Experimental investigation of a novel solar thermal polygeneration plant in United Arab Emirates

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A B S T R A C T
The demands for space air conditioning and clean drinking water are relatively high in Middle East North African (MENA) countries. A sustainable and innovative approach to meet these demands along with the production of domestic hot water is experimentally investigated in this paper. A novel solar thermal poly-generation (STP) pilot plant is designed and developed for production of chilled water for air conditioning using absorption chiller, clean drinking water with membrane distillation units and domestic hot water by heat recovery. The STP system is developed with a flexibility to operate in four different modes: (i) solar cooling mode (ii) cogeneration of drinking water and domestic hot water (iii) cogeneration of cooling and desalination (iv) trigeneration. Operational flexibility allows consumers to utilize the available energy based on seasonal requirements. Performance of STP system is analyzed during summer months in RAKRIC research facility. Energy flows in STP pilot plant during peak load operations are analyzed for all four modes. STP system with trigeneration mode utilizes 23% more useful energy compared to solar cooling mode, which improves overall efficiency of the plant. Economic benefits of STP with trigeneration mode are evaluated with fuel cost inflation rate of 10%. STP plant has potential payback period of 9.08 years and net cumulative savings of $454,000 based on economic evaluation.

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1. Introduction
In United Arab Emirates (UAE), around 30% of electricity requirement is accounted for building air conditioning and it increases to about 70% in peak summer months [1,2]. Another energy intensive process conducted in most of the MENA region is desalination due to non-availability of fresh water resources. Electricity demands in UAE are mostly met by fossil fuels which lead to global warming. These problems have been addressed by few researchers through integration of multiple thermal cycles as polygeneration system driven by renewable energy or waste heat. Calise et al. [3] dynamically simulated a solar (PV/T) tri-generation system for production of electricity, fresh water and cooling and analyzed both energetically and economically. Hussain [4] developed a novel tri-generation system for simultaneous production of cooling, clean water and electricity and analyzed with different technologies to provide cooling with vapor compression and vapor absorption systems and clean water with reverse osmosis and multi-effect distillation. Picinardi [5] analyzed the performance of cogeneration system integrating humidification-dehumidification (HD) desalination unit with absorption chiller. Desalination process is driven by heat rejected from condenser of the absorption chiller. The heat rejection at higher temperatures affects the performance of chiller but improves the efficiency of the cogeneration plant in terms of lower energy usage. Chiranjeevi and Srinivas [6] developed a cogeneration system integrating two stage HD desalination and absorption chiller, which is completely driven by solar thermal energy to achieve high energy utilization factor. Integrated performance of plant is studied for different humidifier efficiency. Optimized system produces 670 l/h of distillate and 75 kW of cooling. Choon et al. [7] investigated the performance of a large waste heat driven adsorption cycle for production of cooling and fresh water with the implementation of adsorption–desorption
Membrane distillation (AGMD) modules for different temperatures and experimentally analyzed the performance of air gap membrane distillation and domestic hot water storage system. The maximum specific distillate flux of 7 l/h m² is achieved with a flow rate of 1200 l/h on both hot and cold sides. With multi-stage configurations better heat recovery and thermal efficiencies are achieved.

Few researchers investigated the possibility of integrating membrane distillation unit with other thermal cycles to develop a polygeneration system. Kullab [14] numerically and experimentally investigated the possibility of utilizing air gap membrane distillation systems in cogeneration power plants. Further, the productivities of multi-effect configurations of two different integration layouts were analyzed for different feed and coolant water temperatures. Liu [15] numerically analyzed the possibilities of integrating membrane distillation units with gas engine to provide power and clean water to chip manufacturing unit. Mohan et al. [16] investigated the possibility of utilizing the waste heat rejected from the combined cycle power plant for producing chilled water by absorption chiller and clean water by membrane distillation technology. The plant had an impressive payback period of 1.38 years and net cumulative saving of $66 Million. Uday kumar and Martin [17] developed a solar thermal cogeneration system for production of clean water using membrane distillation and domestic hot water for residential buildings in UAE. The system is designed to provide 20 l/day of fresh water and 250 l/day of domestic hot water and verified with detailed experimentations.

