally driven refrigeration cycle.

Thermal driven cooling system are usually feasible when a low temperature (below 200 °C) and/or cost efficient heat source is available. In general, solar energy is the most widely available heat source for solar thermal driven cooling applications. Also waste heat from the industrial processes\(^2\) can be an alternative to solar energy whenever is available.

There are four major solar thermal driven cooling systems today. These are absorption, adsorption, desiccant and ejector cooling systems. The following Figure 4 shows the relationship between the COP and the driving temperature. From this analysis it shows the absorption system has comparatively higher COP than other technologies and it is even more higher if absorption technology with higher effect is considered.

\[\text{COP} = \frac{Q_{\text{out}}}{W_{\text{in}}}\]

\(^2\) Industrial processes like power plant. This is also called poly-generation plant
Figure 5: Relationship between COP and the heat rejection temperature. (C.A.Balaras et al.2007)

The below Figure 6 shows how the specific collector area is varying against the initial cost. Though absorption cycle takes relatively high specific collector area, its initial cost is low compared to other cycles.

Figure 6: Relationship between specific collector area and the initial cost (C.A.Balaras et al.2007)

After the review of different solar thermal driven cooling system it is decided to use the absorption systems for the proposed research. As well as the absorption systems\(^3\) that are commercially available have to be considered.

\(^3\) Absorption chillers-There are more than 10 Absorption chiller manufactures in the world in large scale.
2.1.2.1 Absorption Cooling System.

According to the International Energy Agency (IEA), absorption cooling system is the most widely used solar thermal driven cooling system. (IEA, 2002). Absorption cooling dates back to the 1700s, and the first ammonia-water refrigeration system was patented by Ferdinand Carre in 1859 (Srikhirin, Aphornratana & Chungpaibulpatana, 2001).

The main difference of the absorption refrigeration cycle from the vapor compression cycle is the replacement of the compressor with a thermally driven absorption mechanism. The absorption cooling system consists of an absorber, pump, regenerator, generator, expansion valve, condenser and evaporator.

The working fluid of the absorption refrigeration cycle is a solution of two or more fluids. Usually lithium bromide-water (LiBr/H₂O) or ammonia-water (NH₃/H₂O) solution is used. In NH₃/H₂O system, water is the absorbent and NH₃ is the refrigerant. Since the freezing point of the NH₃ is -77°C, NH₃/H₂O systems is possible to use for the low temperature applications. In the case of LiBr/H₂O systems LiBr is the absorbent and the H₂O is the refrigerant. LiBr/H₂O systems are most widely use in air conditioning application since it has freezing point of 0°C.

There are three types of LiBr/H₂O absorption refrigeration cycles available namely single effect (1E), double effect (2E) and triple effect (3E). Single effect and double effect refrigeration cycles are commercially available and triple effect cycles are not yet commercially available in large scale since it is still in research and development stage.

A single effect LiBr/H₂O absorption cycle has two pressure levels, one low pressure level in the evaporator and absorber, and one higher pressure level in the generator and condenser. As shown in Figure 7 the process is someway similar to the vapor compression process. The refrigerant (pure water at low pressure) is evaporated in the evaporator where heat also is absorbed from the condition space. The low pressure water vapor is thereafter absorbed by the absorbent (LiBr). During the process of water vapor absorption heat of condensation is released and thus, the absorber, has to be cooled. During this process, heat is transported from the low temperature in the evaporator to the higher temperature in absorber. The driving force for the heat transfer is the concentration of the absorbent solution (LiBr). The diluted solution is pumped from the absorber to the generator, in order to be brought back to a higher concentration. At the higher pressure level in the generator, the absorber is concentrated through vaporization of water, a process requiring driving heat. The water vapor, that is superheated due to the presence of the absorbent, is then transported to the condenser where it condenses and releases heat before water (liquid)is brought back to the evaporator through an expansion valve.(Victoria Martin., 2004)

![Figure 7: A single effect LiBr/H₂O absorption cycle (Rydstrand et al., 2004)](image-url)
The lowest temperature heat input is in the evaporator and the highest in the generator. The heat output must always be between the generator and evaporator temperature level. Generally single effect absorption chillers has 0.7 COP level (Alefeld and Radermacher, 1994; Schweigler et al., 1996)

The double effect chiller required higher driving heat temperature as compared to the single effect chillers but gives higher COP. The Figure 8 shows the principle for a double effect absorption refrigeration cycle. The main difference from the single effect refrigeration cycle is that an extra pressure level is added with high pressure generator and condenser. Heat release from the high pressure condenser can thereby be reused in low pressure generator. This will have the effect more heat can be absorbed at the low temperature in the evaporator given a specific heat input. The typical cooling COP of up to 1.2 thereby reached. (Alefeld and Radermacher, 1994; Schweigler et al., 1996)

The design for a double effect absorption chiller is more complex compared to a single effect chiller since more heat exchanger and pumps will be required. However cooling tower is needed as heat sink, less cooling tower capacity is needed per unit cooling effect due to the higher COP_{heat} in double effect chiller (AB Energiupdrag, 1996)

Figure 8 :- A double effect LiBr/H₂O absorption cycle (Rydstrand et al., 2004)

In the absorption refrigeration cycle only work input is for the pump. Since pump increases the pressure of the liquid and work input is proportional to the specific volume, the work input for the pump is very small compared to the compressor in the vapor compression cycle and is on the order of 1% of the heat supplied from the generator. (Cengel et al. 2002)

The COP of the absorption refrigeration cycle is define as,

$$COP = \frac{Q_L}{Q_{gen} + W_{pump}} \approx \frac{Q_L}{Q_{gen}}$$  Equation 1

Where $Q_L$ the heat is transferred from the low temperature space (Condition space), $Q_{gen}$ is the heat input to the generator and $W_{pump}$ is the work input to the pump

The absorption chillers can be categorized in to three types. These are single effect, double effect and triple effect absorption chillers. Again absorption chiller types can be categorized into three types according to the energy input to the generator. These are direct fired, hot water fired and steam fired.

The COP for single effect absorption chillers is in the range of 0.6 to 0.7. (Alefeld and Radermacher, 1994; Schweigler et al., 1996). Most manufactures offers single effect chillers in the cooling
capacity range 100RT to 1500RT. (Dorgan, C.B., 1995). These can be fired with steam at 135 to 205 kPag, which corresponds to a steam temperature of 110 to 120°C. (Dorgan, C.B., 1995). Alternatively they can be fired with hot water at 90 to 110°C and a maximum pressure of 8 bar (Dorgan, C.B., 1995). The steam consumption of the single effect absorption chiller is approximately 2.4 kg/hr per kWth (Dorgan, C.B., 1995). The hot water flow required is in the range of 32 to 72 kg/h per kWth depending on the temperature drop allowed. (Dorgan, C.B., 1995).

The COP of the double effect absorption chillers are from ranging 0.9 to 1.4 (Alefeld and Radermacher, 1994; Schweigler et al., 1996). The double effect chillers are approximately in the same range of the capacities like single effect. The commercially available double effect chillers are fired by steam. The steam should be at 9 to 10 bar gauge. Which corresponds to temperature range of 175 to 185°C. According to the research it is possible to fired by hot water, the temperature of which should then be in the range of 155 to 170°C (Dorgan, C.B., 1995). The steam consumption of double effect absorption chiller is 1.4 kg/h per kWth. (Dorgan, C.B., 1995).

Literature from the manufacturers triple effect chillers are in development stage and it gives the maximum COP of 2. The first triple effect chiller was commercialized by Kawasaki chiller manufacture having cooling capacity of 55 kW. This chiller is fired by steam (270°C).

2.2 Solar collectors

One of the major components of the solar thermally driven refrigeration system is solar collectors. These are heat exchangers that absorb solar radiation energy, convert it into heat and transfer this heat to heat transfer fluid (air, water or oil). This collected thermal energy either can be used directly for air conditioning or can be stored in thermal energy storage tanks for later use at night times when the sun is not available. There are two types of solar collectors; stationary (none concentrating) and concentrating. A stationary collector has same intercepting and absorbing area. Concentrating collectors are mostly sun trackers uses concave reflecting surfaces to concentrate solar beams to a small receiving area and increases the radiation flux to many times. This also produces high temperature of the transfer fluid. The following Table 1 shown the important properties of the solar collectors. (Muhammand, 2009)

<table>
<thead>
<tr>
<th>Motion</th>
<th>Collector type</th>
<th>Absorber type</th>
<th>Concentration ratio</th>
<th>Indicative temperature range°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stationary</td>
<td>Flat plate collector (FPC)</td>
<td>Flat</td>
<td>1</td>
<td>30-80</td>
</tr>
<tr>
<td></td>
<td>Evacuated tube collector (ETC)</td>
<td>Flat</td>
<td>1</td>
<td>50-200</td>
</tr>
<tr>
<td></td>
<td>Compound parabolic collector (CPC)</td>
<td>Tabular</td>
<td>1-5</td>
<td>60-240</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5-15</td>
</tr>
<tr>
<td>Single-axis tracking</td>
<td>Linear Fresnel reflector (LFR)</td>
<td>Tabular</td>
<td>10-40</td>
<td>60-250</td>
</tr>
<tr>
<td></td>
<td>Cylindrical trough collector (CTC)</td>
<td>Tabular</td>
<td>15-50</td>
<td>60-300</td>
</tr>
<tr>
<td></td>
<td>Parabolic trough collector (PTC)</td>
<td>Tabular</td>
<td>10-85</td>
<td>60-400</td>
</tr>
<tr>
<td>Two-axis tracking</td>
<td>Parabolic dish reflector (PDR)</td>
<td>Point</td>
<td>600-2000</td>
<td>100-1500</td>
</tr>
<tr>
<td></td>
<td>Heliostat field collector (HFC)</td>
<td>Point</td>
<td>300-1500</td>
<td>150-2000</td>
</tr>
</tbody>
</table>

Table 1: Solar collectors and their important properties. (Soteris A Kalogirou)

4 RT-Refrigeration Tons
6 www.kawasaki.com
2.2.1 Solar thermally driven refrigeration system

Following Table 2 shown the compatible solar collector type with different type of absorption chillers.

<table>
<thead>
<tr>
<th>Type of Absorption chiller</th>
<th>COP</th>
<th>Heat source</th>
<th>Type of solar collector match</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single effect</td>
<td>0.7</td>
<td>98°C hot water</td>
<td>Evacuated tube collector</td>
</tr>
<tr>
<td>Double effect</td>
<td>1.4</td>
<td>180°C hot water</td>
<td>Compound parabolic collectors/Parabolic trough collectors/Linear Fresnel reflectors</td>
</tr>
<tr>
<td>Triple effect</td>
<td>2</td>
<td>275°C steam at 40 bar</td>
<td>Parabolic trough collectors/Linear Fresnel reflectors</td>
</tr>
</tbody>
</table>

Table 2: Absorption chillers heat source requirement (Muhammad, 2009)
3. WEATHER DATA AND OCEANOGRAPHIC DATA

3.1 Weather data

The performances of environmental related systems such as heating, ventilating, air conditioning and refrigeration (HVAC & R) systems, solar collectors, PV cells and cooling towers are closely dependent on the weather variable like dry bulb temperature, wet bulb temperature, wind speed, solar radiation, etc. (Uner, 1998). Therefore in designing or predicting the yearly performances of environmental related system, weather data should be used as an input. Weather data has a strong effect on the performance of the solar collector and the building cooling load.

In general there are two methods for developing annual weather data which are synthetic generation of weather variable and selection among real data. Synthetic generations of weather data variables are useful when there are no recorded weather data for a specific location. The aim in these methods is representing weather variables by mathematical functions. Selecting among the real data is widely used for simulation of building energy systems if weather data is available for that location.

