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Techno-economic optimization of solar thermal integrated membrane distillation for cogeneration of heat and pure water

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ABSTRACT

The aim of this paper is to evaluate optimum design criteria for developing solar thermal integrated membrane distillation system for cogeneration of pure water and heat. The temporal and seasonal variability of the driving variables, such as ambient temperature and solar irradiance requires dynamic simulation of combined system using tools such as TRNSYS. Dynamic simulation and parametric analysis enables to design a functional system and then optimizes the design. In this study, the application of cogeneration system for residential households in United Arab Emirates is considered for per capita production of 4l/day of pure water and 50l/day of domestic hot water. The performance of cogeneration is optimized by varying various design parameters such as collector tilt angle, thermal storage volume and area of the solar collector field. Cogeneration solar fraction and payback period are considered as performance indicators for energetic and economic optimization. Further simulations are extended from small to large family application and for utilizing either flat plate (FPC) or evacuated tubular collector (ETC) systems. Optimized cogeneration system utilizes more than 80% of the available solar energy gain and operates at 45% and 60% collector efficiencies for FPC and ETC systems respectively Also, combined and system efficiencies of the cogeneration system are compared with standalone operational efficiencies for solar heaters and solar membrane distillation systems. Results show that, cogeneration operation reduces 6–16% of thermal energy demand and also enables 25% savings in electrical energy demand. Payback period could be reduced by 2.5–3 years by switching from regular solar water heating to cogeneration systems along with 4-fold increase in net cumulative savings.

Keywords: Solar membrane distillation; Cogeneration; SDHW; TRNSYS; Dynamic simulation

1. Introduction

As per the global risks report 2016, the World Economic Forum named water crises as one of the top three highest global risks to economies, environment and people [1]. Clean, safe and usable water is a limited and valuable resource for many parts of the world especially for gulf nations. In United Arab Emirates (UAE) almost all industrial and residential water is supplied through seawater desalination. Agriculture uses water extracted from aquifers that already showing signs of depletion which again leads to reliance on desalination in future [2]. At present, the total installed desalination capacity in the UAE is 1583 MIGD (million imperial gallons per day), 80% of it is produced using the robust but inefficient multistage flash (MSF) technology. Since, desalination consume large amounts of energy, it is very crucial to make sure water usage in cities is efficiently managed along with minimum wastage. Although municipal supplied desalinated water is suitable for drinking in UAE, people mostly depend on processed bottled water for drinking purpose. In fact, UAE stands top among per capita bottled water consumers in the world [3]. Bottling of already desalinated water further elevates energy demand in the process of drinkable water gen-

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eration and delivery to the end user. Thus elevated energy demand levels for desalination industry, rapid depletion of fresh water sources along with climate changes due to rapid industrialization poses a threat to upcoming generations.

The challenge here is to create sustainable solutions to balance the requirements using clean, affordable energy. One potential solution to meet this challenge is to utilize renewable energy sources especially solar energy that enables increased energy independence and reduces global warming as well. The UAE is recently looking at solar power for desalination. However, solar PV is increasingly seen as an attractive technology to power reverse osmosis (RO) desalinations plants, it's also important to consider thermal energy driven processes [2]. In particular, for small/medium scale applications, solar thermal driven membrane distillation (MD) technology has been gaining importance in recent times [4]. Compared with conventional thermal MSF or RO membrane separation process, MD has distinct advantages of operating at low temperature and pressures. Also, it has been proven by many researchers that MD can tolerate varying feed concentrations and has a better ability to use low-grade or waste heat [5]. Among the many configurations of MD technology available in the world, air-gap membrane distillation (AGMD) technique has been widely used for solar energy integration at pilot scale/commercial levels [6]. Present work utilizes a bench scale AGMD module characterized and tested by the authors for solar thermal integration and augmentation of solar energy utilization though cogeneration of hot water and pure drinking water [7].

Solar thermal heating systems accounts for 80% of the solar thermal market worldwide and are very much common nowadays for fulfilling different domestic and commercial needs [8]. For the production of domestic heat, different collectors with variable temperature ranges can be used depending upon the region, climatic conditions etc. Glazed flat plate collectors (FPC) accounts for 22.4% of the worldwide operational capacity and most commonly used in domestic heating systems [9]. Whereas evacuated tube collectors (ETC) has high market penetration due to its wide temperature range (upto 150°C) and accounts for 70% of the operational capacity worldwide [9]. Countries having low irradiance and overcast weather conditions widely uses ETC systems due to the advantage of low heat losses compared to FPC [10]. In contrast, UAE receives annual solar insolation of more than 2000kWh/m^2 enabling to run any solar domestic hot water (SDHW) systems at more than 90% solar fractions for residential applications [11]. However, during summers the availability of solar heat is very high and DHW demand is low and therefore solar thermal heaters do not exploit their full potential leading to low specific collector yield, even with high annual solar fraction [12]. Therefore, proper selection of collector type for these conditions is crucial not only for maximum energy exploitation but also for maximizing economic benefits. To address this topic, the authors previously introduced a cogeneration system for simultaneous production of hot water and pure water using MD technology thus improving overall performance of solar thermal system [13].

In literature, most studies focus on solar driven membrane distillation (SMD) technologies rather than integrated systems for cogeneration [6]. Recent studies show that cogeneration/polygeneration systems based on renewable energy sources for electricity production, heating, cooling and desalination has been gaining interest from the research community [14,15]. However, the investigation of systems employing membrane distillation technology coupled with solar systems is limited, particularly for cogeneration of pure water and heat. The possibility of integrating MD with heat recovery chiller and gas engines was investigated by Liu and Martin [16] for trigeneration of cooling, power and water in a semi-conductor industry. Utilization of MD in cogeneration power plants was experimentally and numerically analyzed by Kullab and Martin [17] which proves the applicability of MD in waste heat recovery. Mohan et al. [18] also investigated integration of MD into a waste heat recovery power plant for generation of cooling, pure water and electricity. Further pilot experimental studies carried by Mohan et al. [19,20] using solar thermal energy for polygeneration application in UAE. Khan et al. [21,22], performed techno-economic analysis and optimization studies of photo voltaic (PV) driven polygeneration system integrated with MD system and biogas digester to generate electricity, pure water and cooking fuel for rural households in Bangladesh. The authors previous work on performance of cogeneration systems using multicassette MD module provides insight into simultaneous production of heat and pure water [23]. Authors also experimentally characterized single cassette MD module and investigated its performance through solar thermal integration [7,24]. The present paper is based on the previous characterization studies and experimental investigations on solar combined membrane distillation (SCMD) system.

Water heating using solar thermal collectors is commercially available in UAE but currently its use is limited mostly to hotels and government funded housing [2]. This significant untapped potential of solar water heater installations for residential households is picking up in recent times due to changes in policies and regulations. The main goal of this work to investigate both energetic and economic performance of the solar combined MD system through comparison of systems operated individually (separate operation of SDHW and SMD). Techno-economic optimization of cogeneration system is an important analysis that needs to be examined carefully for the dissemination of SCMD systems. As mentioned earlier, the system under study derives from previous works of the authors [7,24] with significant improvement of system layout by including evacuated tube or flat plate solar collectors, auxiliary heaters and additional MD module. The authors have employed TRNSYS dynamic simulation tool to build system environment, by considering also all the components required for actual operation of the system (sensors, controls, load profiles etc.). With respect to reference pilot installation [24], the system solar field and MD modules have been varied based on application for small or large family dwellings in UAE. A sensitivity analysis is performed to evaluate the system performance as a function of main design parameters. Parametric optimization has also been performed through analyzing energetic efficiency and economic benefits of the cogeneration system. Finally, in order to evaluate the economic benefits of combined operation, payback period and net cumulative savings of cogeneration system are compared with individual operation of solar water heaters and solar driven MD systems.

2. System layout

The adopted system layout in this work is derived from one of our previous work which consists of integration membrane distillation water purification technology with solar hot water system [24]. In particular, new layout has been modified in order to integrate either flat plate or evacuated tube collectors. Moreover, in such layout, auxiliary heaters has been added in order to satisfy the thermal demands for MD and DHW in case of cloudy days or increased user demand. Furthermore, additional MD module has been added in series with the existing one for operation at high pure water demand profiles. Also MD feed water storage tank and cold water storage tank has been added for realistic modelling of the system. A schematic layout of the solar cogenration membrane distillation system. System under investigation is shown in Fig. 1. The same operating principle of SCMD employed in the previous work [24] has been used for the solar, DHW loop and MD subsystems. The main components along with input design/operational parameters for solar thermal, DHW loops are summarized in Tables 1 and 2 shows the components and input parameters for MD loop.

