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Novel Solar thermal polygeneration system for sustainable production of cooling, clean water and domestic hot water in UAE

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Abstract

The demands for space air conditioning and clean water are relatively on the higher side in Middle East countries. In UAE, the demand for building air conditioning exceeds 75% of total electricity consumption during the summer, and desalination is predominant. The production of chilled water for air conditioning and clean water using desalination involves a huge amount of heat and electricity input. In UAE, most of the energy demands are provided by fossil fuels which in turn cause global warming. On the other hand, UAE gains high solar irradiation with mean annual reaches 550 W/m². In this research work, a sustainable way to utilize abundant solar energy available in the region for providing the air-conditioning and fresh water requirements along with the additional production of domestic hot water is been presented. A solar thermal poly-generation (STP) system is designed and developed for production of chilled water for air conditioning using absorption chiller, pure water with membrane distillation and domestic hot water by heat recovery. The STP system has four major components: (i) Evacuated tube collector field (ii) 10TR single stage Absorption chiller (iii) Air-gap membrane distillation units (iv) Heat exchangers integrated together to operate in four different modes for complete solar cooling, co-generation of pure water and domestic hot water, tri-generation of cooling, pure water and domestic hot water and co-generation of cooling and pure water. Experiments on different modes and the analyzed results show the advantages of combined operation through effective utilization of heat lost in the process operation. Dynamic simulation of trigeneration system is conducted access the performance of system in full load condition. Annual performance characteristics were also evaluated along with environmental and economic benefits.

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Preface

Publications included in this thesis

1. **Gowtham Mohan, Uday Kumar N T, Manoj Kumar Pokrel, Andrew Martin. 2014, "**Solar thermal polygeneration system for cooling, freshwater and domestic hot water supply: Experimental Analysis", 13th World Renewable Energy Congress, August 3-8, 2014, London, United Kingdom
2. **Gowtham Mohan, Uday Kumar N T, Manoj Kumar Pokrel, Andrew Martin Gauvrav Pravin Raval. 2014,** "Design and development of solar thermal driven trigeneration system in UAE" EUROSUN 2014, International Conference on Solar Energy and Buildings, 16-19 September, 2014, Aix-Les-Bains, France.
3. **Gowtham Mohan, Uday Kumar N T, Manoj Kumar Pokrel, Andrew Martin. 2014,** A novel solar thermal polygeneration system for sustainable production of cooling, clean water and domestic hot water in United Arab Emirates: Dynamic simulation and economic evaluation. (Final stages of submission in Energy conservation and Management)

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Nomenclature

A – Area [m²]
ACH – Air Changes per Hour
AGMD –Air Gap Membrane Distillation
C –Cost [$]
CCCWP –Combined Cooling Clean Water and Power
COP –Coefficient of Performance
DCMD –Direct Contact Membrane Distillation
DHW – Domestic Hot Water
ETC –Evacuated Tube Collector
F_r –Heat Removal Factor
FCU –Fan Coil Units
GCC – Gulf Cooperation Council
GOR –Gain to Output Ratio
HD – Humidification Dehumidification desalination
HS1– Hot thermal Storage tank
HS2– Cold thermal Storage tank
IAM –Incident Angle Modifier
IDA – International Desalination Association
I_r – Incident irradiation
M – Mass flow rate [kg/s]
MD –Membrane Distillation
MED –Multi Effect Distillation
MSF –Multi Stage Flash
N – Molar flux
P – Pressure [bar]
PB –Payback period [years]
PWF –Present Worth Factor
NCS –Net Cumulative Savings
PHE –Plate Heat Exchanger
Q – Heat Energy [kW]
SGMD –Sweeping Gas Membrane Distillation
T– Temperature
U –Overall heat transfer coefficient
UAE –United Arab Emirates
VAC – Vapor Absorption Chiller
VFD-Variable Frequency Drive
VMD –Vacuum Membrane Distillation
X – Molar fraction

Greek symbols
η – Efficiency
τ – Transmittance
α – Absorbance
– Porosity
λ – Latent heat of condensation

Subscripts
amb – Ambient
avg – Average
c – Cold
col – Collector
f –Fuel
gen – Generator
in – Inlet
out – Outlet
h – Hot

1 Introduction

Sustainable production of energy and water are two important needs for a developed economy, several efforts taken in addressing this issue popularly known as 'Energy-Water Nexus'. One of major goal is achieve synergy between energy and water demands coherently and sustainably. Currently, global warming is one of most stressing issues discussed all over the world. Steady raise in global ambient temperature leading to melt of polar ice caps and increase to sea level. Global warming is mainly human-induced phenomenon by combusting fossil fuels for all the energy needs. Release of green house gases during the combustion of fossil fuels is major reason for global warming. In order to avoid all the consequences, several countries and agencies promote renewable energy as the sustainable option to protect environment and the future.

Water is most important needs for survival of human in earth. About 70% of earth's surface is covered with water bodies, but only 3% of it is the fresh water reserves. Out of the 3%, almost 2/3rd of the fresh water reserves are trapped as icecaps, glaciers and deep ground waters which is mostly not accessible [1]. With increase in human population, desalination of sea water for production of clean water emerges as the viable solution to provide all the fresh water demands. Currently around 2.5 billion people lack access to clean water resources, which shows needs for desalination and purification technologies combined with sound water management strategies. Desalination is a huge energy intensive process and according to International Desalination Association (IDA), more 17000 desalination plants are installed in around 150 countries for daily global production of 80 million cubic meters to supply desalinated water to more than 300 million people [2], out of which almost 41% is supplied to Gulf Cooperation Council (GCC) countries [2].

United Arab Emirates is one of major consumer of both energy and water on per capita basis. The country lack in fresh water resources and has one of lowest precipitation rates of 78mm per year [3]. Desalination is main source of clean water supply and UAE has 70 desalination plants for providing the daily needs. Along with water scarcity, another major issue the country faces is building air conditioning. Around 75% of electricity consumption in summer is accounted for air conditioning [4, 5]. This is mainly due to very harsh weather conditions (high temperature and humidity) in the country. All these demands are mostly provided with fossil fuels which is not environmentally sustainable.

With all those issues, the countries gains one of highest solar radiation in the world with an annual mean about 550 W/m^2. Mean global solar radiation of UAE is shown in Figure 1.1. In order to achieve the sustainable synergy between water and energy demands in UAE, solar energy is can be utilized for production of chilled water for building air conditioning and desalination. An innovative and sustainable way to provide both the cooling and fresh water demands is discussed in this research work. Additionally the possibility of domestic hot water production through heat recovery is also analyzed as shown in Figure 1.2.

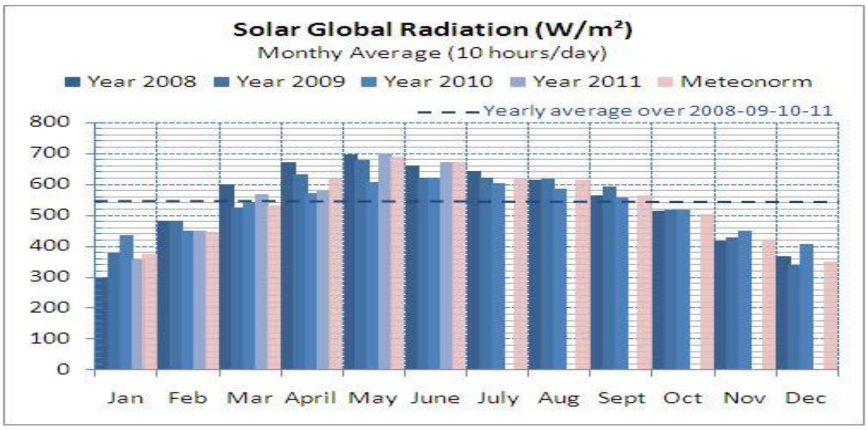


Figure 1.1 Solar Global Radiation in UAE (RAK)

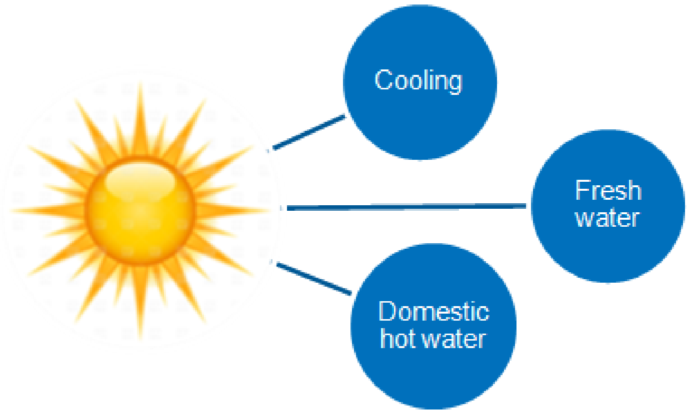


Figure 1.2 Primary objective

1.1 Research objective

This research work focuses on developing a novel polygeneration system for simultaneous production of chilled water for air conditioning using absorption chiller, fresh water using membrane distiller and additionally domestic hot water with heat recovery. The main objective of study is to integrate evacuated tube collector field, single stage absorption chiller, membrane distiller and heat exchangers for developing a sustainable polygeneration system at CSEM-UAE. The schematic conceptual design of polygeneration system is shown in Figure 1.3.

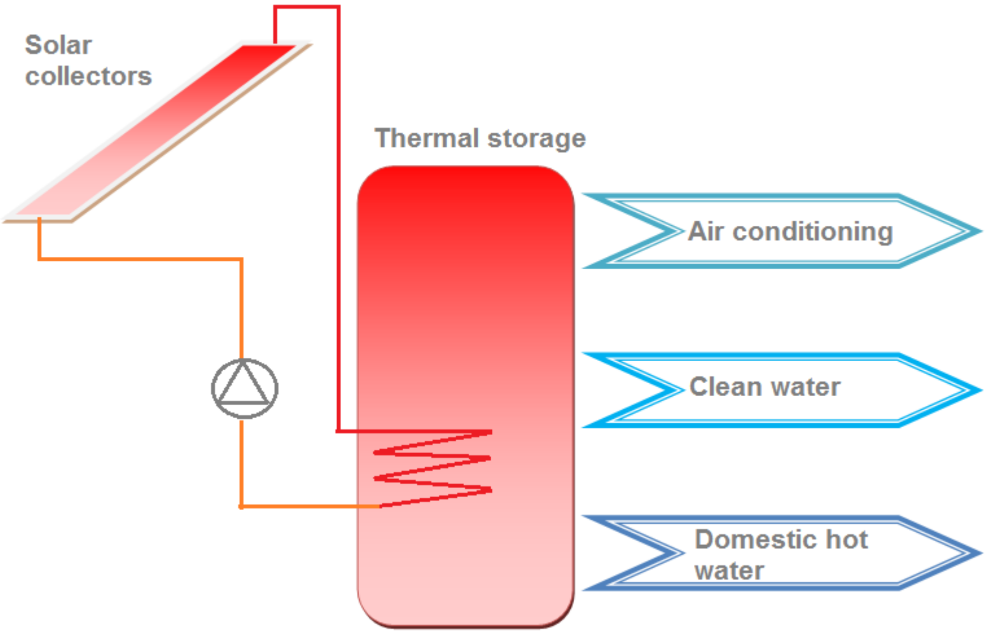


Figure 1.1 Conceptual design of polygeneration system

1.2 Methodology

A detailed research plan was devised to achieve the objective proposed. First and foremost step followed in the project is the detailed literature survey of different cooling, desalination cycles and solar thermal systems. A survey on recent research activities in polygeneration systems and various integration possibilities were also taken into account. Further, a review on membrane distillation technologies is conducted to enhance the understanding of the process and practical difficulties in during operation. One of major advantage of membrane distillation technology is its capability to utilize low grade heat energy (60 – 80°C), which suits the integration with solar thermal energy.

In this research work, Air gap membrane distillation (AGMD) type is utilized for the integration in polygeneration over several other types of membrane distillation. As this configuration of MD has unique advantage to use internal heat recovery, which is been implemented in this project. Along with that AGMD configuration has lower conductive losses due to presence of air gap and operates at lower pressure.

The design of polygeneration with proper arrangement and placement of equipment with necessary piping, wiring and measurement sensors is schedule as first phase of the project. The system comprises of seven circuits as shown below:

- Solar collector circuit
- Hot water circuit
- Cooling water circuit
- Chilled water circuit
- Sea water circuit
- Desalinized water circuit
- Domestic hot water circuit

All the components of the solar thermal polygeneration were integrated and the experimental unit is installed and commisioned at CSEM-UAE test facility. The final leg of the research work is the experimental campaign, where series of experiments are conducted with four different modes.

- Solar cooling mode
- Cogeneration mode 1: Desalination and domestic hot water
- Cogeneration mode 2: Cooling and Desalination
- Trigeneration mode: Cooling, Desalination and Domestic hot water

Additionally, Solar thermal polygeneration system is modeled and dynamically simulated in TRNSYS to analyze the full potential benefit of the polygeneration system both energetically and economically.

2 Literature Review

In this chapter, a brief literature survey regarding various polygeneration system implemented by several researchers. A short overview on different thermal driven desalination and cooling systems is also discussed. Along with the above mentioned technologies, a detailed literature review on different type of membrane distillation techniques and current advancement in the field.

2.1 Solar thermal desalination

In focus of this thesis, different solar thermal desalination technologies are evaluated in this section. Five thermal desalination technologies discussed are shown in Figure 2.1. As main focus is membrane distillation, detailed review on the technology is conducted.

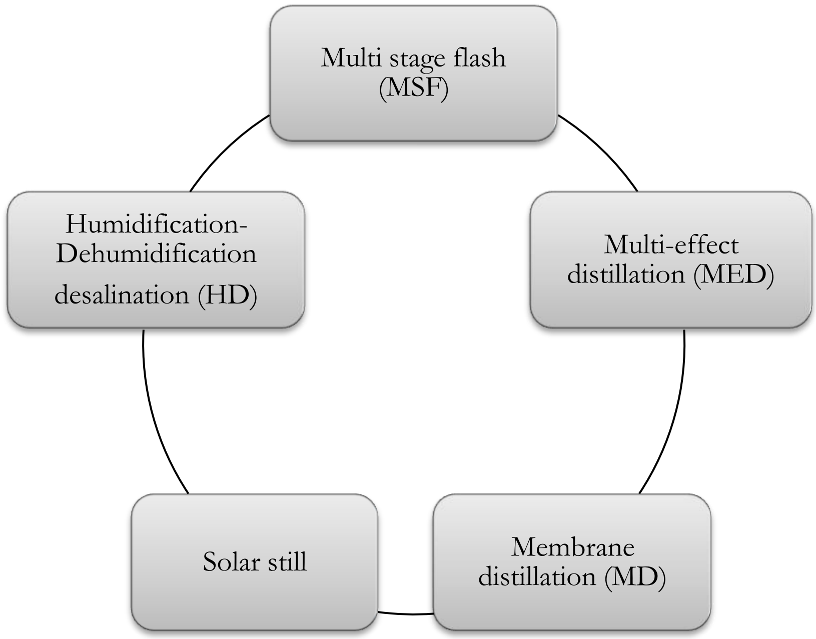


Figure 2.1 Solar thermal desalination technologies

2.1.1 Multi Stage Flash (MSF)

Multi stage flash is a thermal desalination technology operates on the principle of vaporizing saline water by reducing pressure of the chamber and condensing it to produce distillate. The system has multiple stages having different pressure level based on saline water temperature. Each stage is a chamber with concurrent heat exchanger arrangement utilized for condensation of vapor produced during flashing process. Coolant water supplied in coil is preheated by latent heat recovered during condensation, then passed to the heating unit [6]. Schematic sketch of MSF process is shown in Figure 2.2. Number of stage of MSF is generally optimized based starting temperature of process and economical viability. Solar concentrator technologies like parabolic concentrator or linear Fresnel concentrator can be utilized as direct source for steam production for MSF or combined with power generation cycle as co-generation system [7].

Around 90% of thermal desalination market share is occupied by MSF technologies and nearly half is accounted of sea water desalination. In terms of energy consumption, MSF is on the higher side with an average consumption of 17 kWh/m^3 of fresh water. On the other hand, MSF plant is very robust and has life time of 40 years. Larger plants up to 100,000 m^3 capacities are possible in MSF, several installations in GCC countries varies between 50,000 to 100,000 m^3 capacities. It has recovery ratio of 0.6-6 and water cost of water production varies between1-5\$/m^3 [8]. In terms of disadvantages: (i) System cannot be operated below 70% of design capacity (ii) Highly energy intensive (iii) Low recovery ratio (iv) High operation and maintenance costs (v) Scale formations at high operating temperature (around110°C).

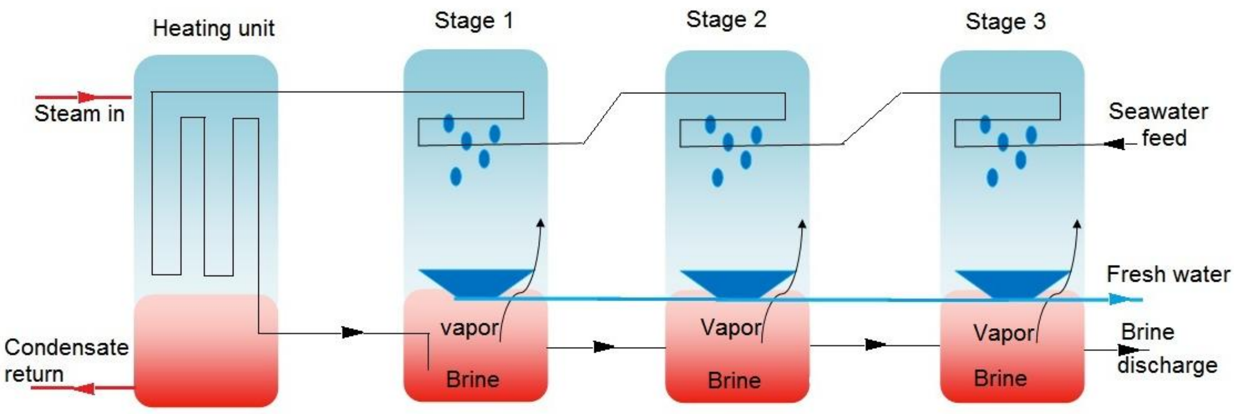


Figure 2.2 Multi Stage Flash process

2.1.2 Multi Effect distillation (MED)

Multi effect distillation technology has series of evaporative heat exchanger connected together forming multiple stages as shown in Figure 2.3. This technology has series of stages which has pressure inside the chamber less than ambient condition. External heat source is required to initiate the process in heating stage, feed water is sprayed over the evaporative coil leading to formation of vapor which is condensed in subsequent stages and collected as distillate. As the pressure is reduced in each stage based on operating temperature, vapor produced in prior stage acts the heat source [6]. Similar to MSF, productivity depends on the number of stages but it will incur higher investment costs. In terms of energy consumption, MED consumes lesser electrical energy as system is designed for once through type. Overall investment and operating cost is slightly lower than MSF [9]. The system is insensitive to initial feed concentrations, but pretreatment is required for removal of suspended solids. In terms recovery ratio, it is much lesser than MSF. The system operates at low temperature (70°C), so it provides flexibility to integrate with waste heat, combined cycle or solar thermal input.

