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Integrated design and construction of a micro-central tower power plant

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ABSTRACT

Concentrating solar power is considered as one of the promising ways for future sustainable electricity generation, especially in the Sahelian region, which is characterized by hot and sandy and high direct solar irradiation, but also a very low electricity access rate. This paper presents a design of a micro-central tower power plant of 10 kW_e for Sahelian countries. The project reported here is specifically focused on a micro-concentrating solar and power project in Burkina Faso. It is designed to address energy access challenges in rural areas in the Sub-Saharan region, using central tower technology. The design of the power plant was thought in such a way to make locally possible the manufacturing of most of the components: local mankind and local materials are promoted and valued. We named after such a power plant CSP4Africa in this paper. The appropriate design, evaluation and selection methods are reported: solar field and its component design, solar receiver, conversion loop selection, thermal storage concept, storage tank design, heat transfer fluid, solar tower, etc. Some challenges faced during the design of CSP4Africa are also reported. Most of the components of the power plant have already been designed, built and under tests before their assembling for the pilot.

Introduction

Electrification rate in Sub-Saharan Africa is about 32% (International Energy Agency (IEA), 2014) in average with high variation from one country to another. The situation is worse in rural areas (rural electrification rate: 16% (International Energy Agency (IEA), 2014)), where about 70% of the population actually lives. Recent studies indicate that, in this region of Africa, it is essential to make provision specifically for increasing rural electrification before embarking on large-scale privatization (Onyeji et al., 2012) in order to significantly facilitate the electricity access to the poor. In West Africa for instance, reforms in electricity sectors had, in best cases, no effects on the increase of electricity access to the poor; the main reason was the government's lack of commitment to support clearly rural electrification development (Onyeji et al., 2012). The strong links between energy access and millennium development goals, especially the connection between energy services and development, public health, gender empowerment, and the degradation of the natural environment and corresponding dramatic consequences of energy poverty as presented by Sovacool (2012), crucially evidence the need to address the challenge of the provision of energy services in Sub Saharan Africa (Adkins et al., 2012). Solar energy could contribute to increase the rural electrification rate with off-grid or micro-grid systems, which appears to be the future of sustainable electricity supply systems, especially in Sub-Saharan countries (Onyeji et al., 2012). Solar energy could allow reducing the energy dependency in many countries, especially Sahelian ones, which use diesel thermal plants and are therefore strongly depending on imports of petroleum products (up to 70% of GDP for Burkina Faso).

For electricity generation, solar energy may be converted via two main different ways: photovoltaic (PV) technologies and concentrating solar power[1] (CSP) technologies. Currently, PV manufactures could hardly be identified in Africa: only few PV manufactories could be identified in South Africa or Senegal where imported cells are assembled. So, from Africa, there is no large room to work on electricity generation cost via photovoltaic technologies.

CSP technology is considered as one of the promising ways for future sustainable electricity generation. Many African countries, especially in the Sahelian region, show high potential for CSP plants because of high direct solar irradiation (Azoumah et al., 2010): Africa is located in the

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[1] Solar thermal electric technology.

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heart of the solar belt (Fig. 1). However, to-date, CSP technologies have been shown to be economically viable only for large power plants (10–50 MWe (Py et al., 2013)), thus requiring high investment costs. The initial cost ranges from 2,500 to 12,500 US$·kW^{-1} (Ziuku et al., 2014). This initial capital cost, combined to the technology is considered as the two main barriers to CSP development in developing countries (Amer and Daim, 2011; Ziuku et al., 2014). Therefore, many Sub-Saharan African countries could not invest in so high cost power plants. For instance, about US$600 millions (CSP World, 2015) were necessary for the construction of the Shams solar power station in Saudi Arabia: this is more than 15% of the State budget of a Sahelian country like Burkina Faso. Furthermore, there are a large number of remote areas requiring relatively small power plant capacity and decentralized energy systems are seen to be one of the most relevant future energy systems options (Onyeji et al., 2012). It is also worth noting that the skills required for the implementation for such power plants are not currently well spread throughout Africa. That is why we choose to investigate the feasibility of a micro-CSP (μ-CSP) plant in Sub-Saharan Africa by analyzing the system through various aspects such as capacity building, economical and technical issues. We aim at developing a cost-effective μ-CSP plant for decentralized micro-grid by designing and experimenting their components using local low cost materials.

In this paper, the design simplification of the power plant is reported. The design is thought in a way to make possible the manufacturing of most of the components by local mankind using locally available materials. Some challenges faced and options made in the curse of the project are also reported. All the main components of the power plant and related issues are addressed.

Existing μ-CSP projects in the world

Five CSP technologies are available today: concentrating photovoltaic (CPV) and four common CSP technologies, which are parabolic trough, dish parabolic, linear Fresnel and central receiver system or solar power tower (Fig. 2). Concentrated solar thermo-electric technology is an emerging technology that is at an early stage of development (Barlev et al., 2011). Parabolic trough is so far the most mature technology and more than 95% of installed large scale CSP plants are built upon this technology. Solar tower technology is the second most matured technology and represents the next alternative to parabolic trough for the following advantages (Zhang et al., 2013):

- Low thermal energy storage costs due to the high temperature increase in the solar receiver compared with parabolic trough since the required mass and volume for the storage material and facilities are lower for a given amount of energy to be stored. Furthermore, the technology is foreseen to be the cheapest CSP technology by 2020.
- The position of the whole piping system and eventual thermal storage tanks next to the tower: this reduces the size and the length of the piping systems and therefore also energy losses, material and maintenance costs.

The number of μ-CSP projects, existing plants or projected plants for electricity generation, is very limited. We have conducted a literature survey on power plants with an electric power output of less than 500 kW. Only about ten projects have been identified worldwide as presented in Table 1. It appears that the maximum power output is actually 100 kW for small scale plants (Table 1).

Apart from SPS from EPFL (academic demonstration plant) and AORA Solar (commercial plant), all the identified projects are dealing with parabolic trough as it is the case for large scale CSP plants. Indeed, μ-CSP are mainly designed for low/medium grade temperature heat source (≤200 °C for all the identified projects) and point focus technologies are usually for high temperature heat output. In addition, only one-axis tracking is required for parabolic trough. For focus technologies, two-axis tracking is required. This tracking aspect leads to a more complex and eventually costly design and maintenance issues.

Almost all these μ-CSP use an organic Rankine cycle (ORC, Table 1) for the conversion loop since these conversion cycles are more relevant for low temperature heat sources. The listed projects are those involving electricity generation.

