International Journal of Environmental Science and Technology (2022) 19:2279–2294
https://doi.org/10.1007/s13762-021-03273-7

ORIGINAL PAPER

Energetic, economic and environmental analysis of domestic solar water heating systems under the African continent

M. A. Ben Taher[1,2] · T. Kousksou[1] · Y. Zeraouli[1] · M. Ahachad[2] · M. Mahdaoui[2]

Received: 4 November 2020 / Revised: 30 January 2021 / Accepted: 12 March 2021 / Published online: 16 April 2021

Abstract
Given the abundance of solar irradiation in Africa, different types of Solar Water Heating technologies can offer practical and reasonable solutions that are valuable for African people and their environment. However, these technologies' impacts were not quantified, and lack of studies could be in part attributed to the weak implementation of solar water heating systems on most countries in Africa. The aim of this paper is first, a model was developed and validated to investigate and analyze the energy performances of the two most domestic used technologies in the African continent: the flat plate collectors and the evacuated tube collectors. Next, the economic and environmental aspects of these systems are also presented. The study was carried out for 43 countries divided in 5 regions: North Africa, West Africa, Central Africa, East Africa and Southern Africa. The energy analysis, in terms of solar fraction, shows that the solar production of domestic hot water varies between 25 and 88% for the evacuated tube and between 10 and 60% for the flat plat collector and this according to the 5 regions mentioned above. Based on the Net present worth, the Benefit–Cost Ratio and the Discounted payback period, the economic analysis shows that these two technologies are beneficial for 16 of the 43 countries studied. That is due to the abundance of other energy resources in the remaining countries.

Keywords Economic method · Environmental impact · Renewable energy · TRNSYS

Abbreviations

SWH	Solar Water Heating
FPC	Flat plate collector
ETC	Evacuated tube collector
Qc	Energy collected (kWh)
Qd	Energy delivered (kWh)
$Qloss$	Energy losses (kWh)
$Qaux$	Auxiliary electrical energy (kWh)
IAM	Incidence Angle Modified
TMY	Typical meteorological year
a_0	Intercept efficiency (%)
a_1	First-order efficiency coefficient W. m^{-2} k^{-1}
a_2	Second-order efficiency coefficient W. m^{-2} k^{-2}
T_m	Mean water temperature (K)
T_{ext}	Ambient air temperature (K)
SF	Solar Fraction (%)
G	Solar radiation (W. m^{-2})
i	Interest rate (%)
d	Discount rate (%)
NPW	Net present worth
BCR	Cost-benefit ratio
DPP	Discounted payback period
SPP	Simple payback period
A	Annual saving ($)
CF	Cash-Flow ($)
N	Life Time (Year)
USPW	Uniform series present worth
SPPW	Single payment present worth
EF	Emission Factor (kg.CO2eq/kWh)
GHG	Greenhouse Gas

Greek symbols

λ	Rate of inflation (%)
μ	Thermal efficiency (%)

Editorial responsibility: Samareh Mirkia.

✉ M. A. Ben Taher
ben-taher.ma@univ-pau.fr

1 Université de Pau Et Des Pays de L'Adour, SIAME, E2S UPPA, 64000 Pau, France

2 Equipe de Recherche en Transferts Thermiques & Énergétique - Département de Physique FST, Université Abdelmalek Essaâdi Tanger, Tangier, Morocco

Introduction

Africa is a young continent full of hope, its countries constitute a zone of development with immense potential. Many of its economies are among the most dynamic in the world today. Concomitantly, the continent is facing an energy crisis as the share of fossil fuel consumption continues to grow (represents 85% of the energy mix). GHG emissions, related to urban population growth and deforestation, are also on the rise. More than 600 million Africans have no access to domestic electricity, despite the high potential for renewable energies. If current trends persist, electricity will not be available to all Africans until 2080 (World Bank Group 2017).

In this context, the African Renewable Energy Initiative (AREI) plans to redress this situation through the development of renewable energies in order to cover a quarter of the continent's energy needs by 2030, which is four times more than that of the current situation. The target set in the continent is to reach 300 GW of renewable energy capacity by 2030, which would require a 680 percent increase in the pace of the current deployment (The Economist Intelligence Unit 2016). Renewable energies (wind, solar, hydroelectric, biomass, etc.) covered 5% of the continent's energy needs in 2013. Thanks to its immense potential, Africa can easily meet 22% of its energy needs by 2030. Thanks to immense solar potential in Africa, several uses of solar can be found, electricity production, photovoltaic (PV) and concentrated solar power CSP (Gabra et al. 2019), solar hydrogen energy production (Hoffmann 2019), solar drying (Lamrani et al. 2019), solar desalination (Mohamed 2020) and solar water heaters (Curry et al. 2017).

In the same context, solar water heaters have been encouraged and supported by many parts of Africa. The capacity of solar technologies was greater than 1 GWth in South Africa, 0.5 GWth in Tunisia and 0.4 GWth in Morocco by the end of 2013. SWH is the most advanced technology for domestic hot water production, which reduces the hot water bill up to 75% and covers 50 to 60% of hot water needs thanks to the energy recovered by solar panels. The energy collected is absorbed by a heat transfer fluid that retains heat to the water tank. The tank stores the hot water and releases it according to use (International Energy Agency 2015).

FPC and ETC are the most used technologies for domestic hot water production. In various parts of the world, many authors have investigated the energy, economic and environmental aspects of both technologies and their achievements are reported in various studies. For example, these two technologies have been well studied in Europe (Aydin et al. 2018), America (Rosas-Flores and Zayas 2016) and Asia (Huang, Fan and Furbo 2019). A few studies have been carried out on these two systems in Africa (Ben Taher et al. 2018). Sami et al., (2018) discussed the energy and economic viability of these systems in Algeria. The results showed that SWH systems could save up to 46% of conventional energy in northern regions and 57% in southern areas. This will undoubtedly contribute to the economic success of investments in solar energy in Algeria. Al Jamar et al. (2019) predicted the evolution of solar water heaters installed in Morocco by 2040.

Endale (Endale 2019) examined the potential and importance of SWHs to reduce energy consumption and the dependency on imported oil and the unsustainable supply of wood for heating purposes in Ethiopia. Hussein, (2002) presented a theoretical and experimental study of Egypt's two-phase closed-circuit thermosiphon flat plate water heating. For different meteorological conditions and initial temperatures of the storage tanks, the experimental results with and without hot water sampling show an acceptable agreement with their corresponding simulations and the current model proved to be an effective tool for the optimization of solar thermosiphon flat-plate water heating. Rajab et al. (2017) proposed to replace the electric heating system with a SWH system. Both alternatives were compared in terms of fuel cost, capital, maintenance and CO2 emissions. It has been found that the SWH system is the optimal solution as Libya is struggling to meet energy needs and it is difficult to build new plants. Given that this country depends on oil and gas for power generation, this will reduce the country's revenue when load demand increases in the near future. Artur et al. (2020) assessed the energetic, environmental and economic impact of the transition from technology hot water to solar thermal systems in Mozambique.

Based on the literature review, the studies carried out have proven the role of SWHs to reduce energy consumption of some African countries. While to the authors' knowledge, no study has reviewed and investigated the energy, environmental and economic performance of these systems on this continent. In this context, a numerical model has been developed in this study and has been validated for both SWH technologies (FPC and ETC) on the basis of experimental results. Further, to clarify the study, 43 African countries are divided into 5 regions: North Africa, West Africa, Central Africa, East Africa, and Southern Africa. Subsequently, an analysis of the current status of SWH in each region was presented. Finally, based on the following model, an energetic, economic and environmental (3E) analysis of both systems was presented in all regions of Africa.

This paper is structured as follows. Section 2 outlines the simulation model, its validation and the analytical method employed. Section 3 discusses the energy potential all regions in the African continent while taking into consideration the results of energy simulation, the economic approach and the environmental assessment. The last section addresses the conclusion of the study. As regards the study, it was carried out during 2020 within FSTT / UAE Morocco and UPPA France.