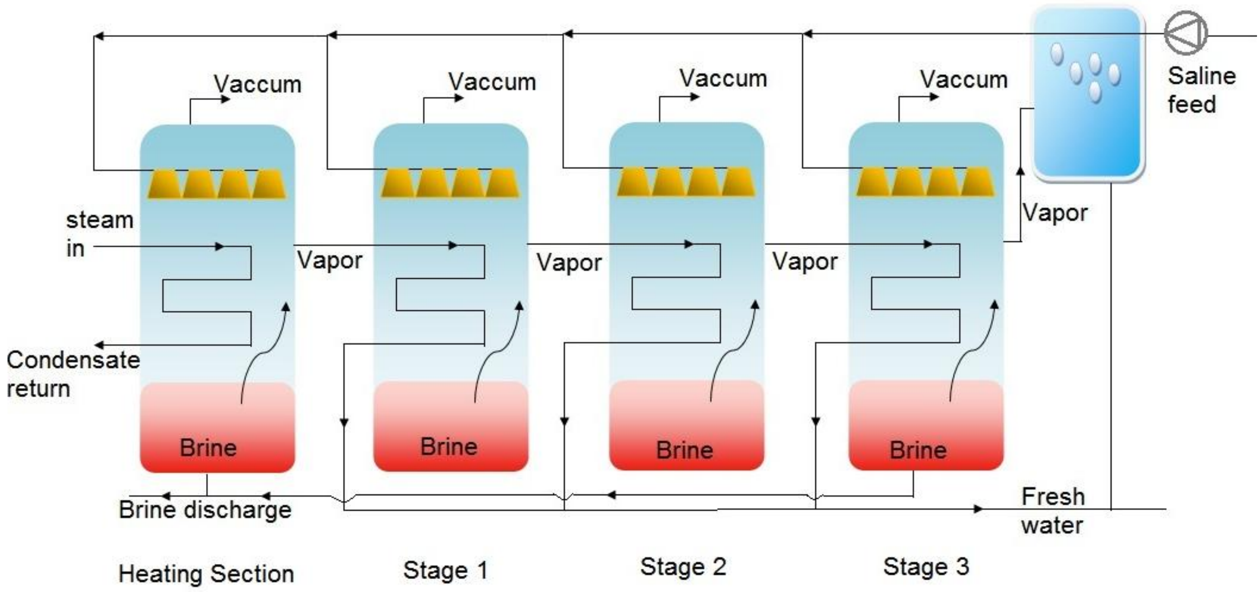


Figure 2.3 Multi Effect Distillation process

2.1.3 Humidification – Dehumidification desalination

Humidification –Dehumidification desalination technology work on same principle as natural water cycle. The system consists of two subsequent chambers – Humidifier and Dehumidifier connected in series, cycle is operated in ambient pressure conditions [10] as shown in Figure 2.4. Hot water is sprayed humidification unit for the formation of moist air with high humidity content close to 80% is subsequently condensed for production of fresh water in dehumidifier. Feed water is supplied to the cooling coils of dehumidifier, which preheats the saline water based on heat recovery through latent heat of condensation. The preheated feed is supplied to heat sources (solar collector) and sprayed in humidification chamber. The process less energy intensive compared to MSF and MED as system is operated at ambient condition. Multiple stages of HD system are possible with proper thermodynamic optimization. This technology is widely researched with different carrier gases, arrangements etc. Small scale commercial plants are installed in Germany, France and few North African countries [11].

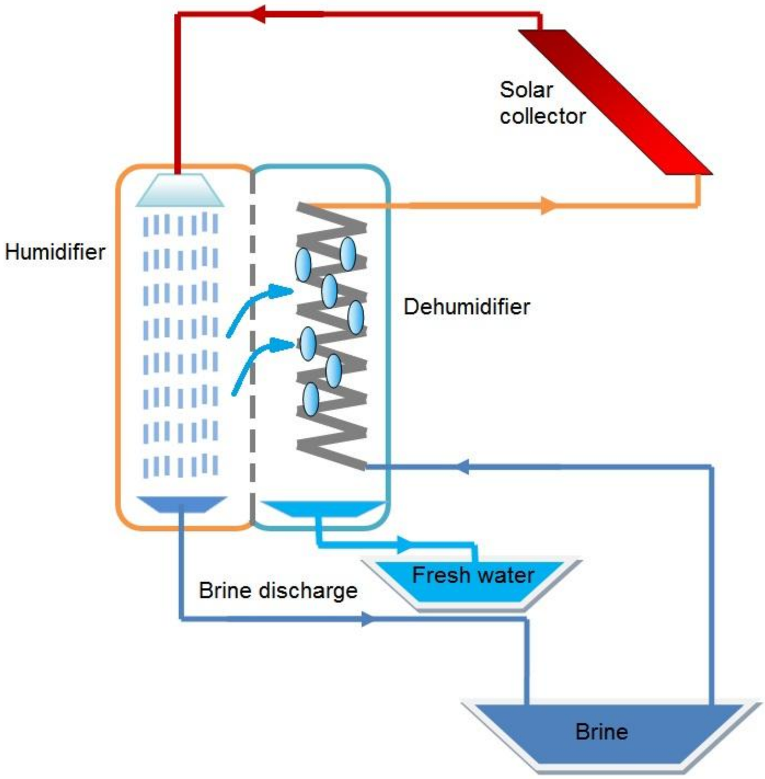


Figure 2.4 Humidification – Dehumidification desalination process

2.1.4 Solar still

Stills are the oldest and most simple desalination process for producing clean water using solar energy. Working principle is similar to HD desalination and whole cycle takes places in single chamber. Flat plate basin type solar still is most commonly used technology with either single slope or double slope glass cover. Flat metal basin acts as evaporator and the glass cover acts as condenser; the whole system is completely insulated to avoid thermal losses. This technology is adopted in rural area with limited access to fresh water. Major drawback in this technology is lower productivity, this can produce up to 4 liters/m^2 [12]. Simple schematic sketch of the process is shown in Figure 2.5.

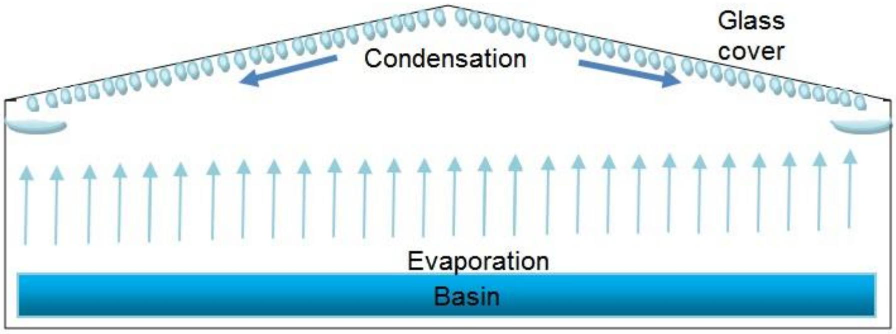


Figure 2.5 Solar Still

2.1.5 Membrane distillation

Membrane distillation is promising desalination and water purification technology with temperature difference between hot and cold sides as the driving force for the process. The system is simple in construction with two flow channels separated by hydrophobic membrane. Saline water with the temperature between 70 and 90°C is used as feed solution membrane distillation processes. In process due to vapor pressure difference between two side, the water vapor can pass through the membrane [13]. Apart from saline water, membrane distiller can process different solution with requirement to separate water like effluent, dyes etc. Only condition to achieve separation is that feed solution should be in direct contact with hydrophobic membrane. The membrane distillation process has several advantages and disadvantages [14].

Advantages: It uses low grade heat energy as it uses relative low temperature than other thermal desalination process; produces high quality distillate; less sensitivity towards variation in feed salinity and pH levels; The system is much more compact and can be decentralized.

Disadvantages: Thermal energy consumption for production of water is high; Low distillate flux yield compared to other membrane process; high rejection rate

There are several types of membrane distillation techniques been developed and tested by researchers, all these techniques has own advantages and disadvantages. Four different membrane distillation techniques are shown below,

2.1.5.1 Direct Contact Membrane Distillation (DCMD):

DCMD is simplest of all configurations and widely used for membrane distillation process, schematic sketch of process is shown in Figure 2.6 (a). The feed solution is supplied to the hot side and fresh water on the cold side. Vapor passes through the hydrophobic membrane due to partial pressure variation, condenses on cold side [15]. Major drawback in this process is conduction heat loss between the two sides.

2.1.5.2 Air Gap Membrane Distillation (AGMD):

In AGMD type as shown in Figure 2.6 (b), a layer of stagnant air gap is provided between condensing surface and membrane, instead directly mixing with cold side. The evaporated vapor condenses on the wall of cold surface [16]. Advantages of AGMD are less heat conduction losses and possibility to use the internal heat recovered by the cold side. However, productivity of distillate is slightly lower than DCMD.

2.1.5.3 Sweeping Gas Membrane Distillation (SGMD):

Schematic sketch of SGMD type is shown in Figure 2.7, inert gas is utilized to sweep the vapor on the permeate side and condense it with an external condenser. Continuous flow gas reduces the heat loss and enhances mass transfer coefficient. Production of distillate increases by 40% compared to DCMD technologies [17]. Drawback in this method is that it requires large condenser as volume of sweep gas is much larger compared to amount of vapor in it.

2.1.5.4 Vacuum Membrane Distillation (VMD):

The schematic of VMD is shown in Figure 2.8. In this configuration, vacuum is developed on the permeate side with help of pump. Which leads to condensation takes place outside the MD system with external condenser [18]. One great advantage of this method is conductive heat losses are negligible in this configuration [13].

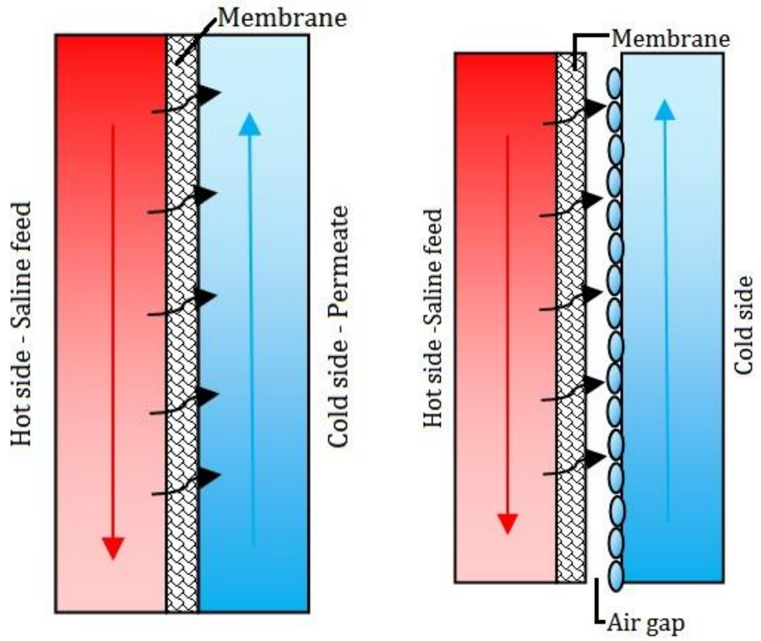


Figure 2.6 (a) Direct contact membrane distillation process (b) Air gap membrane distillation process

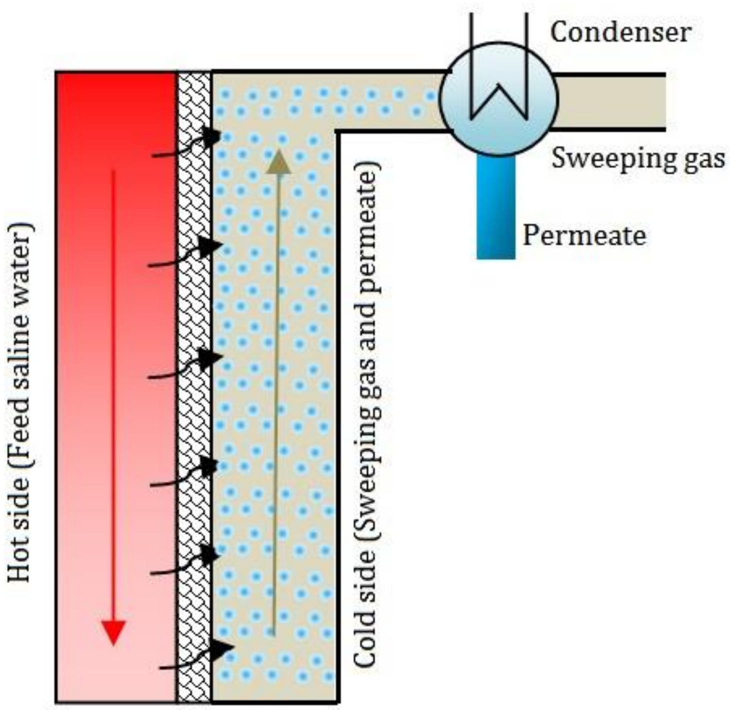


Figure 2.7 Sweeping gas membrane distillation process

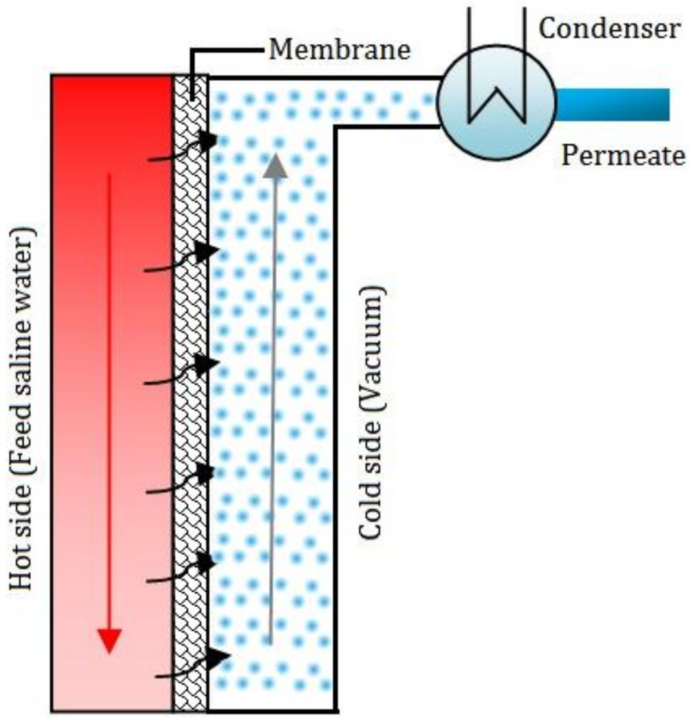


Figure 2.8 Vacuum membrane distillation process

2.2 Polygeneration systems

Polygeneration is one of most efficient ways to maximize the utilization of available energy. Combined heat and power cycles are widely used cogeneration systems and they have transformed to polygeneration system by integration of cooling and desalination cycles. In Middle East countries, most of research in polygeneration focuses on combination of cooling and desalination cycles. Few systems configuration are exciting with potential for huge energy savings.

Picinardi [19] designed and developed a novel cogeneration system to produce cooling energy and fresh water by integrating humidification – dehumidification desalination (HD) technology to the single stage absorption chiller system. In this research, heat rejected from absorber and condenser is utilized to drive the HD desalination system. Critical inference from the research is higher outlet temperatures of cooling water affects the chiller performance. In terms of proper energy utilization, system is a greater success with higher combined efficiency.

Hussain [20] developed multiple hybrid polygeneration systems for Kuwait based on requirements in the region. System is designed to produce power, fresh water and cooling simultaneously. The polygeneration systems are developed by integrating combined power cycle, desalination system and cooling unit. Two different type of desalination and cooling technologies are considered in the analysis. Reverse osmosis (RO) and multi-stage flash (MSF) are considered for desalination purposes, absorption refrigeration (AR) and vapor compression air conditioner (VC) for cooling. The combination of Power-RO-AR configuration provides higher fuel savings compared to all other combinations.

Calise et al. [21] modeled a solar energy based trigeneration for CCCWP applications. Multi-effect desalination unit and vapor absorption chiller are integrated together with PVT collector for combined production of cooling, desalination and power. The transient simulations for different operational and design parameter were conducted and optimized in terms of energetic efficiency and economic viability

Kullab [22] experimentally and numerically analyzed the performance of air gap membrane distillation system developed by SCARAB Development AB for utilization cogeneration power plants. The system was analyzed with two different integration layout and parametric studies with different parameters are also conducted. Liu [23] analyzed different possibilities to integrate membrane distillation with heat recovery chiller and gas engines for production of cooling, power and water for chip manufacturing unit.