General considerations and preliminary choices

Among the four CSP technologies, parabolic trough and dish technologies require curved mirrors while linear Fresnel and solar power tower technologies use flat mirrors. Because flat mirrors are easily available on

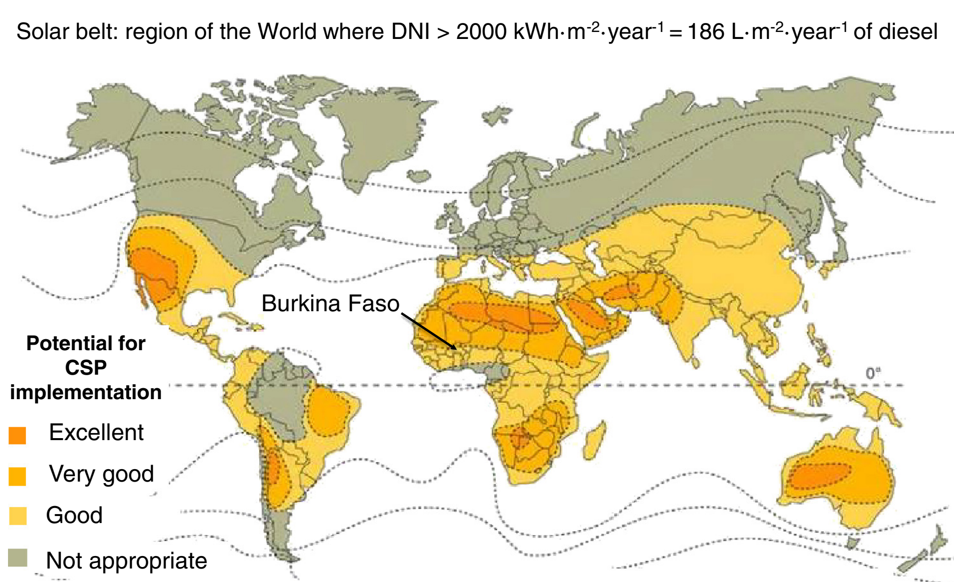

Fig. 1. Regions of the world appropriate for concentrating solar power.
Source: Solar Thermal Power, European Commission, Directorate General TREN cited in World Energy Council (2004).

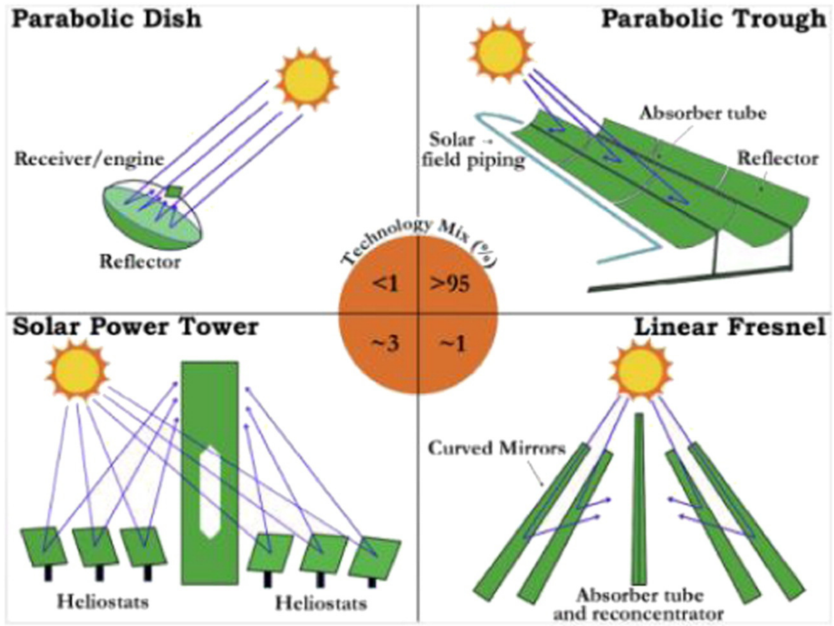

Fig. 2. Currently available common CSP technologies with their installed ratio. Vignarooban et al. (2015).

local markets, linear Fresnel and central tower CSP were seen as the best choices for our study. Both technologies are under study in our laboratory in Ouagadougou: linear Fresnel for relatively low temperature applications[2] and the central tower for relatively high temperature applications (Lovegrove and Csiro, 2012).

This work focuses on the central tower technology with an operating temperature of 210 °C. This temperature is relatively low for a central tower but the target here is to master the process at relatively low temperature level before increasing the temperature level later. In addition, the fixed receiver avoids the need of rotary joints for the heat transfer fluid (Lovegrove and Csiro, 2012), since skills for high temperature piping are not well spread in the region and the local feasibility is a matter of priority in this project. Furthermore, as previously indicated, the solar power tower technology is foreseen to be the cheapest CSP technology by 2020 (Zhang et al., 2013); since it is barely considered in μ-CSP, the present study presents a particular scientific and technological interest.

The improvement of the solar field, the use of local skilled mankind, which is much cheaper[3] than in Europe for instance, and the development of some components at local level (solar receiver, heliostat structure, turbine type, etc.) are assumed to help in reducing the investment cost and make the electricity cost affordable for rural populations. The main layout of the power plant is given in Fig. 3. For the demonstration plant, the nominal solar thermal power supplied to the conversion cycle is set to 100 kW_{th}. The electricity generation duration in reference conditions is set to 3 h. A maximum operation duration of 5 h is foreseen. This means that the thermal loop could operate during 2 h without thermal conversion into electricity. The corresponding solar energy collected is devoted to thermal storage. This thermal storage is rather designed as a buffer storage — management of intermittence such as the passage of a cloud — than as storage for production (electricity generation storage that would help produce electricity after sunset for instance).

[2] Typically, linear Fresnel concentrators operate in a temperature range up to 300 °C while solar power tower systems operate up to 565 °C (Zhang et al., 2013).

[3] Averagely, a junior application engineer is paid 1000 € in Burkina Faso while at the double is required for its homologue in Western Europe.

Design of the main components of a central tower μ-CSP plant

Solar field and multifaceted heliostats

Estimation of the useful active reflecting area of the solar field

For a demonstration plant, a 100 kW thermal power plant was considered in order to generate about 10 kW electrical power, as the conversion efficiency is usually in the range of 10% (Table 1).

First, it is crucial to estimate the useful active reflecting area A_{col} of the solar field. The power to be concentrated on the solar receiver can be estimated by Eq. (1):

$$Q_{receiver} = \eta_{opt} \cdot \mathrm{DNI} \cdot A_{col}. \quad (1)$$

Hence, direct normal irradiance (DNI) and various optical parameters of the solar field (optical efficiency η_{opt}) are needed.

The DNI is estimated from real weather data collected at the 2iE in Ouagadougou using standard equipment. Three year data were available for this design, which is quite acceptable as far as CSP technologies are concerned. Usually, a design point may be selected — for instance in the case of seasonal operating times (Vant-Hull, 2012) — but when the target is to achieve the lowest levelized cost of electricity (LCOE), the design must be done considering the average annual energy harvest. In the present case, we are focused on the demonstration aspect and the local feasibility even if the economic aspects are also important. From the collected data, we choose to generate a "typical day" DNI profile, considering frequency of appearance. This statistical analysis of the real weather data has led to the profiles given in Fig. 4. Because of the demonstration aspect of the pilot, the median curve was considered as the reference. The corresponding profile ($p = 50\%$ in Fig. 4) is the irradiance that is overpassed every other day.

The reference irradiation could then be calculated by integrating the irradiance over the reference operating time (Eq. (2)):

$$\mathrm{DNI}_T = \int_{operating\ time} \mathrm{DNI}_i \cdot dt. \quad (2)$$

Using the reference irradiance ($p = 50\%$) presented in Fig. 4, leads to a $\mathrm{DNI}_T = 2.525\ \mathrm{kWh \cdot m^{-2}}$. To determine the aperture area of the collector A_{col}, the optical efficiency η_{opt} needs to be estimated. The

Table 1
Summary of μ-CSP demonstration plants for electricity generation.

