

Tsafack, Pierre; Ngwashi, Divine; Ducharne, Benjamin; Tanyi, Emmanuel

Article

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Greenness percentage of the said green renewable energy: A case study

Pierre Tsafack^{a,*}, Divine Ngwashi^a, Benjamin Ducharne^b, Emmanuel Tanyi^a

^a Faculty of Engineering and Technology of the University of Buea, Cameroon

^b Institut National des Sciences Appliquées de Lyon (INSA Lyon), France

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ABSTRACT

The manufacturing process of renewable energy components involves some conventional energy at different steps. It is then clear that the fabrication of the components of a renewable energy system will emit an amount of greenhouse gas (GHG). The work carried out in this paper is based on investigating a sample of 1 m² solar panel and analyzing the energy involved in its complete fabrication process as well as the amount of GHG emitted. The energy generated by the sample during its useful lifetime is evaluated and the prevented amount of carbon dioxide (CO₂ recovered) computed; that CO₂ recovered is the amount of GHG which could have been emitted if the conventional energy sources were to be used to generate that same amount of lifetime energy. The greenness percentage with regards to renewable energy material (photovoltaic) is then defined as a ratio of GHG emission (CO₂-eq.) during fabrication and GHG prevented (CO₂ recovered) as a result of had been using the panel throughout its entire lifetime. It appears that if manufactured in china and installed in Cameroon, the 1 m² module exhibits a greenness percentage of 49.14% in *Bamenda* and 29% in *Ngaoundéré*. The same photovoltaic sample is 98.43% green if manufactured in Cameroon and installed in China. Thus, a solar panel installed in china, if manufactured in Cameroon will need only about 0.44 years to compensate the amount of GHG emitted during manufacturing in Cameroon which is equivalent to a gain of more than 29 years of pollution free period out of the 30 years of expected average lifetime of a photovoltaic module.

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1. Introduction

As the world seeks cleaner power, solar energy capacity has increased during the recent years; although the harvesting of electricity from solar installations is clean process, manufacturing solar panels can be harmful to the environment (Weisser, 2007a; Weidema et al., 2008; Whitaker et al., 2012; Warner and Heath, 2012; Kim et al., 2012). Fabricating solar panels involves the use of corrosive chemicals such as hydrochloric acid and sodium hydroxide. This process requires a huge amount of electricity from conventional means which produces greenhouse gases (GHG) and waste (Weisser, 2007a; Weidema et al., 2008; Whitaker et al., 2012; Warner and Heath, 2012; Kim et al., 2012). Some previous works investigated the lifecycle damages (i.e. GHG emissions) of the renewable energy sources (Weisser, 2007a; Weidema et al., 2008; Whitaker et al., 2012; Warner and Heath, 2012; Kim et al., 2012; Hsu et al., 2012; Dolan and Heath, 2012; Padey et al., 2012). The greenness percentage discussed in this paper aimed therefore at considering both those damages and the benefit

(i.e. the amount of GHG prevented thank to the lifetime use of those components) of had used a manufactured module during its entire lifetime.

Considering the total amount of GHG which could have been emitted if conventional energy sources were used to produce the lifetime energy of a sample of 1 m² solar panel, that is “CO₂ recovered” or “CO₂ prevented” as a result of had been using that solar panel, the greenness percentage (GP) represents the ratio of the “CO₂-eq”. due to the fabrication process and “CO₂ prevented”. Given that half of the world’s photovoltaic modules are from China (Teklu, 2010), this research work aimed at evaluating the GP of a 1 m² sample of photovoltaic module manufactured in China.

In view of covering our target, we started with the design process of PV cells highlighting the various steps and products involved in its manufacturing process and their ecological impacts, then continue with the fabrication energy estimate of the sample. Using Cameroon (Localities of *Bamenda* and *Ngaoundéré*) as case study along with the carbon footprint of energy sources in Cameroon and china, this section provides the procedure (along with the results) to evaluate the GP.

* Corresponding author.

E-mail addresses: tsafack.pierre@ubuea.cm (P. Tsafack), ngwashi.divine@ubuea.cm (D. Ngwashi), benjamin.ducharne@insa-lyon.fr (B. Ducharne), tanyi.emmanuel@ubuea.cm (E. Tanyi).