Materials and methods

Physical model

Two-forced circulation SWHs were considered (Table 1): one with FPCs and the other with ETCs each had a 300-L hot water tank. Both systems are supposed to be installed in a residential house (with 4 or 5 occupants) in different capitals of the African continent. It is assumed that the hot water flow rate is 240 l/day supplied at a temperature of 45 °C (Ben Taher et al. 2019). The TRNSYS computer program is used to investigate the annual energy potential of SWH (Fig. 1) by introducing meteorological data (TMY2, "Type109") from each country.

The model can be used to evaluate the energy received Qc, the energy delivered Qd, the overall losses Q_{loss}, the auxiliary electrical energy Q_{aux} and the solar fraction (SF) of SWHs. This fraction is the most important factor to assess the performance of these systems expressed by the proportion of solar heat yield and the total energy necessary to produce hot water.

$$\text{SF} = \frac{Q_c - Q_{\text{loss}}}{Q_c - Q_{\text{loss}} + Q_{\text{aux}}} \quad (1)$$

The thermal efficiency for both collectors is determined by the second-order collector equation defined by**:**

$$\mu = a_0 - a_1 \frac{(T_m - T_{\text{ext}})}{G} - a_2 \frac{(T_m - T_{\text{ext}})}{G} \quad (2)$$

where

a_0: Collector optical efficiency, a_1, a_2: Heat loss coefficients by conduction and convection, G: Total radiation on titled surface, T_m: Mean water temperature, T_{ext}: Ambient air temperature.

The economic analysis is evaluated yearly and all system costs are paid from the beginning of the installation. The degradation of solar system performance is presumed to be 1% per year, the economic analysis period is 20 years (lifetime for both systems), while all the economic parameters used for this study like the rate of inflation (λ), the market interest rate (i), the discount rate (d) (Trading Economics 2018) and the electricity price (UPDEA. Secrétariat Général 2009) are described in Table 2.

Table 1 Collector parameters

Parameters	ETC collector	FPC collector	Unit
Collector area	2.5	2.5	m^2
Tested flow rate	100	100	kg/h
Fluid specific heat	4.19	4.19	kJ/kg. K
Collector optical efficiency	0.821	0.821	–
Heat thermal coefficient by conduction	2.82	3.31	W/m^2. K
Heat loss coefficient by convection	0.0047	0.0181	W/m^2. K^2

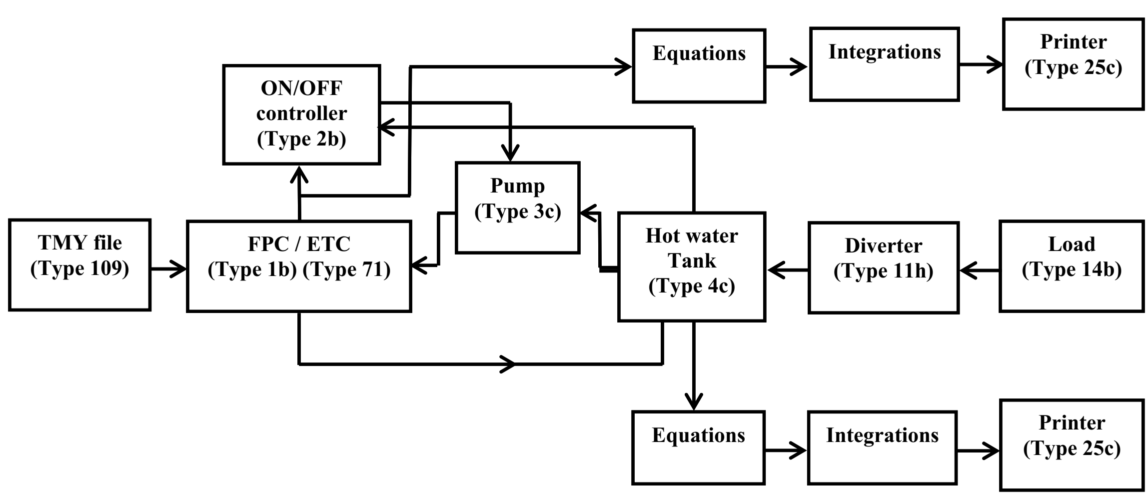

Fig.1 Schematic of TRNSYS for SWH Systems

Table 2 Economic and environmental parameters

Region	Capital	Discounted rate (*d*)	Residential Electricity (US cents/kWh)	Reduced emissions (kgCO2eq/kWh)
North Africa	Rabat	− 0.002439024	13.44	0,66,526
	Algiers	0.019155206	4.84	0.50848
	Tunis	− 0.01810585	9.05	0.47497
	Tripoli	− 0.132266217	1.52	0.65978
	Cairo	0.032272325	1.34	0.42140
	Khartoum	− 0.329347697	3.04	0.17734
West Africa	Nouakchott	0.06134372	2.40	0.70207
	Porto-Novo	0.055555556	14.4	0.69505
	Ouagadougou	0.040836653	20.1	0.70207
	Yamoussoukro	0.034653465	6.51	0.45511
	Accra	0.069469835	8.07	0.24225
	Conakry	0.02003643	8.7	0.70207
	Monrovia	− 0.112164297	34.00	0.70207
	Bamako	0.015549077	15.61	0.70207
	Niamey	0.031589339	11.23	1.05430
	Abuja	0.023339318	1.05	0.41649
	Dakar	0.031589339	17.58	0.61868
	Lomé	0.032608696	13.5	0.13463
	N'Djamena	− 0.02173913	11.07	0.70207
	Yaoundé	0.025768087	11.55	0.17552
	FreeTown	0.061325545	16.22	0.70207
Central Africa	Libreville	− 0.027255639	7.13	0.45995
	Bangui	− 0.025565349	16.9	0.70207
	Kinshasa	0.023738872	2.65	0.00082
	Brazzaville	0.040145985	9.94	0.26623
	Luanda	− 0.017706577	2.08	0.36208
	Lusaka	0.016682113	1.13	0.01827
East Africa	Bujumbura	0.133764833	3.7	0.70207
	Addis Ababa	0.028037383	4.25	0.00099
	Nairobi	0.031220435	6.06	0.16894
	Kampala	0.076320939	23.74	0.70207
	Kigali	0.053946054	13.99	0.70207
	Dodoma	0.035818006	6.46	0.39015
	Mogadishu	0.034648415	5.65	0.70207

Table 2 (continued)

Region	Capital	Discounted rate (d)	Residential Electricity (US cents/kWh)	Reduced emissions (kgCO2eq/kWh)
Southern Africa	Pretoria	− 0.014058107	8.89	1.27120
	Antananarivo	− 0.017706577	2.08	0.70207
	Lilongwe	0.055505005	4.17	0.70207
	Maputo	0.103381643	4.04	0.04138
	Windhoek	− 0.014995314	12.15	0.00853
	Harare	− 0.229577465	2.07	0.64293
	Gaborone	0.014492754	6.4	1.73970

Economic and environmental analysis

The economic assessment adopted in this work was supported by two main factors (the single payment present worth factor "SPPW" and the uniform-series present worth factor "USPW") to calculate the following economic indicators, these factors depend on the composite between discount rate (d) and the life cycle (N).

Net present worth (NPW):

$$NPW = -CF_0 + A \times USPW(d, N) \quad (3)$$

where

CF_0: initial cash flow, A: annual revenues, d: discount rate, N: life cycle, Benefit–Cost Ratio (BCR):

$$BCR = \frac{\sum_{k=0}^{N} A \times SPPW(d, k)}{\sum_{k=0}^{N} CF_k \times SPPW(d, k)} \quad (4)$$

Discounted payback period (DPP):

$$CF_0 = \sum_{k=1}^{DPP} A \times SPPW(d, k) \quad (5)$$

Simple payback period (SPP):

$$SPP = \frac{CF_0}{A} \quad (6)$$

The project is considered economically viable and profitable if the following conditions are fulfilled:

$NPW \geq 0$, $BCR > 1$ and DPP & SPP < Lifetime.

In this work, the environmental analysis based on the intensity of CO2 emissions is addressed by estimating the emission factor (EF) (Table 2) due to the electricity consumed for heating and the energy-collected Q_c. This analysis took into consideration all the stages of the life cycle of the system, from material extraction to the end of life of the SWH.

