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ORIGINAL RESEARCH

Embodied energy and carbon footprint comparison in wind and photovoltaic power plants

Antonio Augusto Morini[1] · Dachamir Hotza[2] · Manuel J. Ribeiro[3]

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Abstract

This work aims to evaluate comparatively the environmental impact of solar photovoltaic and wind power plants. The conceptual design and the initial preliminary design steps in the material selection process were considered. The assessment was made using two different metrics, embodied energy (EE) and carbon footprint (CF). Five different configurations of wind power plants and a set of photovoltaic panels in a power plant were evaluated. In the wind power plants, the generator, the materials, the height, and the tower type were varied. For manufacturing the towers, the following parameters were considered: material, height, and generator power. The photovoltaic power station can provide up to 1.5 MW. The materials selected for embodied energy and carbon footprint assessment followed two criteria: the greatest mass percentage participation and the greatest value of embodied energy and carbon footprint of each material used. For the calculation of distances travelled from suppliers of raw materials and components used in the photovoltaic panels and wind power plants, the considered destination was the city of Viana do Castelo (north of Portugal), one of the regions with tradition in wind power production and installations. The result is favorable to the concrete column, which achieved the best result of EE and CF. The Oebels 1.5 MW tower with an 80-m concrete column showed an EE of 0.0150 kWh/kWh (19.71% a 3.0 MW 120-m concrete column) and a CF of 4.77 gCO_2/kWh (21.90% of the Rocha 3.0 MW 120-m concrete column). Comparing the 1.5 MW photovoltaic plant with the concrete column 1.5 MW wind power, the result is favorable to the concrete column. Taking into account that the values of the photovoltaic power plant are EE of 0.0638 kWh/kWh and a CF of 16.21 gCO_2/kWh, the concrete column 1.5 MW represents 23.51% of the EE and 29,43% of the CF. This advantage of the concrete towers repeats for the other columns. The results show that the best configuration is the wind power plant with a concrete column. For further studies, a comparison between concrete and truss tower at the same work conditions is suggested.

Keywords Embodied energy · Carbon footprint · Life cycle assessment · Wind power · Photovoltaic power · Materials selection

Introduction

The environmental degradation of the planet is a worldwide reality, occurring in all areas of the planet, without distinction between rich, emerging, or poor countries. This has led to the development of new sources of renewable energy, as well as a search for greater energy efficiency [1]. Despite growing concerns about the consumption and availability of resources, like energy and raw materials, what is seen in practice are adaptations and adjustments of environmental requirements to projects and processes already in use, providing solutions that comply with the legal and corporate requirements. Renewable energy sources (RESs), such as solar, wind, hydropower, and

✉ Antonio Augusto Morini
antonio.morini@ifsc.edu.br

Dachamir Hotza
d.hotza@ufsc.br

Manuel J. Ribeiro
ribeiro@estg.ipvc.pt

[1] Electrotechnology Academic Department (DAE), Federal Institute of Education, Science and Technology of Santa Catarina (IFSC), Florianópolis, SC, Brazil

[2] Graduate Program in Materials Science and Engineering (PGMAT), Federal University of Santa Catarina (UFSC), Florianópolis, SC, Brazil

[3] Materials Research and Development Center (UIDM), Polytechnic Institute of Viana Do Castelo (IPVC), Viana do Castelo, Portugal

biomass, have progressed due to several advantages, in special low greenhouse gas emission [2].

As an example, in 2019, the installed capacity of energy in Portugal was 22,090 MW. From this amount, 24.6% (5429 MW) were generated by wind energy [3]. This was only possible due to the spectacular progress of wind energy, which has become the second most important RES after hydropower within a decade [4], remembering that its first wind farm installed in the mainland occurred in 1987, in Sines [5]. Portugal is one of Europe's countries with the longest exposure to the sun. The annual average is approximately 8 h/day with reception above 1200 W/m^2, resulting in an energy potential of 430,000 GWh. Despite these good conditions, the country has an installed capacity of only 465 MW, which is very low compared, for instance, to Greece, which has a similar territorial area and economic situation. Greece currently has 2.6 GW installed, nearly six times more than Portugal [6].