Project	STG (Dumont et al., 2013; Quoilin et al., 2011)	Tianjin (Wang et al., 2010)	Sun2Power (Deltour et al., 2012; Dumont, 2012; Peigneux, 2013)	Micosol (Bouvier, 2013; Communauté d'Agglomération de La Rochelle, 2014)	Powersol [e] (García-Rodríguez and Blanco-Gálvez, 2007; Gálvez and CIEMAT, 2011)
Net electric power [kW_e]	1	1	2.5	3	5
Technology	Parabolic trough	Parabolic trough	Parabolic trough	Parabolic trough	Parabolic trough
Operating temperature range[a]	<200	100–120	140 [d]	250–350	200–250; 100–250
Overall efficiency[b] [%]	6	4.2	5		7
ORC efficiency[c] [%]	10	13	8.5		14
Working fluid of the ORC	R245fa	R245fa	R245fa	Water	Solkatherm® SES36
Location	Ha Teboho (Lesotho)	Tianjin (China)	Marseille (France)	La Rochelle (France)	Almeria (Spain)
Service starting date	2007	2010	2014	2014	2009
Remarks	Cogeneration unit for a village		On-going students' project	Rankine/Hirn cycle (superheated steam generation at 30 bar) Cogeneration heat: 25 kW thermal	Solar driven mechanical power generation for either power generation or to brackish or seawater desalination

Project	SPS (Giroud et al., 2003; Kane et al., 2003)	LIPI (Pikra et al., 2013)	Microsol (Matthieu, 2012)	METU NCC (ElectraTherm, 2010, 2014a)	Cleco (ElectraTherm, 2010, 2014b; Raush et al., 2013)
Net electric power [kW_e]	6.5	10	10	18	15–50
Technology	Linear Fresnel	Parabolic trough	Parabolic trough	Parabolic trough	Parabolic trough
Operating temperature range[a]	80–160	150–200	180	76–107	93–120
Overall efficiency[b] [%]	7.7	4.7	≈6		6
ORC efficiency[c] [%]	13.7	10.6	8	<9%	7.7
Working fluid of the ORC	R123/R134a/R245fa	R123	R245fa	–	R245fa
Location	Lausanne (Switzerland)	Bandung, Indonesia	Cadarache (France)	Northern Cyprus, Turkey	Crowley, Los Angeles (USA)
Service starting date	2001	2012?	2013 (under development?)	2010	2012
Remarks	–	–	Water, electricity and heat generation		
Commercial product expected for 2015	Industrial ORC from ElectraTherm	The system is operated at University of Louisiana.			
Industrial ORC from ElectraTherm					

Project	Tampa (Florida Energy System Consortium, Solar Florida, 2011)	AORA Solar (Aora Solar, 2015)	Daesung (Jang et al., 2012; Lee et al., 2015)	Holaniku at Keahole Point (Power Technology, 2015; Rawlins and Ashcroft, 2013; Keahole Solar Power, LLC, 2015)
Net electric power [kW_e]	50	100	200	500
Technology	Parabolic trough	Power tower	Power tower	Parabolic trough
Operating temperature range[a]	–	–	700–1000	93–176
Overall efficiency[b] [%]	6–10%	–	13%	25
ORC efficiency[c] [%]	–	–	Steam drived turbine	–
Working fluid of the ORC	245fa	–	Steam drived turbine	245fa
Location	Tampa, Florida	Samar (Israel)	Daegu (Korea)	Holaniku, Hawaii
Service starting date	2012?	2009	2011	2009
Remarks	A combined cycle is proposed for power and refrigeration generation while power is the primary goal.	Heat and power Hybrid fuel	Air is used as heat transfer fluid.	3 ORC: 300 kW_e + 100 kW_e + 100 kW_e

[a] Hot heat transfer fluid input temperature range.
[b] Net solar to electric efficiency. In most cases, this value does not take the auxiliary consumption into account as authors usually do not provide the corresponding information.
[c] Calculated based on the thermal power available and the maximum output of the ORC.
[d] Evaporation temperature.
[e] Other designs have been proposed in the framework of the Powersol project; for instance, a parabolic through system for power (200 kW) and seawater desalination co-generation (Li et al., 2013).

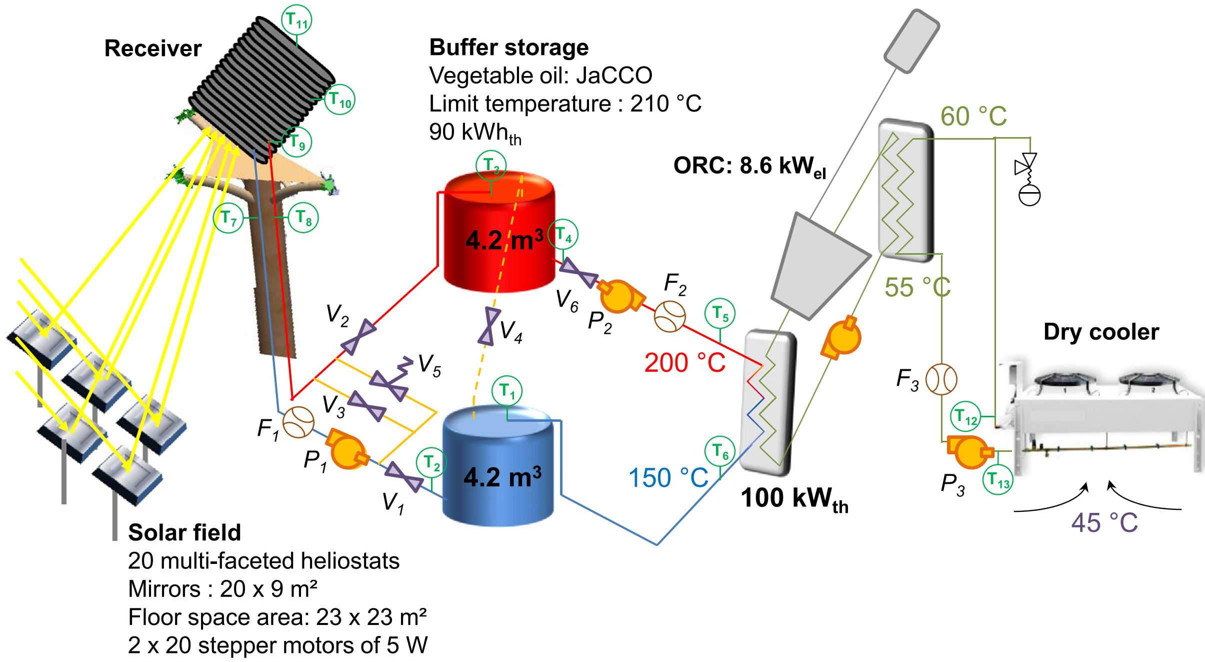

Fig. 3. Layout of the projected solar power plant.

optical efficiency includes cosine losses (η_{cos}), shading losses (η_{sh}), blocking losses (η_{bloc}), reflecting losses (mirrors reflectance) (η_r) and losses due to spillage (portion of reflected radiation missing the receiver due to tracking error and mirrors quality) (η_{spil}) (Fig. 5) as expressed in Eq. (3):

$$\eta_{opt} = \eta_r \cdot \eta_{cos} \cdot \eta_{bloc} \cdot \eta_{sh} \cdot \eta_{spil}. \tag{3}$$

$$\eta_{receiver} = \eta_{abs} \cdot \eta_{cond} \cdot \eta_{conv} \cdot \eta_{rad}. \tag{4}$$

Atmospheric attenuation between the heliostats and the receiver has been neglected due to the fact that the size of the field is relatively small and so is the distance between the heliostats and the receiver. Other effects such as the effect of dust are neglected.