As shown in literature, several combinations for integration of solar cooling and different conventional desalination technologies like RO, MED and MSF were investigated by researchers. The potential of solar thermal driven MD technology and its possibilities of integration were demonstrated by few researchers. However, the possibility of solar thermal polygeneration system integrating absorption chillers and membrane distillation together is not been studied before according to our knowledge. In this paper, solar thermal driven polygeneration system for simultaneous production of cooling by absorption chiller, fresh water by membrane distillation and domestic hot water by heat recovery has been designed, developed and experimentally tested in weather conditions of United Arab Emirates.

2. Methodology

The system investigated in this project is a novel solar thermal polygeneration (STP) system integrating solar collectors, single stage absorption chiller and membrane distillation 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 the system considered for the investigation is shown in Fig. 1 which consists of seven different system loops.

- Solar collector circulation loop (SCW): Circulation of water between solar collector field and source side of hot water storage tank
- DHW domestic hot water
- evp evaporation
- f fuel
- FW fresh water
- gen generator
- HST hot storage tank
- hyd hydraulics
- CST cold storage tank
- ins installation
- n node
- out outlet
- PHE plate heat exchanger
- sc solar collector loop
- T thermal
- VAC absorption chiller
- w water
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 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

Hot water produced in solar collector field is stored in the thermal storage tank during the charging process. Hot water from thermal storage tank is utilized to provide required thermal energy to drive the absorption chiller and membrane distillation units. Chilled water produced by the absorption chiller is stored in the chilled water storage tank and then supplied to office cabins through fan coil units. Sea water from sea water storage tank is supplied to the cold side of MD modules, where it gets preheated. Preheated sea water is further heated with PHE1 where sea water recovers heat from return hot water leaving absorption chiller. Hot sea water is supplied to the hot side of MD modules to initiate the desalination process. Finally, domestic hot water is prepared by extracting heat from returning brine from MD module.

3. Materials and monitoring

3.1. Solar thermal collector circuit

The solar thermal collector circuit consists of two evacuated tube collector field namely large and small field. The large field has 8 evacuated tube collectors with an individual collector gross area of 12 m², 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 m² each, connected in same orderly as large field. The main connection line between solar collector array and thermal storage tank is connected with 42 mm diameter copper pipe with 50 mm thick glass wool insulation and length of the connection is about 150 m. Individual collector arrays are connected with main line with 25 mm diameter copper pipe with same insulation which spans for 20 m in every solar collector row. These collector fields are individually installed for operating different equipment, later integrated together to drive the polygeneration system. The whole collector field is 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 and flowrates to the solar collector field varied between 40 and 50 kg/min. The heat transfer fluid between the collector and storage tank gets heated with available solar radiation. The temperature 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 L capacity is been installed and equal volume of back up thermal storage is also connected but the backup thermal storage tank is not used in this research work. Evacuated tube collector field and thermal storage at RAKRIC facility is shown in Figs. 2 and 3. The useful heat energy supplied by the evacuated tube collector is calculated by following equation [18]:

\[
Q_{\text{useful}} = m C_p (T_{\text{out}} - T_{\text{in}}) = F_r [A (\tau \alpha) - U_{\text{col}} A_{\text{col}} (T_{\text{in}} - T_{\text{amb}})] \cdot t_p
\]

(1)

\(F_r\) is the heat removal factor of the collector, \(\tau \alpha\) is the product of transmittance and absorbance, \(A_{\text{col}}\) is the collector area and \(t_p\) is the...
adjust the mass pumped using Grundfos hot water pump with VFD controller to initiate the cooling process. The hot water from storage tank is single stage LiBr/H2O vapor absorption chiller with a rated capacity of 3.2 kW. Absorption chiller circuit respectively.