In 1976, Klein developed the concept of a design year which was useful for simulating solar heating system (Duffie et al, 2003). More detailed studies conducted in Sandia National Laboratories has led to the generation of a typical meteorological year (TMY) (Hall, Prairie, Anderson & Boes, 1978). The TMY is a data set of hourly values of solar radiation and meteorological elements for a one year period. It consist of months selected from individual year and concatenated to form a complete year (National Renewable Energy Laboratory (NREL), 1995). TMY represent typical rather than extreme conditions, so it is not appropriate for designing systems to meet the worst-case conditions occurring at a location. TMY is useful for representing a long period of time, such as 30 years (NREL, 1995). More recently TMY data sets are replaced by TMY2 data sets which are based on more recent and accurate data (NREL, 1995).

In this study Meteonorm software has been used to generate weather data of the Al Hamra village in RAK. The exact location of the Al Hamra village is latitude of 25.68, longitude 55.95, altitude 8 m and the time zone GMT+4. A TMY2 data set was generated that it can be used for simulation in TRNSYS. The interpolation for a TMY2 weather file are based on three nearest weather stations which are RAK, Sharjah international airport and Dubai international airport.

The following figures shows hourly weather data generated from TMY2 file which include ambient temperature, relative humidity and solar irradiation. The below Figure 9 shows the comparison between monthly average ambient temperature and relative humidity.

![Figure 9: Comparison between monthly average ambient temperature and relative humidity](image-url)
The maximum hourly average ambient temperature is about 45 °C is recorded during the summer period of June to August. The minimum hourly average ambient temperature is about 10 °C during the winter period of December to February.

The following Figure 10 shows the variation of hourly average solar irradiation on a typical hot sunny day. The maximum solar energy resources exceed 1000 W/m² at particular instant during summer. Though there are about 10 to 12 sunny hours per day available, only 8 sunny hours exceeds 600W/m² average solar irradiation. Therefore in this study 8 sunny hours has taken for the selection and designing of the solar thermal collectors.

![Hourly average solar irradiation on a typical hot sunny day](image)

**Figure 10**: Hourly average solar irradiation on a typical hot sunny day

### 3.2 Oceanographic data

Oceanographic data are temperature, salinity, etc of the ocean. There are several organizations those who are continuously monitoring the oceanographic data. The main objective of these organizations is to identify the sea water level rising due to increase of sea water temperature. Argo is the one of the organization which provides the oceanographic data around the world online.

In this study, identification of oceanographic data variation is very important because sea water has been proposed to be used for cooling the chiller condenser. Most of the design parameters and figure of merit are dependent on the sea water temperature. Though Argo provides the oceanographic data of RAK (Near the Oman border) Sea online, actual measurement is also taken to improve the correctness and cross check the reliability of the data. It has been identified that only parameter like temperature and the salinity of the sea water is important for the proposed research, the collection of the data in this regard is considered.

The under mentioned Figure 11 shows the locations of the temperature and salinity measured in Al Hamra village lagoon area and RAK Sea. Table 3 indicates the exact positions (longitude and latitude) of the each location.
Figure 11: - Sea water temperature and the salinity measuring points in Al Hamra village lagoon area and the sea. (Source: Al Hamra Real Estate – RAK)

<table>
<thead>
<tr>
<th>Location</th>
<th>Longitude</th>
<th>Latitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>55.780541</td>
<td>25.691827</td>
</tr>
<tr>
<td>2</td>
<td>55.785284</td>
<td>25.695475</td>
</tr>
<tr>
<td>3</td>
<td>55.783422</td>
<td>25.697341</td>
</tr>
<tr>
<td>4</td>
<td>55.786435</td>
<td>25.699508</td>
</tr>
<tr>
<td>5</td>
<td>55.788900</td>
<td>25.696823</td>
</tr>
<tr>
<td>6</td>
<td>55.788720</td>
<td>25.692260</td>
</tr>
<tr>
<td>7</td>
<td>55.781554</td>
<td>25.698194</td>
</tr>
<tr>
<td>8</td>
<td>55.780726</td>
<td>25.684613</td>
</tr>
<tr>
<td>9</td>
<td>55.778386</td>
<td>25.684737</td>
</tr>
<tr>
<td>10</td>
<td>55.774861</td>
<td>25.698167</td>
</tr>
<tr>
<td>11</td>
<td>55.771384</td>
<td>25.686460</td>
</tr>
</tbody>
</table>

Table 3: - Exact location of the sea water temperature and salinity measured points

Figure 12 shows the sea water average temperature variation in the Al Hamra village lagoon area and the RAK Sea over the period of 6 months in two weeks intervals. Blue graph represent the actual measured temperature and the red graph represent the Argo online data. There is around 1°C temperature difference in between two separate data sets. Figure 13 shows the sea water salinity variation over the period of 6 months in two weeks intervals. All these measurements were taken one meter depth from the surface level of the sea water.
After the analysis of above data, it shows the maximum sea water temperature is occurring in July month which is below 35 °C. Thus 35 °C is taken as maximum sea water temperature throughout the year for the selection of chillers. Therefore selected chillers condenser inlet water temperature\(^7\) is taken as 35 °C.

\(^7\) Chiller condenser sea water inlet temperature is 35 °C and condenser sea water outlet is 40 °C.
4. ESTIMATION OF THE DYNAMIC COOLING LOAD

Calculation of the buildings dynamic cooling load of a selected district is the first step in determining the overall performances of the solar assisted district cooling system. Selection of the building, site, orientation, construction materials and plan are the rudiments of the buildings cooling load calculation. After determination of the above parameters, cooling load calculation method can be utilized. However instead of starting from scratch, it is better to use available software for convenience and accuracy. There are various software’s available for hourly cooling load calculation. One of the most widely used software is the TRNSYS. TRNSYS is extensively used in academic and engineering community and it is continuously developed by the users worldwide. Design Builder (DB) is software which also can use for the building dynamic cooling load calculation. In design builder there is a possibility to multiply if there is similar buildings. As there is accessibility to both softwares have been used for the estimation of cooling load.

At first dynamic cooling load has been estimated by using DB and the results are directly exported to TRNSYS in order to simulate complete solar cooling system in TRNSYS platform.

4.1 Selection and description of district

The selected district for the district cooling system is located in the Al Hamra Village in RAK in UAE. Al Hamra Village covers an area of 5,000,000 m² of RAK in UAE. The Al Hamra Village is located in a coastal area consisting of a cluster of townhouses, hotel, villas, apartments and mall.

The above Figure 14 shows the Al Hamra Village area-RAK-UAE. It is costal area having hot, dry and humid climate. The left hand side figure shows the satellite view of Al Hamra Village in 2005 and the right hand figure shows the architectural view of Al Hamra village after completion. Al Hamra village construction plan is consisted of four phases. Out of these four phases they have already completed three phases. Therefore it is decided to do the feasibility of the solar assisted district cooling system for the phase no.4. Because this phase 4. All these information and requirement are collected from Al Hamra real estate, which is responsible for the development of Al Hamra village area.

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8 http://www.eere.energy.gov/buildings/tools_directory/
9 For more information: http://sel.me.wisc.edu/trnsys/
10 For more information: http://www.designbuilder.co.uk/
Figure 15: Master plan of Al Hamra village consisted of four phase (phase 1, 2, 3 & 4)
(Source: Al Hamra Real Estate – RAK)

The above Figure 15 shows the master plan of the Al Hamra village and the right hand side view shows the exactly where the phase 4 is located in the Al Hamra village area.

The phase -4 of Al Hamra village consist of three types of buildings viz: royal breeze buildings apartments, town houses and the cluster type town houses.

Royal breeze apartment is a block type building. Altogether there are seven numbers of blocks located in the pyramid shape. The number of floors per block is varying in between 14 to 20. The below Figure 16 shows the Design Builder 3D view (left side) and the architectural view (right side) of whole seven numbers block type Royal breeze apartments. There are 2024 numbers of apartments in this whole seven numbers block type Royal breeze apartments as shown in Figure 16 and occupying 117,300 m² of floor area.

Figure 16: Royal breeze residence apartment (Source: Al Hamra Real Estate – RAK)

The second type of the building is Town houses. These are two storey building having separate swimming pool, garden, etc for each town house. Each town house having their own roof terrace and they can enjoy with the beauty of the Al Hamra village like sea, lagoon, gardening, etc.
Figure 17: - Town houses-Type “C” (Source:- Al Hamra Real Estate – RAK)

The above Figure 17 shows the DB 3D view (left side) and the architectural view (right side) of the town house. Each town house consists of 4 nos. bed rooms and 2 nos. dining and kitchen area. There are 296 nos. town houses in this phase 4 of Al Hamra village and it occupying 17,020 m² of floor areas.

The third type of the building is cluster type town houses. There are four numbers of five storey “V” shape building blocks and five numbers of four storey building blocks located in one after another. The Figure 18 below presents the DB 3D view of the Cluster type town houses. There are 640 numbers of apartments in this whole nine numbers block type Cluster type town houses and occupying 72,000 m² floor area.

Figure 18: - Cluster type Town house (Source:- Al Hamra Real Estate – RAK)

The construction materials are one of the main factors for the estimation of building cooling load. Because more than 40% of the heat gain is coming from the external walls through conduction process. The following construction materials have been proposed by the Al Hamra Real Estate for all of these buildings for their\textsuperscript{11} construction.

\textsuperscript{11} These information collected from the Al Hamra real estate managements
<table>
<thead>
<tr>
<th>Assembly</th>
<th>Layer</th>
<th>Thickness (mm)</th>
<th>U-Value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External wall</td>
<td>Cement/Plaster/Mortar</td>
<td>25</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>Concrete block (Medium)</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cement/Plaster/Mortar</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Internal wall</td>
<td>Cement/Plaster/Mortar</td>
<td>25</td>
<td>2.761</td>
</tr>
<tr>
<td></td>
<td>Concrete block (Medium)</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cement/Plaster/Mortar</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Ground floors</td>
<td>Stone-hard stone</td>
<td>150</td>
<td>1.93</td>
</tr>
<tr>
<td></td>
<td>Concrete Reinforced</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cement/Plaster/Mortar</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ceramic/clay/tiles</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Ceiling wall</td>
<td>Wall board</td>
<td>50</td>
<td>0.844</td>
</tr>
<tr>
<td>Flat Roof</td>
<td>Concrete Reinforced</td>
<td>150</td>
<td>2.9</td>
</tr>
<tr>
<td>Pitch Roof</td>
<td>Clay tile-roofing</td>
<td>6</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>Glass fiber wool</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fiber board</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Window</td>
<td>Single plane</td>
<td>6</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Table 4: Composition of different Wall construction (Source:- Al Hamra Real Estate – RAK)

Other input data required for the building cooling load calculation such as occupancy rate, fresh air requirements, window to wall area ratio, lighting rate and the miscellaneous can be tabulated as follows,

| Occupancy (4 people per standard studio type) | 0.1 People/m² |
| Fresh air supply | 8 l/s (ASHRAE standard 90.1) |
| Lighting         | 10 W/m² - 100 lux              |
| Catering         | 5 W/m²                          |
| Miscellaneous    | 5 W/m²                          |
| Window to wall ratio | 20%                             |

Table 5: Activity data (Source: Al Hamra Real Estate – RAK)

---

12 This is a common type of apartment in phase-4 of Al Hamra Village. The bed room, kitchen and the dining area are located in one common area.
4.2 Calculating of the building Cooling Load

The last step in determining the building cooling load is the specification of the indoor design conditions. With reference to the ASHRAE thermal comfort zone shown in the Figure 19. The research sets following indoor design conditions.

Indoor dry Bulb Temperature : - 23 °C ± 1°C
Indoor Relative humidity : 55%RH ± 5%

Figure 19 :-ASHRAE thermal comfort zone (ASHRAE fundamentals -2004)

As described previously, DB is used for cooling load calculations. Buildings are modeled by DB and export the results to TRNBuilt\textsuperscript{13} which is the multi-zone building model (Type 56) in TRNSYS. Cooling options inside the DB is used in the determination of the cooling load.

4.2.1 Cooling load calculation: - Royal Breeze Apartment.

In Royal Breeze Apartments, there are 7 nos. block type (Block No.8 to 14) of buildings located in pyramid shape. Each blocks having almost same floor layout. The cooling loads of the blocks are varying due to their different orientation. The below Table 6 summaries the simulation results of cooling load by using Design Builder software.