Nomenclature

GP	Greenness Percentage
g_{CO_2}	Carbon footprint; that is CO_2 emission (g_{CO_2}/kWh) of each type
GC	Generating Capacity/Representativeness of each type of energy (in percentage)
$G_{CO_2(China-M)}$ in kg_{CO_2}	The total amount of CO_2 emitted to manufacture a 1 m^2 solar panel in China
$G_{CO_2(Cam-M)}$	The total amount of CO_2 emitted to manufacture a 1 m^2 solar panel in Cameroon
E_{inp}	Manufacturing energy of a 1 m^2 solar panel in 2006
E_0	The year zero annual average energy generation in kWh
E_{0-B}	The year zero annual average energy generation in kWh in <i>Bamenda</i>
E_{0-N}	The year zero annual average energy generation in kWh in <i>Ngaoundéré</i>
E_n	Expected energy at the n th year
E_L	Lifetime energy of a 1 m^2 solar panel
E_{LB}	Lifetime energy of 1 m^2 solar panel in <i>Bamenda</i>
E_{LN}	Lifetime energy of 1 m^2 solar panel in <i>Ngaoundéré</i>
$G_{CO_2(Cam-LB)}$	The total amount of CO_2 that would have been emitted in <i>Bamenda</i> if the conventional means for supplying electricity was implemented to provide the same amount of energy
$GP^{China-Cam}_{Bamenda}$	GP of a 1 m^2 solar panel manufactured in China and installed in Cameroon (<i>Bamenda</i>)
$GP^{China-Cam}_{Ngaoundere}$	GP of a 1 m^2 solar panel manufactured in China and installed in Cameroon (<i>Ngaoundéré</i>)
$GP^{Cam-Cam}_{Bamenda}$	GP of a 1 m^2 solar panel if manufactured in Cameroon and installed in Cameroon (<i>Bamenda</i>)
$GP^{Cam-Cam}_{Ngaoundere}$	GP of a 1 m^2 solar panel if manufactured in Cameroon and installed in Cameroon (<i>Ngaoundéré</i>)
$GP^{Cam-China}_{China}$	GP of a 1 m^2 solar panel if manufactured in Cameroon and installed in China
$GP^{China-China}_{China}$	GP of a 1 m^2 solar panel if manufactured in China and installed in China
CO_2	Carbon Dioxide
$POCl_3$	Phosphorus Oxy-Chloride
PV	Photovoltaic
FDI	Foreign Direct Investment
GDP	Growth Domestic Product
NaOH	Sodium Hydroxide
KOH	Potassium Hydroxide
E	Energy
Si	Silicon
source, i	Energy source number “i”
$G_{CO_2(Cam-LN)}$	The total amount of CO_2 that would have been emitted in <i>Ngaoundéré</i> if the conventional means for supplying electricity was implemented to provide the same amount of energy
GHG	Greenhouse gas

Table 1

Materials involved in a solar cell fabrication.

Raw material	Cell type	Doping	Shape & Size	Thickness
Silicon wafer	Mono-Crystalline	P type	$150 \times 150\text{ mm}^2$	$200\text{ }\mu\text{m}$

2. PV cells fabrication process

2.1. Technologies in use

Based on the cell fabrication technologies, there are buried contact solar cells, screen printed solar cells, high efficiency solar cells and rear contact solar cells (Teklu, 2010; Shafiqul Islam et al., 2014; Fthenakis and Wang, 2006). A number of technologies are being used for junction formation which consists of creating a new layer called ‘emitter’ in the substrate material. The technologies commonly used for this doping method are phosphorus diffusion from phosphorus Oxy-Chloride ($POCl_3$), Ortho-Phosphoric acid (Bentzen, 2006), Spin on Dopant Process, Ion Implantation, spraying method, epitaxy (Shafiqul Islam et al., 2000). In addition to these techniques, various chemical vapor deposition methods are used in fabricating solar cells. Some of these are Atmospheric Pressure Chemical Vapor Deposition (APCVD), Low Pressure Chemical Vapor Deposition (LPCVD), and Plasma Enhanced Chemical Vapor Deposition (PECVD) (Ivanda, 2011).

2.2. Selection of a technology

Out of the technologies in use, it is observed that ‘Spin on Doping’ and spraying method are cheaper than diffusion from a $POCl_3$ source and Epitaxial (Shafiqul Islam et al., 2014). The $POCl_3$ diffusion process is slightly expensive as it involves the use of advanced machinery, chemicals that lengthen the process (Bentzen, 2006). $POCl_3$ diffusion method is nevertheless the widely used method by the solar cell manufacturers for emitter formation (Bentzen, 2006; Wolf et al., 2015) because it offers a large processing capability. Another advantage of this approach is the self-governing control of the pre-deposition and the drive-in (Shafiqul Islam et al., 2014). The carrier lifetime of the multi-crystalline wafers is increased tremendously in the $POCl_3$ diffusion process (Lossen and Beneking, 2005). Regarding to the application of the metal contacts, ‘screen printing’ is the simplest and most cost effective (Shafiqul Islam et al., 2014).

3. Mono crystalline solar cell fabrication process using $POCl_3$ diffusion gas source

There is a set of basic materials, machinery, chemical components and equipment. The basic material used for solar cell fabrication is mono crystalline type silicon wafers which are initially p-type doped (Shafiqul Islam et al., 2014). Table 1 portrays the specifications of the basic materials.

Fig. 1 is a flow chart briefly describing the solar cell fabrication process (Shafiqul Islam et al., 2014).

