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# Carbon footprint and energy life cycle assessment of wind energy industry in Libya

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ABSTRACT

The recent investigation has demonstrated that wind energy holds great potential as a viable and environmentally friendly energy source in Libya. The study employed a Life Cycle Assessment (LCA) methodology to evaluate various energy, economic, and environmental indicators for potential wind farm installations at multiple suitable locations across Libya. The assessment encompassed estimations of energy requirements and greenhouse gas (GHG) emissions associated with the conversion of wind energy into electricity throughout the entire life cycle of the proposed wind farms. In light of Libya not being a producer of wind energy converters, a novel approach was developed to define the system's boundaries. These boundaries included distinct subsystems, each corresponding to various stages within the life cycle of a wind energy system, encompassing factors such as shipping emissions from the manufacturer's location to Tripoli's marine ports, land transportation to the wind farm sites, energy and emissions associated with installation, operation, maintenance, and eventual disposal of wind turbines.

Hourly climate data spanning a 25-year period from 1995 to 2020 were gathered from the SolarGis climate information site. The System Advisor Model (SAM) program was utilized to predict the energy yields of 100 MW capacity wind farms at 12 sites in Libya. Additionally, a novel eco-environmental indicator known as the Life Cycle Levelized Cost of Energy (LCLCOE) was introduced, which factors in all environmental damage costs throughout the entire lifespan of wind energy projects. The study's findings revealed that the Gamesa turbine, with a capital cost of $146,916,400 for a 100 MW capacity wind energy farm, exhibited the most favorable economic and environmental performance. GHG emission factors across all examined cities ranged from 32 to 70 gGHG/kWh, with carbon payback durations spanning from 4.5 to 12.3 months. The estimated energy payback period varied from 13 to 22 months, while the LCLCOE ranged from 4.8 to 8.4 ¢/kWh.

## 1. Introduction

Fossil fuels for electricity generation is causing of 35.29 % of all pollutants' emissions that responsible of climate change and global warming [1]. Wind energy is one of the most significant renewable energy sources in the world, that lessens reliance on fossil fuels. Understanding the environmental and financial effects of producing electric power from wind energy is made easier by the process of evaluating the life cycle of wind energy [2].

Several local studies have proven the feasibility of wind energy potential in Libya [3–5]. Therefore, the wind energy must be harnessed to solve the shortage in the supply of electric power, and to fulfill the obligations of the Libyan state towards the international community in reducing the carbon emissions. The life cycle assessment (LCA) is a tool

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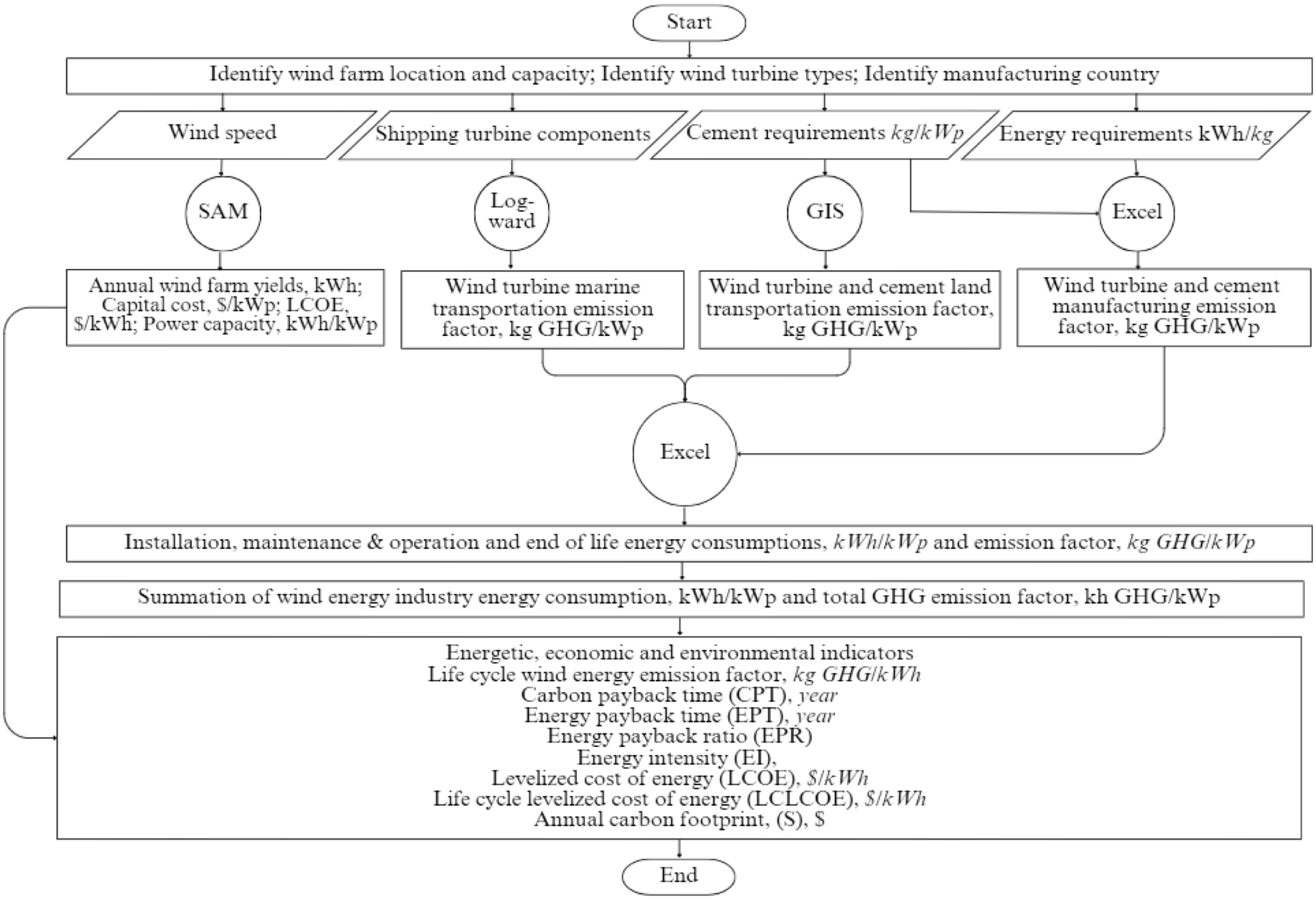

**Fig. 1.** Flowchart of the study.

developed to assist decision makers in comparing various energy systems or technologies and assessing their environmental consequences throughout the life cycle to determine the best technology to be utilized. The life cycle of an energy system or technology is the carbon footprint starting from the machine's production, transportation, installation, operation, maintenance, and ending with machine decommissioning and disposed of in a landfill or recycled in parts [6]. The ISO14040 and ISO14044 methods are a widely used and accepted way to analyze any product's environmental impact [7].

In order to evaluate various technologies, capabilities, locations, analyze environmental consequences and other aspects that may affect decision-making, several studies on LCA have also been carried out in various nations and areas throughout the world [8–13]. LCA of other renewable technologies was also carried out and these technologies were compared with the technique of harvesting electrical energy from wind energy. For example, Raadal et al. compared wind with hydropower [14], whereas Verma et al. compared wind turbines with solar photovoltaic and solar concentrated power plants [15].