3. Simulation model

The cogeneration system model has been developed using TRNSYS software [26]. As shown in Fig. 3, system components are indicated by types in TRNSYS are integrated in order to perform the simulation and obtain results.

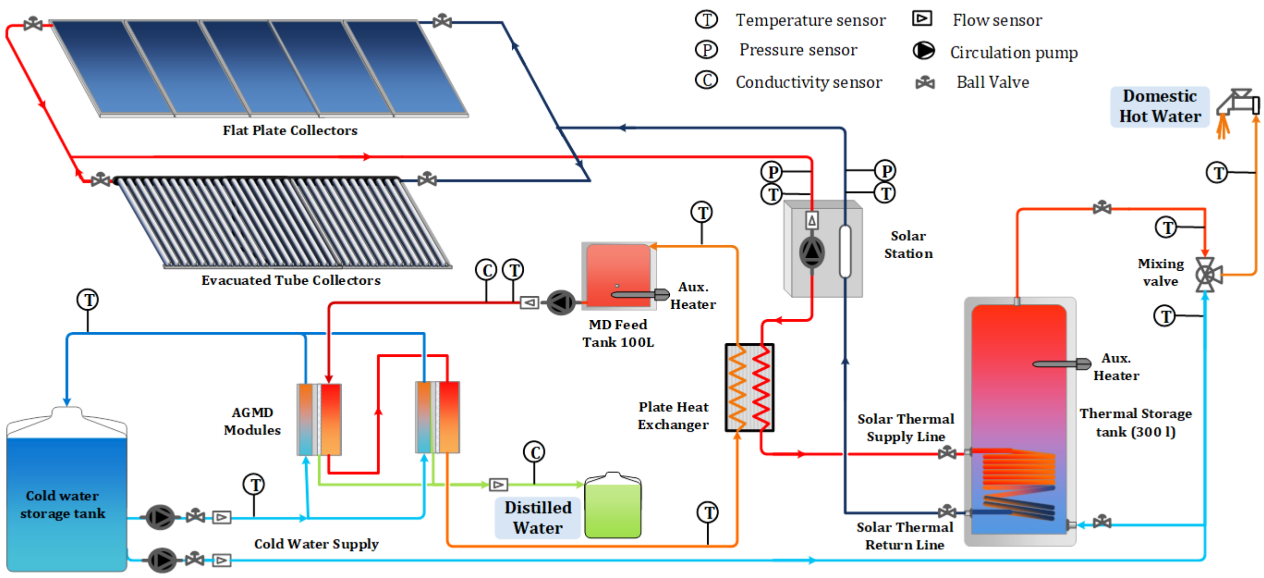

Fig. 1. Schematic representation of SCMD system.

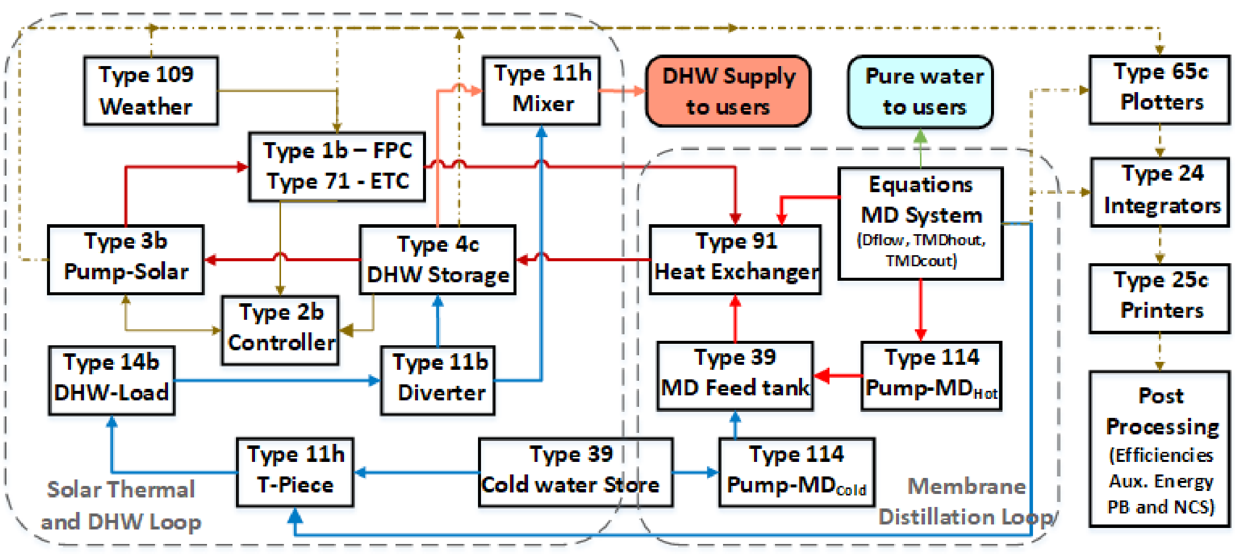

Fig. 2. TRNSYS system diagram for simulation of cogeneration system.

Table 1
Main components and input design parameters for the solar thermal and DHW loop

Component name	Input parameter(s)	Value-FPC	Value-ETC
Solar collectors	Collector aperture area, m^2	11.8	9.01
	Tilt angle, °	35	15
	Tested flow rate, kg/h·m^2	40	45
	Intercept efficiency (η_0)	0.781	0.732
	First order efficiency coefficient (a_1), W/m^2·K	3.65	1.5
	Second order efficiency coefficient (a_2), W/m^2·K^2	0.015	0.0054
Solar pump	Maximum flow rate, kg/h·m^2	25	
	Maximum power, W	60	
Controller	Upper dead band T, °C	6	
	Lowe dead band T, °C	4	
DHW load profile	Daily load, L/d	250	
Diverter, mixer	DHW set point temperature, °C	50	
DHW storage tank	Tank volume, m^3	0.3	
	Tank loss coefficient, W/m^2·K	2.5	
	No. of nodes	6	
	Height of each node, m	0.25	

Table 2
Main components and input design parameters for the MD loop

Component name	Input parameter(s)	Value
MD System (equations)	RSM model for distillate flow and MD outlet temperatures [7]	
	No. of MD modules	1 or 2
	Membrane area/module (A_{MD}), m^2	0.2
MD cold and hot circuit pumps	Flow rate (constant), L/h	360
	Rated power, W	50
MD feed tank	Volume of feed water, L	50 or 100
Plate heat Exchanger	Effectiveness	0.8
Cold water store	Temperature (Amb.) and volume, L	1000

3.1. Solar collectors and thermal storage

Solar thermal collectors are simulated using type 1b and type 71 models for FPC and ETC respectively. ETC's are optically non symmetric, so biaxial incidence modifier (IAM) is supplied as separate external file. The useful heat supplied by the collector is calculated by following equation [27]:

$$Q_{Col} = \dot{m}C_p\left(T_{Sol.\,out} - T_{Sol.\,in}\right) = F_r A_{col}\left[I_{col}\left(\tau\alpha\right) - U_{col}A_{col}\left(T_{sol,avg} - T_{amb}\right)\right] * t_p \quad (1)$$

where $\dot{m}$ is mass flow rate of heat transfer fluid circulated in collector loop, C_p is the specific heat capacity, F_r is the heat removal factor of the collector, $\tau\alpha$ is the product of transmittance and absorbance, A_{Col} is the collector area (typically aperture area), I_{Col} is incident solar radiation, U_{Col} is the overall heat transfer coefficient, $T_{Sol,in}$ and $T_{sol,out}$ are inlet, outlet temperatures of the circulated fluid to the collector, T_{amb} is the ambient temperature and t_p is the time period of operation.

The thermal storage tank is subjected to thermal stratification and modeled using type 4c. The tank is divided into segments and it is assumed that the fluid streams flowing up and down from each node are fully mixed before they enter next segment. The energy balance of the n[th] node model is shown below [28].

$$CP_{th,n}\frac{dT_n}{dt} = \dot{m}_{w,in}C_p\left(T_{n-1} - T_n\right) + \dot{m}_{w,out}C_p\left(T_{n+1} - T_n\right) - U_{HS}A_n\left(T_n - T_a\right) + \frac{S_n\lambda}{\delta}\left(T_{n-1} - 2T_n + T_{n+1}\right) \quad (2)$$

where T, CP and λ are the water temperature, thermal capacitance and conductivity respectively. U is the layer thermal loss coefficient and S is the envelope surface area of the single node.