\textsuperscript{13} TRNBuilt creates .bui file which describes the building in all aspects and this file is necessary for the type56 in TRNSYS.
<table>
<thead>
<tr>
<th>Block No</th>
<th>Cooling Load kW/Floor</th>
<th>No. of Floors</th>
<th>Total Cooling-kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>212</td>
<td>8</td>
<td>1696</td>
</tr>
<tr>
<td>9</td>
<td>222</td>
<td>14</td>
<td>3108</td>
</tr>
<tr>
<td>10</td>
<td>212</td>
<td>14</td>
<td>2968</td>
</tr>
<tr>
<td>11</td>
<td>214</td>
<td>20</td>
<td>4280</td>
</tr>
<tr>
<td>12</td>
<td>222</td>
<td>14</td>
<td>3108</td>
</tr>
<tr>
<td>13</td>
<td>212</td>
<td>14</td>
<td>2968</td>
</tr>
<tr>
<td>14</td>
<td>222</td>
<td>8</td>
<td>1776</td>
</tr>
</tbody>
</table>

92 19,904

Table 6 : Cooling load of Royal Breeze Apartments

Since the entire floor layout is same for the particular block, the cooling load estimation is done for single floor and multiplied by number of floor to get the total. The following Figure 20 shows how the total cooling demand\(^{14}\) is varying in the design day. According to the weather analysis 15th of July is considered as worst outdoor conditions\(^{15}\) day or the design day. The cooling demand is calculated according to the weather data of the design day. All further calculation regarding selection and sizing of different components are based on the peak cooling demand.

Figure 20 :- Typical Cooling load variation of a floor in block-8 on design day (Simulation results from DB)

As mentioned in Table 6, the total cooling demand of the 7 numbers of block type royal breeze apartments is 19.9 MW\(_{cooling}\).

---

\(^{14}\) Total cooling load is the summation of Sensible and the latent cooling load using Design Builder Software.

\(^{15}\) Peak temperature (Dry Bulb) day is considered as worst day of the year or design day.
4.2.2 Cooling load calculation: - Cluster type Town houses.

In cluster type Town houses, there are 9 numbers of block type (Block Type 1 & 2) of buildings located in two blocks facing each other. Each is having same floor layout\(^b\). The cooling loads of these two types of blocks are varying due to their different orientation. The below Table 7 summaries the simulation results of cooling load by using DB software.

Table 7: Cooling load of Cluster Type Town houses.

<table>
<thead>
<tr>
<th>Block No</th>
<th>Cooling Load /Floor</th>
<th>No. of Floors</th>
<th>Cooling load/block</th>
<th>No of Blocks</th>
<th>Total Cooling-kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster Block-1 Type</td>
<td>336</td>
<td>5</td>
<td>1680</td>
<td>4</td>
<td>6720</td>
</tr>
<tr>
<td>Cluster Block-2 Type</td>
<td>338</td>
<td>4</td>
<td>1352</td>
<td>5</td>
<td>6760</td>
</tr>
</tbody>
</table>

As the entire floor layout is same for a particular block, the cooling load has been calculated for one floor for the particular block and multiplied with number of floor to get the total cooling load. The following Figure 21 shows how the total cooling demand and the heat balance is varying on a typical floor of Cluster type town house on design day.

According to the Table 7, total cooling demand of the cluster type town houses is 13.4 MW\(_{cooling}\).

\(^b\) This information was taken from the Al Hamra real estate company which is responsible for the construction.
4.2.3 **Cooling load calculation: - Town houses-Type “C”**

Type “C” town house is a two storey building having two blocks attached with each other. These town houses are categorized according to their orientation which is North-West and West. The below Table 8 summaries the simulation results of cooling load by using Design Builder software.

<table>
<thead>
<tr>
<th>Block No</th>
<th>Cooling Load - kW</th>
<th>No. of Town houses</th>
<th>Total Cooling - kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Town houses-NW</td>
<td>90</td>
<td>26</td>
<td>2340</td>
</tr>
<tr>
<td>Town houses-W</td>
<td>92</td>
<td>11</td>
<td>1012</td>
</tr>
</tbody>
</table>

The arrangement of all the town houses are similar therefore the cooling load has been calculated for the two types of town houses which are North-West oriented and west oriented. The following Figure 22 shows how the total cooling demand and the heat balance is varying on a Town house (West oriented) on design day.

![Figure 22: Typical Cooling load variation on Type “C” Town house (West) (Simulation results from DB)](image)

According to the **Table 8**, the total cooling demand of the Type “C” Town houses is 3.3 MW cooling.
The total cooling demand of the phase-4 Al Hamra village is 37 MW\textsubscript{cooling}. This cooling load is the summation of Royal breeze apartment, Cluster type Town houses and Type “C” Town houses cooling load. The following Figure 23 shows the total cooling load distribution among above buildings.

\textbf{Cooling load distribution-Phase 4 - Al Hamra village}

- Royal Breeze apartment (19.9 MW) 54%
- Cluster type Town houses (13.5 MW) 37%
- Town houses type "C" (3.35 MW) 9%

Figure 23: Total cooling load distribution of phase -4 of al Hamra village
5. DESIGNING OF SOLAR ASSISTED DISTRICT COOLING SYSTEM

In this chapter, design of an integrated model of the solar assisted absorption cooling system is investigated in detail. Actually there is a limited experience and knowledge in planning solar cooling system, and there is no standard or complete guideline available for whole system designing. In this study both single effect and double effect has been analyzed separately in order to identify the best configuration. In each case solar cooling system is hybrid with water cooled vapor compression chillers in order to reduce the solar fraction (SF). Both fresh water and sea water condenser heat rejection technology options are considered for each configuration. The total system analysis can be summarized as follows:

![Diagram of Solar Assisted District Cooling System]

- Single effect Absorption + Water cooled vapor compression chillers
  - 100% SF
    - Fresh water CC
    - Sea water CC
  - 80% SF
    - Fresh water CC
    - Sea water CC
  - 60% SF
    - Fresh water CC
    - Sea water CC
  - 40% SF
    - Fresh water CC
    - Sea water CC
  - 20% SF
    - Fresh water CC
    - Sea water CC
  - Day-Sol
    - Fresh water CC
    - Sea water CC

- Double effect Absorption + Water cooled vapor compression chillers
  - 100% SF
    - Fresh water CC
    - Sea water CC
  - 80% SF
    - Fresh water CC
    - Sea water CC
  - 60% SF
    - Fresh water CC
    - Sea water CC
  - 40% SF
    - Fresh water CC
    - Sea water CC
  - 20% SF
    - Fresh water CC
    - Sea water CC

- 100% Water cooled vapor compression chillers
  - Fresh water CC
  - Sea water CC

SF: - Solar Fraction
Day-Sol: - Day time solar cooling only

---

17 Water cooled vapor compression chillers has higher COP (5) compared to the Air cooled vapor compression Chillers (COP-2.4).
18 In every case sea water(Direct and Indirect) is used for the condenser heat rejection due to high cost of portable water
Solar Fraction

The solar fraction (SF) can be defined as follows.\(\text{(A.Syed,G.G.Maidment,R.M.Tozer,J.F. Missenden., 2002)}\)

\[
\text{Solar Fraction} = \frac{Q_{\text{cooling demand meet by solar cooling}}}{Q_{\text{cooling demand meet by solar cooling}} + Q_{\text{cooling demand meet by electric cooling}}}
\]

Equation 2

Both single effect and double effect solar assisted district cooling system, different solar fractions were considered for the analysis. The following Figure 24 shows how to meet the cooling demand\(^{19}\) with different solar fraction.

\(^{19}\) This is the cooling demand on design day
5.1 Designing of Solar assisted district cooling system with single effect/Double effect Absorption chillers

Solar cooling system design starts with the fundamental decision about the solar energy fraction to be considered in the proposed design. As described earlier the SF is the ratio of solar energy used in the whole system divided by the total energy requirement of the solar cooling plant. In this research there are six configurations considered with the following SF.

- 100 % SF Solar cooling system
- 80 % SF solar assisted cooling system
- 60% SF solar assisted cooling system
- 40 % SF solar assisted cooling system
- 20% SF solar assisted cooling system
- Day time only solar assisted cooling system

100% SF cooling system is self sufficient system. In other words all the required heat for a chiller cooling system is extracted from the sun. In this system cooling load and solar gain should be very well synchronized in this system.

80% to 20% SF solar assisted cooling systems are used to reduce conventional energy by using solar energy. These systems use backup system to provide the required amount of cooling energy. The backup system consists of water cooled vapor compression chillers.

Apart from above six cases, total cooling demand can also be met by using water cooled vapor compression chillers, this option has also considered in order to find a best solution.

5.1.1 Subsystems of the solar cooling system

There are four major subsystems in a solar cooling system (German Solar Energy Society-2005)

These are;

- Building
- Air Conditioning system(Fan Coil Units, Air Handling Units)
- Chilled –water supply circuit (Chiller, pumps, etc)
- Cooling water supply circuit ( Chiller, Fresh water Pumps, Sea water Pumps, Sea water Heat Exchangers, etc)
- Heat –Supply circuit (Solar collectors, Heat storage tank, Pumps,etc)

In the scope of the study Air Conditioning system is not considered, since this requires detailed design of the building. The other three subsystems are investigated in detail.

Building:-

Developed countries continuously improve the energy efficiency requirements of buildings by imposing strict limits on building energy usage. The most widely used standards related to the building energy performance are ASHRAE 90.2-2007 and ISO 13790.

The building used in the simulation of this study is explained in detailed in chapter 4.

---

20 Solar cooling systems always need electricity to drive pumps and auxiliary,etc. Electricity required for these systems are small compared to thermal energy used for cooling. Hence system which uses electricity from the grid can also be assumed as 100% SF Solar cooling system

21 Energy efficient design of low –rise residential buildings

22 Energy performances of buildings
Chilled water supply circuit:-

The chilled water supply circuit is primarily comprised of absorption chillers, chilled water pumps and the building load. In this research, two types of chillers are used for the analysis. These are,

- Direct sea water condenser cooling absorption chiller
- Indirect sea water (Fresh water) condenser cooling absorption chiller

The components of the above two chillers are similar, and the only difference is the way it rejects the heat from the condenser. It can be either sea water or fresh water.

The technical specification related to the chilled water circuit of the selected single effect absorption chiller is presented in Table 9 as follows; (From manufacturers technical catalogues)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Absorption chiller- Direct sea water condenser cooling</th>
<th>Absorption chiller- Indirect sea water(Fresh water) condenser cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling Capacity-kW</td>
<td>2025</td>
<td>1850</td>
</tr>
<tr>
<td>COP</td>
<td>0.63</td>
<td>0.7</td>
</tr>
<tr>
<td>Inlet Temperature-°C</td>
<td>14.5</td>
<td>14.5</td>
</tr>
<tr>
<td>Out Temperature-°C</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Flow rate-m³/hr</td>
<td>193.6</td>
<td>176.8</td>
</tr>
<tr>
<td>Fluid type</td>
<td>Water</td>
<td>Water</td>
</tr>
</tbody>
</table>

Cooling water supply circuit:-

In the cooling water supply circuit, there are different components in these two types of chillers, which are as follows;

Direct sea water condenser cooling absorption chiller: - It primarily consists of absorption chiller and sea water pumps as shown in Figure 25

Figure 25 :- Direct sea water condenser cooling absorption chiller cooling water supply circuit (TRNSYS model)
Indirect sea water (Fresh water) condenser cooling: absorption chiller - It primarily consists of absorption chiller, fresh water pump, sea water heat exchanger and sea water pumps as shown in Figure 26.

