# Multi Criteria Analysis Ranking of Solar Photovoltaic Modules Manufacturing Countries by An Importing Country: A Case of Uganda

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## Abstract

Although solar photovoltaic systems do not emit greenhouse gases (GHG) during their operation lifetime, their manufacturing, transportation, and construction involves energy use and GHG emissions. In this study a life cycle assessment as well as economics analysis of the solar modules from manufacturing to delivery of the final product were evaluated. A multi-criteria analysis (MCA) ranking methodology for solar photovoltaic module manufacturing countries by an importing country based on the modified VIKOR technique was proposed. Uganda, a developing country in sub-Saharan Africa was considered as the country that intends to import solar photovoltaic modules from six (6) selected overseas module manufacturing countries. The results revealed that the solar PV system would have an energy payback time and GHG payback time in the range of 1.32 – 3.28 years and 0.69 – 3.19 years, respectively, due to the high solar irradiance received in Uganda. The importation cost incurred are in the range of 37.10 – 46.38 c$/Wp for a functional unit of 50 kW capacity solar photovoltaic system. The MCA ranking results indicated that Brazil is the best choice module manufacturing country for Uganda to import modules from. The proposed methodology is replicable and applicable in any country for the decision-making process.

***Keyword:*** Solar PV module; GHG emissions induced; Energy used; Importation cost incurred; VIKOR technique

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## Nomenclature

| | | | |
|---|---|---|---|
| BOS | Balance of System | $CO_2$ | Carbon dioxide |
| CP | Compromising Programming | $E_{S,E}$ | Lifecycle energy used for PV module |
| EPBT | Energy Pay Back Time | $E_{output}$ | Annual solar PV energy output |
| GET-FiT | Global Energy Transfer Feed-in Tariff | $\eta_{ee}$ | Energy efficiency |
| GHG | Greenhouse Gas | $D_{T,sea}$ | Sea distance |
| GPBT | GHG Pay Back Time | $D_{T,road}$ | Road distance |
| GWP | Global Warming Potential | $GHG_S$ | Lifecycle GHG emissions induced |
| ISO | International Organization for Standardization | $GHG_{output}$ | Local power plant GHG emissions induced |
| LCA | Life Cycle Assessment | $GHG_M$ | total GHG emissions induced during module manufacturing |
| LCI | Life Cycle Inventory | $GHG_{GEF}^{country}$ | Country grid emission factor |
| LCIA | Life Cycle Impact Assessment | $C_{ijl}$ | Total sea freight cost incurred |
| MCA | Multi Criteria Analysis | $\beta$ | Variable sea freight cost incurred |
| NER | Net Energy Ratio | $\delta$ | Linear approximation |
| POA | Plane of Array | $d_{ij}$ | Distance between the two shipping locations |
| PR | Performance Ratio | $\alpha$ | Fixed sea freight cost incurred |
| PV | Photovoltaic | $t_l$ | Consignment tonnage |
| SAM | System Advisor Model | $D_p$ | VIKOR technique gap distance |
| SoG | Store-on Grid | $\chi^2$ | Chi-square test |
| SoG-Si | Solar Grade Silicon | $N_q$ | Conventional technique rank number |
| UMG-Si | Upgraded Metallurgical-Grade Silicon | $P_q$ | VIKOR technique rank number |

## 1 Introduction

Global trends in energy generation transition reveal increasing acceptance for renewable energy generation technologies, particularly solar photovoltaic (PV) systems (Luo et al., 2018; Masson & Kaizuka, 2020). This is not only about the urge for energy independence and security, but also about the increased awareness and concerns of carbon dioxide emissions, global warming and climate change (Akinyele & Rayudu, 2016; Akinyele, Rayudu, & Nair, 2017; Ramli, Hiendro, & Al-Turki, 2016). Various investigations on the lifecycle assessment (LCA) for solar PV technology report that the energy generated by the technology has comparatively less environmental and human health impacts compared to conventional fossil fuel-based energy generation (Akinyele et al., 2017; Eskew, Ratledge, Wallace, Gheewala, & Rakkwamsuk, 2018; Luo et al., 2018).

The global cumulative installed solar PV capacity has tremendously grown since 2000. The cumulative installed solar PV capacity globally exceeded 635 GW in 2019 (Benda & Černá, 2020; Jäger-Waldau, 2020; Masson & Kaizuka, 2020). An annual installed solar PV capacity of about 120 GW was reported in 2019, accounting for about 47.8% of the installed net power generating capacity of that year (Benda & Černá, 2020; BloombergNEF, 2020; Jäger-Waldau, 2020). Although Germany and Italy have the highest share of the electricity supplied by solar PV power, China and United States lead the global solar PV market (Masson & Kaizuka, 2020; REN21, 2020). In 2019, China and the United States had a cumulative installed solar PV capacity of 205.2 GW and 75.9 GW, respectively (Masson & Kaizuka, 2020; REN21, 2020). Likewise, China is at the forefront of the global solar PV cells and modules manufacturing (Fraunhofer, 2020; Jäger-Waldau, 2019). In 2019, China (mainland) led with a 66% contribution, followed by the rest of Asia-Pacific and Central Asia with 18% contribution, while Europe and United States (including Canada) had 3% and 4% contribution, respectively, of the global solar PV module manufacturing (Fraunhofer, 2020).

Furthermore, it is reported that some of the solar PV module manufacturing investments in other countries such as India, Malaysia and Thailand are mostly owned by the Chinese companies (Jäger-Waldau, 2019).

Solar PV module production market is mainly dominated by silicon wafer-based modules. Silicon wafer-based solar PV modules were reported to have accounted for about 95% of the total solar PV module production in 2019 (Fraunhofer, 2020; Masson & Kaizuka, 2020). Notably, the remarkable trend in solar PV deployment has been backed by the continuous fall in solar PV prices (Benda & Černá, 2020). For instance, on the global market, the solar PV module price has drastically fallen from 4.88 $/W in 2000 to averagely 21.5 c$/W in 2019, an equivalent of about 95.6% price decrease (Benda & Černá, 2020; Masson & Kaizuka, 2020; Our World in Data, 2021). The fall in the solar PV module prices is as a result of improvements in the module production chain (in wafering, cell and module fabrication technologies) over the years that has witnessed a fall in the semiconductor silicon price from 500 $/kg in 2007 to 10 $/kg in 2020 (Benda & Černá, 2020; Masson & Kaizuka, 2020). Solar PV energy has reportedly reached below 1.4 c$/kWh for large scale PV systems, which confirms the increasing competitiveness that solar PV has reached under the best conditions (Masson & Kaizuka, 2020).

Solar PV systems do not emit greenhouse gases (GHG) during their operation lifetime and an assessment on the implementation of solar PV systems as an alternative energy generating technology in developing countries revealed substantial sustainable development benefits to the community (Mukisa, Zamora, & Lie, 2020a). However, during the manufacturing, transportation and construction stages of solar PV systems, considerable amounts of energy use and GHG emissions are involved. Remarkably, the energy used as well as GHG emissions induced during the lifetime of the solar PV systems depends on the energy efficiency and the grid emission factor of the country manufacturing the system's components. Thus, an environmental impact assessment of such an energy generating technology is necessary to provide insights into the energy used and GHG emissions induced over their lifetimes (Akinyele et al., 2017). A broader literature review of several LCA for the solar PV systems revealed widely varying estimates in the energy used and GHG emissions induced.

Studies on the LCA for the solar PV technology have mainly focused on the solar PV technology implementation in the same country or continent where the solar PV system components are manufactured. For instance, in Asia, studies (Chen, Hong, Yuan, & Liu, 2016; Fu, Liu, & Yuan, 2015; Hou et al., 2016; Yang, Liu, Yang, & Ding, 2015; Yu et al., 2017), (Lu & Yang, 2010) and (Nawaz & Tiwari, 2006) focused on China, Hongkong and India, respectively, as the manufacturing and implementation areas; in Europe, study (Krauter & Rüther, 2004) focused on Germany while studies (García-Valverde, Miguel, Martínez-Béjar, & Urbina, 2009; Sumper, Robledo-García, Villafáfila-Robles, Bergas-Jané, & Andrés-Peiró, 2011) focused on Spain; in North America, study (Perez & Fthenakis, 2011) focused on New York; and in South America, study (Fukurozaki, Zilles, & Sauer, 2013) focused on Brazil for their investigations. Only study (Krauter & Rüther, 2004) considered two continents by comparing the solar PV systems manufactured in Germany (Europe) and Brazil (South America) for implementation in either the manufacturing country or the other country to undertake the LCA for Solar PV system. For the case of Africa, Nigeria as the manufacturing and implementation area with a focus on a 1.5 kW mono-crystalline silicon

PV system is discussed in (Akinyele et al., 2017). The investigation established that the EPBT ranges between 0.83 – 2.83 years, considering solar PV system project lifetime of 20 - 30 years (Akinyele et al., 2017).

A breakdown of the life cycle GHG emissions for solar PV system indicates that the cultivation and fabrication of components accounts for about 71.3% of the total GHG emissions (Nugent & Sovacool, 2014). Likewise, Literature revealed that the PV material (from quartz to solar cell stage) production accounts for about 67%, while the module production (glass cover, aluminum frame and encapsulation) stage accounts for about 33% of the embedded energy used during the solar PV module manufacturing process (Zawadzki et al., 2020). Thus, in this study emphasis was focused on the cultivation and fabrication of solar PV modules as well as their transportation to the importing country. The LCA was incorporated with an economic analysis to rank selected solar PV modules manufacturing countries.

It was assumed that Uganda, a developing country located in the sub-Saharan African region is planning on importing solar PV modules from overseas module manufacturing countries. Uganda was considered as the case study country mainly because it had previously pioneered the adoption of the global energy transfer feed-in tariff (GET-FiT) programme in Africa, under which over 40 MW capacity of ground mounted solar PV systems were implemented before the programme's closure in 2018 (ERA, 2018; Kruger & Eberhard, 2018; Mukisa, Zamora, & Tjing Lie, 2021). Likewise, Uganda was assessed for its viability to pioneer the adoption and implementation of the store-on grid (SoG) scheme for rooftop solar PV systems in the industrial sector (Mukisa, Zamora, & Tjing Lie, 2020b; Mukisa et al., 2021). Furthermore, Uganda was considered based on the investigation results of the impact of adopting alternative energy technologies in developing countries, that reported rooftop solar PV technology to have substantial sustainable development benefits to the community in Uganda (Mukisa et al., 2020a). Therefore, Entebbe site, a city in Uganda at coordinates 0.0512 $^{o}$N and 32.4637 $^{o}$E was considered as the destination place for the solar PV modules in the environmental impact assessment of the imported solar PV modules from overseas manufacturing countries in this study. The solar PV modules were considered to be transported by sea freight from a selected seaport in the manufacturing country to Mombasa port in Kenya, from where the modules would be transported by trucks to Entebbe city in Uganda for installation since Uganda is a landlocked country.

Based on the literature review summary in Table 1, it was established that energy payback time (EPBT), GHG payback time (GPBT) and $CO_2$ emissions are the main lifecycle assessment indicators widely considered by researchers. Thus, these key indicators for LCA were adopted in this study. Also, this study investigated the importation cost incurring from procurement of the solar PV modules in the manufacturing country to the destination place. Furthermore, this study proposes that the importing country uses the EPBT, GPBT and importation cost incurred as its objective categories for choosing a manufacturing country to import from. A modified multi-criteria optimization and compromise Solution (VIKOR)) technique was used in the multi criteria analysis methodology to rank the considered the solar PV module manufacturing countries. The following are the study's contributions to knowledge:

- Evaluated the energy used and GHG emissions induced during the manufacturing to delivery stages of the solar PV modules for the considered manufacturing countries.

- Evaluated the EBPT and GPBT of solar PV modules for the considered manufacturing countries.
- Assessed the importation cost incurred to import solar PV modules by the implementing country from the considered manufacturing countries.
- Ranked the considered manufacturing countries based on the weight label categories that decision-makers could use to select a country to import solar PV modules from.
- Undertook a sensitivity analysis of the key LCA indicators and the VIKOR technique gap distance to the variation in key input parameter.

This study's methodological approach is replicable anywhere worldwide by following the steps and outlined activities shown in Fig. 1. Furthermore, the findings of this approach offer a wide scope of criteria for the decision-makers to consider during decision making and policy development. Thus, decision makers could base on such findings as a mapping strategy for appropriate policy framework development and decision making on solar PV technology components' procurement.

The rest of this paper is organized as follows: Section 2 discusses the literature review; Section 3 discusses the methodology used; Section 4 gives the results and discussion of the paper, and Section 5 gives the conclusion and future work of the study.

## 2 Literature review

### 2.1 Solar PV System Lifecycle Assessment

The LCA is a comprehensive methodological approach to evaluate and analyse the environmental impact and energy consumption over the entire life cycle of a product or system. The LCA usually follows the "cradle-to-grave" or "cradle-to-gate" mechanism starting from the extraction of raw materials, transportation, processing of materials, manufacturing, distribution, usage, and final disposal (Ludin et al., 2018). Based on the standardized framework series of the international organization for standardization (ISO 14040), the methodology comprises of four distinct steps, namely, goal and scope definition, lifecycle inventory (LCI), lifecycle impact assessment (LCIA), and interpretation (Ludin et al., 2018; Peng, Lu, & Yang, 2013). The LCI analysis mainly focuses on analysing and recording the flows of resources, materials and pollutants for the different processes involved throughout the life cycle of a system (Carnevale, Lombardi, & Zanchi, 2014; Peng et al., 2013).

The LCAs are often applied as decision support tools for the selection amongst different alternatives providing the same product or service (Turconi, Boldrin, & Astrup, 2013). The main indicators used to evaluate sustainability and environmental benefits of solar PV systems are EPBT, GPBT, Net Energy Ratio (NER) and $CO_2$ emission (Hou et al., 2016; Peng et al., 2013). As shown in Table 1, most of the reviewed studies focused on EPBT, GPBT as well as $CO_2$ emission. As can be noted from Table 1, other indicators such as water footprint, soil toxicity (quality) and energy sources have not been considered in investigations on the LCA for solar PV systems. The omission of these indicators while undertaking the LCA for solar PV systems could be attributed to the scarcity of the relevant data required to assess them, thus, researchers restrict their LCA investigation to mainly EPBT, GPBT and $CO_2$ emissions. Therefore, based on the reviewed literature, this study considered the EPBT, GPBT and $CO_2$ emissions as the main LCA indicators in the analysis. Table 1 summarizes some studies on the LCA for solar PV systems in different locations around the world and highlights some key aspects of the LCA, namely, EPBT, GPBT and $CO_2$ emissions.

Efforts to review more LCA studies for solar PV systems on the African continent in the existing literature never unveiled any other published studies. The inexistent of the LCA studies in literature has previously been reported in (Ito, Lespinats, Merten, Malbranche, & Kurokawa, 2016), asserting that there are no LCA analyses for solar PV systems conducted for locations in Africa. As revealed in the reviewed studies in Table 1, different boundaries are considered in the investigations. It should be noted that some studies included the BOS, while others excluded it. Also, other than study (Lu & Yang, 2010), most of the studies exclude the decommission stage of the solar PV system's during the LCA. This is mainly because to date there has not been any solar PV power plant decommissioned worldwide. However, tonnes of waste from solar PV plants are expected in the future as a result of decommissioning (Stephanie, Andreas, & Garvin, 2016).