In this work, the environmental analysis based on CO2 emission intensity is approached by estimating the emission factor (EF) (Table 2) due to the electricity consumed for heating and the energy collected. Furthermore, the GHG emissions resulting from the life cycle steps of these systems (manufacturing, construction process, operation, end of life) were taken into account in this study based on the reference environmental database for the building (INIES 2020).

Validation

In order to approve the model used in this work, a comparison between the results obtained by a model developed and experimental data of the water temperatures inside the storage tank for both SHWs is performed. The experimental data were evaluated by (Hazami et al. 2013), and is presented as experimental results provided by several measurements made on different days of July (01/07; 10/07 and 20/07). By comparing the values found by the researchers and the values obtained through the simulation of the two systems (Fig. 2), it can clearly check that the TRNSYS model presents values comparable with data based on experimental measurements. In fact, mean absolute error between calculated temperature values and the experimental values, is less than 5%.

Results and discussion

This analysis establishes a precise diagnosis and proposes interesting guidelines to allow access to solar energy for all Africans through two different technologies used for domestic solar water heating (DSWH). The problems with the use of these systems include high upstream installation costs compared to gas and electric boilers as well as the complex

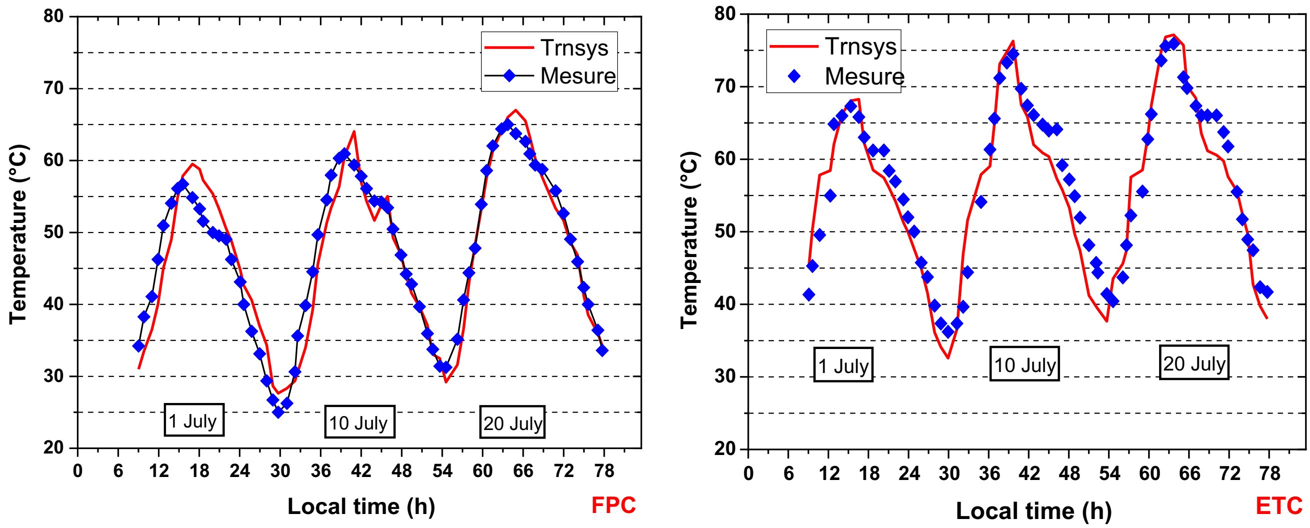

Fig. 2 Comparison between average water temperature measured and simulated from the inside of the hot water storage tank for two collector type

process and associated costs of integrating these solar thermal systems in existing dwellings.

In this context, for a comprehensive study the analysis is made on the five regions of Africa (North Africa, West Africa, Central Africa, East Africa and Southern Africa) (Fig. 3).

North Africa

The North African region comprises six countries (Morocco, Algeria, Libya, Tunisia, Egypt and Sudan), its area is 8244.2 thousand km^2 with 218.4 million inhabitants (African Development Bank Group 2020). Currently, the proportion of renewable energy in final consumption is marginal even though there has been a significant change over the last five years. Moreover, the region has sufficient potential to cover almost all demand, including the various domestic services provided by electricity (lighting, air conditioning and heating).

Today, SWHs are becoming more predominant within the region. In many countries, these systems have known success through many ambitious projects such as PROSOL in Tunisia and PROMASOL in Morocco. The PROSOL program has mobilized around 490,000 m^2 of SWH up until the end of 2012, and the PROMASOL program should have 1.7 million m^2 installed by 2020 (Allali 2011).

In what follows, the study will be detailed in this region. Each country will be characterized by its representative capital. The meteorological data necessary for this study are the ambient temperature, the global horizontal irradiation and irradiation on the inclined surface.

Using TRNSYS, the energy quantities required to evaluate the SF of this region were calculated. The graph (Fig. 4) represents the solar fractions for the countries of North Africa. It should be noted that SF values for ETC technology are higher than FPC technology, which makes ETC more efficient in all countries.

Solar Fraction values in the Maghreb countries (Morocco, Algeria, Libya, Tunisia, Egypt) are very similar with a preference of Tripoli-Libya. On the other hand, also note that the maximum values were reached in Khartoum-Sudan. This can be accounted for by the type of climate of this region, it is hot and the sun shines all year round (maximum solar irradiation in this region compared to other countries). In summer, however, the hours of daylight fall a little, which explains why the values' peaks were reached during the winter period compared to the summer period.

The use of solar systems in daily life reduces GHG emissions significantly compared to other systems. In fact, the environmental aspect must be taken into account when assessing energy systems. Figure 9 represents annual reduced CO2 emissions [kgCO2eq/year] by the operation of SWHs.

Furthermore, the maximum emission values were achieved in Rabat—Morocco and Tripoli—Libya for both systems compared to other countries. This can be explained by the energy captured and the specific factors of these cities. Not to mention that the values of Sudan's emissions are minimal due to the low density of carbon dioxide. Lastly, it can be witnessed that the use of ETCs further reduces GHG outflows compared to FPCs.

To evaluate the profitability of SWH systems, the economic valuation method is applied. The ensuing Table 3