3.1. Wafer cleaning and texturing

The p-type doped starting wafers are initially uneven due to saw damage and it is coated with cutting fluid. In order to remove these, saw damages from the outer layer of the silicon, a strong alkaline (NaOH, KOH) is used (Shafiqul Islam et al., 2014; Bremner, 2009). This is illustrated on Fig. 2.

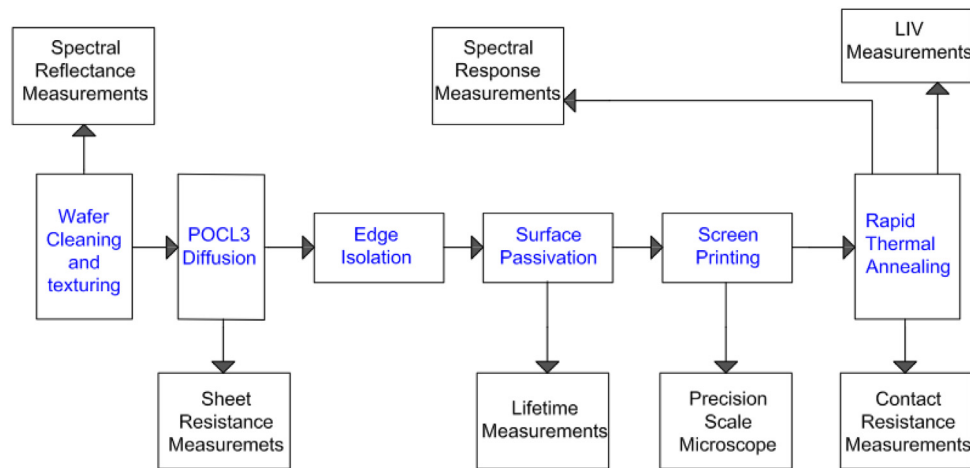


Fig. 1. Flow chart of a solar cell fabrication (Shafiqul Islam et al., 2014).



Fig. 2. Si wafer cleaning and texturing process (Shafiqul Islam et al., 2014; Bremner, 2009).



Fig. 3. Emitter formation (Bremner, 2009; Tomoo, 2012).

3.2. POCL₃ diffusion

POCL₃ Diffusion (n type) is used for emitter formation. Phosphorus is diffused from liquid Phosphorus Oxy-chloride (POCL₃) source in a quartz tube (Shafiqul Islam et al., 2014).

Once the samples are loaded in the tube, the furnace is heated up to the adequate temperature (800–1000 °C) before the process starts. Phosphorous source is fed in the furnace via a carrier gas. The generated phosphorous diffusing into the wafer surface creates a pn junction as illustrated in Fig. 3 (Bremner, 2009; Tomoo, 2012); edges are mechanically isolated.

The diffusion is a two stages process; first, a shallow pre-deposition using a semi-infinite source; second, a higher temperature drive-in diffusion using the pre-deposition as the source.

However, the n type layer at the edges means that the top and the bottom are connected as illustrated in Fig. 4 (Bremner, 2009).

3.3. Edge isolation

Edge isolation paste around the cell is used to separate the continuity, as phosphorus is diffused into both front and rear surfaces (Shafiqul Islam et al., 2014). Fig. 5 shows the edge isolated Si-wafer done mechanically. When the junction is not isolated during diffusion process as illustrated in Fig. 4, the cells are stacked together and clamped on either side to expose only their edges. These edges are then etched away by highly reactive plasma to remove the junction (see Fig. 5) (Bremner, 2009).

3.4. Surface passivation

Passivation, in physical chemistry and engineering, refers to a material becoming “passive”; that is less affected or corroded by the environment of future use. Passivation involves creation of an outer layer of shield material.

Although this process occurs naturally on the surface of stainless steel, it is often useful to accelerate and assist in the development of the passivation layer. Passivation occurs when chromium oxidizes with the oxygen in the air to form a corrosion resistant passivation layer. This process can be accelerated and assisted with a passivation product, ensuring the development of a uniform and thick passive layer.

As a technique, passivation is the use of a light coat of a protective material, such as metal oxide, to create a shell against corrosion.

As illustrated in Fig. 6 (Tomoo, 2012), the passivation is preceded by a stainless steel which is essentially an iron alloy composed of chromium and carbon. The chromium properties provide stainless steel with superior corrosion resistance (Tomoo, 2012).

The main requirement for stainless steels is that they should be corrosion resistant for a specified application or environment. The selection of a particular “type” and “grade” of stainless steel must initially meet the corrosion resistance requirements.

3.5. Screen printing

The bottom surface will have a solid contact covering the entire area and the top surface, a thin grid of metal contacts. This provides a uniform coverage for charge collection while simultaneously allowing light to enter the surface of the silicon (James and Scrapulla, 2012). The rear surface of the panel is screen printed by applying aluminum paste and the front surface, the silver paste as illustrated in Fig. 7a and b (Shafiqul Islam et al., 2014). The final product is depicted on Fig. 10.