**Table 1:** Reviewed Studies on the LCA for Solar PV Technology for Different Locations around the World

| Year | Study | Installation Type | Location | Boundary | Methodology | Main Results |
|---|---|---|---|---|---|---|
| 2010 | (Lu & Yang, 2010) | Rooftop-mounted Building integrated | Hong Kong | Production and use | EPBT, GBPT | EPBT=7.1-20.0 years; GBPT=5.2 years |
| 2010 | (Ito, Komoto, & Kurokawa, 2010) | Large scale, Grid connected, Rooftop-mounted | China | Production (BOS), installation and use | EPBT, $CO_2$ | EPBT=1.8-2.5 years; $CO_2$=43-54 g$CO_2$/kWh |
| 2011 | (Sumper et al., 2011) | Rooftop-mounted | Spain | Production and use | EBPT | EPBT=3.43-9.57 years |
| 2015 | (Hou et al., 2016) | Large scale, Grid connected, Ground-mounted, | China | Production (BOS) to End of life production | EPBT, GHG emissions | EPBT=1.6-2.3 years; GHG=60.1-87.3 g$CO_2$/kWh |
| 2015 | (Kabakian, McManus, & Harajli, 2015) | Rooftop-mounted | Lebanon | Production (BOS), installation and use | EPBT, GPBT | EPBT=16.1-16.9 years; GPBT=3.21=3.52 years |
| 2015 | (Fu et al., 2015) | Ground-mounted | China | Production (BOS) and use | EPBT, GWP | EPBT=2.22-6.05 years; GWP=50.9 g$CO_2$/kWh |
| 2017 | (Akinyele et al., 2017) | Ground-mounted | Nigeria | Production and use | EPBT, $CO_2$ | EPBT=0.83-2.83 years; GWP=1.91-5.82 ton$CO_2$ |
| 2017 | (Sagani, Mihelis, & Dedoussis, 2017) | Rooftop-mounted | Greece | Production and use | EPBT, GBPT | EBPT=1.8 years; GBPT=1.5 years |
| 2018 | (Luo et al., 2018) | Rooftop-mounted | Singapore | Production and use | EPBT, $CO_2$ | EPBT=1.01-1.11 years; $CO_2$=20.9-30.2 g$CO_2$/kWh |
| 2018 | (Eskew et al., 2018) | Rooftop-mounted | Thailand | Production and use | EPBT, GPBT | EPBT=2.5 years; GPBT=0.079 kg$CO_2$/kWh |

A significant variation exists in the energy used and GHG emissions of solar PV systems as well as the EPBT and GPBT evaluation results during the LCA. The variations are brought about by several factors ranging from the type of solar cells, type of module lamination, system location, system design, system retrofitting and installation methods (Kim, Fthenakis, Choi, & Turney, 2012). However, it is quite impossible to gather all the relevant data and to understand each step in the creation of each component of the PV system. Literature reports that the significant uncertainty in the data used about the solar PV module production is due to high competitive market environment, where by some companies report production figures, while other report sales and again other report shipment figures (Jäger-Waldau, 2019). Thus, studies assert that some assumptions may have to be made while carrying out the EPBT and GPBT evaluations (Cheng, 2008; Lu & Yang, 2010). Therefore, sensitivity analysis of the LCA key aspects, namely the energy used, GHG emissions induced, importation cost incurred, the EPBT and GPBT to variations in the input parameter variables was undertaken to depict the how various data uncertainty contributes to the model's overall uncertainty.

## 2.2 Solar PV Module Manufacturing

Silicon wafer-based solar PV modules dominate the market, accounted for about 95% of the total solar PV module production in 2019 (Fraunhofer, 2020; Masson & Kaizuka, 2020). Major polysilicon manufacturers adopted the Siemens process while others adopted the fluidized bed reactor process to manufacture granular polysilicon (Masson & Kaizuka, 2019, 2020). Due to wafer thinning, the amount of polysilicon used for the wafer production decreased from 6.8 g/$W_p$ required in 2010 to an average of 3.2 g/$W_p$ in 2019 (Masson & Kaizuka, 2020; Singh & Agrahari, 2019) and it is predicted to have reduced further to averagely 2.7 g/$W_p$ in 2020. A production efficiency of granular polysilicon improved with an energy consumption reduction from 50 kWh/kg in 2017 to 49 kWh/kg recorded in 2018. With the utilization of advanced technologies, the energy consumption during the granular polysilicon production reduced further to 40 kWh/kg (Masson & Kaizuka, 2019, 2020). The energy consumption of the entire polysilicon production process decreased from 71 kWh/kg in 2018 to 70 kWh/kg in 2019 (Masson & Kaizuka, 2020), and it is predicted to have reduced further to averagely 67 kWh/kg in 2020.

Notably, the levels of energy efficiency as well as national grid emission factors vary from country to country (Kallakuri, Vaidyanathan, Kelly, & Cluett, 2016; OECD, 2016). With many countries engaged in solar PV module manufacturing, China still dominates the solar PV modules production globally (Fraunhofer, 2020; Jäger-Waldau, 2019; Masson & Kaizuka, 2020). In 2018, China accounted for about 58% of polysilicon production for solar cells, 93% of PV wafer production, 74% of solar cell production and 73% of solar PV module production of total global solar PV module production (Masson & Kaizuka, 2019). In 2019, the global share of solar PV polysilicon production from China reached 68%, followed by Germany at 11%, while South Korea and United States accounted for 10% and 6%, respectively (Masson & Kaizuka, 2020).

The production of wafers is also dominated by China which contributed about 96% of the global production in 2019, while other countries such as South Korea, Japan, Malaysia, Norway and United States made up the 4% share (Masson & Kaizuka, 2020). The global solar cell production in 2019 was estimated at about 144 GW, out of which China's production contributed about 76% (Masson & Kaizuka, 2020). Other countries involved in the solar cell production are Malaysia (6%), South Korea (4%), Taiwan (3%), India (1%), United States (1%), Japan (1%) and others (such as Vietnam, Singapore Thailand and Europe) (8%) (Masson & Kaizuka, 2020). In 2019, the global solar PV module production was dominated by China with 71% contribution, followed by South Korea (6% ), Malaysia (6%), United States (3%), Europe (mainly Germany) (2%), India (1%), Japan (1%), Taiwan (1%) and others (9%) (Masson & Kaizuka, 2020). Countries such as Australia, Canada, Thailand, South Africa, Italy, Mexico and Denmark are reported to possess solar PV module production capacity, while countries such as Russia, Algeria, Brazil, Saudi Arabia and Indonesia are reported to have solar PV module production bases (Masson & Kaizuka, 2019, 2020).

Table 2 shows some of the companies and their details of headquaters, manufacturing locations and panel type they manufacture as well as the selected solar PV module manufacturing countries in this study (Solar Feed Magazine, 2019; Solar Power World, 2021). This study specifically focused on six (6) manufacturing countries of solar PV modules, namely; Germany, representing Europe; Brazil, representing South America; USA, representing North America; Australia, representing Oceania; China and India, representing Asia (East Asia and South Asia, respectively). Likewise, Uganda, representing Africa, was considered as the country importing solar PV modules for installation.

**Table 2**: Some of the Solar PV Module Manufacturing Companies and their Locations

| Company Name | Headquaters | Manufacturing Location | Solar PV Module Type | Location of Interest to the Study |
|---|---|---|---|---|
| AE Solar | Germany | China, Georgia | Crystalline Silicon | China |
| Alfa Solar GmbH | Germany | Germany | Crystalline Silicon | Germany |
| Astronergy | China | China, Thailand | Crystalline Silicon | China |
| Australian Solar Manufacturing Pty. Ltd. | Australia | Australia | Crystalline Silicon | Australia |
| Auxin Solar | United States | United States | Crystalline Silicon | United States |
| BYD | China | Brazil<br>China | Crystalline Silicon | Brazil<br>China |
| Canadian Solar | Canada | Brazil, Canada<br>China, Indonesia<br>Thailand, Vietnam | Crystalline Silicon | Brazil<br>China |
| CSUN | China | China, Turkey<br>United States<br>Vietnam | Crystalline Silicon | China<br>United States |
| Hanwha Q Cells | South Korea | China, Malaysia<br>South Korea<br>United States | Crystalline Silicon | China<br>United States |
| JinkoSolar | China | China, Malaysia<br>United States | Crystalline Silicon | China<br>United States |
| LONGi | China | China, India<br>Malaysia | Crystalline Silicon | China<br>India |
| Lumeta Solar | United States | India<br>United States | Crystalline Silicon | India<br>United States |
| Navitas Solar | India | India | Crystalline Silicon | India |
| Sharp Solar | Japan | Germany, Japan<br>Thailand | Crystalline Silicon | Germany |
| SOLARWATT | Germany | Germany | Crystalline Silicon | Germany |
| Tindo Solar | Australia | Australia | Crystaline Silicon | Australia |
| Risen Solar | Australia | Australia | Crystaline Silicon | Australia |

Solar PV module manufacturing is an internationalised commodity business and it is hard to know the exact country in which the various module's components are manufactured from. For most of the module's components, the source country is predominantly China (Masson & Kaizuka, 2019, 2020; REN21, 2020). Also, the considered manufacturing countries in this study were based on their performance in solar PV market (Masson & Kaizuka, 2019, 2020; REN21, 2020). The countries in column five of Table 2 were selected as the considered solar PV module manufacturing countries to give a general representation of different continents. It was assumed that these countries locally produce their solar cells and the other module components. Therefore, the consideration of the different module manufacturing countries in the LCA could result in significant variations in the results of the key indicators.

As aforementioned, most of the studies focus on solar PV technology implementation in the same country or continent where the solar PV system components are manufactured, in so doing, they exclude international transportation of the solar PV technology components in the LCA. The energy used and GHG emissions induced during the modules' transportation to the installation site could be neglected if considering that the installation is in close proximity to the manufacturing factory (Hou et al., 2016). Notably, most countries, especially in the developing world rely on imported solar PV components from overseas manufacturing countries to implement the technology. Considering the international transportation in the undertaking of the LCA of solar PV systems have evident impacts on the results. For instance, literature reports that sea and air freights have an energy consumption of $6.1 \times 10^{-2}$ kWh/kg.km and $2.4 \times 10^{-3}$ kWh/kg.km, respectively (Elie El, 2016; Maersk, 2020). Likewise, the GHG emissions induced by the use of sea and air freights are reported as 3.04 kg$\mathrm{CO_2}/l$ and 2.31 kg$\mathrm{CO_2}/l$, respectively (Ministry for the Environment, 2019). The difference in routes used by the two transportation options may also cause significant variations in the LCA results. Thus, by considering the energy used, GHG emissions and routes used, the LCA results would differ for these transportation options.

With the aspect of importation, the economics involves are of a great concern to the importing party. Any importer would prefer spending less on any given commodity in case of existent alternative. For instance, techno-economic analysis of different types of solar PV modules has been studies with the attention on key metrics such as internal rate of return, payback time and levelized cost of energy (Kang, Hong, Jung, & Lee, 2019; Mukisa, Zamora, & Lie, 2019b; Thopil, Sachse, Lalk, & Thopil, 2020). Also, techno-economic analysis has been done in comparison of solar PV technology with other technologies (Ahmad et al., 2018; Li & Yu, 2016). However, all the techno-economic analyses in literature have not tackled the influence of solar PV modules' manufacturing countries on their results.

Solar PV module prices continued to fall in 2019, and a global average of 0.36 \$/$\mathrm{W_p}$ was recorded (REN21, 2020). Solar PV module prices vary from one manufacturing country to another worldwide and likewise, different transportation cost is incurred by the importing country (REN21, 2020; Van Buskirk & Schwartz, 2019). Literature reports that for any given solar PV module price per watt at the factory door, incorporation of shipping, taxes and distribution would approximately double the price per watt for the customer of the solar PV modules (Van Buskirk & Schwartz, 2019). In some in the Sub Saharan Africa (SSA) countries, the solar PV module price per watt is reportedly in the range of 0.7 – 1.4 \$/$\mathrm{W_p}$ (BloombergNEF, 2019). Thus, solar PV modules importation by considering several manufacturing countries could influence the final price per watt of the solar PV modules in the implementing country.

Importation of goods by any country worldwide necessitates several documents. Some of the required documents for imports include bill of landing or airway bill, certificate of conformity, certificate of origin, customs bond and export manifest (Internationa Trade Administration, 2020; KEREA, 2019). For instance, the certificate of conformity is sent by the seller and shows that the goods supplied meet the required standards of the importing country while the bill of land or airway bill serves as evidence of the means of transportation used to deliver the goods. Based on these import documents, set standards by decision-makers of the importing country are upheld and observed. The LCA is widely applied as decision support tools on products or services (Turconi et al., 2013). Thus, investigating the applicability of the LCA of solar PV products and importation cost incurred in setting the standards acceptable by the importing country could be a game changer in the fight against climate change as well as fostering energy efficiency.

# 3 Methodology

In this analysis, it was assumed that Uganda intends to import the solar PV modules from any of the considered overseas manufacturing countries by using a combination of sea freight and road trucks as the means of transportation. Fig. 1 shows the steps and the replicable activities undertaken at every step of the proposed methodology in this study.

The rest of this section describes the methodology utilized in this study. Subsection 3.1 describes the methodology for undertaking a lifecycle assessment for PV system; Subsection 3.2 describes the methodology for evaluating the transportation cost incurred in importing solar PV modules; and Subsection 3.3 describes the methodology used to rank the considered solar PV module manufacturing countries. Subsection 3.4 describes the verification and application of the modified VIKOR technique proposed in this study.

## 3.1 Life Cycle Assessment (LCA) for PV System

The first two steps of the LCA approach are discussed at length in subsections 3.1.1 and 3.1.2, while the third and fourth steps of the LCA approach are covered in subsection 4.1 of this study.