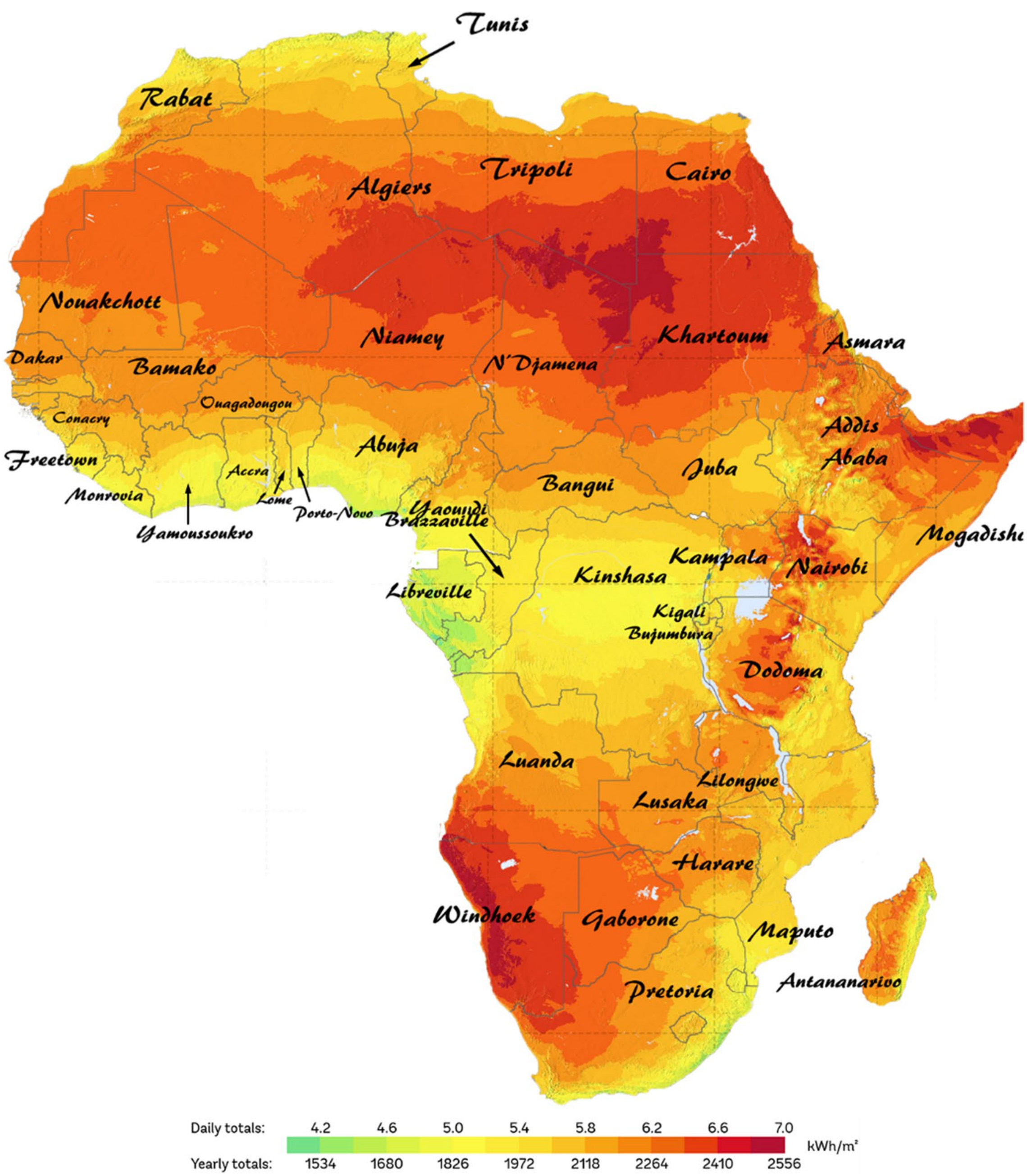

Fig.3 Global Horizontal Radiation Adapted in different regions of Africa

gives a summary of the economic factors calculated using MATLAB. It can be noted that the results of Rabat—Morocco (FPC system: NPW = 1275 > 0, BCR = 1.26 > 1 and SPP & DPP < 20 years; ETC system: NPW = 4405 > 0, BCR = 1.79 > 1 and SPP & DPP < 20 year) and Tunisia–Tunisia (FPC system: NPW = 1162 > 0, BCR = 1.23 > 1 and SPP & DPP < 20 years; ETC system: NPW = 4269 > 0, BCR = 1.6 > 1 and SPP & DPP < 20 year) confirm the validity of the conditions of the economic style. For Tripoli—Libya and Khartoum—Sudan, the SPP (for both systems: more than 20 years) has increased significantly due to economic and political problems. Additionally, it is noted that the conditions of this method do not verify in Algeria and Egypt due to the abundance of other conventional energy sources (natural gas and oil).

Under these conditions, it can be concluded that SWHs with FPC and ETC technologies in North Africa were viable and economically profitable only in Morocco and Tunisia, ETCs being the preferred of the two in terms of investment.

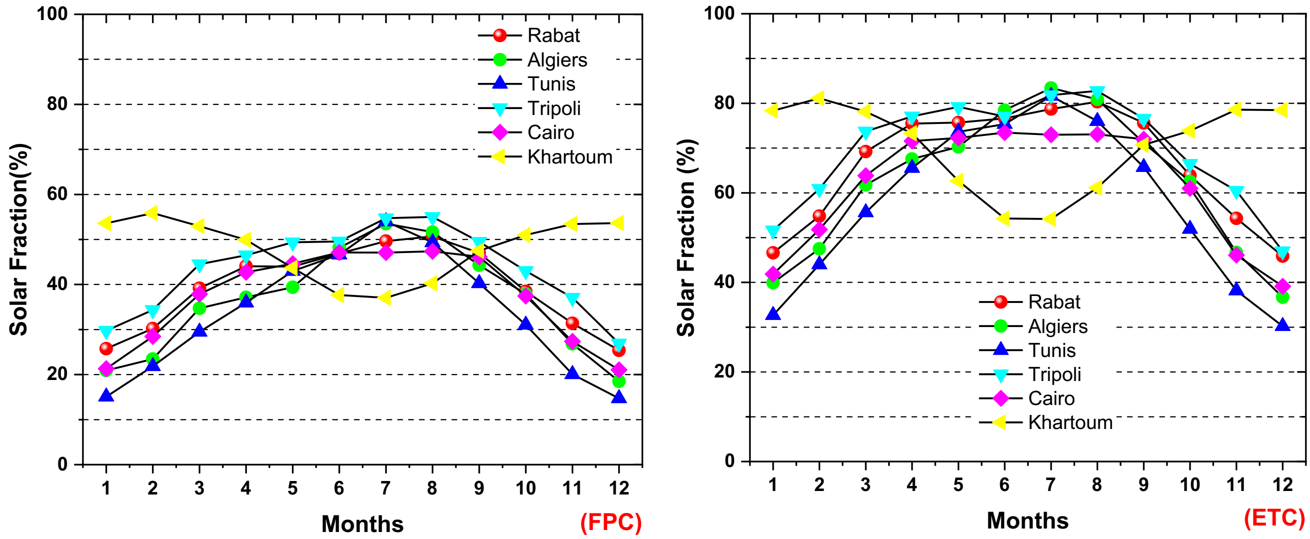

Fig.4 Monthly Solar Fractions in North Africa

West Africa

West Africa occupies an area of 6 140 000 km^2, the vast majority of the countries of this region are underdeveloped despite having several sources of oil and their soils being very rich in minerals, namely gold and diamond. The population of West Africa is estimated at 362 million. Furthermore, political instabilities prevent maximum exploitation and management of resources (UNPD 2017).

In this region, as in further parts of the African continent, renewable energy encompasses a wide range of very diverse energy resources such as the hydropower potential in various countries (Ivory Coast, Liberia, Ghana, Guinea, Sierra Leone and Togo), wind energy in coastal areas (Cape Verde, Gambia, Senegal, Ghana, Mali and Nigeria), solar energy in some countries (Burkina Faso, Niger, northern Ghana and Nigeria), not to mention biomass in the case of West Africa. According to ECOWAS, nearly 54% of these countries' energy supply could be based on renewable energies by 2030 (ECOWAS 2012).

The most widely used solar thermal technologies in West Africa are SWHs, nevertheless, the adoption of these systems has been slower than expected. Concerning this study, (Fig. 5) represents the SFs for both systems. It is clear that these systems are sized to operate more in winter than in summer and that ETC systems have the higher SFs. The impact of radiation and climate change on the SF values can also be noticed in accordance with the geographical dispersion of countries. It is evident that the north of the region had higher values than the south. As a result, ETC technology outperforms FPC technology in all countries.

SWHs in general have a potential direct impact on the quality of the immediate environment. (Fig. 9) shows decreased emanations from SWH operation for FPCs and ETCs. There is still evidence that GHG emissions are diminished to a greater extent by the use of ETCs.

Today, the economic situation in most West African countries is not conducive to an ambitious energy policy directed toward the rural world. Table 3 gives a summary of the economic figures. The results illustrate the influence of the parameters used in the economic evaluation. It can be mentioned that these systems have validated the criteria (NPW > 0, BCR > 1, SPP and DPP < N) in Monrovia-Liberia thanks to its relatively strong energy situation. This table also shows that thermal solar projects in West Africa are economically viable and profitable in these countries: Burkina Faso, Mali, Niger and Chad, with a preference for investment with ETCs in Togo.

Although it is true that the operation of most solar systems does not require significant costs apart from maintenance, its initial investment remains high compared to other clean solutions. Hence, the results of other countries do not meet the requirements of this method of economic evaluation because the research and development funds remain insufficient.

Central Africa

With a large area of 6,640,000 km^2 for a total population estimated at 168.5 million inhabitants in 2018, the current geographical (landlocked countries), demographic (high population growth) economic and social situation (urbanization and income disparities) in Central Africa presents major challenges that will be taken into account in regional and continental integration policies.