In Suntech based in China, the n type layer on the rear surface is chemically (using hydrofluoric acid) removed (see Fig. 8) during edge isolation before applying the aluminum paste at this stage (Tomoo, 2012; James and Scrapulla, 2012).

Fig. 9 depicts a machine printing aluminum paste on the surface of the cell at Suntech (Tomoo, 2012).

3.6. Rapid thermal annealing

After printing, it is fired at a high temperature to fire the metal into the silicon (see Fig. 11a), consuming the n-type layer on the

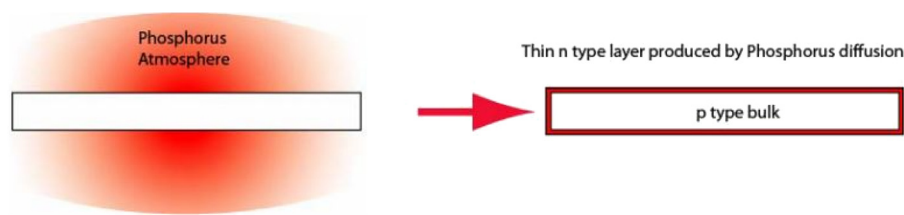


Fig. 4. Emitter formation (edges not isolated) (Bremner, 2009).

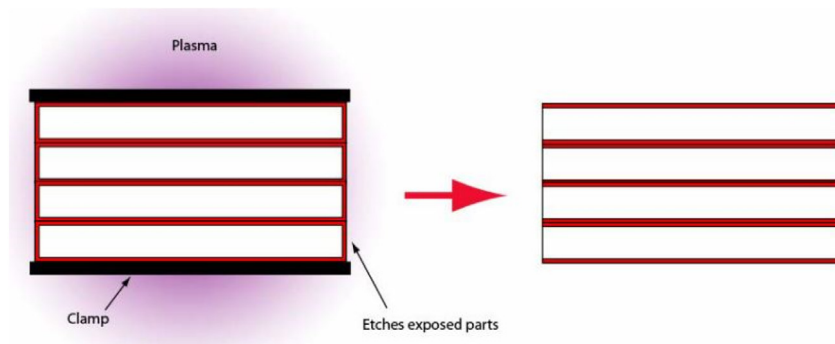


Fig. 5. Edge isolation using plasma (Bremner, 2009).

The Stainless Steel Process

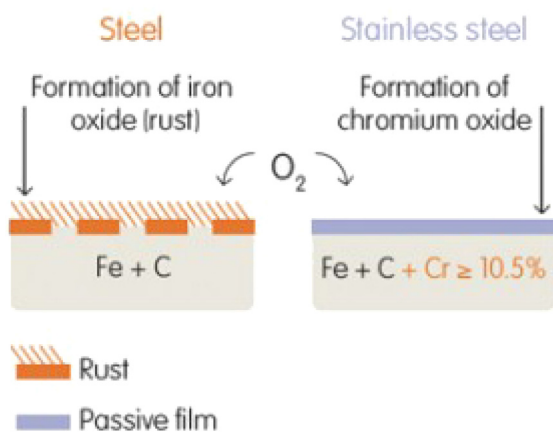


Fig. 6. Stainless steel pickling and passivation (Tomoo, 2012).

rear surface and creating the semi-conductor pn junction on the front surface (see Fig. 11b) (Bremner, 2009).

In Most solar cell manufacturing companies such as Suntech, the cell is fired after the application of both pastes (Bremner, 2009) (see Fig. 12).

4. Energy and CO₂ audit for manufacturing a 1 m² PV cell sample

As indicated in the introduction, the solar cell manufacturing process involves a number of chemicals at the various steps and a consumption of a huge amount of energy. Fig. 13 illustrates the energy consumption in a typical solar cell manufacturing company (starting from the wafer). This section provides the procedure adopted (along with the results) to assess the greenness percentage of a 1 m² solar panel. Starting with the assessment of the energy inputs to manufacture 1 m² solar panel it continues with the yearly and lifetime energy output. The solar panel is

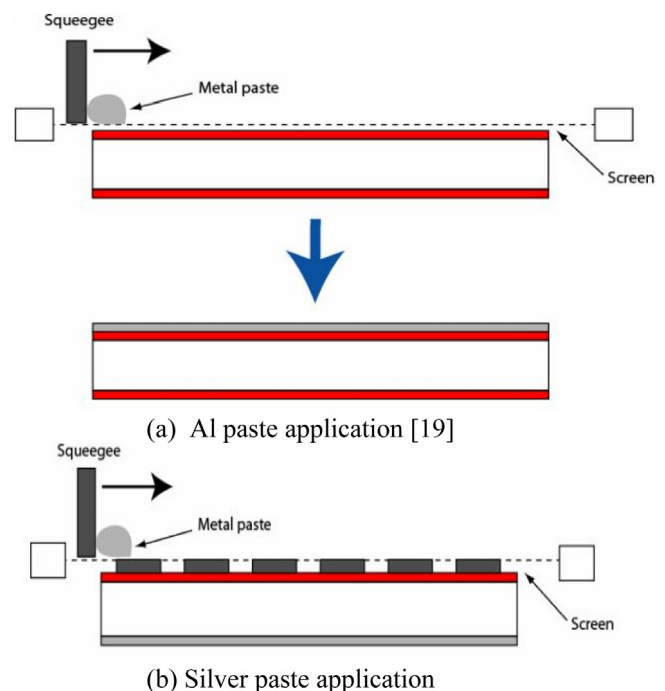


Fig. 7. Paste application (Shafiqul Islam et al., 2014).