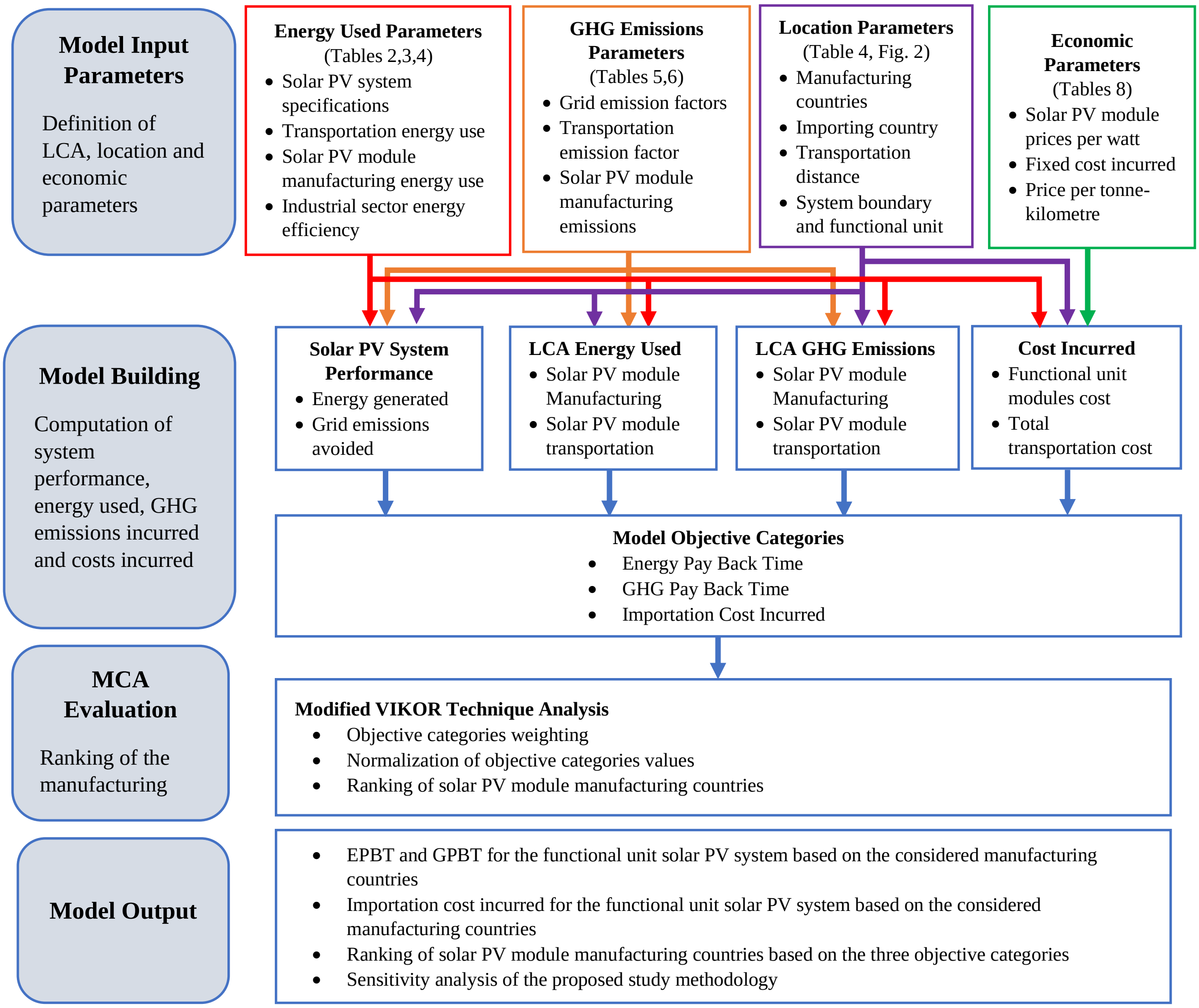


**Fig. 1:** Steps and Activities Involved in the LCA Methodology in this Study

### 3.1.1 Goal and scope definition

The presented LCA methodological approach in this study seeks to establish the best alternative solar PV module manufacturing country that should be considered for exporting their modules for installation in a target country. The rationale of the approach is to establish the minimal LCA energy used and GHG emissions induced by the solar PV modules from the considered manufacturing countries. Fig. 2 shows the graphical representation of the system boundary in the form of input and output. It also shows the different stages that were analysed in the proposed LCA for a solar PV module. The system boundaries were developed based on the methodology guideline on LCA of PV electricity in (Frischknecht, Heath, Raugei, Sinha, & de Wild-Scholten, 2016).

As the functional unit for this study, a 50 kW solar PV system was considered for the analysis of the LCA energy used and GHG emissions induced by a solar PV system whose modules are imported from the selected manufacturing countries around the world. The 50 kW solar PV system was considered for rooftop installation in Entebbe city in Uganda.

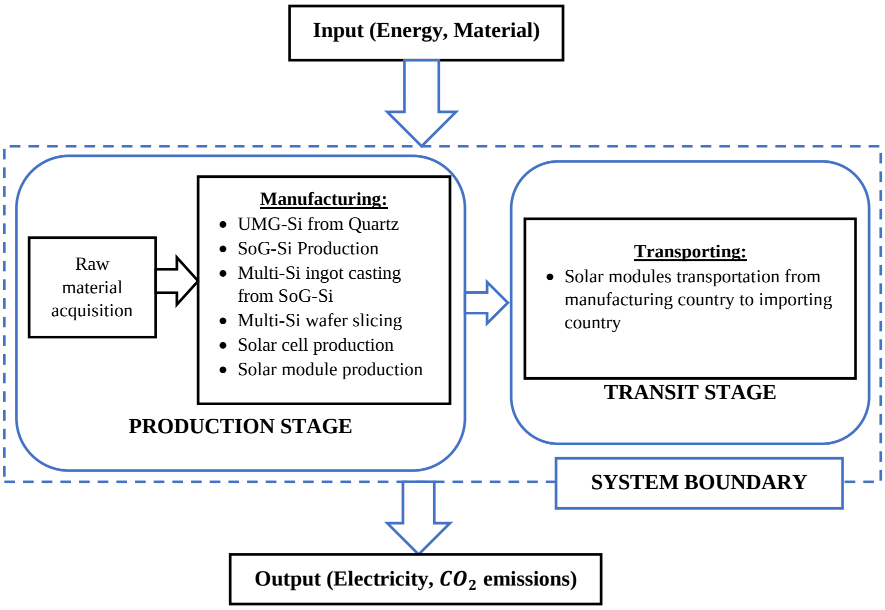


**Fig. 2:** Solar PV System boundary in the form of input and output for the different stages in the proposed LCA

### 3.1.2 Life Cycle Inventory

The inventory analysis was developed based on the ISO 14040 series accounting for the required energy and materials as well as the GHG emissions involved. A large pool of sources was examined for the inventory analysis completion to have as much detailed data as possible. Literature sources and simulations were utilized for the inventory analysis of the solar PV system under this study. Also revealed by the solar PV system boundary used in this study in Fig. 2, the balance of system (BOS) was excluded in this analysis. The BOS is a terminology used to refer to all accessories in solar PV systems that are crucial for their functionality (Kim, Cha, Fthenakis, Sinha, & Hur, 2014). The BOS comprises of the inverters, structural support materials and cables. In most cases, the solar PV modules and BOS accessories used in a solar PV system are not imported from the same country. Thus, due to such uncertainties about the BOS accessories and data limitations, the BOS was excluded in this analysis. Therefore, with such a background, the LCA for the solar PV system in this study only focused on the solar PV modules.

#### 3.1.2.1 Energy Pay Back Time (EPBT)

The EPBT analysis is centred on the amount of energy generated by a PV system and the total LCA energy used. EPBT bases on directly and indirectly energy used to produce the PV system to establish whether there is a net gain of energy to the end-users in its lifetime. The EPBT is defined as the total energy used by a PV system and its balance of system (BOS) divided by the annual energy output by the PV system (Lu & Yang, 2010). In this study, EPBT was evaluated by using the modified expression shown in Eq. (1) (Lu & Yang, 2010; Peng et al., 2013).

$$EPBT = \frac{E_{S,E}}{E_{output}} \tag{1}$$

where, $E_{S,E}$ is the total lifecycle energy used for the PV modules in $\mathrm{kWh/W_p}$; and $E_{output}$ is the annual energy output of the PV system in $\mathrm{kWh/W_p}$.

### a) Energy Output by Solar PV System

The polycrystalline silicon modules and inverters whose specifications are shown in Table 3 were used in this study's analysis. A solar PV system of 50 kW capacity was considered in this study to be installed on the rooftop in Entebbe city in Uganda. Using the inventory in Table 3, a 50 kW capacity solar PV system comprising of 10 modules per string and 20 strings in parallel, with modules at a tilt angle of 25° was evaluated for orientations due East and West. Orientation selection was based on the findings of (Mukisa et al., 2019b), which asserted that solar PV systems oriented due East give the highest energy generation and those oriented due West give the lowest energy generation in Uganda. The weather data used in this investigation was extracted from the Meteonorm database and the solar PV system simulations were done by using the Systems Advisor Model (SAM) tool based on solar PV simulating softwares discussion in (Mukisa, Zamora, & Lie, 2019a), to attain the annual energy generation $\mathrm{E_{output}}$ of a 50 kW solar PV system evaluated in $\mathrm{kWh/W_p}$ using Entebbe city as the site of installation.

**Table 3:** Solar PV Module and Inverter Specifications Used in the Study

| **PV Module** | | **Inverter** | |
|---|---|---|---|
| **Entity** | **Value** | **Entity** | **Value** |
| Module Peak Wattage (Wp) | 250 | Maximum AC power (Wac) | 4,000 |
| Module efficiency (%) | 15.29 | Maximum DC power (Wdc) | 4,193.14 |
| Module area ($m^2$) | 1.66 | Weighted Efficiency (%) | 95.78 |
| Module weight (kg) | 18 | Maximum DC voltage (Vdc) | 480 |
| Open circuit voltage, $V_{OC}$ (V) | 37.8 | Maximum DC current (Adc) | 13.53 |
| Short circuit current, $I_{SC}$ (A) | 8.9 | Minimum MPPT DC voltage (Vdc) | 100 |
| System degradation rate (%) | 0.5 | Maximum MPPT DC voltage (Vdc) | 480 |
| Module area per watt, $M_A$ $\left(\mathrm{m^2/W_p}\right)$ | $6.64 \times 10^{-3}$ | Power consumption at night (Wac) | 1.2 |
| Module weight per watt, $M_W$ $\left(kg/\mathrm{W_p}\right)$ | $7.2 \times 10^{-2}$ | Power consumption during operation (Wdc) | 29.78 |
| Number of Modules required | 200 | Number of Inverters required | 10 |

### b) Energy Used During Manufacturing to Destination

Generally, the total lifecycle energy used is referred to as the energy use induced within the whole life cycle from the extraction of the primary resources, manufacturing process, transportation, installation and decommissioning. The energy used throughout the manufacturing process of the solar PV modules varies from country to country. This is mainly due to the energy efficiency levels of the different countries. Likewise, it is quite impossible to collect the data of all the energy used at every step of module production for all the countries in order to have a conclusive comparison. Thus, in this study the inventory data for the solar PV manufacturing steps shown in Table 4 was assumed as the global average. Thus, it was factored based on the respective country's energy efficiency to determine the estimated energy used per considered country in manufacturing solar PV modules. To account for the uncertainty in the input data, the statistical indices, namely, standard deviation and 95% confidence interval were used in this study.

The energy used during quartz mining is negligible because the energy used is inconsequential compared to the obtained mass of quartz (Hou et al., 2016). Considering that in this study solar PV system modules are exported to Uganda, the energy used during module international transportation was incorporated in the analysis. The energy used in manufacturing and transportation of the solar PV modules to the destination in the importing country was evaluated by using Eq. (2) expressed in $\mathrm{kWh/W_p}$ (Hou et al., 2016; Lu & Yang, 2010).

$$E_{S,E} = (1-\eta_{ee}) \cdot (E_{P1} + E_{P2} + E_{P3} + E_{P4} + E_{P5} + E_{P6}) + \left(E_{T,sea} \cdot M_w \cdot D_{T,sea}\right) + \left(\frac{E_{T,road} \cdot D_{T,road}}{W_c}\right) \quad (2)$$

where, $\eta_{ee}$ is the energy efficiency of the industrial sector of the considered manufacturing country; $E_{P1}$ is the energy used for production of Upgraded metallurgical-grade silicon (UMG-Si) from quartz; $E_{P2}$ is the energy used for solar grade silicon (SoG-Si) production; $E_{P3}$ is the energy used for multi-Si ingot casting from SoG-Si; $E_{P4}$ is the energy used for multi-Si wafer slicing; $E_{P5}$ is the energy used for solar cell production; $E_{P6}$ is the energy used for solar module production; $E_{T,sea}$ and $E_{T,road}$ are the energy used for sea freight and road transporting of PV modules in $kWh/km.kg$ and $kWh/km$, respectively; $M_w$ is the PV module weight per Watt in $kg/W_p$; $W_c$ is the total wattage of the consignment in transit; $D_{T,sea}$ and $D_{T,road}$ is distance covered by the ship and truck in $km$, respectively. The inventory data in Table 4 was extracted from (Andreas & Linda, 2018; Elie El, 2016; Hou et al., 2016; Masson & Kaizuka, 2020; Sui, de Vos, Stapersma, Visser, & Ding, 2020; Zawadzki et al., 2020). The inventory data for energy $E_{P1}$ to $E_{P6}$ in Table 4 has a standard deviation of 0.062 $kWh/W_P$ and a 95% confidence interval of $0.222 \pm 0.061$ $kWh/W_P$.

**Table 4:** Inventory Data used to Evaluate the Energy Used for a PV Module (Andreas & Linda, 2018; Elie El, 2016; Hou et al., 2016; Maersk, 2020; Masson & Kaizuka, 2020; Sui et al., 2020; Zawadzki et al., 2020)

| Entity | Notation | Value |
|---|---|---|
| Energy used for production of UMG-Si from quartz and for SoG-Si production ($\mathrm{kWh/W_P}$) | $E_{P1} + E_{P2}$ | 0.181 |
| Energy used for multi-Si ingot casting from SoG-Si and for multi-Si wafer slicing ($\mathrm{kWh/W_P}$) | $E_{P3} + E_{P4}$ | 0.225 |
| Energy used for solar cell production ($\mathrm{kWh/W_P}$) | $E_{P5}$ | 0.150 |
| Energy used for solar module production (inclusive of glass cover and aluminium frame production) ($\mathrm{kWh/W_P}$) | $E_{P6}$ | 0.290 |
| Energy used by sea freight transportation ($\mathrm{kWh/km.kg}$) | $\mathrm{E_{T,sea}}$ | 0.003 |
| Energy used by truck transportation ($\mathrm{kWh/km}$) | $\mathrm{E_{T,road}}$ | 1.650 |
| Total wattage of the consignment in transit (W) | $\mathrm{W_c}$ | 50,000 |

Since Uganda is a landlocked country, the solar PV module consignment is shipped to Mombasa port in Kenya, from where it is transported by trucks to Entebbe city in Uganda. The road distance from Mombasa port to Entebbe city is about 1,179 km. However, the distance for road transportation of the consignment within the manufacturing country was assumed to be short, in a radius of about 500 km from the considered exporting seaport, thus, it was neglected in the analysis. The consideration of the road transportation between Mombasa and Entebbe is based on the high costs reported along this route. For instance, over the last five years, shipping a 40-foot container from Dubai in United Arab Emirates to Mombasa in Kenya costed between \$ 1,400 – 1,700, but the same container costed between \$ 3,000 – 3,800 to transport from Mombasa in Kenya to Kampala in Uganda by road (Africa Business, 2019; Andreas & Linda, 2018). Also, the Mombasa to Entebbe road distance was considered because of the reported higher energy used by the trucks of about 0.5 $l/km$, an equivalent of about 1.65 kWh/km (Andreas & Linda, 2018) compared to that of developed countries like New Zealand of about 1.48 – 1.56 kWh/km (Wang, McGlinchy, & Samuelson, 2019). Currently, Earthmark Enterprises that operates within Kenya, Rwanda and Uganda charges 2.6 \$/40-ft per km, which is equivalent to \$ 3,065 to deliver a 40-foot container in Entebbe city from Mombasa by truck (Cargorouter, 2021). Table 5 shows the estimated distance between the considered seaports of the module manufacturing countries and Mombasa seaport in Kenya $D_{S,air}$, extracted from (Sea Distances, 2021). Also, Table 5 shows the energy efficiency of the industrial sector of the considered solar PV module manufacturing countries $\eta_{ee}$, extracted from (ACEEE, 2018). The sea distance for the considered module manufacturing countries has a standard deviation of 2,397 km and a 95% confidence interval of 9,541 $\pm$ 1,918 km, while the energy efficiency has a standard deviation of 5.2% and a 95% confidence interval of 12.3 $\pm$ 4.2%.