3.2. Heat exchanger and membrane distillation

Counter flow heat exchanger of Type 91 is used in the model, which relies on an effectiveness minimum capacitance approach in which the maximum possible heat transfer rate is calculated based on the minimum capacity rate

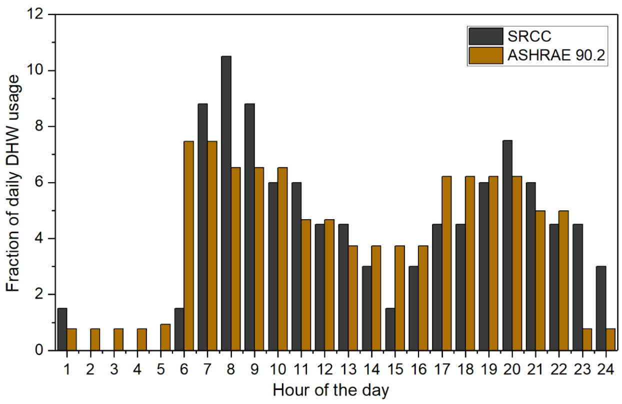

Fig. 3. DHW load profile showing fraction of hourly usage/withdrawal (Adapted from Ref. 29).

fluid and the hot and cold side fluid inlet temperatures [26]. The heat transfer rate of the heat exchanger is obtained based on following equation,

$$\dot{Q}_T = \varepsilon \dot{Q}_{\max} \;\; where \; \dot{Q}_{\max} = ((C_h or\, C_c)_{\min})_{\min} * \left(T_{hi} - T_{ci}\right) \tag{3}$$

where $C_C = \dot{m}_C C_{pc}$ and $C_h = \dot{m}_h C_{ph}$. The outlet temperatures from the heat exchanger are calculated which will provide input to subsequent components, i.e. thermal storage tank and membrane distillation model in present case.

$$T_{ho} = \mathrm{T_{hi}} - \left(\frac{\dot{Q}_T}{C_h}\right) and\; T_{co} = \mathrm{T_{ci}} - \left(\frac{\dot{Q}_T}{C_c}\right) \tag{4}$$

Based on heat exchanger data and flow rates in solar and MD loops, effectiveness is determined to be 0.8 and has been provided as input for heat exchanger. The heat transfer rate from the exchanger is assumed to be completely utilized by MD process for distillate production. Membrane distillation component is added as equation obtained from previously developed models through experimental characterization and response surface modelling [7]. Following equations determine the distillate flow rate $V_d\,(l/h)$ and MD hot outlet temperatures.

$$\begin{aligned} V_d = & -1.314 + 0.032 * T_{MDCin} + 0.03 * T_{MDHin} - 1.172 * 10^{-3} * V_f - 1.154 * 10^{-3} \\ & * T_{MDCin} T_{MDHin} - 0.5 * 10^{-4} * T_{MDCin} V_f + 0.688 * 10^{-4} \\ & * T_{MDHin} V_f + 0.496 * 10^{-3} * T_{MDHin}^2 \end{aligned} \tag{5}$$

$$\begin{aligned} T_{MDHout} = & \; 3.097 + 6.82 * 10^{-2} * T_{MDCin} + 0.772 * T_{MDHin} + 3.5 * 10^{-3} * V_f \\ & + 1.42 * 10^{-3} * T_{MDCin} T_{MDHin} \end{aligned} \tag{6}$$

where V_f is the MD feed flow rate and T is the temperature in and out of MD hot and cold channels.

3.3. Other components

Appropriate control strategies have been implemented for safe operation of solar thermal system similar to previous works [24]. Type 2b controller is used for controlling the solar collector field circulation pump (Type 3b) which switches ON/OFF based on working fluid temperature. The circulation pump is turned off during two conditions (i) Low radiation (i.e. low outlet temperature of collectors) (ii) High storage temperature (>100°C). Upper and lower dead band temperatures have been set to be 6 and 4°C similar to the conditions maintained in experimental system. Operation of MD loop pumps were not controlled as they operate at single flow rate during solar loop operational hours. Additional components such as weather data, printers and integrators have also been added in the simulation built environment.

DHW supply temperature was set at 50°C and hot water is withdrawn using Type 14b time dependent forcing function according to typical load profiles as shown in Fig. 3 [29]. SRCC (Solar Rating & Certification Corporation) profile is chosen for our study as it suits user demand patters in UAE conditions [30]. The system parameters are modified depending upon application and user demand (Single family or large family). Simulations are further extended to individual operation of DHW and MD systems using solar energy. Dynamic simulation results of individual and cogeneration systems are further processed to determine auxiliary heating requirement for MD based on daily fulfillment of hot and pure water demands of the users.

4. Performance efficiency and economic evaluation

Annual solar fractions (SF) for individual and cogeneration operation are used as performance indicators for parametric optimization. SF indicates the total amount of energy delivered by solar thermal system to the total demand of a process in operation. Overall performance of cogeneration system is evaluated using collector efficiency, combined efficiency and system efficiency as indicative parameters. Collector efficiency defined as the ratio of the useful energy gain (Q_{col}) to the incident solar energy. Combined efficiency analyzes the performance of entire solar thermal cogeneration system including solar collectors. System efficiency analyzes the performance of energy consuming devices like membrane distillation unit, thermal storage and heat exchanger, which are integrated together as cogeneration system. Combined efficiency is a ratio of total energy demand for membrane distiller and domestic hot water supply to the total incident radiant energy (Q_{IR}) on collector field [20]. Whereas system efficiency is with respect to useful energy gain i.e. supplied to the system. Table 3 summarizes the performance parameters and related equations used to optimize the combined or individual systems.

An economic model of the cogeneration system has also been developed in this work. The capital costs reported in [25] are used for the components of the system. It is worth noting that the cost of the auxiliary heater and post mineralization system are included in the present economic model. Cost of individual components obtained from existing installation suppliers and other parameters are shown in Table 4.

Economic benefits through selling pure water and fuel savings for DHW production are also shown in the table. Pay Back (PB) period and net cumulative savings (NCS) parameters are used to evaluate the economic performance of individual and cogeneration systems. PB and NCS are calculated using following equations [34].

Table 3
Solar fraction and efficiencies of solar integrated systems

Performance indicator	Equation	No.
DHW solar fraction	$SF_{DHW} = \frac{Q_{DHW}}{Q_{DHW} + Q_{AuxDHW}}$	(7)
MD solar fraction	$SF_{MD} = \frac{Q_{MD}}{Q_{MD} + Q_{AuxMD}}$	(8)
SCMD solar fraction	$SF_{Cogen} = \frac{Q_{Total}}{Q_{Total} + Q_{AuxTotal}}$	(9)
Collector efficiency	$\eta_{Collector} = \frac{\int Q_{col} dt}{A_{Col} \int I_{col} dt}$	(10)
System efficiency	$\eta_{System} = \frac{Q_{MD} + Q_{DHW}}{Q_{Col}}$	(11)
Combined efficiency	$\eta_{Combined} = \frac{Q_{MD} + Q_{DHW}}{Q_{IR}}$	(12)

$$PB = \frac{\ln\left[\frac{C_s(i_F - d)}{C_B} + 1\right]}{\ln\left(\frac{1+i_F}{1+d}\right)} \tag{13}$$

$$PWF = \frac{1}{(i_F - d)}\left(1 - \left(\frac{(1+i_F)}{(1+d)}\right)^N\right) \tag{14}$$

$$NCS = \left((C_B) * PWF\right) - C_I \tag{15}$$

C_I is the initial investment cost for the cogeneration system, C_B is annual cost benefits, i_F is fuel cost inflation rate, d is the discount rate and N is the life time of the system. Initial investment includes investment costs of all the components and installation charges of the cogeneration system as shown in equation (16).

$$C_I = C_{Solar} + C_{MD} + C_{Other} \tag{16}$$
$$C_{solar} = C_{Col}A_{Col} + C_{TES}V_{TES} + C_{PHE}A_{PHE}$$
$$C_{MD} = C_{I,MD}A_{MD} + C_{R,MD} + C_{P,MD} + C_{T,MD}V_{T,MD} + C_{Aux,MD}$$
$$C_{other} = C_{pump} + C_{Ins} + C_{hyd}$$

With regards to the operating costs of the cogeneration system, the demands of electric energy for pumps and auxiliary heating have been taken into account. These operating

Table 4
Individual component costs and benefits

Component	Symbol	Value
Solar collectors [31]	C_{col}	FPC – 216$/m² of apr. area ETC – 406$/m² of apr. area
DHW Thermal storage tank[a]	C_{TES}	4130/m³
Plate heat exchanger [32]	C_{PHE}	2000/m²
Membrane distilltion unit [33]	$C_{I,MD}$	$2,500$/m² of membrane area
Membrane replacement [33]	$C_{R,MD}$	15% of $C_{I,MD}$
Post mineralization[b]	$C_{P,MD}$	25% of $C_{I,MD}$
MD thermal storage tank[a]	$C_{T,MD}$	4130/m³
MD heating element[b]	$C_{Aux,MD}$	150$
Pump [27]	C_{pump}	$881W_P^{0.4}$
Hydraulics [33]	C_{hyd}	0.15 C_{col} + 0.05 $C_{I,MD}$
Installation cost [33]	C_{ins}	5% of total component cost
Fuel cost inflation rate [27]	I_F	10%
Discount rate	d	5%
Lifetime of the system	N	20 years
Cost of fuel [20]	C_F	0.12$/kWh
Distilled water cost [20]	C_{DW}	0.08$/liter
Plant Availability	–	96%

a) Manufacturer provided costs b) Estimated based on personal communication costs are obtained based on the fuel tariffs and the amounts are deducted from the total annual cost benefits (C_B) while calculating PB and NCS.