The hot water outlet of the thermal storage tank is connected to the generator inlet of the absorption chiller using copper piping with SEIDO 1 collector type are 0.73, 1.5 W/m² K and 0.0054 W/m² K respectively. Hot water is supplied to absorption chiller above 88 °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 placed at all inlet and outlet points of absorption chiller to record the temperature and energy flows 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 as shown in Fig. 4. The distribution circuit is heavily insulated and buried underground to avoid thermal losses. Major energy flows in the absorption chiller loop are calculated by,

$$Q_{gen} = m_{v} c_{p} (T_{h1} - T_{h2})$$

$$Q_{chilled} = m_{v} c_{p} (T_{ch1} - T_{ch2})$$

where $Q_{gen}$ is the heat supplied the generator of VAC, $m_{v}$ are the mass flow rate of hot water flowing through the generator, $T_{h1}$ and $T_{ch1}$ are the chilled water inlet and outlet temperatures, $Q_{chilled}$ is the useful chilling energy produced by the VAC and $m_{v}$ are the mass flow rate of chilled water flowing through the evaporator.

Thermal and electrical COP of the absorption chiller is calculated by,

$$COP_{th} = \frac{Q_{chilled}}{Q_{gen}}$$

$$COP_{el} = \frac{Q_{chilled}}{Q_{gen} + Q_{el}}$$

The thermal efficiency of the collectors is calculated using quadratic efficiency curve [19],

$$\eta_{col,T} = a_{0} - a_{1} \left( \frac{T_{avg} - T_{amb}}{T_{r}} \right) - a_{2} \left( \frac{T_{avg} - T_{amb}}{T_{r}} \right)^{2}$$

The values of $a_{0}$, $a_{1}$ and $a_{2}$ are available for any collector tested according to ASHRAE standards. The values of $a_{0}$, $a_{1}$ and $a_{2}$ for the SEIDO 1–16 collector type are 0.73, 1.5 W/m² K and 0.0054 W/m² K respectively.

3.2. Absorption chiller circuit

Absorption chiller utilized in the polygeneration system is a single stage LiBr/H2O vapor absorption chiller with a rated capacity of 35.2 kW. Technical specifications of absorption chiller provided by the manufacturer are shown in Table 1 [20]. Hot water from thermal storage tank is 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. 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 between 70 and 95 °C.

Cold water loop of the absorption chiller is utilized to reject heat from the chiller during the operation. In order to 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 of around 30 °C to ensure ideal operating conditions.

Table 1

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Fig. 3. Hot water thermal storage tanks.

Fig. 4. Installation of fan coil unit.
3.3. Membrane distillation and domestic hot water circuit

Membrane distillation unit used in this research project is a semi-commercial air-gap membrane distillation (AGMD) module 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 specifications of membrane module are shown in Table 2.

The desalination circuit consists of 500 L 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, the temperature difference between the sides of the membrane is the driving force for the operation. The concept of internal heat recovery is employed in the system to maximize the energy recovery. The feed water from sea water storage tank is connected to the cold side of membrane distiller, which allows feed water to preheat with latent heat released by the distillate and conductive heat transfer from the hot side. The feed water is further 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 configurations. 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 sensors (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—68,000 µS (40000—42500 ppm) which is desalinated during the process to 50—100 µS (32—64 ppm). The flow rate of the feed water is set as 1200 L/h based on previous research conducted with same membrane modules [13].

The hot brine leaving 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 Fig. 5. Final installation of Polygeneration plant is shown in Fig. 6.