3 System Design and Integration

3.1 Design of Experimental Unit

The system investigated in this project is a novel solar thermal polygeneration (STP) system integrating solar collectors, single stage absorption chiller and membrane distillation water purification unit. The system is designed to operate during the sunshine hours without any auxiliary electrical heater in the weather conditions of United Arab Emirates. The schematic layout of system considered for the investigation is shown in Figure 3.1 which consists of seven different system loops and lines:

- Solar collector circulation loop (SCW): Circulation of water between solar collector field and source side of hot water storage tank
- Hot water loop (HW): Circulation of water between absorption chiller and load side of the storage tank
- Cooling water loop (CW): Water circulated between cooling tower and absorption chiller
- Chilling water loop (CHW): Chilled water flowing between fan coil units and evaporator of the absorption chiller through a chilled water storage tank
- Saline water line (SW): Water supplied to AGMD module for the desalination process
- Desalinized water line (DW): Fresh water produced from AGMD and collected in storage tank
- Domestic hot water line (DHW): Hot water supplied to end users by recovering heat from AGMD unit

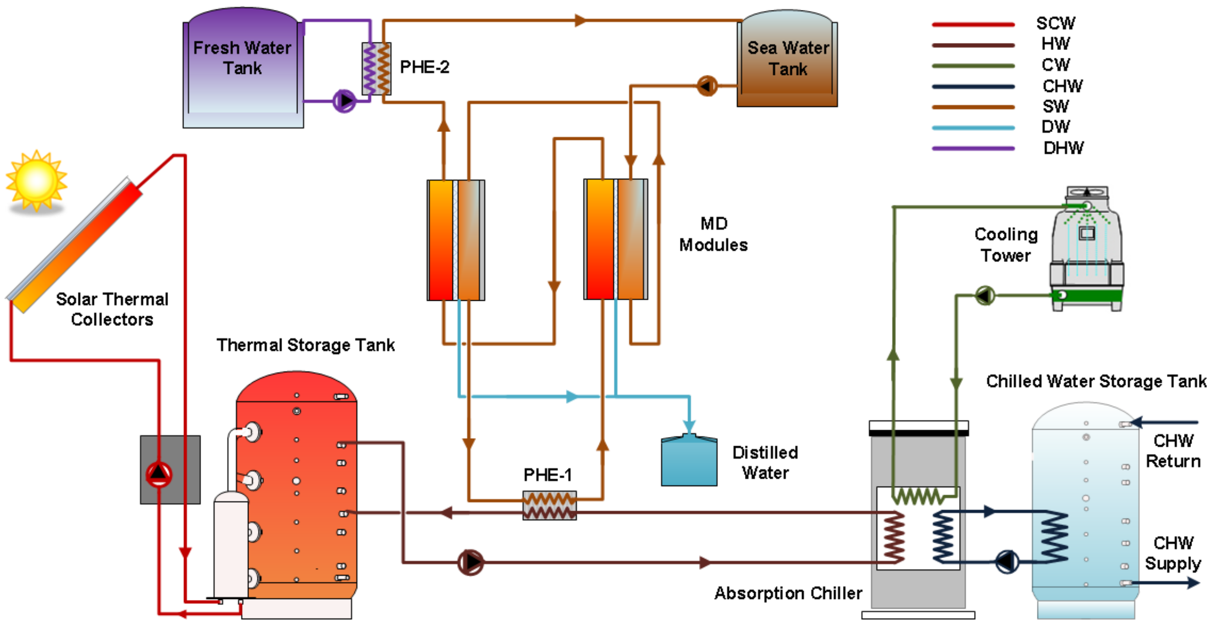


Figure 3.1 Schematic layout of solar thermal polygeneration system

The major components present in the solar polygeneration system are as follow:

- Solar collector field for supplying hot water to thermal storage tank (HS1).
- A single effect lithium bromide – water (LiBr-H_2O) Absorption chiller (VAC), whose generator is supplied with the hot water from solar field.
- Closed loop cooling tower for removing the heat, which is rejected in the condenser of the chiller VAC.

- A thermal storage tank (HS1) that stores hot water from solar collector field supplies heat for absorption chilling unit and sea water desalination process
- A thermal storage tank (HS2) for storing and supplying chilled water to the fan coil units (FCU) installed in portacabins of solar open-air laboratory (SOLAB) in CSEM-UAE.
- Air-Gap membrane distillation modules (AGMD) for producing desalinated water from saline water. Both single and multi-effect MD configurations are tested.
- Two heat exchangers (PHE1, PHE2) for providing heat to sea water and domestic hot water.

3.1.1 Solar thermal collector circuit

The solar thermal collector circuit consists of two field of evacuated collector namely large and small field. The large field has 8 evacuated tube collectors with an individual collector gross area of 12 m^2, two collectors are connected in series to make four rows connected in parallel. The small collector field has 4 evacuated tube collectors of gross area 9 m^2 each, connected in same orderly as large field. The whole collector fields tilted to 15° to maximize the performance in summer as both cooling and fresh water demands are higher in summer.

The solar collector circuit is pressurized to 3 bars during the operation using a Variable Frequency Drive (VFD) controlled station pump, which circulates water between collector field and storage tank in a closed loop. Flow to collectors can be controlled using VFD controller provided inbuilt in the station pump. The heat transfer fluid between the collector and storage tank gets heated with available solar radiation. The temperatures sensors are placed at inlet and outlet of collector field to measure the useful energy gained during the operation. External heat exchange type stratified storage tank of 980 liters capacity is been installed and equal volume of back up thermal storage is also connected. Evacuated tube collector field and thermal storage at CSEM-UAE facility is shown in Figure 3.2 and 3.3.

Figure 3.2 Evacuated tube collector field at CSEM-UAE

Figure 3.3 Hot water thermal Storage tanks

3.1.2 Absorption chiller circuit

Absorption chiller utilized in the polygeneration system is a single stage LiBr/H_2O vapor absorption chiller with a rated capacity of 35.2 kW. Technical specification of absorption chiller provided by the manufacturer is shown in table 3.1 [25].

Hot water from thermal storage tank utilized to drive the polygeneration system. The hot water outlet of the thermal storage tank is connected to generator inlet of the absorption chiller using copper piping with 70 mm rock wool insulation. The return line from generator is connected to bottom of stratified tank with same piping arrangement. Hot water is supplied to absorption chiller above 88°C to initiate the cooling process. Temperature sensors are placed at the inlet and outlet tubes to record the temperature profile of absorption chiller. The hot water from storage tank is pumped using Grundfos hot water pump with VFD controller to adjust the mass flow rate. In order achieve rated capacity, hot water flow rate of 2.33 kg/s is set during the operation. Absorption chiller is designed to operate at hot water temperature range of 70 to 95°C.

Cold water loop of the absorption chiller is utilized to reject heat from the chiller during the operation. In order reject heat, wet cooling tower is installed and connected to the absorber and condenser of the absorption chiller with PVC pipes. The cold water from cooling tower is pumped to absorption chiller with higher flow rate of 5.1 kg/s, in order to maintain a lower temperature difference during the heat rejection. Cold water to the absorber and condenser is supplied at the temperature around 30°C to ensure ideal operating conditions.

The chilled water produced in the evaporator of absorption chiller is continuously supplied to chilled water thermal storage tank at rated flow rate of 1.5 kg/s. Circuit between tank and absorption chiller is completely insulated to avoid heat losses. Temperature (Wika - TS-10) and flow sensors (Burkert-turbine type) are places at all inlet and outlet points of absorption chiller. The chilled water from cold storage tank is distributed to office cabins using distribution pump. The office cabins are equipped with fan coil units to provide cooling, distribution circuit buried underground and heavily insulated to avoid thermal losses.

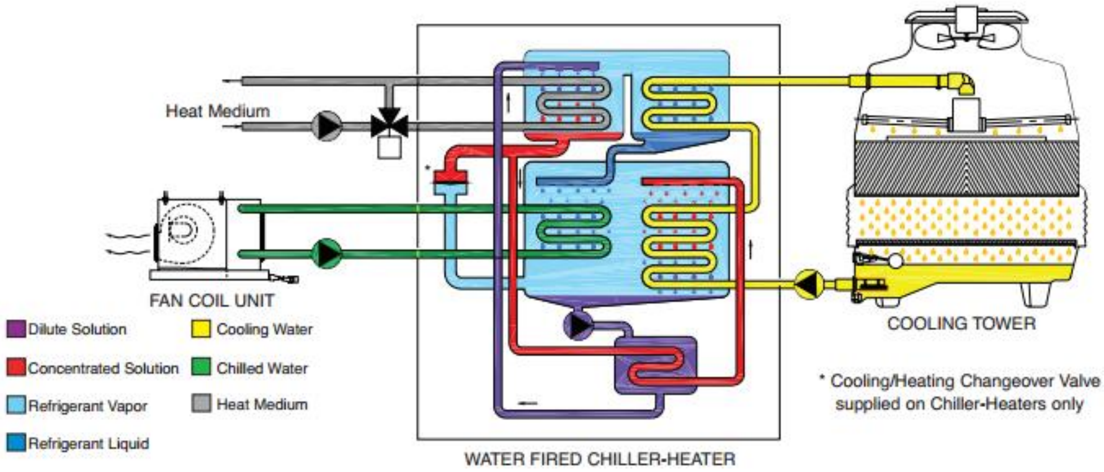


Figure 3.4 Schematic sketch of absorption chiller [25]

Figure 3.5 Yazaki 10TR absorption chiller unit

Item	Parameter	Unit	Value
Cooling capacity		kW	35.2
Chiller water	Inlet temperature	^{o}C	12.5
	Outlet temperature	^{o}C	7.0
	Rated flow rate	m^3/h	5.47
	Max operating pressure	kPa	588
Cooling water	Rated inlet temperature	^{o}C	31.0
	Rated outlet temperature	^{o}C	35.0
	Max operating pressure	kPa	588
	Rated flow rate	m^3/hr	18.4
Hot water	Rated inlet temperature	^{o}C	88
	Rated outlet temperature	^{o}C	83
	Inlet limit	^{o}C	70-95

Table 3.1 Technical specifications of 10TR Absorption chiller[25]

Figure 3.6 Installation of fan coil unit

3.1.3 Membrane distillation and DHW circuit

Membrane distillation unit used in this research project is a semi-commercial air-gap membrane distillation unit developed by SCARAB Development AB, a Swedish manufacturer. The membrane distillation unit is a flat sheet AGMD type, with 10 cassettes connected in parallel. The cassettes are injection molded together forming channels for hot and cold water flows. Technical specification of membrane module is shown in Table 3.2.

Specification	Value
Membrane area	2.8m^2
Porosity (ϕ)	0.8
Membrane thickness (b)	0.2mm
Air gap length (L)	1mm
Height of the module	730mm
Width of the module	630mm
Thickness of the module	175mm

Table 3.2Technical specifications of membrane distillation unit [22]

The desalination circuit consists of 500 liter stainless steel storage tank for sea water reservoir, which is connected to membrane distillation unit through a stainless steel pump with VFD controller to maintain pressure range below 0.3 bar. As explained in earlier section, membrane distillation is works at low pressure and drive force is the temperature difference between the sides of the membrane. The concept of internal heat recovery is employed in the system to maximize the energy recovery. The feed water from storage tank is connected to the cold side of membrane distiller allows feed water to preheat by latent heat released by the distillate and conductive heat transfer from the hot side. The feed water is heated up using titanium plate heat exchanger, which heats the preheated water from cold side of membrane distiller using heat recovered from return line of the generator. System is designed with flexibility to operate in single stage and two stage system. In two stage configuration, two membrane distillation modules are connected in series. Temperatures of the fluid at all inlet and exit points are recorded using temperature sensor (Wika -TR 10). Conductivity transmitters (Burkert) are placed at the inlet of feed circuit and in the distillate production line to measure the quality of the water. Feed water conductivities are recorded as 65,000 – 68,000µS (40000-42500 ppm) which is desalinated during the process to 50-100µS (32 -64 ppm). The flow rate of the feed water is set as 1200 liter/h based on previous research conducted with same membrane modules [24].

The hot water outlet from the membrane distillation unit is connected to second titanium plate heat exchanger for production of domestic hot water. It is an external heat recovery from membrane distillation process, which leads to lesser energy consumption by the MD process. Fresh water from storage tank is supplied to the second heat exchanger, which recovers heat from brine solution to produce DHW as shown in figure 3.7. Final installation of Polygeneration unit is shown in figure 3.8.

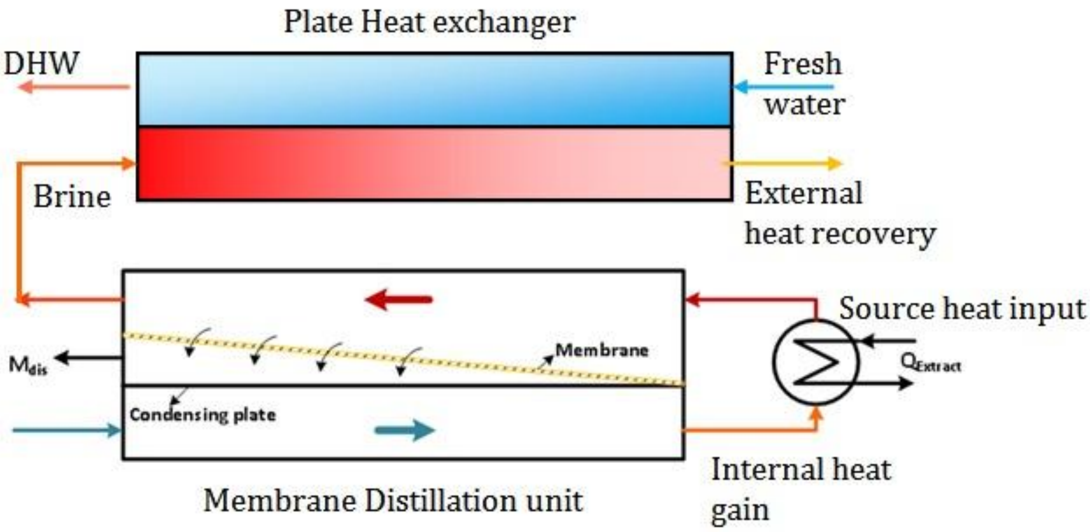


Figure 3.7 Heat recovery in Membrane distillation

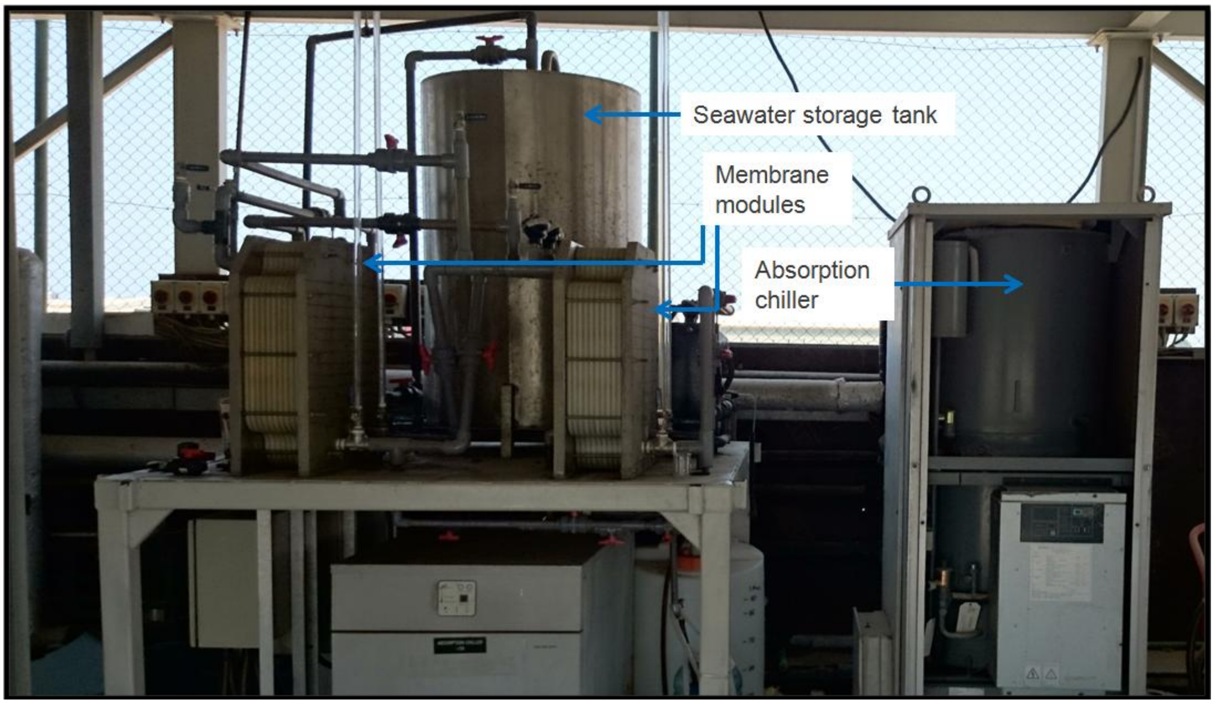


Figure 3.8 Installation of Polygeneration system

4 System Modeling and validation

This chapter deals with modeling of individual components of solar polygeneration system. The complete modeling and simulation is done using TRNSYS software, a commercial dynamic simulation tool used both in academic and industrial purposes. The basic components like solar collectors, storage tanks, pumps, controllers, heat exchanger, cooling tower, absorption chiller and multi-zone building model are chosen from TRNSYS library. Membrane distillation system is modeled via modification of a generic heat and mass transfer module .

4.1 Building model

The building model considered in the project is a multi zone building model (office cabins) located in CSEM-UAE test facility. The office cabin receives the cooling from STP system through fan coil units installed in the facility. The model has three office cabins with a total floor area of 91.75m² and one tent with a floor area of 25m² built in the SOLAB of CSEM-UAE. The detailed description of the material used and construction of the office cabins in figure 4.1. The exploded view of office cabin wall is shown in figure 4.2, a thick layer of polystyrene (38 mm) sandwiched between 4mm plywood sheets provides required insulation for better thermal performance [16].