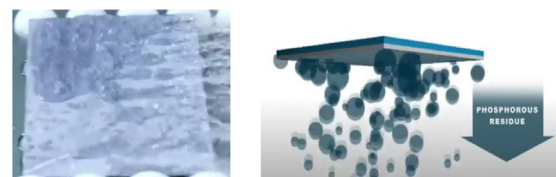


Fig. 8. N-type layer removed chemically.

assumed to be installed in two different locations of Cameroon; that is *Bamenda* and *Ngaoundéré* which can represent the typical

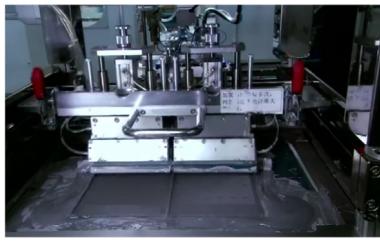


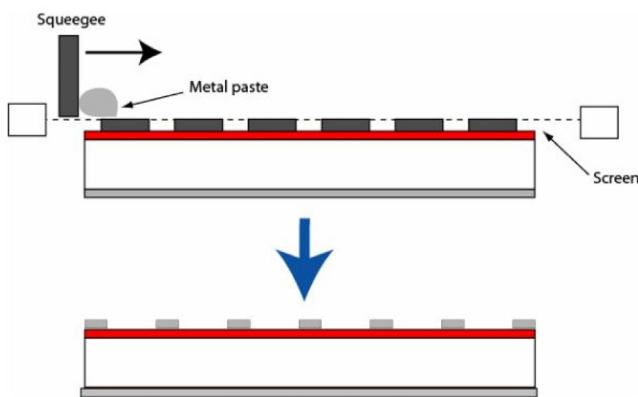
Fig. 9. Printing Al paste at Suntech (Tomoo, 2012).



Fig. 10. Screen printed finished type Si wafer.



(a) N type layer removal



(b) PN junction formation

Fig. 11. N-type layer removal and PN junction formation.

climate of Cameroon (David et al., 2018). We will also evaluate the “CO₂-eq.” due to the input energy (by considering the carbon footprint of the various energy sources) as well as the “CO₂ recovered” or CO₂ prevented as a result of had been using that manufactured solar panel.

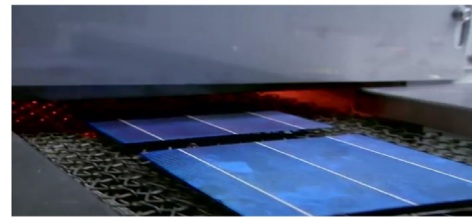


Fig. 12. Contact creation.

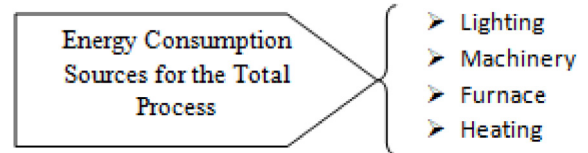


Fig. 13. Energy consumed to manufacture a cell (Dale, 2013a).

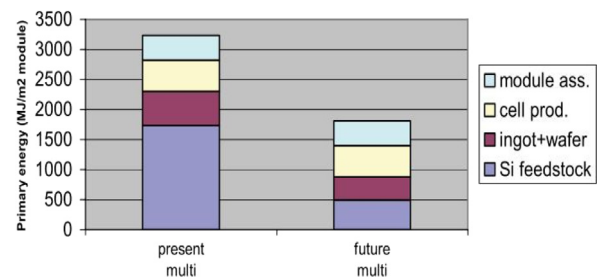


Fig. 14. Primary energy input per square meter module (Alsema et al., 2006).

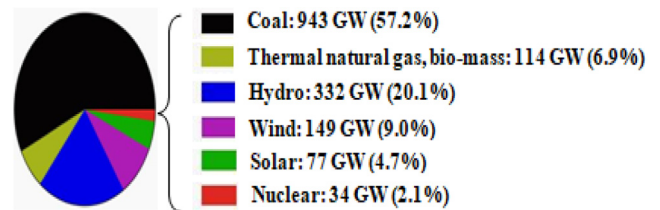


Fig. 15. Generating capacity by source in China (Zhou, 2016).

