J. P. Soaphys, Vol 2, N°1 (2020) C20A08
http://dx.doi.org/10.46411/jpsoaphys.2020.01.08

Journal de physique de la SOAPHYS
http://www.soaphys.org/journal/
ISSN Print : 2630-0958

ASSESSMENT OF DIFFERENT SANDS POTENTIALITY TO FORMULATE AN EFFECTIVE THERMAL ENERGY STORAGE MATERIAL (TESM).

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INFOS SUR L'ARTICLE

Historique de l'article :
Reçu le : 24 novembre 2020
Reçu en format révisé le : 05 février 2021
Accepté le: 20 février 2021

***Keywords**: Dual medium thermocline, thermal stability, Concentrated Solar Power, Storage effectiveness, Sand*

A B S T R A C T

This paper presents a review of solid particles size effect on thermocline storage performance for Concentrating Solar Power (CSP) storage systems. After an overview on the different process to store thermal energy we found that a particle size of 2cm diameter is better to achieve a good sensible heat storage performance within a system call dual-medium thermocline (DMT). The thermal storage potentiality of different sands from Burkina Faso have been carry out to look at the possibility to make a filler material with 2cm diameter. However, two different sands (mining and dune) properties have been assessed. The density of the two samples is more than $2650\text{kg}.m^{-3}$ with low mass losses at 700 °C without any agglomeration at 900 °C and 1000°C. This indicates that the mining sand samples from Bobo Dioulasso and Dune sand from Sahel region in Burkina (Oursi) have the potentials to be used to develop an effective thermal energy storage material or to store thermal energy at high temperature.

I. INTRODUCTION

The global demand for energy is growing and conventional resources like coal and petroleum are depleting. Renewable resources is expected to play a crucial role in the future. One promising of these renewable resources technologies is concentrating solar power (CSP) plants (Ummadisingu and Soni 2011). However, CSP technology affordability is insufficient when there is non-availability of energy storage system from electricity dispatching during the night-time and cloud covering dominates. This is explain the important initial investment of 15% to 20% due to the two-tank storage system and the high price of heat transfer fluid (HTF) like mineral oil and synthetic oil, which are used as storage medium since 1984 at SEGS plant (Herrmann et al., 2004). The most effective thermal energy storage materials are the molten salts, which have high melting temperature and complex management of their thermal stability (Huang et al., 2011; Raade and Padowitz 2011; Hoffmann 2015). Also, mineral oil and molten salt have low thermal stability and impact negatively on the environment. However, studies have shown that there is a possibility to have a broad reduction of CSP cost (33% to 35%) by using one tank as storage system and using eco-materials (like natural rocks and industrial waste) as filler materials (Angelini et al., 2014; Pacheco et al., 2001). Within this tank a thermal gradient call thermocline separates the hot zone from the cold zone. The solid particle size can affect the stratification of this thermal gradient. The following paragraphs give an overview on dual-medium thermocline in the literature and how solid particle size can have effect on its performance.

1.1. Dual-medium thermocline system

Most of CSP pilot and laboratory scale projects for thermocline storage study are dual-medium thermocline (**figure 1**) (Radosevich; 1988; Zunft et al., 2011; Odenthal et al., 2020; Faust et al., 2018; Schlipf et al., 2017; Hoffmann et al., 2016; Zanganeh et al., 2012). DMT tanks are favored because they have economical and technical advantages. The filler material reduces the quantity of the liquid material (oil, molten salt or any fluid) (Radosevich, 1988), which is often the most expensive amongst the components. But many parameters need to be considered to have a good thermal stratification, therefore a good extraction of the thermocline during charging and discharging time is important. Among these parameters and the most important is the filler materials or solid particles (sometimes refers to as solid).