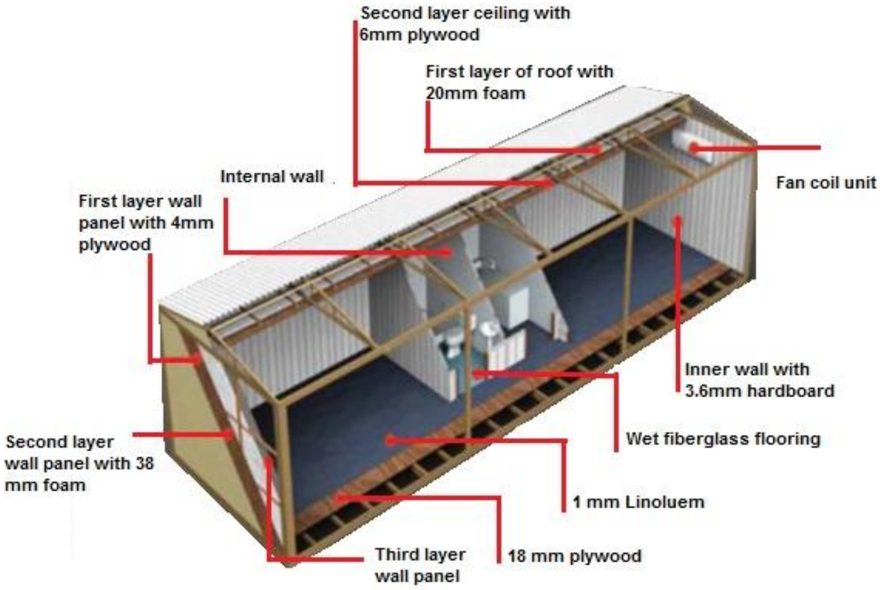


Figure 4.1 Construction of office cabins [16]

The schematic model of tent and material used for construction is shown in figure 4.3. The dimensions of the tent structure are shown in table 4.1. The daily cooling requirement of the office cabins and tent are determined by simulating the building using multi-zone building project application in TRNSYS which launches the in-build TRNBUILD for operations between 0800 to 1800 hours for an indoor temperature requirement of 22°C as shown figure 4.4. The thermal conductivities of walls are determined based on building construction materials used in office cabins and tents. Internal gains in the cabins are modeled for an occupancy range of 1 person per 10m², one personal computer for each person and required lighting loads. Infiltration rates for cabins are set at 0.5ACH and 0.7ACH for tent.

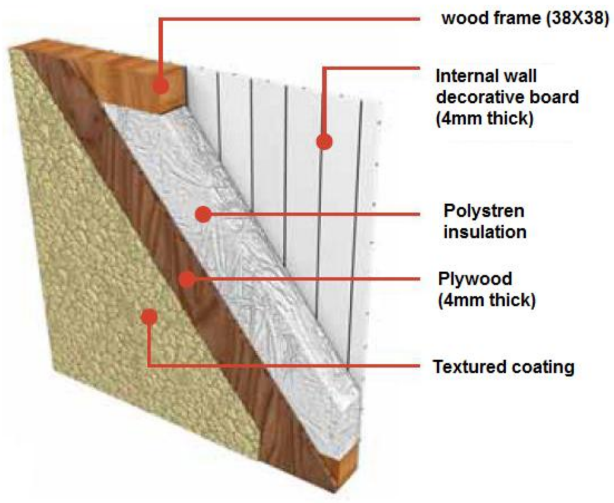


Figure 4.2 Sectional view of office cabins [16]

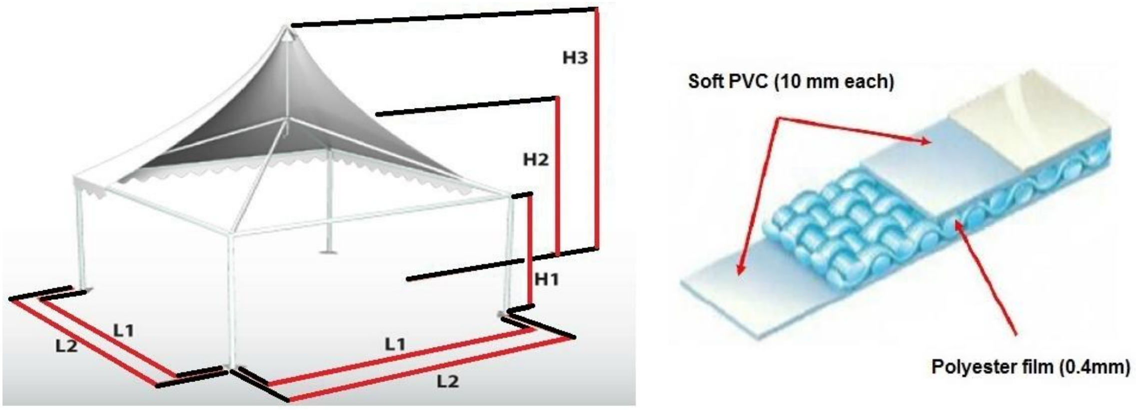


Figure 4.3 (a) 3D view and dimensions of tent (b) Detailed view of material used in tent [16]

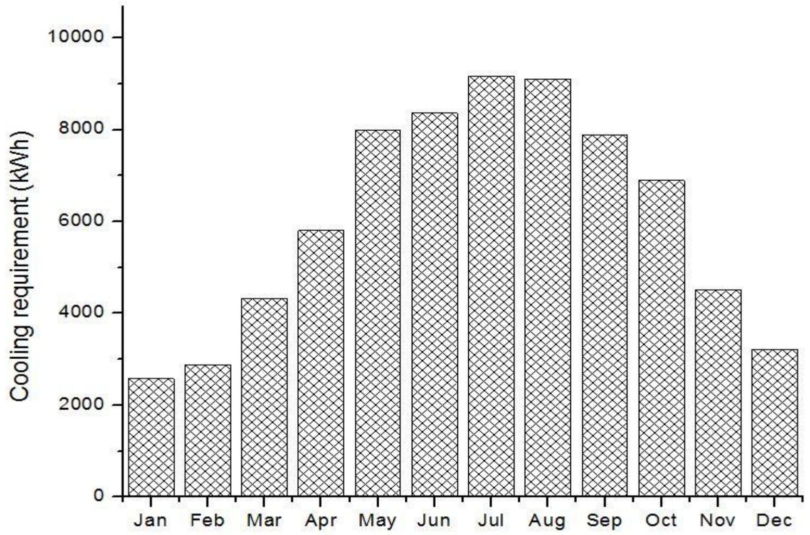


Figure 4.4 Annual cooling load profile of cabins in CSEM-UAE

Parameter	Value (m)
L1	5.00
L2	5.24
H1	2.44
H2	3.75
H3	5.60

Table 4.1 Dimension of tent

4.2 Evacuated tube collector

Evacuated tube collector (ETC) is simulated using type 71 model available in the TRNSYS library. The useful heat supplied by the collector is calculated by following equation [17]:

is the heat removal factor of the collector, is the product of transmittance and absorbance, is the collector area. The thermal efficiency of the collectors is calculated using quadratic efficiency curve [18].

The values of , and are available for any collector tested according to ASHRAE standards. ETC's are optically non symmetric, so biaxial incidence modifier is supplied as separate external file. The values of , and for the SEIDO 1-16 collector type are 0.73, 1.5W/m²K and 0.0054W/m²K respectively. The collector manufacturer data on incident angle modifier (IAM) on both transversal and longitudinal is shown in table 4.2.

$\theta[^o]$	0	10	20	30	40	50	60	70	80	90
IAM_{Tr}	1.00	1.00	1.01	1.04	1.07	1.06	0.99	0.86	0.61	0.00
IAM_{L}	1.00	1.00	1.00	1.00	1.00	0.98	0.95	0.86	0.61	0.00

Table 4.2 Incident angle modifiers

4.3 Thermal storage tank

The STP system includes three thermal storage tanks in the circuit. The first tank (HS1) is placed in solar collector circuit for storing hot water from the collector field. This storage tank is subjected to thermal stratification and provided with external heat exchanger configuration. Type 60c in the TRNSYS library is utilized for the purpose of the hot water storage capacity. The second tank (HS2) is placed between the absorption chiller and the office cabins to store the chilling water produced. HS2 is a non-stratification tank, so type 4a is used. The third tank is the domestic hot water supply tank. It is placed after PHE2 for temporary storage of DHW; it is a non stratified tank. In this project, DHW is utilized as pre-heated water source for the concentrated solar facility based in CSEM-UAE. HS1 is assumed to have five layers of well-mixed fluid volume of equal sizes providing single temperature node to maintain thermal stratification. Apart from that all the tanks are designed with identical connections points and parameters as shown in table 3. The energy balance of the n^{th} node model is shown [19].

Where T, , and are the water temperature, inlet mass flow rate of water to TS1, outlet mass flow rate of water from HS1 and thermal capacitance. is the thermal loss coefficient of the layer, A is the envelope surface area of one node, S is the surface area of HS1, μ is the conductivity and δ is the thickness of HS1. The heat energy ( ) supplied to HS1 is the useful energy obtained from the ETC field. It is calculated by:

Where is the mass flow rate of water in solar loop, is the temperature of water leaving ETC field and is the temperature of inlet water from HS1 to the ETC field, this temperature is equal to bottom temperature ( ) of HS1. The heat energy recovered from HS1 for meeting demands of utilities are provided by:

Where is the mass flow rate of hot water to generator of VAC from HS1, and are the temperature of water at top and bottom level of the HS1.

Parameter	Value
Tank Volume	1 m^3
Tank height	1.85 m
Height of Flow inlet 1	1.80 m
Height of flow inlet 2	0.70 m
Height of flow outlet 1	0.20 m
Height of flow outlet 2	1.80 m
Tank loss coefficient	0.803 kJ/h.m.K

Table 4.3 Connections to thermal storage tank

4.4 Absorption chiller

The absorption chiller cycle considered for the study is single stage LiBr/H_2O vapor absorption chiller with rated capacity of 35.2 kW. The chiller is sized based on the cooling requirements of the office cabins in CSEM-UAE. Detailed technical sketch of heat and mass transfer between internal components of single stage Li-Br Absorption chiller is shown in figure 4.5.

Thermal performance of absorption chiller is determined by amount of chilled energy produced to corresponding consumption of thermal energy in the generator. In generator, dilute mixture of Li-Br and water from absorber is heated separate the solution into water vapor and concentrated Li-Br. The weak solution entering generator has Li-Br in a fraction represented by x. Mass and energy balance of generator is calculated as:

Where is the heat supplied the generator of VAC, are the mass flow rate of hot water flowing through the generator, is the mass of dilute solution into the generator, is the mass of water in the dilute mixture, is the mass of lithium bromide in the dilute mixture, and are the mass of concentrated Li-Br and water vapor leaving the generator. , and are the enthalpies of the fluid at different points. and are the hot water inlet and outlet temperatures from heat source.

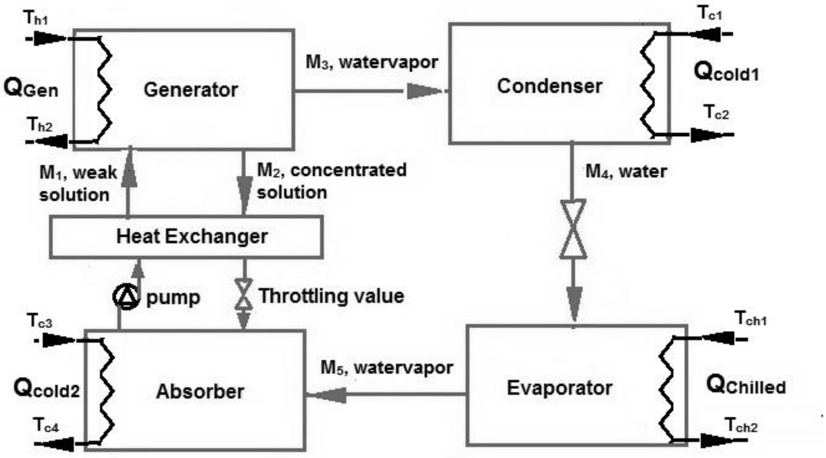


Figure 4.5 Energy and mass transfer in Absorption chiller

The water vapor leaving the generator is passed to condenser at the same pressure range (0.1 bar), condensed water is sprinkled over the coils in the evaporator at much lower pressure (0.01 bar) for production chilled water. Heat and mass balances in absorber and evaporator is given as,

Where is the mass of water entering the evaporator, is the mass of water vapor leaving the evaporator, is the mass flow rate of cold water supplied from cooling tower to the condenser, and are the cold water temperatures at the inlet and outlet of the condenser, and are the chilled water inlet and outlet temperatures, is the useful chilling energy produced by the VAC, is the energy recovered from the condenser.

The concentrated Li-Br from generator and water vapor from evaporator mixes in the absorber to produce the dilute solution and pumped into the generator to initiate the cycle. Energy and mass balances with the absorber is calculated as,

Where and are the cold water temperatures at inlet and outlet of absorber. is the energy recovered from the absorber. The COP of the absorption chiller is determined by, Solar Fraction cooling (SFC) is the fraction of cooling demand met by the STP, FC is used as the decision parameter is sizing the system.

4.5 Heat exchanger

Two counter flow heat exchangers are included in the modeling of STP system. First heat exchanger (PHE1) is utilized to recover heat from return hot water line of generator of VAC. Second heat exchanger is utilized to recover heat from hot saline water rejected from AGMD for production of DHW. Heat transfer rate in a heat exchanger is calculated by:

Where is the overall heat transfer coefficient, is the nominal heat exchanger area and is the logarithmic mean temperature difference.

The heat transferred in the heat exchanger can be calculated by energy balance on hot and cold side of AGMD module.

Where , , and are the temperatures of hot water inlet, hot water outlet, cold water inlet and cold water outlet of the heat exchanger. and are the mass flow rates on hot and cold sides of heat exchanger. The outlet temperature from the heat exchanger is calculated by combining equations 20, 24 and 25.

4.6 Membrane distillation

Membrane distillation configuration considered for the simulation studies in air gap membrane distillation type. The heat energy to AGMD is supplied by PHE1 by extracting it from hot water return line of the VAC. The mathematical model for AGMD is based heat and mass balances between the two sides of the module.

Mass transport in the AGMD is calculated using molar flux (N) of vapor diffusing through the air gap [20].

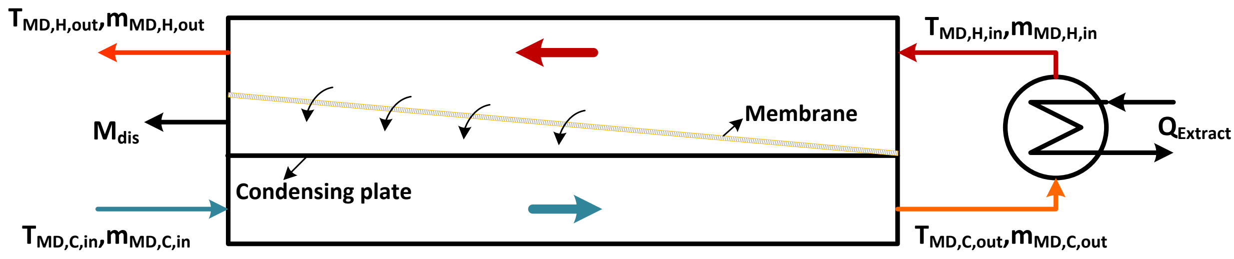


Figure 4.6 Heat and Mass Transport across the MD module

Where N is the molar flux, M is the molar concentration and D is diffusion coefficient of the water vapor-air mixture. The value of the product of molar concentration and diffusion coefficient is obtained in the function of temperature based on experimental investigations in water vapor-air mixture.

Energy balance between the sides of the air gap membrane is modeled by considering two type of heat transfer involved in the process (i) Energy flux due to conduction, (ii) Energy flux due to diffusion.

Where C_p is the heat capacity, and are the mean bulk hot and cold temperatures of fluid. K is the thermal conductivity, it is calculated by

, , and are the temperature of hot water inlet , hot water outlet, cold water inlet and cold water outlet of the AGMD.

is the porosity of the membrane material, is the thermal conductivity of air, it is empirically derived with respect to the hot inlet temperature. is based on material type, value of for PTFE (Polytetrafluoroethylene) is 0.22 $Wm^{-1}K^{-1}$[12].

Molar flux for the membrane region is calculated be integrating equations (30) and (31). Energy flux for the membrane region is calculated by integrating equations (32), (33) and (34).

Where and are the molar flux and energy flux of the membrane region. The molar flux and energy flux of the air gap region is calculated by

In order to achieve better analytical solution for the AGMD, the experimental equation for molar and energy flux is derived in function of membrane thickness, porosity, air gap thickness, inlet temperatures of hot and cold fluids. These equations provide better approximations as it is experimentally verified [12, 13].

Where is the molar flux produced in AGMD, b is the thickness of the membrane, L is the air gap distance, and are the mole fraction of water vapor on at the condensation and evaporation surfaces. Molar fraction are defined by

Where and are the partial pressure of the vapor at hot and cold sides. P is the total pressure. Mass flux can be obtained from molar flux as,

Where is the mass of distillate produced per hour for unit surface area of the membrane. Energy flux ( ) of the AGMD with good approximation level is calculated by [12, 13]:

The outlet hot and cold water temperatures from the AGMD are the governing parameters for integration of multi-effect system (Figure 6). The outlet temperatures of hot and cold water from the AGMD are calculated by energy balances. The heat transferred to the cold side of the AGMD can be calculated by

Where is the mass flow rate of water on the cold side of AGMD, is the heat transferred to the cold side of the AGMD, is the heat gained from distillate due to latent heat of condensation and r is the conversion factor.

Where is the latent heat of condensation. The cold water outlet temperature is derived from equations (47), (48) and (49)

The heat transferred from the hot side of the AGMD is calculated by

Where is the heat transferred from the hot side of AGMD, and are the mass flow rates of water at inlet and outlet of the hot side of AGMD, and are the temperatures of water at the inlet and outlet of the hot side of AGMD. The outlet hot water temperature from the AGMD is calculated by

4.7 Cooling tower

Wet cooling tower is utilized to reject heat from absorber and condenser of the absorption chiller. Since ambient temperatures in the considered location are high, dry cooling is not preferred. The total heat rejected in the cooling tower is sum of heat gained in generator and evaporator of the system. The energy balance of cooling tower is shown as,

At the rated capacity, flow rate of cooling water ( ) at 18400 kg/h is supplied to maintain the temperature difference around 8K.