![Diagram of an absorption chiller system](image)

**Figure 26**: Indirect sea water condenser cooling absorption chiller cooling water supply circuit (TRNSYS model)

The technical specification related to the cooling water circuit of the selected single effect absorption chiller is presented in Table 10 as follows (From manufacturers technical catalogues).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Absorption chiller- Direct sea water condenser cooling</th>
<th>Absorption chiller- Indirect sea water(Fresh water) condenser cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling Capacity-kW</td>
<td>2025</td>
<td>1850</td>
</tr>
<tr>
<td>COP</td>
<td>0.63</td>
<td>0.7</td>
</tr>
<tr>
<td>Inlet Temperature-°C</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Out Temperature-°C</td>
<td>40.6</td>
<td>40.6</td>
</tr>
<tr>
<td>Flow rate-m³/hr</td>
<td>809.6</td>
<td>694.2</td>
</tr>
</tbody>
</table>

**Heat supply circuit:-**

The heat supply circuit is primarily comprised of the solar collector field, hot storage tank and circulation pumps. Among these, the solar collector area and type has an important effect in terms of economics and performances of the solar cooling system. Selection of the collector type depends on the driving temperature of the chiller. Since solar collector efficiency should be at least 50-60% for any solar application, collector efficiency curves should be utilized in order to calculate the collector area required to meet the thermal energy of the chiller (Soteris A.Kalogirou, 2004)

The driving temperature and the other technical specification of the selected single effect absorption chiller as presented in Table 11.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Absorption chiller- Direct sea water condenser cooling</th>
<th>Absorption chiller- Indirect sea water(Fresh water) condenser cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling Capacity-kW</td>
<td>2025</td>
<td>1850</td>
</tr>
<tr>
<td>COP</td>
<td>0.63</td>
<td>0.7</td>
</tr>
<tr>
<td>Inlet Temperature-°C</td>
<td>105</td>
<td>105</td>
</tr>
<tr>
<td>Out Temperature-°C</td>
<td>95</td>
<td>95</td>
</tr>
<tr>
<td>Flow rate-m³/hr</td>
<td>275.3</td>
<td>226.3</td>
</tr>
</tbody>
</table>

38
In this research compound parabolic concentrated (CPC) collector is used as it is capable to deliver high outlet temperature and the low initial cost. The below shows Figure 27, how the power output per collector is varying with the collector outlet temperature.

![Graph showing power output per collector vs collector outlet temperature.](image)

Figure 27: Performance of CPC collector (Source: Manufactures technical catalogues)

Hot water storage tank is the other key element in the heat supply circuit. The main functions of the hot storage are as follows:

- Decouples the solar collector field (heat source) and chiller (heat sink)
- Stores heat from fluctuating source for night time operation
- Reduce energy losses by stratification
5.1.2 TRNSYS Model of Solar assisted district cooling system with single effect absorption chillers

Solar assisted district cooling system model is developed in TRNSYS platform.

TRNSYS components used in the Model:-

Following are the short description of the important component used in the TRNSYS model. The detail explanation of the each items is explained in TRNSYS user manual\textsuperscript{23}(S.A.Klein-.,TRNSYS 16)

Weather data-Type 109:-This component reads weather data at regular intervals from the data file\textsuperscript{24}, converting it to a desired system of units and processing the solar radiation data to obtain tiled surface radiation and angle of incidence for an arbitrary numbers. (S.A.Klein-.,TRNSYS 16)

Psychometrics-Type 33:-This component takes as input the dry bulb temperature and dew point temperature of the moist air and calls the TRNSYS psychometric routine, returning the following corresponding moist air properties: dry bulb, dew point, wet bulb temperatures, relative humidity, absolute humidity ratio and enthalpy (S.A.Klein-.,TRNSYS 16)

Sky Temperature -Type 69:-This component determines an effective sky temperature, which is used to calculate the long-wave radiation exchange between arbitrary external surface and the atmosphere(S.A.Klein-.,TRNSYS 16)

Pumps –Type 3b:-This pump model computes a mass flow rate using a variable control function, which must have a value between 1 and 0 , and a fixed maximum flow rate(S.A.Klein-.,TRNSYS 16)

Building–Type 56:-This component models the thermal behavior of the building(S.A.Klein-.,TRNSYS 16)

Loads (FCUs/AHUs)–Type 682:-In simulating and HVAC system, the cooling loads on the building have been determined, either by measurement or through the use of another simulation program and yet the simulation task at hand is to simulate the effect of these loads upon the system. This component allows for there to be an interaction between such pre-calculated loads and the HVAC system by imposing load upon a liquid flowing through a device (S.A.Klein-.,TRNSYS 16)

Compound Parabolic Concentrated Collectors (CPC)–Type 74:-This component models the thermal performances of the CPC Collectors. This collector consists of a concentrating reflectors and absorber (S.A.Klein-.,TRNSYS 16)

Hot water storage -Type 4b:- This component models a fluid-filled, constant volume storage tank with immersed heat exchangers (S.A.Klein-.,TRNSYS 16)

Heat Exchanger –Type 5e – In this component zero capacitance sensible heat exchanger is modeled. This is the cross flow heat exchanger with both hot and cold side unmixed (S.A.Klein-.,TRNSYS 16)

Single effect hot water fired absorption chiller –Type 680 – In this component model a single effect absorption chiller."Hot Water Fired" indicates that the energy supplied to the machine's generator comes from a hot water stream (S.A.Klein-.,TRNSYS 16)

\textsuperscript{23} TRNSYS User Manual-Mathematical Reference –Volume 5
\textsuperscript{24} TMY data file RAK
Modeling of the Single effect hot water fired absorption chiller in TRNSYS as follows;

**Amount of energy that must be removed from the chilled water stream**:

\[ Q_{\text{remove}} = \dot{m}_{\text{chw}} C_{p_{\text{chw}}} (T_{\text{chw,in}} - T_{\text{chw,set}}) \]  

**Equation 3**

Where;
- \( Q_{\text{remove}} \) = Amount of energy that must be removed from the chilled water stream in order to reach the set point temperature-KJ/hr
- \( \dot{m}_{\text{chw}} \) = Mass flow rate of the ‘chilled water’ stream fluid -kg/hr
- \( C_{p_{\text{chw}}} \) = Specific heat of the “chilled water” stream fluid –KJ/kg.K
- \( T_{\text{chw,in}} \) = Temperature of fluid inlet “chilled water” stream –\(^\circ\)C
- \( T_{\text{chw,set}} \) = Set temperature of fluid “chilled water” stream –\(^\circ\)C

**Amount of energy removed from the hot water stream**:

\[ Q_{\text{hw}} = \frac{\text{Capacity}_{\text{Rated}}}{\text{COP}_{\text{Rated}}} \]  

**Equation 4**

Where;
- \( Q_{\text{hw}} \) = Energy removed from the “hot water”-KJ/hr
- \( \text{Capacity}_{\text{Rated}} \) = Rated cooling capacity of the Chiller-KJ/hr
- \( \text{COP}_{\text{Rated}} \) = Chiller rated Coefficient of Performances

**Energy added to the “cooling water” stream**:

\[ Q_{\text{cw}} = Q_{\text{chw}} + Q_{\text{hw}} + Q_{\text{aux}} \]  

**Equation 5**

- \( Q_{\text{cw}} \) = Energy added to the “cooling water” stream-KJ/hr
- \( Q_{\text{chw}} \) = Energy removed from the “chilled water” stream-KJ/hr
- \( Q_{\text{hw}} \) = Energy removed from the “hot water”-KJ/hr
- \( Q_{\text{aux}} \) = Energy draw of parasitic (solution pumps, controls, etc) KJ/hr

**Total system Coefficient of Performances**

\[ \text{COP} = \frac{Q_{\text{chw}}}{Q_{\text{aux}} + Q_{\text{hw}}} \]  

**Equation 6**
6. POSSIBILITY OF INSTALLING SOLAR THERMAL COLLECTORS ON THE SEA

After the analysis of solar thermal collector installation location, there are only possible two places which are 1 Km away from the Al Hamra village area (Desert area) and other one is on the sea. The below Table 12 justified the reasons for rejecting other possible locations.

<table>
<thead>
<tr>
<th>Location</th>
<th>Space availability - For 37 MW</th>
<th>Installation possibility</th>
<th>Utilization of residences facilities</th>
<th>Architectural view</th>
<th>Remarks</th>
</tr>
</thead>
</table>
| Top of the Building             | 12%                            | slightly hard            | Yes                                 | damage             | 1. Hot water distribution heat losses  
2. Utilize roof Terence  
3. Value of the apartment could be going down |
| Lagoon area                     | 53%                            | slightly hard            | Yes                                 | damage             | 1. Deviate the Master plan of Al Hamra Village.  
2. Loss the bank area of the lagoon for the near residences.  
3. High initial cost |
| In the village premises         | 0%                             | Comfortable              | Yes                                 | No                 | Impossible                                                              |
| In the sea                      | 100%                           | slightly hard            | No                                  | No                 | High initial cost                                                       |
| Distance away from the Al Hamra Village-1Km | 100%                           | Comfortable              | No                                  | No                 | 1. Water distribution losses.  
2. High initial cost (piping) |

This chapter is mainly dedicated to explain the possible design of the solar thermal collector installation on the sea. The following explain main three designs from three different manufacturers.

Figure 28 shows the design of the solar thermal collector platform on the sea from Supplier #1. It consists of two options. The design proposal is such that two options differ from each other by how the collector is fixed on the platform. Option #1 has less number of floating docks and each floating dock is brazed mild steel channel. Option #2 has individually attached floating docks such that it does not require any brazing.

Option #1

Option #2

Figure 28 : Design of Solar thermal collector installation on the sea – Supplier #1
Figure 29 shows the design of the solar thermal collector platform on the sea from Supplier #2. The design is such that it uses less number of floating docks with wooden brazed platform.

![Figure 29: Design of Solar thermal collector installation on the sea – Supplier #2](image)

Figure 29 shows the design of the solar thermal collector platform from the supplier #3, whereby collectors floats on adjoining floating docks with mild steel brazing channel platform.

![Figure 30: Design of Solar thermal collector installation on the sea – Supplier #3](image)

The below Table 13 shows positive and negative impact of solar thermal collector installation of 1 km away from the Al Hamra village and on the sea.

**Table 13: Positive and negative impact of solar thermal collector installation locations**

<table>
<thead>
<tr>
<th>Location</th>
<th>Positive impact</th>
<th>Negative impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance away from the Al Hamra Village-1Km</td>
<td>Easy to install comparing to sea.</td>
<td>Considerable cost for insulated hot water (Around 1km), Considerable temperature drop and collector performances will be drop due to dust.</td>
</tr>
<tr>
<td>On the sea</td>
<td>Less cost for insulated hot water pipes and due to this less temperature drop. The performances of the solar thermal collectors will increase due to less dust on the sea.</td>
<td>Hard to install solar thermal collectors on the sea and also hard to for maintenance.</td>
</tr>
</tbody>
</table>
The following Figure 31 shows the cost variation of the land area (Desert area 1 km away from the Al Hamra village) and the floating docks platform. Land cost shows the lowest cost among these with considering the 2% inflation for 25 years. Supplier #1-option #1 shows the lowest cost of floating dock platform among the floating dock platform suppliers.

Figure 31: Cost variation of land area and floating docks

Therefore to identify and decide on the best solution among above mentioned options, it has been decided to analyze further among two best solutions from above viz: land installation and installation on sea with supplier #1- option #1 proposed system. This will be explained in detail in economical analysis chapter.
7. ECONOMICAL ANALYSIS

Conventional vapor compression cooling system\(^{25}\) is the main competitor of the solar thermal cooling system. Nowadays it is commonly accepted that none of the solar thermal powered cooling plants are cost competitive with conventional vapor compression plants, because the main investment cost in the solar thermal cooling plants is the solar energy collection, land and conversion equipments’ cost (i.e. solar collector cost) (Syed, Maidment, Tozer & Missenden, 2002).

