Thermal Analysis of Parabolic Trough Solar Collector and Assessment of Steam Power Potential at Two Locations in Cameroon

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Abstract- Over the past two decades, Cameroon has devoted enormous financial resources to the construction of thermal power plants operating on Heavy Fuel Oil. Despite these efforts, it has been noted that the production of electricity from fossil sources has not been up to the expectations of the population. In this context, it becomes a necessity to explore other sources of energy production most precisely renewable sources. This paper is concerned with the assessment of the steam production potential from solar sources in the stations of Maroua and Yaoundé using Parabolic Trough Collectors. Two production modes are considered in this study: The direct mode using water and the indirect mode with TherminolVP1 as heat transfer fluid. The system is modeled based on the study of the energy balance between the receiver and the calorific fluids in order to assess the impact of the irradiance on the calorific fluid outlet temperature at hourly time scale over the day. The assessment of the collector characteristics shows an optical efficiency varying between 0.73 and 0.75 while the overall heat loss coefficient extends over wide ranges depending on the environmental conditions and generation mode. It was shown that the temperature of the steam increases with the number of collectors. For an association of 8 collectors, the average daily production time of pressurized steam at 40bars is 8 hours with a maximum temperature of 600 °C in direct mode and 490 °C in indirect mode for the month of February in Maroua. The maximum thermal efficiency for the same month is 72.7% in direct generation and 60.7% in indirect generation. These results confirm the real steam potential for electricity generation for complementing existing heavy fuel oil stations with solar sources for better supply. However, further investigations about the energy demand and the supply are necessary for appropriate sizing of the solar generator.

Keywords- Parabolic Trough Collector; Steam Potential; Heat Exchange; Generation Mode; Calorific Fluid.

Nomenclature

Latin Symbols

A_a	Aperture area (m^2)
A_g	Glass area (m^2)
A_r	Area of the receiver (m^2)
C_{pf}	Heat capacity of the fluid in the receiver
C_{pf2}	Heat capacity of the water in the second loop (J / kg K)
$D_{g,e}$	External diameter of the glass (m)
$D_{g,i}$	Internal diameter of the glass (m)
T_{fo}	Outlet temperature of the fluid (°C)
T_r	Temperature of the absorber (°C)
U_L	Overall heat loss coefficient ($W/m^{-2}/K$)
$\dot{v}$	Volumic flow rate (m^3/s)

Greek Symbols

α_r	Absorption coefficient of the absorber tube
ε_g	Emissivity of glass
ε_r	Emissivity of absorber

e	Heat exchanger efficiency (%)
f	Focal distance of the collector
F_r	Heat dissipation factor along the tube
$h_{r,g-amb}$	Radiative heat exchange coefficient between the glass and the ambient ($W/m^{-2}/K$)
$h_{c,g-amb}$	Convective heat exchange coefficient between the glass and the ambient ($W/m^{-2}/K$)
$h_{r,r-g}$	Radiative heat exchange coefficient between the absorber and the glass ($W/m^{-2}/K$)
I_b	Incident direct solar irradiance (Wm^{-2})
L	Collector length
K	Incident angle modifier factor
$\dot{m}$	Mass flow rate (Kg / s)
$\dot{m}_{f2}$	Mass flow rate of water in the exchanger (Kg / s)
Q_{ab}	Heat received by the absorber (W)
q_{r-g}	Heat exchanged between the receiver and glass cover (W)
Q_f (x)	Heat received by the fluid at abscissa x (W)
Q_{Loss}	Heat lost (W)
Q_u	Usefull heat (W)
q_{r-amb}	Heat exchanged between the glass and the ambient air (W)
R_e	Reynolds number
T_{amb}	Ambient temperature (°C)
T_{fi}	Inlet temperature of the fluid (°C)
T_g	Temperature of the glass Cover (°C)
θ_i	Incident angle
λ	Thermal conductivity (W/m.K)
σ	Stephan Boltzmann constant (W/m^2K^4)
ζ_s	Geometric intercept factor of the collector
η_{opt}	Optical efficiency of the concentrator (%)
ρ	Reflectance of the mirror
ρ_f	Specific mass of heat transfer fluid (Kg/m^3)
τ_g	Transmission coefficient of the glass

Subscripts

amb	Ambient
c	Convective
e	External
g	Glass
i	Inlet
o	Outlet
r	Absorber /Radiative

Abbreviations

ETP	Emergency Thermal Program
PTCs	Parabolical Trough collectors
PVGIS	Photovoltaic Geographical Information

1. Introduction

The global increase in the demand for energy caused by industrialisation and development has made the need for energy a priority at planetary scale. In 2018, this increase amounted to 2.3% in conventional fossil energy and 4% in electrical energy for an overall demand of 23000 TWh [1]. This situation has motivated progress in the development of new generation modes of so-called clean energy because they are environmentally friendly and has forced many countries around the world to search for fossil energy sources as well. A situation that has been the origin of most of the conflicts in the world over the past decades. In fact, global primary energy consumption remains dominated by fossil fuels, i.e. 81.3% in 2019 [1], with an increase on environmental consequences. In this light, it will be important to point out the rising cost of electric energy due to the increase in the prices of fossil and fissile resources, the reduction in fossil fuels potentials at global scale, their contribution to pollution and climate change whose adverse impact has become tragic to the populations around the world.

In spite of these limitations, Cameroon in its plan to emerge by 2035 has set up programs aimed at filling its energy gap by building thermal power stations connected to the national electricity grid and operating on Heavy Fuel Oil. The Emergency Thermal Program (ETP) unfortunately seems insufficient as the country continues to experience crises in the electricity sector characterized by poor quality supply and untimely power outage. Indeed, the cost per kWh is very high in these power plants due to the increase in the price of fuel as well as the financial impact of maintenance. As a result, these plants do not provide a viable solution though the existing ones are still functional. This is what caused the termination of ETP two years after it was launched.

To handle this situation, the production of electricity from renewable sources and primarily solar energy is an alternative that can meet a significant part of the country's electricity demand given its abundance [2]. Cameroon's solar potential varies from one region to another, ranging from about 4 kWh / m^2 / Day in its southern part to about 5.74 kWh / m^2 / Day in the northern region [3].

This solar energy could be used for electricity generation in different ways, with the most promising being photovoltaic and concentrated solar thermal [4] [5] [6]Solar concentrating technologies use direct sunlight and support a good tilt to collect the maximum amount of energy [7]. Concentrated solar thermal energy mainly consists of 4 different technologies that can be used in steam power plants [8]. These include; Solar towers, parabolic collectors, Fresnel mirrors and parabolic trough collectors (PTCs). Nowadays, the most proven method for steam production is PTCs because this technology is easy to implement compared to tower plant and parabolic concentrator and it is more profitable than Fresnel mirrors [9] [10]. Steam production with PTCs can be done in two modes, each having its own particularity and technical constraints. The direct mode [10] uses water as heat transfer fluid in the absorber tubes to generate steam, while the indirect mode [11] uses thermal oils as heat transfer fluid and water as working fluid, both fluids being connected by a heat exchanger. Nowadays, the advancement of this technology has led to innovative steam generation systems using nanofluids as calorific fluid [12] and combining thermal energy storage systems to enhance the thermal efficiency [13].