4.8 Control Strategies

Several control strategies has been implemented for optimal and safe operation of the polygeneration system. Type 2b, ON/OFF type controller is used for controlling the flow parameters

4.8.1 Solar field control

The circulation pump between solar collector field and thermal storage tank is controlled by ON/OFF controller based on working fluid temperature. The circulation pump is turned off during two conditions (i) Low radiation case: If the temperature rise across the collector is less than 2K, (ii) High storage temperature case: If the tank top layer temperature exceed 95^{o}C.

4.8.2 Poly-gen control

The control between the thermal storage tanks and trigeneration system is done using ON/OFF controller. The STP will be turned ON, when the supply temperature from the hot water storage tank is greater or equal to70°C and outlet temperature from the chilled water tank is greater or equal to 12.5°C. STP operations will be turned if both conditions are satisfied at the same time.

4.8.3 Chilled water distribution control

This controller ensures that chilled water is distributed when cooling is required and chilled water temperature in the storage. The chilled water is circulated if the indoor temperature of the room drops below 22°C and chilled water in the storage is lesser than 20°C.

5 Experimental Analysis

With the successful system integration and installation of solar thermal polygeneration system, detailed experimental campaign is conducted to analyze the performance of STP system with different modes of operation. The STP system is operated in four different modes to evaluate the merits and demerits of different modes. The experiments were conducted in July on peak sunny days with peak global solar radiation reaching up to 850 W/m² as shown in Figure 5.1. The global irradiation is measure momentarily through Kipp and Zonen pyranometer. The polygeneration system is operated from 10:00 AM to 5:00 PM local time without auxiliary electric heaters. The polygeneration unit is designed with the flexibility that it can be operated in four different modes. This provides flexibility to the users to vary the system based on their requirements. In this flow rate of saline water to the membrane distillation system is optimized as 1200 l/h based on earlier experimentation in MEDESOL project [24].

(i) Solar cooling mode
(ii) Cogeneration of distilled water and domestic hot water
(iii) Trigeneration
(iv) Cogeneration of cooling and desalination

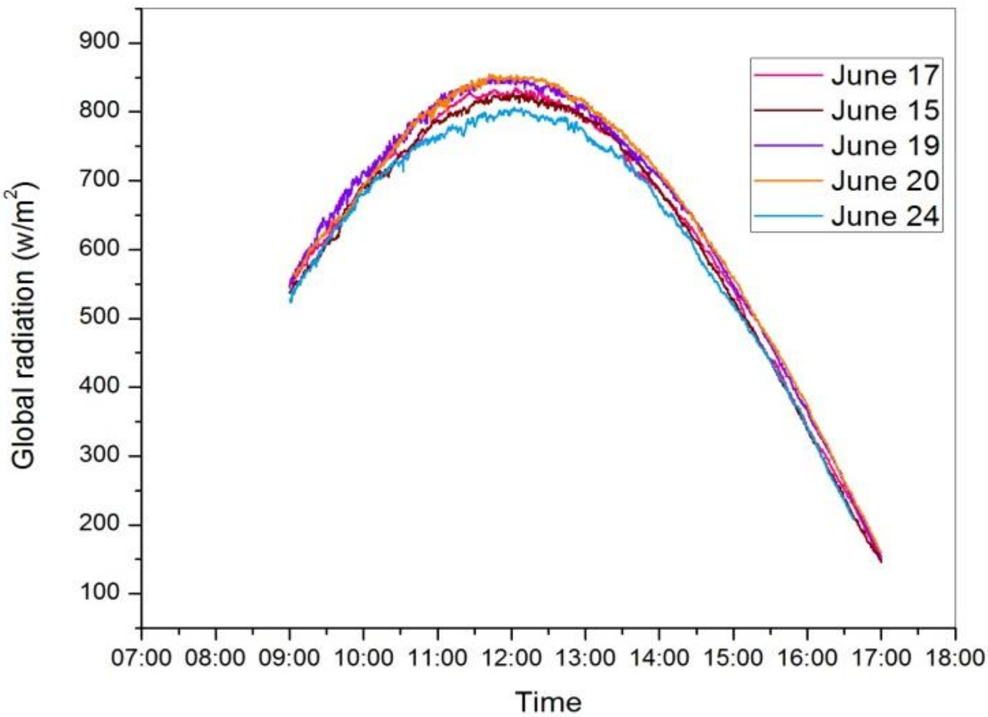


Figure 5.1 Global solar radiation during experimentation (Local time)

5.1 Solar cooling

The first mode of operation of the STP system is complete cooling and it is operated on typical summer day. In this mode, both the desalination and domestic hot water supply systems are not operated. The temperature and energy profiles of the cooling mode are shown Figure 5.2 and figure 5.3. As shown in Figure 5.2, the outlet temperature of collector gradually increases from 8:30 AM and it is utilized completely for charging the stratified tank. The operation of absorption chiller starts at 10:00 AM as the tank top temperature reaches more than 88°C. Due to steep decrease hot water supply temperatures, fluctuations in production chilled energy and COP is obtained during the first hour of operation. Throughout the day, the COP of system varies between 0.55 and 0.62 as shown in Figure 5.3. The refrigeration capacity stabilizes at 25 kW for most parts of the day, which is sufficient to provide cooling for all three office cabins on peak summer day. Energy and temperature profile reaches maximum in noon as expected with incident radiations close to 850 W/m² and COP also follows similar trends.

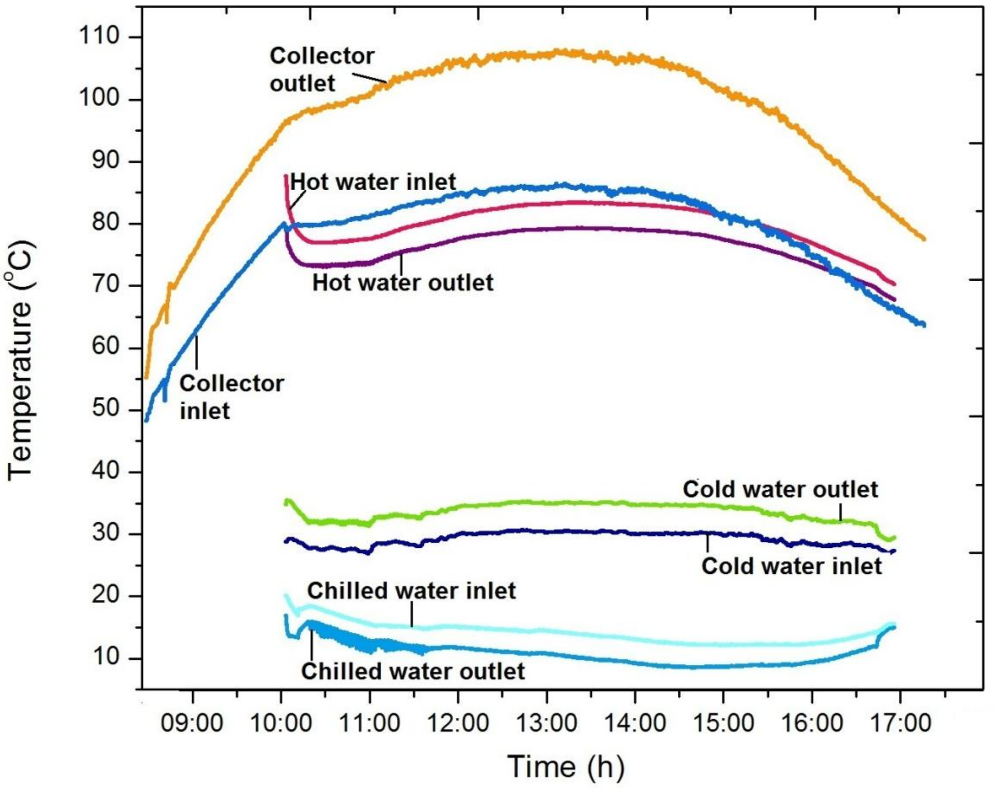


Figure 5.2 Temperature profile of solar cooling mode

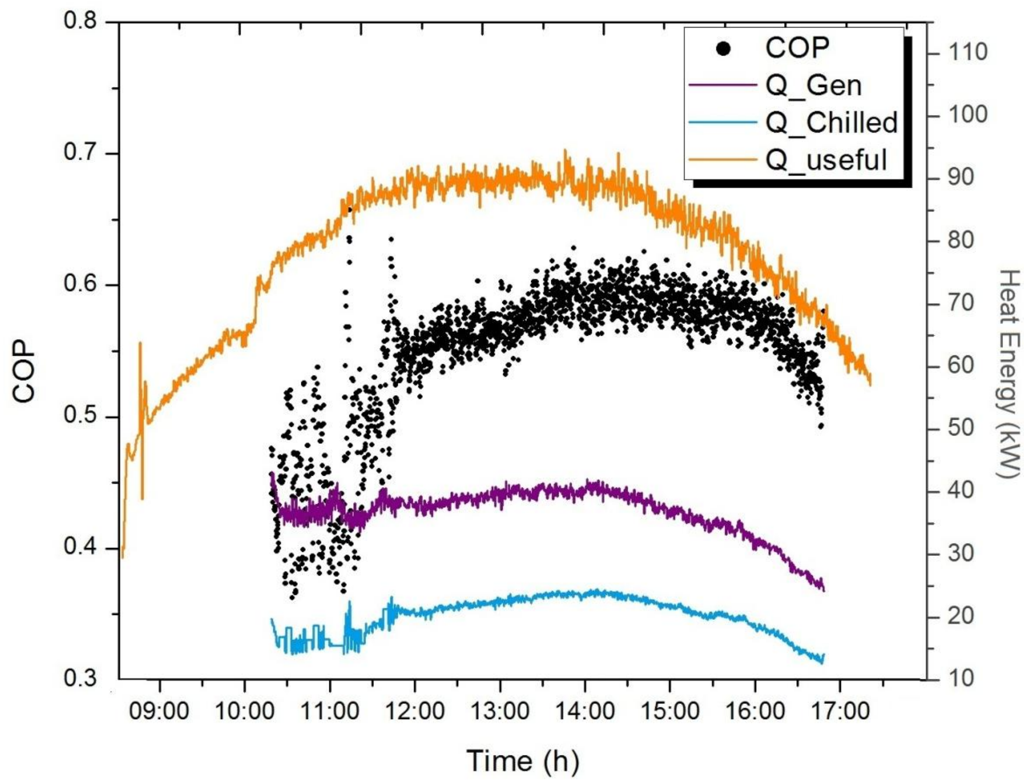


Figure 5.3 Energy profile of solar cooling mode

The energy flows in solar cooling mode during the peak load condition is shown in Figure 5.4. Incident energy from sun is converted into useful heat energy by the evacuated tube collector with an efficiency of 65%. This useful thermal energy is supplied to the polygeneration system, in this mode it is supplied to absorption chiller. Only 45% of useful energy is consumed by absorption for production of chilled water, it mainly due to losses in connections, pipes, tank and other components.

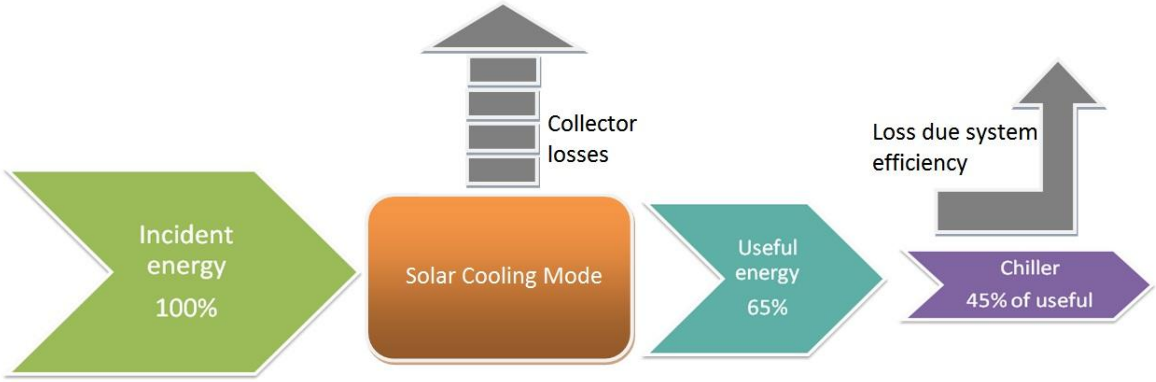


Figure 5.4 Energy flow in solar cooling mode

5.2 Co-generation of distilled water and domestic hot water

In this mode of operation, thermal energy from solar collectors is utilized completely for the MD unit to produce distilled water and heat recovered from MD for production of hot water for domestic applications. The system is operated with both single stage and double stage configuration to analyzed the performance of both the modules. Figure 5.5 shows the temperature profiles and productivity of two-stage MD operation. Saline feed water at conductivities greater than 65,000µS/cm (40,000ppm) was distilled using two AGMD modules to produce distilled water at conductivities less than 50µS/cm. The heat recovered from brine leaving the MD hot side is used to produce DHW with mean temperature around 55°C. Productivity of membrane distillation unit is mostly influenced by two important factors (i) Temperature difference between the hot and cold side (ii) Flow rates. As flow rate is optimized to 1200 liter/h based on previous findings, major factor influencing in terms of performance is temperature difference.

With a feed flow of 1200 l/h, the productivity reached a maximum of 12.5 l/h during noon time as the temperature difference reaches around 55°C. Total of 80 liters of pure water is produced for 7 hours of daily operation as shown in Figure 5.7. In single stage mode, a total of 47 liters of pure water is produced during the same hours of operation. Which proves almost 60% of production is contributed by first stage membrane distillation system as temperature difference in the second stage is on the lower side. Gain to output ratio (GOR) is the performance evaluation parameter commonly used in membrane distillation systems. Overall GOR of two stage systems is 0.7 which is much higher compared to single stage system.

Compared to single stage operation, 45% more productivity is obtained for two stage process and also heat could be recovered effectively from MD hot side for DHW production. As shown in Figure 5.6, from the total useful energy, 50% energy has been utilized for this mode of operation from which 75% is recovered for DHW production and the remaining is used for distillate production.

Energy flows in the cogeneration mode is shown in Figure 5.8. Energy conversion from incident to useful is similar to solar cooling mode. In terms of final conversion, around 57% of the useful energy is utilized by the system.

