An analysis of potential utilization of low cost Cu$_2$ZnSnS$_4$ thin film based photovoltaic in Sumbawa

A Rukini$^1$, L Suhaimi$^1$, A S Pradhipta$^1$, M Anggara$^2$

$^1$Metallurgy Engineering, Universitas Teknologi Sumbawa
$^2$Mechanical Engineering, Universitas Teknologi Sumbawa

E-mail: asywendi@gmail.com

Abstract. Sumbawa has the potential to transition into a smart city, utilizing solar energy as their main source of its alternative energy. Located in the tropical country of Indonesia, Sumbawa’s dry season lasts eight months, during which it sees a solar intensity of 4.51 watt/m$^2$/h, making solar energy a promising resource for the area. Its level of abundance and no pollution attribute are the main factors that make solar energy an attractive renewable resource. Raw calculation showed that solar energy is able to provide massive amount of energy, while solar panel and photovoltaic can produce zero greenhouse gases when converting solar energy into electricity. However, the high initial cost of installing solar cells hinder popularization of it as an alternative energy source, meanwhile some of the substance materials that compose solar panel may have a negative impact on the environment. This study intends to review the potential for inexpensive semiconductor-based solar panels to be applied as independent source of lighting by analysing the cost and environmental impact. Discussion on simple chemical method without high cost equipment instalment is also highlighted in this work, which offers recommendation of methods that can contribute on lowering the production cost of solar panel.

Keywords: solar cell, renewable and sustainable energy, environmental friendly, Cu$_2$ZnSnS$_4$ (CZTS)

1. Introduction

Energy needs compliance from non-fossil resources becomes essential in the middle of global warming issues and oil crisis problem. Photovoltaic and solar cell represent one of the most promising alternative renewable energy. In theoretical calculation where the sun rays intensity that reach earth (land only) is 19%, by considering the ground altitude, solar could produce energy up to 89,300 TWp [1]. Then by assuming that it was absorbed for 6 hours a day solar would provide electrical energy approximately 200 million TWh per year. Latest world electrical consumption was approximately 20 thousand TWh per year [2], while predictions show that the energy earned from solar energy could meet that demand 10,000 times.

The desire to actualize clean energy sources such as solar panels is inspired by the Indonesia's strategic location along the Equator. With average, at least, 8 hours illuminated by optimum solar light and heat, Indonesia has the potential to utilize solar panels as a renewable energy source. However, problems such as the high initial cost, installation and maintenance expense of solar cells, also, the low efficiency are still obstacles in realizing the solar energy as an alternative energy. It has been more than a century since the first complete photovoltaic cell was produced in 1888, yet its development in
industrial scale for energy serving has not covered many levels of society. A survey taken from market report European photovoltaic industry revealed that by the end 2014 only 3% of electricity provided from solar cell or photovoltaic sources [3,4]. The noticeable hurdles for this technology are its high production cost and expensive commercialization.

Early versions of solar cell required around $250 in order to produce 1 watt electricity from solar cell equipment even in summer day-like condition. Meanwhile, it only took $2 to $3 to convert coal calories to electricity in the same time [5]. This was due to the low efficiency of electrical energy conversion, expensive fabrication processes and high price of solar cell’s raw materials. Accordingly, various attempts have been pursued by researchers to improve photovoltaic cell efficiency, invent new cheap combinations of semiconductors and develop affordable methods and technologies. Thus, the future trend of photovoltaic cell will be based on cheap material based, high efficiency and easy fabrication. Currently, the first- and second-generation are the commercial solar cell that widely distributed in the market. However, the one that dominating the market (> 90%) is still the first generation of solar cell or crystalline silicon (c-Si) based solar panel, either mono-crystalline or polycrystalline wafer based [6]. Mono-crystalline wafer of silicon based solar cells apparently are the most expensive kind due to the difficulty of single crystal Si production. On the other hand, second generation or thin film based photovoltaic gain attention in market because its lower price and aesthetically pleasing appearance. Thin film PV offers a less bulky module of solar panel, with some having flexible and even transparent form. Thin film solar cells have several types of semiconductor such as Si-thin film, CdTe/CdS, CIS/CIGS and CZTS/Se. Among the developed semiconductor types, CZTS is the most affordable when comparing the cost of raw materials (Figure 1).