For the above reasons, many countries have opted for PTCs as electricity generation technology. This is for instance the case of Morocco with its NOOR program which includes the Ouarzazate parabolic plant with an installed capacity of 200MW [14]. Also, researchers have been interested in the geometrical and thermal analysis of PTC in view to further its efficiency in steam production. Ghodbane [15] using the direct steam production mode for converting solar energy into thermal energy in Algeria obtained a thermal efficiency exceeding 60%. However, this study which is limited to solar data for a period of four days could not provide objective information on the real potential of the region. Boukkelia [16] dealing with the optimization of the performance of a parabolic collector system using thermal oil and operating in indirect generation mode obtained an output power of 50MW with a maximum conversion efficiency of 69%. The work uses solar data corresponding to period of two months and shows important advances in terms of optical and thermal performances of PTCs as it takes into consideration energy losses and non-uniform distribution of solar flux on the receiver. In the same context of optimization, Martin and Mariano [17] used a mathematical programming technique to optimize the operation of a concentrated solar plant working on regenerative Rankine cycle in the south of Europe. Ghodbane et al. [18] conducted under real weather data an investigation of a solar power plant of PTCs. The study which assessed numericaly the geometric and optical characteristics of a solar collector showed optical efficiency exceeding 77.22 % and localized the maximum local concentration ratio in the lower part of the receiver tube. Behar et al. [19] carried out the validation of a novel parabolic trough solar collector model by comparing experimental data with results of previous studies and obtained improvements in the accuracy of thermal performance prediction. However, knowledge of the power generation potential of a typical area using such optimized concentrating systems is of great importance [20]. In fact, although thermal performance of a parabolic trough solar power plant is critical to the global performance of the system, information on energy potential of a given region ultimately goverm the decision for technical implementation of CSP plants.

It is evident from the literature that most of the research work on design, performance assessment and optimization of PTC solar power plants in Africa is carried out in the Northern part of the continent which possess very large exposed areas. However, equatorial Africa also exhibits high enough solar potential that should be harnessed in order to overcome its energy gap. The study presented here is an attempt to the characterization of this potential and represents a step toward complementing existing Heavy Oil Thermal stations in Cameroon to enhance the power supply of the country. Besides the study of optical and thermal performances of parabolic trough collectors, this work focuses on the assessment of the steam production potential in Cameroon using solar sources as alternative to save fuel and boost the efficiency of existing power plants, while reducing the environmental impact of the plant operation. Two production methods are taken into account according to the calorific fluid, including water for the direct generation and Therminol vp-1 and water for the indirect generation. The study also applies to two stations; Maroua (10.59° N, 14.31° E, 423 m) located in the Sahelian (semi-arid) region of Cameroon where the solar potential is the highest and Yaoundé (3°52 N, 11°31 E, 726 m) in the tropical humid area. The iraradiance data used for each station correspond to five-year averages (2012-2016) for the sunniest and the least sunny months respectively in both localities.

The rest of the paper is organized as follows: Section 2 gives the details on PTCs, calorific fluids and discusses the optical and thermal analysis of PTCs. Section 3 presents the daily profiles of output temperature of water along with the steam power generated and discusses their significance while section four summarizes the work.

2. Materials and method

2.1. Details on PTCs

The parabolic collector consists of a reflector in the form of a parabolic cylinder which concentrates the radiation on a linear receiver placed in its focal plane [21]. The receiver is made up of an absorber protected by a glass envelope. The reflector and absorber assembly is mounted on a metal frame placed on the ground [22]. The main tracking system used is one axis with rotation in the axis of the receiver. The geometric parameters of the system (focal distance, inclination of the receiver, the opening angle of the concentrator) influence its operation, in particular at the level of the energy exchange between the concentrator and the absorber [23]. The cylindro-parabolic reflector is made up of a reflective material mounted on a frame which can be a metal, composite material or glass. Depending on its nature (thick or thin), the reflector can be placed directly on a frame or curved to adapt to the frame. The metal structure of the reflector must be strong enough to withstand the significant mechanical stress associated with the wind. A good quality reflector can reflect up to 97% of incident radiation [24].

The absorber is the main component of the parabolic trough. It generally represents 30% of the cost of construction [25]. In order to limit losses by convective and radiative exchange with the surrounding, a glass casing covers the absorber. Creating a vacuum in the annular space limits heat losses between the absorber tube and the casing glass. These losses can also be limited by reducing the infrared emissivity of the absorber tube (copper or aluminum) using so-called selective surfaces [26]. Nowadays, manufacturers employ coatings using chromium, nickel or titanium oxides. Table 1. presents the details of optical and geometric characteristics of LS2 parabolic trough collector used in this work.

Table 1. Optical and geometrical characteristics of LS2 PTC [27]

Optical parameters	**Values**		**Geometric Parameters**	**Values**
Intercept factor	0.89		Length of the collector (m)	5
Incident angle modifier factor	0.99		Width of the collector (m)	47
Concentrator reflectance	0.94		Internal diameter of the absorber (mm)	66
Glass cover transmittance	0.95		External diameter of the absorber (mm)	70
Absorber absorptivity	0.94		Internal diameters of the glass (mm)	109
			External diameters of the glass (mm)	115
Thermophysical properties of Therminol VP1 as function of temperature(*) [28]				
Property	**Formula**			
Density	$-0.90797\,\mathrm{T} + 0.00078116\,\mathrm{T}^2 - 2.367 \times 10^{-6}\,\mathrm{T}^3 + 1083.25$			
Heat capacity	$0.002414\,\mathrm{T} + 5.9591 \times 10^{-6}\,\mathrm{T}^2 - 2.9879 \times 10^{-8}\,\mathrm{T}^3 + 4.4172 \times 10^{-11}\,\mathrm{T}^4$			
Thermal conductivity	$-8.19477\,10^{-5}\,\mathrm{T} - 1.92257 \times 10^{-7}\,\mathrm{T}^2 + 2.5034 \times 10^{-11}\,\mathrm{T}^3 - 7.2974 \times 10^{-15}\,\mathrm{T}^4$			

(*) Similar properties for water are directly obtained from thermodynamic tables.

2.2. Calorific fluids and description of the model

The choice of working fluid is of utmost importance when designing a concentrating solar power plant. Indeed, this fluid determines the range of the operating temperature as well as the working pressure. In addition, it guides technical aspects such as the integration of thermal storage, the use of an exchanger as well as the generation mode.