Many studies have focused on the evaluation of onshore and offshore wind farms. The effect of wind turbine capacity on their life cycles and greenhouse gas emissions was investigated by Crawford [16]. Tremeac and Meunier evaluated two wind turbines with power of 4.5 MW and 250 W. Their findings revealed that the $CO_2$ gas emission per kWh decreased as wind turbine capacity increased [17]. Vargas et al. performed an examination utilizing LCA technique into the environmental implications of different manufacturing materials and power consumption of two wind turbines erected in Mexico, independent of the fact that both turbines have the same capacity, one has a lower environmental impact than the other. The reason for this is that one of the turbines uses fewer materials than the other [18].

To assess the environmental performance of wind energy in Colombia, Henao and Vivanco conducted a hybrid LCA of a wind farm of 19.5 MW of installed capacity for various impacts. The results showed that the emission factor of the wind farm is relatively low 12.93 g GHG/kWh compared to similar studies; this is due to the high wind speeds in the study area [19]. Guezuraga et al. used the GEMIS simulation program and showed that the materials used in the tower manufacturing account for 55 % of the total materials used in the wind turbine industry, while the energy requirements for the manufacturing stage make up the bulk of the life cycle at 84 %. The study concluded that wind energy, is the cleanest energy source, with an estimated energy payback period of 7 months and $CO_2$ emission factor of 9 g/kWh [20].

In order to determine the primary sources of GHG emissions in Brazil, Oebels and Pacca evaluated the life cycle of an onshore wind farm on the northeast coast of the country. They discovered that the GHG emission factor is 7.1 g GHG/kWh. In addition, most emissions come from the manufacturing stage (80 %), with only 6 % comes from the transportation stage [10]. Marimuthu and Kirubakaran estimated the environmental and energy payoff of wind energy in India, taking into account the annual wind speed values of a wind power farm with a capacity of 1.65 MW. The results showed the energy payback period was about 1.12 years and the carbon payback period was 50 days [21]. LCA was performed by Rajaei and Tinjum for quantitative, comparative analysis and classification of the construction and operation of wind farm (90 wind turbines with a capacity of 1.8 MW for each) in south-central Wisconsin, India. The results indicated that the energy yield is 25.5 %, the energy payback period is 12.3 months and the GHG emission factor is 16.9 g GHG/kWh over the life of the onshore wind farm [22].

A study performed onshore wind farm on a 40 MW in China to conduct a LCA considering the infrastructure showed that the GHG

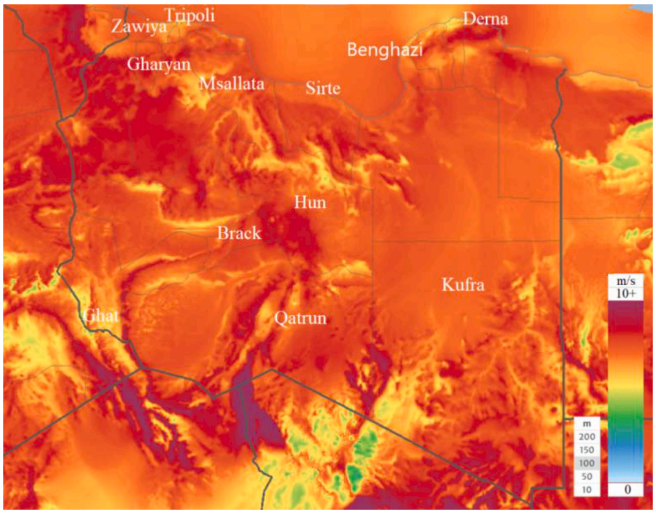

**Fig. 2.** Location and wind speed at 100 m of the selected sites. [].
Source: https://globalwindatlas.info/area/Libya/

emission factor is about 28.2 g GHG/kWh for the wind farm, and the LCOE was estimated at 0.01–0.02 $/kWh [26].

Locally, Al-Behadili and El-Osta investigated the impact of recycling, the basic energy consumption and emissions for the wind farm in Derna – Libya. Their results revealed that the energy payback period is 5.7 months, the payback rate is 42 %, and the $CO_2$ emission factor is 10.4 g $CO_2$/kWh without recycling, while $CO_2$ emission factor is 4.65 g $CO_2$/kWh with recycling processes [9].

From the previous studies, it is notes able that the type, capacity and the location of the wind farm have a significant impact on the results of the LCA. Therefore, to obtain reliable results, many studies should be conducted on different types and capacities of wind turbines in different locations of the country. However, there are only two local studies in Libya, one conducted at the city of Derna [9], and the other at the city of Zawiya [6], which is not enough to cover a vast area country with various climatic and terrain conditions like Libya.

Studying the prior literature revealed a gap in studies that analyze the energy and emissions life cycle of wind energy to countries who are not manufacturers of wind energy technologies. If studies do exist, it was found that the idea of boundary system is unclear, where all phases are considered within one boundary system and emissions are addressed based on the local electricity production system rather than the country of the technology manufactured and international transportation process. Since Libya does not manufacture wind energy technologies, this study used a novel approach to assess the energy needs and GHG emissions during the life cycle of a wind energy farm. For instance, based on the International Energy Agency's (IEA) GHG emission factor inventories for each country, GHG for wind energy were computed in a comprehensive and complete manner using emissions from manufacturing processes in each manufacturing country. Both the emissions during the shipping process from the ports of the industrialized nations to the Tripoli Seaport and the land transportation activities within Libya between the seaport of Tripoli and the 12 sites identified by local researchers to develop wind energy farms at them are calculated. In addition, the $CO_2$ emitted during the production and delivery of cement from various Libyan factories to the sites where wind energy farms will be installed is taken into consideration.

Even though all studies dealing with LCA for wind energy have looked at recycling procedures, the authors have their own opinions on the matter. It is unfair to ascribe the energy used and emissions produced by recycling procedures to the life cycle of wind energy, which is intended to stop with decommissioning and landfilling alone, given that Libya is not a producer of wind energy technology. An alternate plan of action would require businesses to return recyclable materials to their facilities in the foreign country for use in creating wind energy new equipment. This serves as an illustration of how this research varies from past studies and has a scientific element.

Accordingly, the article has the following contributions:

1. Highlighting the wind energy potential of several sites in Libya.
2. Proposing a novel methodology to evaluate the economic, energy and environment life cycle assessment for nations who are exporting the wind energy technology.
3. Introducing a deep meaning to the levelized cost of energy LCOE by involving the environmental damage cost during the life cycle of the wind energy technology (LCLCOE).
4. Identifying the most suitable type of wind turbine for each site in Libya.
5. Defining a new index for energy market competition by including the carbon emission factor of the manufacturers in the economic process (LCLCOE) and in the decision making.

## 2. Methodology

LCA is a well-known and recognized method of conducting energy and environmental analysis of any product.

It is a reference method that adheres to ISO 14040 and ISO 14044 and takes into account the material, energy, and emissions associated with each stage of the product's life cycle. A flowchart illustrating the study's methodology is shown in Fig. 1. This section is divided into 5 subsections handling the following: wind farm's locations; assumptions and limitation of the study; System and subsystem boundaries; life cycle stages; life cycle indicators.

### 2.1. *Wind energy farms' locations*

Fig. 2 displays the location and wind energy potential of the selected twelve sites in Libya. These locations were chosen based on local studies showing the greatest potential for wind energy. As shown in Fig. 2, the average wind speeds range from 5.26 m/s at 10 m to 10.98 m/s at 100 m. In addition, these sites have the necessary infrastructure to install the wind farm such as electricity network and roads. The wind farms will help with the transition to a more sustainable and clean form of energy production, provide the whole country with electricity, and strengthen network reliability and robustness.

### 2.2. *Assumptions, limitations and sources of uncertainty in the study*

The following assumptions were adopted to facilitate the analysis:

The energy consumed for manufacturing the wind energy equipment is only electrical energy.