4.1. Energy consumed to manufacture 1 m² solar panel

In 2006, the energy consumed to manufacture a 1 m² monocrystalline solar panel was estimated to be 3250 MJ; that is equivalent to 903 kWh (Dale, 2013a). This energy takes into consideration the silicon feedstock, the wafer, the cell production and the module assembly as indicated on Fig. 14.

4.2. Energy sources and corresponding carbon footprint

4.2.1. Energy sources in china and cameroon

The emitted CO₂-eq. per kWh varies with the energy source (nuclear, coal, hydro, natural gas etc...). We are henceforth obliged to first identify the contribution percentage of each type of source to the total energy; compute the CO₂-eq. per kWh and deduce that of a given amount of energy.

Fig. 15 shows the energy consumption in China for the year 2016; the contributing sources are also shown (Zhou, 2016).

In Cameroon, the sources of electricity are far different from those of China as presented above. Its primary source is water; nuclear energy is quasi non-existent. Table 2 provides the various sources of electricity in Cameroon in 2014 (David et al., 2018).

Table 2
Repartition of the electricity generation in Cameroon by source [David et al. \(2018\)](#).

Energy source/type	Generating capacity (GC) by source in Cameroon (in %)
Hydro	73
Biomass	1
Oil	12.8
Gas	12.9

Table 3
Carbon footprint of the main types of energy sources.

Technology	gCO ₂ -eq. per kWh electricity
Solar power, Wind power and Water power	10–40
Nuclear power plants	90–140
Combined heat and power in private houses	220–250
Gas burning plants	300–360
New coal burning plants	1000–1100

Table 4
Average carbon footprint of the main types of energy sources.

Technology	gCO ₂ -eq. per kWh electricity (gCO ₂ -eq.)
Solar power, Wind power and Water power	25
Nuclear power plants	115
Combined heat and power in private houses	235
Gas burning plants	330
New coal burning plants	1050

4.2.2. Carbon footprint (cf) of each type of energy source

Once the energy composition is known, we will need the GHG emissions (g CO₂-eq./kWh) of each type. [Table 3](#) obtained from [Peng et al. \(2013\)](#) provides information about the gCO₂-eq. per kWh of electricity generated.

Working out the average values yields to [Table 4](#).

4.3. Calculation of CO₂-eq. due to the manufacture of 1 m² solar panel

4.3.1. In China

Let us compute the GHG emissions per kWh in china and deduce that of manufacturing energy (E_{inp}) of 903 kWh. Considering the generating capacity by source in China presented in [Fig. 15](#) and the average carbon footprint of the main types of energy sources of [Table 3](#), the average carbon footprint of china $g_{CO_2}(China)$ can be given by (1).

$$g_{CO_2}(China) = \sum_i g_{CO_2}(source,i) \times GC_{(source,i)} \quad (1)$$

where source, i stands for one of the six indicated energy sources in [Fig. 15](#); GC stands for generating capacity in percentage; g_{CO_2} stands for an average carbon footprint per kWh electricity.

Considering Eq. (1), the CO₂-eq. in China per kWh is therefore given by (2).

$$g_{CO_2}(China) = 634.235 \text{ gCO}_2\text{-eq./kWh} \quad (2)$$

The total amount of CO₂-eq. ($G_{CO_2}(China-M)$) expressed in kg CO₂-eq.) emitted if the PV panel is manufactured in China in 2016 is therefore given by (3).

$$G_{CO_2}(China-M) = E_{inp} \times g_{CO_2}(China) \quad (3)$$

$$G_{CO_2}(China-M) = 572.71 \text{ kgCO}_2\text{-eq.}$$

This $G_{CO_2}(China-M)$ is the amount of CO₂-eq. emitted during the manufacturing process of 1 m² PV panel.

4.3.2. In Cameroon

Let us first compute the CO₂-eq. per kWh ($g_{CO_2}(Cam)$) in Cameroon. Considering the repartition of the electricity generation in Cameroon by source presented in [Table 2](#) for a kWh, and also the average carbon footprint of the main types of energy sources presented on [Table 4](#), we have the CO₂-eq. per kWh in Cameroon expressed by (4) and computed by (5).

$$g_{CO_2}(Cam) = \sum_i g_{CO_2}(source,i) \times GC_{(source,i)} \quad (4)$$

$$g_{CO_2}(Cam) = 94.35 \text{ gCO}_2\text{-eq./kWh} \quad (5)$$

The total amount of CO₂-eq. ($G_{CO_2}(Cam-M)$ in kgCO₂) emitted if manufactured in Cameroon in 2016 is therefore given by (6).