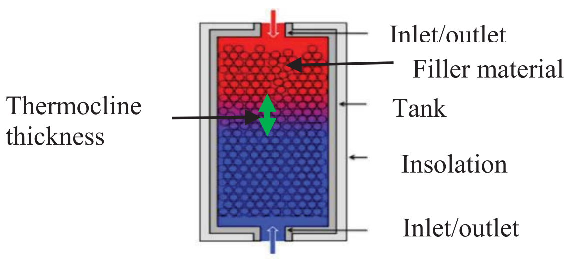

***Figure 1**: DMT thermocline storage system* (Hoffmann, 2015)

1.2 Governing equations

To evaluate the effect of filler material properties on the performance or the behaviors of packed-bed thermocline system usually, most of the models developed in the literature are based on Schuman equations, which were developed since 2029 (Schumann, 2029). This one-dimension model was used for porous medium modelling and combine two energy equations. One for the fluid and one for the solid particles.

$$\varepsilon\rho_f c_{pf}.(\frac{\partial T_f}{\partial t}+u\frac{\partial T_f}{\partial z}) = h.a_s.(T_s - T_f) \quad (4$$

$$(1-\varepsilon).\rho_s c_{ps}.\frac{\partial T_s}{\partial t} = h.a_s.(T_f - T_s) \quad (5)$$

Where a_c in $m^2.m^{-3}$ represents solid surface per volume unit of the bed.

For better understanding thermocline behaviors, the thermal losses, the effective conductivities of the solid, and tank thermal capacity have been added to Schuman model (Esence, 2017; Hoffmann et al., 2016). The energy balance for the tank wall has been considered. Through the years, in order to better analyze temperature distribution based on continuous solid phase assumption and fluid flow the two dimension (Klein et al., 2014) and three dimension (Bruch et al., 2014; Flueckiger et al., 2012; Faust et al. 2018; Mahfoudi et al., 2014) models have been developed. The general description of these models with three equations are presented as follow:

Energy balance for the fluid:

$$\varepsilon\rho_f c_{pf}.\left(\frac{\partial T_f}{\partial t}+\nabla u T_f\right) = \nabla\left(K_{f,eff}\nabla T_f\right) + h_{v,p}\left(T_s - T_f\right) - U_{v,wf}(T_w - T_f) \quad (6)$$

Energy balance for the solid particles:

$$(1-\varepsilon).\rho_s c_{ps}.\frac{\partial T_s}{\partial t} = \nabla\left(K_{s,eff}\nabla T_f\right) + h_{v,p}\left(T_f - T_s\right) + U_{v,w}\left(T_f - T_s\right) \quad (7)$$

Energy balance for the tank wall:

$$\rho_w c_w.\frac{\partial T_w}{\partial t} = \nabla\left(K_{w,eff}\nabla T_w\right) = U_{v,w}\left(T_f - T_w\right) + U_{v,w}(T_s - T_w) + h_{v,ext}(T_w - T_{ext}) \quad (8)$$

Where ε is the porosity of the bed, ρ the density in $kg.m^{-3}$, c_p the specific heat capacity in kJ/kg°C, h the convective coefficient of heat transfer, u the fluid velocity, K the thermal conductivity in W/m.°C, U global coefficient of heat losses in $w.m^2.°C^{-1}$. and T the temperature

A part from energy equations, continuity equation and momentum equation which takes into account the intrinsic permeability of the solid particle should be added(Xu et al., 2013). This intrinsic permeability can be define as follows:

$$k = \frac{{d_p}^2\varepsilon^3}{150(1-\varepsilon)^3}, \quad (9)$$

Where d_p is the spherical particle diameter in m. and K in m^2.

For a given model and tank size, several numerical methods like finite volume or finite element have been used to resolve these energy balance equations numerically. The importance of numerical model is to have data from an ideal system and use it for experimental data validation. The three equation model provide an effective thermal performance study of a storage system than one equation (Hoffmann et al., 2016). Two equations model can effectively study thermocline behaviors(Esence et al., 2020) like three equations model by reducing 18% of computation time (Esence, 2017).

1.3. Thermocline effectiveness

1.3.1. Thermal cycle effectiveness

The stratification efficiency could depend on the charge and discharge efficiency, which is influenced by porosity of the tank, particles size, and storage capacity (Laube et al., 2020). Moreover, thermocline thickness *dX* is defined as the covering length of the thermocline region depend on charging and discharging cycle and can be defined according to Chang and co-workers (Chang et al. 2015) as by:

$$dX = \begin{cases} min\{H(T_{out}), H(T_{crit,h})\} - H(T_{crit,c}) \text{ in discharging cycle} \\ H(T_{crit,h}) - max\{H(T_{out}), H(T_{crit,c})\} \text{ in charging cycle} \end{cases} \quad (10)$$

Where $T_{crit,h} = T_h - 5$ and$T_{crit,c} = T_c + 5$ represent the critical low and hot temperature for evaluating the thermocline thickness respectively.