The energy required to produce 1 kg of manufactured materials for wind turbines is the same in all manufacturers.

The GHG emissions during the extraction and transportation of raw materials from their sources to the factories are not considered in the calculations, due to the lack of information on this topic.

GHG emission factors for the electric power generation system of wind turbines' manufacturing countries were adopted from the inventories of the IEA.

The decline in energy productivity of wind farms over time was neglected.

The amount of energy consumed during the installation, maintenance, operation and end-of-life stages is taken as 5 % of the energy consumed at the manufacturing stage [6].

The Tripoli Seaport is considered the port for the importation of wind energy equipment, which will then be transported by local transportation to wind farms' locations.

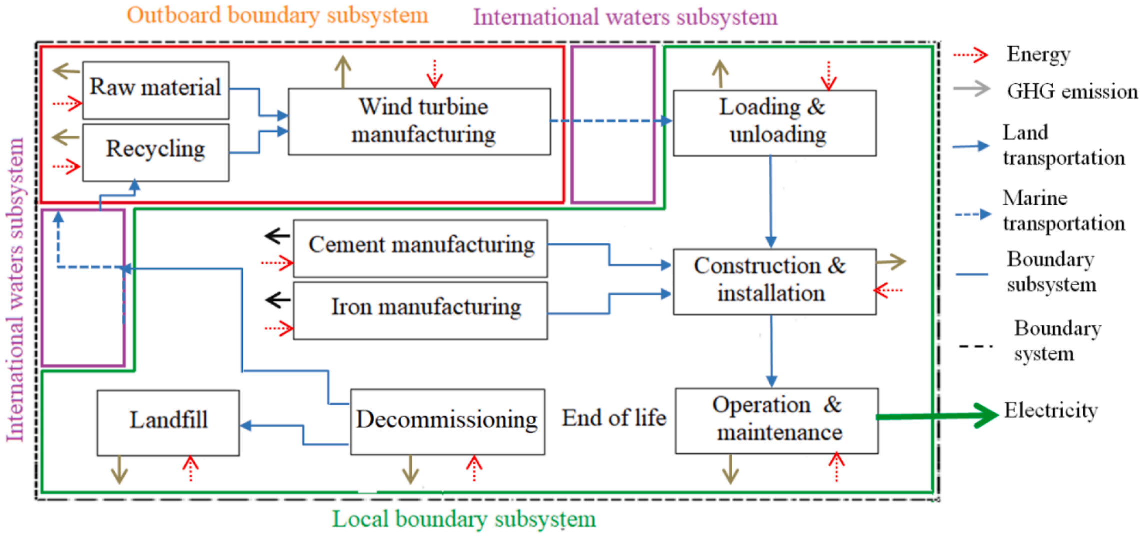

**Fig. 3.** The system and subsystems boundaries of the study.

**Fig. 4.** Wind farm life cycle.

**Table 1**
Energy required to produce 1 kg of matters used in manufacturing wind energy equipment, kWh/kg matter [6].

| Material | Iron | Aluminum | Copper | Glass Fiber | Various contents |
|---|---|---|---|---|---|
| Energy consumption, kWh/kg | 55.4 | 16.4 | 9.5 | 2.4 | 13.0 |

The main limitation of this study is the lack of the results' sensitivity to the energy consumed to produce the materials used in the manufacturing of the wind power equipment. Additionally, the study does not examine the impact of the social cost of GHG variation in the research results.

The main sources of uncertainty are:

1. The life cycle data obtained from various sources related to energy consumption and the relevant emission factor for each stage [23].
2. The discrepancy in the prices of renewable energy equipment exceeding 360 % [24].
3. Large variation in the carbon social cost which ranged from $1 to $120 for a ton of GHG due to the different US political views on the environmental issues [25].

### 2.3. System and subsystems boundaries

Libya is a country that does not manufacture wind energy technologies; therefore, LCA requires a special treatment within the framework of ISO 14040. Accordingly, a new term “subsystem” is introduced in this study. Whereas, for processes that generate multiple energy and emissions burdens must be assigned as an individual subsystem. Fig. 3 shows the boundaries of the system, subsystems and stages. The first stage Starts with the extraction or production of the raw materials, some of which might be recycled materials. After that, it was transported to the factory that makes the parts for wind turbines. This production stage consumes energy and emits pollutants. The manufactured components are then delivered to the installation location. Additionally, the transport phase consumes energy and emits pollutants. On the concrete foundation that was erected at the construction site (9.4 % cement, 5.9 % air and water, 28.2 % sand, and 56.5 % gravel), a wind turbine was mounted. Additionally, oil changes, lubrication, routine maintenance, and equipment replacement are all stages of operation and maintenance that require energy and, of course, emit emissions.

### 2.4. Life cycle stages of a wind turbine

The life cycle of a wind turbine can be divided into five stages: manufacturing, transportation, construction and installation, operation and maintenance, and decommissioning and disposal, as shown in Fig. 4. Each stage will be explained in detail in the following subsections.

#### 2.4.1. Manufacturing stage ($E_{man}$)

In this stage, we used 10 types of turbines with different capacities from 24 different countries that manufacture wind energy equipment. Table A1 summarizes the energy needed for manufacturing as well as the quantity of materials used to create wind energy equipment. However, since it is produced locally and won't be imported with the wind energy equipment, cement for foundations was left out of the inventory of wind turbine components. Accordingly, the specific weight ($M_{i,j}$) was calculated for each material ($i$) of mass $m_{i,j}$ and for each wind turbine ($j$) with a capacity ($P_j$):

$$M_{i,j} = \frac{m_{i,j}}{P_j}, \frac{kg}{kW_p} \tag{1}$$

Assuming that the amount of consumed energy remains constant and only electrical energy is used to produce 1 kg of matter for all manufacturers. Table 1 presents the energy required for production of 1 kg of

**Table 2**
GHG emission factors [kg GHG/kWh] for countries manufacturing wind energy technologies in addition to Libya.

| Country | France | India | Denmark | Spain | China | Germany | Syria | Turkey |
|---|---|---|---|---|---|---|---|---|
| $EF_{CO2}$ | 0.5128 | 0.7082 | 0.42767 | 0.28653 | 0.5374 | 0.58883 | 0.65 | 0.375 |
| Country | Estonia | Iran | Italy | Japan | Netherlands | Norway | Russia | Taiwan |
| $EF_{CO2}$ | 0.59869 | 0.532 | 0.45857 | 0.4658 | 0.45172 | 0.40194 | 0.3102 | 0.442 |
| Country | Ukraine | USA | Brazil | Argentina | Canada | Britain | S. Korea | Libya |
| $EF_{CO2}$ | 0.20145 | 0.42394 | 0.0617 | 0.307 | 0.12 | 0.21233 | 0.4156 | 1.035 |

**Table 3**
The ratio of recyclable materials of the turbine structure and the energy consumed.

| The metal | The ratio of recycling material [27] | energy saving ratio from recycling [28] | Energy consumed in the recycling process, (kWh/kg) |
|---|---|---|---|
| Iron | 87 % | 72 % | 15.514 |
| Copper | 95 % | 85 % | 1.428 |
| Aluminum | 95 % | 95 % | 0.822 |

materials used in manufacturing of wind turbines. The GHG emission factors are displayed in Table 2 for all manufacturing countries. The GHG emission factor of Libyan cement industries are about 850 kg GHG/ton cement [1].

