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# Journal of Renewable Energy and Sustainable Development







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### Journal of Renewable Energy and Sustainable Development



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### Does Renewable Energy Still Need Subsidy

### Dr. Eng. Mohamed Mostafa El Khayat

Chairman of the New and Renewable Energy Authority, NREA Chair of Renewable Energy and Energy efficiency of Arab Experts Committee, League of Arab States, LAS

For many decades, it has been stated that renewable energy, RE, needs subsidy, otherwise it will not be able to compete or sustain. For a certain level, this statement was valid. In this period, the investment costs for both wind and photovoltaic, PV, were high. In other words, production costs of both of them reached around 7.0 and 13.0 Cent US\$ per kWh. On the other hand, oil and natural gas, NG, prices were low; i.e. less than US\$ 30.0 per oil barrel and around US\$ 4.0 per million British thermal unit, MMBTU, of NG. Also, policies of promoting RE were limited; almost there are two main policies, Feed-in-Tariff, FiT, in limited developed countries and international tenders. As a result, investment in RE was usually led by developed countries and minor share from the developing countries. This was the scene of RE before around 10 years.

Nowadays, the scene of RE totally differs. Starting from the policies side, through auctions in both solar and wind energies, new records of prices have been reached. In numbers, in the field of wind energy Morocco and Egypt already signed contracts with prices lower than 4.0 US\$ Cents/kWh. For PV, there is a dramatic devaluation in the prices. Now we are speaking for less than 0.7 million US\$ per MW for turnkey projects. As a result, during the last couple of years, the global RE market witnessed a bundle of an outstanding prices, El-Sewihan Project at Abu Dhabi, 2.42 US\$ Cent/kWh. Mexico and Dubai projects, 3.6 and 3.0 US\$ Cent/kWh. Few days ago, Dubai Electricity and Water Authority, DEWA, received \$9.45 cents per kilowatt-hour for its 200MW concentrated solar power (CSP) plant.

All these figures, and others, gave us important messages; 1) Despite low prices of oil and NG, RE is able to compete and offer outstanding prices, 2) Wind and PV technologies do not need any kind of subsidy, rather than they need a real free market to compete, 3) CSP is a low hanging fruit and it will witness a frog-leap during the coming couple of years, 4) Even CSP still high, compared with both PV and wind, but is a dispatchable energy. So, it is a game changer. 5) There is a need for more R&D efforts in storage technology. 6) The role of small-scale applications; i.e. biomass and PV, still need further development in the developing countries. 7) Most of the outstanding recent prices have been fulfilled by developing countries, which means that their role in promoting RE applications, grow year by year.

### About Mohammed Mostafa El-Khayat

Dr. Mohammed Mostafa El-Khayat, got his Ph.D. from Mansoura University Egypt, and the Business Diploma Certificate from Eslsca School of Business, Paris, France. He is the Chairman of the New and Renewable Energy Authority, NREA in Egypt. Also, he is the Chairperson of Renewable Energy and Energy Efficiency Committee, League of Arab State, LAS. He has over 25 years of experience in the fields of Renewable Energy, environment, and academic activities. He is responsible for the wind and solar energy projects. Also, he is responsible for the energy efficiency activities. Dr. El-Khayat shared in drafting Pan Arab Renewable Energy Strategy issued by League of Arab States. Also, he is participating in drafting renewable energy laws and regulations. El-Khayat received many awards from different countries and worked with different regional and international entities. Finally, he issued 5 books and writing a weekly article in Al Ahram Newspaper.



### Eliminating Heavy Metals from Water with Nano-Sheet Minerals as Adsorbents

### **Shaoxian Song**

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Heavy metals usually referred to those with atomic weights ranging from 63.5 to 200.6. Because of natural-mineral dissolution and human activities such as mining, pesticides, fertilizer, metal planting and batteries manufacture, etc., these heavy metals, including zinc, copper, mercury, lead, cadmium and chromium have been excessively released into water courses, like underground water, lake and river, etc. The ingestion of the heavy metals-contaminated water would raise serious health problems to human beings even at a low concentration. For instance, lead can bring human beings about barrier to the normal function of kidney, liver and reproductive system, while zinc can cause stomach cramps, skin irritations, vomiting and anemia. Mercury is a horrible neurotoxin that may result in damages to the central nervous system, dysfunction of pulmonary and kidney, chest and dyspnea. Chromium (VI) has been proved can cause many diseases ranging from general skin irritation to severe lung carcinoma. Accordingly, the World Health Organization announced the maximum contaminant levels (MCL) for the heavy metals in drinking water.

There are numerous processes for eliminating heavy metals from water in order to provide citizens safe drinking water, including precipitation, adsorption, ion exchange, membrane separation and biological treatment, etc. Adsorption is considered as a potential process for deeply removing heavy metals, in which the selection of adsorbents plays a predominant role.

Nano-sheet minerals as the adsorbents are currently the hottest researches in the field. They are obtained from layered minerals, such as montmorillonite, graphite and molybdenite, through the processing of intercalation, electrochemical and mechanical exfoliation, etc. Nano-sheet minerals are featured by their large specific surface area, relatively low costs and active adsorbing sites, leading to be effective and potential adsorbents for heavy metals removal from water.

Montmorillonite was usually pre-interacted with organics to increase the interlayer space, and then exfoliated to single or several layers by using ultrasonic. Among the nano-sheets, the surfaces are strongly charged negatively, while the edges are positively charged. This characteristic allows the adsorption of cations or anions, as well as the substances with negative or positive charges.

Graphite can be oxidized and exfoliated into graphene oxide (GO), which has a huge specific surface area and plentiful of functional groups such as carboxyl, epoxy, carbonyl and hydroxyl, leading to high adsorption capacity to heavy metals in water.

Nano-sheet molybdenite is a novel two-dimensional material with single or several layers of MoS<sub>2</sub> sheets. The most common method to prepare nano-sheet molybdenite is exfoliated from bulk molybdenite through chemical method based on ion intercalation process. A large quantity of functional groups and S atom on the sheets are the active sites for adsorbing heavy metals in water.

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Nano-sheet minerals are used as adsorbents in the form of three-dimension hydrogels. They are featured by the huge specific surface area and high adsorption efficiency. In addition, the clean and smooth surfaces allow heavy metals to adsorb directly by film dispersion. Without any barrier of mesopores and micropores, the adsorption rate could be well improved. These characteristics would lead to the extremely large adsorption capacity and high adsorption rate. Currently, nano-sheet minerals as adsorbent is a very hot research topic in the field of heavy metal removal. It is expected that nano-sheet minerals will be promising adsorbents in the removal of heavy metals from water.

### **About Shaoxian Song**

Dr. Song has been a professor in the Universidad Autonoma de San Luis Potosi, Mexico, since July of 1996, and is a national researcher level 3 and the member of the Mexican Academy of Science. Concurrently, he is a chair professor of the school of resources and environmental engineering, Wuhan University of Technology, China. He received his Ph. D. in Mineral Engineering in the Central-South University, China in 1991. His main fields of interests include water treatment, mineral processing and colloidal stability. He is the author or co-author of over 280 journal articles (in which over 200 articles have been indexed by SCI), 3 books, 8 book chapters and over 50 proceedings articles.

# Synthesis, Characterization and Performance of Cu<sub>2</sub>SnSe<sub>3</sub> for Solar Cell Application

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Abstract - Cu<sub>2</sub>SnSe<sub>3</sub> (CTSe) powders were prepared by solvothermal (SR) and solid state reactions (SSR) using low cost starting materials. The crystal structure, morphology, UV-Vis absorbance, electrochemical and solar energy properties were investigated using X-ray Diffraction (XRD), Field Emission Scanning Electron Microscopy (FESEM), Electrochemical Impedance Spectroscopy (EIS) and solar energy applications using I-V characteristics measurements. Also, the toxicity of elements like cadmium makes these materials less applicable. A single cubic Cu<sub>2</sub>SnSe<sub>3</sub> was obtained for the two methods of preparations. The calculated crystallite size (L) values for CTSe prepared by SR and SSR are 24.1 and 30.3 nm, respectively. UV-Vis. spectra for SR and SSR preparations showed maximum absorbencies at 240 nm with band gap (Eg) values of 0.9 and 1.4 eV, respectively. The charge transfer resistances (Rct) were equal to 3.5 and 24  $\Omega$  for photoelectrochemical cells (PEC) and the calculated conductivities were equal to 3x10<sup>-2</sup> and 2x10<sup>-2</sup> S.cm<sup>-1</sup> for samples that prepared by SR and SSR methods, respectively. A good photoelectrochemical cell (PCE) has accomplished power conversion efficiency per unit area of about 0.84 and 0.64 % for cells prepared by SR and SSR, respectively.

*Keywords* - CTSe; Solvothermal; Solid State Reaction; Optical properties; Photoelcetrochemical cell (PEC).

### I. INTRODUCTION

Solar cell energy applications have become widely important in the last few decades. This is because of the energy crisis and pollution caused by the traditional energy sources like fossil fuels. So, it is important to develop newer low cost light absorber materials for thin film solar cell energy applications. Recently, relatively high efficient materials were discovered and investigated, for example copper indium gallium diselenide (CIGS) and CdTe [1]-[3]. Such materials encounter the problems of being expensive and unavailable, especially indium, tellurium and gallium. Also, the toxicity of elements like cadmium makes these materials less applicable.

Copper-containing calcogenides, especially compounds of groups (I–IV–VI) have been reported to have wide applications in photovoltaic thin film solar cell devices, light emitting diodes, non linear optical materials [4]. These materials have a suitable band gap range: 0.96-1.35 eV. Meanwhile, they have a relatively high absorption coefficient  $\geq 10^4$  cm<sup>-1</sup> [5],[6]. These advantages make them a promising candidate for thin film solar cell absorbing materials. Copper tin selenide compounds were prepared mainly in the 2:1:3 elemental ratio i.e Cu2SnSe3[7]-[8] and 2:1:4 ratioi.eCu<sub>2</sub>SnSe<sub>4</sub> [9].

Recently, Cu<sub>2</sub>SnSe<sub>3</sub> (CTSe) have gained a great attention in many applications, especially the field of thin film solar cell application. CTSe material is suitable for solar cell energy application because it is environmentally friendly, cheap in preparation, nontoxic, inexpensive and earth-abundant. CTSe was prepared with different methods such as Vertical Bridgman-Stockbarger technique [10],[11], Direct current sputtering technique [12]-[14], Coevaporation process[15]-[17], Colloidal synthetic process[18]-[19], and Solvothermal process[7],[9],[20]. It was prepared with different crystal structures, e.g Cubic[7],[9],[15],[17]-[20] and Monoclinic [10],[11]. The crystallite size range is 12-30 nm [7],[18]. The band gap values range is (0.84-2.1 eV) [7],[12],[15]. All these previous parameters affect the efficiency of a definite prepared phase.

This work was done to study the preparation of Cu<sub>2</sub>SnSe<sub>3</sub> (CTSe) using solvothermal reaction (SR) in comparison with the traditional solid-state reaction (SSR). Furthermore, there are only a are not enough data available about the electrochemical and photovoltaic properties of CTSe such as impedance, resistivity and conductivity, and solar power conversion efficiency so that this work was conducted

to study these properties. In addition to that, a photoelectrochemical cell will be fabricated for the current-voltage measurements.

### **II. EXPERIMENTAL**

# 1. Synthesis of Cu2SnSe3 by Solvothermal (SR) and Solid-State (SSR) Reactions

Cu<sub>2</sub>SnSe<sub>3</sub> was prepared by solvothermal reaction as follows:- a mixture of 3.03 gm Cu(NO<sub>3</sub>)<sub>2</sub> .<sub>3</sub>H<sub>2</sub>O, 2.1 gm of SeO<sub>2</sub>,1.2 gm of SnCl2 was added to 250 ml autoclave then about 200 ml ethylenediamine (ED) was added to the mixture then put in the oven at about 205 °C for about 24 hours (overnight). A black precipitate was obtained which was filtered and washed with distilled water and ethanol three times then put in the dryer at about 60 °C for about 4 hours; a black Cu<sub>2</sub>SnSe<sub>3</sub> powder was obtained and kept for characterization and further investigation

The role of ethylene diamine (en) in the preparation of Cu2SnSe3 by SR can be illustrated by the following equations:



Cu<sub>2</sub>SnSe<sub>3</sub> was also synthesized by solid-state process using stoichiometric ratios of Cu, Sn and Se powders that were mixed and ground well in a mortar. Then, the mixture was put in a boat crucible in a tube furnace at 600 °C for three hours under argon with 5 % H2 atmosphere. It was cooled to the room temperature under the argon atmosphere. A black powder was obtained, which was ground and kept for further investigations.

### 2. Samples Characterization

Samples compositions were identified by an X-ray diffractometer (XRD), model: Brukur advanced D8 Kristalloflex (Ni-filtered Cu K<sub> $\alpha$ </sub> radiation; 1.5406 Å). The microstructure was examined by backscattered electron (BSE) in the field emission scanning electron microscopy (FESEM QUANTAFEG 250). The optical measurements were performed using UV–Vis–NIR

scanning spectrophotometer (PerkinElmer Lambda 1050 Spectrophotometer, USA) using 1 cm path length quartz cell. EIS measurements were done using Potentiostat (Parastat 4000 Princeton, USA).

The impedance measurements amplitude was 20 mV and the frequency range was 1MHz-10 mHz.

### 3. PhotoElectrochemical Cell Fabrication and Measurements

The prepared samples were coated on indium tin oxide (ITO) conducting glass as working electrode the resistivity of the ITO is 30  $\Omega/cm^2$ . The cell configuration was: ITO/Cu2SnSe3/0.5 M KI + 0.5 M I<sub>2</sub>/C. It was fabricated and characterized through current-voltage (I-V) measurements [21].Xenon arc lamp 150 W was used as a light source with solar simulator SciencetechSS150W- AAA. The cell was exposed to light intensity 1 Sun (100 mW cm-2) using Air Mass 1.5 Global Filter. I-V tester is 2400 Keithley Source Meter SSIVT-60WC. The calibrated reference cell consists of a 20 x 20 mm monocrystalline silicon (model SC-LT) photovoltaic cell encased in a 92 x 70 x 16 mm metal enclosure with a protective quartz window. The reference detector (SSIVT-refl) is effective in sensing wavelengths between 190 nm and 1100 nm and is calibrated with the 1 Sun. Parameters measured by I-V Software wereopen circuit voltage (Voc), short circuit current (Isc), maximum power (P<sub>max</sub>), and filling factor (FF).