**Table 5:** Inventory of the Estimated Distance of Manufacturing Countries' considered sea port to Mombasa Seaport in Kenya and their Industrial Sector Energy Efficiency (ACEEE, 2018; Sea Distances, 2021)

| **Manufacturing Country** | **Seaport Considered** | **Sea Distance, $D_{T,sea}$ (km)** | **Energy Efficiency, $\eta_{ee}$ (%)** |
|---|---|---|---|
| USA | Florida | 11,373 | 13.0 |
| Germany | Hamburg | 8,661.3 | 20.5 |
| China | Guangzhou | 9,904 | 12.0 |
| Brazil | Mumbai | 8,975 | 7.5 |
| India | Sorocaba | 5,711 | 14.5 |
| Australia | Melbourne | 12,620 | 6.0 |

#### 3.1.2.2 Greenhouse Gas Pay Back Time (GPBT)

Although solar PV systems do not have GHG emissions during the operation lifetime, it is worth noting that PV systems do generate $CO_2$ and other gases during their lifecycle stages such as extraction, production, transportation and disposal processes. Thus, it is important to establish the system's sustainability by analysing its payback period based on GHG emission. GPBT is referred to as the total GHG induced by the PV modules and BOS divided by the GHG produced by the local power plant for the power generated by the solar PV system. In this study, the GPBT was evaluated by using the modified expression shown in Eq. (3) (Cheng, 2008; Lu & Yang, 2010).

$$GPBT = \frac{GHG_S}{GHG_{output}} \tag{3}$$

where, $GHG_S$ is the lifecycle GHG emissions induced per watt by the PV modules in $gCO_{2eq}/\mathrm{W_p}$; and $GHG_{output}$ is the GHG emissions induced per watt by the local power plant for the power generated by the solar PV system in $gCO_{2eq}/\mathrm{W_p}$.

### a) Total GHG Emissions Induced during Manufacturing to Destination Port

Total GHG emissions induced per watt for the polycrystalline silicon modules from extraction of quartz to the finished solar PV module and transportation to the destination in the importing country was evaluated by using Eq. (4).

$$GHG_M = GHG_m^{qm} + GHG_m^{ue} + GHG_m^{p} + GHG_m^{T} + \left(GHG_{T,air} \cdot M_w \cdot D_{T,sea}\right) + \left(GHG_{T,road} \cdot M_w \cdot D_{T,road}\right) \tag{4}$$

where, $GHG_M$ is the total GHG emissions induced per watt during the polycrystalline silicon module manufacturing; $GHG_m^{qm}$ is the GHG emissions induced per watt during the quartz mining; $GHG_m^{ue}$ is the GHG emissions induced per watt during the UGM-Si extraction from quartz; $GHG_m^{p}$ is the GHG emissions induced per watt during the module manufacturing process; $GHG_m^{T}$ is the GHG emissions induced per watt during the transportation of module manufacturing materials locally; $\mathrm{GHG_{T,sea}}$ and $\mathrm{GHG_{T,road}}$ are the global average specific carbon dioxide emissions for sea freight and truck transportation, respectively.

The GHG emissions induced per watt during the manufacturing of the polycrystalline silicon modules $\mathrm{GHG_m^p}$ depends on the grid emission factor $\mathrm{GHG_{GEF}^{country}}$ of the manufacturing country. The country's grid emission factor shown in Table 6 (column 2) is multiplied by the global average energy consumption reported as 0.846 $\mathrm{kWh/W_p}$ (total standard energy used during the module production process, in reference to Table 4) and by $(1 - \eta_{ee})$ to get the equivalent GHG emissions induced per watt (Table 6 (column 3)) from UMG-Si production to PV module capsulation, expressed by Eq. (5). The grid emission factor data for the selected module manufacturing countries has a standard deviation of 278.8 $\mathrm{gCO_2/kWh}$ and a 95% confidence interval of 508.2 ± 223.1 $\mathrm{gCO_2/kWh}$.

$$GHG_m^p = 0.846 \cdot (1 - \eta_{ee}) \cdot GHG_{GEF}^{country} \tag{5}$$

**Table 6:** Inventory of the Grid Emission Factor for the Selected Manufacturing Countries (Carbon Footprint, 2020), and their Evaluated $GHG_m^p$ Value by Using Eq. (5)

| **Location** | **Grid emission factor ($gCO_2/kWh$)** | **$\mathrm{GHG_m^p}$ Evaluated Value ($gCO_{2eq}/\mathrm{W_p}$)** |
|---|---|---|
| New York, USA | 453 | 333.42 |
| Munich, Germany | 379 | 254.90 |
| Shanghai, China | 555 | 413.18 |
| Brasilia, Brazil | 74 | 57.91 |
| New Delhi, India | 708 | 512.12 |
| Sydney, Australia | 880 | 669.81 |

Table 7 shows the global average GHG emissions per watt from the literature that was used to evaluate the GHG emissions induced per watt by the solar PV module manufacturing and transportation to the importing country by using Eq. (4). The GHG emissions by trucks from Mombasa to Entebbe is reported at about 1,880 kg$CO_{2eq}$ (Cargorouter, 2021). This GHG emission was used in the analysis by standardizing it based on the total wattage of the module consignment in transit ($\mathrm{W_c}$), thus a value of $3.8 \times 10^{-2}$ kg$CO_{2eq}/\mathrm{W_p}$ was used for entity $\left(\mathrm{GHG_{T,road}} \cdot \mathrm{M_w} \cdot \mathrm{D_{T,road}}\right)$ in Eq. (4). The global average GHG emissions $GHG_m^{qm}$, $GHG_m^{ue}$

and $GHG_m^T$ in Table 7 have a standard deviation of 2.76 g $\mathrm{CO_{2eq}/W_p}$ and a 95% confidence interval of 10.44 ± 3.13 g $\mathrm{CO_{2eq}/W_p}$.

**Table 7:** Inventory Global Average GHG Emissions Involved During Polycrystalline Silicon Module Manufacturing and Transportation (Hou et al., 2016; Sui et al., 2020; Wang et al., 2019)

| Entity | Notation | Value |
|---|---|---|
| $CO_2$ emission induced during quartz mining ($g\ CO_{2eq}/W_p$) | $GHG_m^{qm}$ | 7.25 |
| $CO_2$ emission induced during UGM-Si extraction from quartz ($g\ CO_{2eq}/W_p$) | $GHG_m^{ue}$ | 11.97 |
| $CO_2$ emissions induced during module manufacturing process (country specific) ($g\ CO_{2eq}/W_p$) | $GHG_m^p$ | Table 6 |
| $CO_2$ emission induced during local transportation of quartz, UMG-Si, SoG-Si, silicon ingots, wafers and solar cells for 1000 km ($g\ CO_{2eq}/W_p$) | $GHG_m^T$ | 12.10 |
| Global Average Specific Carbon Dioxide Emissions for sea freight ($gkg^{-1}km^{-1}$) | $\mathrm{GHG_{T,sea}}$ | 0.07 |
| Global Average Specific Carbon Dioxide Emissions for truck transportation ($gkg^{-1}km^{-1}$) | $\mathrm{GHG_{T,road}}$ | 0.135 |

### b) GHG Produced by Local Power Plant $(GHG_{output})$

The GHG emission induced per watt $GHG_{output}$, that is to be avoided annually by the implementation of the solar PV system was evaluated by using Eq. (6) in $\mathrm{gCO_{2eq}/W_p}$, where $\mathrm{GHG_{GEF}^{country}}$ is the grid emission factor of the country in $\mathrm{gCO_{2eq}/kWh}$ and $E_{output}$ is the energy generated by the solar PV system in $\mathrm{kWh/W_p}$. Uganda's grid is reported to have an emission factor of 201 $\mathrm{gCO_{2eq}/kWh}$ (EIB, 2020), attributed to its energy generation mix that has a significant percentage of hydropower and fossil fuel-based power plants (ERA, 2021).

$$GHG_{output} = GHG_{GEF}^{country} \cdot E_{output} \tag{6}$$

### 3.2 Solar PV Module Transportation Cost Incurred

Trade amongst countries is impended by the distance. For instance, the literature estimates that doubling the distance halves the trade amongst the countries (OECD, 2006). The influence of distance on the trade is often seen through the transportation costs of the goods and services incurred on either end. Shipping costs substantially rise with increase in the distance. This can be estimated by considering the elasticity of the shipping costs with respect to the distance (OECD, 2006). An econometric model for evaluating the shipment cost by incorporating variable components such as distance was proposed in (Mark Brown & Anderson, 2015). The pricing model accounts for both the fixed costs incurred by firms on a per-shipment basis and variable costs per kilometre shipped. Eq. (7) shows the pricing model for shipping commodities from one location to another.

$$C_{ijl} = \alpha + \beta \tag{7}$$

For $\beta = \delta \cdot d_{ij} \cdot t_l$

where, $C_{ijl}$ is the total cost incurred to transport commodity $l$ from country $i$ to country $j$; $\alpha$ is the fixed cost incurred; $\beta$ is the variable cost incurred; $\delta$ is the linear approximation of the price per tonne-kilometre; $d_{ij}$ is the distance between the two shipping locations (countries); and $t_l$ is the tonnage of the commodity (consignment) to be transported. An estimate of $\delta$

equivalent to 0.10 $\$/ton \cdot km$ was considered based on the ad-valorem model for estimating the freight rates for shipments proposed in (Hummels, 2003).

The current sea freight rate is about 50 c$/kg (Freightos, 2021). For 50 kW solar PV as the functional unit, comprising of 200 modules each weighing 18 kg, the total weight of the modules is 3,600 kg. Thus, the fixed costs incurred for sea freight transportation of the solar PV modules from any of the manufacturing country is $ 1,800. Table 8 shows the solar module prices for the selected manufacturing countries that were obtained from (Alibaba.com, 2020). Since solar module prices vary from one manufacturer to another within a country, average values of solar module prices per watt for each country as well as the fixed cost incurred are shown in Table 8. The road transportation of the module consignment from Mombasa port to Entebbe city was considered as $ 3,065 based on (Cargorouter, 2021), averaged at about 6.13 c$/$W_p$ for truck transported in this study. The PV module price in Table 8 has a standard deviation of 0.24 $/$W_p$ and a 95% confidence interval of 0.24 $\pm$ 0.19 $/$W_p$.

**Table 8:** Solar PV Module Price Per Watt for Each of the Considered Module Manufacturing Countries

| **Country** | **PV module price ($/$W_p$)** | **Fixed cost incurred, $\alpha$ ($)** |
|---|---|---|
| Australia | 0.22 | 1,800 |
| Brazil | 0.26 | 1,800 |
| China | 0.20 | 1,800 |
| Germany | 0.24 | 1,800 |
| India | 0.26 | 1,800 |
| USA | 0.25 | 1,800 |

### 3.3 Ranking Considered Solar PV Module Manufacturing Countries

Seeking to single out the best choice manufacturing country and rank the considered manufacturing countries, the multi-criteria optimization and compromise Solution (Serbian name: VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR)) method was opted for in the decision-making analysis (Akram, Al-Kenani, & Alcantud, 2019; Mardani, Zavadskas, Govindan, Amat Senin, & Jusoh, 2016). The VIKOR technique is a discrete multi-criteria reference-point method based on Compromise Programming (CP) (Henao, Cherni, Jaramillo, & Dyner, 2012). CP defines the best solution as the one in the set of efficient solutions whose point has the least distance from an ideal point (Zeleny, 2012). The gap distance between the triangles is one of the key features of the method and it is calculated by using Eq. (8) in this study, which is a modified version of the CP expression for VIKOR technique in (Henao et al., 2012; Zeleny, 2012).

$$Min\left\{D_p(A_q) = \left(\sum_{j=1}^{3} w_j^p \left|\frac{V_j(A_q) - V_{j,min}}{V_{j,ref} - V_{j,min}}\right|^p\right)^{1/p} \quad q = 1, \ldots, n; 1 \le p \le \infty\right\} \tag{8}$$

where, $D_p(A_q)$ is the defined as the gap distance between the centre of the ideal triangle and the value resulting from modelling the objective category by importing from the manufacturing country option $q$; $\mathrm{V_j}(\mathrm{A_q})$ is the normalized value of the objective category $j$ with respect to the manufacturing country option $q$; $V_{j,ref}$ is the ideal value of objective category $j$ ($V_{j,ref} = 1$); $V_{j,min}$ is the lowest value given to the objective category $j$ ($V_{j,min} =$

0); $w_j$ is the weight value relative to the importance attributed to the objective category $j$; and $p$ is a distance parameter that reflects the attitude of the decision-makers regarding compensation between the deviations in the triangles, typical values for $p$ are 1 and 2. $p = 1$ implies the longest geometric distance between two points while $p = 2$ implies the shortest geometric distance between two points, a straight line (Ringuest, 1992).

To normalize the evaluated results of the LCA energy used, LCA GHG emissions induced and importation costs incurred, Eq. (9) was used.

$$V_j(A_q) = \frac{v_q}{\sum_{q=1}^{n} v_q} \tag{9}$$

where, $V_j(A_q)$ is the evaluated normalized value of the objective category $j$ corresponding to importing solar PV modules from the manufacturing country option $q$; and $v_q$ is the value of the objective category $j$ corresponding to the manufacturing country $q$. Based on the resultant values of $V_j(A_q)$, a triangle with the objective categories at its edges is generated and used to rank the manufacturing countries in ascending order of the minimal values of the $V_j(A_q)$. The normalized value observation-based ranking order $N_q$ of the considered manufacturing countries based on the objective categories of the decision-making process is determined from the evaluated $V_q$ value of the manufacturing country, given by Eq. (10). Ordinarily, the conventional ranking technique, also referred to as normalized value observation-based ranking, is the simplest approach for the decision makers to use to rank the selected module manufacturing countries based on the objective categories set for the decision-making process.

$$V_q = \sum_{j=1}^{3} V_j(A_q) \tag{10}$$

To adopt the modified VIKOR technique, the objective categories are assigned weights by the decision makers of the importing country. In assigning weights to the objective categories, it should be noted that the importers would wish to have the minimal values of the objective categories for the considered manufacturing countries. Thus, the smaller the weight value attributed to an objective category, the more important it is in the decision-making process. That is, an objective category with weight $w_j = 0.167$ is more important to the decision-makers than the one with weight $w_j = 0.500$. This is because the decision-makers' emphasis in adopting the modified VIKOR technique is to attain the least possible gap distance from the ideal minimum triangle, other than from the ideal maximum triangle.

### 3.4 Verification and Validation

In the verification process, an internal evaluation of the study methodology was done to check for correctness of the approaches adopted. In this study, a sensitivity analysis was undertaken for the verification process of the key LCA indicators and the proposed modified VIKOR technique. The sensitivity of the key LCA indicators, namely, LCA energy used, LCA GHG emissions induced, importation cost incurred, EPBT and GPBT, were examined for variations in their main input parameters. The sensitivity of the modified VIKOR technique was examined for the variations in the $V_j(A_q)$ values and the assigned weight $w_j$ values of the objective categories to test the technique's stability and capability with respect to the input parameters. Sensitivity analysis is a powerful tool for analysing the uncertainty and robustness of the technique and eliminate biasness during data collection and analysis (Kumar, Aswin, & Gupta, 2020). Sensitivity analysis depicts how the uncertainty in the output of the technique would be affected by the uncertainty of input parameter variables (Kumar et al., 2020; Sadeghi-Niaraki, 2020).