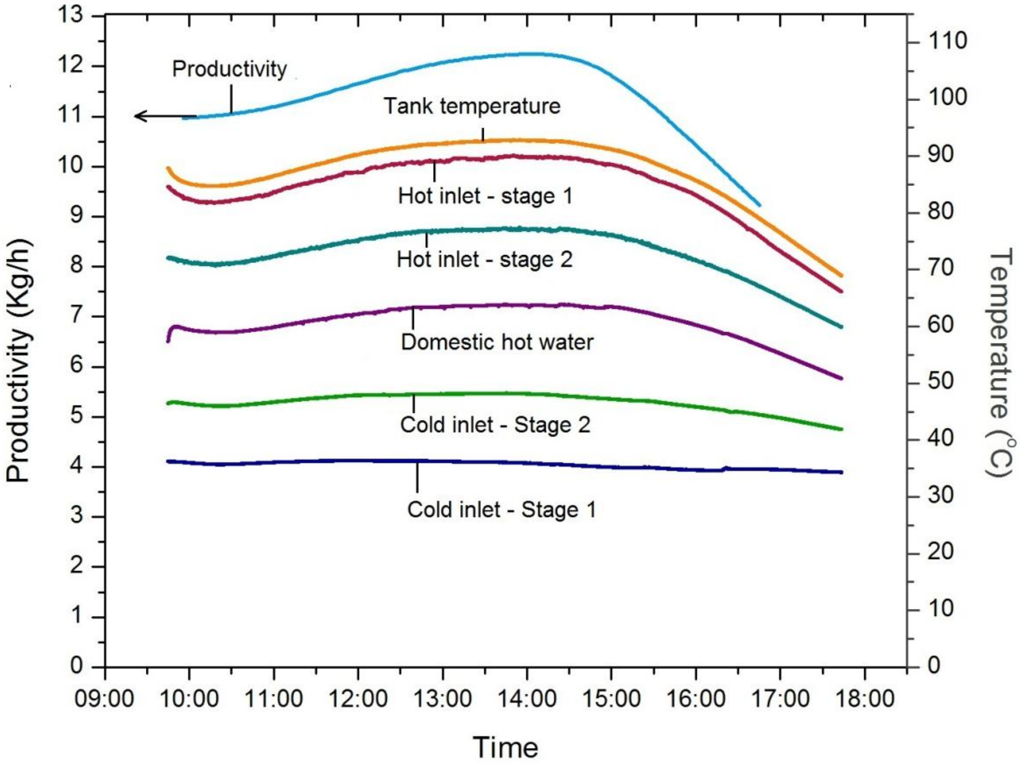


Figure 5.5 Temperature profile and productivity of cogeneration mode

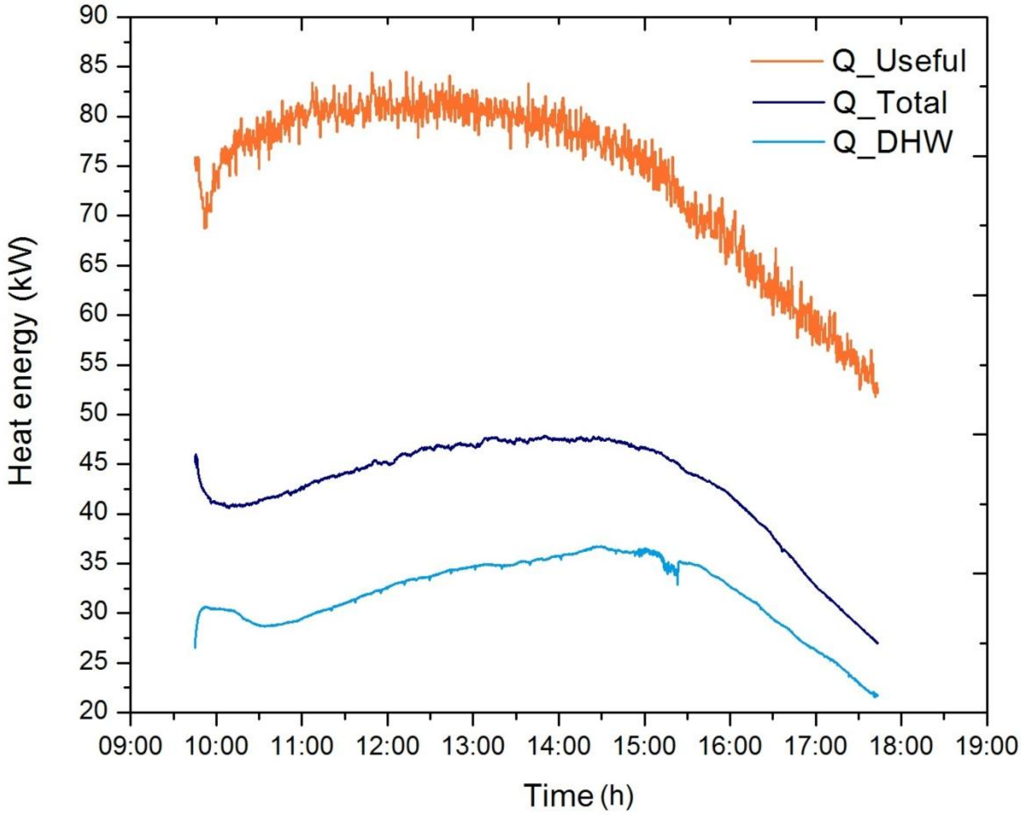


Figure 5.6 Energy profile in cogeneration mode

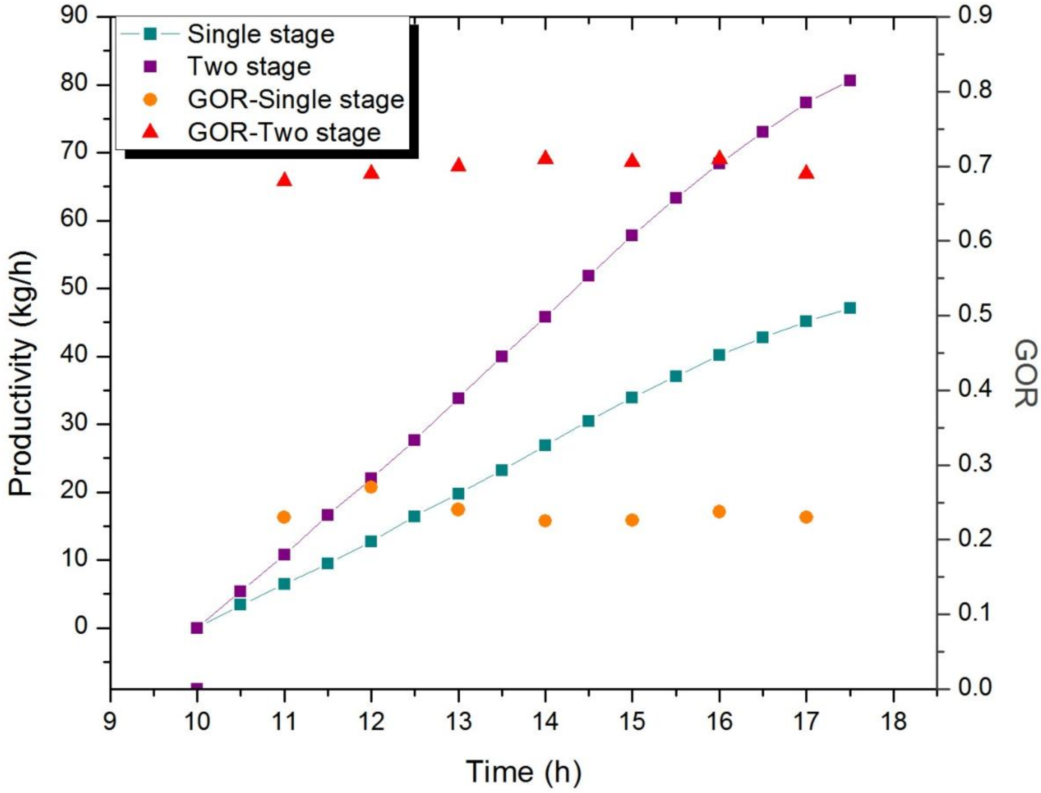


Figure 5.7 Cumulative productivity and GOR

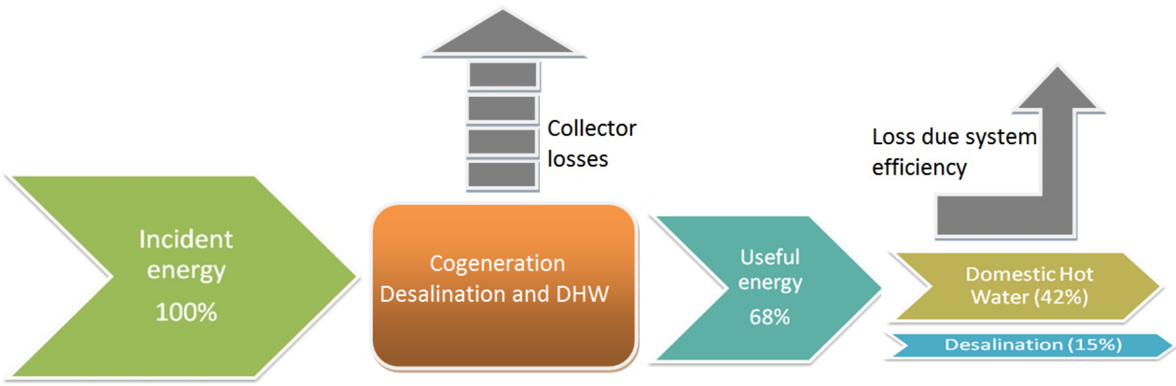


Figure 5.8 Energy flows in cogeneration of desalination and DHW

5.3 Trigeneration Mode

This mode is a combination of complete cooling and cogeneration modes. By integrating membrane distillation and DHW processes with the chiller, turns the whole system into tri-generation mode. Figure 5.9 summarize the performance of absorption chiller. The chilled water is produced at an average of 14°C when the hot water inlet temperature varies between 70°C and 75°C during the day. Mean chilled energy production of 14 kW is achieved in this mode, which is sufficient to fulfill cooling demand of two office cabins with COP varying between 0.45 and 0.50. Figure 5.10 summarize the performance of membrane distiller and DHW processes. In this mode, single stage membrane distillation unit is integrated with the system leading to a mean hourly production of 4 liters/h with an average ΔT of 30°C between hot and cold side of MD. As shown in Figure 5.10, an average energy of 30 kW is consumed by MD process out of which 25 kW is recovered for domestic hot water production at a mean temperature of 55°C. In this case, 170W of thermal energy is used for kg of pure water production which is five times less than the reported values in literature [14] without heat recovery option. This mode has an advantage of utilizing the total available energy effectively to produce DHW along with cooling and pure water production.

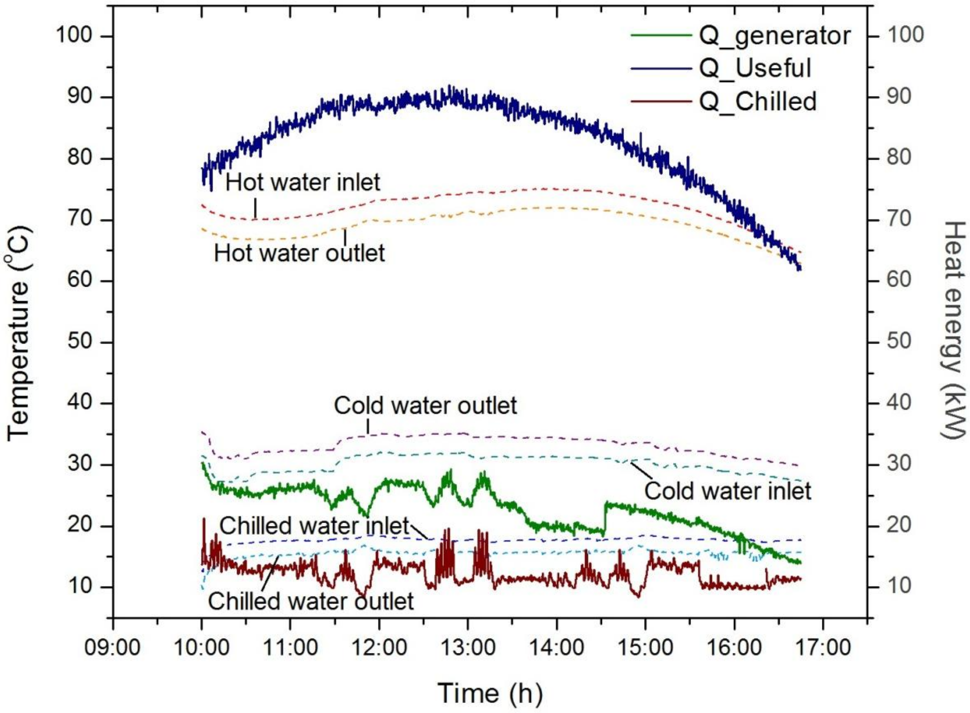


Figure 5.9 Temperature and Energy profile of absorption chiller in trigeneration mode

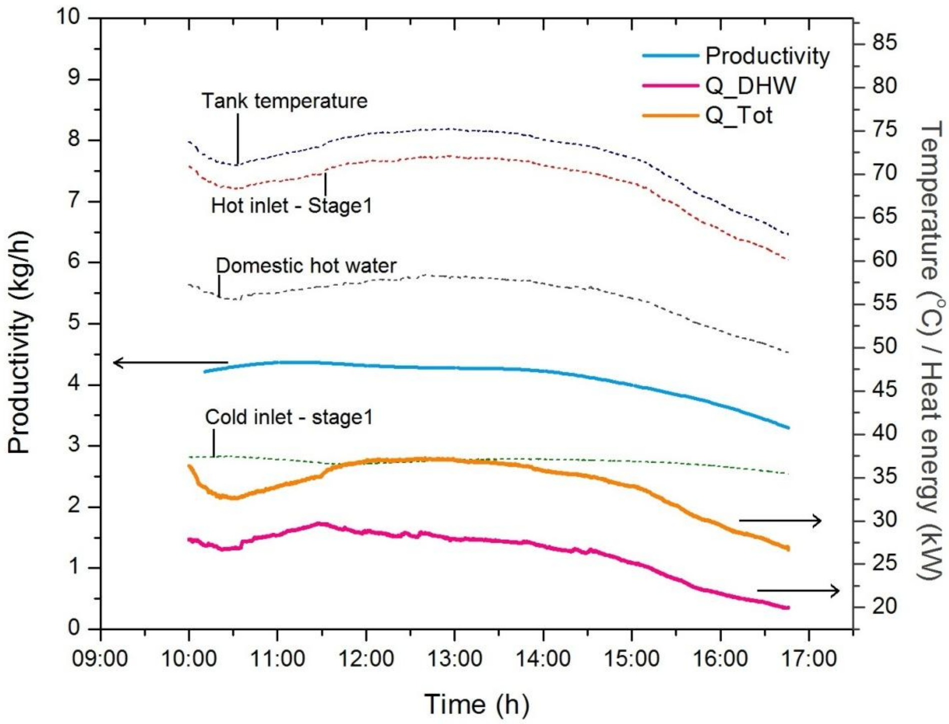


Figure 5.10 Temperature, energy and productivity profile of MD in trigeneration mode

The individual performance of absorption chiller, membrane distiller reduces by 35% but as whole system, system efficiency reaches 67.5%. Collector efficiency maximizes in tri-generation as operating temperatures are much lower than other modes. Energetically, this mode utilizes more amount of available energy compared to other modes as shown in Figure 5.11.

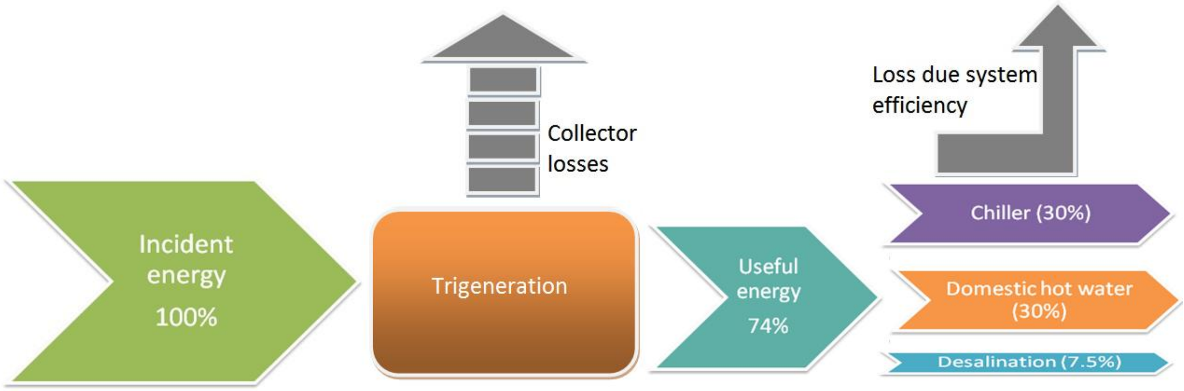


Figure 5.11 Energy flows in trigeneration mode

5.4 Co-generation of cooling and desalination

The fourth mode of operation includes a two-stage MD module to increase the pure water production rather than obtaining sufficient temperatures for DHW during heat recovery through single stage. Figure 5.12 shows the performance of two stage MD and DHW system in tri-generation mode. The performance of solar cooling remains similar to the earlier mode of operation. However, compared to the earlier mode of operation, an average of 2kg/h of distilled water is produced from the two MD modules. Since the DHW could not be obtained at sufficient temperatures (average of 50°C), this mode could be termed as co-generation of cooling and desalination instead of tri-generation. This mode is particularly useful in summers during which DHW is not required at high temperatures and also pure water requirement is higher.

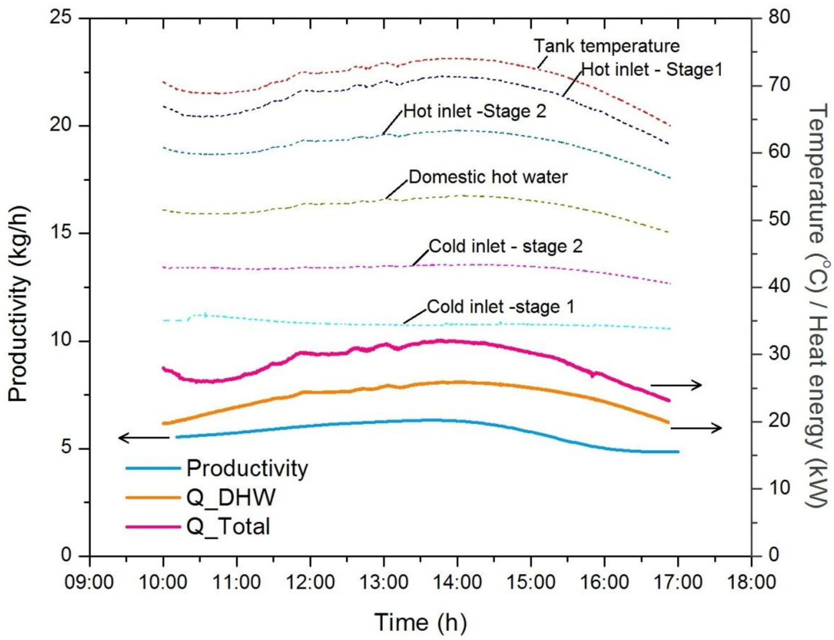


Figure 5.12 Temperature, energy and productivity profile of MD in Cogeneration (ii)

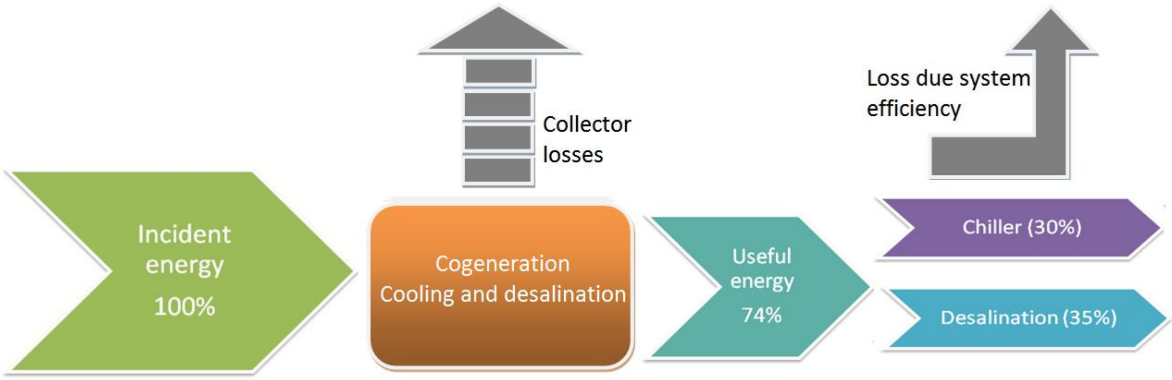


Figure 5.13 Energy flows in Cogeneration mode (ii)

The energy flows in this mode is similar to trigeneration mode, since the DHW produced at lower temperature it is not considered in the energy flows as shown in Figure 5.13.

6 Dynamic simulation and Economic analysis

The solar thermal trigeneration system is modeled and dynamically simulated with all integrated components are operated at peak load conditions. TRNSYS software is utilized for analyzing the performance of the system, as the whole system is modeled as shown in Figure 6.1. The cooling demand of office cabins is used as sizing parameter in the study. SFC- solar fractional cooling is the ratio of cooling demand to chilled energy produced; it is used as the deciding parameter in sizing. The simulation is performed for whole year (8760 h) and one summer day (24h) with a simulation time step of 1.2 min.