### 2.4.2. Transporting stage ($E_{tra}$)

A free source program provided by the German logistics technology company Logward (https://www.logward.com/freebies/co2-calculator) is used to estimate the emission during the marine transportation process from the seaport of the manufacturing country to the Tripoli seaport. The emission due to land transportation is also estimated, and this includes the emission due to the transportation of equipment within Libya from the Tripoli seaport to 12 locations of wind farms construction and the transport of cement from different Libyan factories to the construction sites, specifically the Zliten plant for the western region, the Khums plant for the central and southern region, and the Benghazi plant for the eastern region.

Using the GIS platform, distances between cities along paved roads were obtained. Trucks with a load of 80 tons were suggested for transporting wind energy equipment and cement. For each truck with 80 ton capacity, the GHG emission factor is estimated at 4.533 kg GHG/km [1]. Accordingly, transporting a one ton over a distance of 1000 km results in the emission of 56.6625 kg of GHG.

### 2.4.3. Construction and installation stage ($E_{ins}$)

The construction of the wind energy farm includes the installation of wind energy equipment and devices at the specified location, logistics transportation, which involves the use of cranes, on-site vehicles, lying of internal cables, installation of a transformer station, and connection to the public electricity grid. The energy consumed at this stage is considered as 2 % of the energy consumed at the manufacturing stage [6].

### 2.4.4. Operation and maintenance stage ($E_{o\&m}$)

Operation and maintenance processes include all engineering activities, such as: regular and emergency maintenance, farm performance monitoring, oil and filter changes, lubrication, and the renewal or replacement of worn parts (such as gearbox and bearings) over the life of the wind farm. All logistic processes are also included in the farm such as transportation associated with operation and maintenance. Bonou et al. indicated that the energy consumed at this stage is in the range of 2–4 % [26]. Therefore, the value of 3 % of the energy required from the manufacture of a wind turbine was considered as the value of energy consumed at this stage.

### 2.4.5. End of life stage

*2.4.5.1. Recycling phase ($E_{ryc}$).* Most of the metal components of a wind turbine can be recycled, especially the tower, the nacelle and the rotor shaft. The energy consumed in the recycling process was calculated by multiplying the mass of the various materials of the recyclable parts of the wind turbine, by the specific energy (kWh/kg) of each material. Table 3 shows the percentage of substances managed in the turbine.

*2.4.5.2. Decommissioning and landfill phase ($_{Ed\&l}$).* By deducting the mass of the recyclable parts from the total mass of the wind turbine, one can estimate the remaining parts that need to be buried. The remaining mass of the parts was multiplied by the precise energy used at this stage to determine the amount of energy used at the landfill. The value for decommissioning and landfill operations was set at 0.206 % of the energy used during the manufacturing stage [6].

## 2.5. Life cycle indicators

### 2.5.1. Total energy consumption ($E_{con}$)

The total energy consumed per unit of capacity of a wind farm can be obtained by summing all the consumed energies at each stage of the life of the farm. Thus, the total energy consumed can be formulated as follows:

$$E_{con} = E_{man} + E_{tra} + E_{ins} + E_{o\&m} + E_{d\&l}; kWh/kWp \tag{2}$$

### 2.5.2. GHG emission factor ($EF_{GHG,LC}$)

The GHG emissions per unit of electrical energy consumed for each individual stage is used to estimate the GHG emission factor from the wind farm in units (kg GHG/kWp) as:

$$EF_{GHG,LC} = \sum_{i=1}^{6} EF_i \times E_i; kgGHG/kWp \tag{3}$$

Where: $i$ represents the five stages of the wind energy farm's life, manufacturing, transportation, installation, operation and maintenance, and landfill. $EF_i$ represents the GHG emission factor per unit of consumed electrical energy (kg GHG/kWh) for each stage of energy consumption $E_i$ (kWh/kWp). Considering the difference in the subsystem boundaries for each stage, its occurrence and the emission factor accompanying each stage.

### 2.5.3. GHG emission factor per unit of energy produced by wind farms ($EF_{GHG,wind}$)

This factor is the basis for comparison in assessing the life cycle of wind energy, and can be obtained by dividing the total amount of GHG emissions during the lifetime of the wind farm from manufacturing to landfill (kg GHG), by the energy produced over the lifetime of the wind farm (kWh) [6].

$$EF_{GHG,wind} = \frac{EF_{GHG,LC} \times P}{\sum_{n=1}^{20} E_{wind}} kgGHG/kWh \tag{4}$$

Where: $P$ represents the capacity of the wind farm (kWp), $E_{wind}$ represents the annual electrical energy yields (kWh), and $n$ symbolizes the life of the wind farm, which is estimated at about 20 years. The productivity

**Table 4**
Mass of materials used in manufacturing wind turbines (in tons) as function of wind turbines' capacity (kWp).

| Material | Regression function, ton | R$^2$ | Eqn. no. |
|---|---|---|---|
| Iron | $m_{Fr} = -3 \times 10^{-6}P^2 + 3.82 \times 10^{-2}P - 1.2444$ | 0.773 | (11) |
| Cement | $m_{ce} = 0.4448P$ | 0.759 | (12) |
| Copper | $m_{Cu} = 7 \times 10^{-7}P^2 + 4.41 \times 10^{-3}P$ | 0.827 | (13) |
| Aluminum | $m_{Al} = 1.1 \times 10^{-3}P$ | 0.7 | (14) |
| Fiberglass | $m_{Fg} = -6 \times 10^{-7}P^2 + 1.04 \times 10^{-2}P$ | 0.726 | (15) |
| Miscellaneous | $m_{Me} = 1 \times 10^{-7}P^2 + 6.1 \times 10^{-3}P$ | 0.754 | (16) |
| All components exclude cement | $m_{all/ce} = 2.3229P + 0.0508$ | 0.694 | (17) |

of wind farms for several promising areas in Libya was estimated by the SAM (system Advisor Model) program.

### 2.5.4. *Carbon payback time (CPT)*

This is the period of time required to reduce GHG emissions by the same amount as energy consumption at all life stages of a wind farm. It is given by the following relation [6]:

$$CPT = \frac{EF_{GHG,LC} \times P}{E_{wind} \times EF_{GHG,Libya}}, year \tag{5}$$

Where: $E_{wind}$ the annual productivity of the wind farm is measured in kWh, $EF_{GHG,Libya}$ represents the GHG emission factor from the electric power industry sector in Libya which is 1.035 kg GHG/kWh [23].

### 2.5.5. *Energy payback time (EPT)*

The energy payback time is a meter of the number of years it takes for a wind farm to produce an amount of energy equivalent to that energy consumed during its life cycle's stages. It is defined as the ratio of the total primary energy consumed during the life cycle and the electrical energy produced by a wind turbine annually, and is given by the following relation [6]:

$$EPT = \frac{E_{con} \times P}{E_{wind}}, year \tag{6}$$

### 2.5.6. *Energy payback ratio (EPR)*

The energy payback ratio is defined as the ratio of the energy produced by wind farms during their operational life to the energy consumed during the life cycle, and can be formulated as follows [6]:

$$EPR = \frac{\sum_{n=1}^{20} E_{wind,n}}{E_{cons} \times P} \tag{7}$$

### 2.5.7. *Energy intensity (EI)*

It is defined as the ratio of the primary energy consumed during the life cycle of a wind power farm to the electrical energy produced. It is given by the following relation [6]:

$$EI = \frac{E_{cons} \times P}{\sum_{n=1}^{20} E_{wind,n}} = \frac{1}{EPR} \tag{8}$$

### 2.5.8. *Economic-environment aspects*

As the GHG emissions for all activities during the life cycle of the wind energy farms are known, then the environmental damage cost can be estimated by using the following equation:

$$C_{GHG} = EF_{GHG,LC} \times P \times \varnothing_{GHG} \tag{9}$$

Where $\varnothing_{GHG}$ is the social cost of GHG (14.5 \$/ton) [29]

Equation (9) can also be used to estimate the benefit of greenhouse gas savings through the exploitation of clean energy systems. As the system of electricity generation in Libya is almost 100 % based on fired fossil fuel power stations, then the annual carbon footprint saving ($S_{GHG}$) can be expressed as:

$$S_{GHG} = EF_{GHG,Libya} \times E_{wind} \times \varnothing_{GHG} \tag{10}$$

## 3. Results and discussion

This study investigates the carbon footprint and energy performance of ten proposed wind farms to be installed at selected sites using the LCA method, according to ISO 14040 standards. The objective of this research is to obtain an overview of the benefits of using wind energy at high wind potential sites as a renewable energy source to enhance the energy mix in Libya.