From these equations, we can realize that a thin thermocline can be achieved with an effective thermal stratification and thermal cycle.

A low thermocline thickness conducting to a good cycle efficiency is defined as follows:

$$\eta = \frac{Q_{dis}}{Q_{chg}} = \frac{\int_0^{t_{dis}} \dot{m}\times c_{p,f}(T_{out}-T_{min})dt}{\int_0^{t_{chg}} \dot{m}\times c_{p,f}(T_{max}-T_{min})dt} \quad (11)$$

Where η is the effective discharge efficiency, $t_{dis} = t_{dis,ref}$ is the time at which the HTF temperature drops to a threshold value? The threshold value is usually determined by the application of the interest and is arbitrary chosen like $T_h - 5$, $T_h - 20$, etc.

An effective thermal storage depends on the discharge efficiency and the discharge time.

1.3.2-Particles size effect on discharge effectiveness

Based on transient two-dimensional dispersion-concentric (D-C) model for heat transfer and fluid dynamics in a packed-bed molten salt thermocline thermal storage system (Xu et al., 2013) have shown the possibility reduction discharge efficiency with large particles confirmed by numerous other authors (Laube et al., 2020; Zanganeh et al., 2015). The figure 2 show the effect of particle size on the discharge efficiency

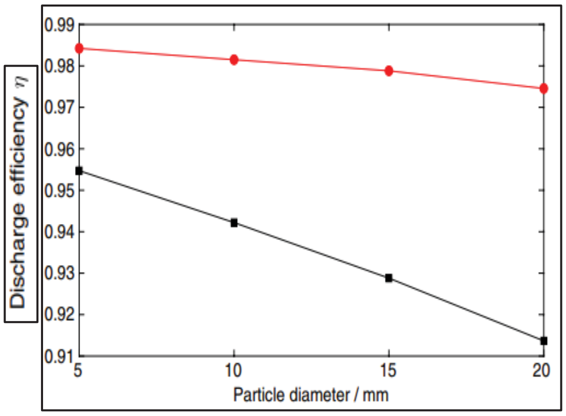

***Figure2**: Effect of particle size on discharge efficiency* (Laube et al., 2020)

To have a thin thermocline with an effective discharge efficiency, small particle diameter is required (less than 2cm) to avoid bad thermal distribution in the particle and to provide a good heat transfer process between the fluid and the particle. But when the particle diameter is smaller enough, the influence of particle diameter on thermal performance becomes negligible (Xu et al., 2013). The impact of particle size on thermocline thickness can be presented in figure 3 as follows:

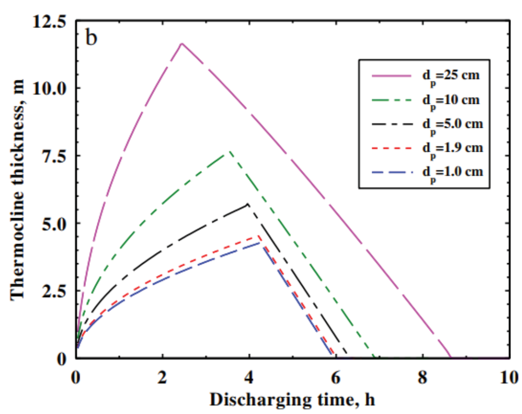

***Figure3**: Variation of thermocline thickness with discharge time for quartzite rock particle diameters* (Xu et al., 2013).

To summarize smaller particles, enhance thermal stratification, reduce the thickness of the thermocline, improve discharge efficiency thereby the storage efficiency. An optimal diameter value could be 2 cm. This is the reason why this study aims to assess the potentiality of sand to develop an optimal storage material. Because sand has good thermal properties and good thermal inertia (Priya et al., 2016; Diago et al.; 2015; Mahfoudi, 2016). Also sand is a material use in building area by mixing it with binder like cement. However sand samples can agglomerate when it is used as heat transfer fluid or in the storage medium keeping its operating temperature low (Iniesta et al. 2015). This is the reason why the objective of this study is to assess the thermal storage potentiality of dune and mining sand from Burkina Faso to check if these sand samples can be used to develop an effective filler material for sensible heat storage at high temperature. This objective could be achievable through size analysis, density and heat treatment analysis of the different sand samples.