The optical efficiency is a fluctuating value. As we have considered the DNI$_T$, we also use a mean value for the optical efficiency. For a first approximation, overall thermal energy collection efficiency of 0.67 is estimated (the third of the energy is lost before recovery; the estimate values for the various efficiency factors, based on a homemade computer code (Clerc, 2011) are provided in Table 2). The required aperture area of the collector A_{col} is therefore (Eq. (5)):

$$A_{col} = \frac{Q_n \cdot \Delta t}{\mathrm{DNI}_t \cdot \eta_{opt} \cdot \eta_{receiver}} = \frac{100\ \ \mathrm{kW} \cdot 3\ \ \mathrm{h}}{2.525\ \ \mathrm{kWh} \cdot \mathrm{m}^2 \cdot 0.67} = 177\ \ \mathrm{m}^2. \tag{5}$$

Heliostat construction and solar field layout

Current heliostat technology is rather very expensive. This fact is due to the cost of some devices like the crown or the heliostat cylinder. Heliostats are estimated to be 40–50% of the total investment cost of a CSP (Thomas, 2000; Kolb et al., 2007) making the solar field investment very high.

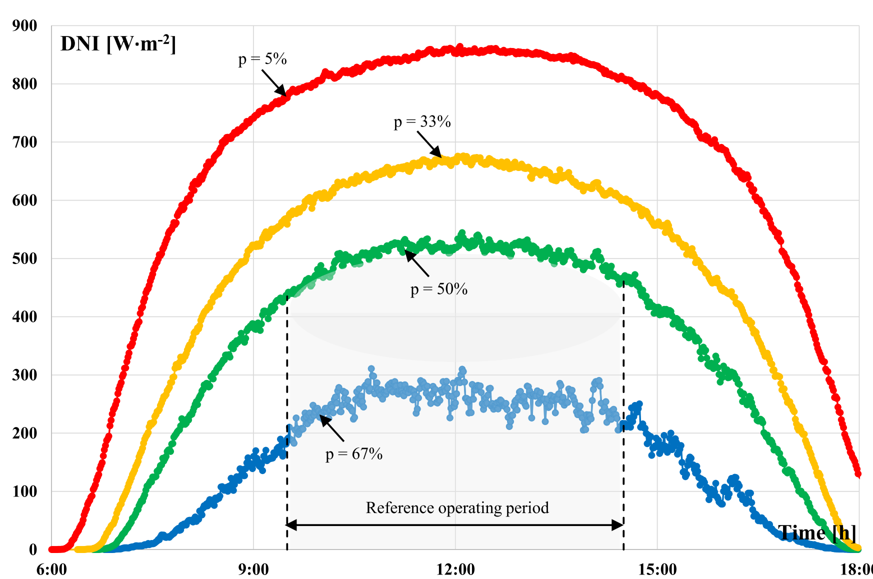

Fig. 4. Daily profiles of DNI as a function of the appearance frequency. 67% means that the DNI profile is above the obtained curve two days in three days (2/3).

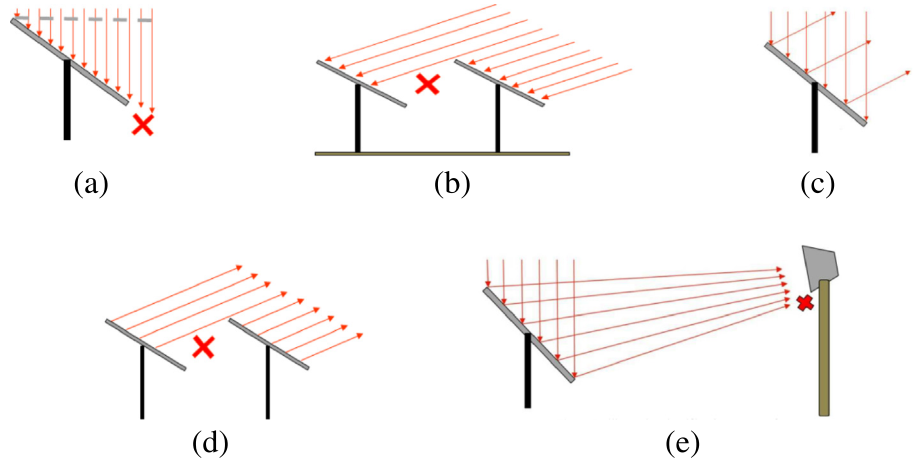

Fig. 5. The main different effects contributing to the optical losses: (a) cosine losses, (b) shading losses, (c) reflecting losses, (d) blocking losses and (e) spillage losses due to tracking error.

The huge size of most of the current heliostats (e.g., 121 m^2 at PS-10 and PS-20 (Blackmon, 2012)) could also be considered as an issue. In fact, many structure problems such as resistance to strong winds and mechanical constraint management arise from their huge size.

In this study, our choice goes for small size multifaceted heliostats that could easily be handled at a "human scale". We have assumed that multifaceted small size heliostats would be easier to be manufactured and handled and do not require work at height. They offer better modularity of the solar field. In Burkina Faso, where cleaning of concentrators may be a challenge due to the high dust deposit, using small size multifaceted heliostats could also facilitate cleaning issues.

From first analysis of this project, the use of the small size heliostats would yield in benefits that could outweigh the economies of scale of large heliostats. The modularity of the solar field also offers the possibility to adjust the thermal power input at the receiver if required. Using a homemade computer code (Clerc, 2011), it has been decided to use 20 heliostats, each one of 9 m^2, which means 180 m^2 of mirrors. The heliostats are spaced far enough to minimize losses (shadowing, blocking, and cosine losses).

The prototype of our multifaceted heliostat is shown in Fig. 6. This design will be adopted for the whole solar field after satisfaction of the ongoing mechanical and optical tests.

The prototype is composed of 9 reflectors of 1 m^2. Each reflector of the heliostat has been manufactured with 9 mirrors of 0.33 m × 0.33 m. Each mirror could then be oriented to focus on the receiver. The system uses local commercial glass mirrors (thickness = 3 mm) that are available at low-cost with an acceptable reflectance.

For the solar tracking system, two-axis (translation) motorized system in open loop has been implemented. The position of the sun is calculated with an algorithm based on the astronomical almanac's algorithm, which has been proposed by Michalsky (1988). The algorithm is loaded on an electronic card so that a connection with a computer is not required for the operating of a heliostat. The precision of the algorithm is 0.01′, which is higher than what could be expected as mechanical precision during the construction of the heliostat. Two stepper motors (2 × 5 W) are used for the tracking of the heliostat.

Various arrangements have been simulated with the height of the tower varying from 10 m to 20 m (the higher the tower, the lower the cosine losses since the mirrors tilt only slightly, as they receive solar rays that are practically vertical all over the year). The cosine losses appear to be the main losses over the year. The height of the solar tower has been therefore set to 15 m. The final arrangement for the solar field is shown in Fig. 7. The whole area of the solar field is 463 m^2, and then, a solar field density of 38% which is rather high (usually it is below 30% (Schramek et al., 2009)).

Table 2
Various estimated efficiency factors.

Efficiency	η_r	η_{cos}	η_{spil}	$\eta_{bloc} \cdot \eta_{sh}$	$\eta_{receiver}$
Value	0.85	0.90	0.97	0.95	0.95

Solar receiver

Receivers and turbines for CSP are considered as high technology subsystems of a CSP plant and would therefore exhibit high barriers to local manufacturing in developing countries (Blohmke, 2014). However, it would be possible to design and manufacture locally receivers, since they basically are heat exchangers, especially for the central tower technology.

The type of receiver is critical when designing a CSP plant: the receiver mainly defines the configuration of the whole solar field. Therefore, a comparison between the two major types of solar receivers, external receiver and cavity receiver, has been performed during this study (Table 3).