Thermal efficiency of membrane distillation process is determined by gain to output ratio (GOR). GOR is calculated by,

\[ \text{GOR} = \frac{M_{\text{dis}} h_{\text{evap}}}{Q_{\text{Supply}}} \]  

\[ M_{\text{dis}} \text{ is the mass of distillate produced, } h_{\text{evap}} \text{ is the specific enthalpy of evaporation and } Q_{\text{Supply}} \text{ is the heat energy supplied to the membrane distillation unit. }Q_{\text{Supply}} \text{ is calculated by,} \]

\[ Q_{\text{Supply}} = (m_{\text{MD}} C_p (T_{\text{MD,H,in}} - T_{\text{MD,C,out}})) - Q_{\text{DHW}} \]  

\[ Q_{\text{DHW}} = m_{\text{FW}} C_p (T_{\text{DHW,Out}} - T_{\text{DHW,In}}) \]

where \( m_{\text{MD}} \) is mass flow rate of saline water to membrane distillation module, \( C_p \) is the specific heat capacity of saline water, \( T_{\text{MD,H,in}} \) is the hot water inlet temperature supplied from the heat exchanger, \( T_{\text{MD,C,out}} \) is the temperature of cold water entering the heat exchanger and \( Q_{\text{DHW}} \) is the heat energy recovered for domestic hot water preparation.

\[ m_{\text{FW}} \] is the mass flow rate of fresh water supplied for DHW preparation, \( T_{\text{DHW,In}} \) and \( T_{\text{DHW,Out}} \) are the inlet and outlet temperatures of freshwater supplied to the PHE2.

4. Results and discussions

With the successful system integration and installation of STP system, detailed experimental campaign is conducted to analyze the performance of plant with different modes of operation. The STP system is operated in four different modes to evaluate its merits and demerits. The experiments were conducted in July during peak sunny days with peak global solar radiation reaching up to 850 W/m² as shown in Fig. 7. The global irradiation is measured momentarily through Kipp and Zonen pyranometer. The polygeneration system is operated from 10:00 AM to 5:00 PM local time without auxiliary electrical heaters. Performance of the evacuated tube collector field (Eta_Array) was tested during the period of operation. Efficiency of solar collector field (Eta_collector) is compared with instantaneous efficiency obtained from quadratic efficiency equation as shown in Fig. 8. The results prove that performance of collector field matches manufacturer’s specification. The
Polygeneration unit is designed with the flexibility that it can be operated in four different modes.

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

This provides flexibility to the users to vary the system based on their requirements. Flow rate of saline water to the membrane distillation system is optimized as 1200 l/h based on earlier experimentation in MEDESOL project [13]. The cooling energy produced by the STP is utilized for providing air conditioning to the office cabins of RAKRIC. A total of eight fan coils units are installed among three office cabins with a total floor area of 91.75 m² and tent with floor area of 25 m². The sectional view of an office cabin is shown in Fig. 9. The building was constructed with plywood and insulated with thick layer of foam. Tent is constructed with a composite of polyester film with soft polyvinylchloride sheet to achieve lower heat losses.

4.1. Solar cooling

The first mode of operation of the STP system is solar 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 Figs. 10 and 11. As shown in Fig. 10, the outlet temperature of collector gradually increases from 8:30 AM and it is utilized completely for charging the stratified tank for 90 min. The operation of absorption chiller starts at 10:00 AM as the tank top temperature reaches more than 88 °C. Due to steep decrease in hot water supply temperatures, fluctuations in production of chilled energy and COP are obtained during the first hour of operation. The absorption chiller produces chilled water within 10 min from the start of the operation and it is distributed to office cabins through fan coils. The heat rejection loop of absorption chiller works efficiently as the cold water supplied is around 30 °C throughout the operation. Cold water leaving the chiller is supplied to wet cooling tower to liberate the heat from absorber and condenser components of absorption chiller.

Throughout the day, the thermal COP of system varies between 0.55 and 0.62 as shown in Fig. 11. A total of 42 kWh of electricity is
consumed by various pumps during the eight hour operation, which leads to an electrical COP between 0.45 and 0.54. The refrigeration capacity stabilizes at 25 kW for most parts of the day, which is sufficient to provide cooling for all building loads during 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.

The energy flows in solar cooling mode during the daily operation is shown in Fig. 12. Incident energy from sun is converted into useful heat energy by the evacuated tube collectors with collector efficiency of 61%. This useful thermal energy is supplied to absorption chiller in this mode as other components are not active during the operation. Only 45% of useful energy is consumed by absorption chiller for production of chilled water, it mainly due to losses in connections, pipes, tank and other components.