Table 3 Results of the economic valuation method in Africa (FPC and ETC)

	Cities	NPW		BCR		SPP		DPP	
		FPC	ETC	FPC	ETC	FPC	ETC	FPC	ETC
North Africa	Rabat	1275	4405	1.26	1.79	16.3	11.5	16.1	11.3
	Algiers	− 3050	− 2751	0.39	0.51	42.3	32.4	87.5	51.1
	Tunis	1162	4269	1.23	1.6	18.7	18.3	16.7	16.7
	Tripoli	5896	8435	2.18	2.51	55.7	48.5	15.1	14.1
	Cairo	− 3862	− 2361	0.23	0.58	64.1	25.5	98.9	52.8
	Khartoum	1,175,827	1,571,593	236.2	281.6	37.8	31.8	6.51	6.11
West Africa	Nouakchott	− 3850.3	− 4033.6	0.23	0.28	49.34	40.56	54.09	53.19
	Porto-Novo	− 1441.1	− 25.80	0.71	1	18.11	12.95	39.88	20.15
	Ouagadougou	2477.7	5399	1.50	1.96	9.02	6.87	11.48	8.22
	Yamoussoukro	− 2773.4	− 2333.7	0.45	0.58	32.01	24.44	122.8	55.12
	Accra	− 2992.4	− 2569.7	0.40	0.54	26.49	19.66	46.85	49.12
	Conakry	− 1503.5	− 394.2	0.70	0.93	23.37	17.58	31.85	21.89
	Monrovia	53,096	85,126	11.62	16.20	7.52	5.39	5.14	3.98
	Bamako	2416.4	5467	1.48	1.98	11.51	8.64	12.78	9.35
	Niamey	35.24	1589.5	1.01	1.28	14.56	11.42	19.81	14.39
	Abuja	− 3900	− 4219	0.22	0.25	71.92	64.22	137.2	139.5
	Dakar	1457.5	4479.2	1.29	1.80	11.35	8.15	14.28	9.57
	Lomé	− 909	760.7	0.82	1.14	17.75	12.81	26.95	16.81
	N'Djamena	3258.3	6364	1.65	2.14	15.38	11.89	13.12	10.46
	Yaoundé	− 1611	− 64.22	0.68	0.99	22.83	15.66	34.89	20.30
	Free Town	− 1032.4	− 721	0.34	0.56	24.21	20.35	57.23	41.65
Centrale Africa	Libreville	− 633.08	1017.98	0.87	1.18	31.00	22.91	22.16	17.56
	Bangui	1582.26	4988.03	1.32	1.89	15.66	10.91	15.30	10.72
	Kinshasa	− 3618.34	− 3656.7	0.28	0.35	57.09	45.46	140.1	172.1
	Brazzaville	− 2350.28	− 1438.8	0.53	0.74	25.61	18.27	120.8	33.58
	Luanda	− 3546.85	− 3631.3	0.29	0.35	56.72	46.89	209.9	120.4
	Lusaka	− 4173.21	− 4532.6	0.17	0.19	68.61	59.52	56.29	55.25
East Africa	Bujumbura	− 4264.67	− 4544.1	0.15	0.19	46.71	36.43	28.29	27.25
	Addis Ababa	− 3186.42	− 2823.6	0.36	0.50	41.77	30.56	130.3	70.29
	Nairobi	− 3111.76	− 2539.4	0.38	0.55	38.95	26.92	113.8	59.68
	Kampala	− 1265.48	986.48	0.75	1.18	13.51	8.58	63.58	14.47
	Kigali	− 1914.58	− 372.8	0.62	0.93	19.54	12.92	81.64	22.71
	Dodoma	− 2532.95	− 1717.7	0.49	0.69	28.59	20.35	138.5	37.09
	Mogadishu	− 2732.42	− 1945.2	0.39	0.58	24.32	16.32	121.5	62.32
Southern Africa	Pretoria	166.42	2134.5	1.01	1.38	20.12	14.05	20.28	14.36
	Antananarivo	− 1859.4	− 539.85	0.63	0.90	22.83	15.87	44.79	23.13
	Lilongwe	− 3180	− 2918.5	0.36	0.48	36.61	27.83	58.33	46.81
	Maputo	− 3870	− 3971.3	0.23	0.29	36.32	28.21	33.01	32.06
	Windhoek	1038	3558	1.21	1.64	12.91	9.53	15.78	11.03
	Harare	2,599,186	3,620,036	5199	6465	56.98	45.82	5.55	5.20
	Gaborone	− 3198.6	− 3129.4	0.36	0.44	50.22	41.01	69.31	52.61

With regard to the energy situation, Central African countries have considerable resources. In fact, the Congo Basin contains the world's second largest forest, with an area of more than 300 million hectares, accounting for 11% of the world's volume. Water resources are estimated at about 100 GW, which can cover the entire region's needs (Bakehe 2018). Solar and wind energy are the other renewable sources that can contribute to the energy mix. However, all countries have sufficient potential for solar applications in this region.

Solar thermal technologies that have been adopted in African countries include SWHs, solar dryers and solar

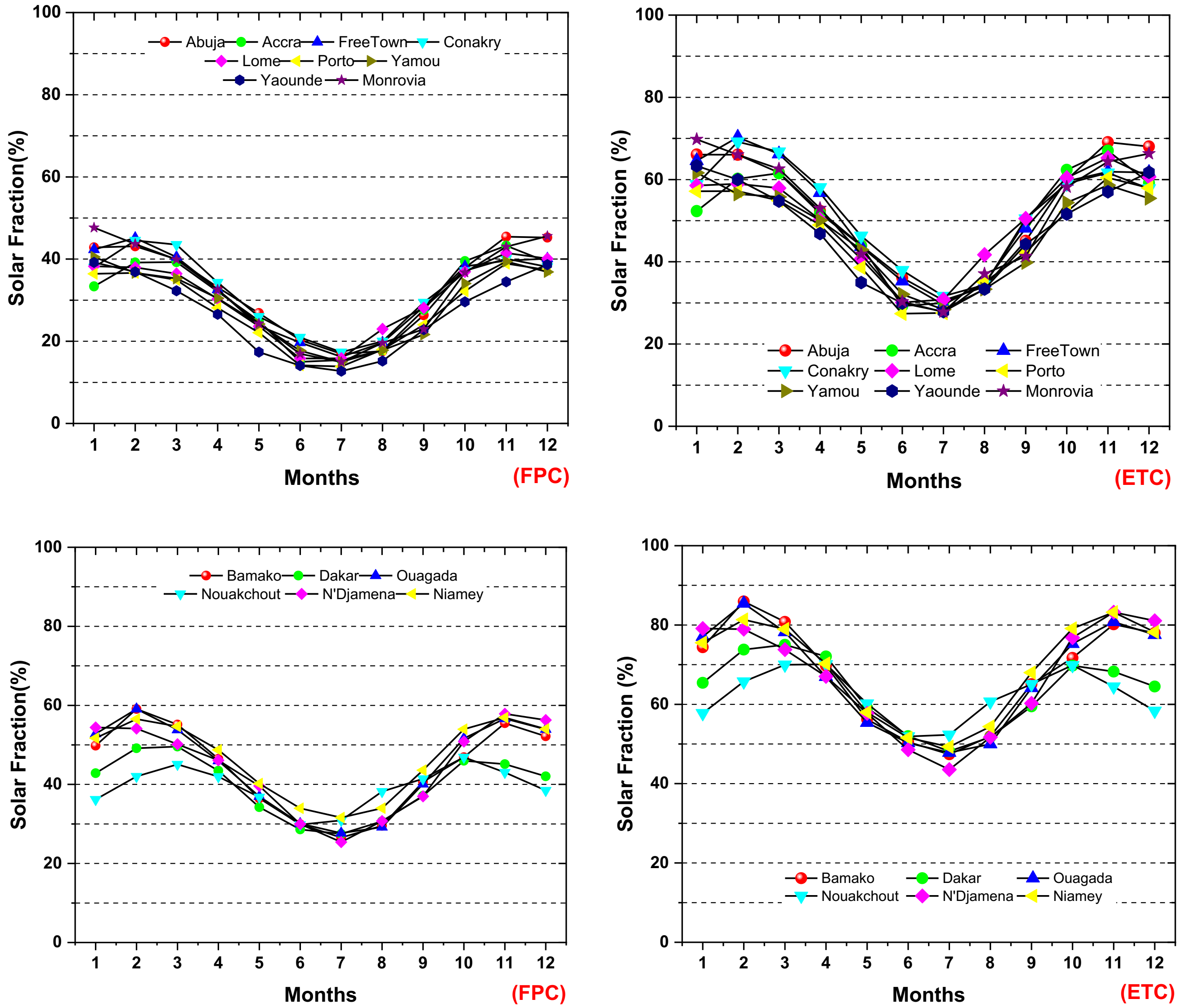

Fig.5 Monthly Solar Fractions in West Africa

cookers. In some developing countries, due to liquefied petroleum gas (LPG) subsidies, it is difficult for SWHs to be competitive. Subsequently, most of these systems are purchased by high-income households and institutions.