The cavity receiver has been selected for this study. The choice is guided by many facts:

- The daily operating time is limited and typically, symmetrically around noon: a cavity receiver would offer here better optical and thermal efficiencies. The optical efficiency is not much affected by cosine effect and it could even be better compared with external receiver, especially when considering that the size of the solar field is relatively limited.
- The cavity receiver leads to a polar configuration or a field located on one side; this facilitates the design of tracking system for the selected design of heliostats.
- Due to the small size of the field, the type of receiver has no significant effect on the height of the tower and, subsequently, on length of vertical piping and related cost.

The solar receiver has been designed, locally built and is currently under testing (Fig. 8). The aim of these tests is mainly to evaluate the thermal performance (thermal losses at operating temperature, heat transfer coefficient, etc.).

The main design parameters of the receiver are presented in Table 4. It is made of a galvanized steel pipe coiled around a drum during the construction. Both galvanized steels and copper were available on the local market. However, the mechanical resistance of copper, whose price is relatively high, is very low compared with galvanized steel: the bottom coils tend to flatten under the weight of the whole heat

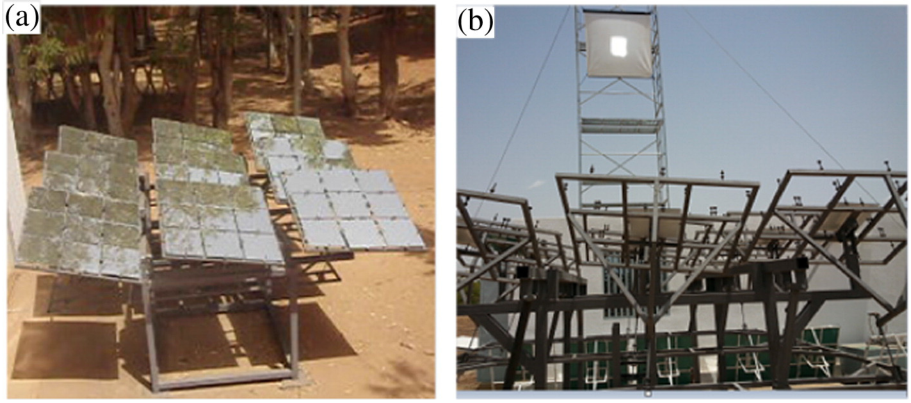

Fig. 6. (a) The prototype of multifaceted heliostat built at 2iE and (b) heliostat under test at the μ-CSP test platform.

exchanger. The detailed design of the solar receiver and first experimental results are presented in Seshie et al. and Seshie (2013).

Thermal storage and heat transfer

Selection of storage concept

One of the main components of a classical CSP plant is the thermal energy storage system, which may be designed for all or any of the following reasons (Steinmann, 2012):

- The efficiency and the financial aspect of the power plant can be improved by shifting electricity generation to higher-priced hours or when solar energy is not available, for instance at night-time. This is the most significant advantage for CSP over other renewable energy technologies since thermal storage is at the moment much cheaper and more efficient than electricity storage.
- The efficiency of the power cycle is improved by avoiding transients, due to solar intermittence, in particular during temporary cloud cover or individual passing cloud periods. In addition, a better lifespan of the power cycle is ensured, since strong fluctuations may limit the lifespan of a turbine in a Rankine cycle, for instance.
- The duration of the power plant starting up is reduced through receiver preheating, using energy provided by the storage system.
- The possibility to have an environmentally friendly energy storage for both small and large scales. In particular, in West Africa, electric batteries last only 4 years and induce critical environmental impacts due to uncontrolled disposal. Their change every 4 years increases the operating cost too. Comparatively, thermal energy storages are acknowledged to last 20 to 30 years without problem.

For this pilot project, only the last three listed reasons have been considered relevant since i) the capacity of the power plant is relatively small, ii) there is no need to continue production night-time, iii) the power plant is designed for operating about 3 h a day. This type of storage could be named “management storage” or “optimisation storage”, in opposite to “production storage”. We have chosen sensible storage with two-tank system because it is relatively easy to be implemented and is used in most CSP plants worldwide. In such a system, the heat transfer fluid and the storage material are one and the same, eliminating the need for costly heat exchangers and the corresponding irreversibilities. A single tank, using thermocline concept, could be cheaper but requires some experiences that we do not have locally. Because the storage is not intended for production but management, reactivity is of first concern. The heat transfer fluid/storage material should then have the ability to release the stored heat very quickly. Thermal oils meet very well this criterion. Molten salts are even more reactive but they are suited for higher temperature range since most of them are at solid state between 150 and 250 °C. Furthermore, their financial (1165 $€ \cdot t^{-1}$ (Strasser and Selvam, 2014)) and environmental costs (resource availability, site classification for security issues, material final repository, etc.) are prohibitive. The main issue with the choice of operating with oil is fire hazards since storing large volumes of oil where heat and oxygen are available is hazardous.

Storage material and heat transfer fluid

For the storage material, we opt for the promotion of a vegetable oil that is locally produced: *Jatropha curcas* crude oil (JaCCO). To the authors' best knowledge, JaCCO has not been considered as thermal storage material or heat transfer fluid yet. The main advantage of a possible use of JaCCO as thermal storage or heat transfer fluid is that the oil is locally produced and available at low cost (Table 5). Therefore, no import of synthetic from abroad oil is required. Hence, this use would meet the three spheres of sustainability, which are economy (local production, local job creation, low cost, etc.), environment (Kumar et al., 2012) (vegetable oil, CO_2 emission reduction, renewable resource, etc.), society (the oil is not consumed by human being so that there is no intrinsic competition between the oil and food production, no displacement of food crops is necessary, etc. (Silitonga et al., 2011)). JaCCO is biodegradable in case of accidental release in the environment or explosion. Crude *J. curcas* seed oil production is with growing interest in developing countries worldwide, where it provides livelihood for many families (Silitonga et al., 2011). Regarding resource availability, about 175 species of *Jatropha* are listed worldwide with nearly 200 names, indicating its occurrence in various countries (Garba et al., 2013).

Since JaCCO has never been considered as thermal storage medium, we have performed some preliminary studies to check its potential to be used as a heat transfer fluid or thermal storage material in concentrating solar power (CSP). Table 5 presents comparison of JaCCO with well-established thermal oils that are currently used in commercial CSP: the most cost-effective and practical organic oils (Dowtherm A, Therminol VP-1) (Moens and Blake, 2008) and Syltherm 800 (Moya, 2012; Ortega et al., 2014; Vignarooban et al., 2015). This comparison does not include piping or thermal storage equipment.

The comparison of the energy storage density, price and flash point of the various oils, disregarding the degradation over cycles, indicates that the proposed vegetable oil has better potential than the others. However, the dynamic viscosity of JaCCO is relatively high, compared with the others; therefore, the electrical consumption for circulation pumps would be the highest in the case of the use of JaCCO, for a given circulating flow rate. Anyway, the effect of this drawback would be limited, since circulation pump consumptions are usually small compared with the electricity generation of the power plant.