In the solar assisted cooling system, solar collector cost is between 50 to 80% of the overall system cost and is strongly dependent on the operating temperature of the solar thermal driven chiller. Cooling systems with chillers which are driven with low grade temperatures are more economical (Syed et al, 2002). However increasing fossil fuel prices, decreasing solar collector prices and technical improvement of the solar collectors favor the proliferation of solar thermal cooling plants installation in near future. Apart from that there are indirect benefits of the solar thermal cooling plant installations like electricity peak demand reduction and green house gas emission mitigation and these indirect benefits also have an economical value, but for now they do not have direct effect on solar thermal cooling plant users in most of the countries. Some governments in the world, especially developing countries, support financially like subsidies and incentives to install solar thermal cooling plants. The Kyoto protocol is the main driving force which put government in action in supporting solar thermal technologies.

There are many studies related to the economics and feasibility of the solar thermal cooling technologies that are compared with each other and with conventional vapor compression technologies. (Syed et al 2002)(Elsafty & Al-Daini, 2001)(Tsoutsos, Anagnostou, Pritchard, Karagiorgas, 2003) and (Casals, 2006)

In this chapter, investment cost, operational cost, life cycle costs (LLC), average levelized cost, payback period and environmental impact analysis of the solar thermal and conventional cooling system are compared. Solar thermal systems have been analyzed by considering different solar cooling technologies like single effect and double effect Chillers.

7.1 Cost

An initial estimate of the costs has been computed in order to determine the economical feasibility of the proposed system. The cost presented in this study produce a very good estimate of the investment costs and operating cost Eq. 1 shows that the total cost of system consist of three main variables, namely the initial cost, the operating cost and finally the maintenance cost;

\[
\text{Total Cost} = \text{Investment Cost} + \text{Operating Cost} + \text{Maintenance Cost}
\]

Equation 7

Investment cost of the solar thermal cooling system includes cost of components such as collectors, chillers (Single effect and Double effect), storage tank, heat rejection equipments, pumps, heat exchangers, controllers and accessories. Investment cost of the water cooled vapor compression system includes water cooled chillers, heat rejection equipments, pumps and accessories. In this study sea water has been considered for the rejection of the heat generated from vapor absorption chillers and water cooled vapor compression system. Sea water is utilized in two different technologies which are fresh water (Direct sea water) and Sea water (Indirect sea water).

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\(^{25}\) This vapor compression cooling system is mainly driven by the grid electricity.
Investment cost of the air cooled vapor compression system includes air cooled chiller, pumps and accessories. All the cost comparison has been done compared considering the air cooled vapor compression system as baseline scenario because this is the system client has already proposed to install to phase 4 of Al Hamra village.

The operating cost, which includes the cost of electricity, wages of employees, suppliers, water and materials, are those incurred by the actual operation of the system. In this cost of electricity, water and materials have been considered as operating cost. The total cost of electricity is estimated based on (operation hours) that is retrieved from the results of TRNSYS system simulation.

The maintenance cost is the final cost to be estimated for air-conditioning system. The maintenance cost is difficult to quantify because it depends on a larger number of variables such as local labor rates, their expenses, the age of the system, length of time of operation, etc. Therefore author assumed in this study, the maintenance cost is 3% of the investment cost (Ursula Eicker, 2008)

The physical size of the absorption system is larger than the size of the vapor compression system; this increase in size requires a larger building, moving equipment and support systems. This results in a higher installation cost for the vapor absorption system.

### 7.2 Economic Analysis

There are various economic comparison methods available for optimizing and evaluating the solar cooling systems. Some of these methods are Life Cycle Cost (LCC), Annual–life cycle cost (ALCC), Payback period (PB), Return on investment (ROI), (Duffie et al., 2003). LCC and PB are the mostly used methods in solar energy system economic analysis.

In this study LCC and PB methods are employed. In LCC method all the costs, investment, operational and maintenance, associated with the cooling system over its lifetime are summed.

\[
LCC = C_i + \left( C_{op} + C_M \right) \times \left( \frac{1 - (1 + d - f)^n}{(d - f)} \right)
\]

\[\text{Equation 8 (Ursula Eicker, 2008)}\]

Where:
- \(LCC\) = Life Cycle Cost (US $)
- \(C_i\) = Investment Cost (US $)
- \(C_{op}\) = Operational Cost (US $)
- \(C_M\) = Maintenance Cost (US $)
- \(d\) = Interest rate
- \(f\) = Inflation rate
- \(n\) = Life time of the system (Years)

\[
PBP = \frac{\log \left( \frac{C_i}{E + \frac{i}{100}} + 1 \right)}{\log \left( 1 + \frac{i}{100} \right)}
\]

\[\text{Equation 9 (Ursula Eicker, 2008)}\]

\[26\] The Client is Al Hamra Real Estate- RAK - UAE

\[27\] Most of the studies in the solar cooling system, maintenance cost has been taken as 2-3% of the investment cost
Where;

- \( PB \) = Payback period (Years)
- \( C \) = Investment Cost (US $)
- \( E \) = Energy saving (US $ /Year)
- \( i \) = Energy Inflation

### 7.3 Environmental Impact Analysis

#### 7.3.1 Primary Energy Analysis

Comparison of the primary energy consumptions for different configurations of solar assisted cooling system and conventional vapor compression cooling system, indicates parameter for global warming impact analysis. Solar cooling system requires back up electricity to operate its auxiliary devices and conventional vapor compression cooling system requires electricity power. The electricity is usually from the grid which is secondary energy source. In this study grid electricity is assumed to be generated by natural gas plant\(^28\). Yearly natural gas consumption of the conventional vapor compression cooling system can be calculated using below:

\[
NG_{\text{conv}} = \frac{E_{\text{cool}}}{\eta_{\text{ng}} \cdot COP \cdot e_{\text{ng}}} \tag{Equation 10} \text{ (SyedA., Maidment G.G., Tozer R.M. 2002)}
\]

Where;

- \( NG_{\text{conv}} \) = Yearly natural gas consumption conventional cooling system (m\(^3\))
- \( E_{\text{cool}} \) = Yearly cooling demand (kW seconds)
- \( \eta_{\text{ng}} \) = Efficiency of the natural gas plant
- \( COP \) = Coefficient of performances of cooling system
- \( e_{\text{ng}} \) = Energy value of 1m\(^3\) of natural gas (i.e. 38305 kJ/m\(^3\))

Natural gas consumption of the solar cooling system can be calculated from following Eq. 2

\[
NG_{\text{sol}} = \frac{E_{\text{aux}}}{e_{\text{ng}}} \tag{Equation 11} \text{ (SyedA., Maidment G.G., Tozer R.M. 2002)}
\]

Where;

\(^28\) 70% of the total electricity supply is generated by natural gas plant(http://www.eia.gov/cabs/UAE/Full.html)
\[ NG_{sol} = \text{Yearly natural gas consumption of solar cooling system (m}^3\) \\
\[ E_{aux} = \text{Yearly auxiliary energy demand (kW seconds)} \]

### 7.3.2 Global Warming Impact Estimation

Total equivalent warming impact (TEWI) is a method for estimating direct and indirect global warming potential of equipment. The direct component relates to release of refrigerants (like HFCs) to the atmosphere whereas indirect effect is the production of carbon dioxide in powering these equipments. (Muhammad, 2009)

The concept of GWP has been developed to compare the ability of a greenhouse gas to trap heat in the atmosphere relative to the effect of carbon dioxide (CO\(_2\)) and varies depending on the time frame considered (Usually a 100 years period) (Muhammad, 2009)

\[ \text{TEWI} = \text{Direct global warming potential} + \text{Indirect global warming potential} \]

**Direct global warming potential** = \((\text{GWP} \times L \times n) + (\text{GWP} \times m \times (1-\alpha))\)  
Equation 12 (Muhammad, 2009)

Where 
- \(L\) = Leakage rate per year, kg 
- \(n\) = System operating time, years 
- \(m\) = Refrigerant charge in the system, kg 
- \(\alpha\) = Recycling factor

**Indirect global warming potential** = \(n \times E_{annual} \times \beta\)  
Equation 13 (Muhammad, 2009)

Where 
- \(n\) = System operating time, years 
- \(E_{annual}\) = Energy consumption per year 
- \(\beta\) = CO\(_2\) emission per kWh energy production, kg
8. RESULTS AND DISCUSSION

8.1 Dynamic cooling load estimation

From the simulation done with the TRNSBuilt (Type 56) of TRNSYS to determine the total cooling demand of Al Hamra village under the study indicate that cooling demand is required throughout the year to maintain the comfort conditions. The TRNSYS model used in the simulation is given in below Figure 32.

Figure 32: TRNSYS model for building cooling load calculation

Figure 33 shows the simulation results of TRNSYS model where it indicates the peak cooling demand is happening on the July month which is close to 37 MW of cooling. And also results shows how the cooling demand is varying with the outdoor temperature.
Figure 33: Total cooling demand variation throughout the year (Peak cooling demand 37 MW)

The following Figure 34 shows how the cooling energy demands variation of different type of buildings. Royal Breeze apartment takes lowest cooling energy and the Type “C” Town houses takes highest cooling energy. This is because Royal Breeze apartments are multi storey building and having less external wall exposed to the sun. Therefore solar heat gain from the external wall/windows is less. But in Type “C” Town houses have more walls exposed to the sun. Therefore solar heat gain from the external walls/windows is high. Since this Type “C” Town houses two storey building, there is a considerable amount of solar heat gain coming from the roof as well.

![Cooling demand variation - W/m²](image)

Figure 34: Cooling demand variation –W/m²

8.2 Simulation of TRNSYS model

8.2.1 Simulation of TRNSYS model of solar assisted district cooling system with single effect absorption chillers

The below Figure 35 shows the TRNSYS model of single effect hot water fired absorption chiller system with fresh water condenser cooling. All the components of this TRNSYS model has explain in detail in chapter 5. The single effect hot water fired absorption chiller mainly consist of chilled water circuit , hot water circuit and cooling water circuit. Hot water circuit is main input to chiller for continues operation. Hot water is generated from the solar thermal collectors with controllers and accessories. Cooling water is also use as input which reject heat generated from chiller. The chilled water circuit is main output of the chiller and this generated chilled water is circulates through AHUs/FCUs (loads) in order to produce cooling effect.
Figure 35: TRNSYS Model- Single effect hot water fired absorption chiller system fresh water condenser cooling
The following Figure 36 and Figure 37 show the simulation results of the TRNSYS model.

Figure 36 represents the variation of the chiller COP against cooling demand. This figure indicates how the chiller COP is varying with the total cooling demand. This simulation result is very important because it implies that the selected chiller is capable enough or not to meet the cooling demand throughout the year.

Figure 37 shows the solar thermal collector outlet temperature variation against solar irradiation and ambient temperature. From the above Figure 36 and Figure 37, it can be concluded that the chiller is operating at its higher COP levels when the solar thermal collector outlet temperature is above 105°C, indicating that the chiller design and selected parameters are explained in detail in chapter 5.

The below Figure 38 shows the same above configuration of Figure 35 TRNSYS model, but only the cooling water circuit is different. Figure 35 TRNSYS model has a cooling water circuit with fresh water condenser cooling, while Figure 38 TRNSYS model has a cooling water circuit with seawater condenser cooling.
Figure 38: TRNSYS Model - Single effect hot water fired absorption chiller system direct sea water condenser cooling
The following Figure 39 shows the simulation results of TRNSYS model explained in Figure 38. In this results clearly conclude that COP of this model has dropped (0.63) compared to the TRNSYS model explained in Figure 35 this is due to usage of sea water. Sea water condenser cooling absorption chiller has low COP compare to the fresh water condenser cooling chillers. This is because construction of sea water condenser is Titanium (heavy duty) to sustain sea water scaling.

![Figure 39: Chiller COP variation against cooling demand](image)

8.2.2 **Simulation of TRNSYS model of solar assisted district cooling system with double effect absorption chillers**

The components of the TRNSYS Model with double effect absorption chiller system are almost same as single effect absorption chiller system except chiller and steam supply circuit. Type 676 is the double effect steam fired chiller and steam generator is placed to generate required rate of steam for chiller. In the heat generation side 220 °C heated oil has circulated to generated steam. Below Figure 40 shows the total components of the TRNSYS model with double effect steam fired absorption chiller system with fresh water as condenser cooling. Details of each component have explained in chapter 5.
Figure 40: TRNSYS Model- Double effect steam fired absorption chiller system fresh water condenser cooling
The below Figure 41 shows the simulation results of above TRNSYS model. This shows the COP variation with cooling demand throughout the year. The COP is varying from 0.6 to 1.4 to meet the dynamic cooling demand.