In what follows, (Fig. 6) represents the solar fractions for the two systems installed in this region. There is significant variance in these values due to the diversity of the climate. The maximum values were reached in Lusaka-Zambia and Angola-Luanda by virtue of the subtropical climate of this zone, with a hot, humid and rainy season from October to March, and a dry season from April to November. A preference is given to Lusaka-Zambia as a result of solar radiation on the inclined surface.

For the rest of this region, SF values vary according to the equatorial climate over four seasons and extend to Bangui-CAR, Kinshasa-DRC, Brazzaville-Congo and Libreville-Gabon. In winter (November to February). In the Bangui and Libreville, they are maximized because the climate is extremely dry and sunny during this period. For Kinshasa and Brazzaville, average temperature and irradiation were peaking from February to May according to meteorological data, which is why there is a rise in SFs during this period.

In fact, the environmental aspect of solar systems in Central Africa remains low compared to other areas of the continent. This can be explained by the small annual amount of

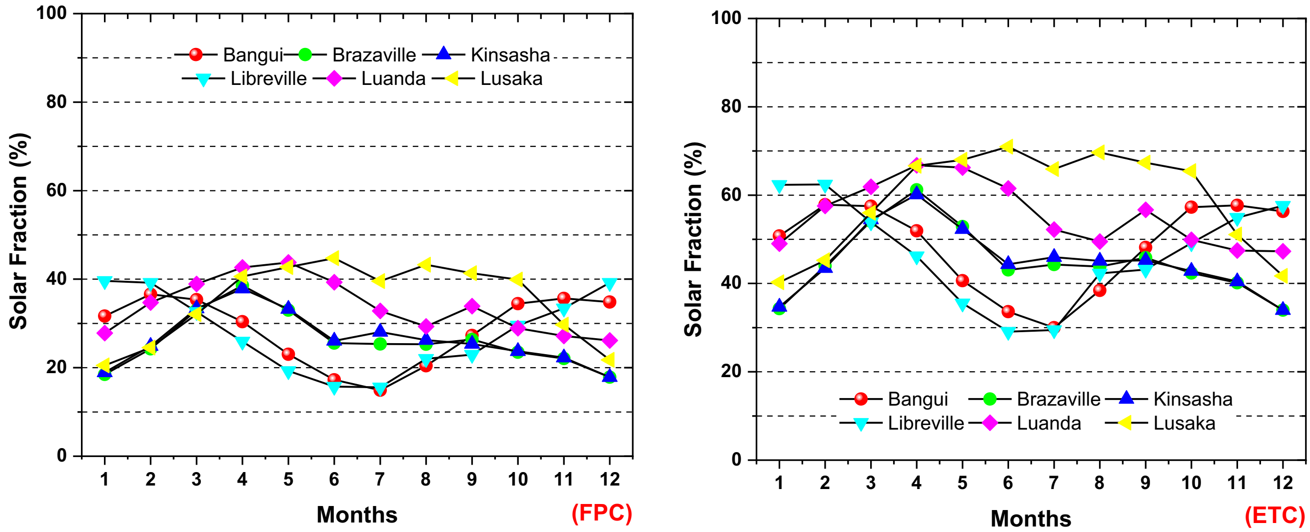

Fig.6 Monthly Solar Fractions in Central Africa

GHG emissions reduced by the exploitation of these solar systems (Fig. 9) and the emission factors for each country.

Despite the large energy resources, the economic fragility of the Central African countries is worrying. According to Table 3, the two SWH systems have validated the criteria of the economic evaluation method (NPW > 0, BCR > 1, SPP and DPP < N) only in Bangui-RCA, with a preference for ETC investments in Libreville-Gabon. The remaining areas are characterized by a volatile security context. Political instability and high levels of poverty render the SWH systems unprofitable and therefore unfeasible.

East Africa

East Africa is a portion of Sub-Saharan, surrounding the easternmost region of Africa. Their population was estimated at 342 million in 2016, in fact this area will experience a strong demographic growth of more than 150% by 2050. This region is endowed with a wide assortment of resources, still largely underutilized, in the five renewable energy sectors (biomass, hydroelectricity, solar energy, geothermal energy and wind energy). Despite these natural assets, the energy sector in the region remains largely underdeveloped with a low electrification rate of 20 to 30% (The World Bank 2017).

Concerning energy analysis, the graphs (Fig. 7) represent the solar fractions extracted from the simulation. The instability of these values for the countries of this region is still noticeable and ETC systems have higher solar fractions. During the winter season, maximum values were achieved by ETC technology in Addis Ababa-Ethiopia, Mogadishu-Somalia and Kampala-Uganda. This can be explained by daytime temperatures (high and stable throughout the season) and by strong solar irradiation throughout the year, especially in winter. In summer, the hours of sunshine diminish, especially in July and August. The sky is often cloudy, which is why there is a drop in SF values. It is the other way around for Bujumbura-Burundi, Kigali-Rwanda and Dodoma-Tanzania. Because of their locations south of the equator (sunshine is abundant in the dry season, especially in June and July), it is noticeable that the SFs peaks in the summer. Moreover, in Nairobi-Kenya (near the equator), temperatures are high and almost constant, resulting in a small change in SFs throughout the year.

Regarding the economic situation in the region, inflation reached a rate of 14.5% in 2018, and 12.5% in 2019, the highest figures in Africa (African Development Bank Group 2019). In fact, the zone still faces numerous dangers that could hinder economic growth and development prospects such as the rapid decline of the currency and the GDP contraction due to lack of peace and security on a large scale. High inflation is generally related to the depreciation of the currency, making the two main factors used in the economic analysis (inflation rate and interest rate) rather unstable. Thus, through Table 3 it is concluded that the SWH installation projects are not favored during this period of regional economic crisis.

In environmental terms, there is a difference in the amount of GHG emissions reduced which are significant for Mogadishu-Somalia (3100 kg CO_2eq and 2150 kg CO_2eq for ETC and FPC) and negligible in Addis Ababa-Ethiopia (Fig. 9). As mentioned in previous regions, this is due to the energy produced by the systems and the

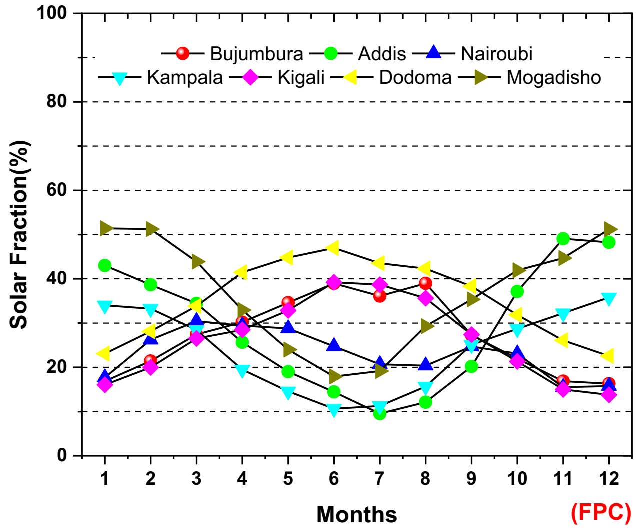

Fig.7 Monthly Solar Fractions in East Africa

emission factors per kWh of electricity consumed in each country.