4.2. Co-generation of distilled water and domestic hot water

In this mode of operation, thermal energy from solar collectors is utilized completely for desalination and domestic hot water preparation. The membrane distillation (MD) units are utilized to produce distilled water and heat recovered from saline brine is used for production of domestic hot water (DHW) preparation. The MD system is operated with both single stage and double stage configurations to analyze the performance of multimode integration. Saline feed water with conductivities greater than 65,000 µS/cm (40,000 ppm) was distilled using two AGMD modules to produce distilled water at conductivities less than 50 µS/cm. The heat recovered from brine leaving the hot side of desalination unit 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 L/h based on previous findings, major factor influencing in terms of performance is temperature difference.

Fig. 13 shows the temperature profiles and productivity of two-stage MD operation. The hot water is supplied around 90–80 °C to the first stage and 80–70 °C in the second stage. Cold water is supplied around 35 °C to the first stage of modules, temperature raise close to 7 °C is achieved due internal gain during the first stage. The distillation production varied between 12.5 and 10 l/h during the operation. 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 in first and second stages reaches around 55 °C and 35 °C respectively.

Total of 80 L of pure water is produced for 7 h of daily operation as shown in Fig. 14. In single stage mode, a total of 47 L 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 with multiple stage configuration. Heat from saline brine is efficiently recovered with plate heat exchanger for DHW production. Around 50% of the total useful energy is utilized by the cogeneration unit, out of which 75% is utilized for domestic hot water preparation is shown in Fig. 15. Energy flows in the cogeneration mode is shown in Fig. 16. Energy conversion from incident to useful is slightly higher than solar cooling mode. In terms of final conversion, around 50% of the useful energy is utilized by the system. Cogeneration mode with desalination and DHW achieves 40% in term overall efficiency, which is much higher than efficiency obtained in solar cooling mode.
4.3. Co-generation of cooling and desalination

This 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. Temperature and energy flows in absorption chiller during the operation are shown in Figs. 17 and 18. The hot water supply temperature to the absorption chiller varied between 70 °C and 75 °C during the operational period. In term of energy utilization, close to 30% of the useful energy is consumed by the absorption chiller for generation of chilled water. Chilled water is produced at an average temperature of 14 °C and continuously circulated to the office cabins for air conditioning. Mean chilled energy production of 14 kW is achieved in this mode, which is sufficient to fulfill cooling demand of two office cabins with thermal COP varying between 0.45 and 0.50 and electrical COP fall between 0.37 and 0.42. Ideal operation of absorption chiller is ensured with the cold water supply temperature around 30 °C during the entire operation.

Fig. 19 shows the performance of two-stage MD in co-generation mode. Return hot water from the generator of absorption chiller is utilized for the cogeneration of freshwater and domestic hot water. The hot sea water is supplied with temperature range of 60–70 °C and cold water is supplied around 35 °C in the 1st stage MD. Whereas, in the second stage of MD, hot sea water is supplied between 57 °C and 63 °C and cold water is supplied around 42 °C. Two-stage MD produces 5.8 L/h with an average temperature difference of 30–15 °C between hot and cold sides of AGMD 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 drinking water requirement is higher. Mean thermal energy consumed by the desalination process is 30 kW out of which most of the energy is recovered for domestic hot water at 50 °C. Collector efficiency maximizes in this mode as the operating temperatures are much lower than other modes. Energetically, this mode utilizes more...
amount of available energy compared to other modes as shown in Fig. 20. Collector losses are minimized in this mode of operation due to lower operating temperatures compared to previous modes. Overall efficiency of efficiency of STP during daily operation reaches close to 50%. Since the DHW produced at lower temperature, it is not considered in the energy flows.