### **III. RESULTS AND DISCUSSION**

### 1. Cu<sub>2</sub>SnSe<sub>3</sub> Samples Characterization

The Cu<sub>2</sub>SnSe<sub>3</sub> compound prepared by SR and SSM is characterized by XRD as shown in Fig. 1. The pattern of the XRD shows main three peaks at  $2\theta$  equal to  $27^{\circ}$ ,  $45^{\circ}$ , and  $53^{\circ}$ . The crystal structure of this compound is cubic phase for both samples prepared by SR and SSR methods with miller indices of (111), (220) and (311) planes. The obtained results are in agreement with JCPDS data (01-089-2879) [7],[9],[15],[17]. Furthermore, the crystallite size was calculated from Scherer equation:

$$L = \frac{0.94}{\beta \cos}$$
(1)

Where; (L) is the crystallite size (nm), ( $\lambda$ ) is wave length of the target (1.5406 Å for Cu), ( $\beta$ ) is full

width half maximum (FWHM) in radians, and ( $\theta$ ) is the chosen diffraction angle [22]. The calculated crystallite size values for CTSe prepared by SR and SSR are 24.1 and 30.3 nm, respectively



Fig .1. XRD pattern of Cu2SnSe3 prepared by (a) SR and (b) SSR

The morphology of the prepared samples is characterized by SEM inspection as shown in Fig. 2.The sample prepared by SR has homogenous spherical particles with a particle size of about 40 nm. On the other hand, the sample prepared by SSR shows agglomerate bulked shape. The particle size of the sample prepared by SSR is about 100 nm.





Fig .2. SEM photo for (a) CTSe prepared by SR (b) CTSe prepared by SSR

### 2. Optical Measurements

UV-Vis. absorbance measurements are used to reveal the energy structure and optical properties of the as-prepared Cu<sub>2</sub>SnSe<sub>3</sub> architecture as shown in Fig. 3. Cu<sub>2</sub>SnSe<sub>3</sub> crystal gives maximum absorbance wavelength of 240 nm that is somewhat near the visible region for both samples prepared with SR and SSR. The absorbance characteristics of the samples obey the model equation  $\alpha hv = A (hv-Eg)^{0.5}$  for the direct transition, where  $(\alpha)$  is the optical absorption coefficient, (h) is Planck's constant, (v) is the photon frequency, (A) is a constant, and  $(E_g)$  is the energy gap [23].The energy band gap of Cu2SnSe3 is obtained from the plot of  $(\alpha hv)^2$  vs. hv (photon energy) by extrapolation as shownalso in Fig. 3. The energy gab of SR sample equals 0.9 eV that is smaller than the SSR one, 1.4 eV and this is attributed to the small particle and crystallite sizes of the CTSe prepared by SR. Also, the obtained value agrees with the previously reported values [7], [24]. It has been reported that CTSe thin films have a wide range of band gap energies, 0.7-1.38 eV [25], [26].



Fig .3. UV-Vis. Absorbance and band gap diagrams for CTSe prepared by (a) SR and (b) SSR ATSe

### 3. Electrochemical Impedance Spectroscopy (EIS) Measurements

EIS is applied for pellets of dimensions: radius (r) 0.675 cm and thickness (t) 0.35 cm of the prepared CTSe powder to measure the resistance of the material itself. Nyquist plot for CTSe pellets prepared by SSR and SR is shown in Fig. 4. The conductivities of CTSe powders materials prepared by SR and SSR are  $3x10^{-2}$  and  $2x10^{-2}$  S.cm<sup>-1</sup>, respectively.



Fig .4. Nyquist plot for CTSe pellets prepared by (a) SR and (b) SSR

The EIS is also applied for photoelectrochemical cell (PEC) containing the sample plated on ITO glass as

working electrode against glassy carbon counter electrode in electrolyte of iodine in potassium iodide. Cell configuration is: ITO/CTSe/ 0.5 M KI + 0.5 M I2 /C. The double layer capacitance (CdI) is calculated using equations:

$$C_{dl} = 1/\omega R_{ct}$$
 (2)

$$\omega = 2\pi f \tag{3}$$

Where; ( $C_{dl}$ ) is the double layer capacitance (Farad), ( $\omega$ ) is the radial frequency (radians/second), (f) is the frequency (hertz) and ( $R_{ct}$ ) is the charge transfer resistance ( $\Omega$ ).

Nyquist plots for CTSe photo electrochemical cell (PEC) are shown in Fig. 5. For the CTSe sample prepared by SR two semicircles are presented with two values of charge transfer resistances R<sub>ct</sub> and two values of double layer capacitance (C<sub>dl</sub>). The charge transfer resistances ( $R_{ct}$ ) are equal to 32.2 and 6  $\Omega$  for the sample prepared by SR. and While, Rct of CTSe prepared by SSR is 40.1  $\Omega$ . The two semicircles can be attributed to the bulk and grain boundary resistances of CTSe [27],[28]. Double layer capacitances (Cdl) for photo electrochemical cells (PEC) and for the sample prepared by SR are equal to 7.8x10-9 and 6.67x10-5 F and for the sample prepared by SSR C<sub>dl</sub> is equal to 2.51x10<sup>-8</sup>F. EIS results show higher conductivity of CTSe prepared by SR than that prepared by SSR with higher double layer capacitances (Cdl) for photo electrochemical cells (PEC) because electron transfer through double layer interface for cell prepared by SR is higher than that prepared by SSR which may be attributed to the fine structure of the samples obtained from SR as explained previously[29].



Fig .5. Nyquist plot for CTSe Photo Electrochemical Cell (PEC) prepared by (a) SR and (b) SSR

### 4. PhotovoltaicProperties

To obtain the power output characteristics of the photo electrochemical cell (PEC),  $V_{oc}$  and  $I_{sc}$  are recorded for the prepared CTS samples. The semiconductor | liquid junction proposed operating mechanism is illustrated in Fig. 6 diagram.



Fig .6. Representation of photoelectrochemical cell proposed operating mechanism

Table 1. I-V characteristics results of  $\mathsf{Cu}_2\mathsf{SnSe}_3$  which was prepared with the two methods

| Preparation<br>Method         | Voc (V) | lsc<br>(mA.cm-2) | FF % | η%   |
|-------------------------------|---------|------------------|------|------|
| Solvothermal<br>Reaction (SR) | 0.47    | 7.2              | 25   | 0.85 |
| Solid State<br>Reaction (SSR) | 0.42    | 4.6              | 24   | 0.64 |

I–V curves are shown in Fig. 7. The power conversion efficiency ( $\eta$  %) and fill factor (FF %) are given by the following equations:

$$FF = \underbrace{V_{max} I_{max}}_{V_{oc} I_{sc}} 100 \qquad (4)$$

$$\eta = \underbrace{FF V_{oc} I_{sc}}_{I_{sc}} 100 \qquad (5)$$

Where: Voc: open circuit potential for working electrode,

 $I_{sc}$ : short circuit current measured at zero voltage,  $V_{max}$ , and  $I_{max}$  are the optimum maximum voltage and current, respectively of the I-V characteristic relation, A: area of the working electrode, 1 cm<sup>2</sup> and P<sub>in</sub> is the incident intensity of the light (1Sun = 100 mW cm<sup>-2</sup>). Photovoltaic I-V characteristics results are summarized in Table I. This study is considered one of the priority researches reported about the solar efficiency for Cu<sub>2</sub>SnSe<sub>3</sub>[30].



Fig .7. I-V characteristics curve for CTS prepared by (a) SR (b) SSR under 1 sun and AM 1.5

### **IV.CONCLUSIONS**

Cu<sub>2</sub>SnSe<sub>3</sub>(CTSe) compound has been prepared with two different ways, Solvothermal (SR) and solid state reactions (SSR). Single cubic Cu<sub>2</sub>SnSe<sub>3</sub> phase was obtained. CTSe sample papered with SR present better morphological, optical, electrochemical and photoelectrochemical measurements in comparison with the sample prepared with SSR. The crystallite size (L), Eg,Rct, conductivities and power conversion efficiency per unit area values for CTSe prepared by SR and SSR are 24.1 & 30.3 nm, 0.9 & 1.4 eV, 3x10<sup>-2</sup> & 2x10<sup>-2</sup> S.cm<sup>-1</sup> and 0.84 & 0.64 %, respectively. This demonstrates the advantage of the SR method for the preparation of such compounds over the SSR method. The results also show the ability for the development of such compound for the application in solar cell fabrication.

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### Potential of Solar-driven CDI Technology for Water Desalination in Egypt

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Abstract - Freshwater scarcity is one of the most challenging problems facing the world today. Rivers, lakes, and surface ice represent only 1.2% of the fresh water sources on earth, while ground water represents over 30% of the potential fresh water. The Egyptian quota from the River Nile is limited to 55 billion m<sup>3</sup>/yr, and expected to decrease due to increasing demand of water by other Nile basin countries. According to an Egyptian government report, the total population of Egypt increased from 22 million in 1950 to around 85 million in 2010. This increase in population will continue for decades and it is likely to increase to between 120-150 million by 2050. Egypt has reached a state where the quantity of water available is imposing limits on its national economic development. As indication of water scarcity, Egypt passed the international threshold value of 1000 m3/capita/year in the nineties, and it is expected to cross the threshold of absolute water scarcity of 500 m3/capita/yr by 2025. Capacitive deionization (CDI) is a relatively new technology that was developed as recently as the late 1960s. In CDI systems, saline water is made to pass between a pair of electrodes connected to a voltage source. lons are stored inside the pores of electrodes in CDI via the applied electric field strength. CDI is a membrane less technology and the problems of membrane fouling in the Reverse Osmosis technology are not present in CDI. It has the potential to be energy efficient compared with other related techniques and robust technology for water desalination. This paper explores low cost and efficient desalination technologies for brackish water for irrigation and drinking purposes using the abundant solar energy in Egypt.

*Keywords* - solar photovoltaic; capacitive deionization; water desalination.

### I. INTRODUCTION

Around 75 % of the Earth's surface is covered by water, out of which 97.5 % (for sake of consistency) is in the form of oceans. The remaining percentage is

attributed to ice mass, ground water, rivers and lakes [1]. Rivers, lakes, and surface ice represent only 1.2% of the Fresh water, while ground water represents over 30% of the potential fresh water. Over 1.5 billion people lack ready access to drinking water and approximately 2.3 billion people suffer from water shortages around the globe [2]. As a result of population growth and the increasing quality of the people lifestyle, it is expected that over two-thirds of the population will be facing fresh water shortage in the near future [3]. Due to the limited Egyptian quota from the River Nile and the continuous increase in population, Egypt has reached a state where the quantity of water available is imposing limits on its national economic development [4].

As such, there is a growing need in Egypt and other MENA countries to explore desalination technologies to meet their growing need for fresh water. Currently, the MENA region accounts for 53.4 of the world production of desalinated water. The World Bank published a study in 2012 [5] that recommended renewable energy desalination as a potential solution to close the water gap in the Middle East and North Africa.

Several water desalination technologies are currently used based on utilization of thermal energy, mechanical energy and electrical energy [6]. The most widely used processes for desalination include membrane separation systems: reverse osmosis electro-dialysis (ED); and thermal (RO) and separations including: multistage flash distillation (MSF), multi-effect distillation (MED) and mechanical vapor compression (MVC). Among these processes, RO and MSF methods are employed in the bulk of the plants (90%) to desalinate seawater worldwide. In ED, while being a membrane process, the driving force is a potential applied between two electrodes; the same driving force as the Capacitive Deionization (CDI) process. Among membrane-based plants, 86% belong to RO plants while electro-dialysis represents only 14%.

The CDI [7] has attracted interest in the recent years mostly because of its low energy consumption. The objective of this paper is to explore low cost and efficient desalination technologies for brackish water for irrigation and drinking purposes using the abundant solar energy in Egypt. The development of low cost desalination technology for brackish water would be of great interest not only for Egypt, but for many countries in the Middle East and North Africa as well as many other arid and semi-arid areas in the world.

The rest of this paper is organized as follows: an introduction to the capacitive de-ionization technique is introduced in Section II. Next, in Section III, a CDI model for evaluation of a solar driven CDI cell is proposed. A directly driven PV/CDI system is discussed in Section IV.

### II. DESALINATION USING CAPACITIVE DE-IONIZATION

In CDI systems, saline water is made to pass between a pair of porous electrodes connected to a voltage source. The phenomenon of desalination using CDI is as illustrated in Figure 1. A CDI is a twostep process; the first step is ion adsorption or charging that results in a pure permeate stream where ions are adsorbed in porous charged electrodes. As the voltage is applied to the electrodes, due to the presence of electrostatic field in between the electrodes, there is movement of ions such that the positive ions, or cations, move to the cathode and anions to the anode. Two layers of opposite polarity are formed at the electrode-solution interface, which is referred to as electrical double layer (EDL), and ions are stored in these EDL's. In the next step, voltage is reversed so that the ions get desorbed and flow out of the CDI cell as a brine stream and thus cause regeneration of electrodes. CDI differs from Electrodialysis in the sense that it does not use membranes. The problems of membrane fouling are not present in CDI. It has the potential to be energy efficient, robust technology for water desalination.



Fig .1. Schematic design of a cell for Capacitive Deionization [7].

The early work in the CDI technology was reported by Farmer et al. in 1995. They showed experimental results of apparatus, which was developed at Lawrence Livermore National Laboratories [8-10], in which they use carbon aerogel as porous electrode material. Since then the process came to be known as Capacitive De-ionization. The recent advances in nanotechnology and carbon nanostructures have recently fueled the interest in Capacitive Deionization process. The basis of the process is a phenomenon called Electrostatic Double Layer (EDL). EDL forms inside the carbon electrodes micropores. The ions are immobilized as they are adsorbed into the electrostatic double layers. These electrical double layers become charged and discharged as the cell voltage is varied and stores and releases the charge. After the micropores get saturated with adsorbed ions, the cell voltage can be reduced to zero or reversed to release the ions from the electrode pores and thus the electrodes are regenerated. A stack of electrode pairs can be used to improve the efficiency of the process. The cell in this case consists of titanium current collector plates, with carbon aerogel or activated carbon glued on both sides by suitable conducting material. The CDI process removes ions from water rather than removing water from the salt and thus requires less energy for desalination. Table I compares the energy required in kWh/m<sup>3</sup> for various desalination technologies. The table clearly shows that CDI has the least energy demand among the existing desalination technologies.

Table 1. ENERGY DEMANDS OF DIFFERENT DESALINATION TECHNOLOGIES [13]

| Desalination method | Energy demand in kWh/m <sup>3</sup> |
|---------------------|-------------------------------------|
| MSF                 | 10-58                               |
| MED                 | 6-58                                |
| RO                  | 2-6                                 |
| ED                  | 0.4-8.7                             |
| CDI                 | 0.1-2.03                            |

Several authors addressed the comparison between CDI technology and RO desalination technology [7, 13, 15]. A comparison summary is shown in Table II. RO requires extensive pre-filtering because the membranes are susceptible for fouling, and requires anti-sealant chemical additives. RO is also very sensitive to disinfectant and cannot tolerate chlorine concentration more than 0.1ppm. Membranes require frequent acid cleaning, which causes serious environmental impacts. On the other hand, CDI does not require special filtering, is immune against fouling, and does not require chemical additives. CDI can work efficiently at high environmental temperatures, while RO efficiency deteriorates rapidly with higher environmental temperature. The CDI process generally has relatively low energy consumption, which ranged from less than 0.6 -1.2 kWh m<sup>-3</sup> for total dissolved solids (TDS) removal from brackish water [7, 15]. The CDI process has about three times lower production cost as compared with a lowpressure RO desalination facility [15]. The initial investment of CDI is comparable with RO for the same capacity. However, the operational cost and maintenance cost of CDI is much lower than RO due to the frequent replacement of the RO membranes and maintenance cost of the high pressure pumps. CDI is also space efficient. For example, a CDI unit for brackish water from Voltea [16] produces about 168 m3/day, while its size is 1.1 x 1.5 x 2.4 = 3.96 m<sup>3</sup>. The specific production capacity per m3 of space is about 42.2 m3/day. On the other hand, a commercial RO for brackish water [17] produces 758 m3/day, and has a size of about 33 m3. The specific production capacity is about 23 m3/day. This shows clearly that CDI is space efficient. In the commercial scale, RO systems usually require pre-treatment of inlet water by additive chemicals to reduce the deteriorating effect of fouling on the membranes, which raises health and environmental concerns. On the other hand, CDI is a green technology with minimal impact on the environment.