Southern Africa

Southern Africa occupies all the territories located at the southernmost extremities of the African continent, its surface area is 2.675.000 km^2 and its population is approximately 260 million. The climate varies from semi-arid to sub-tropical. The insolation map of annual solar irradiance is between 2000 and 2400 kWh / m^2. These levels of sunshine are significantly higher than most European countries. It can be said that this region has enormous potential for green energy production to ensure its energy security and stability (Ouedraogo 2017).

To generate the necessary financing, the majority of nations are engaged in some programs of reform of their energy market. In fact, renewable thermal energy offers new solutions to residential problems by accelerating the implementation of solar energy technologies. This is a daunting task to further explore the potential and technology options for an accelerated introduction of SWHs, as one of the renewable energy options best suited to the conditions of southern Africa.

The South African government's vision for its energy future is to deploy these technologies in poor communities to reduce peak electricity demand, reduce carbon emissions and improve energy efficiency to develop the quality of life of households. The SWH Program targets the installation of 1.75 million units in 2019 and 5 million by 2030. For Malawi, it is estimated that 5 K domestic solar systems and 2 K SWHs are installed in its territory. In the rural areas of Namibia, the Ministry of Energy subsidizes solar systems for domestic use. It has currently funded some 1600 systems. In Botswana, the energy strategy implemented the removal of the import tax for SWHs to reduce 25% of total final energy consumption by 2023 (REN21, 2018).

As already mentioned above, this paper attempts to examine the energy potential of SWHs in terms of energy saving and emissions. Due to the enormous solar radiation, the maximum values of the SF (exceed 40% and 65% for installations with the FPC and the ETC, respectively) were reached in Windhoek-Namibia (Fig. 8), which is the most favorable location of these systems for both technologies. From these results, it is possible to deduce the effect of irradiation and ambient temperatures on the design of solar systems.

The economic calculation results are displayed in Table 3. In view of the investment costs and the discount rate of each country, the SWHs systems validated the criteria of the economic valuation method only in Windhoek-Namibia and Pretoria-RCA. As a result of the huge efforts of the governments in these countries, especially from South Africa, renewable energies are strengthened and quality of life is improved. For other countries, because

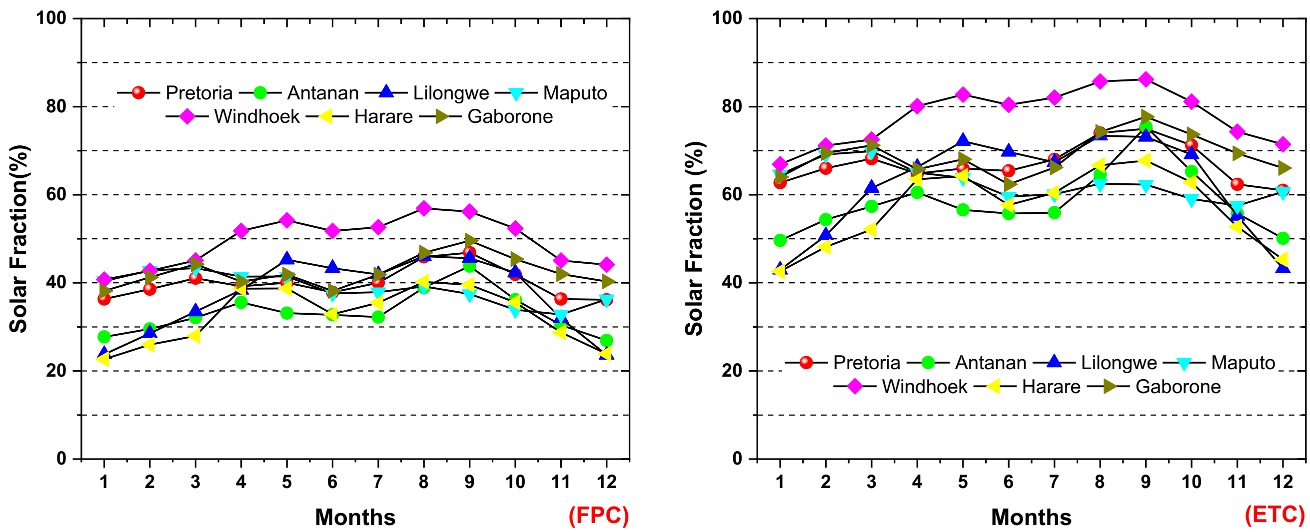

Fig.8 Monthly Solar Fractions in Southern Africa

of the nightmare of hyperinflation, especially in Harare-Zimbabwe, the economic results do not fit the requirements of the previously described method.

At the environmental level, harnessing green energy in the daily lives avoids the production of harmful effluents and reduces GHG emissions. As shown in the graph below (Fig. 9), the estimated diminishment of CO2 is due to SWHs. It is noted that the maximum reduced emissions have been achieved in Gaborone-Namibia and Pretoria-RCA, and GHG emissions are decreased the most by the use of ETC-SWHs.

Conclusion

Africa is facing serious political, economic and energy crises because of the excessive use of petroleum energy. Ironically, despite the availability of natural resources (weather conditions and available solar irradiation are among the most favorable in the world), there is a lack of appropriate technologies and infrastructure to exploit these resources. Undoubtedly, the energy needs must be treated with extreme caution. So much so that conventional energy technologies will not be enough to dispense the destitution of energy on this continent.

For this reason, the issue of access to energy is receiving increasing attention in energy policies. In fact, because of limited understanding of energy efficiency, lack of talented labor, as well as lack of funding for projects to tap into renewable energy resources, it is necessary to develop strong and cooperative governance mechanisms that have effective methods of energy analysis. Hence, it is in everyone's interest to harness technologies that will help meet the growing request for energy while improving energy efficiency and reducing GHGs.

In general, African governments urgently need to accelerate the deployment of renewable energies. It has been found that SWH can alleviate energy needs and economic issues. From this work, a study was carried out for 43 countries divided into 5 regions: North Africa, West Africa, Central Africa, East Africa and Southern Africa. The energy analysis, in terms of solar fraction (SF), shows that the solar production of domestic hot water varies between 25 and 88% for the ETC and between 10 and 60% for the FPC and this according to the 5 regions mentioned. It is noted that that almost all African countries have significant potential in the application of SWH systems and ETC technology is more energy-efficient.

This paper also presents an environmental and economic study of both FPC and ETC systems. The results of this study have shown that, the use of these systems allows to reduce greenhouse gas emissions for all continent countries. For the economic component, despite the scarcity of data and the need of proficiency in the field, based on the Net present worth (NPW), the Benefit–Cost Ratio (BCR) and the Discounted payback period (DPP), the economic