5. Results and discussion

As discussed in the previous sections, the aim of this paper is to simulate cogeneration of pure water and heat using solar thermal integrated MD for residential households in UAE. The scope of this system is to improve the energy demand efficiency through cogeneration instead of operating MD and SDHW systems independently. A base case study was developed in TRNSYS and simulated for cogeneration operation with both flat place and evacuated tube solar collectors incorporating the weather data measured on site at Ras al khaimah, UAE. As mentioned before, the simulation model presented in this paper includes several components and each simulation returns a huge amount data, such as dynamic profiles of temperatures, distillate flow rates and energy gain/demand. Further, simulation tool allows to integrate hourly results on different time basis (days, weeks, months or year).Annual simulation data is used to determine performance indicators (e.g. Solar fraction) and the results are also presented with sensitivity analysis and techno-economic optimization of parameters. Optimization is aimed at determining the values of system design parameters, minimizing the payback period and maximizing solar energy utilization for MD and/or DHW. Further a scenario of increased hot and pure water demands has been devised to determine optimum design parameters for large family households. Finally, efficiency of cogeneration operation is compared with individual operation of solar MD, domestic hot water systems and the integration benefits are presented in terms of payback period and net cumulative savings.

5.1. Weekly analysis of SCMD operation

A weekly integration results are presented here for better interpretation of the hourly data which shows annual variation of various parameters. Fig. 4 shows the availability of solar resource, ambient temperature levels along with the total thermal energy gains of both FPC and ETC configurations having similar aperture area of 10 m^2 and installed at tilt angles equal to latitude of the experimental setup location. An average weekly thermal energy gains of 205 kWh and 257 kWh are obtained respectively for FPC and ETC. The total incident energy on the collector surface is 2180 kWh/m^2·year at an average ambient temperatures of 28°C.

As per Fig. 4, for similar aperture area evacuated tube collectors gained 25% higher energy than flat plate system. As a consequence, overall production decreased by 40% for FPC configuration and unable to meet the desired demand of 20 L/d for small family application (see Fig. 5). Even though annual pure water demand of 7300 L/d is fulfilled by ETC system, a deficit is still observed in winter period as shown in Fig. 5. An average deficit of 1.6 L/d and 5 L/d is observed that needs to be fulfilled through auxiliary heaters. Average temperatures in solar and MD loop are also shown in Fig. 5. For both solar thermal systems,

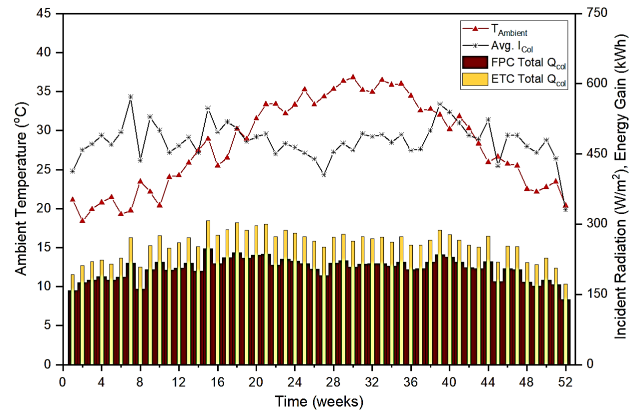

Fig. 4. Weekly average profiles of incident radiation, ambient temperature and energy gain from collectors.

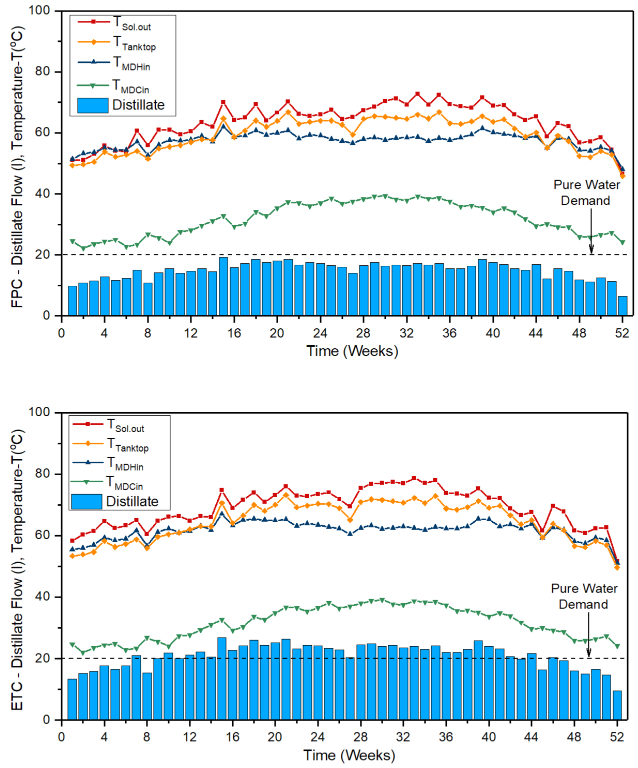

Fig. 5. Weekly analysis: average temperatures, total incident radiation and distillate flow using FPC (top) and ETC (bottom).

an annual average delta T ($T_{MDHin} - T_{MDCin}$) of 30°C has been maintained. DHW thermal storage tank top temperatures are maintained at an average of 60°C and 65°C for FPC and ETC systems enabling them to operate at 84% and 91% solar fractions respectively for hot water generation.

In Fig. 6, thermal and electrical energy flows related to the cogeneration operation using both FPC and ETC configurations are shown. MD system utilized 60% of the total thermal energy gain from the collectors whereas 15% is utilized for DHW generation and the remaining being losses. Fig. 6 also shows the electrical energy demand for operation of pumps with an average values of 5.3 and 6 kWh/week

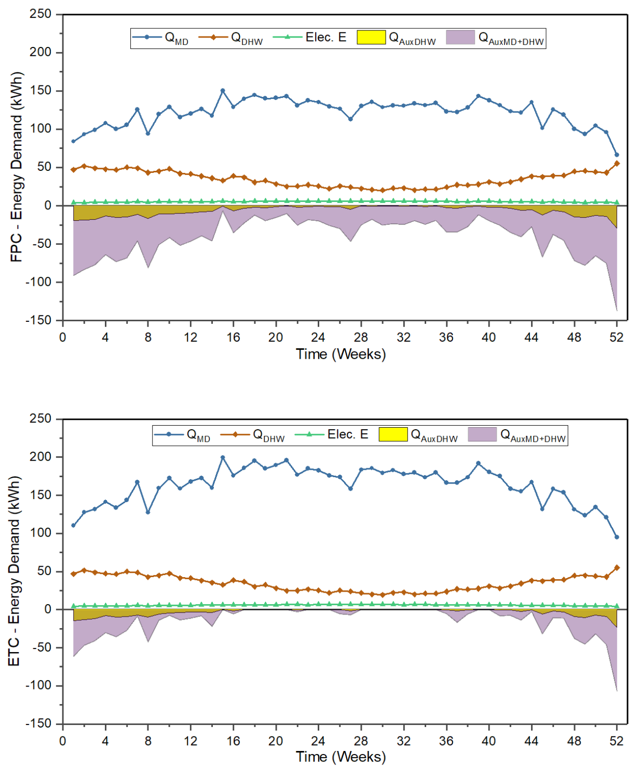

Fig. 6. Weekly analysis of thermal and electrical energy demand using FPC (top) and ETC (bottom).