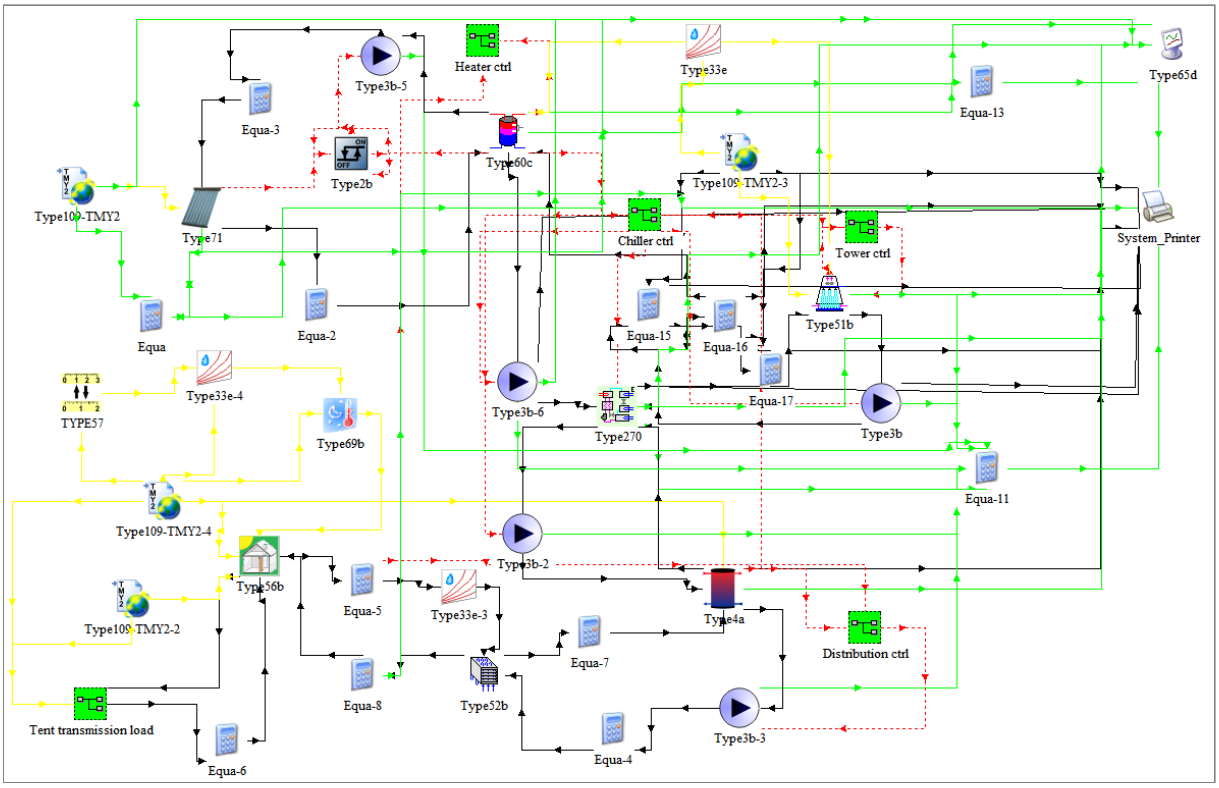
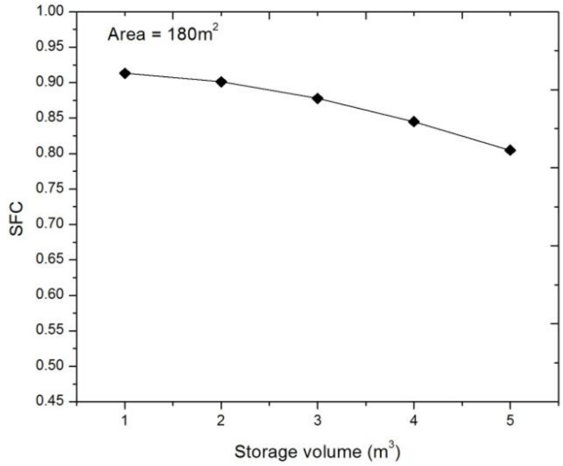


Figure 6.1 Solar thermal polygeneration system modeled in TRNSYS

6.1 System sizing

The component sizing is conducted in solar collector circuit by varying the collector area and storage volume to achieve complete cooling requirement. The simulations are performed for cooling season (i.e) series of months having higher cooling requirements between March and November. Other performance parameters like tilt angles of collector and flow rates are also analyzed during the simulation. The results on tilt angles and flow rates are agreeable with current working condition. As the performance of system maximizes at 15° tilt angle. The performance of STP system is analyzed by varying the storage capacity between $1m^3$ and $5m^3$ as shown in Figure 6.2 (a). The SFC decreases with increase in storage volume, because load requirements are during the day time and higher storage capacity leads to long charging process. With the optimized the storage volume, the performance of STP is further evaluated by varying collector area. The three collectors with gross area of $4m^2$ each is connected in series in the experimentation, so the area of collectors are incremented by 12 m^2. In order to achieve complete cooling, total gross area of 216 m^2 is required as shown in Figure 6.2 (b). This area is 40% higher than the installed capacity of evacuated tube collectors in CSEM-UAE.



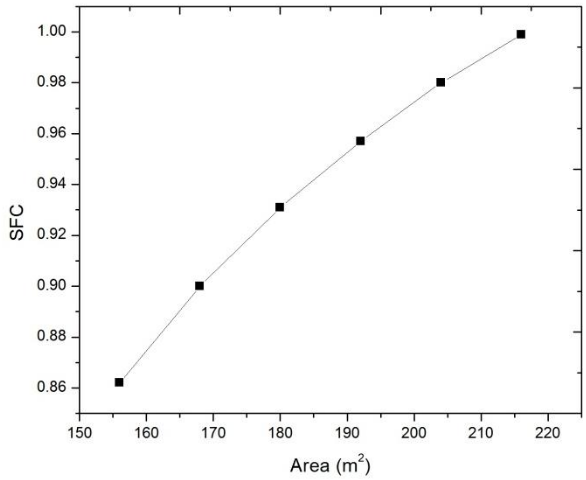


Figure 6.2 (a) Performance variation with storage capacity (b) Performance variation with collector area

6.2 Thermal performance of tri-generation system

6.2.1 Performance of absorption chiller

Thermal performance of the single stage absorption chiller at full load condition is analyzed in this section. The temperature and energy flows in the absorption chiller for a summer day is shown in Figures 6.3 and 6.4. Hot water supply temperature to the generator is set between 70°C and 95°C using chiller controller and chilled water is supplied to the cabins at 12°C through chilled water distribution control. The charging of storage tank takes places during first two hour of operation from 8:00 AM to 10:00 AM, operation of chiller starts as soon as the temperature of hot water reaches 94°C. Fluctuation in temperature profile is achieved due to ON/OFF controller monitoring the flow temperatures of chiller. The chilled water is continuously produced around 12.5°C during the 8 hour operation. Mean chilled energy of 34 kW is achieved the operating hours. COP of the absorption chiller falls between 0.7 and 0.73 for a typical summer day as shown in Figure 6.4.

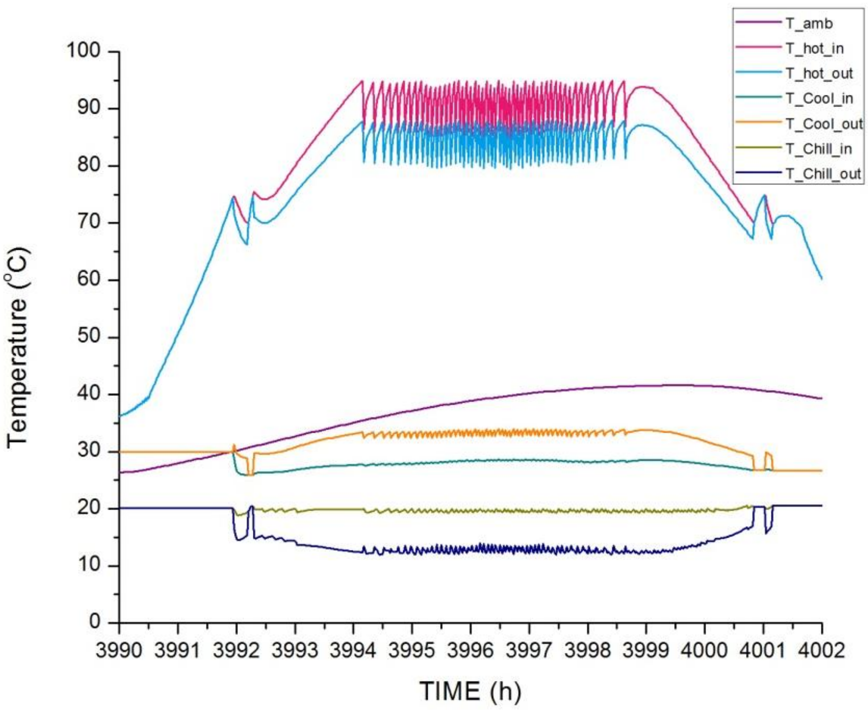


Figure 6.3 Temperature profile of absorption chiller during a sunny day

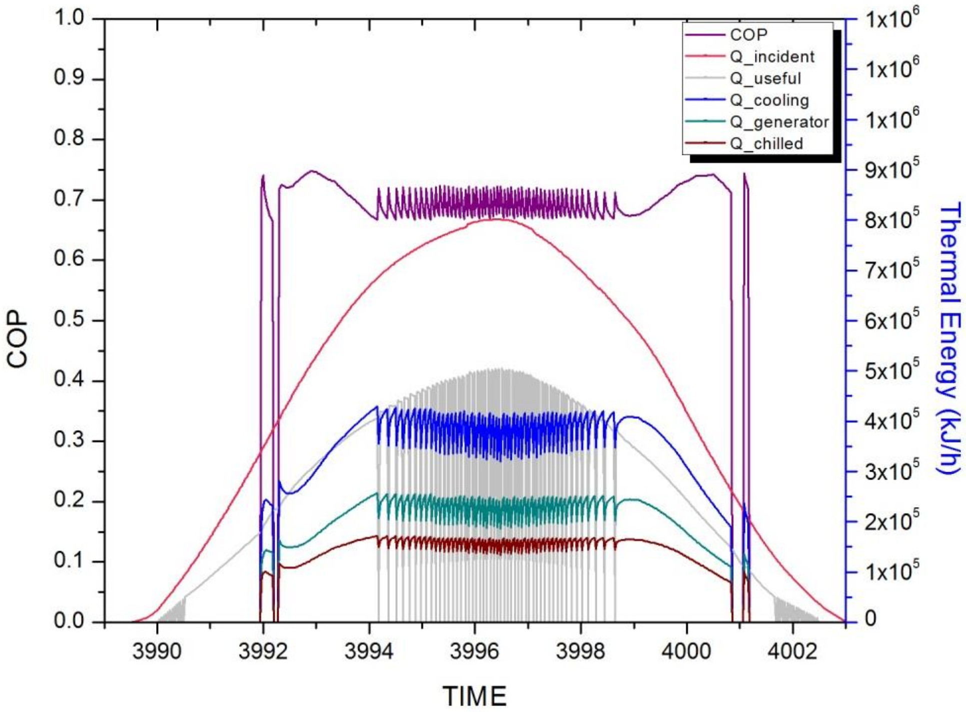


Figure 6.4 Energy profile of absorption chiller during a sunny day

6.2.2 Performance of desalination and DHW system

Temperature flows and distillate flux in the membrane distillation system with multi-effect configuration is shown in Figure 6.5. The hot sea water is supplied in the range of 70°C to 80°C during the peak operational period. Cold water leaving the AGMD unit is pre-heated by internal heat recovery from the hot side. Heat energy available in the rejected brine is utilized for domestic hot water production using the heat exchanger, PHE2. During the peak operational hours, 1200 l/h of domestic hot water is produced and continuously supplied to concentrated solar facility. Temperature and energy profile of domestic hot water production is shown in Figure 6.6. Energy consumption for the domestic hot water decreases during noon as the ambient temperature gradually increases. The annual performance of domestic hot water system is shown in Table. 6.2, the energy consumption in the winter is higher due to lower ambient temperature.

Performance of AGMD system with double effect configurations are analyzed, the mean hourly production lies in the range of 12 liters for double-effect configuration as shown in Figure 6.5. Annual performance of membrane distillation system in terms of daily production is shown in Table 6.2. Daily productivity of membrane system for all the months lies between 70 to 94 l/day. Productivities in the winter months are augmented by lower inlet temperature on the cold side.

6.2.3 Combined efficiency

The performance of solar polygeneration system is evaluated using combined efficiency as an indicative parameter. Combined efficiency is a ratio of all the useful work from absorption chiller ( ), membrane distiller ( ) and domestic hot water supply ( ) to the incident solar energy, combined efficiency is calculated by

The combined efficiency for a typical summer day is shown in Figure 6.7, fluctuations in the efficiencies are due to ON/OFF controlling provided to the chiller. Mean monthly combined efficiencies varies from 30% to 38% as shown in Table 6.1.

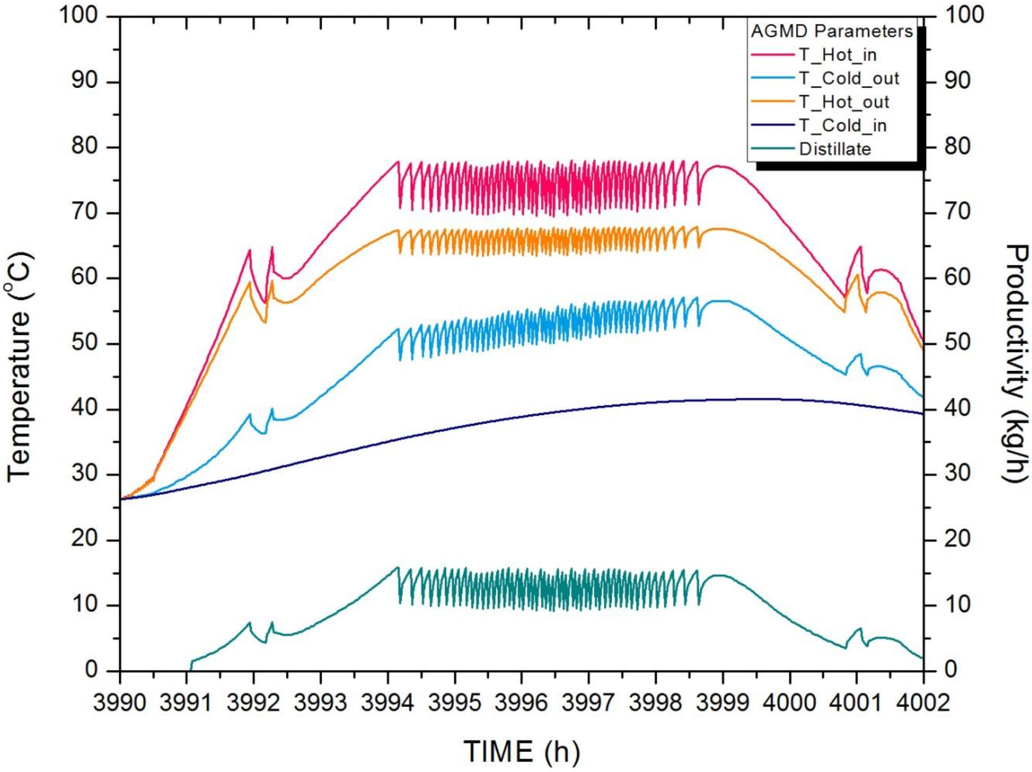


Figure 6.5 Temperature profile and productivity of membrane distillation system during a summer day

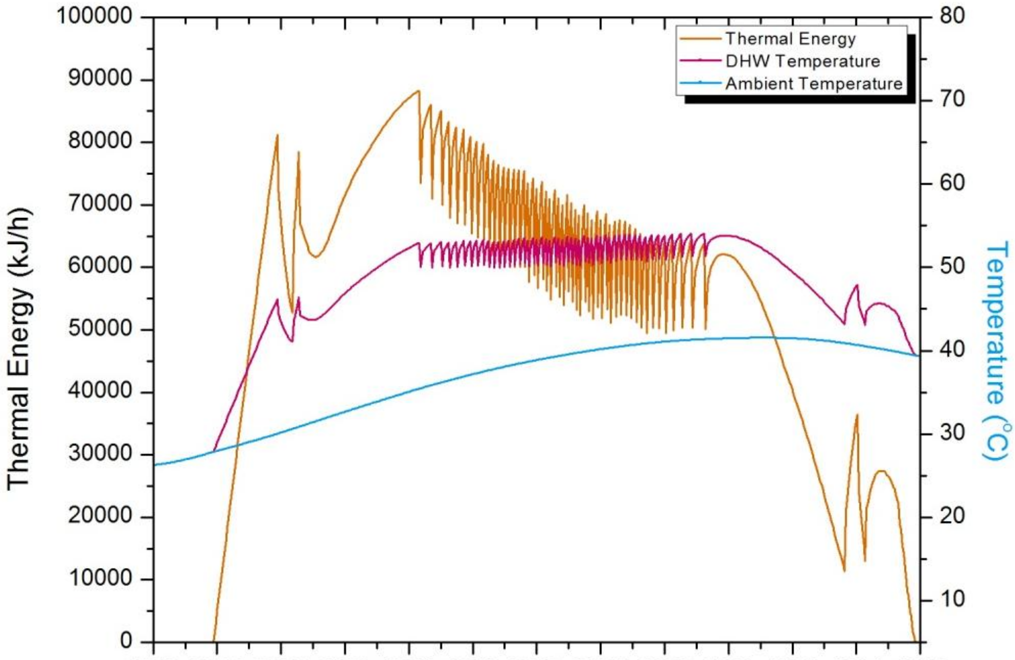


Figure 6.6 Temperature and energy profile of domestic hot water supply

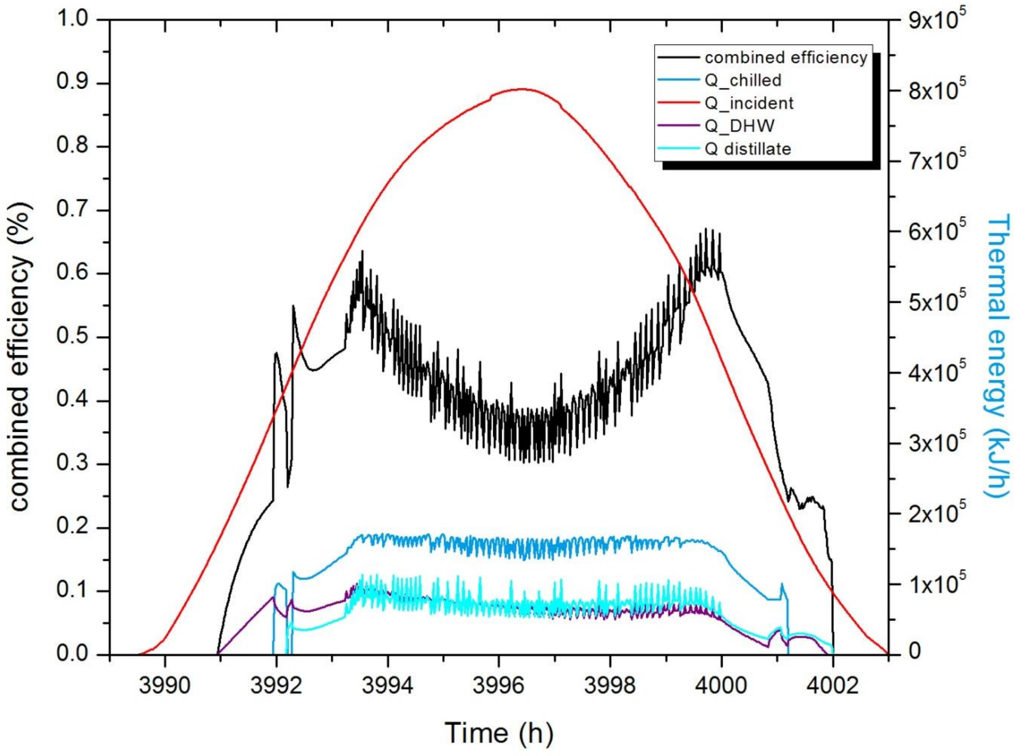


Figure 6.7 Energy flows and combined system efficiency – Summer day

6.3 Validation of model

The model developed in TRNSYS is validated with the experimental results by dynamically simulating the system with same area of the collectors. The results obtained between experimental and simulated model is shown in Table 6.1. The validation is conducted for tri-generation mode with single stage integration, results obtained with both theoretical and experimental works matches closely. Thus the model is validated. Poly-gen efficiency is considered in validation, where energy utilized by the generator of VAC is considered in the evaluation.