Figure 41 :- Chiller (2E) COP variation against cooling demand

The below Figure 42 shows solar thermal collector outlet temperature is varying with solar irradiation and ambient temperature. From the Figure 41 and Figure 42 conclude that chiller is operating its higher COP levels when the solar thermal collector outlet oil temperature is above 220 °C that is the chiller design and selected parameters which are explained detail in chapter 5.

Figure 42 :- Solar collector outlet temperature variation against Solar Irradiation

The Figure 43 below shows the same above configuration of Figure 40 TRNSYS model and only different is the cooling water circuit. Figure 40 TRNSYS model has cooling water circuit with fresh water condenser cooling and the Figure 43 TRNSYS model has cooling water circuit with sea water condenser cooling.
Figure 43: Chiller (2E) COP variation against cooling demand
The below Figure 44 shows the simulation results of above TRNSYS model. This shows the COP variation with cooling demand throughout the year. The COP is varying from 0.6 to 1.2 to meet the dynamic cooling demand. In this system configuration COP has dropped compared to the TRNSYS model explained in Figure 40 due to usage of sea water.

Figure 44 :- Chiller (2E) COP variation against cooling demand

The below Figure 45 shows the solar irradiation variation against the cooling demand of the design day on 15th of July. All the design calculation and equipment selection is base on according to this. In APPENDIX A-1 to A-4 shows the results of solar cooling system equipment selection and designing in different configuration which are explained in chapter 5.

Figure 45 :- Solar irradiation variation against cooling demand on design day (15th of July)
8.3 Economical analysis

As described in chapter five under the topic of designing of solar assisted district cooling system, basically there are three main systems to be analyzed. That is single effect absorption chillers with water cooled vapor compression chillers, double effect absorption chillers with water cooled vapor compression chillers and water cooled vapor compression chillers system. These three proposed systems are compared with conventional air cooled vapor compression chiller system to identify the best techno-economical system. The following section explains how the above economical parameters are varying in different configurations.

8.3.1 Single effect absorption Chiller with water cooled vapor compression chiller system configurations

The following Figure 46 shows the LCC variation of different configuration of solar cooling system with single effect absorption chillers and water cooled vapor compression chillers. In this graph X-axis stands for different solar fraction and Y-Axis stands for LCC.

In the calculation of LCC;

Investment Cost (IC):- Investment cost has been obtained after the designing the solar assisted cooling system (In different configurations). The cost is estimated based on offers received from suppliers, and called quotation from suppliers.

Operational Cost (C_op):- Operational cost has been obtained from the results of simulation of different configuration of solar assisted cooling system using TRNSYS software.

Maintenance Cost (C_m):- Maintenance cost has been assumed 3% of the investment cost.

Interest rate (d):- Interest rate taken as 6% (A. Al- Alili, M.D. Islam, I.Kubo,Y.Hwang,2010)

Inflation rate (f):- Inflation rate taken as 3% (A. Al- Alili, M.D. Islam, 2010)

Life time of the system (n):- Life time of the system is taken as 25 years.

Water cooled vapor compression chillers act here as backup system. Because this system has higher COP next to the existing air cooled vapor compression chiller system.
Figure 46: Variation of LCC of different configurations – with land cost

Figure 46 shows variation of LCC of different configurations considering land cost as part of the investment cost. Considering the solar assisted cooling system, 100% SF solar cooling system has highest life cycle cost which is around 500 million US$ and 20% SF solar cooling system has lowest life cycle cost which is around 150 million US$. In between SFs solar cooling systems are gradually decreases except 50% SF solar cooling system. 50% SF solar cooling system shows considerable low life cycle cost since its low investment cost. Therefore considering the above scenarios, 50% SF with fresh water condenser cooling is the economically best among the solar cooling system.

Cooling system with water cooled vapor compression chiller and cooling system with air cooled vapor compression chiller have lowest life cycle cost which is below 90 million US$. This evaluation is done to compare the with the solar cooling system.

The below Figure 47 presents the variation of life cycle cost without considering the land cost as part of the investment cost. In this figure is also concluded that the 50% SF solar cooling system is the economically best solution among the solar cooling system. The life cycle cost of the 50 SF solar cooling system has dropped by around 50 million US$ since land cost has not been considered.

Figure 47: Variation of LCC of different configurations – without land cost
The below Figure 48 shows the average levelized cost of cooling energy variation in different cooling configurations considering the land cost as part of the investment cost. This graph implies that solar assisted cooling system has higher average levelized cost of cooling energy compare to other cooling system. 100 % SF solar cooling system has highest average levelized cost and 20 % SF solar cooling system has lowest average levelized cost among the solar cooling system. In between SFs shows gradually decrement of average levelized cost. But the 50 % SF solar cooling system significant low economical average levelized cost among solar cooling systems. Because this 50 % SF solar cooling system has low investment cost.

Water cooled and air cooled vapor compression system has lowest average levelized cost of cooling energy out of all configurations. Since objective of this study is solar assisted cooling system, detail analysis of this water cooled and air cooled system are not considered. This is only for comparison.

![Figure 48](image1.png)

The below Figure 49 presents the variation of average levelized cost without considering the land cost as part of the investment cost. In this figure is also concluded that the 50 % SF solar cooling system is the economically best solution since it has comparatively low average levelized cost.

![Figure 49](image2.png)
The below Figure 50 shows the variation of payback period of the different cooling configurations systems considering land cost for the investment cost. There are two graphs in same figure which represent one for sea water condenser cooling and other one for fresh water condenser cooling system. 50 % solar fraction system has lowest payback period among the solar assisted cooling system this is because it has comparably low investment cost and low operational cost. Cooling system with water cooled vapor compression system has lowest payback period among all configuration since it has lowest investment cost. All these payback periods have been calculated against the air cooled vapor compression cooling system which is the system that Al Hamra real estate (client) already proposed to install.

Figure 50 :- Variation of Payback period of different configuration –with land cost

The below Figure 51 shows the same above details but without considering the land cost for the investment cost. In this configuration also 50 % SF solar cooling system has low payback period since it has comparable low investment and operational cost. 50 % SF solar cooling system has around 15 years of payback period. From the below Figure 51 concluded that all of the configuration payback period has been dropped by around 5 years due to negligence of land cost.

Figure 51 :- Variation of Payback period of different configuration –without land cost
The Figure 52 shows the primary energy consumption and saving of the different cooling configurations. There are four columns representing under one configuration viz: primary energy consumption with fresh water as condenser cooling, primary energy saving with fresh water condenser cooling, primary energy consumption with sea water condenser cooling and primary energy saving with sea water condenser cooling. 100% solar cooling system has lowest primary energy consumption with highest primary energy saving because this system uses less natural gas to function the system. Cooling system with water cooled vapor compression system has highest primary energy consumption and lowest primary energy saving since it uses considerably high natural gas to function the system.

The following Figure 53 (On the left side axis) shows money saving (US$) per year due to saving of primary energy and on the right side of the Figure 53 shows the tons of CO$_2$ emission saved per year. 100% solar cooling system save highest money per year while maintaining the lowest CO$_2$ emission per year to the environment. Cooling system with water cooled vapor compression chiller system has lowest money saving and lowest CO$_2$ emission saving per year. There are two graphs represent on each axis for the fresh water condenser cooling and the sea water condenser cooling system.

Figure 52 :– Primary energy consumption and saving of different configuration –with land cost.

The following Figure 53 (On the left side axis) shows money saving (US$) per year due to saving of primary energy and on the right side of the Figure 53 shows the tons of CO$_2$ emission saved per year. 100% solar cooling system save highest money per year while maintaining the lowest CO$_2$ emission per year to the environment. Cooling system with water cooled vapor compression chiller system has lowest money saving and lowest CO$_2$ emission saving per year. There are two graphs represent on each axis for the fresh water condenser cooling and the sea water condenser cooling system.
Figure 53: Money saving and tons of CO₂ emission saving of different configuration—without land cost

8.3.2 Double effect absorption Chiller with water cooled vapor compression chiller system configurations

Under this topic explained how the above parameters which has been explained in earlier topic, varying with double effect absorption chillers. The parameters like variation of LCC, variation of levelized cost of cooling energy, variation of payback period, primary energy consumption and saving and money saving and tons of CO₂ emission saving shows the same pattern (as shown in figures 54 to 61) of the above on the following figures with different values. Therefore each and every figures on the following has not been explained individually.

From this analysis can conclude that there is no significant different of the above mentioned parameters in between single effect and double effect absorption chiller system. This is because single effect chiller system has low investment cost compared to the double effect absorption chiller system. Though double effect absorption chillers has higher COP compared to the single effect absorption chillers due to its system complexity it finally gives a high investment cost compared to the single effect absorption chiller.

---

30 Single effect absorption chillers with water cooled vapor compression chiller system configuration.
Figure 54: Variation of LCC of different configuration—with land cost

Figure 55: Variation of LCC of different configuration—without land cost
Figure 56: Variation of levelized cost of cooling energy of different configuration—with land cost

Figure 57: Variation of levelized cost of cooling energy of different configuration—without land cost
Figure 58: Variation of payback period of different configuration—with land cost

Figure 59: Variation of payback period of different configuration—without land cost
Figure 60: Primary energy consumption and saving of different configuration – with land cost

Figure 61: Money saving and tons of CO₂ emission saving of different configuration – without land cost
8.3.3 **Investment Cost Analysis-With Single effect Absorption chiller system**

The investment cost is the initial cost of the equipment to make the required system configuration. The distribution of the investment cost of each system configuration has been showed in the APPENDIX A1 to A-4 in detail. The following selected figures explain how the investment cost is distributed among different components.

The Figure 62 shows the investment cost distribution of 50% of SF solar cooling system with single effect absorption chiller system with fresh water condenser cooling with considering the land cost to accommodate the equipments. The total investment cost for this system is US $ 141,956,994.00. Figure 62 implies that cost of land (38% of the total investment) and the cost of solar collectors (22% of the total investment cost) have considerably portion of the total investment cost. Therefore author decided to do the cost analysis for the same configuration without considering the land cost to identify the most feasible and economical solution.

![Figure 62](image)

**Investment cost distribution for different items-50% of solar fraction-Fresh water condenser cooling-With land cost**

The following Figure 63 shows the same above graph but without considering the land cost for accommodating the equipments. Because author assumes the land cost could be covered from the government subsidies as promotion of sustainable energy. The total investment cost for this system is US $ 88,060,788.00.

![Figure 63](image)

**Investment cost distribution for different items-50% of solar fraction-Fresh water condenser cooling-Without land cost**

31 These are selected from the results and discussion chapter.
The below Figure 64 indicates the investment cost distribution of the single effect absorption chiller system with 50% of solar fraction with sea water condenser cooling and also considering the land cost for the accommodate the all equipment. The total investment cost for this configuration is US $ 142,229,100.00.

The following Figure 65 indicates the same above graph but without considering the land cost for the accommodating the equipments. Because it has been assumed that the land cost could be covered from the government subsidies as promotion of sustainable energy. The total investment cost for this system is US $ 82,647,214.00. It can be inferred from the results that government subsidies is a must to promote the sustainable energy technologies for the district cooling system because land requires the 40% of the total investment cost.

The following Figure 66 indicates the investment cost distribution of the system with single effect absorption chiller system with fresh water condenser cooling. In this system is analyzed considering solar collators are installed on the sea. The aim of this configuration analysis is identify the possibility to installed solar thermal collectors on the sea to reduce the investment cost of the land area. The detail analysis of the possibility to installed solar thermal collectors on the sea has been explained in chapter 6. The small fraction (3%) of the land is needed to accommodate the other equipment like chillers, pumps, heat exchangers, etc. The total investment cost for this configuration is US $ 131,850,028.00. This system save around 10 million US$ compared to the solar thermal collector installed on the land.
Figure 66: Investment cost - 50% solar fraction - Fresh water condenser cooling – Collector installation on the sea (SEABC)

The below Figure 67 explain the same above graph with sea water condenser cooling system. The total investment cost for this configuration is US $ 130,999,035.00. This system save around 12 million US$ compared to the solar thermal collector installed on the land.