The analysis included an assessment of the energy consumptions and GHG emissions from the proposed wind farms at proposed sites during the manufacturing, transportation, installation, operation and maintenance, and decommissioning and landfill stages. The results of this evaluation are illustrated in the following subsections.

### 3.1. *Estimation of materials for manufacturing wind energy farms*

Estimation of materials for 10 different wind turbines from different manufacturers were presented mathematically as a function of turbines' capacity in Table 4.

### 3.2. *Annual energy production of proposed wind farms in Libya*

Twelve wind farms of 100 MW capacity were proposed to be installed at twelve sites in Libya. The selected wind turbines were manufactured by several manufacturers from different countries. The energy production for each wind farm was estimated by SAM software version 29–2-2020, and the results are tabulated in Table 5.

## 4. Ghgs emissions

### 4.1. *Ghgs emissions during manufacturing WTs* ($\boldsymbol{EF_{GHG-man}}$)

Fig. 5 shows the GHG emission factor $[kgGHG/kWp]$ for different countries at different contents, where it could be noticed that this factor varies according to materials used and energy sources to produce different wind turbines' components, as stated in Table 2.

### 4.2. *Estimated emissions from external and internal transportation*

Emissions of GHGs due to outboard transporting of wind turbines' components from different countries to Libya ($EF_{GHG(ext-trn-wind)}$) and internal transportation inside Libya ($EF_{GHG(int-trn-wind)}$) of these components or parts of them were estimated. The GHGs due to shipping ($EF_{GHG(ext-trn-wind)}$) was estimated using Logward platform, and the GIS platform was used to estimate distances from Tripoli seaport to different destinations of the proposed wind farms to transport the wind turbines components through trucks. The distances from cement factories to the proposed wind farms was estimated and counted for GHGs emissions due to transportation. Distances of transporting recycled wind turbines components from wind farms to Misurata, since it has recycling industries, were estimated to be included in the GHGs LCA phase due transportation. The GHG emission factor was estimated as 56.66 kg of GHGs for each 1000 kg per ton of material, according to ref. [1].

**Table 5**
Wind speed and electric energy production for each manufacturer corresponding to each location.

| Site | $\overline{V}_{100m}$ m/s[†] | France | Denmark | Germany | Spain | Chain | | India | | USA | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GW wind 0.85 MW | Vestas V90-3.0 MW | Gamesa 114–2.0 MW | Enercon_E82-2.5 MW | Semins | Gold wind GW87-1.5 MW | Suzlon 3.3 MW | Nordex N62-1.0 MW | Acciona AW82-1.8 MW | SGRE3.5 MW |
| Tripoli | 8.24 | 129 | 135 | 215 | 87 | 117 | 206 | 117 | 107 | 116 | 172 |
| Zawiya | 7.98 | 287 | 295 | 296 | 278 | 190 | 287 | 197 | 297 | 282 | 295 |
| Derna | 9.02 | 211 | 251 | 352 | 283 | 216 | 196 | 247 | 204 | 184 | 229 |
| Hun | 8.77 | 114 | 141 | 218 | 123 | 114 | 103 | 135 | 110 | 95 | 130 |
| Msallata | 8.73 | 167 | 174 | 255 | 151 | 140 | 132 | 169 | 160 | 124 | 160 |
| Brack | 9.03 | 183 | 218 | 306 | 189 | 175 | 170 | 212 | 200 | 158 | 201 |
| Gharyan | 8.80 | 219 | 167 | 245 | 145 | 192 | 127 | 162 | 153 | 118 | 154 |
| Sirte | 8.46 | 156 | 188 | 270 | 162 | 213 | 144 | 182 | 172 | 134 | 172 |
| Ghat | 8.95 | 96 | 121 | 193 | 105 | 144 | 85 | 115 | 92 | 78 | 112 |
| Benghazi | 8.55 | 209 | 218 | 306 | 189 | 246 | 170 | 212 | 200 | 158 | 201 |
| Kufra | 9.96 | 170 | 117 | 193 | 90 | 141 | 79 | 93 | 107 | 72 | 108 |
| Qatrun | 11.46 | 108 | 136 | 218 | 117 | 163 | 95 | 130 | 124 | 88 | 125 |

[†] Data from Wind Atlas-Libya (https://globalwindatlas.info/en/area/Libya).