The selection of wind and photovoltaic power plants for this study was based on the relevance of these two energy sources. Since 1990, renewable energy sources have grown at an average annual rate of 2%, which is slightly higher than the growth rate of the world's total primary energy supply (TPES), 1.7%. Growth has been especially high for solar photovoltaic and wind power, which grew at average annual rates of 37.0% and 23.4%, respectively [7].

Today's wind turbine models have some well-defined technological options such as three-blade rotors, horizontal axis, and frontal rotor. However, other technological options still do not find consensus and may be different for each manufacturer and installation site. Among these are the materials used in the manufacture of the blades and the towers [8].

The focus of this work is related to comparing the photovoltaic and wind power plants, taking into account the embodied energy and the carbon footprint produced by these two different ways of energy generation. The investigation of upstream and downstream processes in the life cycle of an electricity production power plant is necessary to evaluate the magnitude of its embodied energy and carbon footprint [9].

For the comparative study of the embodied energy and the carbon footprint between wind and photovoltaic power plants, the first step was to identify the main materials used in the construction and installation of each piece of equipment. The criteria were the highest mass percentage and the highest embodied energy/carbon footprint of each material.

According to the main goal of this work, two questions should be answered:

- Which of the two ecologically viable alternatives, wind or photovoltaic power plant, has the lowest environmental impact, considering embodied energy and carbon footprint?
- Is it possible to make the best decision, quickly and reliably, even in the early stages of product development?

Methodological approach

In the academic world, concepts such as life cycle assessment (LCA) and design for environment (DFE) or EcoDesign have promoted discussions and changes in design methodologies, which traditionally do not contain, in a clear way, environmental and sustainability requirements.

In face of this reality, the need for design methodologies that effectively take into account environmental requirements has been developed, such as the EcoDesign (Europe) or DFE (the USA) and LCA (worldwide). In all these methodologies, the materials selection has a relevant role in the development of products with less environmental impact.

Materials selection

Four essential requirements are generally associated with the selection of the materials: conditions of service, deterioration of properties in service, economic, environmental, and social factors [10].

Materials selection is the final decision in the engineering design process and can determine its success or failure [11]. During the selection of materials for sustainable product design, decisions are made based on cost, environmental aspects, and other important properties. However, this decision is not simple and, generally, the objectives are in conflict [12].

The choice of material is critical to the manufacturing process and plays an important role in the product life cycle. In materials selection, project designers should examine the life cycle impacts of their choices and have easy access to existing life cycle data and methodologies. Regardless of the project objective, in recent years environmental factors have increased in importance, making material selection a multicriteria decision [13].

About 80% of the environmental impact generated by the product or service is defined in the initial phases of the project [14]. Therefore, it is important to develop tools that can support designers to develop environmentally correct products in a practical, fast, and reliable way [15].

Requirements for material selection include not only the technical but also the economic and environmental factors. Among the existing options, Ashby [16] and their team developed a software tool (CES-Selector) to help designers make the best choice [17]. Using CES-Selector, the comparative evaluation of different materials is possible by the adoption of a methodology based on materials properties

[18]. The CES-Selector is not the only solution developed for material selection, but it is simpler than CAD tools, which combine technical properties, stress analysis, material selection, and LCA [19].

Selecting materials through dedicated software with a reliable database can assist designers in obtaining relevant information about related materials and processes. Based on a simplified LCA concept, the CES-Selector 2021 also offers the EcoAudit tool, which works with two indicators to measure the environmental impact: embodied energy and carbon footprint. This software identifies which products and processes will lead to smaller environmental degradation and which is the best way throughout the life cycle. EcoAudit covers the life cycle from cradle to grave, i.e., through the material selection, manufacturing, transportation, use, and disposal phases. The result is shown through graphs and reports [20].

LCA—life cycle assessment

Life cycle assessment (LCA) is a well-known methodology for assessing the environmental impact related to products and services, from raw materials extraction to final life, requiring consistent data collection throughout the product life cycle [21].

LCA is an important tool in assessing the environmental impact, and its use ensures environmentally acceptable product planning. However, its implementation is not easy, requiring knowledge and hard work from designers committed to environmental management, which limits its application to larger companies, with enough resources to maintain specialized staff.