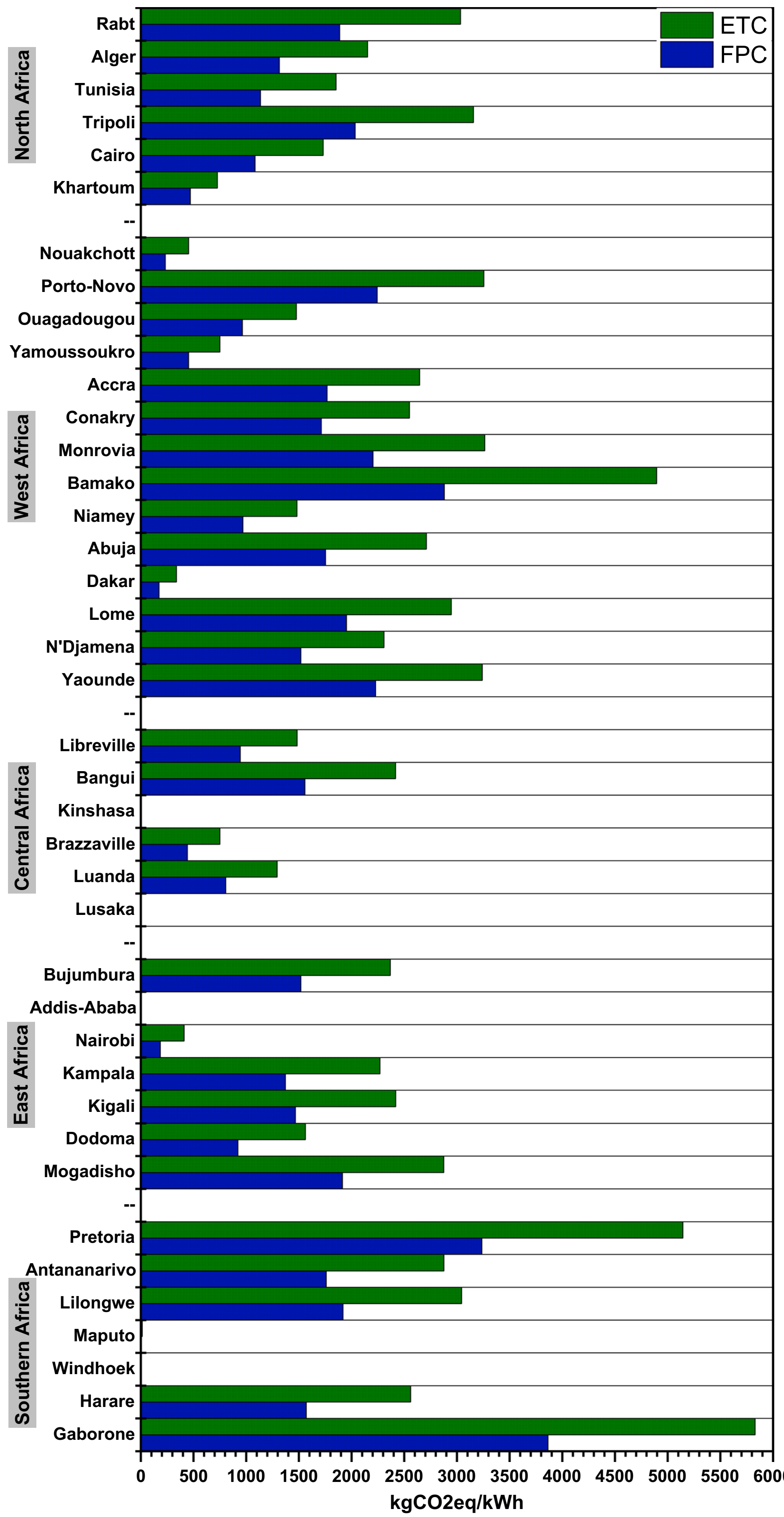

Fig. 9 Quantities of reduced GHG emissions in Africa

analysis shows that these two technologies are beneficial for 16 of the 43 countries studied. Note that, the price of energy (electricity) and government support are factors that have a significant impact on the profitability of these systems.

Moreover, this paper aims to highlight the assessment of potential impacts on energy security, provide a strong rationale for the importance of SWHs in daily life, and assist African policymakers who have scarce information in managing the solar energy resources available. Many benefits have been cited that these systems bring to their owners for the production of domestic hot water, be it energy savings, cost reduction, or reduction of GHG emissions.

Lastly, it is recommended that further research should focus on the penetration of DSWHs in other types of buildings (large scale) with different load profiles, given the meteorological conditions and the technical–economic situation in each country. Other technical aspects can be focused on improving the performance of these systems, notably at the level of the heat transfer fluid (use of nanofluids). A combination of these suggestions would be very useful to carry out a well-detailed survey of these systems.

Acknowledgements The authors extend their acknowledgement to the research component of the German cooperation project GIZ / DKTI IV (Grant number 15.2169.9-001.00) for supporting the development of this work

Declarations

Conflict of interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

The Economist Intelligence Unit (2016) *Power Up: Delivering Renewable Energy in Africa*.

The World Bank (2017) *World Development Indicators database for population.*

Trading Economics (2018) *TRADING ECONOMICS*.

African Development Bank Group (2019) *Macroeconomic developments and prospects Political economy of regional integration*.

African Development Bank Group (2020) *African economic outlook: Developing Africa's workforce for the future*, *Annual yearly review study*.

A Al Jamar et al. (2019) Forecast of the Installed Capacity of Solar Water Heaters and Its Economic and Social Impact in Morocco: A Time Series Analysis, In International Conference on Advanced Intelligent Systems for Sustainable Development. Springer, pp 347–357

Allali I (2011) PROMASOL: Democratizing access to solar water-heaters. Growing Inclusive Markets, Morocco

Artur C et al (2020) 'Domestic hot water technology transition for solar thermal systems: An assessment for the urban areas of Maputo city. Mozambique', J Clean Prod 260:121043. https://doi.org/10.1016/j.jclepro.2020.121043

Aydin E, Eichholtz P, Yönder E (2018) The economics of residential solar water heaters in emerging economies: the case of Turkey. Energy Econ 75:285–299

Bakehe NP (2018) Agricultural productivity and deforestation in the Congo Basin. Économie rurale Société Française d'Économie Rurale 366(4):5–19

Ben Taher, M. A. *et al.* (2018) Energy, environmental DND economic study RF different solar water heating systems Ln different Moroccan climate zones, In Proceedings of 2018 6th International Renewable and Sustainable Energy Conference, IRSEC 2018. doi: https://doi.org/10.1109/IRSEC.2018.8702918.

Ben Taher MA et al (2019) Energy study of different solar water heating systems in MENA region. Adv Intell Syst Comput. https://doi.org/10.1007/978-3-030-12065-8_26

Curry C, Cherni JA, Mapako M (2017) The potential and reality of the solar water heater programme in South African townships: lessons from the city of Tshwane. Energy Policy 106:75–84

ECOWAS (2012) Renewable energy in West Africa, Renewable Energy in West Africa.

Endale A (2019) Analysis of status, potential and economic significance of solar water heating system in Ethiopia. Renew energy. 132:1167–1176

Gabra S, Miles J, Scott SA (2019) Techno-economic analysis of stand-alone wind micro-grids, compared with PV and diesel in Africa. Renew Energy 143:1928–1938. https://doi.org/10.1016/j.renene.2019.05.119

Hazami M et al (2013) Long-term performances prediction of an evacuated tube solar water heating system used for single-family households under typical Nord-African climate (Tunisia). Sol Energy. 94:283–298

Hoffmann JE (2019) On the outlook for solar thermal hydrogen production in South Africa. Int J Hydrogen Energy 44(2):629–640. https://doi.org/10.1016/j.ijhydene.2018.11.069

Huang J, Fan J, Furbo S (2019) Feasibility study on solar district heating in China. Renew Sustain Energy Rev 108:53–64

Hussein HMS (2002) Transient investigation of a two phase closed thermosyphon flat plate solar water heater. Energy Convers Manag 43(18):2479–2492

INIES (2020) Environmental and health reference data for building.

Lamrani B, Khouya A, Draoui A (2019) Energy and environmental analysis of an indirect hybrid solar dryer of wood using TRNSYS software. Sol Energy 183:132–145. https://doi.org/10.1016/j.solener.2019.03.014

Mohamed SA (2020) Application of geo-spatial Analytical Hierarchy Process and multi-criteria analysis for site suitability of the desalination solar stations in Egypt. J Afr Earth Sc 164:103767. https://doi.org/10.1016/j.jafrearsci.2020.103767

Ouedraogo NS (2017) 'Modeling sustainable long-term electricity supply-demand in Africa', *Applied Energy*. Elsevier 190:1047–1067

International Energy Agency (2015) Technology Collaboration Programme on Solar Heating and Cooling : Annual Report.

Rajab Z et al. (2017) Techno-economic feasibility study of Solar Water Heating system in Libya', In: 2017 8th International Renewable Energy Congress (IREC). IEEE, pp. 1–6.

REN21 (2018) SADC Renewable Energy and Energy Efficiency Status Report.

Rosas-Flores JA, Rosas-Flores D, Zayas JLF (2016) Potential energy saving in urban and rural households of Mexico by use of solar water heaters, using geographical information system. Renew Sustain Energy Rev 53:243–252

Sami S et al (2018) Viability of integrating solar water heating systems into high energy performance housing in Algeria. Energy 149:354–363

UPDEA. Secrétariat Général (2009) 'Etude comparative des tarifs d'électricité pratiqués en Afrique', (December).

UNPD (2017) 'World Population Data prospectus'.

World Bank Group (2017) State of Electricity Access Report 2017, State of Electricity Access Report 2017. World Bank, Washington, DC. doi: https://doi.org/10.1596/26646