On the other hand, for the validation process, an external evaluation of the modified VIKOR technique was used to check for the agreements between the results for the modified VIKOR technique and the conventional ranking technique. The ranking orders for the selected solar module manufacturing countries based on the modified VIKOR technique were compared with the conventional ranking technique that is based on the summation of the normalized values of the objective categories by using Eq. (10). The Chi-Square goodness-of-fit test was used for the validation of the proposed modified VIKOR technique in this study.

The chi-square goodness-of-fit test is used in statistical modelling to ascertain whether the model actually reflects the observed data, or whether the observed values are close to an expected distribution corresponding to a fitted model (Ranjith, Setunge, Gravina, & Venkatesan, 2013). The chi-square test statistics is based on the null hypothesis that tests whether the observed frequency matches with the predicted frequency (Ranjith et al., 2013; Wellalage, Zhang, & Dwight, 2015). In this study, the modified VIKOR technique performance was assessed by using the Chi-square of goodness-of-fit test ($\chi^2$) given by Eq. (11) (Ranjith et al., 2013; Wellalage et al., 2015).

$$\chi^2 = \sum_{q=1}^{n} \frac{\left(N_q - P_q\right)^2}{P_q} \tag{11}$$

where, $N_q$ is the conventional ranking technique rank number, $P_q$ is the modified VIKOR technique predicted rank number, and $n$ is the number of manufacturing countries considered.

This hypothesis testing allows for the establishment of whether the modified VIKOR technique is consistent with rankings based on the conventional ranking technique used to validate the methodology. A 95% confidence level is used to evaluate the fitness of the ranking models. Notably, if the test statistic ($\chi^2$) is larger than the critical chi-square value, the proposed modified VIKOR technique should be rejected. It has been argued that the mean values with 95% confidence interval limits can be used to approximate the true values, and the risk that the true value is not in the 95% confidence interval limits is 5%. Thus, this confidence interval represents the uncertainty level in the estimation (Wellalage et al., 2015).

## 4.0 Results and discussion

### 4.1 Life Cycle Impact Assessment and Interpretation

Two orientations were considered and simulated in the SAM tool based on system specifications in Table 3. The weather data file for the considered solar PV installing site was generated from the Meteonorm database. The simulation results revealed the possible energy generation (in $\mathrm{kWh/W_p}$) from the solar PV systems installed at either array orientation at the selected location. A tilt angle in the range of 0 – 5° is reported to result in the highest solar irradiance received on the plane of array (POA) by any solar PV array in Uganda (Mukisa et al., 2019b). However, most of the rooftops in Uganda are tilted averagely at 25°, thus, a tilt angle of 25° was utilized in the solar PV system performance simulation. Fig. 3 shows the energy generation from a 50 kW capacity solar PV system at Entebbe site in Uganda.

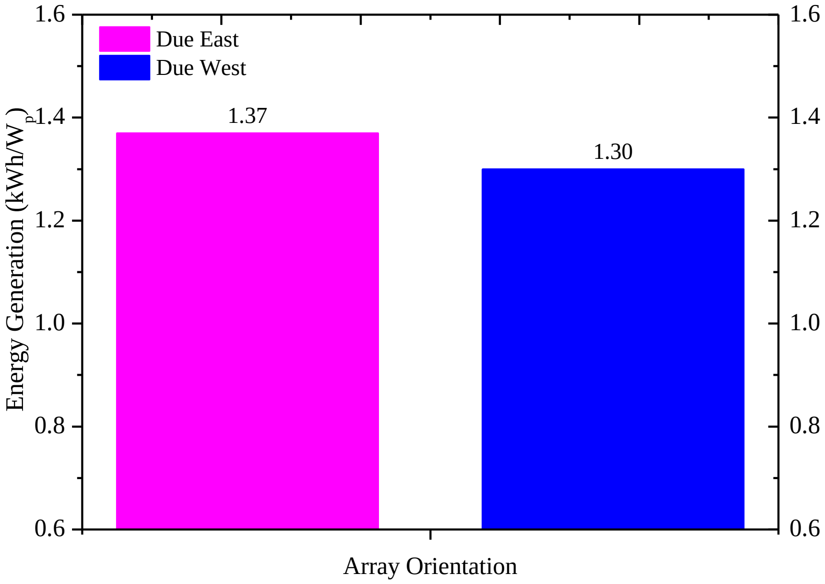


**Fig. 3:** Energy Generation for a 50 kW Capacity Solar PV Systems at Entebbe Site in Uganda for East and West Orientations

The disparities in the energy generation shown in Fig. 3 at the selected site can be explained by the difference in the solar irradiance received by the solar PV array at these orientations. The solar irradiance received at a location can efficiently be represented by the daily annual average solar irradiance received on the POA of the solar PV systems of the considered array orientations at the location. This study focused on the worst-case scenario for its analysis; hence, the due West orientation of the solar PV system was considered for the Entebbe site. Thus, the least energy generation for the orientation due West case was considered in order to evaluate the maximum possible energy payback time for the solar PV systems in Uganda.

To depict the impact of the international transportation on the EPBT for the selected module manufacturing countries, the inventory data in Tables 4 and 5 was used in Eq. (2). The energy used per watt in the manufacturing of polycrystalline silicon modules, sea freight and truck transportation to Entebbe as well as the total energy used till delivery at Entebbe site were evaluated. Fig. 4 shows the results of the evaluation for all the considered solar PV module manufacturing countries for a 50 kW capacity solar PV system.

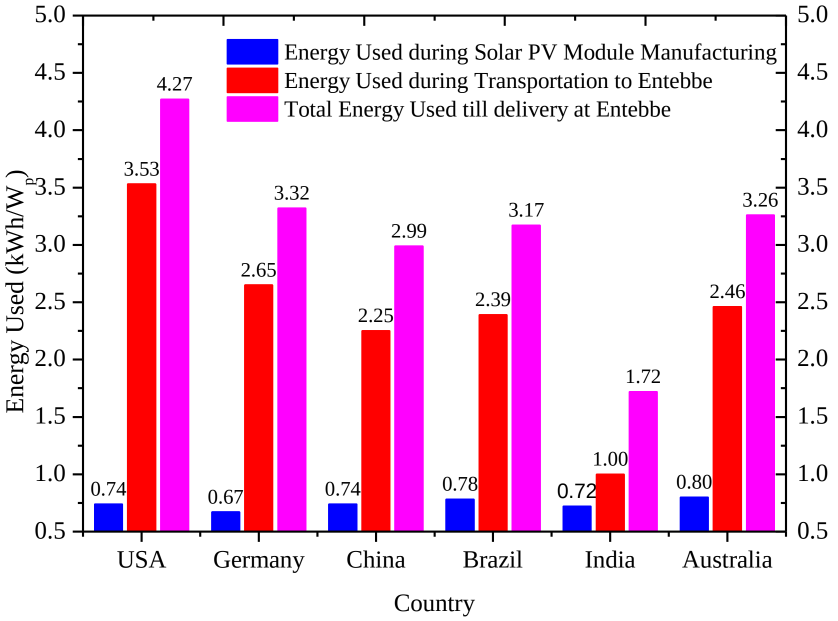


**Fig. 4:** Energy Used per watt in Manufacturing and Transportation to Destination of a 50 kW Capacity Solar PV Modules to Entebbe City

By considering the LCA energy used for solar PV modules as the selection criterion of the module manufacturing country by decision makers in Uganda, Fig. 4 shows that for implementations of solar PV systems in Uganda, India is the best choice country to import solar PV module from, followed by China and Brazil. This is mainly attributed to their shorter sea freight distances compared to the other considered module manufacturing countries as shown in Table 5. Since all the selected module manufacturing countries have almost the same energy used during the module manufacturing process, the difference in the energy used during the transportation to the destination matters most for this criterion. For instance, due to the long distance between Florida port in USA and Mombasa port in Kenya as shown in Table 5, Fig. 4 shows that the energy used during transportation to Entebbe for the case of USA of 3.53 kWh/W$_p$ exceeds the total energy used till delivery at Entebbe for all the other considered module manufacturing countries, which ranges between 1.72 – 3.32 kWh/W$_p$. Overall, the LCA energy used for the selected module manufacturing countries ranges between 1.72 – 4.27 kWh/W$_p$ and has an average of 3.12 kWh/W$_p$.

By using Eq. (1), the EPBT for the functional unit imported from the considered solar PV module manufacturing countries was evaluated. The solar energy generation of the system installed due West (shown in Fig. 3) and the energy used per watt based on the module manufacturing country (shown in Fig. 4) were used in Eq. (1). Fig. 5 shows the energy payback time (EPBT) for the solar PV systems at Entebbe site in Uganda.

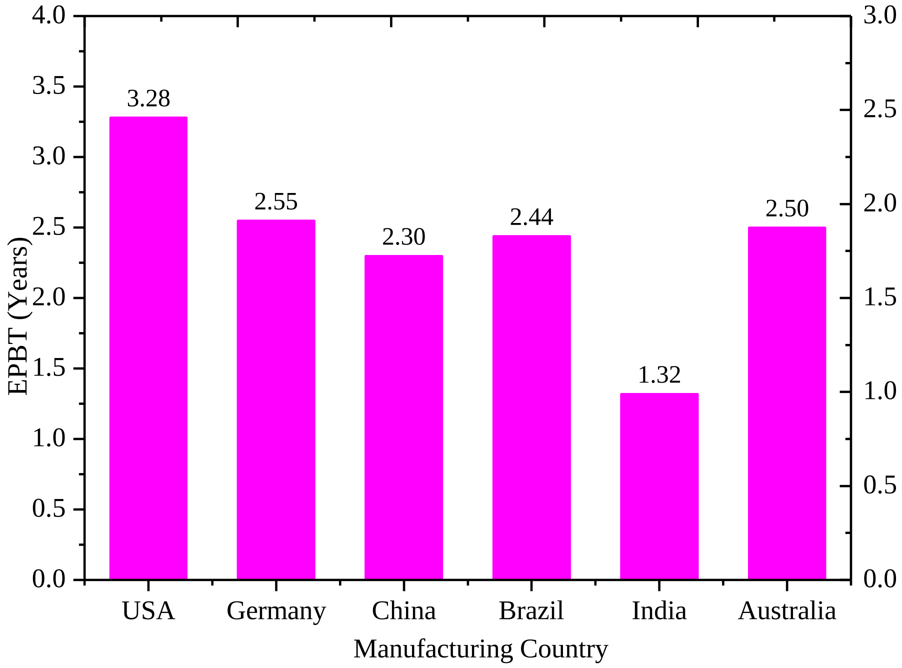


**Fig. 5:** Energy Payback Time for Solar PV Modules from the Selected Manufacturing Countries

Fig. 5 reveals that the maximum EPBT is 3.28 years for the solar PV modules imported from the USA, attributed to the long sea freight distance of about 16,183 km between Florida port and Mombasa port in Kenya that accounts for more energy used per watt as shown in Fig. 4. The minimum EPBT is 1.32 years for the solar PV modules imported from India, attributed to the short sea freight distance between Mumbai port and Mombasa port in Kenya of about 4,445 km. Thus, based solely on the EPBT, India would be the best choice module manufacturing country to import the solar PV modules from, followed by China. Overall, the EPBT for all the considered module manufacturing countries ranges between 1.32 – 3.28 years and has an average of 2.40 years. The solar PV system implemented in Uganda can suitably pay back all the energy used over its lifecycle due to the high daily solar irradiance received in the country. Uganda receives on average a daily solar irradiance in the range of 5 – 6 kWh/m$^2$ that guarantees high energy generation at any location in Uganda (Mukisa et al., 2019b).

Although the solar PV module's production process for all the considered module manufacturing countries have almost the same quantity of the energy used, as shown in Fig. 4, the GHG emissions induced during the module manufacturing process varies. The considered countries have different grid emission factors due to their electricity generation mix, as shown in Table 6. The respective grid emissions of the module manufacturing countries and the GHG emissions induced during the international transportation of the solar PV modules to the implementing country contribute to the resultant GBPT of the solar PV systems. The total GHG emissions induced through the solar PV module production till delivery at Entebbe site were evaluated by using the inventory data in Tables 6 and 7 in Eq. (4). Fig. 10 shows the results of the evaluation for all the considered solar PV module manufacturing countries for a 50 kW capacity solar PV system for implementation in Entebbe city.

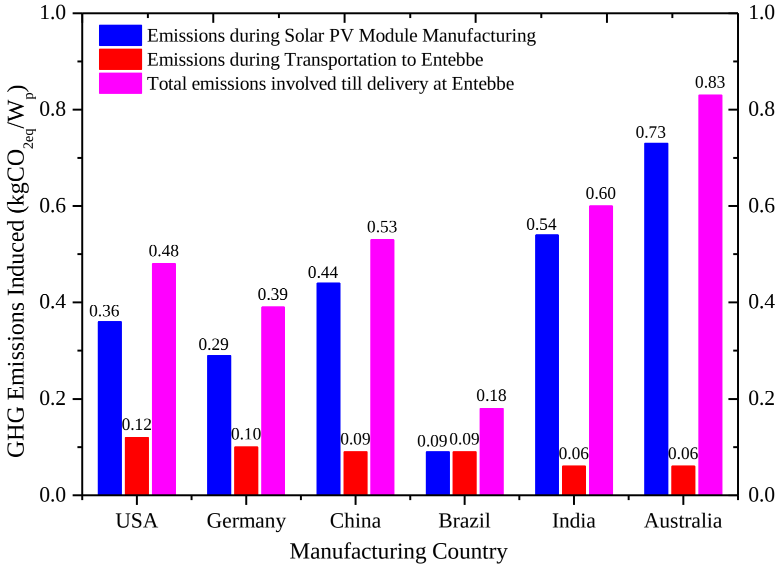


**Fig. 6:** GHG Emissions Induced per watt in Manufacturing and Airplane Transportation of a 50 kW Capacity Solar PV System Components to Entebbe Airport

Fig. 6 reveals that the manufacturing of solar PV modules contributes the biggest share of the total GHG emissions induced till delivery at Entebbe site. This is attributed to both the grid emission factor and the high GHG emissions induced during the production process of poly silicon as shown in Table 7, in comparison to the sea freight transportation GHG emissions induced. Fig. 6 shows that by considering the LCA GHG emissions induced as the selection criterion for the module manufacturing country, Brazil is the best choice module manufacturing country followed by Germany and USA. Although USA ranked the last choice to import modules from under the LCA energy used criterion, as shown in Fig. 4, under the LCA GHG emissions induced criterion, as shown in Fig. 6, it emerges as the third best choice out of the considered module manufacturing countries This is mainly attributed to the cleanness of the electricity grid systems as indicated by their grid emission factors in Table 6. Overall, the LCA GHG emissions induced for the selected module manufacturing countries ranges between 0.18 – 0.83 $gCO_{2eq}/W_p$ and has an average of 0.50 $gCO_{2eq}/W_p$.