![Minimum cost of raw materials of each thin films](http://dx.doi.org/10.5772/50702)

Figure 1. Minimum cost of raw materials of each thin films (© 2013 Jiang M, Yan. Published in IntechOpen under CC By 3.0 license. Available from: http://dx.doi.org/10.5772/50702.)

Naturally, technology that is used to produce solar cell module also determine the cost in the market. Physical methods mostly required high tech equipment which in turn also need certain quality of substrate in order to generate a good consistency solar panel or thin films. On the other hand, the chemical route is able to utilize simpler equipment and wide range quality of substrate, although the products generated from this method sometimes have lower precision due to several controlled variable. Logically, the combination of inexpensive solar cells and a simple fabrication process are important steps towards developing low cost solar panels on an industrial scale. Therefore, second generation CZTS based solar cell produced via chemical method is the projection of manifesting more affordable solar panel.

2. Cu$_2$ZnSnS$_4$ (CZTS) semiconductor as an alternative

Cu$_2$ZnSnS$_4$ or often called as CZTS is a thin film compound which has recently been used as an absorbent material in photovoltaic cell devices as an alternative to the chalcopyrite-based CuInSe2 (CIS)
thin film, CuIn1-xGaxSe2 (CIGS) and Cu (In, Ga) (S, Se) (CIGSS) [7,8]. Before CZTS was well developed, CIS, CIGS and CIGSS were well known as the most potential candidates to be used as absorbents on thin film based photovoltaic or thin film solar cell (TFCS’s). With efficiencies at almost ~20%, CIS compound generated from co-evaporation route was considered attractive to be developed commercially [9–11]. Unfortunately, the supply of rare metal Indium in the future mass production is considered problematic. One estimation for CIS based solar panel show that 30 tons of Indium is required to produce 1 gigawatt of electricity [9]. Even though the prior requirements might be met, one also needs taking the demand for the production of an indium tin oxide (ITO) transparent substrate into account, the demand for ITO production in the future might also lead to competition that can limit CIS production [10].

CZTS is considered a potential candidate for absorbance material obtained by substituting half of the indium with zinc (Zn) and the other half with tin (Sn). For CIGS or CIGSS semiconductor, the In and Ga elements are substituted by Zn and Sn. All the constituent components of CZTS are plentiful in the earth crust (earth abundant) unlike Ga, In and Se which are rare (rare earth) elements. Sequential levels of Cu, Zn, Sn and S are around 50 ppm, 75 ppm, 2.2 ppm and 260 ppm from the earth’s crust [11]. While the content of In, Ga, and Se are each small than 0.05 ppm [11]. This thin film has been developed with diverse method either physically or chemically, which those experiments verified that the band gap of CZTS thin film ranged from 1.4 to 1.5 eV [12]. Aside from suitable optical properties, CZTS elements are also low cost and non-toxic to be applied as solar cell semiconductor.

3. Cost and environmental impact of CZTS

CZTS is a one of kind of low-cost quaternary thin film that is easy to acquire due to its earth abundant elements, therefore has relatively low cost and is easy to obtain. However, simply being affordable is not sufficient. Developing clean and environmental friendly energy is also an important aspect for generating new technology or device. As a clean energy source, CZTS based solar panel also contributes minimize the effect of global warming, yet another environmental factor such toxicity at production process is also need to be assessed.