$$G_{CO_2}(Cam-M) = E_{inp} \times g_{CO_2}(Cam) \quad (6)$$

$$G_{CO_2}(Cam-M) = 85.19805 \text{ kgCO}_2\text{-eq.}$$

4.4. Yearly energy generation of a 1 m² module in Cameroon: Case study of Bamenda and Ngaoundéré

The yearly energy generation was calculated using the information on the sunshine duration ([David and Ngwa, 2013](#)); [Ngaoundéré](#) and [Bamenda](#) are considered. The annual average sunshine indicated by T_1 in [Bamenda](#) and by T_2 in [Ngaoundéré](#) are respectively 2844.7 h/year and 2336 h/year ([David and Ngwa, 2013](#)). The initial average energy generation in kWh, that is the energy generated during the first year of installation, can be given by Eq. (7) ([Dale, 2013b](#)).

$$E_0 = A \times P \times T \times r \quad (7)$$

Where A is the area of the solar panel in m², P the standard solar panel's input rate (1000 W/m² ([Dale, 2013b](#))), T the period of time in hours and r the efficiency (about 15% ([Lossen and Beneking, 2005](#))) of the solar panel.

The annual average energy generation of 1 m² solar panel in [Bamenda](#), indicated by E_{0-B} , will therefore be given by (8).

$$E_{0-B} = 426.705 \text{ kWh/year} \quad (8)$$

The annual average energy generation of 1 m² solar panel in [Ngaoundéré](#), indicated by E_{0-N} , will therefore be given by Eq. (9).

$$E_{0-N} = 305.4 \text{ kWh/year} \quad (9)$$

4.5. Lifetime energy generation of a 1 m² module: case study of Bamenda and Ngaoundéré, Cameroon

Solar panels convert about 15% ([Lossen and Beneking, 2005](#)) of the sun's energy to electricity with an efficiency drop for crystalline silicon panels of 0.5% per year ([Weisser, 2007b](#)). A typical solar panel lasts for about 30 years ([Weisser, 2007b](#)). Considering the efficiency drop of a module, the output energy will drop as show in the equations below, where E_n indicates the expected energy at the nth year.

$$\begin{cases} E_1 = E_0 \\ E_2 = E_1 - 0.005E_0 = E_0 - 0.005E_0 \\ E_3 = E_2 - 0.005E_0 = E_0 - 2(0.005)E_0 \\ E_4 = E_3 - 0.005E_0 = E_0 - 3(0.005)E_0 \\ \vdots \\ E_n = E_{(n-1)} - 0.005E_0 = E_0 - (n-1)(0.005)E_0, (0 < n \leq 30) \end{cases}$$

The lifetime energy indicates here by E_L will therefore be the sum of annual energies generated in 30 years; that is expressed by Eq. (11).

$$E_L = nE_0 - (0.005)E_0 \sum_{n=1}^{n-1} (n)$$

$$= nE_0 - (0.005) \left(\frac{n(n-1)}{2} \right) E_0 \quad (10)$$

For $n = 30$.

$$E_L = 27.97E_0 \quad (11)$$

Considering the above calculated annual average energy generation in *Ngaoundéré* and in *Bamenda* of 1 m² solar panel given by Eqs. (8) and (9), the lifetime energy expressed by (11), the corresponding lifetime energies generation E_{LB} and E_{LN} of 1 m² solar panel respectively in *Bamenda* and in *Ngaoundéré* will therefore be given by the Eqs. (12) and (13).

$$E_{LB} = 11.93494 \text{ MWh} \quad (12)$$

$$E_{LN} = 8.54 \text{ MWh} \quad (13)$$

The total amount of CO₂ recovered, $G_{CO_2(Cam-LB)}$, that is GHG which could have been emitted in *Bamenda* if the conventional means for supplying electricity were implemented to provide the same amount of energy is given by (14).

$$G_{CO_2(Cam-LB)} = E_{LB} \times g_{CO_2(Cam)} = 1126.1 \text{ kgCO}_2\text{-eq.} \quad (14)$$

The total amount of CO₂ recovered, $G_{CO_2(Cam-LN)}$, that is GHG which could have been emitted in *Ngaoundéré* if the conventional means for supplying electricity were implemented to provide the same amount of energy is given by (15).

$$G_{CO_2(Cam-LN)} = E_{LN} \times g_{CO_2(Cam)} = 805.94 \text{ kgCO}_2\text{-eq.} \quad (15)$$

The emitted GHG (CO₂-eq.) are indicated above in Eqs. (3) and (6) for a solar panel manufactured respectively in China and in Cameroon, assuming the same energy input. Likewise, assuming that this solar panel if installed in China could generate about the same amount of electricity as in Cameroon (*Ngaoundéré* for instance) throughout its lifetime, the “CO₂ recovered” indicates here by $G_{CO_2(China-LCh)}$, would be given by (16).

$$G_{CO_2(China-LCh)} = E_{LN} \times g_{CO_2(China)} = 5417.7 \text{ kgCO}_2\text{-eq.} \quad (16)$$