Notably, although India is closest module manufacturing country to Uganda and was the best choice under the consideration of the LCA energy used criterion, as shown in Fig. 4, its high grid emission factor of about 708 $gCO_{2eq}/kWh$ greatly affects its ranking under the LCA GHG emissions induced criterion, as shown in Fig. 6. Therefore, due to global climate change concerns, the importing countries of solar PV components should take into consideration the LCA GHG emissions induced as a result of the solar PV module manufacturing as a decision-making procurement criterion. In case this is globally adopted and implemented, it could influence the module manufacturing countries to embrace cleaner energy generating technologies in order to remain competitive in the global market.

By using the grid emission factor for Uganda of 201 $gCO_{2eq}/kWh$ (EIB, 2020) and the energy generation of a solar PV system orientated due West of 1.3 $kWh/W_p$ in Eq. (6), the GHG induced per watt by the local power plant for the power generated by the PV system was evaluated. The value of $GHG_{output}$ was evaluated as 0.26 $kgCO_{2eq}/W_p$. Eq. (3) was used to evaluate the GPBT for the functional unit of 50 kW capacity solar PV system installed in

Entebbe city. Fig 7 shows the GHG payback time (GPBT) for the functional unit of 50 kW capacity solar PV system for modules imported from the selected manufacturing countries.

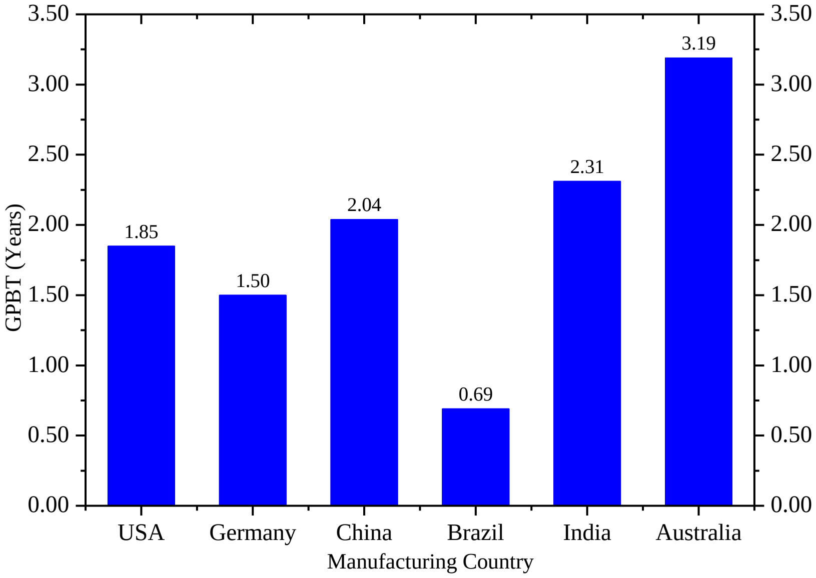


**Fig. 7:** GHG Payback Time for Solar PV Modules from Selected Manufacturing Countries

For all the selected module manufacturing countries, Fig. 7 shows that Australia has the highest GPBT of 3.19 years, while Brazil has the least GPBT of 0.69 years. This can be attributed mainly to the grid emission factor of these two countries. As shown in Table 6, Brazil has a grid emission factor of 74 $\mathrm{gCO_{2eq}/kWh}$, while Australia has a grid emission factor of 880 $\mathrm{gCO_{2eq}/kWh}$, which is approximately 12 times that of Brazil. Likewise, although India and Germany are closer to Uganda, because of their higher grid emission factor compared to Brazil, Brazil yields the least GBPT. Thus, based solely on GPBT, Brazil would be the best choice module manufacturing country to import the solar PV modules from, followed by Germany. Overall, the GPBT for all considered module manufacturing countries ranges between 0.69 – 3.19 years and has an average of 1.93 years.

From the results in Figs. 5 and 7, the EPBT and GPBT for the solar PV modules imported from the selected manufacturing countries to Uganda were compared. Thus, in the case that the GPBT is prioritized during the decision-making process, Brazil with GPBT of 0.69 years would be the best choice to import from, followed by Germany with GPBT of 1.50 year. On the other hand, if the EPBT is prioritized in the decision-making process, India with the EPBT of 1.32 years would be the best choice followed by China with the EPBT of 2.30 years. However, if both criteria are considered during the decision-making process to select the module manufacturing country to import from, at this stage it is hard to single out the country to consider since each of the criteria gives a different best choice country. That is, the decision-makers must choose between Brazil and India as the best choice module manufacturing countries to import modules from.

This study's LCA results were compared with some of the previous findings reported in Table 1. Table 9 shows the comparison of the previous studies on the LCA of rooftop solar PV and this study's findings. Most of the previous studies considered the solar PV components as locally manufactured near the sites or in the country of installation. However, the strength of this study lies in the consideration of the importation solar PV components to an overseas implementing country as well as the grid emission factors of the individual manufacturing countries. These aspects are crucial in the LCA investigations since they contribute to the energy used and GHG emissions induced by the solar PV system.

**Table 9:** Comparison of Previous Studies and Current Study's Finding on LCA of Solar PV Systems

| **Year** | **Study** | **Installation Type** | **Location** | **Boundary** | **LCA Indicators** | **Main Results** |
|---|---|---|---|---|---|---|
| 2010 | (Lu & Yang, 2010) | Rooftop-mounted Building integrated | Hong Kong | Production and use | EPBT, GBPT | EPBT=7.1 − 20.0 years;<br>GBPT=5.2 years |
| 2011 | (Sumper et al., 2011) | Rooftop-mounted | Spain | Production and use | EBPT | EPBT=3.43 – 9.57 years |
| 2015 | (Kabakian et al., 2015) | Rooftop-mounted | Lebanon | Production (BOS), installation and use | EPBT, GPBT | EPBT=16.1 – 16.9 years;<br>GPBT=3.21 – 3.52 years |
| 2015 | (Fu et al., 2015) | Ground-mounted | China | Production (BOS) and use | EPBT, GWP | EPBT=2.22 – 6.05 years;<br>GWP=50.9 g$CO_2$/kWh |
| 2017 | (Akinyele et al., 2017) | Ground-mounted | Nigeria | Production and use | EPBT, $CO_2$ | EPBT=0.83 – 2.83 years;<br>GWP=1.91 – 5.82 ton$CO_2$ |
| 2017 | (Sagani et al., 2017) | Rooftop-mounted | Greece | Production and use | EPBT, GBPT | EBPT=1.8 years;<br>GBPT=1.5 years |
| 2018 | (Luo et al., 2018) | Rooftop-mounted | Singapore | Production and use | EPBT, $CO_2$ | EPBT=1.01 – 1.11 years;<br>$CO_2$=20.9 – 30.2g$CO_2/$kWh |
| 2018 | (Eskew et al., 2018) | Rooftop-mounted | Thailand | Production and use | EPBT, GPBT | EPBT=2.5 years;<br>GPBT=0.079kg$CO_2/$kWh |
| **2020** | **Current Study** | **Rooftop-mounted** | **Uganda** | **Production, Transportation and use** | **EPBT, GPBT, $CO_2$** | **EPBT=1.32 – 3.28 years;<br>GPBT=0.69 – 3.19 years;<br>$CO_2$=0. 18 – 0.83 kg$CO_{2eq}$/W$_P$** |

A significant variation exists in the EPBT and GPBT of the solar PV systems based on factors such as site location, installation type and LCA boundary as reported in (Kim et al., 2012). The studies compared in Table 9 are from different locations receiving different daily solar irradiance as well as the LCA boundaries considered. Nonetheless, the comparison in Table 9 reveals that this study's findings agree with the trend of the previous studies' findings worldwide. The Implementation of rooftop solar PV systems in Uganda was investigated and reported to result in substantial sustainable development benefits to the communities (Mukisa et al., 2020a). Likewise, based on this study's findings, the importation of solar PV modules for implementation in Uganda would generally have fewer environmental impact concerns as shown in Table 9 for the selected module manufacturing countries. Therefore, Uganda's decision-makers can decisively import solar PV modules from overseas module manufacturing countries with minimal concerns about the modules' global environmental impacts over their lifecycle.

## 4.2 Importation Cost Incurred

By using Eq. (7) and the data in Tables 5 and 8, the importation cost incurred was evaluated. Table 10 shows the total transport cost incurred per watt till deliver at Entebbe site. Fig. 8 shows the total solar PV module cost in the manufacturing country ($), transport cost incurred till Entebbe ($) and the total cost incurred with respect to the manufacturing country (c$/Wp).

**Table 10:** Evaluated Importation Cost Incurred with Respect to Individual Manufacturing Country

| Country | Total PV modules cost ($) for 50 kW | Transport Variable cost ($) | Total Transport cost to Mombasa ($) | Transport cost from Mombasa to Entebbe ($) | Total Transport to Entebbe cost ($) | Total Transport cost (c$/Wp) | Total Importation Cost Incurred (c$/Wp) |
|---|---|---|---|---|---|---|---|
| USA | 12,500 | 5,826 | 7,621 | 3,065 | 10,686 | 21.37 | 46.37 |
| Germany | 12,000 | 4,344 | 6,144 | 3,065 | 9,209 | 18.42 | 42.42 |
| China | 10,000 | 3,686 | 5,486 | 3,065 | 8,551 | 17.10 | 37.10 |
| Brazil | 13,000 | 3,911 | 5,711 | 3,065 | 8,776 | 17.55 | 43.55 |
| India | 13,000 | 1,600 | 3,400 | 3,065 | 6,465 | 12.93 | 38.93 |
| Australia | 11,000 | 4,031 | 5,831 | 3,065 | 8,896 | 17.79 | 39.79 |

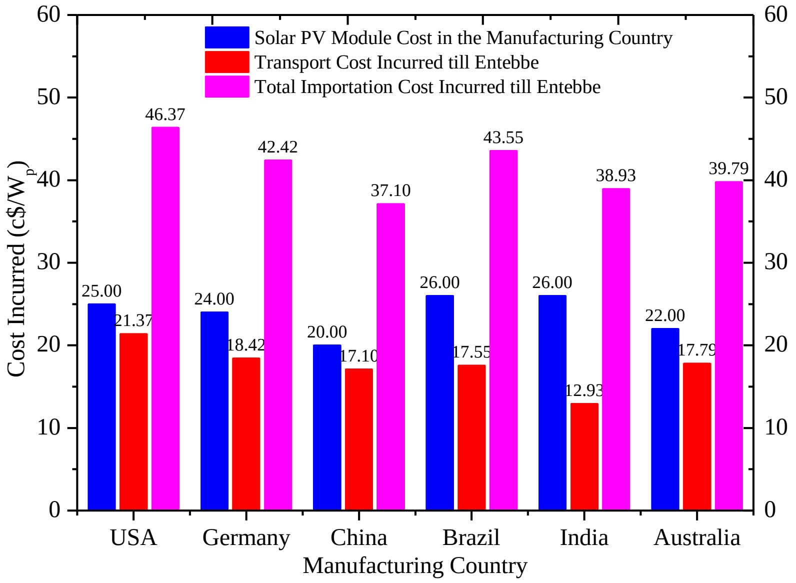


**Fig. 8:** Cost Incurred by Importing Solar Modules from any of the Selected Manufacturing Countries

The results in Table 10 and Fig. 8 agree with the assertion made by study (Van Buskirk & Schwartz, 2019) that the incorporation of the transportation cost almost doubles the solar PV module price per watt offered at the factory gate. Fig. 8 shows that of all the considered module manufacturing countries, solar PV importation would record minimal cost incurred by importing the modules from China, followed by India and Australia. Although India is the closest to Uganda of all the selected module manufacturing countries, India's high local (factory gate) solar module price per watt of 0.26 $/W$_p$ makes it costly to import from in comparison to China with price per watt of 0.20 $/W$_p$. Overall, the total importation cost incurred to import modules from the selected module manufacturing countries ranges between 37.10 – 46.38 c$/W$_p$ and has an average of 41.36 c$/W$_p$. Notably, the range for the importation cost incurred for the solar PV modules in this study is lower than the solar PV module price per watt in some of the SSA countries that was reported in the range of 0.70 – 1.40 $/W$_p$ (BloombergNEF, 2019). This mainly because the retailers in these countries sell at a higher rate than the importation cost incurred in order to make some profits from the transaction after taxation. Therefore, for a potential solar PV implementer, it is cheaper to import the solar PV modules than to buy from the local retailers in some of the SSA countries.

Considering the LCA energy used and GHG emissions induced criteria, where the importer had to choose from Brazil and India, the inclusion of the importation cost incurred criterion introduces China as another best choice module manufacturing country to be considered by the decision makers. Thus, at this point, the decision makers must adopt any of the ranking techniques presented in subsection 3.3 in order to single out the overall best choice module manufacturing country to import modules from. Therefore, to conclusively select the best choice manufacturing country to import from, multi-criteria analysis techniques have been utilized in subsection 4.3 taking into consideration all the three criteria (objective categories), that is, the LCA energy used per watt, LCA GHG emissions induced per watt and importation cost incurred per watt.

### 4.3 Ranking of Selected Module Manufacturing Countries

The multi-criteria analysis techniques take into consideration the three key objective categories addressed in this study to rank the module manufacturing countries considered. Table 11 shows the values of the LCA energy used per watt, LCA GHG emissions induced per watt and importation cost incurred per watt extracted from Figs. 4, 6 and 8, respectively, that were evaluated for a functional unit of 50 kWp system whose modules are considered for importation from the selected module manufacturing countries.

**Table 11:** Values of Objective Categories for each of the Module Manufacturing Countries

| Country | LCA Energy Used (kWh/Wp) | LCA GHG Emissions Induced kgCO$_2$/Wp) | Importation Cost Incurred (c$/Wp) |
|---|---|---|---|
| USA | 4.27 | 0.48 | 46.37 |
| Germany | 3.32 | 0.39 | 42.42 |
| China | 2.99 | 0.53 | 37.10 |
| Brazil | 3.17 | 0.18 | 43.55 |
| India | 1.72 | 0.60 | 38.93 |
| Australia | 3.25 | 0.83 | 39.79 |

The data in Table 11 was used in Eq. (9) to normalize the values of the LCA energy used per watt, LCA GHG emissions induced per watt and importation cost incurred per watt for the considered module manufacturing countries as shown in Table 12. Fig. 9 shows the triangles generated from results of Eq. (9) for the individual selected module manufacturing countries.