3.1 Cost

CdTe and CdSe based thin films possess such high absorption coefficient and efficiency [13–15] by the consequence as the highest manufacturing cost among other thin film photovoltaic [16]. By comparing the minimum cost of thin films production on Fig. 1, CZTS only needs less than half cost to produce 1 watt electricity from CIGS based thin films. The availability of Zn and Sn source is relatively competitive compared to In and Ga source [15], but the annual production of two former elements reach hundred thousand and thousand times that of the later elements [16]. Although known as the second most abundant elements in earth’s crust, the production process of silicon requires a lot of energy and cost twice than Zn and Sn that cost under $100/kg. With above ten thousand tons of production per year in element combination, CZTS could be one of the sustainable thin films to produce. Although the constituent elements are affordable, complete solar cell panels do not consist of semiconductor alone. Cost calculation of solar cell panels also includes a complete module construction and the output such as efficiency. From online supplier platform survey, thin film modules do not have significant lower prices over c-Si based module. This happened due to some considerations such as efficiency, required space area, temperature coefficient etc. Up until now, the highest efficiency produced by Si based solar cell. The higher the efficiency, the lower the cost to convert per watt electricity. Recent highest efficiency record for single cell is GaAs cell at 30.5% and for multi-junction cells GaInP/GaAs/GaInAsP/GaInAs at 46.0% [17]. In the other word, CZTS has low cost and sustainable sources, yet, it is not necessarily urgent to replace Si based solar cell when it comes to complete module cost confrontation.

3.2 Environmental Impact

Solar energy known as green energy due to its less pollution and zero CO/CO₂ emission. However, elements on semiconductors are not always environmental friendly. For instance, arsenic in GaAs thin films is notorious for its toxicity. Likewise, cadmium based thick films (CdS, CdSe, CdTe), Cd is potentially restricted due to heavy metal pollution and Te suffer from strong carcinogenicity [15]. Every element in CZTS compound is not only earth abundant but also safe with relatively no harm effect to its
surroundings, while Se in CIGSS could potentially cause environmental problem [7,18,19] and some found that low amount of Cd metal can be present in CIGS solar cell [20]. Therefore, with respect to health and environmental concerns, CZTS is one of the best thin film options to produce.

4. Promising low cost methods on thin film making

One of the most effective steps towards lowering price of a product is to modify the methods used. In the 1960s, a solar power corporation (SPC) worker named Elliot Berman found that low price is one of the ultimate magnets for alternative energy demands. In 1969 the production cost of electricity from photovoltaic cell assemble was $100/watt and it was lowered up to $20/watt by analyzing and eliminating the unnecessary steps [21]. By eliminating polishing process and anti-reflective layer coating step, Berman developed rough silicon wafer that were far more effective at adsorbing solar rays. Refining the methods by eliminating redundancies leads to the development of cheaper, more efficient solar cells.

In general, the methods used to produce thin films can be categorized into physical and chemical, which can be divided into more specific processes. In the physical route, thin films target is deposited into substrate by using external force in vacuum evaporation condition or well-known as sputtering, where the target is transferred in a gas state. Meanwhile, the chemical method involves chemical reaction among precursor around substrate surface. Among many established methods, there are several chemical-derived methods that only require simple step and easily acquired equipment. Solution-based approaches could potentially be applied for industrial scale production to attain low cost solar panel [22], specifically, sequential solution-phase deposition such as successive ionic layer adsorption and reaction (SILAR), electrochemical layer deposition (ECALD), and ionic layer gas reaction (ILGAR), all of which will be discussed in the section bellow.

4.1 SILAR method

Successive ionic layer adsorption and reaction (SILAR) is a derived technology developed from modification of chemical bath deposition (CBD) method and deposit thin films similar to atomic layer deposition method. SILAR was first experimented by Nicolau and his colleague in 1985 [23,24]. Due to unnecessary precipitation, CBD were modified into SILAR to avoid the precipitate byproduct. SILAR is considered as a potential method to deposit thin films on industrial scale without expensive technology and high maintenance equipment. Advantages of SILAR method listed by Pathan and Lokhande [25] are as follows: It is easy to doping a particular element into films with various proportion only by add the element into solution; SILAR does not require high quality substrate nor vacuum condition, Deposition rate and film thickness can be controlled by changing the deposition cycle, There is no local overheating that harm the materials like some particular physical method, There is no material limit for substrate either in dimension or surface profile and SILAR is easily applicable to a wide area of deposition.