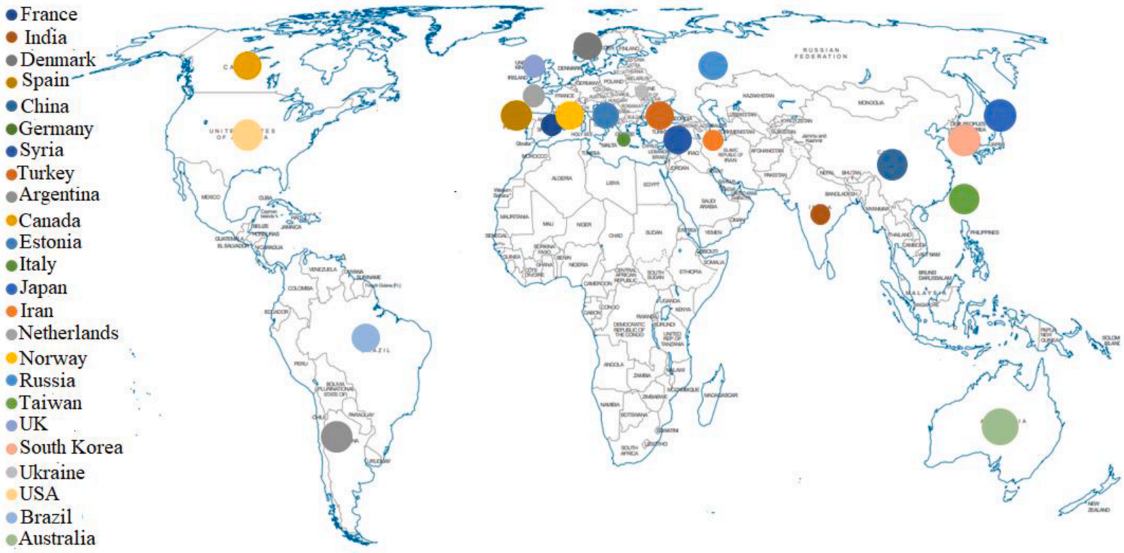

**Fig. 5.** GHG emission factor $[kgGHG/kWp]$ for different manufacturing countries.

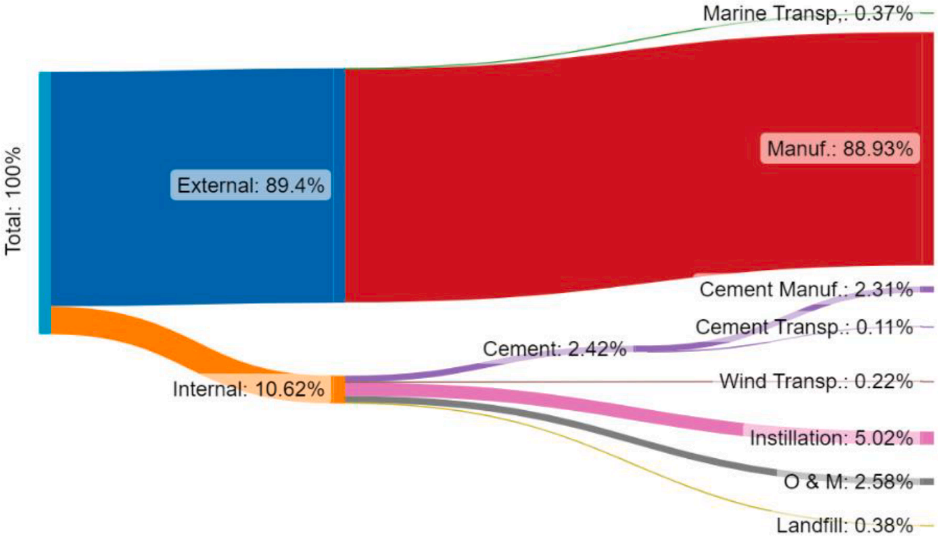

**Fig. 6.** The percentage of the emission factors contribution through life cycle phases of Gamesa wind turbine in Brack city.

**Table 6**
Economic and environmental indicators corresponding to each wind farm site.

| Site | $EF_{GHG}$ $gGHG/kWh$ | $(CPT)$; month | $(EPT)$; month | $(EPR)$ | $(EI)$ |
|---|---|---|---|---|---|
| Tripoli | 52.778 | 12.238 | 19.788 | 12.13 | 0.082 |
| Zawiya | 45.445 | 10.538 | 15.132 | 15.86 | 0.063 |
| Derna | 32.347 | 4.500 | 15.036 | 15.96 | 0.063 |
| Hun | 52.230 | 12.108 | 19.572 | 12.26 | 0.082 |
| Msallata | 37.708 | 5.496 | 16.728 | 14.35 | 0.070 |
| Brack | 43.226 | 7.628 | 13.92 | 17.25 | 0.058 |
| Gharyan | 46.637 | 10.764 | 17.388 | 13.81 | 0.072 |
| Sirte | 41.462 | 7.296 | 15.756 | 15.23 | 0.066 |
| Ghat | 70.047 | 16.248 | 22.068 | 10.88 | 0.092 |
| Benghazi | 43.358 | 7.968 | 13.92 | 17.25 | 0.058 |
| Kufra | 45.170 | 10.248 | 22.092 | 10.86 | 0.092 |
| Qatrun | 52.187 | 12.096 | 19.548 | 12.28 | 0.081 |
| **Average** | **46.883** | **9.761** | **17.579** | **14.01** | **0.073** |

**Table 7**
Emission factor of GHGs of different power plants' technologies.

| Energy generation technology | Emission factor,$gGHG/kWh$ | |
|---|---|---|
| | Rate | Average |
| Biomass energy | 100–1000 | 350 |
| Biogas energy | 25–600 | 100 |
| Thermal solar energy | 15–150 | 40 |
| Photovoltaic solar energy | 20–200 | 60 |
| Geothermal energy | 10–80 | 25 |
| Tidal energy | 10–80 | 25 |
| Wave energy | 12–50 | 25 |
| Hydropower | 2–60 | 20 |
| Off shore wind energy | 5–70 | 15 |
| On shore wind energy | 5–70 | 15 |
| Nuclear energy | 10–20 | 12 |
| Thermal power plant | 800–1500 | 800 |

From equation (17) GHGs emission factor can be estimated for road transporting wind farm components inside Libya $EF_{GHG(int-trn-wind)}$ per unit power $[kgGHG/kWp]$ as in equation (18).

$$EF_{GHG(int-trn-wind)} = \frac{56.6625}{1000} \times (2.3229P + 0.0508) \times D_{wind} \tag{18}$$

Where $D_{wind}$ is the distance between the Tripoli seaport and wind farm site ($km$). And the number $\frac{56.6625}{1000}$ stands for the land transportation emission factor (kg GHG/ton/1000 km) that mentioned in subsection 2.4.2. In a similar manner, GHG emission factor of transporting cement from cement factories to a proposed wind farm site $EF_{GHG(int-trn-cement)}$ per unit power $[kgGHG/kWp]$ can be estimated as follow:

$$EF_{GHG(int-trn-cement)} = \frac{56.6625}{1000} \times 0.4448P \times D_{cement} \tag{19}$$

Where $D_{cement}$ is the estimated distance from cement factories to the proposed wind farm sites ($km$).

### 4.3. Estimation of GHG emission factor through wind energy farm life cycle ($EF_{GHG,\ LC}$)

The impact assessment of the proposed wind farms was conducted as the summation of all substances emitted into the atmosphere from all phases of the selected wind turbines. The results obtained pertain to the extraction of raw materials, manufacturing of different wind turbines' components, transportation phases, installation phase, and operation and maintenance, decommissioning of wind farms by recycling and/or landfill phases. GHG emission factor can be estimated through the wind farm life cycle by adding the emission factor of each stage as presented in Table A2, which was designed to comply with system boundary depicted in Fig. 3; by processing emission data through excel sheet. Table A2 presents extracted data of all mathematical process of all GHG emission factor in $kgGHG/kWp$, which was classified into three subsystems:

**First**: Manufacturing countries of wind turbines' technology subsystem (red color), includes manufacturing phase of wind turbine's components. The average estimated emission factor to this stage $EF_{GHG-man}$ about 1515.980 $kgGHG/kWp$.

**Second**: International transportation subsystem (purple color), includes shipping of wind turbines' components from manufacturing countries to Tripoli. The average emission factor $EF_{GHG(ext-trn-wind)}$ was estimated at 69.625 $kgGHG/kWp$.

**Third**: Countries consuming wind energy technology subsystem - Libya (green color), includes several processes such as:

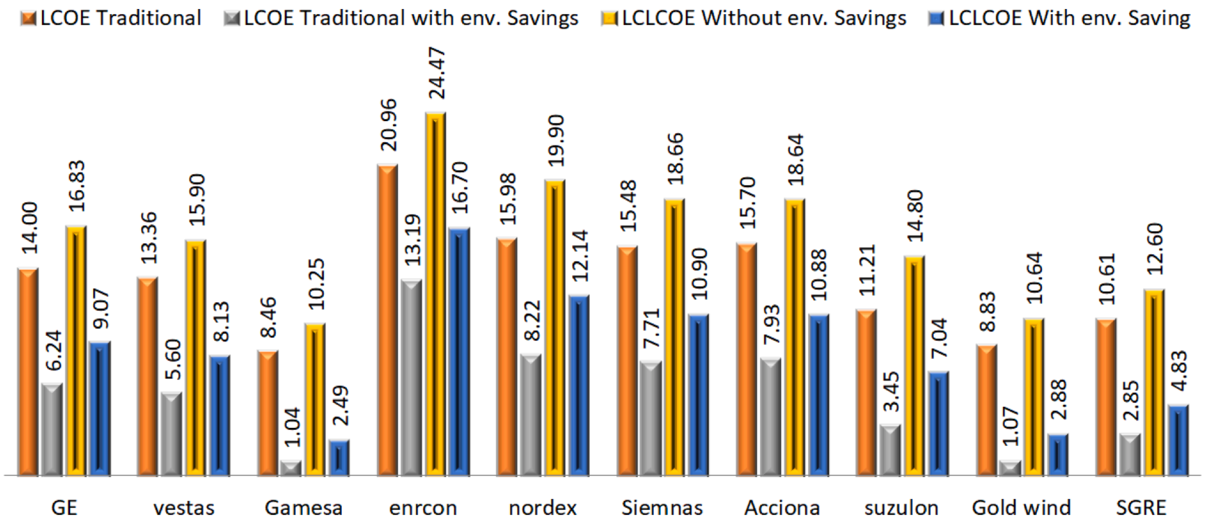

**Fig. 7.** A comparison in approaches for calculating the LCLCOE and LCOE for several wind turbines' technologies.

**Table 8**

Turbine type, capital cost, annual productivity and LCLCOE correspondence to each site.