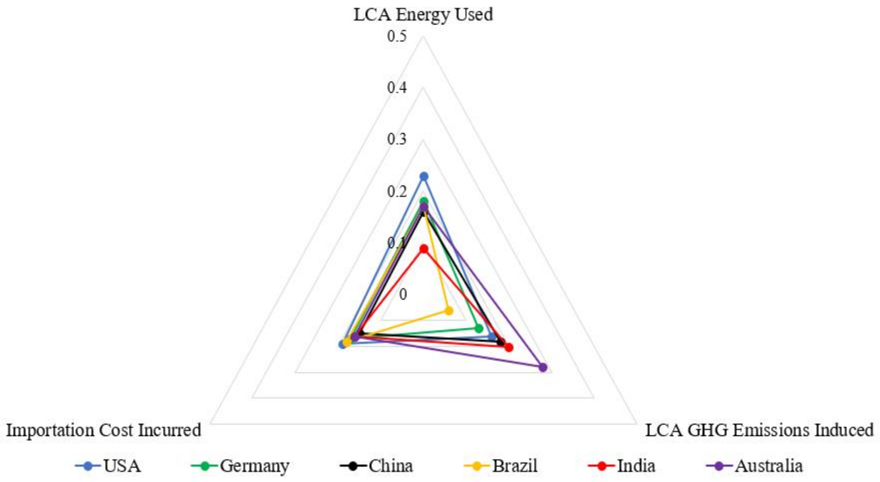


**Fig. 9:** Normalized Evaluated Objective Categories for the Considered Module Manufacturing Countries

Fig. 9 shows that the choice of the module manufacturing country cannot solely be determined at this stage. Because there is an overlap of the triangles, it is impossible to single out a module manufacturing country as the best choice to be considered based on the three objective categories. Therefore, the modified VIKOR technique in Eq. (8) was utilized to evaluate the minimal gap distance of the evaluated triangles from the ideal minimum. In this stage, all the objective categories were assigned a weight $w_j = 0.33$, that is, considering all the objective categories to have equal importance to the decision makers of the importing country. Also, the conventional ranking technique was utilized to rank the module manufacturing countries based on the sum of their $V_j(A_q)$ values by using Eq. (10). Table 12 shows the values of $V_j(A_q)$ evaluated by using Eq. (9), the $V_q$ value evaluated by using Eq. (8) and the minimum gap distance $Dp$ evaluated by using Eq. (8), for $p = 2$ and weight $w_j = 0.33$. Also, Table 12 shows the ranking results of the considered module manufacturing countries based on both the modified VIKOR and conventional ranking techniques. The Minimum gap distance results in Table 12 are presented in 3 decimal places for precision purposes due a very small difference in the values that could greatly affect the ranking if truncated or rounded-off to 2 decimal places.

**Table 12:** Minimum gap distance of the objective categories and the ranking orders of the manufacturing country considered

| **Objective** | **$V_j(A_q)$ values** | | | **Conventional Ranking Technique Based** | | **Modified VIKOR Technique Based** | |
|---|---|---|---|---|---|---|---|
| **Country** | **LCA Energy Used** | **LCA GHG Emissions Induced** | **Importation Costs Incurred** | **$V_q$ Value** | **Rank Number** | **Gap Distance, $Dp$** | **Rank Number** |
| USA | 0.23 | 0.16 | 0.19 | 0.58 | **5** | 0.112 | **5** |
| Germany | 0.18 | 0.13 | 0.17 | 0.48 | **3** | 0.092 | **3** |
| China | 0.16 | 0.18 | 0.15 | 0.49 | **4** | 0.094 | **4** |
| Brazil | 0.17 | 0.06 | 0.18 | 0.41 | **1** | 0.084 | **1** |
| India | 0.09 | 0.20 | 0.16 | 0.45 | **2** | 0.090 | **2** |
| Australia | 0.17 | 0.28 | 0.16 | 0.61 | **6** | 0.120 | **6** |

From the ranking orders in Table 12, it can be concluded that of all the considered module manufacturing countries, Brazil is the overall best choice country to import solar PV modules from for both ranking techniques. Notably, Table 12 reveals that the modified VIKOR technique gives the same ranking order of the module manufacturing countries as the convention ranking technique. Furthermore, the priorities of the decision makers are enacted by the weight assigned to the individual objective categories. Using the modified VIKOR technique, the assigned weight values to the objective categories were altered. A scale of 0 to 1 was used whereby the sum of all the weight values should always equate to 1. Table 13 shows the weights used for each of the objective categories. It should be noted that the objective category assigned with the least weight is of great importance to the decision-makers, while the category with the highest weight is of low importance to the decision-makers when selecting the module manufacturing country to import from.

**Table 13:** Considered Weight Label Categories for the Objective Categories

| **Objective Category** | **LCA Energy Used ($w_E$)** | **LCA GHG Emissions Induced ($w_G$)** | **Importation Cost Incurred ($w_C$)** | **Weight Label Categories** |
|---|---|---|---|---|
| **Weight Value** | 0.33 | 0.33 | 0.33 | **WL1** |
| | 0.17 | 0.33 | 0.50 | **WL2** |
| | 0.17 | 0.50 | 0.33 | **WL3** |
| | 0.33 | 0.17 | 0.50 | **WL4** |
| | 0.33 | 0.50 | 0.17 | **WL5** |
| | 0.50 | 0.17 | 0.33 | **WL6** |
| | 0.50 | 0.33 | 0.17 | **WL7** |

Based on the weight label categories in Table 13, the modified VIDOR technique was used to rank the selected module manufacturing countries. Table 14 shows the gap distance ($Dp$) and the ranking of each of the selected countries based on the weight label categories in Table 13 and $p = 2$ applied in Eq. (8).

**Table 14:** Modified VIKOR Technique Ranking of Selected Countries based on Weight Label Categories

| **Weight Label Categories** | **USA** | | **Germany** | | **China** | | **Brazil** | | **India** | | **Australia** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $Dp$ | **Rank No.** | $Dp$ | **Rank No.** | $Dp$ | **Rank No.** | $Dp$ | **Rank No.** | $Dp$ | **Rank No.** | $Dp$ | **Rank No.** |
| **WL1** | 0.112 | 5 | 0.092 | 3 | 0.094 | 4 | 0.084 | **1** | 0.090 | 2 | 0.120 | 6 |
| **WL2** | 0.116 | 5 | 0.100 | 3 | 0.099 | 2 | 0.097 | **1** | 0.105 | 4 | 0.126 | 6 |
| **WL3** | 0.109 | 4 | 0.091 | 2 | 0.106 | 3 | 0.073 | **1** | 0.114 | 5 | 0.152 | 6 |
| **WL4** | 0.125 | 6 | 0.106 | 3 | 0.097 | 2 | 0.107 | 4 | 0.092 | **1** | 0.109 | 5 |
| **WL5** | 0.115 | 5 | 0.093 | 2 | 0.107 | 3 | 0.071 | **1** | 0.108 | 4 | 0.153 | 6 |
| **WL6** | 0.134 | 6 | 0.108 | 4 | 0.099 | 2 | 0.104 | 3 | 0.077 | **1** | 0.111 | 5 |
| **WL7** | 0.131 | 6 | 0.104 | 4 | 0.103 | 3 | 0.092 | 2 | 0.084 | **1** | 0.128 | 5 |

Table. 14 shows that for weight label categories WL1, WL2, WL3 and WL5, Brazil could be the best choice module manufacturing country to import solar PV modules from, while for weight label categories WL4, WL6 and WL7, India is the best choice country to import solar PV modules from. Generally, Table 14 shows that for all the weight label categories, the best choice country to import from would either be Brail or India, while China and Germany only emerge as second best choice countries. Since Brazil emerges as the best choice module manufacturing countries four times out of the seven weight label categories, it can be asserted that Brazil is the overall best choice module manufacturing country for Uganda to import modules from out of all the considered module manufacturing countries in this study.

From Table 14, based on the weight label category used, the decision-makers can choose the manufacturing country to import solar PV modules from. Therefore, decision-makers ought to set clear priorities on the objective categories so that weight label category to be used is specified. The values of $V_j(A_q)$ of any of the objective categories for the considered module manufacturing countries as shown in Table 12 are in close range to each other. Therefore, the weight assigned to these objective categories makes the biggest difference amongst the considered module manufacturing countries and makes the ranking by the decision-makers of the importing country easier.

### 4.4 Verification and Validation

#### a) Chi-Square Test

Considering the ranking orders in Tables 12 and 13, the $\chi^2$ value for the modified VIKOR technique was evaluated by using Eq. (11). In this study, $\chi^2_{0.05,5}$ [95% confidence level and five degrees of freedom] was the critical chi-square test for the considered module manufacturing countries. From the chi-square distribution table, the critical chi-square value for $\chi^2_{0.05,5}$ was established to be 11.07. The ranking orders based on the weight label categories were evaluated at 95% confidence interval. For all the weight label categories, the mean and standard deviation values are 3.50 and 1.87, respectively, while the 95% confidence interval lower and upper limits are 2.00 and 5.00, respectively. Table 15 shows the $\chi^2$ values for the modified VIKOR technique that were evaluated based on the ranking orders in Table 15 for the module manufacturing countries considering the different weight label categories.

**Table 15:** Ranking Orders of the VIKOR Technique with 95% Confidence Interval and $\chi^2$ value

| **Weight Label Category** | $\chi^2$ **Value** ($\leq \chi^2_{0.05,5}$) |
|---|---|
| **WL1** | 0.00 |
| **WL2** | 3.00 |
| **WL3** | 2.88 |
| **WL4** | 5.62 |
| **WL5** | 1.83 |
| **WL6** | 4.95 |
| **WL7** | 2.45 |

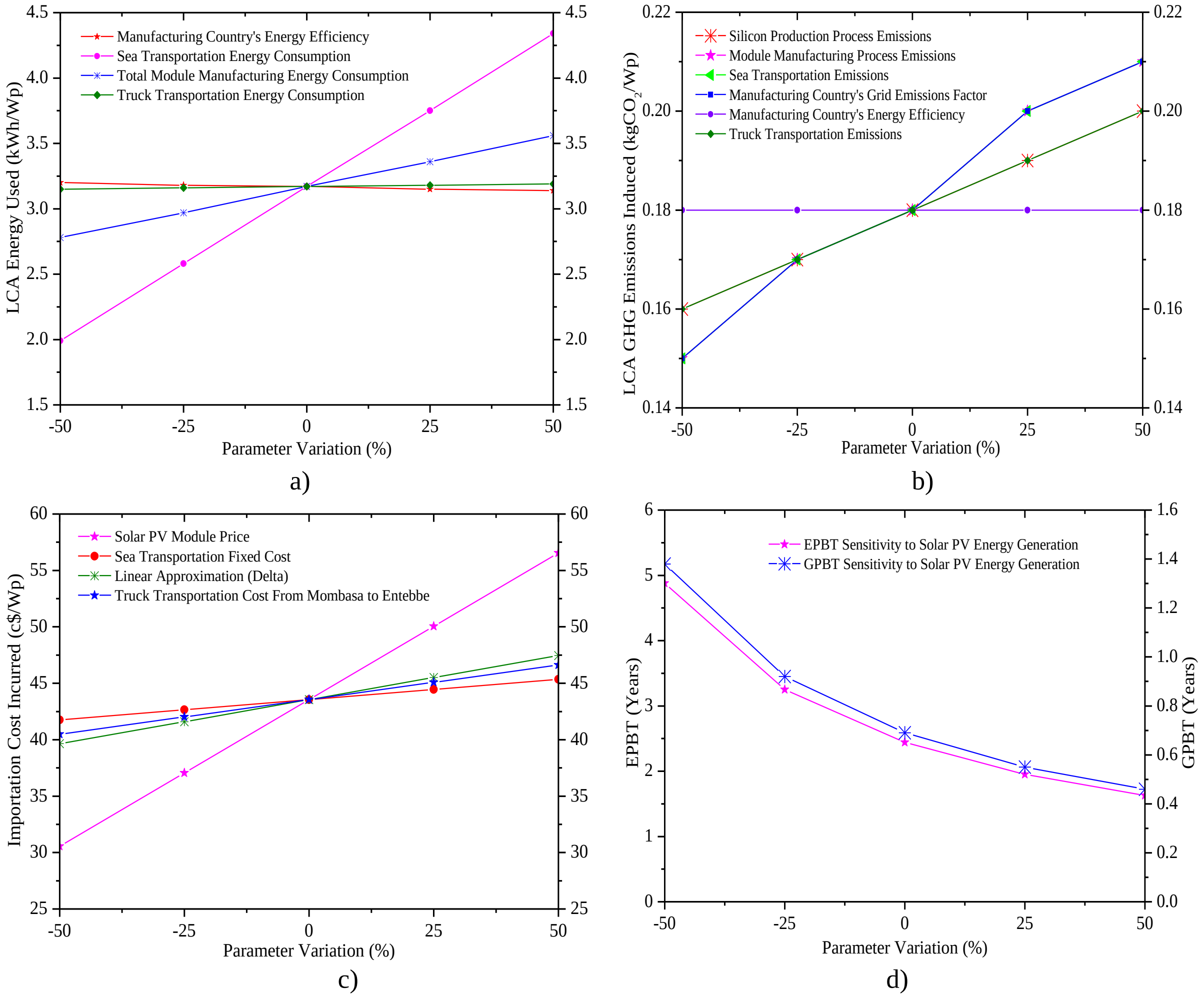
From Table 15, it is revealed that all the $\chi^2$ values for the modified VIKOR technique proposed in this study are less than the critical chi-square value ($\chi^2_{0.05,5}$) of 11.07. This indicates that the proposed technique is suitable for the intended multi-criteria analysis. Therefore, the modified VIKOR technique is valid and acceptable to be used in the decision-making process to rank the best choice module manufacturing country to import solar module from.

#### b) Sensitivity Analysis

To ascertain how the different sources of data uncertainty in the presented study methodology affect the overall uncertainty, a sensitivity analysis was undertaken in this subsection. This subsection presents the sensitivity analysis of the LCA indicators considered in this study to the variation in the input parameters. Also, this subsection presents the sensitivity analysis of the modified VIKOR technique to the variation in the input parameters.

### i) LCA Indicators

Since Brazil emerged as the best choice module manufacturing country to import solar PV modules from for both the ranking techniques used in this study, as shown in Table 12 and in four out of seven weight label categories as shown in Table 13, the sensitivity analysis undertaken in this subsection for the LCA indicators focused on Brazil. Fig. 10 shows the sensitivity analysis of the LCA energy used, LCA GHG emissions induced, importation cost incurred and the EPBT as well as the GPBT to the variation in key input parameters for Brazil as the solar PV module manufacturing country.



a)

b)

c)

d)

**Fig. 10:** Sensitivity Analysis of: (a) LCA Energy Used; (b) LCA GHG Emissions Induced; (c) Importation Cost Incurred; and (d) EPBT and GPBT to the Variation in Key Input Parameters for Brazil

Fig. 10 a) reveals that the LCA energy used for the solar PV modules is more sensitive to the variation in the sea transportation energy consumption, followed by the total module manufacturing energy consumption, while it is slightly sensitive to the variation in manufacturing country's energy efficiency and truck transportation energy consumption. The high sensitivity of the LCA energy used for the solar PV modules to the sea transportation energy consumption is attributed to the sea freight distance in Table 5 that the ship must cover to deliver the consignment. That is, as revealed in Fig. 4, the shorter sea distance between the two locations, the lower the LCA energy used for the solar PV modules is. Furthermore, as the module production process continues to improve and become more efficient, Fig. 10 a) shows that as the total module manufacturing energy consumption reduces, a significant reduction in the LCA energy used for solar PV modules would be recorded. Notably, although the module manufacturing country's energy efficiency and truck transportation energy consumption significantly impact the module manufacturing energy consumption and energy consumption for truck transportation from Mombasa to Entebbe, respectively, they only make a slight impact on the LCA energy used for solar PV modules as shown in Fig. 10 a).