The main step of SILAR on depositing thin film compound is dipping the substrate in cation and anion precursor solutions separately. The dipping is repeated in sequence until the film’s desired thickness is obtained. Duration of immersion time affected the optical properties of thin film [26]. As it show in Figure 2, there are rinsing processes in between cation and anion precursors. The aim of rinsing process is to avoid unnecessary aggregates growth. Due to its simplicity, this process can be done manually with hands, beaker glasses and a timer. However, chemical compound of thin film generated by this method might not be stoichiometric.
4.2 ECALD method

Electrochemical atomic layer deposition (ECALD) is based on layer by layer electrodeposition [27] wherein each film’s constituent is deposited one by one separately in cycle, and in underpotential deposition condition of the elements. Underpotential deposition condition means an atomic layer of one element can be deposited onto the other’s element surface under the potential that needed to deposit the element itself. This deposition is somewhat similar to SILAR, only the deposition process involves reduction-oxidation replacement or electrochemical reaction as illustrated in Figure 3. ECALD method allows high quality thin film formation and stoichiometric compound [28]. No rinsing process, yet ECALD process capable of controlling the deposition process at room temperature. Other than that, this method does not require any further thermal treatment such as annealing to form highly ordered crystalline structure [29].

4.3 ILGAR method

Ion layer gas reaction (ILGAR) is part of chemical deposition techniques wherein the metal precursors are dipped or sprayed on the surface’s substrate. The sequence including precursor’s absorption, drying and followed by sulfurization and then repeat in cycles depends on desired thickness of thin film (Figure 4). Contrary to SILAR, reaction on ILGAR happen in solid-gas state. Similar to other sequential approach, this method does not require vacuum and high-temperature condition. The quality of thin film depends on the precursor preparation. Sprayed
ILGAR generally possess higher growth rates and allows reagent gas more easily penetrates the substrate compared to the SILAR method [30,31].

![Basic principle of ILGAR method](Image)

**Figure 4.** Basic principle of ILGAR method

5. Discussion and recommendation

There are several potential sources of renewable energy that can meet the energy needs of Sumbawa. The survey shows some potential electricity sources to be developed in NTB province range from micro-hydro power sources from rivers and dams, sources of electricity from wind, sources of electricity from sunlight, biogas and geothermal energy. However, in Sumbawa, only solar and micro-hydro can really be utilized. As for now, only Maronge and Batu Lanteh regions have been able to develop independent energy based on solar power as a source of lighting [33][34]. The annual report from the Bidang Energi (national energy board) [32] showed the average intensity of solar radiation in NTB is 4.5 watts/m²/hour. BMKG (meteorology and geophysical unit) noted that on average Sumbawa sees four wet months throughout the year; December, January, February and March. The rest is a dry month with nearly zero rainfall and optimum sunlight intensity of more than 8 hours a day. As such, solar cells are more promising than micro-hydro as the latter relies on full flowing rivers that most of the time low debited and discharge during the dry season.