Figure 67: Investment cost - 50% solar fraction - Sea water condenser cooling – Collector installation on the sea (SEABC)
8.3.4 Investment Cost Analysis-With Double effect Absorption chiller system

In this section explain the investment cost distribution of the configuration with 50% of solar fraction with double effect absorption chiller system. This 50% of solar fraction is selected because of this the most economic solar fraction among the others. The following Figure 68 shows the investment cost distribution of the system, 50% of solar fraction double effect absorption chiller with fresh water condenser cooling with considering the land cost to accommodate the equipment. The total investment cost for this system is US $127,929,056.00. In this system land cost contribution for the total investment cost is low compared to the single effect absorption chiller system since high cost of solar thermal collectors. In this system has used PTC type solar thermal collectors which are comparably high cost than compound parabolic type solar thermal collectors.

Figure 68: Investment cost - 50% solar fraction-Fresh water condenser cooling with land cost (DEABC)

The below Figure 69 indicate the same above graph but without considering the land cost to accommodate the equipment. The total investment cost for this system is US $90,431,997.00. Here it concluded that land cost has significant effect for the feasibility of this project because it reduced around 38 million US$ from the total investment cost. Therefore in here also government subsidies for the land cost are a must for the implementation for this project.

Figure 69: Investment cost - 50% solar fraction-Fresh water condenser cooling without land cost (DEABC)

32 Detail explanation is given is the discussion chapter
The below Figure 70 show the investment cost distribution of the 50% of solar fraction double effect absorption chiller system with sea water condenser cooling considering the land cost to accommodate the equipments. The total investment cost for this system is US $ 123,696,243.00

**Investment cost distribution for different items-50% of solar fraction-Sea water condenser cooling-With land cost**

Figure 70 :- Investment cost - 50% solar fraction-Sea water condenser cooling with land cost (DEABC)

Figure 71 indicates the same above graph but without considering the land cost to accommodate the equipment. The total investment cost for this system is US $ 82,432,220.00.

**Investment cost distribution for different items-50% of solar fraction-Sea water condenser cooling-Without land cost**

Figure 71 :- Investment cost - 50% solar fraction-Sea water condenser cooling without land cost (DEABC)
The below Figure 72 show the investment cost distribution of the 50 % solar fraction double effect absorption chiller system with fresh water condenser cooling. In this system analyzed the feasibility to install the solar thermal collectors on the sea. The aim of this configuration is also analysis is to identify the possibility to installed solar thermal collectors on the sea to reduce the investment cost of the land area. The detail analysis of the possibility to installed solar thermal collectors on the sea has been explained in chapter 6. It shows the 24 % of the investment cost is contributed to install the solar thermal collectors on the sea. The total investment cost for this system is US $ 112,949,899.00. This system save around 15 million US$ compared to the solar thermal collector installed on the land.

Figure 72 :- Investment cost - 50% solar fraction-Fresh water condenser cooling –Collector installation on the sea (DEABC)

Figure 73 indicates the same above graph with sea water condenser cooling system. The total investment cost for this system is US $ 107,121,005.00. This system save around 17 million US$ compared to the solar thermal collector installed on the land.

Figure 73:- Investment cost - 50% solar fraction-Sea water condenser cooling –Collector installation on the sea (DEABC)
8.3.5 Investment Cost Analysis—with Water Cooled Vapor Compression Chillers

In this section, the investment cost distribution of the cooling system with water cooled vapor compression chillers has been explained. The below Figure 74 show the investment cost distribution of water cooled vapor compression chiller system with fresh water condenser cooling with considering the land cost to accommodate the equipment. Comparing to the above main system configurations that is single effect chiller system and double effect chiller cooling systems, this water cooled vapor compression chiller system consumes less land area to accommodate their equipments. The total investment cost for this system is US $ 23,019,930.00

Figure 74: Investment cost – Water cooled vapor compression chillers -Fresh water condenser cooling with land cost

Figure 75 indicates the same above graph but without considering the land cost to accommodate the equipments. The total investment cost for this system is US $ 22,774,594.00. In here it concluded that this system land cost is not considerable amount compared to the solar cooling system. Therefore government subsidies is not required to implement this system since cost of land is 1% of the total investment cost.

Figure 75: Investment cost – Water cooled vapor compression chillers -Fresh water condenser cooling without land cost
The below Figure 76 shows the investment cost distribution of the water cooled vapor compression chiller system with sea water condenser cooling considering the land cost to accommodate the equipments. The total investment cost for this system is US $ 20,789,036.00.

![Image of Investment Cost Distribution for Different Items - Water Cooled Vapor Compression Chillers - Sea Water Condenser Cooling - With Land Cost](image1)

Figure 76: Investment cost – Water cooled vapor compression chillers - Sea water condenser cooling with land cost.

Figure 77 indicates the same above graph but without considering the land cost to accommodate the equipments. The total investment cost for this system is US $ 20,625,600.00. In this configuration land cost is not significant because it consumes less portion of the total investment cost. In this system also government subsidies is not required to implement this system since cost of land is 1% of the total investment cost.

![Image of Investment Cost Distribution for Different Items - Water Cooled Vapor Compression Chillers - Sea Water Condenser Cooling - Without Land Cost](image2)

Figure 77: Investment cost – Water cooled vapor compression chillers - Sea water condenser cooling without land cost.
Table 14 condensed the economical parameters of solar cooling system with 50% solar fraction. After the analysis economical parameters of the all solar fractions (i.e. 100%, 80%, 60%, 50%, 40% and 20% solar fractions) author come to know the best economical solar fraction among these is 50% under the 50% of solar fraction solar assisted district cooling system there are main two configurations which is single effect and double effect and again each of configuration categorized to direct sea water condenser cooling and fresh water condenser cooling. On each case economic parameters are also calculating considering the carbon credit. The carbon credit of the region has taken as 15 US$/Tons of CO$_2$(Mazda R & D Division).

Table 15 condensed the economical parameters of cooling system with water cooled vapor compression chillers. Under the above system there are two main categories which are direct sea water condenser cooling and fresh water condenser cooling. In here also economic parameters has revised according to the carbon credit. As explain in the earliest chapters’ water cooled vapor compression chiller system is also efficient system comparing to the air cooled vapor compression chiller system which is already proposed system to install for phase 4 of Al Hamra village.
Table 14: Comparison of economic parameters of 50% solar fraction solar assisted cooling with single effect and double effect chillers

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Solar Cooling with Single effect Absorption chillers and water cooled vapor compression chillers</th>
<th>Solar Cooling with Double effect Absorption chillers and water cooled vapor compression chillers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Solar assisted Cooling system-50% SF</td>
<td>Solar assisted Cooling system-50% SF</td>
</tr>
<tr>
<td></td>
<td>Direct sea water condenser cooling</td>
<td>Direct sea water condenser cooling</td>
</tr>
<tr>
<td></td>
<td>Fresh water condenser cooling</td>
<td>Fresh water condenser cooling</td>
</tr>
<tr>
<td>Investment Cost -US $</td>
<td>82,647,214 (Without land cost) 142,229,100 (With land cost)</td>
<td>88,060,788 (Without land cost) 141,956,994 (With land cost)</td>
</tr>
<tr>
<td>Operational &amp; Maintenance cost -US$</td>
<td>4,241,478 (Without land cost) 3,468,376 (With land cost)</td>
<td>2,986,842.01 (Without land cost) 3,404,392.67 (With land cost)</td>
</tr>
<tr>
<td>Life-cycle cost -US$/For 25 Year</td>
<td>135,754,537 (Without land cost) 216,086,587 (With land cost)</td>
<td>148,456,132 (Without land cost) 221,122,390 (With land cost)</td>
</tr>
<tr>
<td>Average levelised cost - US$/kWh_{cooling}</td>
<td>0.0865 (Without land cost) 0.1397 (With land cost)</td>
<td>0.08577495 (Without land cost) 0.12262249 (With land cost)</td>
</tr>
<tr>
<td>Pay Back period -years</td>
<td>15.3 (Without land cost) 10.9 (With land cost)</td>
<td>15.1 (Without land cost) 10.5 (With land cost)</td>
</tr>
<tr>
<td>Primary energy consumption-m$^3$/year</td>
<td>3014 (Without land cost) 3683 (With land cost)</td>
<td>2887 (Without land cost) 3443 (With land cost)</td>
</tr>
<tr>
<td>Primary energy Saving-m$^3$/year</td>
<td>5397 (Without land cost) 4727 (With land cost)</td>
<td>5523 (Without land cost) 4968 (With land cost)</td>
</tr>
<tr>
<td>Cost of energy saving-US$/year</td>
<td>2,501,388 (Without land cost) 2,191,124.34 (With land cost)</td>
<td>2,560,087 (Without land cost) 2,302,531.90 (With land cost)</td>
</tr>
<tr>
<td>Tons of CO$_2$ emission saved/year</td>
<td>13,874 (Without land cost) 12,165 (With land cost)</td>
<td>14,198 (Without land cost) 12,778 (With land cost)</td>
</tr>
<tr>
<td>Amount of money receive from Carbon Credit -US$/25 year</td>
<td>5,202,705 (Without land cost) 4,561,875 (With land cost)</td>
<td></td>
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</tbody>
</table>

Revised parameters with Carbon Credit

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Solar Cooling with Single effect Absorption chillers and water cooled vapor compression chillers</th>
<th>Solar Cooling with Double effect Absorption chillers and water cooled vapor compression chillers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Solar assisted Cooling system-50% SF</td>
<td>Solar assisted Cooling system-50% SF</td>
</tr>
<tr>
<td></td>
<td>Direct sea water condenser cooling</td>
<td>Direct sea water condenser cooling</td>
</tr>
<tr>
<td></td>
<td>Fresh water condenser cooling</td>
<td>Fresh water condenser cooling</td>
</tr>
<tr>
<td>Life-cycle cost -US$</td>
<td>128,739,923 (Without land cost) 209,071,972 (With land cost)</td>
<td>142,305,525 (Without land cost) 214,971,783 (With land cost)</td>
</tr>
<tr>
<td>Average levelised cost - US$/kWh_{cooling}</td>
<td>0.0819 (Without land cost) 0.1351 (With land cost)</td>
<td>0.0810 (Without land cost) 0.1179 (With land cost)</td>
</tr>
<tr>
<td>Pay Back period -years</td>
<td>14.8 (Without land cost) 19.6 (With land cost)</td>
<td>20.8 (Without land cost) 18.1 (With land cost)</td>
</tr>
</tbody>
</table>

If Solar collectors installed on Sea(With Carbon Credit)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Solar Cooling with Single effect Absorption chillers and water cooled vapor compression chillers</th>
<th>Solar Cooling with Double effect Absorption chillers and water cooled vapor compression chillers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Solar assisted Cooling system-50% SF</td>
<td>Solar assisted Cooling system-50% SF</td>
</tr>
<tr>
<td></td>
<td>Direct sea water condenser cooling</td>
<td>Direct sea water condenser cooling</td>
</tr>
<tr>
<td></td>
<td>Fresh water condenser cooling</td>
<td>Fresh water condenser cooling</td>
</tr>
<tr>
<td>Life-cycle cost -US$</td>
<td>194,794,899 (Without land cost) 200,480,928 (With land cost)</td>
<td>160,551,026 (Without land cost) 173,612,703 (With land cost)</td>
</tr>
<tr>
<td>Average levelised cost - US$/kWh_{cooling}</td>
<td>0.1256 (Without land cost) 0.1286 (With land cost)</td>
<td>0.1031 (Without land cost) 0.1111 (With land cost)</td>
</tr>
<tr>
<td>Pay Back period -years</td>
<td>18.8 (Without land cost) 20.0 (With land cost)</td>
<td>16.8 (Without land cost) 18.3 (With land cost)</td>
</tr>
</tbody>
</table>
Table 15: Comparison of economic parameters of cooling system with water cooled vapor compression chillers