Table 2. DETAILED COMPARISON BETWEEN CDI AND RO TECHNOLOGIES [14]

| Desalination Technology  | CDI    | RO     |
|--------------------------|--------|--------|
| Pre treatment            | Low    | High   |
| High temp system*        | Yes    | No     |
| Scaling and fouling      | Low    | High   |
| Dynamic TDS adjustment   | Yes    | No     |
| Problematic ions in feed | No     | Yes    |
| Chlorine tolerance       | Yes    | No     |
| Chemicals                | No**   | Yes    |
| Consumables              | Low    | High   |
| Maintenance              | Low    | High   |
| Energy use               | Low    | High   |
| Operational pressure     | Low    | High   |
| Water recovery           | 75-90% | 20-75% |
| Operation costs          | \$     | \$\$\$ |
| Price                    | \$\$   | \$\$   |

\* Above 45°C/110°F.

\*\* Acid injection may be required in some applications

### III. MODELLING OF CAPACITIVE DE-IONIZATION CELL

A schematic of a CDI cell as shown in Figure 2. A CDI cell is basically a conduit of rectangular cross section of width We, length Le and height de. CDI cell consists of electrodes (activated carbon) of thickness d<sub>c</sub>, and each electrode of a CDI cell is attached to a current collector. The activated carbon electrode layer is merged and fully in contact with the salty water. The top current collector is connected to a dc voltage signal of +u1 and bottom current collector to a dc voltage signal of -u1 during purification that causes the anions to move towards anode and cations to move towards cathode. During regeneration, the CDI cell is powered off with zero voltage or a voltage of opposite polarity is applied to the current collectors. The purification and the regeneration steps complete the CDI cycle. The water flows at a flow rate of qin to the CDI cell and the flow rate at the exit qo can be controlled using a valve.



Fig .2. CDI cell operation during purification – anions gets adsorbed on the anode and cations to the cathode.

An electric circuit model of a CDI cell with two electrodes is sh-own in Figure 3.



Fig .3. (a) Electric Circuit model of a CDI, (b) Equivalent electric circuit of a CDI cell.

The top activated carbon electrode capacitance is represented by capacitor  $C_1$  and bottom electrode capacity is represented by capacitor  $C_2$ , which is negatively charged. The capacitance associated with both electrodes is equal to maintain charge balance in solution i.e.  $C_1 = C_2$ .  $R_w$  is the electrical resistance of the water between the two opposite electrodes and i is the current flowing in the CDI cell through  $R_w$  resistance. The resistance of water is given by the formula.

$$R_w = \frac{\rho_e d_e}{A_c} \tag{3.1}$$

where  $A_c$  is the physical area of the activated carbon in  $m^2$ ,  $d_e$  is the distance between the activated carbon electrodes, and  $\rho_e$  is the resistivity of the water.

The resistivity of water depends on temperature and concentration, and for saline water is given approximately by [11]

$$\rho_e \simeq \frac{5}{x(1 + \alpha_T(T - 25))}$$
(3.2)

where x is the concentration of salt in kg/m³ (or grams/I) and  $\alpha_T=0.022/^\circ\mathrm{C}$ 

Let  $A_c = L_e W_e$  be the physical Area of the capacitor. The effective area of the capacitance associated with each electrode is given by

$$A_e = (A_c d_c \rho_{ac}) S_{ac} \tag{3.3}$$

where  $S_{ac}$  is the specific surface area of the activated carbon, which is typically around 800-2500 m<sup>2</sup>/gram, and  $\rho_c$  is the density of activated carbon.

The effective capacitance associated with each electrode is given by

$$C_e = \frac{A_e \varepsilon_0 \varepsilon_r}{t_{cs}} \tag{3.4}$$

where  $t_{cs}$  is the thickness of the double layer which is of the order of nanometers. The electrical double layer thickness is often approximated as Debye length using Gouy Chapman model [12]. Debye length is given by  $\lambda_D$  as

$$\lambda_D = \sqrt{\frac{\varepsilon_r \varepsilon_0 RT}{2F^2 x}} \tag{3.5}$$

Where  $\varepsilon_0$  is the permittivity of free space,  $\varepsilon_r$  the relative permittivity of water (78), *R* is the universal gas constant (8.3144621 *J*  $K^{-1}moles^{-1}$ ), *F* is the Faradays constant (96500 coulombs), *x* is the concentration of salt in bulk solution (macropores), and *T* is the temperature in Kelvin (297.15 *K*).

As such during charging and discharging, the CDI cell can be modelled as a super capacitor in a simple RC circuit as shown in Figure 3(b). From the symmetry of the circuit, the equivalent capacitor is basically  $C_e = C_1 = C_2$ , while the applied voltage is U<sub>1</sub>. The applied voltage is limited to a maximum of 1.5 volts to avoid electrolysis of water into hydrogen and oxygen.

### IV. PV DRIVEN CDI CELL

The researchers will consider here a small CDI system directly driven by a typical low cost PV panel, as in Figure 4. The operation of the system consists of five steps as shown in Table III. At the start of the

day, Valve v1 is turned on to allow the raw brackish water to fill the cell, while Valves v2 and v3 are off. When the cell becomes full, Valve v1 is turned off and the excitation voltages E1 and E2 are turned on taking the required power from the PV cells through appropriate electronics. At the sun set, Valve v2 is turned on, and the fresh water is taken from the cell to a fresh water tank. After draining the fresh water, Valve v2 is turned off, and the excitation voltage is connected to zero voltage, while Valve v1 is turned on until the cell is full again. The captured ions now return to the water to form high concentration brine. After sufficient time to ensure all the captured ions have left the activated carbon, the highly salty water is drained through Valve v3. The cycle is then repeated next day.



Fig .4. Block diagram of a directly driven CDI by PV solar panels.

In the above steps, the water recovery ratio is basically 50%. In many situations, the brackish water could be brought from deep wells at high cost. As such, higher recovery ratio is desired. Water recovery ratio can be improved by recycling the brine during the regeneration stage. For example, if the brine is recycled three times, the water recovery ratio would be 75%.

The following analysis is based on a small unit driven by a single commercial PV panel. The most common PV panels are approximately (1m x 1.5m) with about 16% efficiency, producing about 240 Watts at 1000 watts/m<sup>2</sup> solar insolation. With typical solar radiation in Egypt of 5 kWh/day per m<sup>2</sup>, the expected daily energy from this panel is ES = (1) (1.5) (5.0) (0.16) = 1.2 kWh/day.

| Table 3. | OPERATION | STEPS O | F SYSTEM |
|----------|-----------|---------|----------|
|          |           |         |          |

| Step | V1  | V2  | V3  | E1  | E2  |
|------|-----|-----|-----|-----|-----|
| 1    | On  | off | off | 0   | 0   |
| 2    | Off | off | off | +U1 | -U1 |
| 3    | Off | on  | off | +U1 | -U1 |
| 4    | On  | off | off | 0   | 0   |
| 5    | Off | off | on  | 0   | 0   |

The researchers assume that about 30% losses will occur due to wire and water resistive losses, as such the net energy stored in the capacitance  $E_{sn} = 0.84$  kWh. The energy stored in the capacitance is given as

$$E_S = \frac{1}{2} C_e U_1^2 \tag{3.6}$$

Since the maximum voltage is limited to  $V_{max} = 1.5$  Volts, the required capacitance to store the available solar energy is given by

$$C_e = \frac{2E_S}{V_{\text{max}}^2} = \frac{2(0.84)(3600000)}{(1.5)^2} = 2,688,000$$
 Farad (3.7)

The captured charge, Q, by the capacitor

$$Q = C_e V = 4032000$$
 Coulombs (3.8)

They further assume that the cell is used to produce fresh water (permeate) for drinking purpose with total dissolved solids (TDS) of  $X_p = 350$  ppm from brackish water with TDS of  $X_f = 4000$  ppm.

The amount of salt (in kg) to be removed is given by

$$M_{s} = V_{p}(X_{f} - X_{p})$$
(3.9)

where  $V_p$  is the volume of fresh water (permeate).

The mass of the removed salt is related to the ionic charge in the CDI capacitance by the relation.

$$Q = \frac{M_s}{M_{Ws}}F$$
(3.10)

where F is Faraday constant and  $M_{Ws}$  is the molecular mass of salt. Assume for simplicity the salt is NaCl, with MWs = 58.44 grm/mole.

Combining equations (3.7), (3.8), and (3.9), it becomes clear that the produced volume ( $V_p$ ) of fresh water per day can be calculated as

$$V_{p} = (\frac{Q}{F})(\frac{M_{Ws}}{X_{f} - X_{p}})$$
(3.11)

Then, the volume of fresh water  $V_{\text{p}}$  = 699.1 Liters/day.

In the next analysis, the researchers calculate the physical size of the matching CDI cell. Assume activated carbon with specific area of  $S_{ac}$  =1500 m<sup>2</sup>/grm, and density of 0.4 grm/cm<sup>3</sup> is used in the CDI cells as an electrode layer of thickness  $t_{ac}$  = 2 mm.

From (3.3) and (3.4), the physical area of the capacitor is given by

$$A_{c} = \frac{1}{d_{c}\rho_{ac}S_{ac}}\frac{C_{e}t_{cs}}{\varepsilon_{0}\varepsilon_{r}}$$
(3.12)

Then the mass of the activated carbon is given by

$$M_{AC} = A_c d_c \rho_{ac} \tag{3.13}$$

Using the value of  $C_e$  in (3.7), the required physical area  $A_c$  came to about 101 m<sup>2</sup>, and mass of activated carbon came to about 80 Kg for the entire unit. The design of the cell suggested an array of 50 (1m x 2m) cells stacked in a tank of about (1x1x2 meters). This modular system can be repeated to meet the required fresh water production rate.

The efficiency of the system can be improved by reducing the electric losses in the wires and water. The resistance of water can be reduced by having tighter spacing between anodes and cathodes. The wire losses can be reduced by using thick conducting buses. The majority of the stored energy in capacitors can also be recovered during the regeneration cycle by discharging the capacitors using appropriate electronic DC/DC converter which feeds batteries, another secondary CDI stage, or, in large scale projects, return the energy to the power grid.

### V. CONCLUSION

A directly driven solar powered CDI system was studied. It is shown that a PV module of 240 watts can produce about 700 Litres of drinkable fresh water per day. The adsorption stage is performed during the day time, while the regeneration stage is performed at night. The CDI cell is designed to match the PV and to synchronize its operation with solar power. Several improvements can be introduced to reduce the electric resistive losses and to recover the capacitor energy during the regeneration cycle. The system module can be used for small communities and resorts.

This model can serve as a benchmark to study the performance of CDI system under different configurations, different operating conditions, understanding the effect of different parameters on system performance and also optimization of the system parameters to achieve maximum efficiency.

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### Practical Investigation for Road Lighting using Renewable **Energy Sources**

Sizing and Modelling of Solar/Wind Hybrid System for Road Lighting Application

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Abstract - Hybrid renewable energy systems are recently used to counteract the limitations of solar and wind as solo renewable energy sources due to adverse weather conditions. This study explains a design of a fully independent -off grid- hybrid solar and wind road lighting system according to geography and weather conditions recorded from the National Research Institute of Astronomy and Geophysics. The computerized model is designed step by step by the aid of Simulink-Matlab and the simulation was successfully run to show the performance of each module.

Keywords - PV; Wind; Hybrid; Simulink; Matlab; Modelling.

### I. INTRODUCTION

With the recent advances of research in the renewable energy field and the continuous development and innovation process to push the limits of such clean, environmental friendly energy sources, many methods are being developed to tackle the challenges continuously faced due to adverse weather conditions, e.g. clouds, rain, snow and hail which reduce the solar irradiation and low wind speed that affect the productivity from wind turbines. One of those methods is the use of hybrid designs which utilize more than one renewable energy source to overcome the limitations associated with the use of a single energy source to meet the load demand; such designs provide long term stability and efficient performance for the application intended [1].

The hybrid renewable energy system may also combine renewable and traditional energy sources, e.g. using a wind turbine connected to a diesel generator to reduce fuel consumption [2] can be a standalone off-grid or grid connected.

In this research, the researcher will present the sizing and modelling of hybrid solar and wind off-grid road 258

lighting system using weather data and Matlab-Simulink software.

### **II. SIZE OPTIMIZATION**

The size of each individual component of the system is optimized to meet the load demand while maintaining an economically feasible design with a long-term stability of performance. Sizing is conducted according to real time data measurements of solar irradiation and wind speed recorded throughout the year 2012 by the solar radiation and metallurgical station at the National Research Institute of Astronomy and Geophysics in Helwan, Egypt (Latitude =  $29.5^{\circ}$  N, Longitude =  $31.2^{\circ}$  E, Elevation=130 m) [3].

### A. Photovoltaic module sizing

The mean monthly averages of solar irradiation are presented as bar chart Fig.1. The lowest average solar irradiation 343 W/m<sup>2</sup> was recorded in December, thus the sizing of the PV is designed according to the minimum solar irradiation, Fig. 2 represents the average variance of solar Irradiation per day during December 2012.



Fig .1. Monthly averages of solar irradiation during year 2012 at Helwan.



Fig .2. Average variance of solar irradiation per day during December 2012

As the system is required to power a 30 W luminar light for 13 hours, the total power demand equals 390 Wh/day; As 3.5 hours (the hours in the day during which maximum solar irradiation) provides 343 W/m<sup>2</sup>; average solar irradiation with estimated 35% PV module efficiency, the size of the PV module was chosen accordingly to be 150WP as per the following equations:

Total appliance use = (30W x 13hours) = 390 Wh/day
(1)

Total PV panel energy needed =  $390 \times 1.35$ (Estimated losses) = 526.5 Wh/day. (2)

Total Wp of PV panel capacity needed = 526.5/3.5hrs=150Wp (3)

### B. Wind turbine module sizing

Wind speed data collected throughout the same year in the same location is presented in Fig.3 with lowest average wind speed value of 4.33 m/s in November. The daily wind speed average values during the same month are represented in Fig.4



Fig .3. Mean monthly wind speed during year 2012 at Helwan.