One of the key parameters to be checked is the thermal stability of the oil i.e., the maximum bulk temperature at which no significant degradation of the oil properties is observed (Moya, 2012). So, the evolution of some thermophysical properties (viscosity, density) and the JaCCO

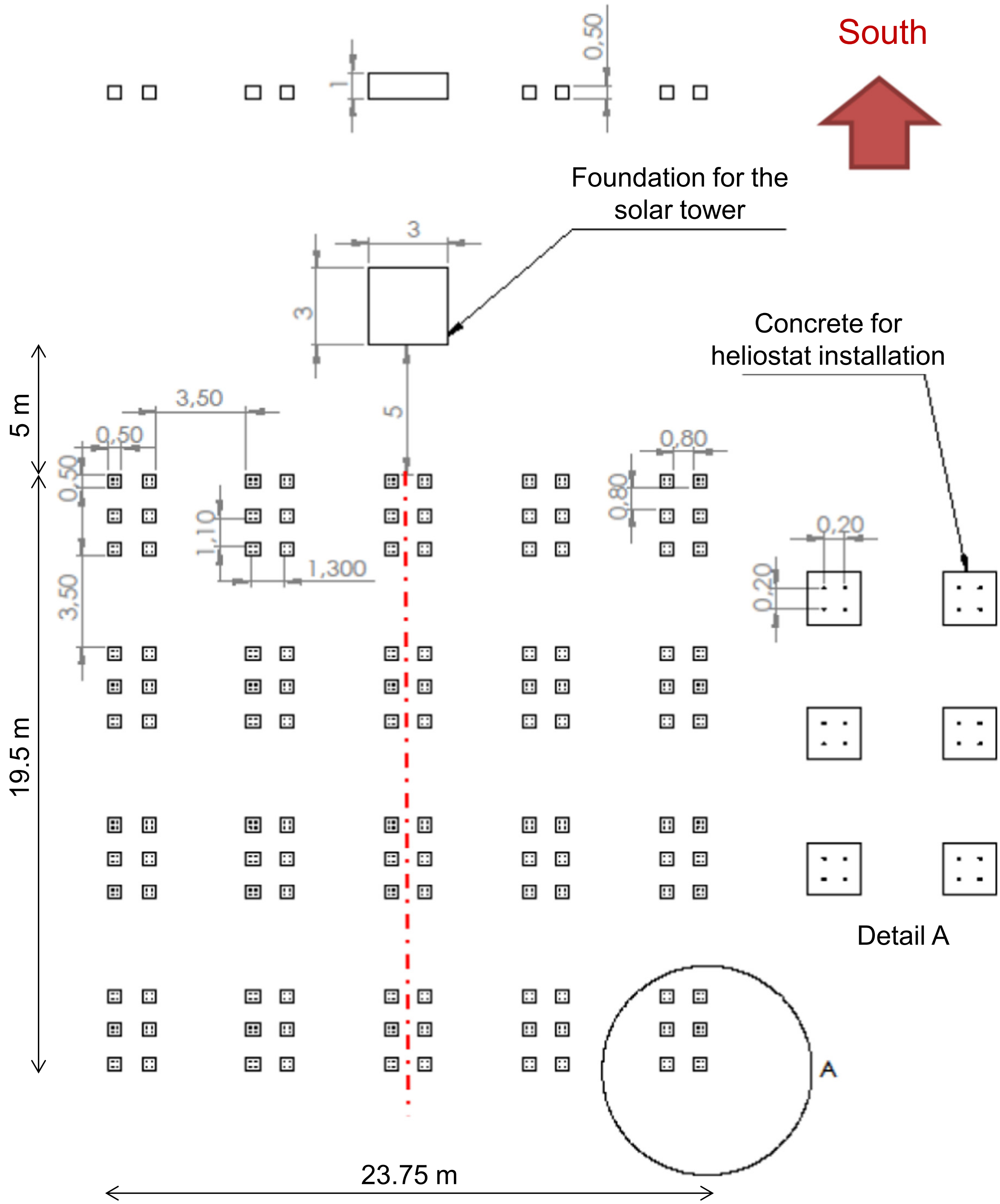

Fig. 7. Layout of the solar field: 20 heliostats in 4 rows by 5 columns.

stability (flash point, acidity number, iodine value, peroxide value and chemical composition) have been experimentally monitored. A quantity of 2500 ml of JaCCO is put in a reactor made of zinc galvanized steel. The reactor is introduced in a bath and heated up to 210 °C, which is the maximum operating temperature set for the target application. Then, the reactor is naturally cooled down to room temperature, without any plateau at 210 °C. A sample of 150 ml is taken and subjected to the different above-mentioned tests and analysis. The remaining oil in the reactor is again submitted to the same procedure. Ten cycles have been made so far. The measured thermophysical properties (viscosity at 100 °C, density) remain practically constant after ten cycles (Kenda et al., 2015). This is also the case of the total acidity number. However, the evolution of the chemical composition of the oil, especially the presence of elements such as iron and zinc, suggests a continuous corrosion activity. The flash point drops regularly from 235 °C to 185 °C. This is still above the flash points of Therminol VP-1 and Syltherm 800 and stabilization is expected after further cycles. JaCCO remains therefore a promising heat transfer fluid and storage material for CSP plants although further tests are necessary and are ongoing.

Storage tank design

The useful amount of thermal energy to be stored has been estimated to 90 kWh (Ouali, 2014). Assuming a maximum heat loss of 5% in the

Table 3
Comparison of external receiver and cavity receiver.
Stine and Geyer, 2012; Vant-Hull (2012).

	External receiver	Cavity receiver
Field configuration	Surrounding field design because the absorbing surface can be seen from all the directions	Either multiple cavities are placed adjacent to each other, or the heliostat field is limited to the view of the cavity aperture i.e., heliostats are positioned either at the north or the south of the tower, depending on the hemisphere since heat is collected within a cone.
Advantages	Shorter and lower cost tower and vertical piping because the heliostats are closer to the tower for a given power level	Limited thermal losses because the cavity is insulated Higher optical efficiency around noon
Drawbacks	Absorbing surface is completely exposed to the surrounding, resulting in relatively significant radiative and convective thermal losses.	Lower annual energy harvest compared with surrounding field because lower optical efficiency in the morning and afternoon due to larger cosine effect

storage tank (i.e., the storage efficiency $\eta_{st} = 0.95$), the useful volume of the storage tank can then be obtained very simply (Eq. (6)):

$$V_{tank} = \frac{E}{\eta_{st} \cdot \rho \cdot C \cdot (T_{max} - T_{min})} = \frac{90 \cdot 3600}{0.95 \cdot 787 \cdot 2 \cdot (200-150)} = 4.3\text{m}^3. \tag{6}$$

The average value of the specific heat capacity of the oil in the temperature range (150–200 °C) has been considered for the evaluation. We choose to use a cylindrical geometry, with a spherical cap in order to manage dilatation of the tank wall. Giving the same value for the diameter and height of the tank leads to the minimum surface (sidewall surface + bottom + roof) and thus, the minimum wall material and also heat loss surface. So, both storage tanks have the same dimensions: $d_{tank} = h_{tank} = 1.75$ m (Fig. 9).

The tank is made of stainless steel 316L. The long-term high temperature operation compatibility of the heat transfer fluid with other materials would be performed later on in order to identify eventual cheaper material for following prototypes. The wall thickness has been calculated using the standard EN 14015 (British Standards Institution, 2005) (Eq. (7)):

$$e_{tank} = \frac{d \cdot [g \cdot \rho_{oil} \cdot (h-0.3) + P]}{2 \cdot \sigma} = \frac{1.75 \cdot [9.81 \cdot 1 \cdot (1.75-0.3) + 0]}{2 \cdot 180} = 0.07 \text{ mm}. \tag{7}$$

Table 4
Main features of the receiver.

	Unit	Value
Inside diameter of the pipe	mm	25.4
Outer diameter of the pipe	mm	27
Height of the coil	m	1
Internal diameter of the coil	m	0.7
Length of the pipe	m	83.6
Pitch	mm	0
Number of coil turns	–	38
Total internal surface area	m^2	6.7

The minimum wall thickness suggested by the standard is 5 mm, and it is retained for this project. The tank is insulated with glass wool with a thickness of 15 cm. This leads to thermal losses of less than 5 kWh in 24 h, using the method presented in (Kumana and Kothari, 1982).