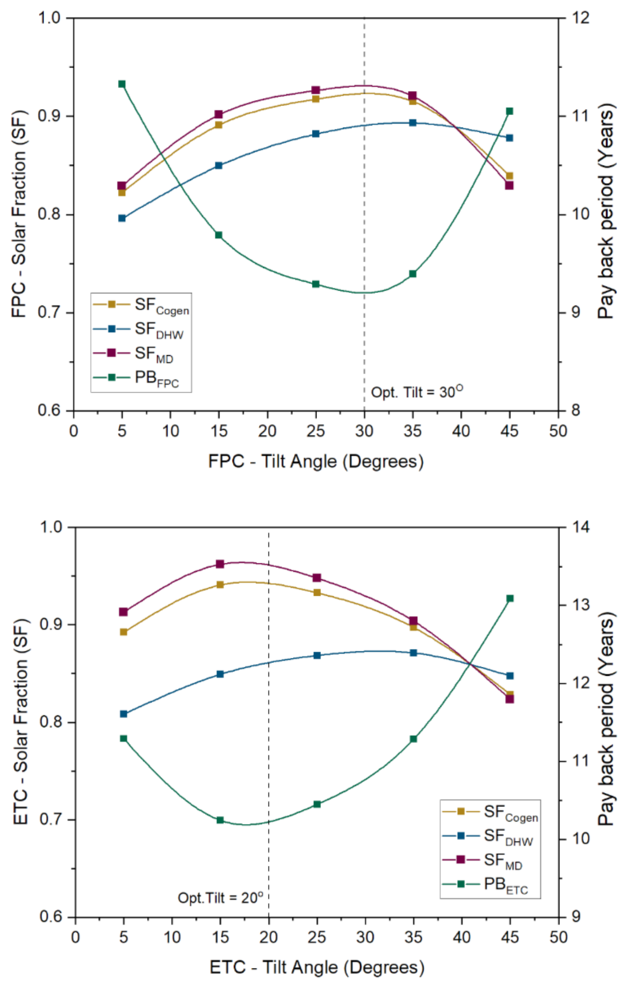

Fig. 7. Variation of SCMD performance with collector tilt angle: FPC (top) and ETC(bottom).

for FPC and ETC configurations respectively. Higher electrical demand for ETC is due to the extended operational hours for MD in summer thereby increasing annual water productivity. Also shown are auxiliary energy demand profiles for fulfilling daily demand of both DHW and MD. The total auxiliary demand for ETC is 56% less than the auxiliary demand for FPC system owing to higher energy gain and increased water production. However, considering the gross area of ETC system which is 28% higher than FPC system, overall economic benefits are similar or even less compared with FPC operation. Therefore, a comprehensive sensitivity analysis need to be performed to analyze techno-economic benefits of using different collectors for cogeneration operation.

5.2. Sensitivity analysis and techno-economic optimization

A constructive approach has been followed in this paper in order to analyze the performance of cogeneration system by changing various design variables. Each optimized parameter is used as a system design parameter for next parameter optimization. Among these variables, for sake of brevity, the sensitivity analysis is shown only with respect to the following parameters: collector tilt angle, volume of thermal energy storage (TES), area of the collectors. Annual solar fractions for cogeneration operation (SF_{Cogen}), individual solar fractions of MD and DHW (SF_{MD} and SF_{DHW}) along with payback (PB) period are considered as performance indicators.

Depending upon the location, collector tilt plays major role for balanced operation of the cogeneration system through out different seasons. Ideally a typical SDHW system need to be optimized for maximizing winter demand and tilt angle should be latitude plus 10° (35° in case of UAE). Similarly, a typical SMD systems will be optimized for summer maximum and operated with collector tilt of latitude minus 10° (15° in case of UAE). Whereas for cogeneration operation, a balance need to be maintained for fulfillment of annual demands of both MD and DHW. Therefore, tilt needs to be optimized for maximum cogeneration solar fraction with minimum payback period. Fig. 7 shows the trends of SF_{cogen} and PB with different tilt angles of both flat and evacuated tube collectors. The trends clearly show that for SCMD operation, 30° and 20° are optimum tilts for FPC and ETC configurations respectively.

Fig. 8 shows the sensitivity analysis as a function of volume of TES operated with optimized tilt angles obtained in the earlier evaluation. TES volume is most sensitive to DHW solar fraction at lower volumes and scarcely sensitive to MD solar fraction. In fact, it is well known that the system storage capacity improves with larger TES volumes,

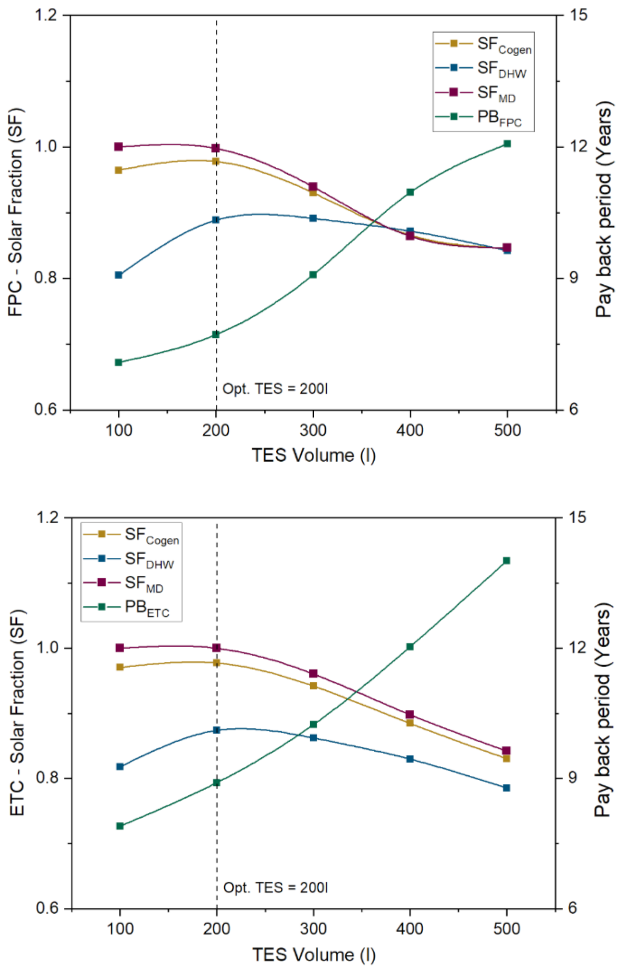

Fig. 8. Variation of SCMD Performance with TES volume: FPC (top) and ETC(bottom).

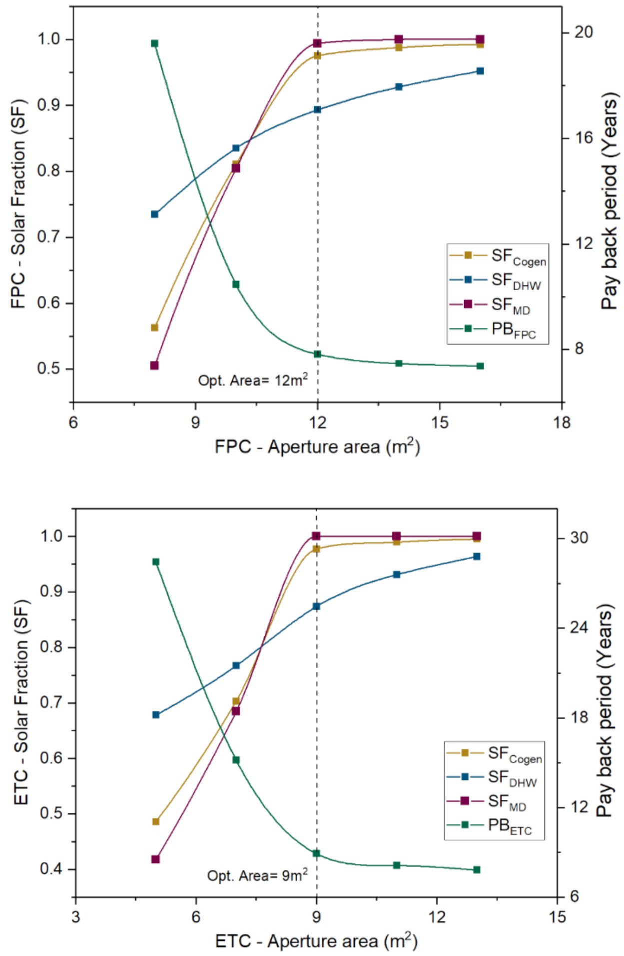

Fig. 9. Variation of SCMD Performance with collector area: FPC (top) and ETC(bottom).

due to increase in amount of solar energy delivered to user. On the other hand, larger TES volumes lead to higher thermal losses toward the environment. As shown in Fig. 8, DHW solar fraction decreases for larger TES volumes beyond 200 L. Also, at TES volume greater than 200 L a steep decrease in cogeneration solar fraction is observed due to reduced heat delivery to MD thereby lowering SF_{MD} below 1. Results also shows nearly linear increase in pay back period with every 100 L increase in storage volume. From the economic point of view, the best configuration (lowest PB) is achieved for smaller TES volumes. Therefore, for both FPC and ETC configurations, TES volume of 200 L will be optimum for SCMD operation.