The smallest wind generator WG available commercially is 420W (12V) and generates power equals to 25W (Fig. 5) at 4 m/s wind speed [4], 250Wh/day assuming 10 hours average running time at 4m/s or higher, which is sufficient to meet around 45% (250W from wind / 527 Load Demand) from the load demand.



Fig .4. Average daily wind speed during November 2012.



Fig .5. Output power curve for WT-420.

### C. Battery module sizing

Finally, the battery sizing at nominal battery voltage 12V and Days of autonomy equal to 1.5 day with 30% deep of discharge, the size of battery capacity is chosen accordingly to be 100 Ah.

### **III. MODELLING**

A computerized model of the system designed by the aid of Simulink/Matlab will be used to study different weather conditions and will be validated against the real-time data produced after installation of the system. Fig.6 shows a diagram of the main system components.



Fig .6. Diagram of main components of hybrid wind/PV road lighting system.

### A. Wind system modelling

Wind system consists of wind turbine to convert kinetic energy to mechanical energy, permanent magnet synchronous generator to convert mechanical energy to electric energy and a rectifier to obtain DC supply as shown in Fig.7 and according to the following equations.



Fig .7. Wind system Model

### 1. Wind kinetic energy: [5]

 $K.E = 0.5 \text{ m } v^2$ Where

$$1- m:mass = \rho V \tag{4}$$

Where:  
1.1 
$$\rho$$
 = air density kg/m<sup>3</sup>  
1.2 V= volume = AL m<sup>2</sup>.m  
A=Area  
L=Length

Energy=power\*time (5)  
Power = energy/time  
Power = 
$$0.5 \text{ m v}^2/T$$
  
=  $0.5 \rho \text{ V v}^2/T$   
=  $0.5 \rho \text{ A L v}^2/T$   
Where:  
T=time, L/T=v  
Power in air = $0.5\rho \text{ Ay}^3$  (6)

### 2. Wind turbine mechanical energy: [6]

The available energy part in wind is described by the power coefficient Cp.

P turbine = 
$$0.5 \rho A v^3 C \rho$$
 (7)

Where:

Cp is specification related and ranges from 0.4 to 0.5 for industrial turbines

The power coefficient is a function of the tip-speed ratio  $\boldsymbol{\lambda}$ 

$$\lambda = r \Omega / v \tag{8}$$

Where:

r is the rotor radius  $\Omega$  is the angular rotor speed.

### 3. Generator electrical energy:

Mechanical torque from the wind turbine is calculated by Simulink in pu of the nominal generator torque. The nominal torque of the generator is based on the nominal generator power and speed.

### B. Photovoltaic modelling[7]

The equivalent circuit of a PV cell is as shown in figure 8.



Fig .8. PV equivalent circuit

The current source lph represents the cell photocurrent.  $R_{sh}$  and  $R_s$  are the intrinsic shunt and series resistances of the cell, respectively. Usually the value of  $R_{sh}$  is very large and that of  $R_s$  is very

small, hence they may be neglected to simplify the analysis.

The photovoltaic panel can be modeled mathematically as given in equations (9) - (10) - (11) - (12).

### Module photo-current:

 $lph = [ lscr + Ki (T - 298) ] * \lambda / 1000$ (9)

### Module reverse saturation current - Irs:

# The module saturation current lo varies with the cell temperature, which is given by

### The current output of PV module is

Ipv = Np \* Iph - Np \* Io [ exp { (q \* ( Vpv + Ipv Rs ))/(Ns A K T) } -1] (12)

Where:

Vpv is output voltage of a PV module (V), Ipv is output current of a PV module (A), Tr is the reference temperature = 298 K , T is the module operating temperature in Kelvin, Iph is the light generated current in a PV module (A), Io is the PV module saturation current (A), A = B is an ideality factor = 1.6, k is Boltzman constant = 1.3805 × 10<sup>-23</sup> J/K, q is Electron charge =  $1.6 \times 10^{-19}$  C, R<sub>s</sub> is the series resistance of a PV module ,Iscr is the PV module short-circuit current at  $25^{\circ}$ C and 1000W/m<sup>2</sup> = 9.1A. Ki is the short-circuit current temperature co-efficient at  $I_{SCr}$  = 0.0017A /°C ,  $\lambda$  is the PV module illumination  $(W/m^2) = 1000W/m^2$ , Ego is the band gap for silicon = 1.1 eV, Ns is the number of cells connected in a series, and Np is the number of cells connected in parallel.

### Reference model:

150W PV module is taken as the reference module for simulation and the name-plate details are given in Table 1.

| Rated Power                                 | 150 Wp |
|---------------------------------------------|--------|
| Voltage at maximum power (V <sub>mp</sub> ) | 18.1   |
| Current at maximum power ( $I_{mp}$ )       | 8.26   |
| Open circuit voltage (Voc)                  | 21.6   |
| Short circuit current (Iscr)                | 9.1    |
| Total number of cells in series (Ns)        | 36     |
| Total number of cells in parallel (Np)      | 1      |

The electrical specifications are under test conditions of irradiance of 1 kW/m<sup>2</sup>, and cell temperature of  $25^{\circ}$ C. By using the equations given with the Simulink modeling to be done in Fig.9.

### C. Hybrid boost charger controller modeling

Hybrid charger controller is boost converter to convert variable DC to constant DC from both wind and PV systems as shown in Fig.10 [8].

### D. Battery modelling

The lead acid gel battery is implemented with 30% state of charge (SOC) and resistive load lead system 12VDC, 2.5 amps, 30 watt, as shown in Fig.11.

The mechanism of the battery for charging and discharging is explained as follows: when SOC of the battery goes under 30%, the connected load with the battery will be removed; while when SOC goes to between 40% and 100%, the load is applied, so the battery only supplies the 2.5 amps load as shown in Fig.12.



Fig .9. PV Simulink Model



Fig .10. Hybrid boost charger controller modeling.



Fig .11. Lead-acid battery Simulink model.



Fig .12. Battery discharge characteristics.

## E. The hybrid PV / Wind / battery modeling with the load

Finally, all models are connected together as shown in Fig.13 to show the final waves formed from wind turbine and PV, their effects on the R load and storage of the extra energy in lead acid battery to maintain the system performance even in the worst weather conditions expected throughout the year.



Fig.13 Full system Model

### **IV. RESULTS**

The final model includes wind speed of 4 m/sec, temperature  $25^{\circ}$ C and irradiation of 600 watt/m<sup>2</sup> as input and gives the output for each module as follows:

### A. Wind system modelling

For different wind speeds and for blade pitch angle  $\beta$  = 0 degree is illustrated below. Figure 14 is obtained with the default parameters (base wind speed = 4 m/s, maximum power at base wind speed = 0.06 pu (kp = 0.73) and base rotational speed =0.8 pu).



Fig .14. Turbine power characteristics with pitch angle = 0 degree

The mechanical power Pm as a function of generator speed,

For converting from P.U:ns=120\*f/p=1500r.p.m(13)

where p = no. of poles = 4 (14)

P.U=Reading/Base

Max. Power at 4 m/s acts 25 watt where P.U power = 0.06 at base power 420 watt Torque=power/ω (15)

Where  $\omega = 2 \pi$  ns / 60 Then torque base = 2.8 n.m

The mechanical torque is the output from wind turbine as shown in Fig.15 in negative mode, the negative torque is applied to the permanent magnet synchronous machine so it acts as a generator mode, the three-level bridge block is then used as AC-DC converter.



Fig .15. Wind turbine mechanical torque in negative mode.

### B. Photovoltaic modelling

The PV module characteristics are estimated at different conditions as follows:

- I-V and P-V characteristics under different irradiation starting from 200W/m<sup>2</sup> to 1000W/m<sup>2</sup> at constant temperature 25°C are obtained as shown in ffigures 16 and 17, respectively.
- I-V and P-V characteristics under different temperatures starting from 25°C to 45°C at constant irradiation are obtained as shown in







Fig.17. P-V characteristics under different irradiation at 25°C.



Fig.18. I-V characteristics under different temperatures.



Fig.19. P-V characteristics under different temperatures.

### C. Battery modelling

The power of the battery is dissipating through resistor and simultaneously charged by a DC voltage source from wind/PV module. The value of SOC (state of charge) is varying with changing the value of DC voltage source around 13V. If the DC voltage is more than the nominal voltage of battery, SOC will remain the same, while if the DC voltage is less than the nominal voltage of battery, SOC will decrease.



Fig.20. Results and system performance.

### **V. RESEARCH IN PROGRESS**

The results generated by Simulink/Matlab model will be compared and validated against the real-time data produced by the system currently being installed in Faculty of Engineering, Helwan University facility, the differences – if any - found between the computerized model and the practical application will be used to either apply correction factor or refine the model to give more accurate estimation. The model will then be used to adapt the system to different weather conditions in different geographical locations. The possibility of diverting the extra energy to be used to power an advertisement installed on the pole is also under research.

### **VI. CONCLUSION**

The step-by-step procedure for sizing and modeling a PV/wind hybrid road lighting system is presented, the performance of the hybrid PV/Wind system was investigated to utilize road lighting pole with DC - R load by using Matlab/Simulink simulation at starting wind speed of 4 m/sec and solar irradiation of 600 W/m<sup>2</sup> at constant temperature 25°C after analyzing the geography and weather data from National

Research Institute of Astronomy and Geophysics. The system components were optimized and chosen to be 150W photovoltaic module, 420W wind generator, 100Ah acid gel battery and LED lighting luminar 30W - 12VDC. Simulink/Matlab model results showed that the system will perform efficiently even under the worst environmental condition. After the current work in progress, the researchers can compare and present accurate dynamic performance of solar and wind energy system of each case to validate the sizing and the modeling system with the real-time system implementation to develop a unit sizing method which avoids complexity in the design of the hybrid system.

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### Synthesis of Nanocrystalline Copper Ferrite film by Electrochemical Technique for Toxic Gas Sensing, Li Ion Batteries and Medical Applications

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Nanocrystalline spinel copper ferrite Abstract -CuFe<sub>2</sub>O<sub>4</sub> thin film has been studied and synthesized via the electrodeposition-anodization process. Electrodeposited CuFe<sub>2</sub> alloys were obtained from aqueous sulphate bath. The formed alloys were electro oxidized (anodized) in aqueous (1 M KOH) solution, at room temperature, to the corresponding hydroxides. The anodized CuFe2 alloy films were annealed in air at 400 °C for 2 h. The parameters controlling of the electrodeposition of CuFe2 alloys such as the bath temperature, agitation and the current density were studied and optimized. The crystal structure, crystallite size and microstructure of the produced ferrites were investigated using X-ray diffraction (XRD), Fourier transform infra red (FT-IR) and scanning electron microscopy (SEM). XRD shows that CuFe<sub>2</sub>O<sub>4</sub> had a spinel structure and the crystallite size of CuFe<sub>2</sub>O<sub>4</sub> phase was ~ 2 nm. SEM micrograph of the formed ferrite particles shows agglomeration structure morphology with a narrow distribution of the particles.

*Keywords* - Copper ferrite; Electrodeposition; Thin film; Cyclic voltammetry; Nanoparticles.

### I. INTRODUCTION

Polycrystalline metal iron oxide (ferrites) having the general formula  $MFe_2O_4$ , where M is divalent metal ion such as Mg, Mn, Zn, Ni, Co, Cu, Cd and Fe have wide ranging applications in various technical fields [1]. Owing to their important electrical and magnetic properties, metal iron oxides are used in electronics industries [2].

Most of the transition metal oxides (MO) can react with  $Fe_2O_3$  to form the corresponding ferrites. These ferrites have the general formula  $MFe_2O_4$ , where M represents a divalent metal ion, such as copper which has many applications in various technical fields [3]. Ferrite has been demonstrated to be good materials for gas sensing applications [4-6]. Pulsed laser deposition techniques [7-9], dip coating [10], sputtering [11], laser ablation [12], vacuum arc evaporation [13] and the sol-gel method [14] have been used to synthesis mixed iron-oxide thin films. To obtain crystallization, these techniques require heating the substrate for several hundred degrees Celsius. Accordingly, the used substrate should have high heat resistance and a high thermal expansion coefficient that can prevent the deposited materials from degeneration, after high-temperature exposure. Also, all these techniques are expensive and the resultant film particles are rather large and nonuniform in size. Moreover, non-reproducible products and toxic gases are produced during sintering [15]. To overcome the difficulties arising from the above mentioned techniques, the electrochemical deposition method has attracted much attention because the electrochemical formation of oxide films is economical and suitable for large-scale applications [16-17]. Electricity accomplishes the oxidation and reduction, so that there are no by-product species [16]. The method has low processing temperature and its raw materials or equipment have low costs. The film composition and morphology can be controlled controlling the electrochemical by parameters. It is ability to deposit a film on a complex surface. This method is the easiest, non-vacuum method for preparing large area electrodes. Homogeneous, fine and reproducible nanocrystalline films can also be obtained [18-20].

Copper ferrite is one of the important spinel ferrites MFe<sub>2</sub>O<sub>4</sub> because it exhibits phase transitions, changes semiconducting properties, shows electrical switching and variation when treated under different conditions in addition to interesting magnetic and electrical properties with chemical and thermal stabilities. Meanwhile it is used in the wide range of applications in gas sensing, catalytic applications, Li ion batteries, high density magneto-optic recording devices, color imaging and bio-processing [21-25].

The present study aims to prepare nanocrystalline  $CuFe_2O_4$  thin film using the aqueous electrochemical deposition method. The effect of synthesis conditions such as agitation, temperature, current density, and deposition voltage on the properties of ferrite film was investigated. The electrochemical properties were examined using cyclic voltammetry, choronoamperometric and chronopotentiometeric techniques. The crystal structure, crystallite size and microstructure of the produced ferrite films were investigated by x ray diffraction (XRD) and scanning electron microscope (SEM).

### **II. EXPERIMENTAL**

### A. Materials

Analytical grade ammonium ferrous sulphate (Fe  $(NH_4)_2$  (SO<sub>4</sub>)<sub>2</sub>.6 H<sub>2</sub>O), copper sulphate (CuSO<sub>4</sub>-5 H<sub>2</sub>O) and potassium hydroxide (KOH) were used as starting materials. Electrodeposition experiments were carried out using freshly prepared solutions. The electrolyte was kept unstirred.

### B. The cell

The experimental set-up is shown in Fig.1. A standard three-electrode cell (40 cm<sup>3</sup>) with a Pt plate (1 cm<sup>2</sup>) was used as working electrode, (1 cm<sup>2</sup>) as counter electrode and silver/silver chloride saturated in KCI (Ag/AgClsat) as reference electrode. The working and the counter electrodes were mounted parallel to each other at a distance of 0.5 cm.

Electrocodeposition of copper iron alloy: Experiments of electrodeposition were executed using a potentiostate-galvanostate (25 V/3A) in a galvanostatic mode. Just before deposition, the working electrode was anodically cleaned for 60 s at a current density of 0.01 A cm<sup>-2</sup> in a bath similar to that used for alloy deposition.