II. MATERIAL AND METHODS

2.1. Material selection

Two sand samples from selected locations in Sahel region (Dune sand) and High Basin (mining sand) of Burkina Faso were studied. The samples were collected in the sand extraction area (mining sand) of Borogodougou located at 15 km away from Bobo Dioulasso and Dune sand of Oursi (sahel region). At a first glance, the most striking difference between them is the colour, which is light cream for mining sand and red tones for dune sand. Figure 4 presents a collection site map of samples.

***Figure 4:** Sampling site*

2.2. Materials for characterization

2.2.1. Particle size analysis

Every sand sample was separated through a series of wire mesh sieves. The chosen standard was NFP 18-560 and the sieves used had nominal aperture sizes of 16, 12.5, 10, 8, 6.3, 5, 4, 3.15, 2.5, 2, 1.6, 1.25, 1, 0.8, 0.63, 0.5, 0.4, 0.315, 0.25 0.2, 0.1, 0.16, 0.125, 0.1, and 0.080.

The particles stopped between each pair of sieves were weighted and recorded. The sauter mean diameter was calculated using equation 11 as follows:

$$SMD=\sum_i (m_i d_{av})/M \qquad (12)$$

Where m_i in g is the mass stopped by a given sieve *i*; *dav* in mm is the mean size between the stopping sieve *i* and the immediate larger one; and *M* in g is the total mass sieved for a given sample.

2.2.2. Density and porosity measurement

The bulk density has been measured with a tare of 2 litters. The sample was put in the tare by placing it at least 1 meter above the tare of volume V. The surplus one was flatten and weighed. The method used can be presented in the figure 5 as follows:

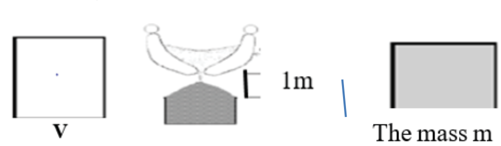

***Figure 5**: Bulk density measure process.*

The bulk density or apparent density is given by

$$\rho_b = \frac{m}{V} \qquad (13)$$

Where m in g is the sample weight and V in cm^3 is the volume of the tare.

Also the particle density has been determined through a water displacement pycnometer. The different sand samples were washed, and dried at 105°C within an oven during 24 hours. A balance with 0.1g of accuracy was used to measure the different weights and an aspirator was used to remove all air in the pycnometer during one hour. And the particle density is computed as follows:

$$\rho_p = \frac{m_s}{(m_{p+s} - m_p + m_{p+w}) - m_{p+s+w}} \times \rho_w \qquad (14)$$

Where m_s in g is the weight of the sample, m_{p+s} in g the weight of the pycnometer plus the sample, m_{p+w} in g the weight of the pycnometer plus water, m_{p+s+w} in g the weight of the pycnometer plus water plus the sample and ρ_w density of water in $kg.cm^{-3}$

The fraction of void (porosity) in the different sample has been assessed as follows:

$$\varepsilon = \frac{\rho_p - \rho_b}{\rho_p} \qquad (15)$$

2.2.3. Loss on ignition and agglomeration analysis

The different sand samples of around 50g were heated at 700 °C in a programmable muffle furnace Model 650-58 under air atmosphere to assess the mass of volatile elements loss of ignition in the different sand samples. The temperature was hold during 1 hour at 700°C. The LOI was computed using the following relation:

$$LOI = \frac{m_0 - m_1}{m_0} \times 100 \qquad (16)$$

Where, m_0 in g is the weight of the sample before calcination and m_1 in g the weight after calcination.

In the same way the water content was determined, but in that case the different samples were dried within an oven under air atmosphere during 24 hours at 105°C.

The different sand samples were also heated under air atmosphere at 900°C and 1000°C for agglomeration test in the programmable muffle furnace Model 650-58 (figure 6) with accuracy of 5°C to observe the impact of high temperature or thermal cycle on sand. So at least 50 g of each sample was heated with heating rate of 10°C /min and hold at 500°C, 700°C during 30mn and three hours at 900°C. At 1000°C the heating rate was 10°C/min from room temperature to 500°C, and 5°C/min from 500°C to 1000°C and hold during 30min at 500°Cand 700°C and 2 hours at 1000°C, with a cooling rate of 3°C/min. One cooled they were laid on a flat white surface and a photograph was taken.