Commercial power plants with indirect steam generation have two fluid cycles, including the calorific fluid which is a thermal oil and the working fluid which is water. Thermal oils are fluids that allow temperatures of around 400 °C at the outlet of the solar generator. They guarantee stable operation of the system due to their thermophysical properties and low operating pressures [29]. For these reasons, Therminol vp 1 is used in this study. Figure 1.a give the details of the indirect steam generation system used in this work. Pump 1 takes care of the circulation of the thermal oil while pump 2 maintains the pressure in the water loop. The flow in the two loops is at constant mass rate in accordance with the security conditions provided by the constructors. The thermal connection between the two loops is made through a heat exchanger which serves as steam generator [30] [31]. The condenser in the water loop reduces the temperature of the working fluid while assuring its total phase change in order to maximize heat collection at the level of the heat exchanger.

Figure 1.a shows the direct production system where steam is directly generated in the absorber tubes of the solar collector . Only one pump is used to circulate water in this case since the steam goes directly to the turbine after the solar collector. The use of water as heat transfer fluid allows for higher temperatures of about 600 °C with high pressures [27], which induces high efficiencies. The absence of heat exchanger allows for higher conversion efficiency and a reduction of almost 10% in the production cost of electricity [28]. However, the absence of an intermediate heat transfer fluid can affect the system stability and performance as the system has to cope with the intermittent nature of incident solar energy. In addition, rapid fluctuations in heat input can result in incomplete vaporization of the water and thus damage the turbine. Another technological challenge is the construction of a receiver that can withstand the high pressures and temperatures relevant for a Rankine cycle [32].

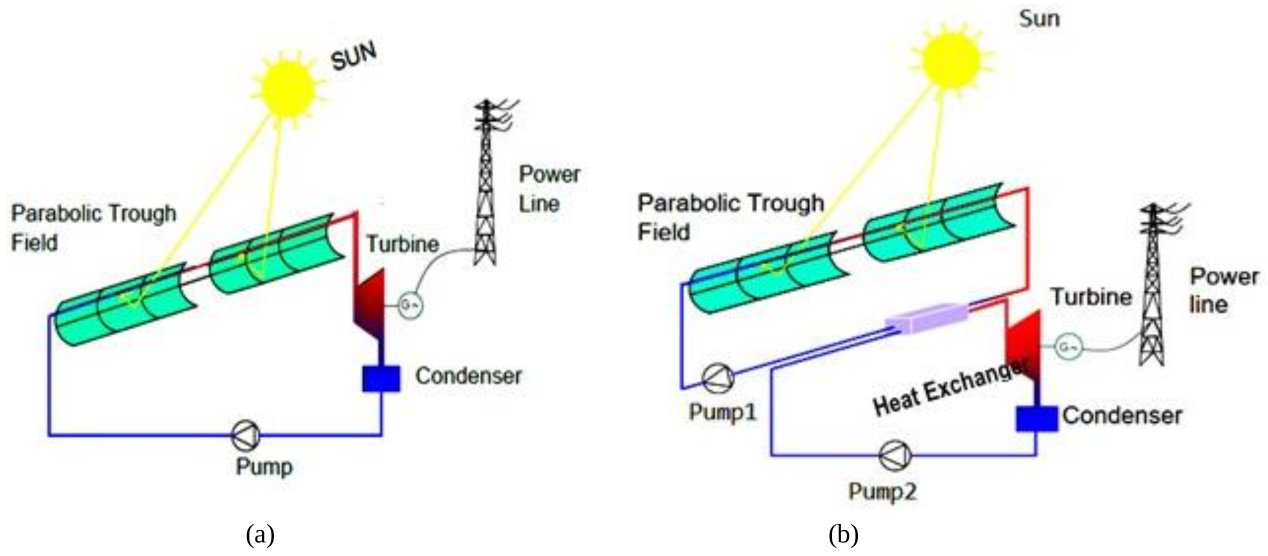

Fig 1. Direct (a) and (b) indirect steam generation systems

2.3. Solar data

The solar irradiance data used in this work is obtained from Photovoltaic Geographical Information System (PVGIS) [33]. PVGIS is the official website of the European Union which provides access to solar irradiance data, ambient temperature and tools for assessing the performance of photovoltaic systems. Satellite data used for solar irradiance estimates are provided by METEOSAT satellites covering Europe, Africa and most of Asia. The site produces for a given station one image at hourly time scale from January to December, which allows generating averages at desired time scale. The resolution of satellite images is higher just below the satellite (nadir) and decreases as we move towards the edge of the image. In Cameroon, the northern region has the highest solar potential [2]. This is the reason for the choice of Maroua site which is one of the three stations with the highest solar potential in the country with an annual average of 2080.5 kWh / m^2 / year. Yaoundé station located in the equatorial area was chosen because of its power demand that grows rapidly with the consequence of regular power outages which cause significant losses in economic activities. The annual average irradiance there is 1350.6 kWh / m^2 / year. The average direct normal solar irradiance data used for both stations corresponds to five-years period ranging from 2012 to 2016.

Figure 2 illustrates the daily profile of incident solar irradiance as a function of time during February and August for Maroua and Yaoundé. It can be noticed that Maroua station receives significantly more sunshine with an average peak exceeding 750W/m^2 during the hottest month (February). This can be explained by its geographical situation since Maroua is located in the semi-arid region of Cameroon unlike Yaoundé which is in the equatorial region. The maximum solar irradiance is usually reached in the late morning (11:00-12:00) in both stations for the periods of the year chosen in this work. This peak is globally followed by a decrease until sunset.

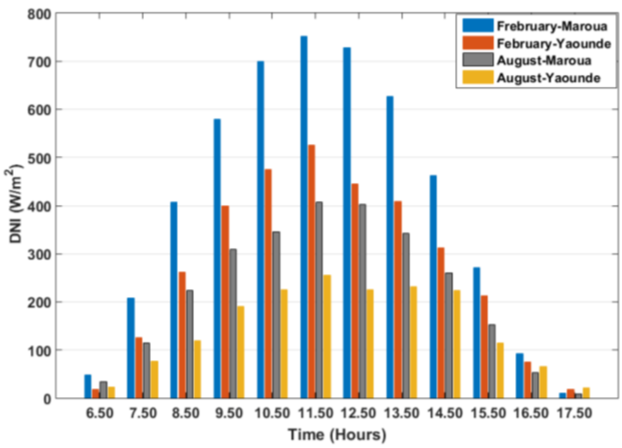

Fig 2. Daily profile of incident solar irradiance for Maroua and Yaoundé [35].