In a second step, the deposited copper iron alloy film was anodized in 1 M KOH where the alloy film acts as anode and the counter Pt- electrode acts as cathode. The resulting film was rinsed thoroughly with distilled water and dried under vacuum in desiccators for at least 2 h.



Fig.1. Experimental set-up.

Cyclic voltammetric (CV) tests were performed at room temperature using a conventional threeelectrode cell, in which pt was used as working electrode and auxiliary electrode of area 1 cm<sup>2</sup>. The reference electrode used was a saturated silver/silver chloride electrode (Ag/AgClsat), E0 = 0.200 mV vs. standard hydrogen electrode (SHE) reference electrode. The deposition potentials were determined from the polarization curves. Cyclic voltammograms performed with computer-controlled were а potentiostate (Volta-lab 21) PGP 201 potentiostate, galvanostate 20V, 1A with general generator.

Electrodeposition was identified galvanostatically using constant currents ranging from -20 mA to -100 mA. Apparent current densities were obtained by dividing the applied current by macroscopic surface area of the deposit. The deposition conditions were optimized to get good quality of CuFe<sub>2</sub> alloy films with maximum thickness.

The alloy films were anodized using aqueous 1M KOH. The anodization current density and time were optimized to get well-adhered oxide films to the substrates. After anodization, the films were washed with distilled water and annealed after drying.

The crystalline phases in the different annealed ferrite samples were investigated using X-ray diffraction (XRD) on a Brucker axis D8 diffractometer using the Cu-K $\alpha$ ( $\lambda$  = 1.5406 A°) radiation and secondary monochromator in the range 2 $\theta$  from 20° to 80°. Fourier transform infrared spectrosopy (FTIR) was conducted on a Thermo Electron Magna 760. The ferrite particle morphologies were examined by Field Emmission Scanning Electron Microscope and Scanning Electron Microscope (SEM) (JEOL—model JSM-5410). The crystallite size was calculated automatically by the X–ray diffractometer.

### III. RESULTS AND DISCUSSION

### A. Cyclic Voltammetry (CV).

Fig.2(a-c) showed the cyclic voltammogram (CV) of 0.05 M of CuSO<sub>4</sub>, 0.1 M Fe (NH<sub>4</sub>)<sub>2</sub> (SO<sub>4</sub>)<sub>2</sub> and CuFe<sub>2</sub> alloy, respectively, from aqueous sulfate bath. Voltammetric studies were performed within the range of 0 to -2 V using a scan rate (S.R.) of 10 mVs<sup>-1</sup>. The CV of 0.05 M of CuSO<sup>4</sup> is represented by one cathodic peak (C) at potential -1.3 V. This cathodic peak is associated with the deposition of Cu<sup>+2</sup> ions to metallic copper equation (1). However, on reversing scan in positive direction at potential -2 V, an anodic peak was obviously exhibited around - 0.1V. This anodic peak relates to the dissolution of Cu metal into its ions as ascribed in equation (2).

$$Cu^{2+} + 2e^{-} \rightarrow Cu \tag{1}$$

$$Cu \rightarrow 2e^{-} + Cu^{2+}$$
 (2)

Fig.2 (b) depicts the CV of 0.1M of Fe  $(NH_4)_2(SO_4)_2$ . Iron electrodeposition was started at potential -1.2V for non-stirred solution. Thus, this peak was corresponded to the electrodeposition of iron. This iron deposition process was reported to be sensitive to mass transfer. However, on reversing scan in positive direction at -2 V, an anodic peak appeared around -0.1 V. This anodic peak deduced the dissolution of iron metal into its ions.

Fig.(2c) represents the cyclic voltammograms for electrodeposition of CuFe<sub>2</sub> alloy. It can be seen that one cathodic peak and one anodic peak were observed for CuFe<sub>2</sub> alloy. The first cathodic peak (C1) was detected at potential -1.4V for non-agitated solution. This peak belongs to the co-deposition of CuFe<sub>2</sub> alloy. However, on reversing scan in positive direction at -2 V, an anodic peak (A1) appeared around -0.03 V. This peak was due to the dissolution of the deposited alloy.





Fig.2. Voltammograms obtained on Pt electrode in different aqueous solution using scan rate 10 mV/S. (a): 0.05M CuSO<sub>4</sub>.
(b): 0.1M (NH<sub>4</sub>)<sub>2</sub>Fe(SO<sub>4</sub>)<sub>2</sub>. (c): CuFe<sub>2</sub> alloy deposited from solution of 0.1 M Fe (NH<sub>4</sub>)<sub>2</sub> (SO<sub>4</sub>)<sub>2</sub> +0.05M CuSO<sub>4</sub>.

### 1. Influence of bath Agitation

Fig. (3a) represents the cyclic voltammetric curves for electrodeposition of CuFe2 alloy on Pt substrate at different agitation rates. This figure is characterized by three cathodic peaks and three anodic peaks. The first cathodic peak (C<sub>1</sub>) appeared at potential E = -1.4V at non agitated solution. Agitating the solution up to 500 rpm shifted the cathodic potential to more negative potential and the potential shifted from -1.4 V (C<sub>1</sub>) for non-agitated solution to -1.58 V (C<sub>2</sub>). Also the potential shifted from -1.4 V (C<sub>2</sub>) to -1.7 V (C3) for agitated at 1000 rpm. Moreover, agitating the solution changed the solution cathodic current density from -70 to -120 mA/cm<sup>2</sup>. Increasing the solution agitation rate reduces the thickness of the adjacent cathodic layer, which in turn shortens the diffusion path of metal deposition [26-27]. However, on reversing scan in positive direction at -2 V, anodic peaks (A1, A2, and A3) appeared around. The anodic peak was due to the dissolution of the deposited alloy.



Fig.3a. Voltammograms of CuFe<sub>2</sub> alloy deposited in 0.1 M Fe  $(NH_4)_2$  (SO<sub>4</sub>)<sub>2</sub> + 0.05M CuSO<sub>4</sub> solution at different agitation rates. (1): 0rpm. (2): 500 rpm. (3): 1000 rpm. Scan rate 10 mV s<sup>-1</sup>.

### B. linear sweep voltammetry

### 1. Influence of operating temperature

Fig. (3b) describes the linear sweep voltammetric curves (LSV) for electrodeposition of CuFe<sub>2</sub> alloy on Pt substrate at different bath temperatures. It is seen that the increasing bath temperature from 25 to 40 °C has subsequently formed a decrease in CuFe<sub>2</sub> deposition potential from E = -1.58 V, (peak C<sub>1</sub>) to E = -1.32 V, (peak C<sub>2</sub>). Indeed, increasing bath temperature from 40 to 60 °C resulted into a decrease in CuFe<sub>2</sub> deposition potential from E = -1.1 V, (peak C<sub>3</sub>). The deposited films at room temperature were more adherent, homogeneous and coherent.



Fig.3b. Linear sweep voltammetric curves of CuFe<sub>2</sub> alloy deposited in 0.1 M Fe (NH<sub>4</sub>)<sub>2</sub> (SO<sub>4</sub>)<sub>2</sub> + 0.05M CuSO<sub>4</sub> solution at different temperatures. (1): 25  $^{\circ}$ C. (2): 40  $^{\circ}$ C. (3): 60  $^{\circ}$ C. Scan rate 10 mV s<sup>-1</sup>.

Generally, the raise in bath temperature increases the grain size of the deposited materials and consequently a decrease in deposition potential at a higher temperature was observed. Additionally, the increment of bath temperature enhances the rate of diffusion and ionic motilities which enhances the conductivity of deposition bath. The decrease in deposition potential with increasing temperature might be due to the increase in the content of more noble metal in the deposited alloy [28].

### C. Chronopotentimetric study

Fig.(4) demonstrates the chronopotentiometric (galvanostatic) curves for electrodepositon of CuFe<sub>2</sub> alloy films from the solution of 0.05M CuSO<sub>4</sub> + 0.1M Fe (NH<sub>4</sub>)<sub>2</sub>(SO<sub>4</sub>)<sub>2</sub>. In order to find out the suitable current for deposition, the depositions at different current values i.e., -20, -30, -40, -50, -60 and -100 mA/cm<sup>-2</sup> was performed respectively.

The deposition rate at these currents was found out. During the deposition, the potential first increases to a certain extent and then it decreases very fast up to a steady state value. The fast decrease in potential indicates the faster coverage of electrode surface by layer while the steady state indicates that the coverage of electrode surface is nearly complete. The value of deposition rate at -100 mA/cm<sup>-2</sup> was observed maximum with high film thickness, thus cathodic current density of -100 mA/cm<sup>-2</sup> was found to be suitable for the deposition of thin films.



Fig.4. Chronopotentiometric curves recorded at various current densities in aqueous solution of CuFe<sub>2</sub> alloy deposited from solution of 0.1 M Fe (NH<sub>4</sub>)<sub>2</sub> (SO<sub>4</sub>)<sub>2</sub> +0.05M CuSO<sub>4</sub>). (a): -20 mAcm<sup>-2</sup>. (b): -30 mAcm<sup>-2</sup>. (c): -40 mAcm<sup>-2</sup>. (d): -50 mAcm<sup>-2</sup>. (f): -60 mAcm<sup>-2</sup>. (e): -100 mAcm<sup>-2</sup>.

### D. Chronoamperometric study.

Fig.(5) deduces the chronopotentiometric (potentiometric) curves recorded with Pt substrate in the deposition solution of 0.05 M CuSO<sub>4</sub> + 0.1 M Fe (NH<sub>4</sub>)<sub>2</sub> (SO<sub>4</sub>)<sub>2</sub>. In order to find out the suitable potential for deposition, the depositions at different potential values i.e., -0.9V, -1, -1.1, -1.2,-1.3 and - 1.4V were performed respectively. The deposition rate at these potentials was found out. The value of deposition rate at -1.2V has observed maximum deposition with high film thickness. It increases to a certain extent and then it decreases very fast up to a

steady state value. The fast decrease in potentials shows that the coverage of electrode surface becomes fast. Thus, potential -1.2V was found suitable for the deposition of thin films. During the deposition, the first current during the steady state indicates that the coverage of electrode surface is nearly complete.



Fig.5. Variation of current density with time at constant potentials for CuFe<sub>2</sub> deposited from solution of 0.1 M Fe  $(NH_4)_2$   $(SO_4)_2 + 0.05M$  CuSO<sub>4</sub>. (a): -0.9 Volt. (b): -1Volt. (c):-1.1 Volt. (d): -1.2 Volt. (e): -1.3Volt. (f): -1.4 Volt.

Scharifker and Hills suggested model to describe the nucleation process during initial few seconds using chronoamperometric technique. The nucleation process may be either progressive or instantaneous. Progressive nucleation corresponds to slow growth of nuclei on a less number of active sites; all of these sites are activated at the same time. Instantaneous nucleation corresponds to fast growth of nuclei on many active sites on the cathode.The effect of deposition potential on nucleation of alloy during initial time (S-H model) is shown in Fig. 6 (a-b).

The transients have been analyzed by comparing the chronoamperometric curves to the dimensionless theoretical curves for the diffusioncontrolled nucleation and growth of crystals in three dimensions (3D) proposed by Saba et al [20] and Kim et al [29]

The expressions for the instantaneous and progressive nucleation are given by the following equations, respectively [28, 30]:

 $I^{2}/i^{2}_{max} = 1.9542 [t_{max}/t] \{1-exp [-1.2564 t/t_{max}\}^{2} (3)$ 

 $l^{2}/i^{2}_{max} = 1.2254 [t_{max}/t] \{1-exp [-2.3367 (t/t_{max})^{2}\}^{2} (4)$ 

Where  $i_{max}$  and  $t_{max}$  are the maximum current density observed at the maximum time  $t_{max}$ .



Fig.6. Nondimensional  $i^2/i^2_{max}$  vs  $t/t_{max}$  plots for electrodeposited CuFe<sub>2</sub> alloy at different potentials. (A): -0.9 Volt. (B): -1.4 Volt.

### E. Film thickness measurements of CuFe2 alloy

CuFe<sub>2</sub> alloy film thickness was determined by the method of gravimetric weight difference in which area and weight of the film was measured, before and after alloy deposition [31-32].

The samples were precisely weighed; the difference of two masses gives the mass of the alloy film. The thickness was obtained by assuming density of bulk MFe<sub>2</sub> expressed as:

$$\rho = \rho_1 x_1 + \rho_2 x_2$$
 (6)

Where  $\rho_1$ ,  $\rho_2$  and  $x_1$ ,  $x_2$  are densities and atomic fractions of M and Fe elements in alloy, respectively.

Fig.7 offers a plot of CuFe<sub>2</sub> film thickness against current density. The thickness of the CuFe<sub>2</sub> film increased (6700nm) with increasing deposition current density up to -100 mAcm<sup>-2</sup>. With further increase in deposition time, film thickness was decreased. This is attributed to the formation of porous, foggy, less adherent film and/or the film may have tensile stress that tends to cause delimitation, when it becomes thick [31].



Fig.7. Variation of film thickness with current density CuFe<sub>2</sub> alloy deposited from solution of 0.1 M Fe (NH<sub>4</sub>)<sub>2</sub> (SO<sub>4</sub>)<sub>2</sub> + 0.05M CuSO<sub>4</sub>.

The relation between film thickness and deposition potential is shown in Fig.8. The variation of film thickness with deposition potential is observed. Initially as deposition potential increases, film thickness increases, attains maximum value 3030 nm for -1.2 V deposition potential of CuFe<sub>2</sub>, further increase in deposition potential leads the film peelings off from the substrate due to porous, foggy and less adherent film formation.



Fig.8. Variation of film thickness with potential for  $CuFe_2$  alloy deposited from solution of 0.1 M Fe  $(NH_4)_2$   $(SO_4)_2$  + 0.05M  $CuSO_4$ .

### F. Current efficiency of study of CuFe2 alloy

Current efficiency was calculated by dividing the mass of the film actually deposited on the electrode by the mass expected to be deposited in accordance with Faraday's law.

$$W = ----- grams$$
 (7)  
26.8 A. hr.

Where:

I :Current intensity in Ampers

If is the  $\bar{\mathbf{w}}$  weight of metal actually deposited at the cathode, then,

The plot of current efficiency of CuFe<sub>2</sub> alloy deposition against various current densities of 5 min deposition at room temperature is shown in Fig.9. Current efficiency increases with increasing current density and afterwards decreases with further increase in current density. At -100 mAcm<sup>-2</sup> an efficiency of 98 % was observed. The reduction rate of protons is less than the rate of metal deposition below the maximum current efficiency. Further increase in current density only leads to an increase in the rate of the reduction of water molecule. It is assumed that both single metals are reduced in two consecutive steps [33].

Cu (II) + 
$$e^- \rightarrow Cu(I)_{ads}$$
. (9)

 $Cu (I)_{ads} + e^{-} \rightarrow Cu(S)$  (10)

 $Fe (II) ) + e^{-} \rightarrow Fe(I)_{ads}.$ (11)

 $Fe (I)_{ads} + e^{-} \rightarrow Fe(S)$  (12)

Reduction of proton and dissociation of water molecule produces hydrogen evolution that may occur as a side reaction (equation 13-15) [34].