4.4. Trigeneration

The fourth mode of operation is a combination of solar cooling and cogeneration modes. In this mode, desalination and domestic hot water preparation processes are integrated with the absorption chiller to tri-generate cooling, fresh water and DHW. Fig. 21 shows the performance of two stage MD and DHW system in trigeneration mode. The performance of solar cooling remains similar to the earlier mode of operation. Fig. 18 summarizes the performance of membrane distiller and DHW processes in the trigeneration mode. The hot saline water is supplied to MD with temperature range of 60–70 °C and cold water is supplied around 35 °C throughout the operation. In this mode, single stage MD unit is integrated with the system. Single stage MD produces 4 L/h with an average temperature difference of 30 °C between hot and cold side of AGMD.

Mean thermal energy is consumed by the desalination and DHW production processes are around 30 kW, out of which 25 kW is recovered for domestic hot water production. DHW is prepared at a mean temperature of 55 °C. This mode has an advantage of utilizing the total available energy effectively to produce DHW along with cooling and pure water production. The energy flows are similar to prior mode of operation, the individual performance of absorption chiller, membrane distiller reduces by 35%. But as whole system, the system efficiency reaches 71% as shown in Fig. 22.

4.5. Seasonal variations

Seasonal performance of membrane distillation units and absorption chiller are analyzed by conducting experiments in two different months as shown Figs. 23 and 24. Total incident solar radiation and cumulative daily productivity of two stage membrane distillation unit during summer (July) and autumn (October) are shown in Fig. 23. Peak solar isolation of 850 W/m² and 625 W/m² are obtained during July and October respectively. Membrane
Distillation unit performs better in summer with a total cumulative productivity of 80 kg/day, whereas it reduces by 25% during autumn. Which is influenced by higher hot water supply temperatures leading to higher temperature difference between the hot and cold sides. Energy flows in the absorption chiller during summer and reduces to 0.61 during the month of September. Overall system performance is better in summer compared to autumn due to higher supply temperatures.

4.6. Economic analysis

Major hindrance in any renewable energy driven processes are high initial investment cost, so payback period and net cumulative savings are chosen as economic criteria to evaluate the benefits based on design parameters. In this research work, payback period (PB) is calculated based on time period required to recover initial investment incorporating fuel cost inflation rates [21]. Payback period (PB) and net cumulative saving (NCS) are calculated by:

\[
PB = \frac{\ln \left( \frac{C_B(i_F)}{C_s} + 1 \right)}{\ln(1 + i_F)}
\]

\[
NCS = \left( \sum_{t=1}^{N} (C_B)^t (1 + i_F)^t \right) - C_s
\]

\(C_s\) is the initial investment cost for the polygeneration system, \(C_B\) is annual cost benefits and \(i_F\) is fuel cost inflation rate. Initial investment includes investment costs of all the components of the polygeneration system as shown in Equation [13].
\[ C_s = C_{SC}A_{SC} + C_{PHE} + C_{VAC} + C_{CST}V_{CST} + C_{HST}V_{HST} + C_{pump}P_{pump} \\
+ C_{AGMD} + C_{R,AGMD} + C_{Fin} + C_{hyd} + C_{land} \tag{13} \]

The costs of individual components are shown in Table 3. Annual electricity cost for operation of pumps and general maintenance cost including parasitic water losses around 2 kg/h in cooling tower are considered in the economic analysis. Individual electricity consumption by various components are shown in Fig. 25. Detailed annual cost benefits from production of cooling, fresh water and domestic hot water and operational costs are shown in Table 4.

The total investment cost required for installation of STP is $184,490.60 and distribution of investment cost for different sub-systems are shown in Fig. 26. Major shares of investment cost are accounted for absorption chiller and land cost, as they occupy 65% of total investment cost. Land cost plays vital role in determination of economic benefits. Roof top installations are ideal solution to avoid land cost and to achieve higher economic benefits. Thus economic analyzes are conducted with and without including land cost in overall investment. Sensitivity analyzes on payback period and net cumulative savings for STP plant were conducted with different inflation rates. Impressive payback period of 8.8 years and net cumulative savings of $1.8 Million are achieved with higher inflation rate as shown Fig. 27. The payback period reduces by 18% and NCS increases by 10.7% by subsidizing land costs with nominal inflation rate of 10%. Annual cash flows of STP system with and without including land costs are shown in Fig. 28. Potential payback period of 9.08 years and net cumulative savings of $455,000 are achieved with an inflation rate of 10% for roof top installation.