The effectiveness of using the LCA method depends on the experience and ability of the project designers since there is no single method for collecting data and developing the work. Nevertheless, some points are mandatory so that the document must present at least: objective and scope of work, inventory analysis, impact assessment, and results interpretation.

Data collection is the first inventory analysis step, where the unavailability or the poor quality of data may lead to the need to make estimates impacting inherently uncertain decisions. The quality and consistency of the data are key issues; therefore, this may be the most laborious stage of the development of an LCA [22]. The results will be effective only if the data used are compatible with the reality of the application site [23].

The impact assessment is based on the list of resources consumed and emissions generated, presented in the inventory. With this data, it is possible to verify the significance of possible environmental impacts, through several indicators of environmental quality, such as acidification potential, climate change potential, eutrophication potential, land use, and resource depletion.

Embodied energy and carbon footprint

According to Cabeza [24] and Dixit [25], there are different meanings and conceptual approaches for the term "embodied energy" [26–29]. In the field of building and construction, a well-accepted definition [30] describes the embodied energy applied to materials as "the energy consumed during the extraction, processing of the raw material, manufacture materials and components plus the energy used in the various processes during construction and demolition." Ashby and Miller [31] define embodied energy as "the energy of the fossil fuel consumed to make one kilogram of material." This definition is present in the embodied energy values of the materials in the CES-Selector database.

In contrast, the carbon footprint (CO_{2eq}.) considers direct and indirect carbon emissions and has been present in debates on the effects of climate change around the world, making it the most popular ecological indicator adapted by NGOs, companies, governments, among others. Due to the recent impact of climate change, some companies, such as Coca-Cola and BMW, have developed a detailed carbon footprint survey of their products as a way to reduce the impacts of climate change [32].

However, the amount of emissions depends on the efficiency in the conversion of energy and the amount of carbon of the different fuels. Rydh and Sun [33] proved that the relationship between the energy consumed and the carbon emission can be represented by a linear equation.

Results and discussion

A comparison of the embodied energy and the carbon footprint, per kWh, between wind power generators of 1.5 MW and 3.0 MW assembled over columns of 80, 100, 120, and 150 m was made against a 1.5 MW photovoltaic power plant.

For the support of the wind power generators, three material options of tower columns were included: steel sheet, steel truss, and concrete. The generators are driven by a set of three blades, which are mainly made of glass fiber and epoxy resin. The steel truss column is galvanized, the concrete column is not painted, and the steel sheet column is painted with epoxy paint.

The photovoltaic power plant is composed of a set of 255 W photovoltaic panels. The photovoltaic panel has a frame composed of 60 monocrystalline silicon cells encapsulated with a film of ethylene vinyl acetate (EVA) and protected in its front by a tempered glass and in the back by an aluminum plate. This set is enclosed with aluminum profiles

and assembled over a galvanized steel frame installed on the ground.

In this work, all the main components of the solar panel and its support structure in galvanized steel were evaluated. The values of embodied energy (EE) and carbon footprint (CF) of the main materials used in the wind towers, such as concrete, steel, glass fiber, epoxy resin, epoxy paint, and copper, are related to the average values of CES-Selector EcoAudit 2021, as described in Table 1.

Considering the values of EE and CF presented in Table 1, the extremely high value of the monocrystalline silicon cell and the low value of the concrete are the more relevant results in relation to the other materials. These two materials are decisive in the comparative result of embodied energy and carbon footprint of the wind power generator and photovoltaic power plant.

For example, with focus only on the wind tower generator materials and having the monocrystalline silicon cell as the basis of calculation, the EE of the concrete represents only 0.05% of the monocrystalline silicon cell embodied energy; that is, 1 kg of monocrystalline silicon cell has the same embodied energy that 2105 kg of concrete. In the case of the galvanized steel, it represents only 1.46% of the monocrystalline silicon cell embodied energy; that is, 1 kg of monocrystalline silicon cell has the same embodied energy that 68.1 kg of galvanized steel. In the same way, glass fiber has 3.0%, copper has 2.5%, epoxy resin has 7.02%, and epoxy paint has 7.09% of the monocrystalline silicon cell embodied energy.