 $H^+ + e^- \rightarrow 1/2 H_2$  (13)

$$H_2O + e^- \rightarrow 1/2 H_2 + OH^-$$
 (14)

 $H_2O \to H^+ + OH^- \tag{15}$ 



Fig .9. Variation of current efficiency with current density for CuFe<sub>2</sub> alloy deposited from solution of 0.1 M Fe  $(NH_4)_2$  (SO<sub>4</sub>)<sub>2</sub> +0.05M CuSO<sub>4</sub>.

### G. Anodization of the Alloy

Electrochemical oxidation of CuFe<sub>2</sub> alloy films prepared at the optimum electrodeposition synthesis parameters was carried out at room temperature (25 <sup>o</sup>C) according to the conditions summarized in Table 1.

The conversion of  $MFe_2$  alloy to the corresponding ferrite ( $MFe_2O_4$ ) via the hydroxide form can be explained with the following reaction

$$\mathsf{MFe}_2 + \mathsf{8OH}^{-} \rightarrow \mathsf{MFe}_2\mathsf{O}_4 + \mathsf{4H}_2\mathsf{O} + \mathsf{8e}^{-} \tag{16}$$

| Items                   | Conditions                |
|-------------------------|---------------------------|
| Electrolyte             | 1 M KOH                   |
| Anodic current density  | 10 (mA/cm <sup>-2</sup> ) |
| Intercalation time      | 5 (min)                   |
| Electrolyte temperature | 25 (°C)                   |

Table 1. Conditions of the Anodization Process for the Synthesis of Copper Ferrite Thin Film.

After oxidation, the hydroxide films were washed with deionized water and preserved in desiccators. Then, annealing of the hydroxide converted into the corresponding oxide (ferrite) should remove some of the defects, which may be presented during the electrodeposition and anodization steps, such as voids, grain boundaries, dislocations, stresses, in homogeneity, etc. Thus, annealing is a process related to the stress relief and local structural rearrangements resulting in recovery of the alloy elements ratio of the film [20]. The formed CuFe<sub>2</sub> hydroxide precursors were annealed at 400 °C for 2 h.

The XRD pattern and microstructure of CuFe<sub>2</sub> alloy prepared on gold substrate are mentioned and published previously by Elsayed and Saba [31].

### H. Physical characterization of Cu Fe<sub>2</sub>O<sub>4</sub>

### 1. Crystal structure

Fig.10 represents the XRD pattern of  $CuFe_2O_4$  thin film; the results indicated that cubic spinel copper ferrite  $CuFe_2O_4$  phase was observed. No extra peak related to tetragonal  $CuF_2O_4$  was matched. The crystallite size of  $CuFe_2O4$  phase was 2 nm.

Typical diffraction peaks of cubic CuFe<sub>2</sub>O<sub>4</sub> were indexed at 20 position of 29.8, 35.51, 43.2, 57.4, 62.8 and 57.5 corresponding to diffraction planes of (220), (311), (400), (511), (440) and (533), respectively (JCPDS# 00-025-0283). The strong, relatively sharp peaks of the sample demonstrate a good crystalline state of the cubic CuFe<sub>2</sub>O<sub>4</sub> as formed film. The sharpness of XRD peaks has essentially attributed to the small diameter size of the CuFe<sub>2</sub>O<sub>4</sub> film. From the main diffraction peaks and Scherer equation. The average size of crystallites for CuFe<sub>2</sub>O<sub>4</sub> from the most intense peak (311) was based on Scherer's equation. The average crystalline size was found to be about 2 nm taking coefficient k = 0.9, which proves that the films are nanocrystalline. The crystallite size was calculated automatically by the X -ray diffractometer.



Fig.10. XRD patterns of CuFe<sub>2</sub> alloy oxidized in 1 M KOH are followed by annealing in air at 400 <sup>o</sup>C for 2 h, where the peaks of substrate are marked with asterisks.

Fourier transform infra red spectrum (FTIR) of sample thermally treated at 400 ° C was recorded in the range of 400-800 cm<sup>-1</sup> at room temperature and the obtained result is shown in Fig.11. It is known that ferrites have two common bands. The high wave number band  $u_1$  at 540-600 cm<sup>-1</sup> is assigned to the tetrahedral complexes, while the lower wave number  $u_2$  at 450-490 cm<sup>-1</sup> is assigned to the octahedral complexes. Therefore, in the investigated sample, the high wave number represents the vibration of Fe3+-O2in the sub-lattice site A, while the lower wave number band represents the divalent metal - oxygen vibrations at the octahedral B-sites. The difference in  $u_1$  and  $u_2$  band positions is expected because of the difference in the Fe<sup>3+</sup>-O<sup>2-</sup> distances for the octahedral and the tetrahedral sites. FTIR transmission spectrum revealed two dominant absorption bands at u1 (560 cm<sup>-1</sup>) and  $u_2$  (475 cm<sup>-1</sup>) due to tetrahedral Fe<sup>3+</sup>-O<sup>2-</sup> and octahedral site for pure copper ferrite film.



Fig.11. FT-IR spectrum of CuFe<sub>2</sub> alloy oxidized in 1 M KOH followed by annealing in air at 400 <sup>o</sup>C for 2 h.

### 2. Microstructure



Fig.12. SEM picture of copper ferrite thin film electrodeposited from sulfate bath at current density -100 mAcm<sup>-2</sup> deposited from solution of 0.1 M Fe  $(NH_4)_2$  (SO<sub>4</sub>)<sub>2</sub> +0.05M CuSO<sub>4</sub> and annealed at 400 °C.

Fig.12 illustrates the SEM surface morphology of copper ferrite electrodeposited from sulphate bath at cathodic current density 100 mA cm<sup>-2</sup>. The specimens were subjected to microscopic examination at X 10.000. The micrograph of copper ferrite surface shows agglomeration structure morphology with a narrow distribution of the particles.

More aspects were considered for CuFe<sub>2</sub>O<sub>4</sub> by Field Emmission Scanning Electron micrograph. Figure.13 depicts the formed particles that exhibited nanosphere like structure.



Fig.13. FE-SEM image of copper ferrite film electrodeposited at current density -100 mAcm<sup>-2</sup> and followed by annealing in air at 400 °C for 2 h.

### **IV. CONCLUSIONS**

The results can be summarized as follows: Copper ferrite has been successfully synthesized via a novel approach of electrodeposition –anodization process.

Electrodeposited  $CuFe_2$  alloy was formed from aqueous sulphate bath at a cathodic current density 100 mAcm<sup>-2</sup> with a high current efficiency 98%.

The formed alloy was anodized in 1 M KOH to form copper ferrite precursors which are annealed at 400  $^{\circ}$ C for 2 h.

The results revealed that agitation effect had enhanced effect on current density, but had opposite effect on film adhesion.

The results also revealed that bath temperature had strong promoting effect on copper –iron alloy deposition.

Chronoamperometric curves showed that a higher application of constant current leads to a higher potential plateau during film deposition.

As the deposition current increases, the thickness of the deposited film increases and optimum current efficiency is reached at cathodic current density 100 mA  $cm^2$ .

According to XR patterns the prepared film was copper ferrite with spinel crystal structure, the crystallite size was 2 nm predicted the film was nanocrystalline.

According to theoretical SH model, it is observed that the nucleation and growth mechanism prevailed experimentally instantaneous nature at lower and higher potentiostatic condition from -0.9V to -1.4V.

SEM micrographs showed that compact crystallite shapes with smallest particle size and full covered surface and shows agglomeration structure morphology with a narrow distribution of the particles noted.

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### Production and Management of Energy: The Interdisciplinary Approach of ENEA to Concentrated Solar Power

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Abstract - Clean and efficient energy generation by environmental friendly methods and technologies is now one of the major challenges worldwide. New and heterogeneous methods to produce energy pose the challenge of how to guarantee energy security, storage of exceeding production and distribution. In addition to that, the exploitation of next generation energy sources must consider the impact it may have on other productive systems and on rural areas (e.g. solar vs agriculture, biomass vs food production). ENEA has got and follows an interdisciplinary approach to "challenge the challenge" of a sustainable energy production, merging together materials science, agronomy and biotechnology, solar energy studies, energy efficiency management and more, in collaboration with industries and often in collaboration with the other stakeholders in the Mediterranean area. This paper describes the state of the art technology and how concentrating solar power (CSP) technology could be modulated to meet different energy needs, both spatial needs (e.g. off grid use vs dispatchability) and temporal needs (day vs night and energy on demand).

*Keywords* - Concentrating Solar Power ;CSP; Solar Energy; Renewable Energy; Energy Security; Mediterranean; Italy; Egypt; EU; Engineering; Solar Plans; Nanomaterials; Materials Science; Energy; Efficiency;Industry

### I. INTRODUCTION

### • setting the scene

The conversion of the energy system to a new one which maximizes the use of renewable energy sources as alternative to fossil fuels is a major objective effecting science, technology and policy choices nowadays. Yet, despite the global political will of exploiting clean and sustainable energy sources, the energy conversion depends on energy price market since few countries and their citizens in general are willing to bear production costs for the sake of an environmental friendly label<sup>1</sup>. Thus, performance and availability of the energy sources in terms of costs and security represent a must to ensure the appropriate penetration of any kind of energy source<sup>2</sup>. To date, 19.2% of global energy consumption is fuelled by renewables3, and renewable energy could represent the fastest growing power source over the next decades<sup>4</sup>; however, limits and challenges of such new age of energy generation must be considered, such as cost and security as already mentioned, but also distribution, storage and often complementarity with existing production and consumption systems and compatibility with future ones.

Among renewable energy approaches, concentrating solar power (CSP) holds a significant promise for adoption as an utility-scale. Different from many other direct renewable

technologies, by the use of cost-effective thermal energy storage, CSP is easily dispatchable, and exhibits versatility in its output capability (heat, steam, chemical energy, mechanical work, or electric power). CSP enables integration Additionally, with conventional power stations, by producing steam with quality standards to drive a conventional turbine <sup>5</sup>. In a nutshell the technology enables to capture the solar heat by using mirrors or lenses to concentrate the sun rays captured on a wide area onto a much smaller surface like a Solar receiver tube with high photothermal efficiency and mechanical reliability to produce high temperature heat, similar to the heat recovered from traditional fuel combustion. As a result, the same technology usually applied for thermal conversion processes (e.g. steam turbines) can be applied for several energy applications (e.g. electrical power production). A conceptual scheme of the CSP basic components is represented in Fig. 1.

### 1. The CSP Technology

A CSP plant is basically composed of a "solar field", i.e. a large area covered with a number of solar collectors, each made of a supporting structure (anchored to the ground) for reflective panels (mirrors) and a solar tracking drive to continuously move and orient the mirrors in the direct normal ray direction.

The shape and orientation of the mirrors in the solar field allow focusing the solar rays captured by the reflective panels on the surface of the so-called "solar-receiver". The ratio between the overall mirrors' area and the solar receiver area represents a measure of the number of times the solar radiation is concentrated: depending on the CSP technology and application, the solar radiation is generally concentrated from tens to thousands times.

Clearly, for a given solar field and a receiver configuration, the effective captured heat flux depends on the overall efficiency which, in turn, depends on several efficiency factors like optical efficiency, tracking efficiency, mirrors' reflectance and cleanness, receiver's efficiency, etc. All these efficiency factors must be optimized in order to get the best overall performance of the CSP pant (e.g. annual production).

A "heat transfer fluid" (HTF) flows inside the solar receiver to remove the high-temperature heat from

the receiver and transfers it, through a specific piping system, to the final heat loads and users. Depending on the CSP technology and conversion process requirements, the HTF can be pressurized water/steam, gas, oil, or molten salts.

At the end of the cycle, the HTF transfers its heat directly to the heat load, such as a steam generator for the production of super-saturated steam to drive a turbine in a Rankine cycle for electrical power production. Alternatively, the high-temperature heat can be used to drive purely thermal duties, like industrial thermochemical conversion reactors and processes for the production of the so-called "solar fuels". When the power load is lower than the available heat carried by the HTF, the excess heat is stored in a thermal energy storage (TES) system, to be used when necessary. After heat transfer to the thermal load(s), during hours with satisfactory direct solar radiation, the HTF is pumped to re-start the heat collection loop.

The solar field and the TES system can be integrated with a suitable "back-up" unit. The back-up unit is a device specifically designed to replace the solar field when the solar radiation is not adequate and the TES system is completely discharged, in order to sustain the heat demand (e.g. after extended cloudy periods). The back-up unit usually consists of a fuel combustor contributing to usually less than 10-15% of total energy production per year.

Clearly, the above mentioned elements and units comprising a CSP plant have to be operated using suitable control tools and procedures to maximize the solar power production and the security of power supply.

The development of the above mentioned units extensive wide multi-disciplinary requires an approach primarily aiming at innovation and the overall system improvement. This includes structural and mechanical engineering (e.g. for solar collectors and tracking drives), expertise in optics and materials efficiency coating (e.g. for improvements, qualification, reflective panels and solar-receivers development and maintenance), material science (e.g. for the heat transfer fluid and the TES), chemical engineering (for the thermochemical conversion), heat transfer skills (e.g. for the back-up unit, steam generator, etc.), hydraulics and fluid-dynamics (e.g. for the piping system), electronics skills (for the

control and automation system), astronomical expertise (for the solar collectors' tracking system), etc.

ENEA's staff covers all the above mentioned expertise required for the full development of the CSP technology, from the individual components to the integrated plant design, construction and operation.

Concentrating solar technologies are divided in point and linear focusing systems. Point focusing systems include solar towers and parabolic dishes<sup>6</sup>. Linear CSP technologies are parabolic troughs or linear Fresnel reflectors which concentrate the solar radiation on receiver tubes. Since the '80s several hundred MW have been installed worldwide mainly in parabolic trough CSP plants typically using thermal oil HTF up to 400°C and a two-tank TES using molten salts as heat storage medium operating in the temperature range between 290°C and 380°C. More recently, large solar tower CSP plants have been installed, commonly with direct heating of molten salts up to 565°C: thus, compared to traditional parabolic trough CSP plants typically using thermal oil HTF up to 400°C, the overall efficiency of the conversion process in tower plants with direct molten salts is increased by increasing the upper temperature of the power cycle.

Since 2001 ENEA has developed a new CSP concept which benefits of the main advantages of solar troughs and tower systems: solar parabolic troughs are applied for the direct use of molten salts as HTF and TES medium up to 550°C. This development was made possible by the above mentioned wide interdisciplinary potentials of ENEA in applied research. Hence, each component has been individually developed in laboratory and then tested in a prototype test plant at ENEA-Casaccia (Fig. 2).

After performance assessment and qualification, the developed components are made ready for replication in CSP plants on the demonstration and commercial scale. The first commercial- size plant (5 MW electrical) has been commissioned in 2010 in Sicily.