Simulations are further carried using optimum tilt and TES volume in order to determine optimum collector area required for desired operation. This is the primary parameter for the design of cogeneration system under investigation. According to the design procedure developed in this paper, an increase of the collector area leads to corresponding increase of solar loop flow rate. With MD loop flow rate being fixed, it's important to consider that optimum point should be where SF_{MD} = 1. In fact, practically it's never feasible to obtain SF_{DHW} = 1 and hence maximizing MD solar fraction improves cogeneration solar fraction. Starting point for simulations is minimum collector area requirement for optimum SMD operation i.e. 7 m² for FPC and 5 m² for ETC. Further simulations with increased collector area shows a steep increase in SF_{MD} as shown in Fig. 9 and reaches 1 at 12 m² and 9 m² aperture areas of FPC and ETC configurations respectively. At this point SF_{DHW} is close to 0.9 and increased further with collector area.

Also in Fig. 9 the economic results show that payback periods rapidly decrease with increase in collector area showing better economic performance with larger solar field area. This result is due to the fact that the capital cost obtained for the solar thermal field is sufficiently balanced by the savings due to its heat and pure water productions. However, for extremely large solar collector fields, some amount of heat should be rejected being higher than the needed demand by the users. This would result in a non-monotonic trend of the PB periods, after the point where SF_{MD} = 1. A slight increase in SF_{DHW} could be obtained beyond this point but it's not significant considering the capital cost increase with increase in collector area. To summarize, optimum design parameters for cogeneration system to fulfill annual demand (SF_{cogen} = 0.98) of a single family household with 5 persons in UAE are:

- For FPC solar field: 30° tilt, 200l TES volume and 12 m^2 collector aperture area
- For ETC solar field: 20° tilt, 200l TES volume and 9 m^2 collector aperture area

5.2.1. Increased DHW and MD demand

According to few studies, the average family household in UAE comprises of 5 persons whereas the average might even get doubled if we consider households of citizens [10,35]. Considering the large family households in the region, the demand for both hot and pure water will increase thereby increasing the thermal energy demand for SCMD [36]. Fig. 10 shows the trends of solar fractions and payback period with simultaneous increase in both DHW (50l/day per person) and MD production (4l/day per person) demands. With the optimized configuration of both FPC and ETC systems the cogeneration solar fraction reduces to 0.5 by doubling user demands. DHW solar fractions are reduced by only 5% with doubled demand whereas MD solar fractions reduced by more than 60%. At the same time, payback period increased by 2.5 times owing to substantial increase in thermal energy requirement for MD operation. Henceforth, based on the demography it's important to obtain optimum set of design conditions for a large family household in the region.

Simulations are further performed to obtain optimum collector area required for a large family comprising of 8 members in UAE. Fig. 11 shows the trends of solar fraction and payback periods for a total pure water production of 32 L/d along with 400 L/d of DHW production. Since its practically not possible to fulfill daily pure water demand using single module MD (0.2 m^2 membrane area), an extra module is integrated in series for enhanced production doubling the MD membrane area to 0.4 m^2. Also, the size of thermal storage tank is increased to 300 L to improve storage capability for DHW generation. From Fig. 11 we can conclude that optimum collector area requirement for FPC configuration is 19 m^2 whereas for ETC configuration 14 m^2 is required. With complete pure water demand fulfillment along with 80–85% demand fulfillment for DHW using solar thermal energy, overall cogeneration solar fraction could be as high as 0.95 for the large family SCMD system.

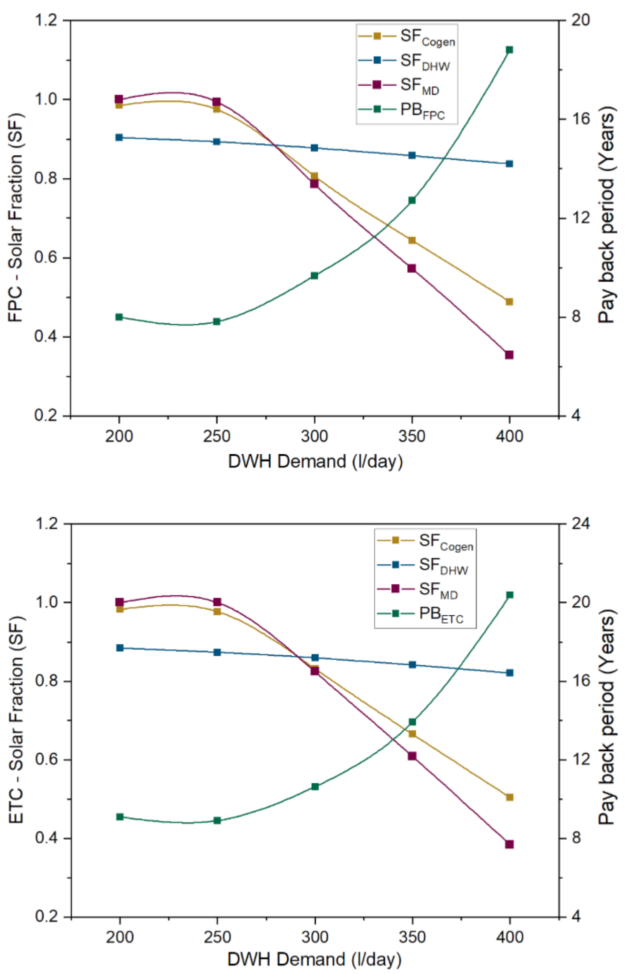

Fig. 10. Variation of SCMD Performance with increased DHW, MD demands: FPC (top) and ETC (bottom).

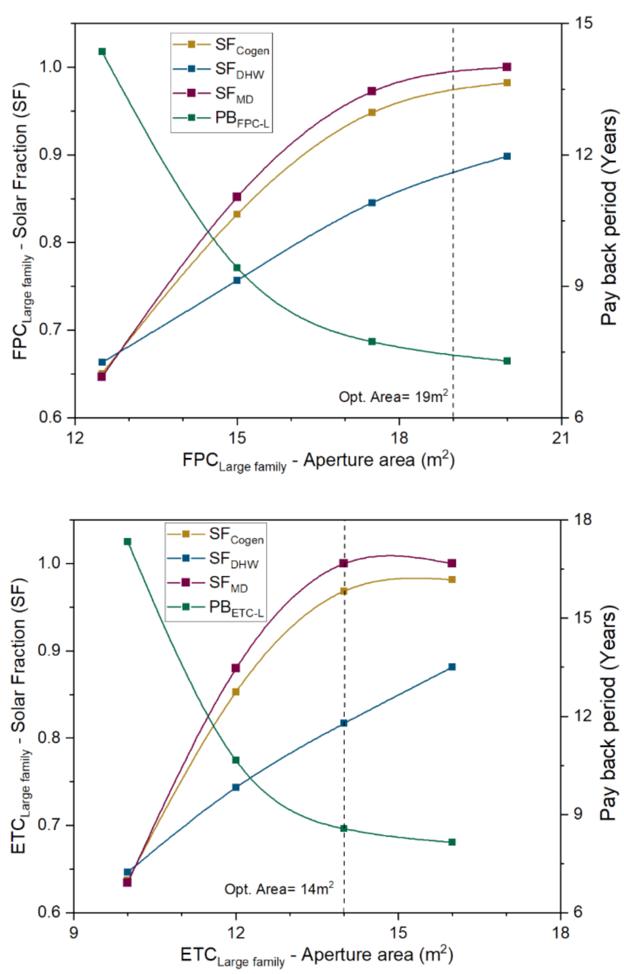

Fig. 11. Variation of SCMD performance with collector area for large family household: FPC (top) and ETC(bottom).

5.3. Cogeneration vs individual operation

The advantages of cogeneration operation must be critically analyzed through comparison of systems operated individually. In this paper the energetic and economic performance of the SCMD system is compared with SDHW and SMD systems. Simulation models are developed in TRNSYS for individual operation and the obtained results are analyzed in terms of thermal, electrical demand, performance efficiencies and also payback, net cumulative savings.