Analyzing the values of the photovoltaic panel, glass has the lowest value of embodied energy (10.11 MJ/kg), representing only 0.60% of the monocrystalline silicon cell; that is, 1 kg of monocrystalline silicon cell has the same embodied energy that 166 kg of glass. Considering the other materials, EVA has 4.65% and aluminum has 7.47% of the monocrystalline silicon cell embodied energy.

Main materials used in the wind power towers

The most relevant data for the calculation of the embodied energy and the carbon footprint of the wind energy towers used for the present study were taken from Oebels and Pacca [34], which refers to the amount of steel, concrete, epoxy resin, epoxy paint, glass fiber, and other materials used in the construction of the columns evaluated, like steel sheet towers, steel truss towers, and concrete towers. The works of Rocha [35] and Henriques [36] provided information on the quantities of steel and concrete used in wind power towers.

Considering the total mass of an 80-m tower with a 1.5 MW generator, Oebels and Pacca [34] found that the overall percentage of concrete and steel for this tower, assembled with a steel column, reaches 96.79% of the total mass of the tower. In the case of the tower with a concrete column, the sum of steel and concrete used reaches 97.99% of the total tower mass, as shown in Figs. 1 and 2, respectively.

With these high percentages of steel and concrete in the wind towers construction, it would be convenient to assume the use of only these two materials for the embodied energy and carbon footprint determinations. However, it was decided not to restrict the analysis of EE and CF for only those elements. This decision was performed considering that although concrete and steel quantities are much larger than the other components, their values of embodied energy and carbon footprint are lower, when comparing with the other materials presented in Table 1.

Table 2 shows the quantities of glass fiber, epoxy resin, epoxy paint, and copper in the 80-, 100-, 120-, and 150-m towers. The following considerations were made:

- The concrete columns and truss columns are not painted.
- The 80-m tower values built in steel or concrete [34] were used as a reference to calculate the amounts of glass fiber,

Table 1 Embodied energy and carbon footprint for the main materials used in wind and photovoltaic power plants

Power plant	Materials	Embodied energy (MJ/kg)	Carbon footprint ($kgCO_2$/kg)
Wind	Galvanized steel	24.72	1.79
	Steel CA – 50	20.55	1.47
	Concrete – Portland	0.80	0.12
	Glass fiber “type E”	51.11	2.91
	Epoxy resin “glass filler”	118.30	6.29
	Epoxy paint “flexibilized”	119.40	6.12
	Copper 12,500 “soft”	42.20	2.67
Photovoltaic	Monocrystalline silicon cell	1684.00	126.30
	EVA 9000	78.26	2.06
	Aluminum 6063 T5/Aluminum 5005	125.81	8.39
	Glass	10.11	0.70

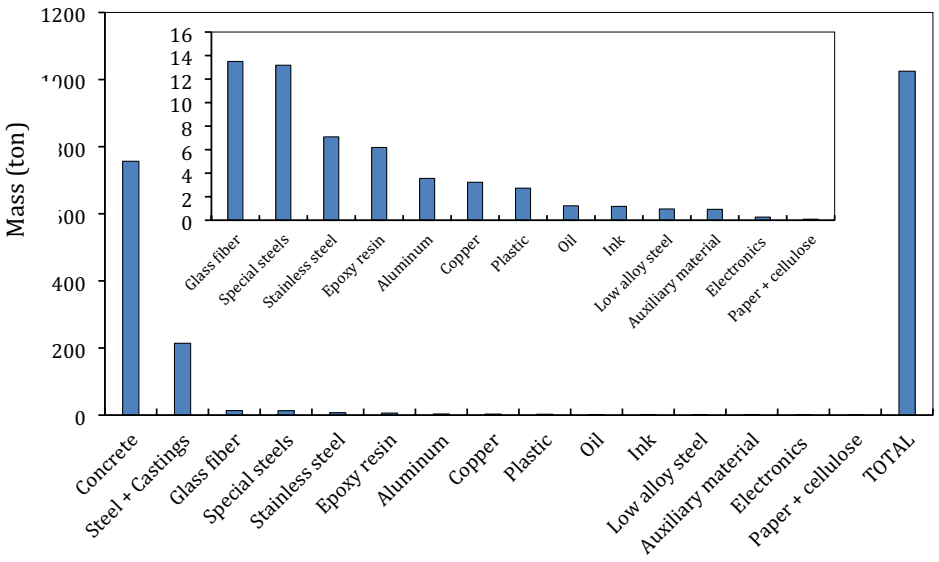


Fig. 1 Mass of the materials used in the steel towers (adapted from [34])