Based on the preliminary experience, in the forthcoming years ENEA's research on concentrating solar technology has been focused on further improvements of the technology with respect to individual components, plant integration, process optimization and new application scenarios. Fig. 3

represents a general process scheme conceived by ENEA for the application of this concentrating solar technology to heat and power production. Accordingly, the HTF consisting of a molten salts mixture (usually the binary mixture NaNO<sub>3</sub>/KNO<sub>3</sub> 60%wt/40%wt, though different formulation are under investigation) in the solar field is heated from about 290°C up to 550°C and then stored in a thermal energy storage tank to be used for different applications: steam generation, electrical power production,

thermochemical conversion and residual heat for heating/cooling of buildings or sea water desalination; in Fig. 3 a biomass-based back-up unit integrated in the plant scheme is also shown.

### 2. Current Projects and Future Studies on CSP

The CSP technology can be considered a mature technology for the market and, besides public research, several initiatives are on-going worldwide<sup>7</sup>.

Therefore, the value of the approach is not questionable, but since the start of manufacturing plans the challenge is now how to improve the performance in different terms: construction costs, economy of production, training, easiness of use, flexibility of the system and integration with traditional and new technologies. Alternative molten salts mixture is under investigation at ENEA to ease operation and management of the plant (e.g. lower melting temperature). The molten salts at 550°C are collected in a storage tank. ENEA has conceived an innovative TES system based on a single tank directly integrated with the steam generator, as represented in Fig. 3. Moreover, CSP technology results in many products at different stages towards energy production (Fig. 3) that could be used alternatively; the first product of solar concentration is heat, namely concentrated solar thermal (CST) energy that could be either stored or used for those industrial processes that traditionally need to burn a fuel (the explanatory case of methane steam reforming is shown in Fig. 3). This use would lead to the deployment of greener industrial plants where combustion driven facilities, chimneys and combustion products would be minimized. Therefore, the produced heat at 550°C can then be used to power a heat demanding thermochemical process like steam reforming and/or the produced steam used for electrical power production in a steam Rankine cycle (Fig. 3) for power generation to feed the electric grid or used

locally (e.g. off-grid networks). Finally, residual heat can be used for district heating and cooling or for sea water desalination, a by-product which represents an extremely high added value to the process<sup>8</sup>. When the solar radiation is not adequate to heat the molten salts up to 550°C, a molten salts heater is applied; this back-up unit can be fed by waste biomassderived fuels in order to obtain a 100% renewable energy conversion process to satisfy the heat and power demand with high flexibility. Such energy conversion schemes based on CSP are developed by ENEA in the framework of national and international projects. Among these are the projects MATS<sup>9</sup> (power, heating/cooling and desalination from a CSP plant based on ENEA's technology) and CoMETHy<sup>10</sup> (steam reforming assisted by solar molten salts at 550°C). Specifically, in MATS (Multipurpose Application by Thermodynamic Solar) a plant with the specifications reported in Table 1 is developed, built and demonstrated in the City of Borg El Arab (Egypt). In CoMETHy a molten salts heated steam reforming technology for hydrogen production has been developed and successfully proved with a pilot plant at ENEA-Casaccia research centre in Rome.

| Solar Field            | Туре     | Linear Parabolic<br>Collectors (Solar<br>Trough)   |
|------------------------|----------|----------------------------------------------------|
|                        | Size     | ca. 10,000 m <sup>2</sup> active                   |
|                        |          | mirrors' surface                                   |
| Thermal                | Туре     | Single Tank<br>integrated with Steam<br>Generator  |
| Storage                | Size     | ca. 14 MWh<br>(thermal), equivalent<br>ca. 4 hours |
| Back-up unit           | Туре     | Gas burner                                         |
|                        | Size     | ca. 2.3 MW thermal                                 |
|                        | Туре     | Steam Rankine Cycle                                |
| Electric<br>Power Unit | Power    | 1.0 MWe                                            |
| Desalting              | Туре     | MED: Multi-Effect<br>Desalinator                   |
| Unit                   | Capacity | 250 m <sup>3</sup> per day                         |

Table 1. Main Features of MATS Plant Built as in Borg El-Arab, Egypt.

# 3. Technological Transfer and Social Impact of Industrial CSP

Technological transfer to industry is a key moment to ensure that the performance obtained at the research and development stage can be translated in cost effective/efficient energy production. As mentioned in the previous section, ENEA was the first organization in the world that developed to the prototype and commercial level (12.5 MW thermal, about 5 MW electrical equivalent) the linear focusing CSP technology with solar salts HTF (up to 550°C)<sup>11</sup>. This process lasted about a decade (Fig. 4) and requested a role of the government, in fostering the public research into CSP, from project start-up to prototyping and an industrial role, that involved both the manufacturers and the distributor of energy and resulted in the construction of a demonstrative plan<sup>12</sup>. This "best practice" enabled the creation of a complete new high technology manufacture plant and merged together inter-disciplinary public research, component manufacturing and energy production and dispatch actors. To date, industry is fostering CSP technology in Italy and worldwide<sup>13,14</sup>, and the forecast is that CSP will contribute to global energy production with 90 GW (worst scenario<sup>15</sup>) to 266 GW (best scenario<sup>16</sup>) by 2030 and for a total share of about 28% of all renewable generation by 2060 (the highest growth potential<sup>10</sup>). The path therefore seems to be defined, and future challenges will focus on increasing the technological and economical value of the system.

The social impact of investing in CSP must not be underestimated when capacity is built in countries that are growing in demographical and/or economical terms; in short, the realization of e.g. 50 MW with thermal storage system would employ about 1,500 people during the construction phase of the components and construction of the plant (about 2-3 years). To this figure, 50 permanent jobs must be considered for the management and maintenance of the power station. Moreover, it is worth to underline that about 65% of the new jobs would be located in the regions where the plants will be located<sup>17,18,19,20</sup>.

### 4. CSP as Example of Technology Integration and the Role in the Smart Energy Generation and Management

А sustainable energy production is globally considered a core objective in a historical moment of demographic growth, increasing welfare trends and environmental problems. The simple paradigm "increased population/decreased sources" is articulated and solutions must nowadays more match apparently opposite needs, such as the urbanization and the need of cultivated land, the change in population composition (e.g. the ageing

society) and the different diets in different parts of the society around the globe<sup>21,22</sup>.

Generation and management of renewable energy implies several technological challenges at input and output levels; energy may be generated by different sources and at different times, and enter the electric distribution grid in different places. While renewable energy systems are capable of powering houses and small businesses without any connection to the electrical grid, any excess electricity production shall be stored. These aspects, if one considers the electric grid as traditionally conceived, are revolutionary. Thus, transition to renewable energies poses various levels of technological complexity.

Concentrated Solar Power is a key technology that solves many of the issues mentioned above; the flexibility of the system is important also in terms of societal impact, as the possibility to work in different scenarios and deliver different products may provide answers to the different needs; to make a specific example, in Sub-Saharan Africa (SSA) unreliable power supply poses a major impediment to reduce extreme poverty and boost shared prosperity. "Low density/Long Distance" human settlements and rural areas are lacking access to the grid and this makes costly the distribution of electrical power. This results in poor quality, environmental unfriendly and often unhealthy systems to produce power, that could be overcome if off-grid energy is locally provided<sup>23</sup>; this issue can be solved by the introduction of small CSP plants with single-tank thermal energy storage systems like the one shown in Fig. 3, which could feed small communities with local "mini" distribution grids, together with the production of desalted water and other co-generation services (e.g. heating and cooling of buildings).

ENEA is the first organization in the world that developed to the prototype and commercial level an high performance (550°C) linear focusing CSP technology and is now implementing alternative applications of these technologies; this implies a strong interdisciplinary approach of far related disciplines, from material science and nanotechnology to engineering and ICT to energy management, smart grid concept, climatology, agronomy, etc. All together, this is needed to create the know-how for an efficient use of energy, which would complement CSP with other generations system (e.g. biomass and photovolatics) and should be embedded in the energy and social context of the region where it is implemented. A technology to deliver clean, sustainable energy, and with energy, information, education, health, food production, in industrialized areas as well as in small, isolated communities is the approach ENEA uses also in the framework of strong international cooperation and in collaboration with industries in order to avoid the risk of taking the technology development far away from the societal needs.



Fig .1. Conceptual scheme of the basic components of a CSP plant.



Fig .2. CSP components test plant at ENEA-Casaccia.



Fig .3. General process scheme of a co-generative CSP plant by ENEA.



Fig .4. The basic step of the development of the CSP technology over time and future outlook.

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### REAL OPTIONS ANALYSIS OF RENEWABLE ENERGY INVESTMENT SCENARIOS IN THE PHILIPPINES

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Abstract - With the continuously rising energy demand and much dependence on imported fossil fuels, the Philippines is developing more sustainable sources of energy. Renewable energy seems to be a better alternative solution to meet the country's energy supply and security concerns. Despite its huge potential, investment in renewable energy sources is challenged with competitive prices of fossil fuels, high start-up cost and lower feed-in tariff rates for renewables. To address these problems, this study aims to analyze energy investment scenarios in the Philippines using real options approach. This compares the attractiveness of investing in renewable energy over continuing to use coal for electricity generation under uncertainties in coal prices, investments cost, electricity prices, growth of investment in renewables, and imposing carbon tax for using fossil fuels.

*Keywords* - real options approach, investment under uncertainty, dynamic optimization, renewable energy.

### NOMENCLATURE

| ADF   | Augmented Dickey-Fuller               |
|-------|---------------------------------------|
| BAU   | business as usual                     |
| DCF   | discounted cash flow                  |
| FiT   | feed-in tariff                        |
| GBM   | geometric Brownian motion             |
| IRENA | International Renewable Energy Agency |
| NPV   | net present value                     |
| O&M   | operations and maintenance            |
| PV    | photovoltaic                          |
| RES   | renewable energy resources            |
| ROA   | real options approach                 |

### I. INTRODUCTION

Increasing environmental concerns and depleting fossil fuels have caused many countries to find cleaner and more sustainable sources of energy. Currently, renewable energy sources (RES) supply 12.65% of the total world energy demand in 2016 which includes wind, solar, hydropower, biomass, geothermal, and ocean energies [1]. In the recent years, new investments in renewable energy have grown from US\$1043.8B (2007-2011) to US\$1321.9 (2012-2016) with a geographic shift from the Asia-Pacific region [2], [3]. In the Philippines, renewable energy accounts to 25% of the energy generation mix, mostly from geothermal (13%) and hydropower (10%) [4]. The country is aiming to increase this percent share to 60% in 2030 by investing and developing localized renewable sources at 4% annual growth rate [5]. According to International Renewable Energy Agency (IRENA), the country's topography and geographic location makes a good potential for renewable energy with 170GW from ocean, 76.6GW from wind, 4GW from geothermal, 500MW from biomass, and 5kWh/m2/day from solar energy [6]. Despite its potential, the country's 60% renewable energy goal seems unachievable as the growth in electricity demand increases faster than investment and generation from RES. Meanwhile, the country is burdened by heavy dependence on imported fossil fuels, particularly coal and oil. As more power plants are needed due to closing old coal plants and rising electricity demand, renewable energy seems to be the long-term solution to address the country's problem on energy security and sustainability. However, investment in renewable energy sources is challenged by competitive prices of fossil fuels, high investment cost and lower feed-in tariff (FiT) rates for renewables. These serve as an impetus to evaluate the comparative attractiveness of renewable energy over coal for electricity generation in the Philippines.

This study presents a general framework of investment decision-making for shifting technologies from coal to renewable sources that can be applied to developing countries. By taking the case of the Philippines, this study applies the real options approach (ROA) to analyze various investment scenarios. Traditionally, the discounted cash flow (DCF) or net present value (NPV) techniques are mostly used in evaluating investment projects. These

methods, however, do not cover highly volatile and uncertain investments because they assume a definite cash flow. This assumption makes DCF and NPV underestimate the investment opportunities leading to poor policy and decision-making process, particularly to energy generation projects. Further, these approaches do not allow an investor to define the optimal time to invest or to estimate the true value of project uncertainties [7]. ROA overcomes this limitation as it combines risk and uncertainty with flexibility of investment as a potential positive factor, which gives additional value to the project [8]. This approach evaluates investment projects by considering the investor's flexibility to delay or postpone his/her decision to a more favorable situation [9]. These ROA characteristics are highlighted in this paper as the decision-making process to invest in RES is evaluated in every investment period (annually) using dynamic optimization under various uncertainties.

Recent studies employ ROA to analyze investment decisions, specifically renewable energy, including: Zhang et al. [10] on investment in solar photovoltaic (PV) power generation in China by considering uncertainties in unit generating capacity, market price of electricity, CO<sub>2</sub> price, and subsidy; Kim et al. [11] on analyzing renewable energy investment in Indonesia with uncertainties in tariff, energy production, Certified Emission Reduction price, and operations and maintenance (O&M) cost; Kitzing et al. [12] on analyzing offshore wind energy investments in the Baltic under different support schemes as FiT, feed-in premiums, and tradable green certificates; Tian et al. [13] on evaluating PV power generation under carbon market linkage in carbon price, electricity price, and subsidy uncertainty; and Ritzenhofen and Spinler [14] on assessing the impact of FiT on renewable energy investments under regulatory uncertainty. This research contributes to existing literatures by presenting a multi-period investment coupled with uncertainties in coal prices, cost of renewable technologies, growth of renewable energy investment, FiT price of renewables, and externality for using coal.

The main goal of this paper is to analyze investment scenarios that make renewable energy a better option than continuing to use coal for electricity generation. Specifically, this study employs ROA to evaluate the (1) maximized option value of either continuing to use coal or investing in renewables, (2) value of waiting or delaying to invest in renewables, and (3) optimal timing of investment characterized by the trigger price of coal for shifting technologies from coal to renewables. Sensitivity analyses are done to investigate how the above-mentioned uncertainties affect the optimal investment strategies.

### **II. METHODOLOGY**

The proposed real options methodology is divided into two subsections. The first subsection describes dynamic optimization to calculate the maximized value of investment and identify the optimal timing of investment. The second stage includes the sensitivity analyses with respect to growth rate of renewable energy investment, prices of renewable energy, investment costs, and CO<sub>2</sub> prices.

### Real options model

Consider a renewable energy project with lifetime  $T_{R}$ , which can be irreversibly initiated in three installment periods  $\tau$ ,  $\tau$  + 5, and  $\tau$  + 10 with investment costs  $I_{R_0}$ ,  $I_{R_5}$ , and  $I_{R_10}$ . Assume that the project construction can be finished instantaneously and operated in full load after project completion. If renewable energy project starts in period t, the total net present value of the project  $NPV_R$  can be represented by Equation 1.

$$NPV_{R} = NPV_{R_{0}} + NPV_{R_{5}} + NPV_{R_{10}} = \sum_{r=0,5,10} \left[ \sum_{t=\tau+r}^{T_{R}+r} \rho^{t} PV_{R,t} - (1+\varphi_{r}) I_{R,r} \right]$$
(1)

where r is the installment periods of renewable energy investment,  $\varphi_r$  is the growth of renewable energy investment cost, and  $\tau$  is the period where investor decides to invest in renewable.