Power cycle: organic Rankine cycle

The maximum temperature level defined for the current application is below 210 °C, and the typical operating temperature range is 150–200 °C. In this range, an ORC can achieve better efficiencies than steam turbines, especially for small scale plants (Lovegrove and Pye, 2012; Quoilin et al., 2013) as it is the case here. Therefore, an ORC appears to be appropriate for the plant design and it has been decided to acquire a commercially available unit, due to the short timeframe of the project. The performance corresponds to the data presented in Fig. 3: the gross power output is 8.6 kW. So, the ORC efficiency is 8.6%.

For the heat removal from the ORC, a wet cooling tower or a dry cooler are the two major classical alternatives. The first one requires a significant amount of water (more than 125 $L \cdot h^{-1}$ or 15 $kg \cdot kWh_e^{-1}$ to be evaporated in the present case) while the latter needs water only in the cooling loop. In a country like Burkina Faso where the raining season lasts 4 months along with a year and water resources are rare, with regular water service interruptions in dry hot season, a dry cooling system has been thought preferable for the CSP plant. The main drawback is the investment since wet cooling towers are more cost effective than dry coolers. In addition, more auxiliary electricity consumption and less cycle efficiency have to be considered although they are eventually relatively limited (Kelly, 2005). This can represent an equivalent of 7 to 10% decrease in the plant efficiency but in the present case, it is nothing compared with the water resource issues.

In this regard, a Tesla turbine is foreseen as a good candidate for the ORC. Research activities are being conducted on this not very well known and unused turbine for the CSP technologies. This turbomachine, patented in 1913 by Tesla (1913), uses disks instead of classical blades for its rotor. The boundary layer effect through the thin gap between

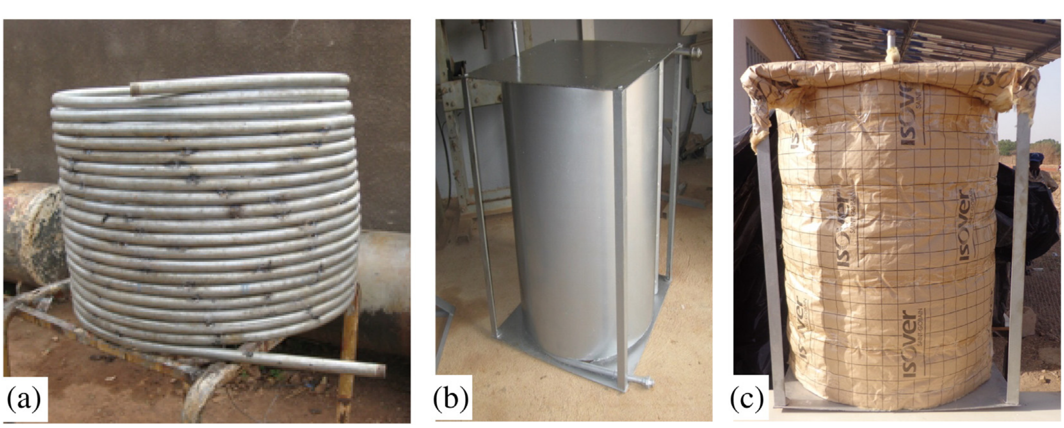

Fig. 8. The solar receiver: (a) during manufacturing, (b) completely built and (c) under testing (with insulation).

Table 5
Comparison of physical properties of JaCCO with main organic thermal oils that are used in CSP plants.

Category	Unit	Therminol VP-1 (Guyer, 1999; Solutia, Inc., 1999; Eastman Chemical Company, 2015) [a]	Dowtherm A (The Dow Chemical Company, 1997; Moens and Blake, 2008) [a]	Syltherm 800 (The Dow Chemical Company, 2001)	JaCCO [b]
		Synthetic	Synthetic	Synthetic	Vegetable
Density at 200 °C	$kg \cdot m^{-3}$	913	907.1	773.3	787 (Haïdara, 1996; Veny et al., 2009)
Specific heat capacity at 200 °C	$kJ \cdot kg^{-1}\ °C^{-1}$	2.048	2.079	1.916	2 (Sundarapandian and Devaradjane, 2007; Segura, 2013)
Thermal storage capacity at 200 °C	$kJ \cdot m^{-3}\ °C^{-1}$	1870	1886	1482	1574
Dynamic viscosity at 40 °C	mPa·s	2.62	2.56	7	36
at 200 °C		0.395	0.39	1.05	1.73[c]
Thermal conductivity at 200 °C	$W \cdot m^{-1} \cdot K^{-1}$	0.114	0.11	0.1012	0.14
Maximum bulk temperature	°C	400	400	400	>300
Fire point	°C	135	118	193	274 (Silitonga et al., 2011)
Flash point	°C	124	113	160	220-240 (FACT Foundation, 2010; Silitonga et al., 2011; Shambhu et al., 2013)
Crystallization point (1013 mbar) or minimum pumping temperature	°C	12	12	−60	3 (Silitonga et al., 2011)
Atmospheric boiling point	°C	257.0	257.1	≈200	295 [d] (Folaranmi, 2013)
Vapor pressure at 200 °C	bar	0.24	0.24	0.95	–
Cost[e]	$€ \cdot t^{-1}$	25,000[f]	25,000[f]	36,000 (Dumont, 2012)	835
	$€ \cdot kWh^{-1}$	879	866	1353	30
Others	–	Aromatic and hazardous degradation products such as benzene, phenol, and terphenyls (Moens and Blake, 2008) Persistence in the environment after rejection: 1 to 5 years. In temperate climate, where the temperature may drop below 12 °C, keeping fluid on temperature during winter nights may result in significant costs.		–	–

[a] Therminol VP-1 and Dowtherm A are commercial names of eutectic mixtures of two very stable organic compounds, namely biphenyl ($C_{12}H_{10}$) and diphenyl oxide ($C_{12}H_{10}O$) (Moens and Blake, 2008; Vignarooban et al., 2015); these oils are generic chemical equivalent fluids (Guyer, 1999).
[b] Properties of JaCCO, in particular the density and the viscosity may be different, depending on the extraction method (Karaj and Müller, 2009; Belewu et al., 2010).
[c] Dynamic viscosity at 210 °C: our own measurements. Value at 100 °C: 12 mPa·s (Haïdara, 1996; Bilal et al., 2013).
[d] Distillation temperature, as indicated by several sources. Ref. Dubey et al. (2011) indicate a boiling temperature of 395.9 °C, which is above this distillation temperature.
[e] These costs do not include handling, in particular, transport cost, which may be significant when importing products to Burkina Faso.
[f] This is the price that we obtain from an official distributor in 2013. Vignarooban et al. (2015) indicates 100 $USD \cdot kg^{-1}$, that is relatively high (≈90,000 $€ \cdot t^{-1}$).

the disks is optimized in a way to drive the rotor. Tesla turbine enables the choosing among various transfer fluids such as air, water, and refrigerant, among other things. Three small-scale prototypes (Fig. 10) were designed, manufactured and tested. Results from their experimentation are very encouraging ones. In fact, about 35% at 35,000 rpm and 0.5 kW_e were obtained. A new designed prototype (under manufacturing), would have about 1 kW_e power. This last one will be used on our CSP power plant for characterization issue.