Based on current data, there are around 1013 and 608 units of solar home systems (SHS) in Sumbawa and Sumbawa Barat respectively, with one unit of communal solar panel in each area. The total solar energy that is currently able to be produced by solar panel in each region is 129,998 kWh and 82,692 kWh [33]. Figure 5 shows the average utilization of solar energy in Sumbawa and Sumbawa Barat area as well as a projection for the next five years. Current solar energy consumption is about 1,142 barrel of oil equivalent (BOE) and is expected to increase by 18% in 2025. Also, the status of current consumption from solar energy is under 0.1% of Energy needs in Sumbawa region [33].
In 2015, 500 units of SHS were installed in Sumbawa and Sumbawa Barat, and by 2025 it is estimated that only 350 units added. A unit SHS has 50Wp (watt peak) capacity. Assumed that the maximum sun radiation is 4.5h, therefore, capacity of a unit SHS is 225 watt hour/day. While, current communal solar system installed is 5000 kW and added by the same amount in the next five year as resumed in table 1. If a BOE is equivalent with 1.7 MWh electricity, then energy projection in 2025 (2.3 MWh) seems hard to be in accordance with the plan on table 1. If the expenditure cost of every 50Wp instalment is USD 694 [34] and the interest rate of every 5 year is 12%, the total investment to installed SHS in Sumbawa region in 2025 is about USD 242,900. While the budget on communal solar panel is USD 90 million by 2025. The low future development of solar energy in Sumbawa most probably is caused by familiar problems that already mentioned before, such as the high cost of installation and high initial cost of solar cells. Utilization of CZTS or amorphous Si based thin film is relevant to overcome intensive initial cost. Referring to levelised cost of electricity generation (LCOE) report in 2015, average capital cost of c-Si, amorphous Si and CIS/CIGS is 0.35 USD/KWh, 0.30 USD/KWh and 0.31 USD/KWh respectively [34]. As CIS/CIGS based solar panel suitable on utility or communal scale application, therefore, if the initial cost of CZTS based solar cell occurs in range of CIS/CIGS’ cost, then the USD 90 million-communal solar budget can afford 2.9 MWh.

| Year | SHS development plan | Communal SC development plan |
|------|----------------------|------------------------------|
|      | Sumbawa | Sumbawa Barat | Sumbawa | Sumbawa Barat |
| 2010 | -        | -               | -       | -              |
| 2015 | 300 units | 200 units | 0.005 MW | 0.005 MW |
| 2020 | 200 units | 150 units | 0.005 MW | 0.005 MW |
| 2025 | 200 units | 150 units | 0.005 MW | 0.005 MW |

(Information adapted from CASINDO NTB (2011))

Contributions from local researchers to develop or at least adopt simple technology that is capable of being applied on an industrial scale are necessary. By developing inexpensive semiconductor-based solar panels via simple chemical methods discussed above (SILAR, ECALD and ILGAR), it is expected to reduce the initial cost. Investment cost on wet chemical method significantly lower compared to physical route. Such costly equipment and high-quality substrate in table 2 are not required in chemical procedure. Thus, with the same amount of budget, if local researcher could independently produce low cost semiconductor and self-
assemble solar panels, electricity target produced from solar power in Sumbawa can be fulfilled. Other than low-cost and environmental issue, concern in the future might be related to the energy storage or batteries and the efficiency of energy conversion.

### Table 2. Investment comparison between wet chemical method and physical method

|                              | Wet Chemical Method | Physical Method |
|------------------------------|---------------------|-----------------|
| Deposited material          | Dissolved in water  | Ionized raw material |
| Substrate                   | Low quality can be accepted | High quality substrate |
| Vacuum equipment             | X                   | ✓               |
| Sputtering or deposition device | X               | ✓               |
| Annealing oven               | Optional            | ✓               |

6. Conclusion

Analysis on environment impact and availability supply of raw materials suggests CZTS as the strong candidate among thin film types to be used as semiconductor in Sumbawa’s solar panel. Even though a complete module of thin film solar panel is not competitively cheaper than Si-based, high initial cost problem can be reduce by preparing CZTS via recommended low-cost methods such as SILAR, ECALD and ILGAR method. Using the same amount of budget, Sumbawa region potentially afford more number of solar panel to be installed in Sumbawa when CZTS based solar panel generated via low cost method substitutes the first generation type panel. Nonetheless, investigations on energy storage and performance of solar panel need to be included in the future study.

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