5. Conclusions

A solar thermal driven poly-generation system has been developed with a flexibility of operating it in different configurations. Main focus of this paper is to analyze the advantages of combining different processes together rather than operating individually. The system is installed in RAKRIC and experiments were conducted in four different modes during the peak summer month of July. Experiments have been carried on the system consisting of evacuated tube solar thermal collectors, absorption chiller, membrane distillation unit and heat exchangers for heat absorption and recovery. Some conclusions drawn from the experimentation as listed below.

- Sea water with TDS of 40,000 ppm is desalinated in the STP system to a salinity level less than 30 ppm.

- In solar cooling mode, 25 kW of chilled energy is produced with COP of 0.6. This mode is ideally suited for peak summer days.

- STP in trigeneration mode utilizes 23% more useful energy than solar cooling mode, which is advantageous both energetically and economically.

### Table 3

<table>
<thead>
<tr>
<th>Component</th>
<th>Abbreviation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar collector [22]</td>
<td>( C_{SC} )</td>
<td>294$/m²</td>
</tr>
<tr>
<td>35 kW absorption chiller [23]</td>
<td>( C_{VAC} )</td>
<td>61800$</td>
</tr>
<tr>
<td>Land [24]</td>
<td>( C_{Land} )</td>
<td>180$/m²</td>
</tr>
<tr>
<td>Membrane distillation unit [25]</td>
<td>( C_{AGMD} )</td>
<td>7000$/unit</td>
</tr>
<tr>
<td>Plate heat exchanger [26]</td>
<td>( C_{Fin} )</td>
<td>5% of ( C_{AGMD} )</td>
</tr>
<tr>
<td>Hot storage tank</td>
<td>( C_{HST} )</td>
<td>4130$/m³</td>
</tr>
<tr>
<td>Cold storage tank (^a)</td>
<td>( C_{CST} )</td>
<td>4130$/m³</td>
</tr>
<tr>
<td>Pump [18]</td>
<td>( C_{pump} )</td>
<td>881W/°C</td>
</tr>
<tr>
<td>Hydraulics [25]</td>
<td>( C_{hyd} )</td>
<td>0.15( C_{SC} ) + 0.05( C_{AGMD} ) + 0.05( C_{VAC} )</td>
</tr>
<tr>
<td>Installation cost [25]</td>
<td>( C_{Ins} )</td>
<td>5% of total component cost</td>
</tr>
<tr>
<td>Fuel cost inflation rate [18]</td>
<td>( I_F )</td>
<td>10%</td>
</tr>
<tr>
<td>Plant availability</td>
<td>( N )</td>
<td>20 years</td>
</tr>
<tr>
<td>Lifetime of the system</td>
<td>( P )</td>
<td>96%</td>
</tr>
</tbody>
</table>

\(^a\) Provided by the manufacturer (Tisun).
Membrane distillation system is operated with internal and external heat recovery technique in trigeneration mode, which consumes 6 times lesser energy than MEDESOL project [13]. Around 75% of energy is recovered for production of DHW at 55 °C.

In trigeneration mode with single stage membrane module integration, it produces 4 l/h and with double stage (cogeneration of cooling and desalination), daily production increases by 48% by sacrificing domestic hot water.

Cogeneration mode with production of distilled water and domestic hot water is useful in winter as cooling is not required. Around 80 L of fresh water is produced by two stage mode with gain to output ratio of 0.7.

In terms of economic benefits, STP plant has potential payback period of 9.08 years and net cumulative savings of $454,000 considering an inflation rate of 10% for roof top installations.

Land costs plays vital role in the economic analysis, subsidizing land cost will improve the payback period by 18% and net cumulative saving by 10.7%.

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References