4.6. Relative Greenness percentage

Using the energy source repartitions in Cameroon and China along with the carbon footprint of each type, and the energy input to manufacture 1 m² solar panel, we have set the ground to estimate the Greenness Percentage (GP). Considering the total amount of CO₂ recovered, that is the amount of GHG which could have been emitted if the conventional means for supplying electricity were implemented to provide the same amount of energy throughout the lifetime of a 1 m² solar panel, the GP represents the ratio of the CO₂-eq. during manufacturing and the “CO₂ recovered” (i.e. GHG prevented thank to the use of the manufactured PV) throughout the lifetime of that sample of 1 m² solar panel. The Greenness Percentage, mathematically speaking can be expressed by (17).

$$GP = \left[1 - \frac{CO_2\text{-eq.}}{CO_2 \text{ Recovered}} \right] \times 100 \quad (17)$$

where “CO₂-eq.” is the GHG emitted during manufacturing; “CO₂ Recovered” represents the equivalent amount of CO₂ which would have been generated if the conventional means for supplying electricity were implemented to provide the same amount of PV sample lifetime energy. For the GP to be 100%, no GHG should be emitted during manufacturing.

A solar panel if manufactured in China and installed in Cameroon (*Bamenda*) would have been 49.14% green as evaluated in Eq. (18).

$$GP_{Bamenda}^{China-Cam} = \left(1 - \frac{G_{CO_2(China-M)}}{G_{CO_2(Cam-LB)}} \right) \times 100$$

$$GP_{Bamenda}^{China-Cam} = \left(1 - \frac{572.71}{1126.1} \right) \times 100 = 49.14\% \quad (18)$$

Also if manufactured in China and installed in Cameroon (*Ngaoundéré*) it would have been 29% green as evaluated in Eq. (19).

$$GP_{Ngaoundere}^{China-Cam} = \left(1 - \frac{G_{CO_2(China-M)}}{G_{CO_2(Cam-LN)}} \right) \times 100$$

$$GP_{Ngaoundere}^{China-Cam} = \left(1 - \frac{572.71}{805.94} \right) \times 100 = 29.00\% \quad (19)$$

If the solar panel is manufactured and installed in Cameroon, the GP in *Bamenda* and *Ngaoundéré* would have been 92.43% and 89.4% respectively as computed by (22) and (23).

$$GP_{Bamenda}^{Cam-Cam} = \left(1 - \frac{G_{CO_2(Cam-M)}}{G_{CO_2(Cam-LB)}} \right) \times 100 \quad (20)$$

$$GP_{Ngaoundere}^{Cam-Cam} = \left(1 - \frac{G_{CO_2(Cam-M)}}{G_{CO_2(Cam-LN)}} \right) \times 100 \quad (21)$$

Eqs. (13), (14) and (15) into (20) yields

$$GP_{Bamenda}^{Cam-Cam} = 92.43\% \quad (22)$$

$$GP_{Ngaoundere}^{Cam-Cam} = 89.4\% \quad (23)$$

If the solar panel is manufactured in Cameroon and installed in China, the GP would have been 98.43% as evaluated by (24).

$$GP_{China}^{Cam-China} = \left(1 - \frac{G_{CO_2(Cam-M)}}{G_{CO_2(China-LCh)}} \right) \times 100 \quad (24)$$

$$GP_{China}^{Cam-China} = 98.43\%$$

If the solar panel is manufactured and installed in China, the GP would have been 89.43% as evaluated by (25).

$$GP_{China}^{China-China} = \left(1 - \frac{G_{CO_2(China-M)}}{G_{CO_2(China-LCh)}} \right) \times 100 \quad (25)$$

$$GP_{China}^{China} = 89.43\%$$

5. Greenness percentage and discussions

The notion of green energy appears to be highly related to the manufacturing industry location and its conventional energy sources as well as their related carbon footprint.

So if renewable energy components are manufactured in an industrial country where the conventional energy sources have high carbon footprint, it would significantly affect how much green the energy produced from their use in any renewable energy system will be. But some considerations like the installation site are also to be considered. For example, a solar panel fabricated in China and installed in China is 89.43% green, but just 49.14% green if installed in Cameroon (*Bamenda*). This can be explained by the fact that Cameroon conventional energy sources are mainly hydroelectric which has only about 25 gCO₂-eq./kWh as carbon footprint compared to about 1050 gCO₂-eq./kWh for coal in China. But it becomes more interesting when those components are manufactured and installed in a high carbon footprint

country or manufactured in a low carbon foot print country and installed in a high carbon footprint country; for instance, if manufactured in Cameroon and installed in China a solar panel would be 98.43% green.

6. Conclusion

The greenness percentage of a solar panel varies substantially with the operating region and the carbon footprint of the conventional energy sources used throughout the fabrication process. However, the panel compensates more GHG when installed in high polluting countries.

The solar panel installed in china, if manufactured in Cameroon would be 98.43 green compare to about 49.14% if manufactured in China and installed in Cameroon. This shows how polluted is China compared to Cameroon.

The solar panel manufactured and installed in china is 89.43% green.

The fight for a green world could then find some real improvements if more manufacturing companies are instead installed in countries with low carbon footprint conventional energy sources.

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