| Site | Wind turbine type | Manufacturer | Capital cost; $ | Productivity; MWh/year | LCLCOE; Â¢/$kWh$ |
|---|---|---|---|---|---|
| Tripoli | Gamesa 114–2.0 MW | Germany | 147,275,650 | 215,245 | 7.305 |
| Zawiya | Acciona AW82-1.8 MW | USA | 147,145,345 | 281,540 | 4.820 |
| Derna | Enercon_E82-2.5 MW | Spain | 135,246,900 | 283,315 | 3,862 |
| Hun | Gamesa 114–2.0 MW | Germany | 146,978,400 | 217,660 | 7.227 |
| Msallata | Gamesa 114–2.0 MW | Germany | 146,978,400 | 254,640 | 5.947 |
| Brack | Gamesa 114–2.0 MW | Germany | 146,978,400 | 306,150 | 4.686 |
| Gharyan | Gamesa 114–2.0 MW | Germany | 146,978,400 | 245,010 | 6.249 |
| Sirte | Gamesa 114–2.0 MW | Germany | 146,978,400 | 270,305 | 5.516 |
| Ghat | Gamesa 114–2.0 MW | Germany | 146,978,400 | 193,040 | 8.355 |
| Benghazi | Gamesa 114–2.0 MW | Germany | 146,978,400 | 306,150 | 4.683 |
| Kufra | Gamesa 114–2.0 MW | Germany | 146,978,400 | 192,775 | 8.013 |
| Qatrun | Gamesa 114–2.0 MW | Germany | 146,978,400 | 217,975 | 7.009 |

1- Land transportation: Includes transporting wind turbines' components from Tripoli Seaports and cement from cement factories through trucks. The average estimated emission factor to all onshore transport to all sites about is 8.729 $kgGHG/kWp$.
2- Logistic processes: Includes all constructor, commissioning, operation and maintenance, and the decommissioning and landfill. The average estimated emission factor to all logistic processes of the proposed wind farms of all sites about is 117.788 $kgGHG/kWp$.
3- Cement manufacturing: has an average estimated emission factor about 54.084 $kgGHG/kWp$.

Details of estimated emission factors of each country, technology company, each proposed wind farm and cement industry in Libya are presented in Table A2. Fig. 6 presents the breakdown of percentage of the emission factor contribution through life cycle stages of a wind turbine type (Gamesa 114–2.0 MW) in Brack city. Table 6 presents the economic and environmental indicators of each site of the proposed wind farms in Libya. The final emission factor was derived as:

$$EF_{GHG}\left[\frac{kgGHG}{kWh}\right]=\frac{EF_{GHG,Lc}\left[\frac{kgGHG}{kWp}\right]}{Energycapacity\left[\frac{kWh}{kWp}\right]} \tag{20}$$

The results show that the payback period percentage for both the consumed energy and the greenhouse gases emitted during the lifetime of wind energy farms are much less than the lifetime of wind turbines itself, which were estimated as 7.3 % and 4.6 %, respectively. That highlights the important role of wind energy in climate change mitigation and energy sustainability. The results also confirm that the GHGs emitted during the lifetime of wind energy farms are negligible compared to conventional fired fossil-fuel power plants which is estimated at 1,035 g GHG/kWh [23].

### 4.4. *Comparison between wind energy technology and other power plants technologies*

Table 7 shows emission factor of GHGs of different power plants' technologies [26]. The on-shore as well as off-shore wind energy has the lowest emissions after nuclear power plants.

### 4.5. *Life cycle- levelized cost of energy (LCLCOE)*

A new approach for calculating LCOE from wind energy farms was introduced in the present research, where the total environmental impact during the life cycle of the wind farms is considered. This includes:

1. Construction stage ($C_{GHG,I}$); is the cost of emissions from the first phase that include; manufacturing process, transportation (both sea and land transportation) and installation.
2. Production stage ($C_{GHG,II}$); is the cost of emissions from operation and maintenance, and
3. End life stage ($C_{GHG,III}$); is the cost of emissions from the end of life (EoL) of the wind farms (decommissioning, landfill and transportation).

The Life cycle- levelized cost of energy (LCLCOE) is expressed as:

$$LCLCOE=\frac{\frac{i(1+i)^{n}}{(1+i)^{n}-1}\times\left(C_{inv}+C_{GHG,I}\right)+\left(C_{o\&m}+C_{GHG,II}\right)+\frac{(1+i)^{n}-1}{i(1+i)^{n}}\times C_{GHG,III}-C_{GHG,saving}}{E_{wind}};\ \$/kWh \tag{21}$$

Where $C_{inv}$ presents the capital investment in ($), $C_{o\&m}$ is the operation and maintenance cost in ($), and $C_{GHG,saving}$ is the cost of environment impacts of conventional power plants that was displaced by the proposed wind farms in ($). $E_{wind}$ is the annual electric energy produced by the wind farms (kWh), $i$ is the interest rate and $n$ is the wind turbine life time (years). Fig. 7 illustrates a comparison in approaches for calculating the LCLCOE and LCOE for several wind turbines' technologies.

Calculating LCLCOE in this way reflects humanity's union in addressing global warming and climate change. Each stage can be in a different region of the world; therefore, everyone in different country will work to reduce their share of GHG emissions. SAM simulation program was used to simulate the proposed wind farms of 100 MW each using different wind turbines' technologies. The results of the annual energy production and the LCLCOE (eq.18) are given in Table 8. Table 8 shows that the wind energy is economical in the studied sites. Where the LCLCOE of each farm competes with the energy produced from the solar cell field in the city of Ghadames, whose production will be injected into the public electricity grid at a price of 10 ¢/kWh, as announced by - the Libyan General Company of Electricity and Renewable Energy.

It is clear from Table 8 that the wind energy option can be economical in all of the studied locations. The LLCOE of each farm can compete with the energy produced from the solar cell field in the city of Ghadames, whose production will be injected into the public electricity grid at a price of 10 ¢/kWh, as it announced by the Libyan General Company of Electricity and Renewable Energy (LGCERE).

## 5. Conclusions and recommendations

This study focuses on the assessment of the environmental impact of producing 1 kWh of wind energy. It examines the contributions of various stages of wind turbine technology to this impact, particularly for countries like Libya that import wind energy technologies. The boundary system used here encompasses three subsystems: the outboard subsystem, international waters, and the domestic subsystem. The life cycle assessment (LCA) involves six primary stages: procuring raw materials, manufacturing, installation, operation and maintenance, and end-of-life, which includes disassembling turbine parts and recycling or landfilling materials.