5.3.1. Thermal and electrical energy demand

Fig. 12 shows weekly thermal energy demand profiles for individual and cogeneration operation. SDHW and SMD systems are operated at tilt of 35° and 15° in order to achieve optimum conditions in winter and summer seasons respectively. Individual operation trends show identical energy demand profiles for both FPC and ETC configurations. Daily average energy demands for SDHW and SMD are 33 kWh and 165 kWh respectively. For cogeneration operation energy demand profiles are different due to the difference in solar radiation availability during winter and summer. Since optimum collector field angles for FPC and ETC are 30° and 20°, it affects the magnitude of the collectors energy production. The average daily solar thermal energy consumed by SCMD system is 170 kWh/d and 186 kWh/d for flat and tubular collector fields. Compared with individual operation, total thermal energy demand for cogeneration is reduced by 14% for FPC and 6% for ETC.

In Fig. 13 the electrical energy demand profiles for individual and cogeneration operation are shown. For all modes of operation, electrical energy demand is higher for ETC configuration. This is due to increase in operational hours of ETC due to its inherent characteristic of absorbing more heat than FPC during early morning and late evening hours. For SDHW the operational hour's difference is 2 h whereas for SMD and SCMD systems its reduced to 1 h. Average daily total electrical energy demand for individual operation would be 7 kWh/d and 8 kWh/d for FPC and ETC respectively. Whereas for cogeneration operation E_{SCMD} reduces to 5.3kWh/d and 6kWh/d leading to 25% savings in electrical energy demand.

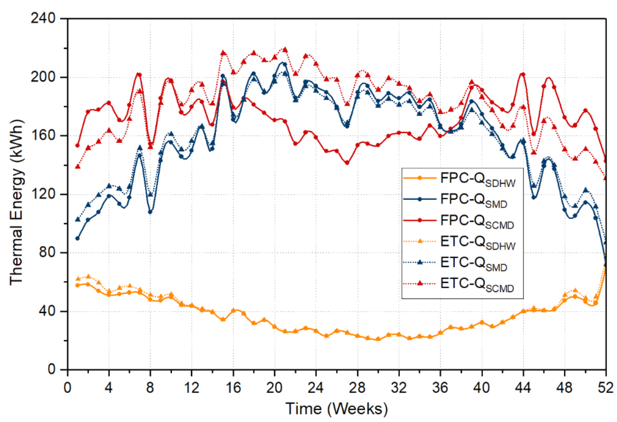

Fig. 12. Comparison of weekly thermal energy demand profiles.

5.3.2. Efficiencies of various operational modes

As mentioned earlier, 3 types of efficiency indicators are used to analyze cogeneration system performance. Fig. 14 shows weekly trends of collector, combined and system efficiencies. For both FPC and ETC configurations, system efficiencies are almost similar showing the ratio of total energy demand to useful energy gain from collectors. More than 80% of the available energy could be utilized for SCMD systems. Interestingly, system efficiencies are lower in summer indicating the availability of extra useful energy gain from the collectors. During summer, DHW demand decreases owing to high cold water temperatures and the extra energy would be potentially useful for MD. Increased water production in summer would be beneficial for gulf climatic conditions which is an added advantage for cogeneration operation. Fig. 14 also shows profiles of collector efficiency with an average values of 45% and 60% for flat plate and evacuated tubular solar thermal configurations. Collector efficiencies are almost constant throughout the year showing the balanced operation of the system. Overall combined efficiency of 37% and 50% are obtained for FPC and ETC configurations respectively. Higher efficiencies for ETC owes to lower aperture area of the collectors however

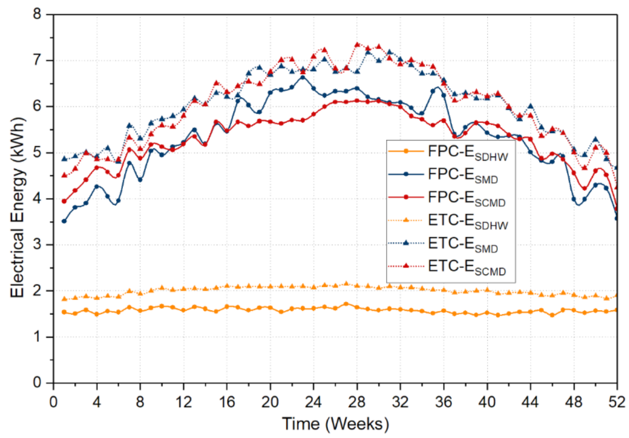

Fig. 13. Comparison of weekly electrical energy demand profiles.

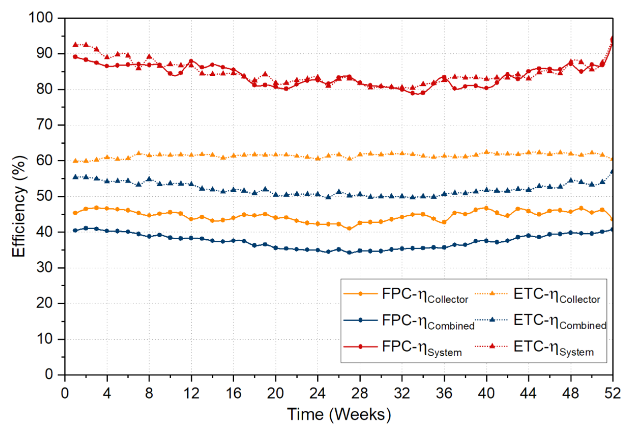

Fig. 14. Performance efficiencies of SCMD system.

from economic view point payback periods are higher for ETC compared to flat plate arrangement.

Table 5 summarizes collector, combined and system efficiencies of individual and integrated operation of DHW and MD system for both single or large family applications. Cogeneration has a clear advantage over SDHW operation with improved combined and system efficiencies between 40–60%. Individual operation of SMD system shows slight improvement in performance however it's not significant from economic viewpoint. The results show the technical feasibility of cogeneration system which can be considered as an efficient design option for end used application in UAE.

5.3.3. Payback and NCS

Economic analysis is performed with fuel inflation rate of 10% along with a discount rate of 5% for different configurations under study. A capital investment cost of 6.2 k$ and 7.5 k$ is estimated by the economic analysis for SCMD operation using FPC and ETC solar fields. These values are 2.5 and 3 times higher in magnitude compared to regular SDHW system whereas the magnitude is reduced to 0.75 times when compared with SMD system. Overall capital investment savings of 10–15% could be achieved for cogeneration operation when compared with cumulative investments costs for individual operation. This reduction is due to efficient use solar thermal energy DHW and pure water production and also reducing operational expenses related to pumping.

The difference of capital investment cost between SCMD and SDHW systems and the saving achievable determine an average PB period of 8 and 9 years for SCMD using FPC and ETC solar fields. For daily demand fulfilment, PB period is further increased by 1.4 years for both configurations. As shown in Fig. 15 payback could be reduced by 2.5–3 years by switching from regular SDHW to SCMD systems along with a 4-fold increase in NCS. Switching from SMD to SCMD had a slight benefit as well in terms of NCS. With increase in user demand (i.e. for large family), NCS would further increase by 55–60% for cogeneration system with similar PB as of small system. Such result shows that the cogeneration system is profitable from the economic point of view when compared with individual installations. Table 6 summarizes the capital investment comparison of individual and cogeneration systems along with their pay back periods for variable user demand demands.

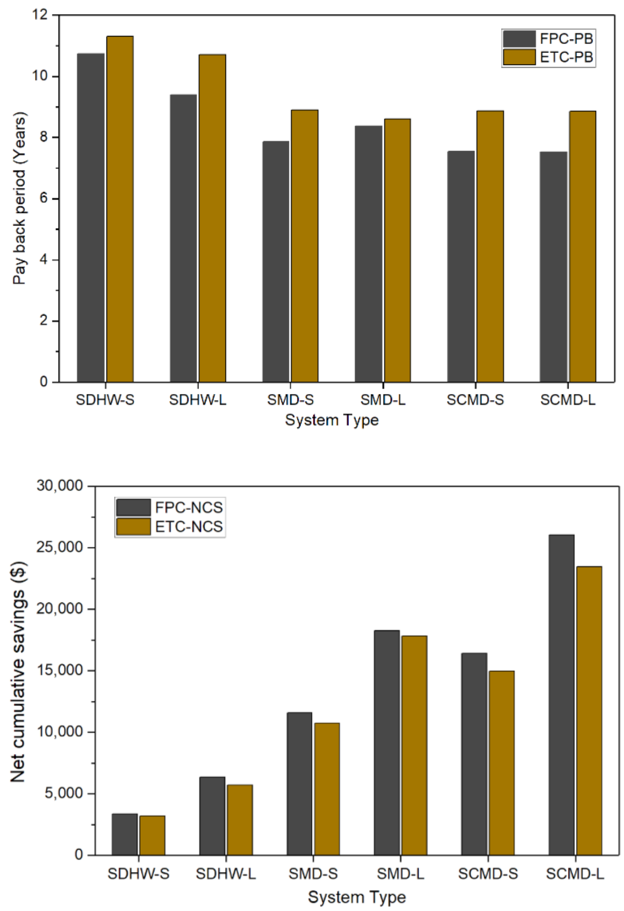

Fig. 15. Comparison of payback period (top) and net cumulative savings (bottom).