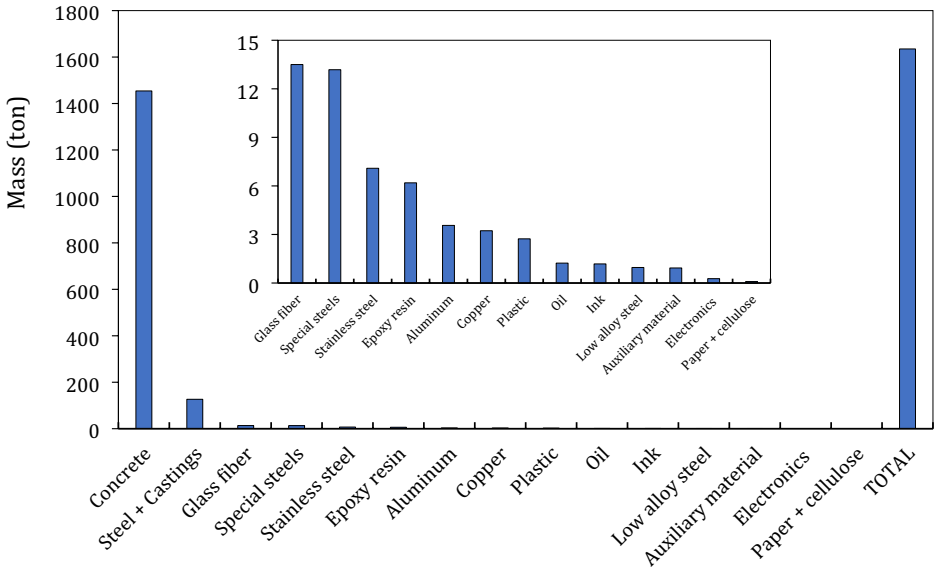


Fig. 2 Mass of the materials used in the concrete towers (adapted from [34])

Table 2 Complementary materials of the wind power plants

Material	80-m Tower (kg)	100-m Tower (kg)	120-m Tower (kg)	150-m Tower (kg)
Glass fiber	11,860	14,820	17,790	22,240
Epoxy resin	6190	7740	9285	11,610
Epoxy paint	1030	1290	1545	1930
Copper	1180	1475	1770	2210

epoxy resin, epoxy paint, and copper used in the 100, 120, and 150 m, maintaining its proportionality.

As expected, the amount of materials increases proportionally with the blades length and the mass of glass fiber is the dominant amount of material in the production of a wind tower.

Table 3 shows the amount of concrete and steel used in the construction of steel towers according to the literature with a tower of 80 m and a 1.5 MW generator [34], with towers of 80, 100, 120 m and generators of 3.0 MW [35] and with a column of 150 m and a 2.5 MW generator [36]. The results show that when comparing the 80-m towers, the Oebels and Pacca [34] structure is lighter in both steel (34.7%) and concrete (47.9%), than the Rocha [35] structure. This can be explained by the fact that the turbine used by Oebels and Pacca [34] has 50% of the turbine power used by Rocha [35], with lower torque and mass.

The amount of concrete and steel used in the construction of towers made of steel truss column compared to the quantities used in the steel sheet column, according to the works of Henriques [36] with a tower of 150 m and a 2.5 MW generator, can be found in Table 4. The results show that comparing the 150-m towers constructed on cylindrical steel sheets against the same ones constructed in steel truss, as expected, the latter is lighter than the steel sheet column, with 46% less steel and 67.7% less concrete.

Table 5 shows the amount of concrete and steel used in the construction of concrete towers according to the works of Oebels and Pacca [34], with a tower of 80 m and a 1.5 MW generator and Rocha [35] with towers of 80, 100, 120 m and 3.0 MW generator. The results show that when comparing the 80-m towers, the Oebels and Pacca [34] structure uses less concrete (2.1%) but more steel (10.0%) than the Rocha [35] structure. The main reason for this difference is that the concrete tower has a steel part at its upper end.