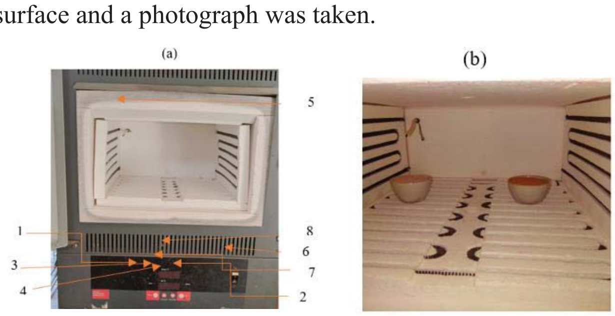

***Figure 6**: (a) Opened muffle Furnace, (b) opened muffle furnace with sample inside for heat treatment of the different sample. (1) Menu key use to fix the maximal temperature, the soak time and the heating and cooling rate; (2) Program run LED use to run the program; (3) Increase key: Use in this study to increase temperature, for calibration and increase the heating rate; (4) Decrease key: Use to decrease the temperature and cooling rate and for calibration; (5) Thermocouple give the temperature; (6) Power switch: Use to on and off the furnace; (7) Set temperature display; (8) Actual temperature display given by the thermocouple*

III. RESULTS

3.1. Particle size

Table 1 shows the calculated Sauter mean diameter (SMD) for each sample. The particles stopped between each pair of sieves and weighted have been recorded and plotted as showed in fgure7. The red and green plots represent respectively the profile of dune and mining sand accumulated weight in percentage.

***Table1**: The sauter mean diameter for the different sand sample*

Sample	Dune sand	Mining sand
Sauter mean diameter (SMD)	0.26	0.901

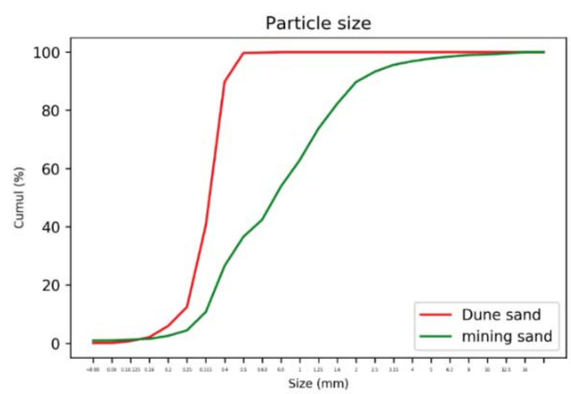

***Figure 7**: Recorded cumulated weight percentage of particles stopped between every given pair of sieves for samples 1 and 2.*

3.2. Density and porosity

The mechanical properties, densities and porosity measured values are presented in table 2. The bulk density of dune sand is lower than the bulk density of mining sand while it is not the case for particle density. The porosity of the dune sample is higher than the one of mining sand.

Table2: Density and porosity of the different sand samples

Sample	Dune sand	Mining sand
Bulk density ($kg.m^{-3}$)	1471	1551
Particle density ($kg.m^{-3}$)	2659	2655
Porosity	0.45	0.42

3.3. Loss of ignition and agglomeration issues

The table 3 presents the results of loss of ignition (LOI) and water content. The LOI of dune sand is higher than its water content while the both LOI and water content are the same for mining sand.

Table3: Results of LOI and water content

Sample	Dune	Mining sand
LOI (%)	0.52	0.55
Water content (%)	0.09	0.55

The figure8 present the results of heat treatment. A colour change is observed for each sample becoming redder for the two sample at 900°C and 1000°C

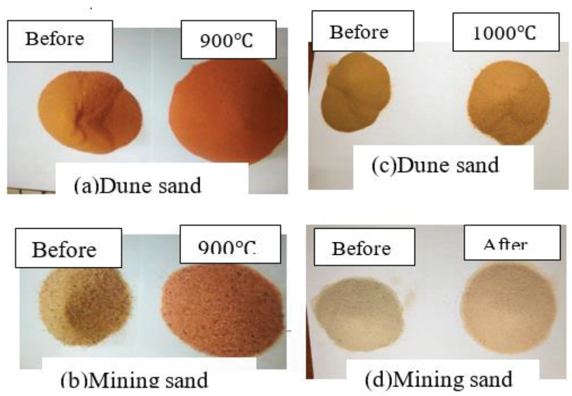

***Figure 8**: Result before and after heat treatment at 900°C of: a) dune sand, b) mining sand and at 1000°C of: c) dune sand, d) mining sand.*