LCA was utilized to evaluate the technical and environmental advantages of establishing a 100 MW wind farm at twelve sites in Libya, chosen based on previous research and recommendations from local experts. Key findings include:

1. The average investment required for a 100 MW wind farm in Libya is approximately $146,351,300. The annual energy production ranges from 193 to 253 GWh, depending on the wind potential at each site, with an average of 248 GWh.
2. Tailoring the choice of wind turbine to each specific site.
3. Estimating the Levelized Cost of Energy (LCLCOE), which varies from 4.8 to 8.4 ¢/kWh, with Derna having the highest wind potential and Ghat the lowest.
4. The average GHG emission factor for manufacturing wind turbines is 46.883 g GHG/kWh, with a carbon payback period of approximately 0.814 years (about 9.761 months).
5. The average energy payback period is around 1.168 years (approximately 14.01 months).
6. Wind energy emerges as a favorable choice for future power plants due to its environmental benefits and potential to reduce pollutants and conserve oil and natural gas for industrial use.
7. The study highlights that about 85 % of GHG emissions in the LCA result from manufacturing and shipping wind turbines to Tripoli seaport. Within Libya, construction work contributes 5 %, recycling 5 %, the cement industry 2 %, and road transportation 3 % to the GHG emissions.

The study recommends that policymakers give increased attention to wind energy as a promising alternative for power plant development and transitioning to sustainable, green energy systems. Further research is encouraged to assess wind energy potential concerning environmental issues and to devise strategies for reducing emissions associated with transporting wind turbines. Suggested solutions include utilizing eco-friendly transportation systems and adopting emission-reducing technologies, as well as implementing policies that require manufacturing countries to decompose or recycle wind turbines at the end of their life cycle to mitigate environmental impacts and energy consumption.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Acknowledgement

None

## Appendix

See Tables A1-A2.

**Table A1**
The weight of the material used to fabricate several wind Turbines in ton.

| Manufacturer country | France | India | Germany | | | Chaina | Denmark | | Spain | USA |
|---|---|---|---|---|---|---|---|---|---|---|
| Type and power of turbine | GE wind (0.85 MW) | Suzlon (3.3 MW) | Enercon (2.5 MW) | Gamesa (2.0 MW) | Nordex (1.0 MW) | Gold wind (1.5 MW) | Vestas (1.65 MW) | Vestas (3.0 MW) | Acciona (1.8 MW) | SGRE (3.5 MW) |
| Material | [17] | [18] | [18] | [6] | [26] | [17] | [26] | [17] | [20] | [17] |
| Low alloy steel | 8.78 | 36.75 | 32 | 26.05 | 12.64 | 21.98 | 24 | 28.06 | 25.34 | 38.71 |
| High alloy steel | 5.02 | 12.4 | 11.78 | 10.7 | 8.11 | 9.3 | 10.12 | 13 | 11 | 12.78 |
| Cast iron | 12.63 | 42.36 | 14 | 48.38 | 17.3 | 18.96 | 17.8 | 22.63 | 45.5 | 64.82 |
| Reinforced iron | 69.07 | 44.8 | 16.49 | 40.05 | 15.76 | 60.92 | 23.25 | 33.99 | 19.14 | 41.55 |
| Copper | 0.87 | 1.38 | 3.5 | 1.52 | 1.5 | 14.98 | 1.8 | 112.5 | 3.93 | 1.96 |
| Aluminum | 0.31 | 4.773 | 3.42 | 2.31 | 0.599 | 1.36 | 1.58 | 3.87 | 1.9 | 4.773 |
| Fiber glass | 3.01 | 27.12 | 24.76 | 23.47 | 8.724 | 12.04 | 14.9 | 25 | 18.2 | 28.01 |
| Brass | 2.07 | 12.01 | 8 | 34 | 7.01 | 10.09 | 13 | 8.02 | 1.02 | 3.26 |
| Polymers | 1.46 | 6.93 | 11.7 | 4.57 | 5.26 | 1.77 | 2.3 | 7.8 | 11.04 | 11.36 |
| Glass reinforced Plastic | 0.88 | 1.02 | 8.6 | 2.61 | 6.54 | 0.698 | 0.785 | 1.24 | 1.28 | 2.09 |
| Cement | 480 | 1,176 | 700 | 1,110 | 525 | 1,687 | 805 | 1,140 | 1,200 | 808 |
| Miscellaneous other materials | 1.03 | 8.03 | 13.281 | 10.75 | 1.23 | 4.2 | 2.6 | 3.87 | 1.85 | 7.67 |
| Total | 585.13 | 1,373.57 | 847.53 | 1,314.41 | 609.67 | 1843.3 | 917.14 | 1399.98 | 1340.2 | 1024.98 |

**Table A2**
Summary of specific GHG emissions for each stage..[$kgGHG/kWp$]

| Cement factory location | Cement manufacturing | Cement transportation | Construction, operation & maintenance, decommissioning and landfill | Total internal subsystem | Wind energy farm location | Land transportation of wind energy equipment | | Shipping | Manufacturing | Countries |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | **Libya-Tripoli seaport** | 78 | 1820.352 | France |
| | | | | | | | | 105 | 2513.989 | India |
| | (D) | (C) | (B) | A+B+C+D | | (A) | | 70 | 1518.155 | Denmark |
| | | | | | | | | 53 | 1017.133 | Spain |
| | | | | | | | | 88 | 1907.678 | China |
| | | | | | | | | 92 | 2090.246 | Germany |
| AlKhomos | 54.084 | 0.425 | 117.79 | **172.299** | Tripoli | 0.0 | | 102 | 2307.389 | Syria |
| AlKhomos | 54.084 | 0.516 | 117.79 | **172. 390** | Zawiya | 0.5 | | 63 | 1331.186 | Turkey |
| AlKhomos | 54.084 | 0.115 | 117.79 | **171.989** | Msallata | 0.8 | | 55 | 1089.798 | Argentina |
| AlKhomos | 54.084 | 2.491 | 117.79 | **174.365** | Brack | 5.7 | | 27 | 425.9795 | Canada |
| AlKhomos | 54.084 | 0.465 | 117.79 | **172.339** | Gharyan | 0.8 | | 93 | 2125.247 | Estonia |
| Zliten | 54.084 | 1.204 | 117.79 | **173.078** | Sirte | 3.6 | | 81 | 1888.509 | Iran |
| Zliten | 54.084 | 2.347 | 117.79 | **174.221** | Hun | 4.8 | | 67 | 1627.845 | Italy |
| Zliten | 54.084 | 4.561 | 117.79 | **176.435** | Qatrun | 8.2 | | 79 | 1653.51 | Japan |
| Zliten | 54.084 | 5.0676 | 117.79 | **176.942** | Ghat | 10.7 | | 70 | 1603.529 | Netherland |
| Benghazi | 54.084 | 0.0 | 117.79 | **171.874** | Benghazi | 8.2 | | 66 | 1426.818 | Norway |
| Benghazi | 54.084 | 4.287 | 117.79 | **176.161** | Kufra | 8.8 | | 54 | 1101.157 | Russia |
| Derna | 54.084 | 0.0 | 117.79 | **171.874** | Derna | 10.2 | | 74 | 1569.024 | Taiwan |
| | | | | | | | | 36 | 753.7352 | UK |
| | | | | | | | | 72 | 1475.309 | South Korea |
| | | | | | | | | 31 | 715.1131 | Ukraine |
| | | | | | | | | 72 | 1504.915 | USA |
| | | | | | | | | 19 | 219.0245 | Brazil |
| | | | | | | | | 124 | 2697.87 | Australia |

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