Photovoltaic solar plant dimensioning

The data used for the present work were taken from the project of a photovoltaic plant developed in two different papers, Granja [37] and Lopes [38]. For comparison with the wind generators described by Oebels and Pacca [34], it was decided to define a 1.5 MW wind power. The materials included in the evaluation of the embodied energy and the carbon footprint of the photovoltaic solar plant were silicon, steel, aluminum, glass, and EVA (ethylene vinyl acetate).

Table 6 shows the technical specifications of the photovoltaic panel and the inverters used in this solar plant design.

The number of photovoltaic panels required to produce 1.5 MW of power can be defined by the direct relationship

Table 3 Steel and concrete amounts used in the steel tower

Tower blade height (m)	Steel tower (t)	Steel foundation (t)	Steel (others) (t)	Steel (total) (t)	Concrete (t)	References
80	155	22.5	15.5	193	757	Oebels and Pacca [34] (1.5 MW)
80	183.6	53.1	59	295.7	1454	Rocha [35] (3.0 MW)
100	330.6	62.9	74	467.5	1697	
120	685.7	82.5	89	857.2	2210	
150	610	111	61	782.0	3070	Henriques [36] (2.5 MW)

The amount of concrete referred is related only to the steel tower foundation

Table 4 Concrete and steel, a comparison between sheet and truss column, for tower blade height with 150 m (Adapted from [36])

Steel sheet column (t)	Steel truss column (t)	Steel foundation (t)	Steel (others) (t)	Steel (total) (t)	Concrete (t)	References
–	350.4	36	35	421.4	992	Henriques [36] (2.5 MW)
610	–	111	61	782.0	3070	

Table 5 Concrete and steel used in the concrete tower (Adapted from [34, 35])

Tower blade height (m)	Steel column (t)	Steel foundation (t)	Total steel (t)	Concrete column (t)	Concrete foundation (t)	Total concrete (t)	References
80	67.0	33.5	100.5	697.5	756.6	1454.1	Oebels and Pacca [34] (1.5 MW)
80	52.2	38.5	90.4	734.4	1102	1836.4	Rocha [35] (3.0 MW)
100	74.0	47.0	121	1096.8	1493	2589.8	
120	88.9	72.8	161.7	1459.0	1858	3317	

Table 6 Technical specifications of the photovoltaic panel and inverters

	Electrical parameters	Symbol	Unit	Value
Photovoltaic panel	Nominal power	P_n	W_p	255
	Power tolerance	ΔP	W	+5
	Efficiency	η	%	15.7
Inverters	Maximum output AC power	P_{out}	kW	33
	Maximum input DC power	P_{in}	kW	34–45
	Maximum efficiency	η	%	98.5

between photovoltaic power (P_{cv}) and the nominal power of the panel (P_n), resulting in an initial number of 5882 photovoltaic panels. However, these panels' amount is not definitive and must be adjusted according to the technical specifications of the inverter that will be used. Since the maximum output power of the selected inverter is 33 kW, the number of photovoltaic panels that can be connected to an inverter can be defined by the direct ratio between the maximum output power (P_{out}) of the inverter and the nominal power of the panel photovoltaic (P_n), resulting in 129 panels.

The photovoltaic power plant will have double strings (two lines of solar collectors connected), so the number of panels per inverter should be even and multiple of six (six lines per inverter), resulting in 126 panels per inverter. Thus, the number of inverters can be calculated by the ratio between the total number of panels (5882) divided by the number of panels per inverter (126), and the resulting value is 47 inverters.

As a result, the photovoltaic power plant will have 5922 photovoltaic panels that can generate 1.510 MW. Figure 3 shows the connection layout of the strings to the inverters.

This design was developed for Portugal, in the northern hemisphere, and will have a fixed structure. The best performance of the photovoltaic arrangement is usually obtained by orienting it toward the equator with a slope close to the location's latitude [39].

As an example, in that case, the optimal solar panel slope for the city of Viana do Castelo is α = 38º, facing the south. In this example, the distance "d" (Fig. 4) that must be maintained between the lines of panels, to minimize the shading, is 6.91 m.