2.4. Thermal Analysis of PTCs

Thermal modelling of the collector allows to assess the temperature of the heat transfer fluid at the outlet of the absorber, as well as heat losses and thermal efficiency. The energy balance of the absorber tube in this analysis is based on following hypotheses [15]:

- The heat transfer fluid is incompressible and undergoes a permanent and one-dimensional flow.
- The incident solar flux on the absorber is uniformly distributed and the ambient air temperature assumed to vary over the day.
- The glass is considered opaque to infrared radiation.
- Heat transfer by conduction in all the elements of the concentrator is neglected.

- Thermophysical properties of the working fluid change as function of its temperature.

Figure 3 describes the longitudinal section of the absorber tube and heat transfer processes involved in the energy balance analysis.

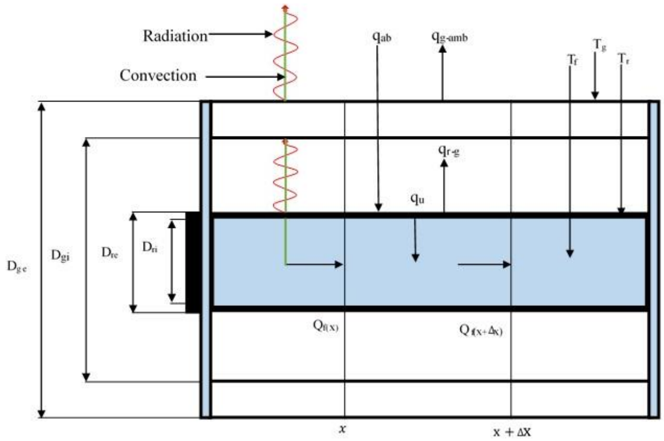

Fig 3. Longitudinal section of the absorber tube and heat transfer processes.

Heat exchange by forced convection between the internal surface of the absorber and the fluid in a tube section between x and x + dx leads to the following equation:

$$q_f(x+\Delta x) - q_f(x) = q_u(x)\,\Delta x \tag{1}$$

Where $q_f(x+\Delta x) = \rho_f\, c_{pf}\, \dot{v}\, T_f(x+\Delta x)$, $q_f(x) = \rho_f\, c_{pf}\, \dot{v}\, T_f(x)$ and q_u the useful power necessary to heat the fluid.

Replacing $q_f(x+\Delta x)$ and $q_f(x)$ in Eq. (1) yields:

$$\frac{\rho_f\, C_{pf}\, \dot{v}\, T_f(x+\Delta x) - \rho_f\, C_{pf}\, \dot{v}\, T_f(x)}{\Delta x} = q_u(x) \tag{2}$$

i.e $$\rho_f\, c_{pf}\, \dot{v}\, \frac{\partial T_f(x)}{\partial x} - q_u(x) = 0 \tag{3}$$

Heat exchange between the absorber and the glass casing gives:

$$q_u(x) + q_{r-g}(x) = q_{ab} \tag{4}$$

Where q_{r-g} is the amount of heat exchanged by convection and by radiation between the absorber and the glass i.e.

$$q_{r-g} = q_{c,r-g} + q_{r,r-g} \tag{5}$$

Considering now the glass envelope and the environment, we have:

$$q_{r-g}(x) - q_{g-amb}(x) = 0 \tag{6}$$

Where q_{g-amb} is the amount of heat exchanged between the glass and the environment by convection and radiation:

$$q_{g-amb} = q_{c,g-amb} + q_{r,g-amb} \tag{7}$$

The useful heat Q_u supplied to the fluid can be expressed as

$$Q_u = \dot{m}\, C_{pf}(T_{fo} - T_{fi}) \tag{8}$$

with $\dot{m}$ the mass flow (kg/s).

This heat can also be computed by [18]

$$Q_U = F_r \times [\eta_{opt} I_b A_a - U_L A_{r,e}(T_{fi} - T_{amb})] \tag{9}$$

Where F_r is the heat dissipation factor along the tube. Combining Eq. (8) and (9) yields

$$F_r = \frac{\dot{m}\, C_{pf}(T_{fo} - T_{fi})}{[A_a I_b \eta_{opt} - A_{r,e} U_L (T_{fi} - T_{amb})]} \tag{10}$$

η_{opt} is the optical efficiency of the concentrator given by [18]

$$n_{opt} = K(\theta_i)\, \zeta_s\, \rho\, \tau_g \alpha_r \tag{11}$$

$K(\theta_i)$ is the correction coefficient of the incidence angle. This factor allows to take care of the deviation between sun rays and the normal at the collector due to imperfection in tracking system, imperfection in support structure or the imperfections resulting from manufacture and is given as

$$K(\theta_i) = 1 - \frac{f}{L}\left[\left(1 + \frac{l^2}{48 f^2}\right)\right] \tan(\theta_i)$$
(12)

Where f is the focal distance, L and l the length and width of the collector respectively. θ_i is the incidence angle.

U_L is the overall heat loss coefficient [34] defined based on the collector geometry and its operating condition as

$$U_L = \left[\frac{A_{r,e}}{(h_{c,g-amb} + h_{r,g-amb}) A_{g,e}} + \frac{1}{h_{r,r-g}}\right]^{-1} \tag{13}$$

Where $h_{c,g-amb}$ is the convective heat exchange coefficient between the glass and the ambient given by [34]

$$h_{c,g-amb} = \frac{0.3\, R_e^{\;0.6}\, \lambda}{D_{g,e}} \tag{14}$$

R_e is the Reynolds number, λ the thermal conductivity and $D_{g,e}$ the external diameter of the glass.

$h_{r,g-amb}$ is the radiative heat exchange coefficient between the glass and the ambient given by

$$h_{r,g-amb} = \varepsilon_g \sigma (T_g + T_{amb})(T_g^2 + T_{amb}^2) \tag{15}$$

$h_{r,r-g}$ the radiative heat exchange coefficient between the absorber and the glass given by

$$h_{r,r-g} = \frac{\sigma (T_g + T_r)(T_g^2 + T_r^2)}{\frac{1}{\varepsilon_r} + \frac{A_r}{A_g}\left(\frac{1}{\varepsilon_r} - 1\right)} \tag{16}$$

The fluid outlet temperature from equation (8) can then be written as a function of Q_U and the inlet temperature as [35]

$$T_{fo} = T_{fi} + \frac{Q_u}{\dot{m}.C_{pf}} \tag{17}$$

Similarly, the thermal efficiency [36] is given by

$$\eta = \frac{Q_u}{Q_{ab}} = \frac{\dot{m}C_{pf}(T_{fo} - T_{fi})}{n_{opt} I_b A_a} \tag{18}$$

For the indirect generation mode, the heat transfer fluid leaving the absorber passes through a counterflow heat exchanger of efficiency *e* where it releases part of its heat to the water of mass flow rate $\dot{m}_{f2}$, specific heat $C_{p,f2}$ and inlet temperature $T_{f2,i}$. The temperature of the water at the outlet of such an exchanger is expressed as:

$$T_{f2,o} = T_{f2,i} + \frac{e\,\dot{m}C_{pf}}{\dot{m}_{f2} C_{p,f2}}(T_{fo} - T_{f2,i}) \tag{19}$$

Figure 4 presents the flowchart used to conduct the numerical study of the plant.