Fig. 10 b) shows that the LCA GHG emissions induced by the solar PV modules has a high and similar sensitivity to the sea transportation emissions, module manufacturing process emissions and manufacturing country's grid emissions factor. The high sensitivity of the LCA GHG emissions induced to the sea transportation emissions is attributed to the long sea freight distance in Table 5 considering that sea freight has relatively very low GHG emissions of about 0.07 $\mathrm{gkg}^{-1}\mathrm{km}^{-1}$ as reported in Table 7. Thus, the shorter the sea shipping distance to cover, the lower the LCA GHG emissions induced by the solar PV modules. Also, the sensitivity to the module manufacturing process emissions and manufacturing country's grid emissions factor reveals that the cleaner the electricity grid of the module manufacturing country becomes, the lesser the LCA GHG emissions induced by the solar PV module would be. Furthermore, the LCA GHG emissions induced by solar PV modules has a similar sensitivity trend to both the truck transportation emissions and silicon production process emissions that is attributed to their high emissions' values reported in Table 7. Thus, an improvement in the GHG emissions involved in the silicon production process and truck transportation would result in a significant reduction in the LCA GHG emissions induced by the solar PV module. Also, Fig. 10 b) reveals that the LCA GHG emissions induced by the solar PV module is not sensitive at all to the variations in the manufacturing country's energy efficiency. Although the variation in the energy efficiency impacts the total module manufacturing GHG emissions (sum of module manufacturing process emissions and silicon production process emissions), its impact is not significant enough to reflect in the LCA GHG emissions induced by the solar PV module as shown in Fig. 10 b).

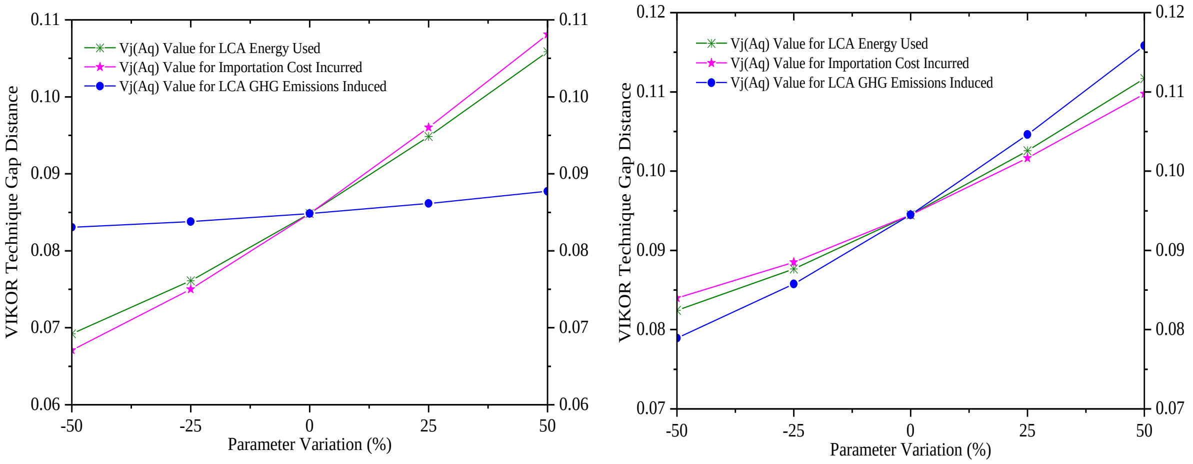
Fig. 10 c) shows that the importation cost incurred is very sensitive to the solar PV module price, while slightly sensitive to the sea transportation fixed cost, linear approximation ($\delta$) and truck transportation cost from Mombasa to Entebbe. The high sensitivity of the importation cost incurred to the solar PV module price is due to the direct representation of the solar PV module price in its evaluation. Given that the importation cost incurred is a direct sum of the solar PV module price and shipping costs, then any variation in the module price would have a direct impact on the importation cost incurred. Furthermore, although the variation in the linear approximation ($\delta$) has a significant direct impact on the sea transport variable cost based on Eq. (7), Fig. 10 c) shows only a slight sensitivity of the importation cost incurred to the linear approximation ($\delta$) variation. Also, a variation in the sea transport fixed cost and truck transport from Mombasa to Entebbe makes a slight impact on the total transport cost of modules, thus, their slight impact on the importation cost incurred as shown in Fig. 10 c).

Fig. 10 d) shows that the variation in the solar PV energy generated has a similar pattern of impact on both the EPBT and GPBT. This is mainly because the solar PV energy generated is inversely proportional to the EBPT based on Eq. (1), which is also true for the GPBT when Eq. (6) is factored into Eq. (3), that is, the more energy the solar PV system generates, the more the GHG emissions avoided from the grid would be. Therefore, in case the considered solar PV system implementing location happens to receive lower solar irradiance such that the solar PV system ends up generating less energy, then it would take the system a longer period to pay back its lifecycle energy used and GHG emissions induced, as shown in Fig. 10 d).

### ii) Modified VIKOR Technique

In this subsection, the sensitivity analysis for VIKOR technique was undertaken based on two module manufacturing countries, namely, Brazil and China. This was done because Brazil emerged as the overall best choice module manufacturing country to import modules from, while China was chosen because the objective categories for China have almost the same $\mathrm{V_j}\left(\mathrm{A_q}\right)$ values, which could be based on to conclusively ascertain the sensitivity of the modified VIKOR technique, unlike the case of Brazil with a wider difference in the $\mathrm{V_j}\left(\mathrm{A_q}\right)$ value for LCA GHG emissions induced in comparison to the other objective categories. Thus, it was deemed important for this analysis when assessing the impact of the variation in the weight $w_j$ and $\mathrm{V_j}\left(\mathrm{A_q}\right)$ values to the objective categories to consider both Brazil and China.

The sensitivity analysis for the VIKOR technique gap distance in Fig. 11 was undertaken considering that all the objective categories of the multi-criteria analysis were assigned the same weight ($w_j = 0.33$) by the importing decision makers. Brazil and China were considered as the module manufacturing countries in undertaking the sensitivity analysis of the VIKOR technique gap distance to the variation in the $V_j\left(A_q\right)$ values of the objective categories.



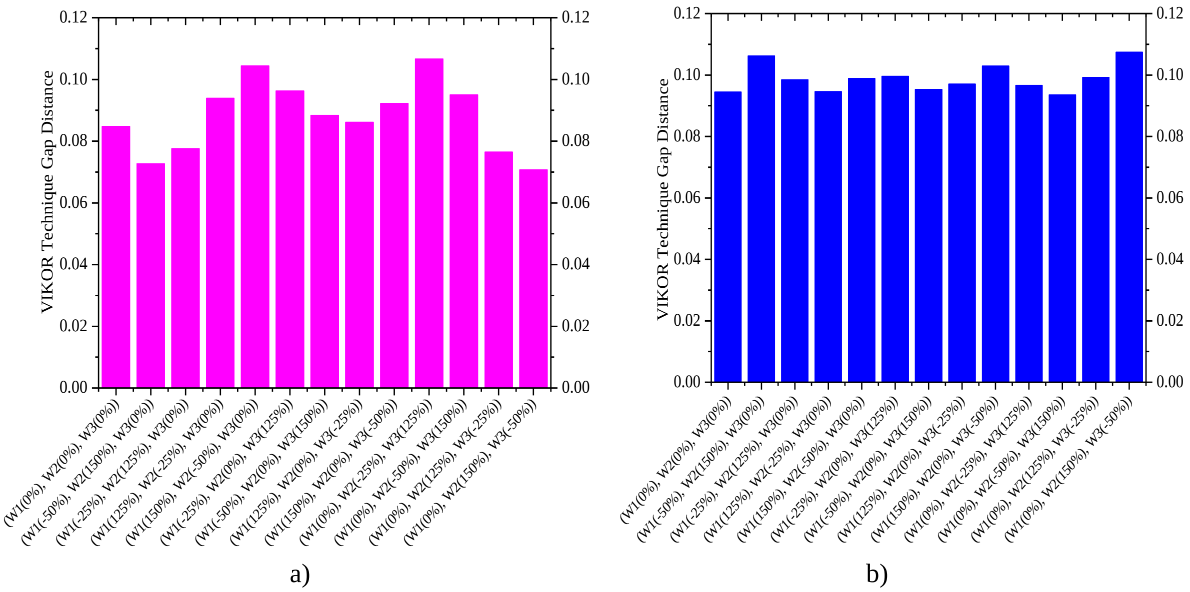
a) b)

**Fig. 11:** Sensitivity Analysis of the VIKOR Technique Gap Distance to the Variation in the $V_j\left(A_q\right)$ Values for $w_j = 0.33$ and $p = 2$ for: a) Brazil; and b) China

Fig. 11 a) shows that the modified VIKOR technique gap distance is very sensitive to the variation in the $V_j\left(A_q\right)$ values for the LCA energy used and importation cost incurred, while slightly sensitive to the variation in the $V_j\left(A_q\right)$ value for the LCA GHG emissions induced.

The high sensitivity to the $V_j(A_q)$ values for the LCA energy used and importation cost incurred could be attributed to the relatively high values of these objective categories (LCA energy used of 3.17 kWh/Wp and importation cost incurred of 43.55 c$/Wp) in Table 11 in comparison to that of the LCA emissions induced of 0.18 $kgCO_2$/Wp. Thus, a variation in the LCA energy used or importation cost incurred value would greatly impact the modified VIKOR technique gap distance. However, the same is not the case for the LCA emissions induced since it already has a small value, hence its little impact on the modified VIKOR technique gap distance shown in Fig. 11 a). However, by considering China, whose $\mathrm{V_j}(\mathrm{A_q})$ values are 0.16, 0.18 and 0.15 for the LCA energy used, LCA GHG emissions induced and importation cost incurred as shown in Table 12, Fig. 11 b) shows that the modified VIKOR technique gap distance has almost the same sensitivity to the variation in the $\mathrm{V_j}(\mathrm{A_q})$ values of the objective categories for China. Furthermore, as reported in Table14 with the variation in the weight label categories, in case the objective categories had slightly the same $\mathrm{V_j}(\mathrm{A_q})$ values, the modified VIKOR technique gap distance would exhibit a slightly similar sensitivity to the variation in the values. Therefore, based on Fig. 11, it can be generalized that the proposed modified VIKOR technique gap distance has a similar sensitivity to the variation in the $\mathrm{V_j}(\mathrm{A_q})$ values for the considered objective categories in this study.

Also, the VIKOR technique gap distance was assessed for the sensitivity to the variation in the weight $w_j$ assigned to the objective categories of the multi-criteria analysis by the importing decision makers. Fig. 12 shows the sensitivity of the VIKOR technique gap distance to the variation in the weight $w_j$ assigned to the objective categories for Brazil and China by considering the $\mathrm{V_j}(\mathrm{A_q})$ values for the considered objective categories in Table 12.



a) b)

**Fig. 12:** Sensitivity Analysis of VIKOR Technique Gap Distance to Variations in Assigned Weights of the Objective Categories: a) Brazil; and b) China

Fig. 12 reveals that there is a significant sensitivity of the VIKOR technique gap distance to the variation in the weight $w_j$ assigned to the objective categories for Brazil, shown in Fig. 12 a), while there is a slightly uniform sensitivity of the VIKOR technique gap distance to the variation in the weight $w_j$ assigned to the objective categories for China. The significant sensitivity of the VIKOR technique gap distance for Brazil is mainly attributed to the $V_j(A_q)$

values of the objective categories that have a wider margin amongst themselves. On the other hand, because of slightly similar $V_j(A_q)$ values of the objective categories for China, the VIKOR technique gap distance only has slight sensitivity to the variations in the weight $w_j$ assigned to the objective categories. The VIKOR technique gap distance has a variation range of about 0.07 – 0.11 for Brazil, while it has a variation range of about 0.09 – 0.11 for China for all the considered weight $w_j$ changes in Fig. 12. Therefore, based on Figs. 12 and Table 14, it can be generalized that the proposed modified VIKOR technique gap distance has a similar sensitivity to the variation in the weight $w_j$ assigned to the considered objective categories in this study.

## 5.0 Conclusion and Future work

This study proposed a methodology for ranking the solar PV module manufacturing countries by any country intending to import and install solar PV systems. The methodology is based on the LCA and economics analysis of the solar PV modules considered for importation. In this study, six countries were considered as the solar PV module manufacturers representing the different continents, while Uganda was considered as the country intending to implement the solar PV systems. The study evaluated the LCA energy used, LCA GHG emissions induced, EPBT and GPBT as well as the importation cost incurred for the solar PV modules. The study further undertook a sensitivity analysis of the proposed methodology to the variation in the key input parameters. The following are the key findings of this study:

- Considering all the module manufacturing countries, the LCA GHG emissions induced by the solar PV module was in the range of 0.18 – 0.83 $\mathrm{kgCO_2/W_p}$, with an average value of 0.50 $\mathrm{kgCO_2/W_p}$ for a 50 kW capacity solar PV system. For the LCA GHG emissions induced as the only prioritized decision-making criterion, Brazil emerged as the best choice module manufacturing country to import modules from, followed by Germany mainly due to the cleanness of their electricity grid that has a lower GHG emissions factor compared to the other module manufacturing countries.
- Considering all the module manufacturing countries, the LCA energy used by the solar PV module was in the range of 1.72 – 4.27 $\mathrm{kWh/W_p}$, with an average value of 3.12 $\mathrm{kWh/W_p}$ for a 50 kW capacity solar PV system. For the LCA energy used as the only prioritized decision-making criterion, India emerged as the best choice module manufacturing country to import modules from, followed by China, mainly due to the shorter sea freight distance to be covered compared to the other module manufacturing countries.
- The EPBT for the considered module manufacturing countries ranges between 1.32 – 3.28 years, with an average of 2.40 year, while the GPBT for the considered module manufacturing countries ranges between 0.69 – 3.19 years, with an average of 1.93 year. This is mainly attributed to the high solar irradiance received in Uganda that results in a high yield of about 1.30 $\mathrm{kWh/W_p}$ at Entebbe site that would enable the solar PV system to pay back its LCA energy used and LCA GHG emissions induced in a very short period.
- Considering all the module manufacturing countries, the importation cost incurred for all the module manufacturing countries was in the range of 37.10 – 46.38 $c\mathrm{\$/W_p}$, with an average value of 41.36 $c\mathrm{\$/W_p}$. The study also revealed that consideration of the transportation cost almost doubles the module price at the factory gate. For the importation cost incurred as the only prioritized decision-making criterion, China

emerged as the best choice module manufacturing country to import modules from, followed by India. Although India is the closest module manufacturing country to Uganda, China’s low module price at the factory gate outweighed India’s advantage of a shorter sea freight distance.

- By applying both the conventional ranking technique and the modified VIKOR technique, Brazil was ranked as the overall best choice module manufacturing country based on the three objective categories (criteria). By considering seven weight label categories for the decision-making criteria, Brazil emerged as the best choice in four categories, while India emerged the best in the other three categories.
- The chi-square test was applied to check the goodness of fit between the proposed modified VIKOR technique and the conventional ranking technique results. The test showed that the modified VIKOR technique is acceptable for the decision-making process to decide which solar PV module manufacturing country to import from based on the objective categories set by the decision makers.

The proposed methodology was applied on a selected few module manufacturing countries as well as a single importing country. In future, this methodology shall be extended to other countries in order to broaden the scope as well as ascertain its suitability in the multi criteria analysis process. Also, due to data limitations, some of the data used in this study was assumed or relied on the previous literature. Thus, with the possibility of data availability especially for the different stages of module production, this methodology shall further be investigated. Furthermore, some indicators such as water footprint and soil quality were not considered in the lifecycle assessment of the solar PV modules in this study. Therefore, such indicators could be considered and assessed in the future works, and where appropriate be incorporated as objective categories for module manufacturing countries by the importing decision makers.

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