IV. DISCUSSION

4.1. Particles size analysis

The figure 7 shows that more than 99% of Dune sand have a diameter less than 0.5mm and less than 2mm for the mining sand. This could explain by the sauter mean diameter which are 0.26mm and 0.9 mm respectively for the dune and mining sand. The small diameter of these sample could provide a good thermal stability or thermal resistance to a refractory material developed from them(Sawadogo et al., 2020). Also if the size of raw materials (sand in this study) is high it will increase the porosity of the formulated material (ceramic, refractory bricks, rocks etc.) driving to it mechanical performance losses (hardness, bulk density) (Tiskatine et al., 2016). Base on that, dune sand could be more suitable to formulate refractory materials for sensible heat storage.

4.2. Mechanical properties analysis

Thermal energy storing depend on the particle density of the storage material. The storage capacity is better when the storage material has a good density, but depends also on the specific heat capacity. In the literature dune(desert sand) sand has a mean heat capacity between 105°C and 1100°C is 926 $J.kg^{-1}K^{-1}$, 973 $J.kg^{-1}K^{-1}$ at 200°C and 1041 $J.kg^{-1}K^{-1}$ for river sand (Wang et al., 2003; Priya et al., 2016; Esence et al., 2018). It assumes that the two sample used in this study should have at least 926 $J.kg^{-1}K^{-1}$ as average heat capacity. So with a particle density of 2659 $kg.m^{-3}$ and 2655 kgm^{-3} respectively for dune sand and mining sand, their means storage capacities could be 2.46 $MJ.m^{-3}.k^{-1}$, which is higher than 2 $MJm^{-3}k^{-1}$ (the minimum storage capacity required for a thermal energy storage material (Fernandez et al., 2010)). Combining these particles together could allow to approve these different properties and to shape the storage material, increasing then the performance of the sensible heat storage in concentrated Solar Power plant.

4.3. Agglomeration test analysis

The agglomeration analysis provided us information on the purity state and the thermal stability of the sand. Sand agglomeration at high temperatures is a problem that may affect the operation of the system when using only sand in the storage medium (Diago et al., 2015). These conglomerates can block the flow of sand through the particle solar receiver when sand is using as HTF (Iniesta et al., 2015). For the two samples we did not observe any agglomeration at 900°C, showing that they different sand samples content less impurity like calcium carbonate ($CaCO_3$), calcium hydroxide ($Ca(HO)_2$), aluminum, magnesium, etc. which may be. responsible of sand grain assemblage during heat treatment (Diago et al., 2015; Iniesta et al., 2015; Wang et al., 2003). Just a color change has been observed due to the heating process. This result can be confirmed by the mass loss on ignition and water content of the different samples. Mining sand loss of ignition at 700°C is similar to its water content showing that it does not content organic elements. However, the dune sand presents a fire loss of 0.52% more than the water content (0.09%). Dune sand may content some volatile element explaining its low bulk density while its particle density is higher than the mining one.

V. CONCLUSION

To conclude, thermocline storage system can provide an effective cost of CSP, but remain immature. In the literature the solid particle of the solid storage material influences the storage performance through its size, shape and thermal properties. The analysis of two different sand samples properties from Burkina Faso to formulate such solid particles was conducted. The size and particle density analysis show that dune sand (desert sand) could be more suitable to develop an effective storage material. The loss of ignition at 700°C and agglomeration test at 900°C and 1000°C show that the samples have good thermal stability and do not contain enough impurity. In addition to that, with good density, these sands can provide a good storage capacity. So, with the smaller size, these sample sand could be used to shape thermocline storage filler material (solid particle) with a good storage density, which can improve the performance of DMT thermocline system.

In our next works, the sand and other raw materials like clay and ash will be used to develop ceramics ball with around 2cm diameter to store sensible heat for CSP applications after their thermal properties analysis.

The combination of CSP technologies and thermocline storage for different energy system reported by Muritala et. al., (2020) could be applied for electricity, chemicals, fuels and process heat production for various purposes in order to reduce dependence on fossil fuels and to enhance green economy.

ACKNOWLEDGEMENTS

This work is part of West African Science Services on Climate Change and Adapted Land use (WASCAL) program ongoing at Abdou Moumouni University of Niamey in the faculty of Science & Technology. This research is also supported by the "Laboratoire de Physqiue et de Chimie de l'Environnement (LPCE)".

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