	Peak Collector efficiency (%)	$Q_{Chilled}$ (kW)	COP	Productivity (kg/day)	Poly-gen efficiency (%)
Experiment	70	14.2	0.5	26	67.5
Simulation	67	17.8	0.55	28.5	71

Table 6.1 Validation of Model

6.4 Environmental analysis

UAE is 8th largest carbon dioxide emitter in terms of per capita in the world [30], thus renewable energy driven cycles provides an opportunity to reduce the emission of greenhouse gases and global warming. The environmental impact is calculated in terms of amount of CO_2 avoided by fuel saving. CO_2 emission coefficient for United Arab Emirates is 600g of CO_2 per kWh of electricity production [32].

Figure 6.8 shows the amount of CO_2 avoided in function of collector area and solar fractional cooling. A total of 114 tons of CO_2 is reduced per annum by the STP. Potential cost saving through carbon credits is analyzed, carbon credits between \$10 and \$20 per ton of CO_2 avoided is considered in the study.

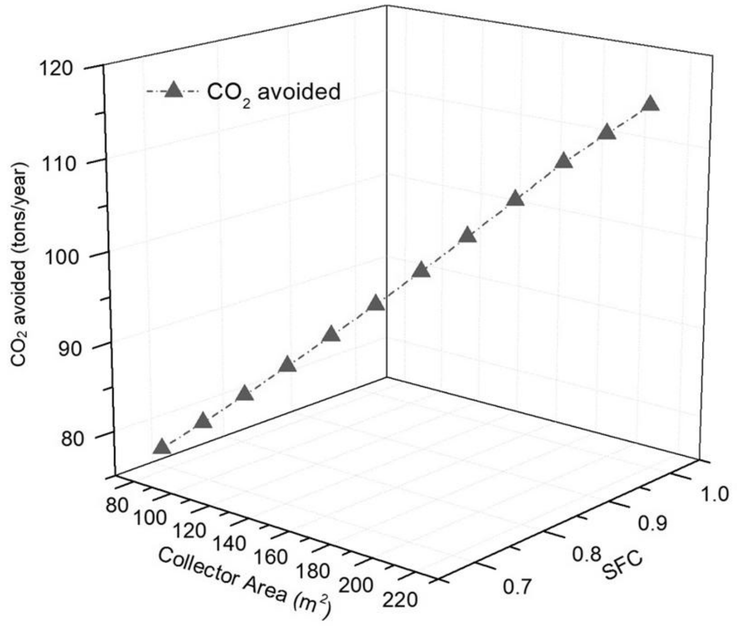


Figure 6.8 Total CO2 Avoided by STP

Month	Collector efficiency (%)	Productivity (kg/day)	$Q_{chilled}$ (kWh/day)	Q_{DHW} (kWh/day)	System efficiency (%)	Combined efficiency (%)
January	45.99	81.6	114.78	286.85	68.84	31.66
February	49.02	88.96	143.48	301.67	68.91	33.78
March	49.54	89.92	181.10	280.092	67.56	33.47
April	51.46	92.8	240.56	251.78	65.50	33.71
May	53.13	90.4	262.16	200.31	66.91	35.55
June	57.1	84.16	369.60	195.43	65.95	37.66
July	58.3	85.12	297.54	177.94	60.70	35.39
August	55.6	86.5	295.79	170.52	60.20	33.48
September	51.4	84.45	269.78	211.95	63.90	32.86
October	49.44	81.28	248.27	197.79	65.39	32.33
November	48.31	80.34	180.93	230.195	66.61	32.18
December	46.91	70	156.07	211.38	65.91	30.92

Table 6.2 Annual performance of tri-generation system

6.5 Economic analysis

Solar thermal driven polygeneration system considered in the study has lower operational costs compared to conventional cooling and desalination systems when operated separately. Major hindrance in solar thermal driven processes is high initial investment cost, so payback period is chosen as economic criteria to evaluate the benefits based on design parameters. In this research work, payback period (PB) is calculated based time period required to recover initial investment with cumulative fuel saving [33]. Net cumulative saving (NCS) from the project over the lifetime is determined through present worth factor (PWF).

The costs of individual components are shown in Table 6.3. Sensitivity analysis is performed with different collector types and fuel costs.

Component	Abbreviation	Value
Solar collectors [24]		294\$/m^2
35kW Absorption chiller including Wet cooling tower, pumps and sensors [25]		61800\$
Land [26]		180\$/m^2
Membrane distillation modules [27]		AGMD1-7000\$/unit
Membrane replacement [28]		15% of
Titanium heat exchanger [28]		2000\$/m^2
Hot storage tank*		4130\$/m^3
Cold storage tank*		4130\$/m^3
Pump [17]		881$W_p^{0.4}$
Hydraulics [27]		0.15 + 0.05 +0.05
Installation costs [27]		5% of total component cost
Inflation rate [17]		10%
Interest rate	D	5%
Cost of fuel		0.12\$/kWh
Lifetime of the system	n	20 years

* Provided by the manufacturer (Tisun)

Table 6.3 Cost of individual components

is the initial investment cost for the polygeneration system, is fuel inflation rate, is the discount factor, is the total energy saved and is the cost of the fuel. Initial investment is includes investment costs of all the components of the polygeneration system as shown in equation (61).

Payback period variations and cumulative saving potentials are shown in figure 6.9. Analogies based on different fuel cost were analyzed, impressive payback period and net cumulative savings are achieved if the fuel prices are higher. Payback period will be shorten by 50% for fuel prices between 0.08$/kWh and 0.16$/kWh. Net cumulative savings potential of the project increases by 3.75 times across different fuel costs as shown in figure 6.9. Annual cash flows and net cumulative savings of the solar polygeneration system is estimated with current fuels of 0.12$/kWh is shown in figure 6.10. Net cumulative saving of $516,978 will be achieved by implementing the project based on current fuel costs in UAE. Implementation of carbon credits reduces the payback period by 6.75% and net cumulative saving increases by 15.8%. The payback period and net cumulative saving for different values of carbon credits are shown in figure 6.11.

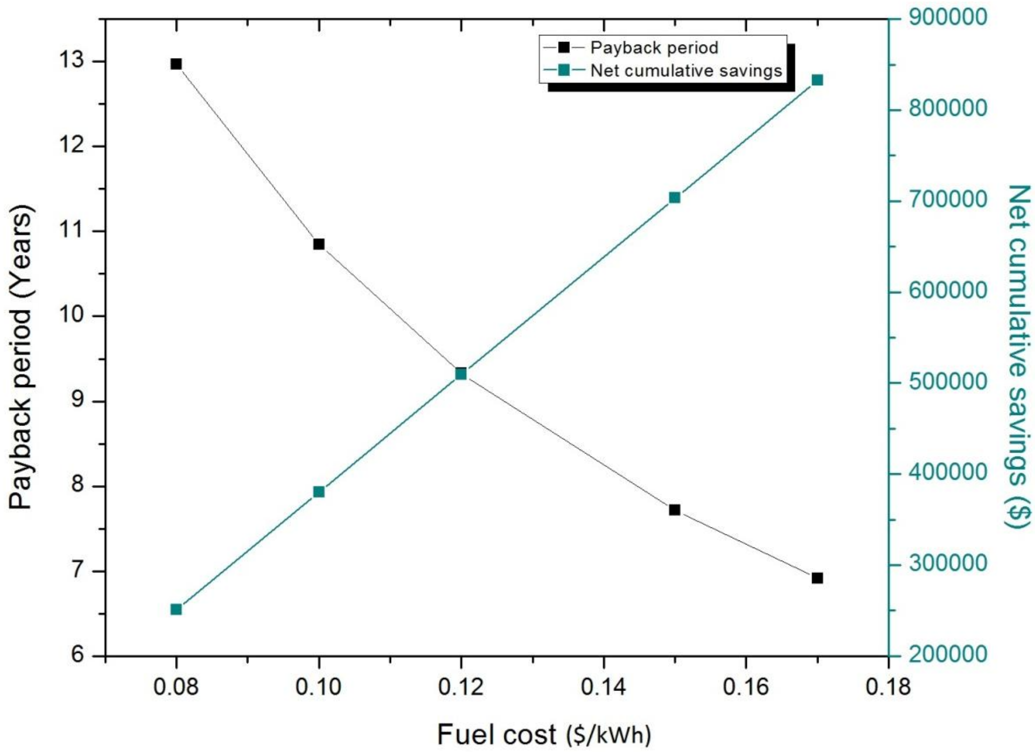


Figure 6.9 Payback period and net cumulative savings for variation of fuel costs

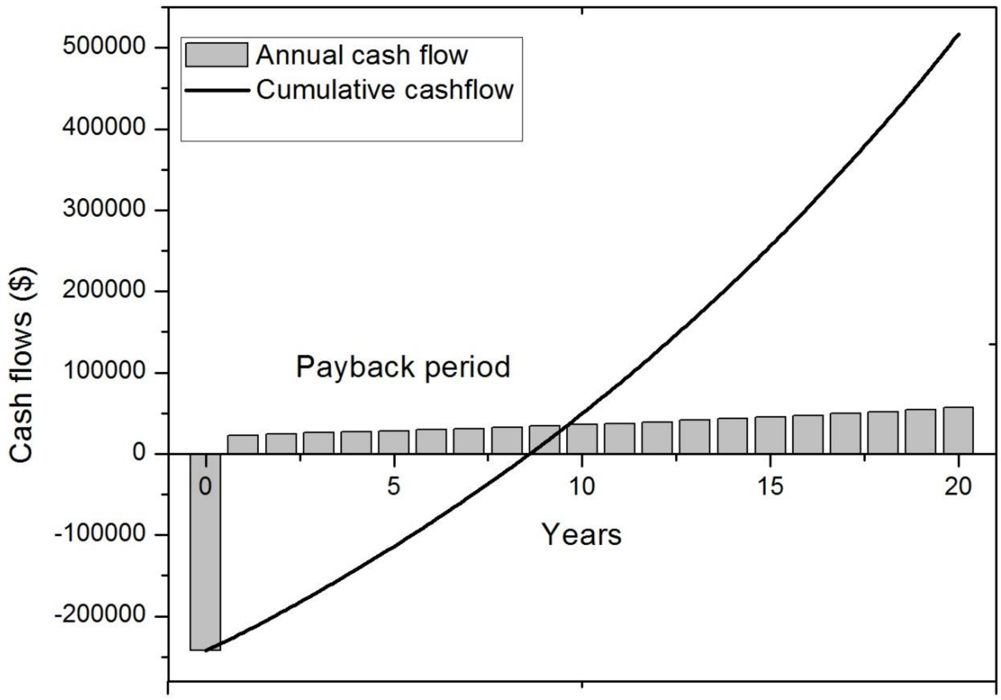


Figure 6.10 Annual cash flows

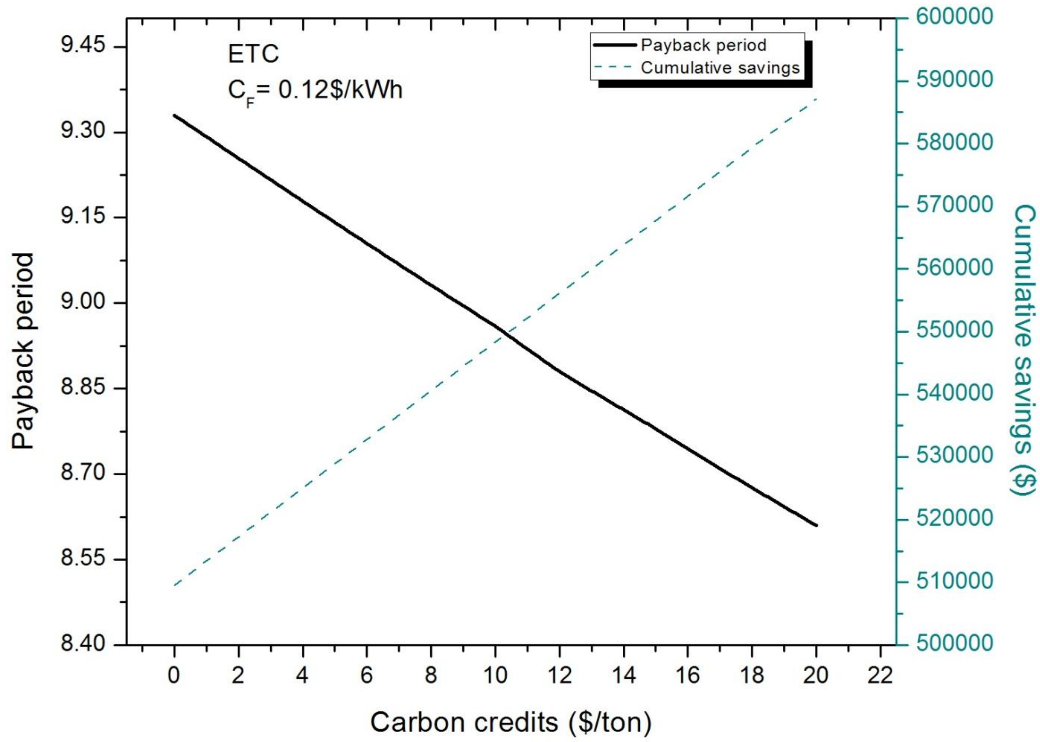


Figure 6.11 Variation in payback period with carbon credits

7 Conclusion

Solar thermal polygeneration system is developed by integrating evacuated tube collectors, absorption chiller, membrane distillation and heat exchangers for simultaneous production cooling, fresh water and domestic hot water. The system is installed in CSEM-UAE and experiments were conducted in four different modes during the peak summer month of July. Some conclusions drawn from the experimentation as listed below

- Membrane distillation system is operated with internal and external heat recovery technique, which consumes 6 times lesser energy than MEDESOL project [14]. Around 75% of energy is recovered for production of DHW at 55°C
- Sea water with TDS of 40,000ppm is desalinated in the STP system to a salinity level less than 30ppm.
- Solar polygeneration system utilizes 22.5% more useful energy in trigeneration mode than solar cooling mode, which is advantageous both energetically and economically
- Cogeneration mode with production of distilled water and domestic hot water is useful in winter as cooling is not required. Around 80 liters of fresh water is produced by two stage mode with gain to output ratio of 0.7
- In trigeneration mode with single stage membrane module integration, it produces 4 l/h and with double stage, productivity increases by 48%

Further the system is dynamically simulated to analyze the performance in peak load conditions of the components attached to the STP system. Some conclusion drawn from the results are shown. The model is also validated with the experimental results.

- In order achieve full potential of STP system, gross collector area should be increased by 40% or equivalent amount of auxiliary energy should be supplied
- On a peak summer day, system produces around 90 liters of fresh water and 34 kW of chilled energy.
- In terms of annual performance, productivity of desalination system varies between 70 to 94 liters per day. In terms of system efficiency, performance is better in winter months due to lower ambient weather conditions
- Combined efficiency of STP maximizes in summer with 37.5% due to the lower collector efficiency in winter months.
- With optimized design conditions, payback period of 9.33 years and net cumulative savings of $516,972 were achieved in terms of fuel savings
- In terms of environmental protection, 114 tons of CO_2 emissions are avoided by using STP system
- Avoided CO_2 provides cost saving by implementation of carbon credits, net cumulative saving is increased by 15.8% and payback period is reduced by 6.75%

Future work:

- The system developed is tested with evacuated solar collector field with any back up auxiliary electrical heater. Which is suitable for office building, in the future system can be tested for residential installation with suitable auxiliary heater.
- Optimization of individual components of the polygeneration system for a particular scale is required.
- Development of automated control unit for monitoring pressure and temperature at the inlet conditions for safer operation of membrane distillation unit can be developed
- Robust and lightweight construction of membrane distillation should be developed for proper commercialization of system.

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