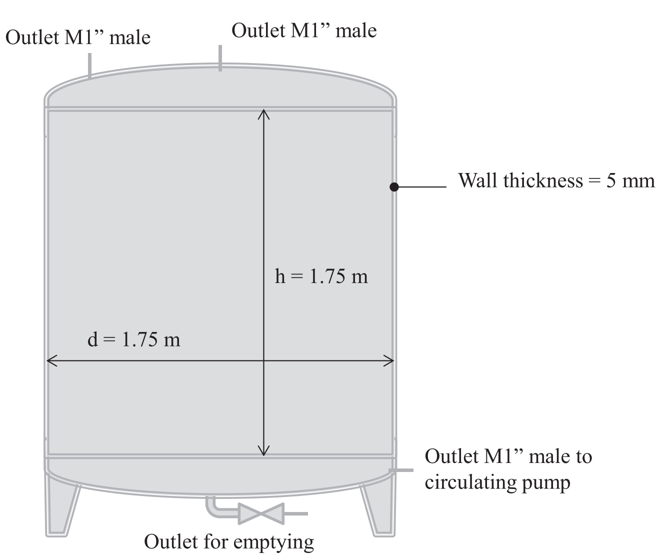

Fig. 9. Schematic of the thermal storage tank.

Solar tower

The solar tower has also been designed and it looks like a baobab, a tree that appears as a symbol of the African Savana (Fig. 11).

Auxiliary consumption

An estimation of the power consumption of various auxiliaries is provided in Table 6. The consumption of the ORC and the dry-cooler, including the corresponding circulation pump is data provided by the manufacturer of the power block. The power consumption of the oil circulating pumps has been estimated based on pressure drop calculation and an overall efficiency of 0.55 for the pumps. For the tracking power of the heliostats, the 40 stepper motors actually lead to 200 W. However, these are stepper motors, which do not operate continuously. A reduction factor of 0.5 is then associated with their power consumption. The power consumption of monitoring and control devices has been neglected.

The parasitic consumption of the system is then 2.6 kW. As the gross electric output of the ORC is 8.6 kW, the net electric output is then 6 kW. The net electric efficiency, considering the thermal energy delivered by the thermal storage tank is 6%.

Conclusion

CSP technology offers an interesting potential for power generation in rural areas in Africa where the electrification rate remains very low. The design and construction of main components of a μ-CSP has been presented as well as various technological options made in the design and construction process, with a stress on the local capacity building

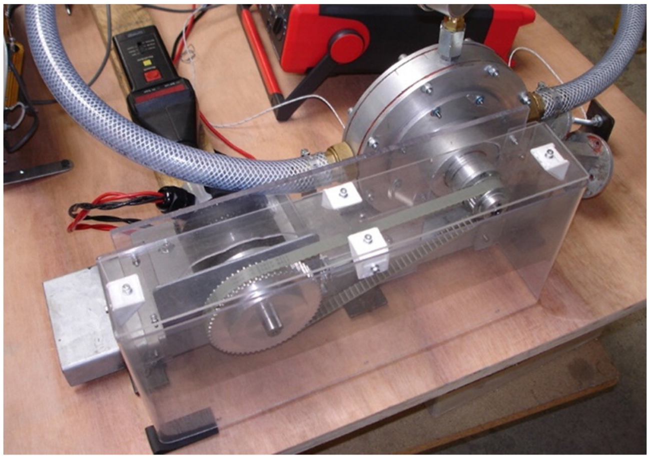

Fig. 10. Prototype of Tesla turbine manufactured within this project.

and contribution. Hence, some challenges faced and options made in the curse of the project have been exposed. The main components of the power plant have been designed, defined and developed. A solar tower technology has been retained in order to use locally available mirrors for the heliostats and gain experience with small scale solar tower technology. 20 multifaceted heliostats, with a total mirror area of 180 m^2, compose the solar field that could deliver 100 kW_{th} to the thermodynamic cycle. The latter is an ORC generating 8.6 kW_e, coupled with a dry cooler because of the low availability of water. A local thermal oil, JaCCO, is seen to be promising as heat transfer fluid and storage medium. The storage tanks have a useful volume of about 4 m^3. The solar receiver is a coil heat exchanger, made of galvanized steel. The maximum operating temperature has been set below 250 °C in order to avoid dealing with more complex high temperature level processes, which are not commonly locally managed.

The project is also a capacity building opportunity that involves researchers, lectures and engineering school students. Its high replication potential, if it used, would generate local income and jobs, contributes to energy security and poverty alleviation.

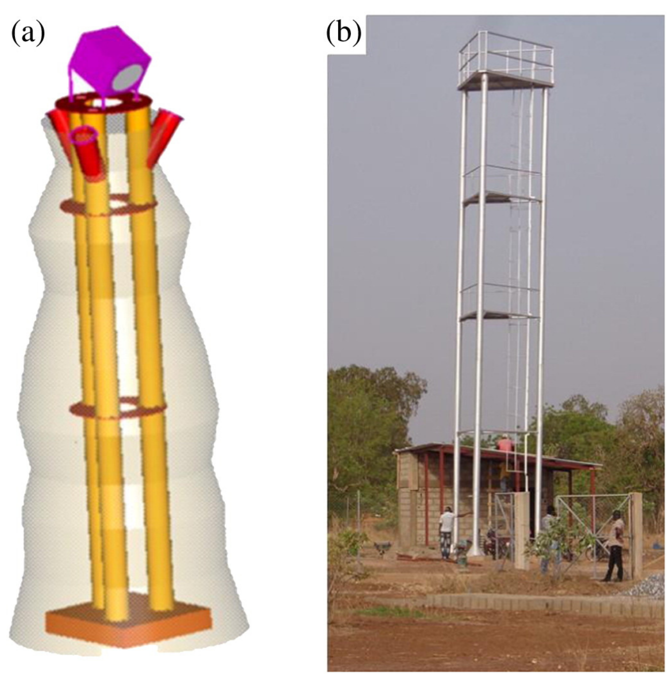

Fig. 11. (a) Layout of the solar tower with a baobab look-like and (b) solar tower under construction.

Table 6
Power consumption of auxiliaries.

	Power [kW]
ORC consumption	0.6
Dry-cooler and corresponding circulating pump	1
Oil circulating pumps	0.9
Total tracking power for the heliostats	0.1

The LCOE of the power plant will be evaluated when the plant would be under operation. The design would be improved for next generation of μ-CSP that would be installed in rural areas for decentralized electricity generation. Innovative cleaning method development is necessary to deal with important dust deposit, which is very common in the Sahelian region.

Nomenclature

Abbreviations

2iE	International Institute for Water and Environmental Engineering
CSP	concentrating solar power
DNI	direct normal irradiation
LCOE	levelized cost of electricity
PV	photovoltaic

Latin symbols

A	area [m^2]
C	specific heat capacity [$kJ \cdot kg^{-1} \cdot °C^{-1}$]
d	diameter [m]
E	energy [kJ]
g	gravitational acceleration [$m \cdot s^{-2}$]
h	height [m]
P	pressure (above the liquid) [mbar]
Q	power [W]
t	time [s]
T	temperature [°C]
V	volume [m^3]

Greek symbols

η	efficiency [−]
ρ	density [$kg \cdot m^{-3}$]
σ	tensile strength of the wall material [MPa]

Subscripts/superscripts

abs	absorption
bl	blocking (losses)
cond	conduction
conv	convection
cos	cosine (losses)
i	instantaneous
max	maximum
min	minimum
n	nominal
opt	optical
r	reflectance (losses)
rad	radiation
sh	shading losses
spil	spillage (losses)
st	storage
T	total
tank	tank

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