The yearly cash flow  $PV_{R,t}$  of renewable energy project comprises of returns from selling electricity from RE and O&M cost  $C_R$ .

$$PV_R = \pi_R = P_{ER}Q_R - C_{R,r} \tag{2}$$

On the other hand, there exists a power plant generated with coal. The net present value of yearly cash flow from coal depends on the returns from selling electricity from coal, O&M cost  $C_c$ , stochastic

cost of fuel  $P_{C,t}$ , and  $CO_2$  price  $C_{C_2CO_2}$  as given in Equation 3

$$NPV_{C,t} = \sum_{t=0}^{\tau} PV_{C,t} = \sum_{t=0}^{\tau} \rho^{t} \pi_{C,t} = \sum_{t=0}^{\tau} \rho^{t} \{P_{EC}Q_{R} - P_{C,t}Q_{C} - C_{C} - C_{C_{c}CO_{2}}\}$$
(3)

where  $\rho$  is the social discount factor,  $P_{EC}$  and  $P_{ER}$  are the prices of electricity from coal and renewable,  $Q_R$  is the quantity of electricity generated from coal/renewable, and  $Q_C$  is the quantity of coal needed to generate  $Q_R$ .

Following previous literatures [15]-[19], this research assumes that the price of coal is stochastic and follows Geometric Brownian motion (GBM). The current price of  $P_C$  depends on its previous price, and the drift and variance rates of time series of coal prices as shown in Equation 4

$$P_{C,t} = P_{C,t-1} + \alpha P_{C,t-1} + \sigma P_{C,t-1} \varepsilon_{t-1}$$
(4)

with  $\alpha$  and  $\sigma$  are the GBM rate of drift and variance of coal prices, and  $\varepsilon$  a random number.

The parameters  $\alpha$  and  $\sigma$  are approximated using augmented Dickey-Fuller (ADF) test from time series of coal prices [20]. The estimates obtained in ADF test are used to generate a matrix of random numbers that represent possible prices of coal from initial values of zero to US\$200 at every investment period from zero to T. These values are then used to calculate the present values of electricity generation from coal for each period.

Using Monte Carlo simulation, the expected NPV for generating electricity from coal is estimated by calculating the  $NPV_{C,t}$  in Equation 3 and repeating the process for a sufficiently large number J = 10000 times. Expected net present value is calculated by taking the average of  $NPV_C$  for every initial price of coal  $P_{C,0}$  as shown in Equation 5.

$$\mathbb{E}\left\{NPV_{C,J} \middle| P_{C,0}\right\} \approx \frac{1}{J} \sum_{j=1}^{J} NPV_{C,J} \approx \mathbb{E}\left\{NPV_{C} \middle| P_{C,0}\right\}$$
(5)

The next exercise in identifying the optimal timing and associated trigger price of coal for shifting technologies is done with dynamic optimization as shown in Equation 6.

$$\max_{0 \le \tau < T+1} \mathbb{E}\left\{\sum_{t=0}^{\tau} \rho^t \pi_{C,t} + \sum_{t=\tau}^{T} \rho^t \pi_{C,t} \left(1 - \mathbb{I}_{\{\tau \le T\}}\right) + [NPV_R + NPV_C] \left(\mathbb{I}_{\{\tau \le T\}}\right)\right\}$$

$$(6)$$

where  $\mathbb{I}_{\tau \leq T}$  is an indicator equal to 1 if switching to renewable energy, otherwise, equal to 0. This model describes an investor who is given a specific period Tto decide whether to continue generating electricity from coal or invest in renewable energy. In this model,  $\sum_{t=0}^{\tau} \rho^t \pi_{C,t}$  accounts to the net present value of using coal from initial period T= 0 until T when the investor makes the decision. If the investor chooses not to invest  $(\mathbb{I}_{\tau \leq T}=0)$ , he/she incurs a net present value of  $\sum_{t=\tau}^{T} \rho^t \pi_{C,t}$  from period  $\tau$  until the end of the coal plant's lifetime. If the investor chooses to invest  $(\mathbb{1}_{\tau \leq T}=1)$ , he/she incurs a net present value of  $NPV_R$  from successive (three-period) investment in renewables plus  $NPV_C$ , as generation from coal will continue at a lower quantity because other electricity will be generated from renewables.

From Equation 6, the investor's problem is to choose the optimal timing of investment  $\tau$ , to maximize the expected net present value of investment. The problem is solved backwards using dynamic programming from the terminal period for each price of coal  $P_{c,t}$  as shown in Equation 7

$$V_t(P_{c,t}) = max\{\pi_{C,t-1} + V_t(P_{c,t-1}), NPV_R + NPV_C\}$$
(7)

with  $V_t$  as the option value of investment at coal price  $P_{c,t}$ .

The optimal timing of investment  $\widetilde{P_C}$  is characterized by the minimum price of coal so that switching to renewable energy is optimal as shown in Equation 8 [19], [21].

$$\widetilde{P_c} = \min\{P_{c,t} | V_0(P_{c,t}) = V_{\mathrm{T}}(P_{c,t})\}$$
(8)

Finally, investment strategy is described by a decision to invest when  $\widetilde{P_c} \leq P_c$ , otherwise, investment can be delayed in later periods until  $\widetilde{P_c} = P_c$ .

# • Parameter Estimation and Investment Scenarios

The following scenarios describe various environments that affect investment decisions in renewable energy in the Philippines. Sensitivity of investment values and optimal timing are analyzed with respect to growth rate of renewable energy investment, price of electricity from renewable energy, investment cost, and carbon prices.

The first scenario is the BAU case which describes the current renewable energy investment scenario in the country. To estimate a suitable set of parameters in this scenario, secondary data from the Philippine's Department of Energy and Energy Information Administration are used [12], [22]. A 30-year period of average annual coal prices from 1987-2016 is used to run the ADF test described in Equation 4. The ADF test result (see Supplementary Information -Table 2) implies that the null hypothesis that  $p_t$  has a unit root cannot be rejected at all significant levels, hence, coal prices conform with GBM. From this test, the estimated GBM parameters are  $\alpha$ =0.032027 and  $\sigma$ =0.249409, and are used to approximate stochastic prices of coal for each investment period. The social discount rate is set to 7.5%. From Equation 3,  $C_{C CO_2}$  is set to zero as there are no existing carbon prices in the Philippines at present. The growth rate of renewable energy investment is set to 2% per annum. This is equivalent to 470GWh of electricity generation from renewables. From this value, the investment cost and operations and maintenance cost for renewables are estimated, as well as the costs and quantity of coal needed to generate this amount. The prices of electricity,  $P_{FR} =$  $P_{EC}$ =US\$182.2/MWh are set equal to the current domestic electricity price, constant during the entire investment period, and independent of the domestic demand. Assumptions indicate that renewable energy sources can generate electricity at an annual average of  $Q_R$  all throughout its lifetime; there are no technological innovations that affect energy efficiency and overnight costs of renewables; and stochastic prices of coal are independent of the demand for renewable energy.

The second scenario describes a situation of an accelerated growth rate of renewable energy investment from the current 2% to 4%, 6%, and 8%.

Meanwhile, the third scenario analyzes the effect of prices of electricity from renewable energy by increasing the current FiT rates to proposed rates. Three prices are set: US\$182.2/MWh at the BAU case, US\$160/MWh which is 10% lower than the BAU case, and US\$200/MWh which is 10% higher. The third scenario describes a situation of a decline in investment costs for renewable energies by 5%, 10%, and 15%, respectively. The last scenario proposes a government policy of introducing carbon tax for electricity generation from coal. The carbon tax is set to US\$ 0.504/MWh.

### III. RESULTS AND DISCUSSION

### • Business as usual scenario

The dynamic optimization process described in the previous section results in three significant values. First is the option value which is equal to the maximized value of either investing in renewables or continuing to use coal. Second is the value of waiting as described by the vertical distance between option value curves: initial period (dotted) and terminal period (bold) of investment. This value approximates the gains of an investor if investment is delayed or postponed to some period. The last estimated value is the optimal timing of investment denoted by the trigger prices of coal for shifting electricity source from coal to renewables. This trigger price is illustrated as the intersection of the two option value curves, and indicates the threshold where the value of waiting is zero and that an investor has no benefit to delay the investment to renewables.

Figure 1 shows the dynamics of option values at different prices of coal in the business as usual scenario. The first point of interest is the positive option values. It indicates that investment in renewable energy incurs positive returns at the current energy situation in the Philippines. This contradicts with the result of Detert and Kotani [19] where the optimization yields negative option values describing a government controlled, operated, and subsidized energy regime. The next point of interest is option value curves sloping downward. This indicates that option values decrease with increasing cost for input fuel. At certain point on the curves, the option values become constant. These are the prices of coal where investment in renewable is a better option than continuing to use coal for electricity generation. The positive values further indicate

positive  $NPV_R$  for investing in renewables. In this scenario, the result shows that the trigger price of coal for shifting technologies is US\$ 129/short ton. This trigger price is higher than the current price of coal US\$93.13/short ton (year 2016), and implies that delaying investment in renewables is a better option. However, at the current coal price, the value of waiting to invest is -US\$105.4 million. This negative value indicates possible losses incurred from delaying investment in renewables.



Fig .1. Option values at the business as usual scenario

### • Growth rate of renewable energy investment scenario

This scenario describes an accelerated growth of investment in renewable energy sources. While the country is aiming to increase the current share of energy generation from renewables from 25% to 60% by 2030 at 4% annual growth rate [5], this goal seems unattainable as the country's electricity demand is increasing at a faster rate than renewable investments [4]. This scenario examines how changing the rate of growth in renewable energy investment affects the option values and trigger prices.

The results of dynamic optimization at various growth rates are shown in Figure 2. It can be observed that option value curves shift upwards. This implies that increasing investment in renewables incurs higher returns from economies of scale. Doubling of wind farms could result in price reductions as the costs can be spread over large production of electricity [23]-[25]. It can be noticed that the trigger prices of coal have also decreased from US\$129/short ton in the BAU scenario, to US\$120, US\$113, and US\$105 at

4%, 6%, and 8% growth rates. Finally, the value of waiting to invest varies from -US\$105.4M at BAU scenario, to -US\$139.5M at 4% growth, -US\$146M at 6%, and -US\$153.7M at 8% growth rates. These results suggest that accelerating the current growth rate from business as usual prevents potential losses from waiting to invest in renewables.



Fig .2. Option values at different rates of renewable energy investment

### · Price of electricity from renewable energy

In this scenario, the effect of changing electricity prices from renewables on option values and trigger prices is analyzed. Currently, the Philippines is one of the countries with the highest electricity rates in the Asia-Pacific region. Compared with neighboring countries including Thailand, Malaysia, South Korea, Taiwan, and Indonesia, the prices are lower as the government subsidized the cost through fuel subsidy, cash grants, additional debt, and deferred expenditures. In the Philippines, electricity prices are higher due to no government subsidy, fully costreflective, imported fuel-dependent, and heavy taxes across the supply chain [26], [27]. By changing the value broadly, this scenario presents how potential government actions regarding electricity prices affect investment conditions in renewable energy.

Figure 3 illustrates the optimization outcomes with varying electricity prices. The result shows an upward shift of option values at higher electricity prices. This result is expected as higher price increases the revenues and the net present value of electricity generation from renewable energy. On the other hand, the result shows the inverse relationship of electricity prices and trigger prices from

US\$129/MWh in BAU to US\$100/MWh at 10% higher and US\$159/MWh at 10% lower electricity price. The values of waiting to invest also show a similar trend from -US\$105.4M at BAU to -US\$25.9M at higher and -US\$241.6M at lower electricity price. This implies that setting the price of electricity generated from renewables higher than current tariff provides a better environment for renewable energy investments. Nevertheless, this study also considers the possibility that extensive electricity generation from renewable energy sources has significant impact on the electricity prices as stated in previous literatures [28-30].



Fig .3. Option values at various electricity prices from renewable sources

### Investment cost scenario

This scenario describes how decline in overnight cost affects investment in renewables. In the recent years, growth in renewable energy investments is driven by several factors including the improving costcompetitiveness of renewable technologies, policy initiatives, better access to financing, growing demand for energy, and energy security and environmental concerns [2], [31] This scenario focuses on the effect of renewable energy cost on investment option values and trigger prices of coal for shifting technologies.

Figure 4 shows the dynamics of option values at various investment cost scenarios. The result shows an upward shift in the option value curves. This outcome is evident as lower investment cost incurs higher net present value for renewable energy, leading to higher option values. The trigger prices decrease from US\$129 in BAU to US\$124, US\$119, and

US\$114 at 5%, 10%, and 10% cost reduction. The value of waiting also decreases from -US\$105.4M in BAU to -US\$86.5M, -US\$68.6M, and -US\$52.2M, respectively. This result confirms the rapid growth in investment as caused by the sharp decline in renewable technology costs.



Fig .4. Option values at different decline trends of renewable investment cost

### Externality scenario

The last scenario discusses the effect of carbon prices for electricity generation from coal. Currently, there are no carbon prices in the Philippines. This study evaluates the effect of imposing carbon tax as proposed in previous literatures [32]-[34]. As shown in Figure 5, the option values and trigger prices decrease with the addition of externality cost. This result is anticipated as additional cost decreases the value of electricity generation from coal. It can also be noted that the trigger price is lower than the current price of coal equal to US\$93/short ton (year 2006). This implies that investing in renewables is a better option than continuing to use coal if carbon tax is imposed. Furthermore, with carbon tax, the demand for carbon-intensive inputs, including coal and oil, will decrease, while less carbon- and carbon free energy inputs eventually increase. This finally supports the research aim of analyzing renewables as a cleaner and more sustainable source of energy and a better alternative to coal.



Fig .5. Option values with externality cost for using coal

### **IV. CONCLUSION**

This study presented various investment scenarios that represent energy switching decisions that apply to developing countries. By taking the case of the Philippines, this study employed real options approach to evaluate the maximized option values of investing in renewables, value of delaying investment, and trigger prices of coal for shifting technologies from coal to renewable sources. While numerous studies applied this approach to analyze renewable energy investments, this study expanded the existing body of research by considering a multi-period investment and taking account of uncertainties in input fuel prices, renewable technology cost, growth of investment in renewables, and externality cost for using coal.

The analyses conclude that renewable energy is a better option than continuing to use coal for electricity generation in the Philippines. Delaying the investment in renewables may lead to possible welfare losses. Shifting from fossil-based to renewable sources is very timely as the costs of renewable technologies have decreased immensely throughout the years and expected to continuously fall. To support investments in renewable energy, the government must set higher FIT rates than business as usual and impose carbon tax for using carbon-intensive fuels. Further, the growth in investment in renewables should be increased to meet the country's goal of 60% energy generation from renewable sources and decrease its dependence on imported fossil fuels.

While this study compared coal and renewables, particularly wind energy, for electricity generation, future studies may also analyze other sustainable

sources including hydropower, energy solar. geothermal, biomass, tidal/ocean, and other technologies designed to improve energy efficiency. Further, environmental uncertainty, such as climate variability and weather disturbances, that affects energy generation may also be included to further capture investment scenarios relevant to climate change policy.

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