Although the whole techno-economic analysis until now is based upon annual demand fulfilment for cogeneration system, it's also important to analyze the system performance considering the daily demand fulfillment for pure water production. Fig. 16 shows PB trends with 3 different cases of economic performance analysis. In order to produce 4 L/d per person using MD system (Single family – 20 L/d, Large family – 32 L/d), sufficient back up thermal energy would be needed thus increasing overall PB period.

Table 5

Collector area and efficiencies of individual and cogeneration operation

Mode of operation	Collector area (m^2)		$\eta_{Collecter}$		$\eta_{Combined}$		η_{System}	
	FPC	ETC	FPC	ETC	FPC	ETC	FPC	ETC
SDHW-S	5	3	0.39	0.59	0.17	0.29	0.45	0.49
SMD-S	9.5	6.5	0.42	0.61	0.4	0.59	0.96	0.96
SCMD-S	12	9	0.45	0.61	0.37	0.5	0.83	0.83
SDHW-L	7	5	0.4	0.56	0.2	0.28	0.5	0.5
SMD-L	18	10	0.35	0.66	0.34	0.64	0.96	0.97
SCMD-L	19	14	0.46	0.63	0.4	0.56	0.87	0.89

Table 6
Capital investment and pay back periods for small family application

System type	Capital investment ($)		PB-Annual demand		PB-Daily demand	
	FPC	ETC	FPC	ETC	FPC	ETC
SDHW	2,460	2,628	10.2	11.3	–	–
SMD	4,666	5,372	7.86	8.9	9.16	10.25
SCMD	6,182	7,460	7.54	8.87	8.13	9.26

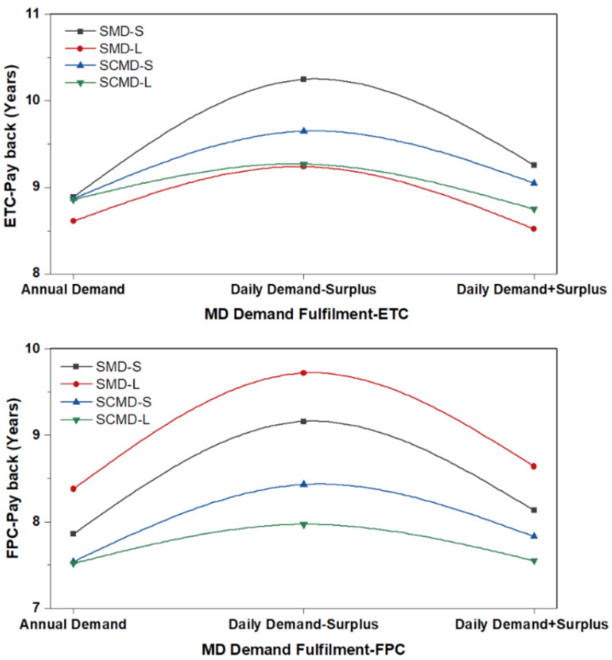

Fig. 16. Variation of payback period with different demand fulfillment types.

However, when we consider the benefits of extra amount of water produced apart from annual demand fulfillment, the PB would remain almost same as annual demand PB. Practically design of cogeneration system on annual demand basis would be sufficient considering user demand profile variability along summer and winter seasons. For large family application (8 members in our case), the difference in payback with variable demand fulfilment is minimal when compared with small family application.

6. Conclusions

The dynamic simulation model of a cogeneration system based on the integration of flat plate and evacuated tube solar thermal collectors with membrane distillation technology was presented. The modelled system produces thermal energy utilized for simultaneous production of domestic hot water and pure water. The system is also equipped with an auxiliary heater used in case of high hot or pure water demand and low availability of solar energy. The case studies adopted for system simulation consists of a small or large family household in UAE comprising of 5 or 8 persons. The cogeneration system was analyzed for different time bases: weekly and yearly for annual production of 7300 L of pure water along with 250 L/d of hot water at 50°C. Sensitivity analysis is performed in order to determine system performance as a function of the main design parameters. Following are the results of the dynamic simulations and techno-economic optimization:

- Annual simulation based on pilot installation in UAE show that out of the total solar energy gain, 60% is utilized by MD system, 15% is utilized for DHW generation and the remaining are losses.
- Optimum design parameters for cogeneration system to fulfill annual demand of a single family household with 5 persons in UAE are;
- For FPC solar field: 30° tilt, 200l TES volume and 12 m^2 collector aperture area
- For ETC solar field: 20° tilt, 200l TES volume and 9 m^2 collector aperture area
- For large family households (8 persons), the optimum collector area requirement for FPC configuration is 19 m^2 and 14 m^2 for ETC configuration.
- Optimized cogeneration system utilizes more than 80% of the available solar energy gain with collector efficiencies of 45% and 60% for FPC and ETC respectively.
- Average daily solar thermal energy demand by cogeneration system is 170 kWh/d and 186 kWh/d for FPC and ETC configurations. Whereas average daily electrical demands are 5.3 kWh/d and 6 kWh/d respectively.
- Cogeneration operation reduces 6–16% of thermal energy demand and also enables 25% savings in electrical energy demand.
- PB could be reduced by 2.5–3 years by switching from regular solar water heating to cogeneration systems along with a 4-fold increase in NCS.
- With increase in user demand (i.e. for large family), NCS could be further increased by 55–60% for cogeneration system with PB period of 8–9 years.
- Considering drinking water demand variability of users along summer and winter seasons, its practical to design a cogeneration system on annual demand basis rather than daily demand fulfilment.

In summary, this study proved the technical feasibility of a cogeneration system which can be considered as an efficient design option for residential application in UAE. In fact, the results also showed that the system under investigation would be economically viable in a number of configurations. In addition, cogeneration option operated with two MD modules in series will be profitable a swell for higher user demand profiles. This system will become more and more attractive in gulf region in the next few years as a consequence of drastic turn towards sustainability and abundant availability of solar renewable energy sources. Future work will include a detailed energetic and economic optimization of cogeneration system aiming at evaluating the profitability of the system for different weather conditions around the world, also considering the related energy markets.

Symbols

A_{Col}	—	Area of the collector field
A_{MD}	—	Membrane surface area
A_{PHE}	—	Heat exchanger area
C_B	—	Cost benefits
C_{DW}	—	Distilled water cost
C_F	—	Fuel cost
C_I	—	Initial investment cost
C_{MD}	—	MD unit related costs
C_{Solor}	—	Solar field related costs
d	—	Discount rate
E	—	Electrical energy
I_{col}	—	Instantaneous incident radiation per m^2
i_F	—	Fuel inflation rate
Q_{Col}	—	Collector useful energy gain
Q_{MD}	—	Energy demand by MD
$\dot{Q}_T$	—	Heat transfer rate across heat exchanger
$\dot{Q}_{\max}$	—	Maximum heat transfer rate
Q_{DHW}	—	Energy demand for DHW
Q_{IR}	—	Incident radiant energy
Q_{Aux}	—	Auxiliary energy demand
S	—	Surface area
T	—	Temperature
t_p	—	Time period
V	—	Volume
W_p	—	Peak pumping power
α	—	Absorptance
δ	—	Thickness
ε	—	Effectiveness of heat exchanger
τ	—	Transmittance
η	—	Efficiency
λ	—	Conductivity
CP	—	Thermal capacitance
FPC	—	Flat plate collectors
ETC	—	Evacuated tube collectors
NCS	—	Net cumulative savings
PB	—	Payback period
SCMD	—	Solar combined membrane distillation
SDHW	—	Solar domestic hot water system
SMD	—	Solar membrane distillation system
-L	—	Large family system
-S	—	Small family system

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