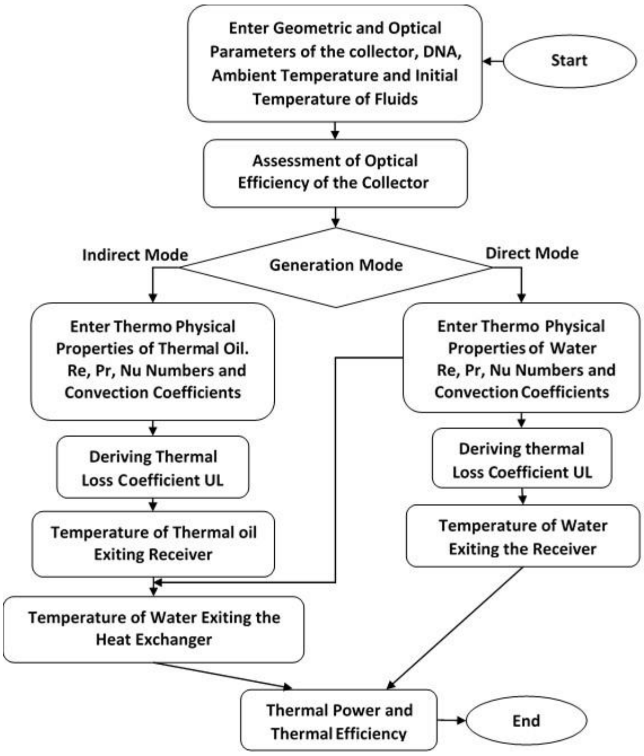

Fig. 4. Assessment procedure flowchart

3. Results

The following results were obtained using a LS2 parabolic trough collector with the optical and geometric characteristics summarized in Table 1. The heat transfer fluid (water in direct mode and Therminol vp-1 in indirect mode) circulates inside the absorber at a rate of 0.6Kg/s. The pressure of the working fluid (water) for both modes of steam generation is 40 bars with the corresponding saturation temperature of 250 °C. Beyond this temperature, the working fluid changes to the vapor.

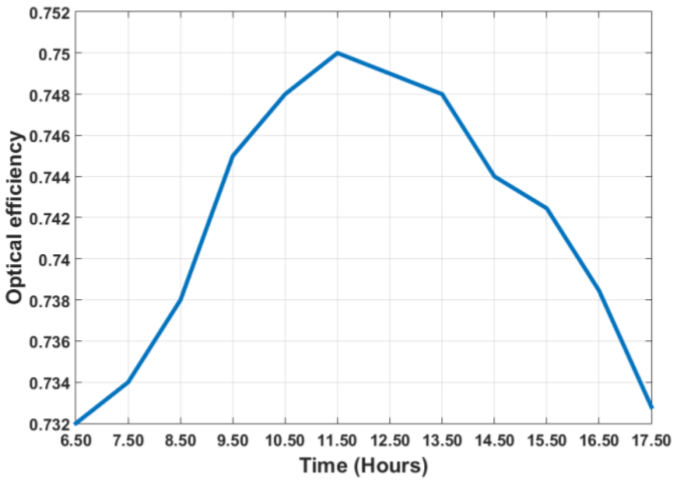

Fig. 5. Optical efficiency of the collector

According to Fig. 5 obtained from Eq. (11), the minimum value of optical efficiency (0.73) is obtained at sunrise and sunset and the maximum value 0.75 at the zenith. The optical efficiency is reduced for greater values of incident angle. Indeed, the variation of optical efficiency is always inversely proportional to the incidence angle and reducing the value of this angle decreases the total loss at the collector aperture [18].

Figure 6 shows the daily variation of the overall heat loss coefficient in both generation modes. This coefficient varies as a function of the geometric configuration and thermophysical properties of the heat exchange medium. Because these properties change with the thermal profile of the material which in turn is controlled by climatic conditions, there is a strong dependence of U_L on irradiance. In fact, the greater the difference between the temperature of the absorber and that of the ambient air, the more energy is lost from the absorber to the environment. This result is in agreement with Godbane et al [29] who obtained a maximum U_L of 8.963 W/m^2.°C for a collector of 2m long. For an assembly of 8 collectors, the present study demonstrated maximum values of 35 W/ m^2 °C and 28 W/ m^2 °C for the month of February respectively in Maroua and Yaoundé, confirming the high dependence of U_L on the irradiance. It is important to point out in agreement with Ghodbane et al [34] that the maximum values are recorded at peak sunshine when the highest temperature difference occurs.

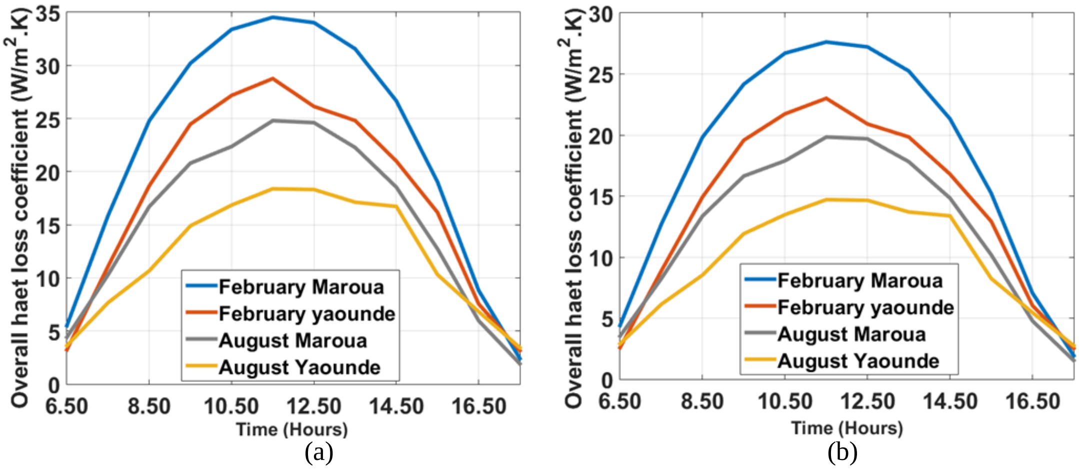

Fig. 6. Profile of the overall heat loss coefficient (a) in direct generation and (b) in indirecte generation modes.