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Water cooled vapor compression cooling system</th>
<th>Direct sea water condenser cooling</th>
<th>Fresh water condenser cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invesment Cost -US $</td>
<td>20,625,600</td>
<td>20,789,036</td>
<td>22,774,594</td>
</tr>
<tr>
<td>Operational &amp; Maintenance cost -US$</td>
<td>2,963,124</td>
<td>3,182,200</td>
<td></td>
</tr>
<tr>
<td>Life -cycle cost -US$/yr (For 25 Year)</td>
<td>72,222,924</td>
<td>72,443,279</td>
<td>78,186,716</td>
</tr>
<tr>
<td>Average levelised cost - US$/kWh&lt;sub&gt;cooling&lt;/sub&gt;</td>
<td>0.0416</td>
<td>0.0418</td>
<td>0.0451</td>
</tr>
<tr>
<td>Pay Back period -years</td>
<td>9.7</td>
<td>9.8</td>
<td>11.3</td>
</tr>
<tr>
<td>Primary energy consumption-m³/year</td>
<td>5503</td>
<td></td>
<td>5883</td>
</tr>
<tr>
<td>Primary energy Saving-m³/year</td>
<td>2908</td>
<td></td>
<td>2528</td>
</tr>
<tr>
<td>Cost of energy saving-US$/year</td>
<td>1,347,672</td>
<td></td>
<td>1,171,576</td>
</tr>
<tr>
<td>Tons of CO₂ emission saved /year</td>
<td>7,442</td>
<td></td>
<td>6,472</td>
</tr>
<tr>
<td>Amount of money receive from Carbon Credit - US$/25 year</td>
<td>2,790,750</td>
<td></td>
<td>2,427,000</td>
</tr>
<tr>
<td>Revised parameters with Carbon Credit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Life -cycle cost -US$</td>
<td>68,460,259</td>
<td>68,680,614</td>
<td>74,914,482</td>
</tr>
<tr>
<td>Average levelised cost - US$/kWh&lt;sub&gt;cooling&lt;/sub&gt;</td>
<td>0.0391</td>
<td>0.0393</td>
<td>0.0430</td>
</tr>
<tr>
<td>Pay Back period -years</td>
<td>8.8</td>
<td>8.9</td>
<td>10.6</td>
</tr>
</tbody>
</table>
After the analyzing of above results it has been decided to propose two solutions from environmental and economical standpoints respectively.

From environmental standpoint, best system solution is solar assisted cooling system with 50% solar fraction with sea water condenser cooling. Under this solution there are two main categories which are single and double effect absorption chiller systems. Table 16 shows the how the main parameters varying among these two systems. Concerning the payback period of the single effect and double effect chiller systems, there is no significant difference among these two systems. Therefore considering the simplicity of the system, the best solution for the phase 4 of al Hamra village concerning the environmental point of view is cooling system with solar assisted cooling system with single effect absorption chillers (with 50 % solar fraction and direct sea water condenser cooling).This system save primary energy 5,397 m$^3$ annually and save 13,874 tons of CO$_2$ emission annually. The payback period of this system is 14 years and 10 months and which save the money US $ 2,501,388 in every year.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Solar cooling system with Single effect absorption chillers</th>
<th>Solar cooling system with Double effect absorption chillers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary energy Saving-m$^3$/year</td>
<td>5,397</td>
<td>5,523</td>
</tr>
<tr>
<td>Tons of CO$_2$ emission saved /year</td>
<td>13,874</td>
<td>14,198</td>
</tr>
<tr>
<td>Pay Back period -years</td>
<td>14.8</td>
<td>14.6</td>
</tr>
<tr>
<td>Cost of energy saving -US$/year</td>
<td>2,501,388</td>
<td>2,560,087</td>
</tr>
</tbody>
</table>

Table 16: Parameters analysis of the solution concerning the environmental point of view

In economical point of view the best solution or best cooling system is cooling system with water cooled vapor compression chiller system. Table 17 indicates the parameters varying of the proposed solution concerning the economical standpoint.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Solar cooling system with Single effect absorption chillers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary energy Saving-m$^3$/year</td>
<td>2,908</td>
</tr>
<tr>
<td>Tons of CO$_2$ emission saved /year</td>
<td>7,442</td>
</tr>
<tr>
<td>Pay Back period -years</td>
<td>8.8</td>
</tr>
<tr>
<td>Cost of energy saving -US$/year</td>
<td>1,347,672</td>
</tr>
</tbody>
</table>

Table 17: Parameters analysis of the solution concerning the economical point of view

This system saves primary energy 2,908 m$^3$ annually and save 7,442 tons of CO$_2$ emission annually. The payback period of this system is just 8 years and 10 months and which save the money US $ 1,347,672 in every year.
9. CONCLUSION

Solar cooling technologies arouse more interest day by day. Among many solar cooling technologies, solar—thermal powered absorption cooling system seems to be a viable option. In this thesis, yearly performances of the solar absorption cooling system are investigated in detail. As well as load side (i.e. building) of the system is modeled and parameters that should be considered in building design are presented. Finally, economic analysis is done in order to understand the economic feasibility of the solar thermal cooling systems compared to the already proposed system. TRNSYS is used for the simulations. Integrated models of the different cooling configurations are developed in TRNSYS. A total number of 27 different system configurations have been analyzed in TRNSYS platform to identify the best economical and environmentally friendly system configuration. The main outcomes of this study are discussed and explained in the ensuing paragraph.

In chapter 3, typical meteorological year (TMY) weather file and oceanographic data for the site location is generated throughout the year. Among these oceanographic data, sea water temperature has been found as playing the most important role for deciding the selection of system. Furthermore, the depth from where sea water can be retrieved is also important as the sea water temperature varies depth-wise. In overall, the sea water temperature level at the surface of the sea seems to be feasible for the rejection of heat even at peak summer.

In chapter 4, cooling load of the buildings in phase 4 of Al Hamra village is estimated using Design builder and TRNSYS softwares. A total of 37 MW of cooling system has to be designed.

In chapter 5, design methodology for solar thermal cooling system is presented. Importance of the solar fraction in the design is emphasized. Integrated model developed in TRNSYS is explained in detail.

In chapter 7, economic analysis of the different configurations of the solar assisted district cooling systems is done. Investment and operational costs of these systems are calculated and compared. Usually solar assisted district cooling systems are characterized with high investment cost and low operational cost. Life-cycle cost (LCC) analysis is done to compare the solar assisted cooling system with different system configuration and solar fractions. As a results of LCC analysis, it reveals that solar assisted district cooling system are not yet economically competitive with grid powered conventional vapor compression cooling system. But it shows that the water cooled vapor compression cooling system is more economical than the air cooled vapor compression cooling system which has been proposed by the client according to the existing design for phase 4 of Al Hamra Village.

From the results of the research the best environmental standpoint solution is cooling system with solar assisted cooling system with single effect absorption chillers (with 50 % solar fraction and direct sea water condenser cooling). This system save primary energy 5,397 m³ annually and save 13,874 tons of CO₂ emission annually. The payback period of this system is 14 years and 10 months and which save the money US $ 2,501,388 in every year.

From the results of the research the best economical standpoint solution is cooling system with water cooled vapor compression chiller system. This system saves primary energy 2,908 m³ annually and save 7,442 tons of CO₂ emission annually. The payback period of this system is just 8 years and 10 months and which save the money US $ 1,347,672 in every year.

The client can select either solution according to their financial capabilities and environmental concept. These proposed two solutions are economical and environmental friendly compared to the already proposed air cooled vapor compression chiller cooling system.

Already proposed system is the Air cooled vapor compression chiller system.
10. RECOMMENDATION

Because of the limitation of the time frame resources available for the research has to be paused in six months and documented the outcomes as master thesis. Due to the complexity of the subject matter, there are still many fronts in this research that needs further investigation and improvements. The ensuing paragraph presents recommendation and future works, that may help lead the project for its completion.

- Either system can be implemented. i.e. solar assisted cooling system with 50 % solar fraction OR water cooled vapor compression system.

- Investigate the possibility to apply green building technologies to the phase 4 of Al Hamra Village. (According to the rough estimation 40 % buildings cooling load can be reduced due to applying of green building technologies. It will help decrease the size of the cooling system required. That ultimately may propose more optimistic economical values.

- Analyze the possibility to install polygeneration plant which covers the electricity, cooling and sea water desalination. Because investment cost for the solar powered absorption cooling system is since high cost of solar thermal collectors. If absorption chiller can run with waste heats which are generated from the power plant, the overall system efficiency could be improved.
REFERENCES


## APPENDIX -A

### Appendix A-1: Equipment selection /Designing of Single effect absorption chiller system with fresh water condenser cooling

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### Appendix A-2: Equipment selection/Designing of Single effect absorption chiller system with direct sea water condenser cooling

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**Calculation Details:**

1. **Chiller Cooling Capacity:**
   - Calculated kW based on the cooling demand and the number of chillers.

2. **Condenser Water Circuit:**
   - Calculated based on the required water flow rate per chiller.

3. **Storage Tank Circuit:**
   - Calculated based on the total flow rate and the number of chillers.

4. **Selected Pump Flow Rate:**
   - Calculated based on the required pump flow rate.

5. **Number of Storage Tanks:**
   - Calculated based on the required water volume and the number of chillers.
### Appendix A-3: Equipment selection/Designing of Double effect absorption chiller system with fresh water condenser cooling

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APPENDIX –B

Sources for the cited cost of the different components

The costs of components used in the design were based on quotations obtained from the manufactures.

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| Solar collectors| Dezhou Mingnuo new energy Co.Ltd  
Room 102,Xujiahui Garden, South wanping road, Shanghai , China  
daavidcheng@gaia-solar.com  
www.gaia-solar.com  
Tel – 0086-13953485199  
Linuo Ritter International  
No. 30766,East jingshi road, Shandong province , Jinan , China  
shangl@jiuno-ritter-international.com  
www.jinou-ritter-international.com  
Tel – 0086-13953485199  
Industrial Solar GmbH  
Emmy- Noether- Str.2  
79110 freiburg, Germany  
tobias.schwind@industrial-solar.de  
www.industrial-solar.com  
Tel – 0049 761 767111-22 | May 2011 |
| Chillers        | Kawasaki Thermal Engineering Co. Ltd  
2-6-5, Minamissuna, Koutou-Ku-Tokyo 1368588  
Tel – 0081 336155821  
Kamitori_y-krk@corp.khi.co.jp  
www.kawasaki.com  
UTS carrier LLC  
PO 6735, Zabeel road, Dubai, UAE  
Tel – 00971 043965455  
Jatin.Gupta@carrier.utc.com  
www.carrieruae.com | May 2011 |
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<td>SIKO Marine solutions&lt;br&gt;167, Route du Village, Entredozon, 74410 Saint Jorioz, France&lt;br&gt;<a href="mailto:dvdsl@sikomarine.com">dvdsl@sikomarine.com</a>&lt;br&gt;www.sikomarine.com&lt;br&gt;Zhongya Marine&lt;br&gt;Postat code 318020, PR China&lt;br&gt;Tel – 0086 00576008411&lt;br&gt;<a href="mailto:rambo@futongc.com">rambo@futongc.com</a>&lt;br&gt;www.futongc.com</td>
<td>May 2011</td>
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<td>Hot/cold water storage tanks and sea water heat exchangers</td>
<td>CheqPoint Tech-LLC&lt;br&gt;P.O. Box 25236&lt;br&gt;Dubai, UAE&lt;br&gt;Tel: +971 4 2830095&lt;br&gt;Fax: +971 4 2830096&lt;br&gt;www.cheqPoint.com&lt;br&gt;Nantong Showa Machinery Co.Ltd&lt;br&gt;<a href="mailto:zhoujan@ntshowa.com">zhoujan@ntshowa.com</a></td>
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