3.1. Direct generation mode

This mode assumes that the steam used in the energy production process comes directly from the solar generator. Figure 7 shows the variations of the outlet temperature of the heat transfer fluid over time for a steam production system having respectively 1, 2, 4 and 8 PTCs mounted in series at Maroua and Yaoundé.

The temperatures obtained in both stations in February are higher than those obtained in August with consistent differences between the two stations. These deviations once again show the great solar potential of Maroua because the outlet temperature of the heat transfer fluid is a close function of the incident solar flux. Moreover, the increase in the number of sensors connected in series makes it possible to achieve higher heat transfer fluid outlet temperatures. With one concentrator (Fig. 7a), the fluid's temperature takes on significant values from 8:30 am and the peak is reached around 12:00 at both stations. However, the maximum temperatures of 135° C and 95° C reached in February in Maroua and Yaoundé respectively are not sufficient to produce steam at 40 bars. With an association of 2 collectors (Fig. 7b) in series, the thermal profile remains substantially the same as for 1 collector, but the temperatures obtained are higher. In the case of 4 collectors (Fig. 7c), the temperatures obtained are very high in February, sometimes exceeding 250° C.

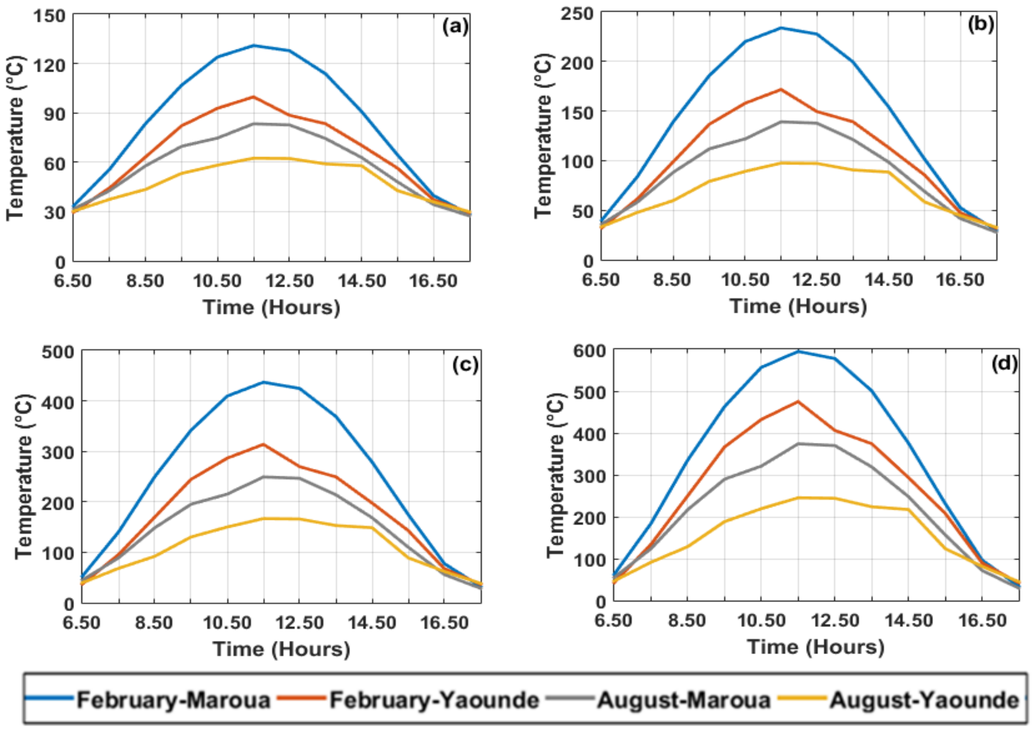

Fig. 7. Water outlet temperature for (a) one, (b) two, (c) four and (d) eight PTCs mounted in series.

At Maroua station in February for instance, the steam production capacity is achieved between 9 am and 3 pm. In August, however, it is not possible to generate steam in both stations because the temperatures are below 250 °C. In the case of 8 concentrators (Fig. 7d), satisfactory temperatures are obtained at both stations even in August, the least sunny month at both localities. There is high a possibility for steam production at 40 bars between 9 am and 3 pm because during this time interval, outlet temperatures are higher than 250° C for both stations.

In conclusion, the increase in the number of collectors connected in series yields higher heat transfer fluid outlet temperatures. In fact, the increase in the length of the tube (number of manifolds in series) leads to that of the exchange surface and thus more heat collection. This feature is clearly expressed by table 2 that summarizes the daily duration of steam production in the two stations as a function of the number of concentrators.

Table 2. Daily duration for steam generation at 40 bars.

Number of Concentrators (N)	Daily duration for steam generation			
	Yaoundé		Maroua	
	February	August	February	August
N=1	0	0	0	0
N=2	0	0	0	0
N=4	3	0	6	0
N=8	7	2	8	6

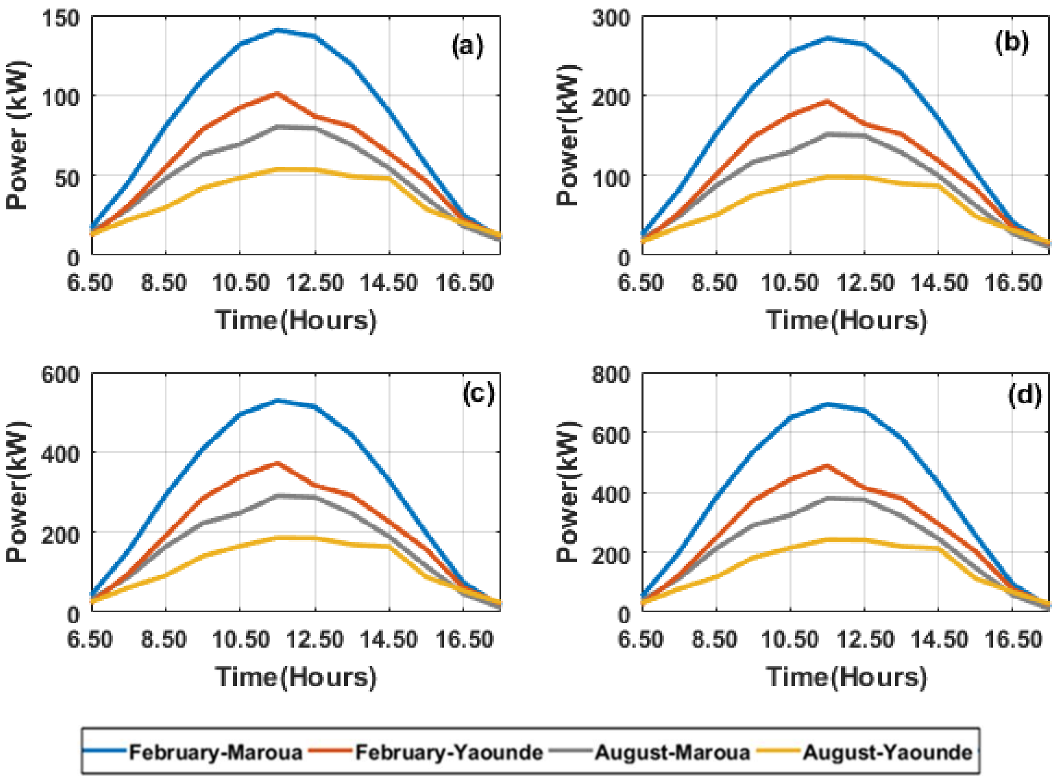

Fig. 8. Output power of steam for (a) one, (b) two, (c) four and (d) eight PTCs mounted in Séries.

The power carried by the calorific fluid follows the same pattern as the outlet temperature of the fluid which varies as function ot the irradiance and the number of PTCs in the system. The maxima are then obtained at the peak of the sunshine around midday and for an association of larger number of collectors. As shown in figure 8d, with eight concentrators connected in series, the steam power is sufficiently high in the two stations and varies globally between 10 and 710 KW. This result shows that the PTC-based solar plant could be localy used in conjunction with heavy fuel thermal station in a view to reduce the dependence of the country in fossil fuel. However, the number of PTCs in the association in this case should be in perfect agreement with power generation objectives.

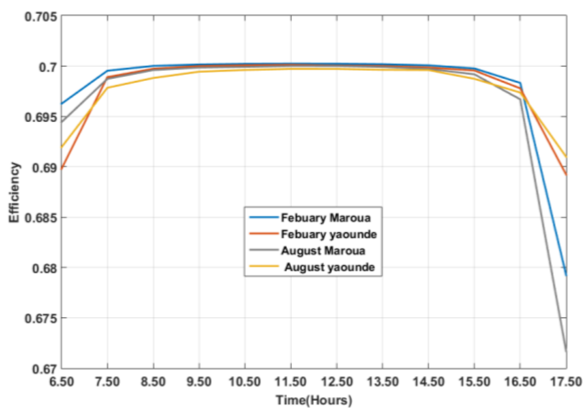

Fig. 9. Thermal conversion efficiency for an association of 8 collectors

The thermal efficiency in the case of 8 collectors is relatively high, varying between 0.67 and 0.70 for the two stations as shown in figure 9. The system is more efficient and stable when there is sufficient sun (from 7.50 to 15.50). It can also be noticed that the decrease in the efficiency after the maximum value of 70% becomes very significant as from 16.50. Indeed, at this period of the day, the incident solar energy has consistenly reduced and also the difference ($T_{fi} - T_{amb}$) (see Eq. 9) tends to increase, a situation that stimlates thermal losses from the water to the ambient. Similar profile was obtained by ghodbane et al. [34] with mean value of the thermal efficiency of 74.30 % although the analysis was done on a shorter collector.

3.2. Indirect generation mode

In this mode of steam generation, Therminol vp1 is used as heat transfer fluid and water as working fluid. This thermal oil was chosen because of its high heat capacity compared to other oils and its low corrosion potential. The temperature range it can reach is limited to about 400 °C and does not require working at high pressures as it is the case in the direct mode with water. The connection between the two fluids is made via a counter-flow heat exchanger with 70% efficiency. Figure 10 shows the profile of the outlet temperature of the working fluid and figure 8 presents the steam power produced as a function of solar time at the two stations involved with this analysis.

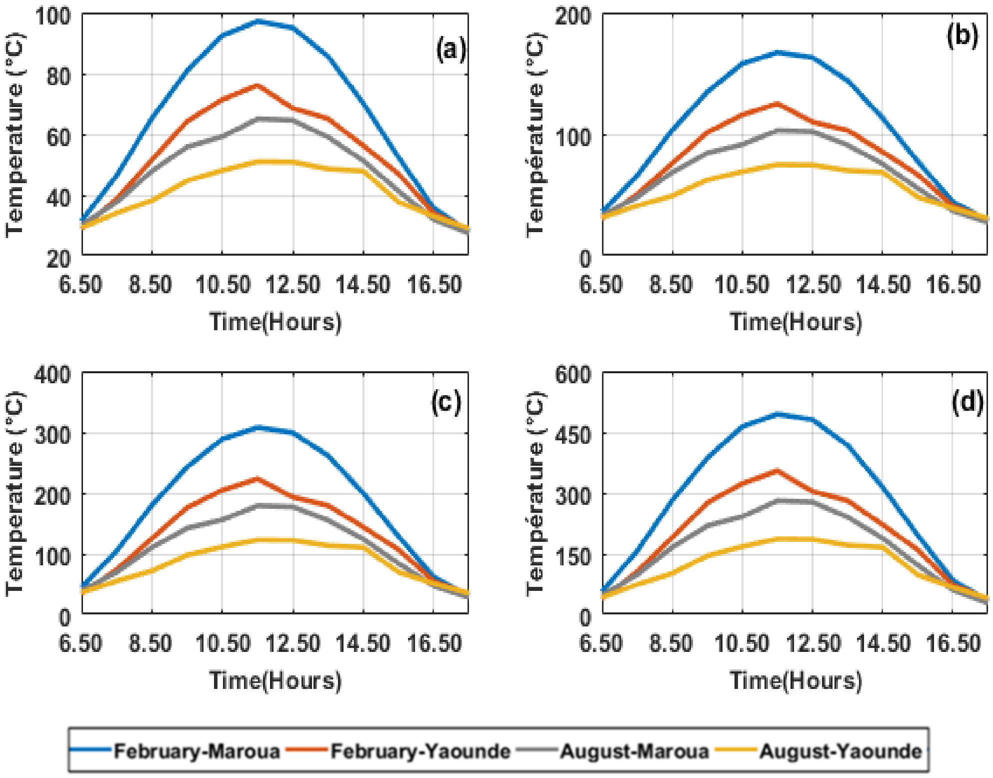

Fig. 10. Water outlet temperature for (a) one, (b) two, (c) four and (d) eight PTCs mounted in series.

The temperature profile of the calorific fluid at the outlet of the collector in the indirect mode of steam generation is broadly similar to that of the irradiance. For a single collector, the energy transferred during the day by Therminol vp1 via the heat exchanger allows the water circulating with a flow rate of 0.6 Kg/s to raise its temperature up to a maximum value of 98 °C (figure 10a). This temperature is 165 °C (figure 10b) for an association of 2 PTCs, 310 °C (figure 10c) for 4 PTCs and 490 °C (figure 10d) for 8 PTCs at Maroua in February. Indeed, these maxima are recorded at the peak sunshine. Lower values are achieved at Yaoundé for similar collectors associations. These results show that in this case of indirect generation too, the increase in the number of collectors leads to the increase in the outlet temperature of steam which is directly related to the outlet temperature of the calorific fluid. However, temperatures remain lower than that those obtained under the same conditions in direct mode. Table 3 summarizes the daily duration of steam production as a function of the number of concentrators at both locations. It can be seen from table 3 that additional collectors are needed to generate steam at Yaoundé during least sunshine period.

Table 3. Daily duration for steam generation at 40 bars for indirect mode.

Number of Concentrators (N)	Daily duration for Steam Generation			
	Yaoundé		Maroua	
	February	August	February	August
N=1	0	0	0	0
N=2	0	0	0	0
N=4	0	0	3	0
N=8	4	0	8	2

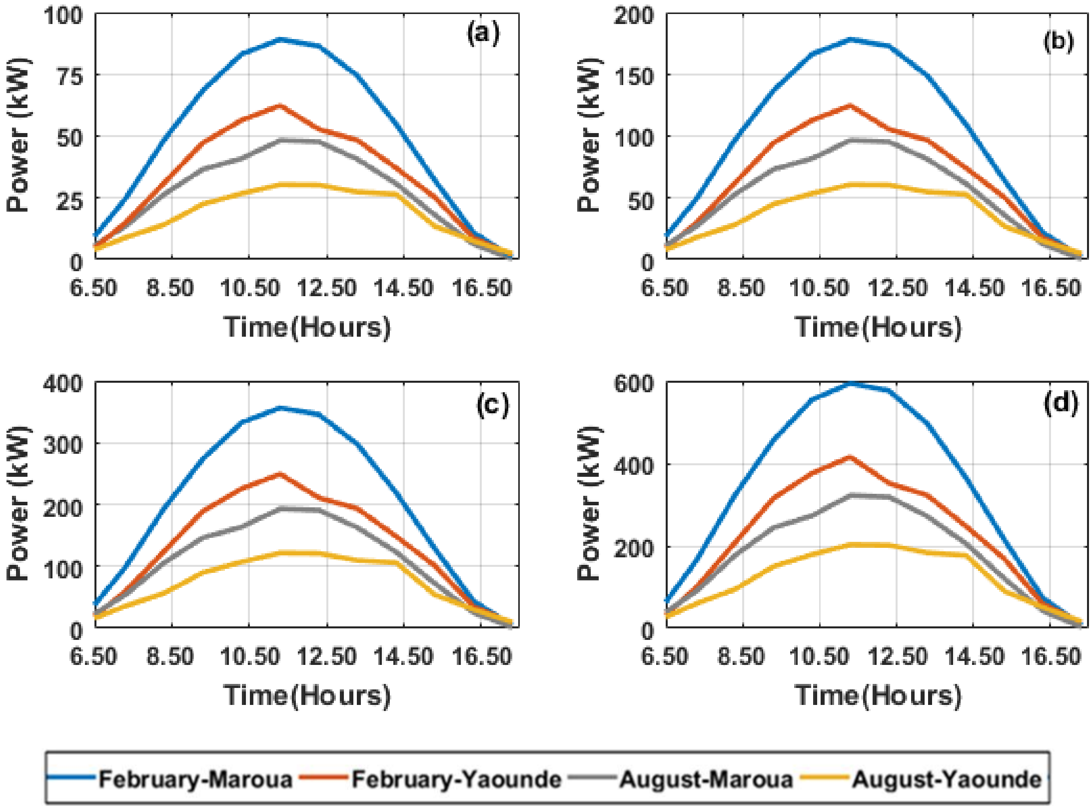

Fig. 11. Output power of steam for (a) one, (b) two, (c) four and (d) eight PTCs mounted in séries.

Figure 11 shows the steam power produced by the concentrator in indirect mode for series associations of PTCs. It can be observed that for an association of 8 collectors, a maximum power of 600 KW (figure 11d) is achieved in February at 12.50 pm at Maroua while 410 KW is obtained at Yaoundé. The increase in the number of sensors thus makes it possible to achieve higher thermal power at the output as with the temperature. This result confirms the possiblibity of energy generation combining solar sources with existing heavy fuel oil stations for better efficiency. However, further investigations about the energy demand and the supply are necessary for appropriate sizing of the solar generator.

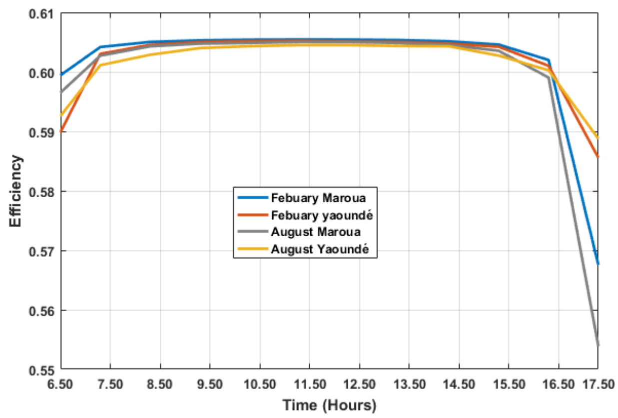

Fig. 12. Thermal efficiency for an association of four concentrators.

The maximum thermal efficiency for the indirect mode is 60.5% (figure 12). It's shape is comparable to that the direct mode, but is slightly weaker. This is due to the presence of an intermediate fluid and the heat exchanger in indirect generation as well as the fact that the direct mode requires working at high pressure and temperature.

4. Conclusion

This work assessed the steam production potential of Maroua and Yaoundé using parabolic trough collectors in direct and indirect modes in the perspective of complementing existing thermal plants with solar sources in Cameroon. It was noted that pressurized water at 40 bars with a flow rate of 0.6kg/s can be used to generated steam for an average daily duration of 8 hours with a maximum temperature of 600 °C in direct generation and 490 °C in indirect generation. These results where observed for a combination of 8 PTCs during the most favorable month at the two stations. The direct mode permits the achievemrnt of higher temperatures than the indirect mode because water used as a calorific fluid in direct mode has better thermophysical properties than Therminol vp1. The maximum thermal efficiency for an association with 8 collectors in February at Maroua is 72.7% in direct mode and 60.5% in indirect mode. This difference is due to the presence of an intermediate fluid and losses at the level of heat exchanger in indirect generation. However, the direct mode, although it has many advantages presents a real problem of instability linked to the need for high pressure in the absorber. Thus, the choice of a generation mode depends on many factors which must be carefully taken into account. These two stations have real potential for producing steam from solar sources. It will of great advantage to harness this energy in a steam power cycle for electricity generation, so as to reduce the drawbacks of the existing thermal plants. Hence, further investigations on energy demand and supply are necessary for appropriate dimensioning of the solar generator. Also, economic analysis of the solar systeme taking into consideration the technical and environmental constraints relative to each of the generation modes would be determinant for the sizing of the electricity generation system.

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