Main materials of the photovoltaic solar plant

The solar panel fixing structures are made with a U-profile (100 × 50 × 3.04 mm) of galvanized steel, which will be considered in this material EE and FP calculations. Other accessories used for fixing the photovoltaic panels are not considered in this calculation; instead, 5% was added to the final value. This galvanized steel U-profile, with a mass of 4.48 kg/m, was chosen for the vertical structure, whereas the rectangular profile [] (50 × 30 × 4.75 mm) with 3.54 kg/m was chosen for the panels support. Both

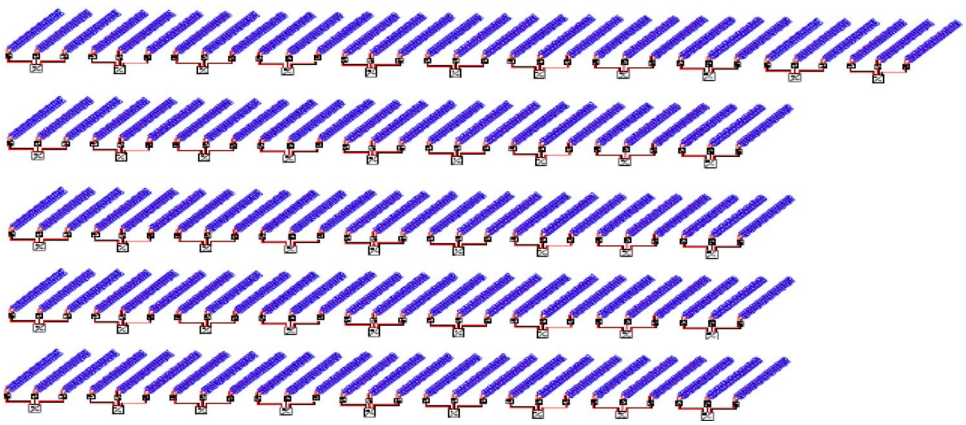


Fig. 3 Photovoltaic system design for a power plant with its respective inverters

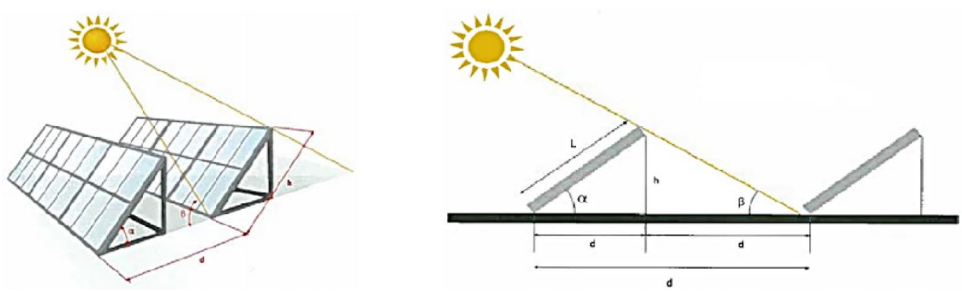


Fig. 4 Schematic representations of the distance between the panels (adapted from [38])

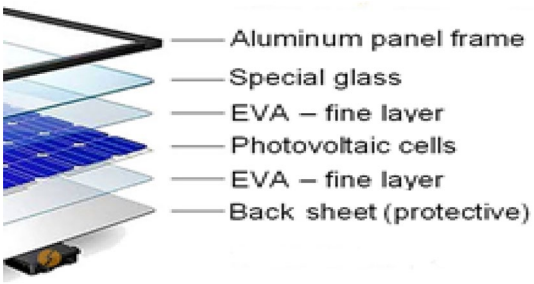


Fig. 5 Photovoltaic panel view with the main layers

of solar irradiation. In this way, the panels are assembled as shown in Fig. 5.

The panel has an area of 1.627 m^2 (1.640 × 0.992), and the area of the photovoltaic cells was 1.46 m^2, with 60 (6 × 10) cells of 156 × 156 mm. The main materials used to build the photovoltaic power panels, shown in Table 8, are aluminum, glass, EVA, and silicon, this one considering single crystalline silicon for photovoltaic cells.

Distance traveled

Table 9 shows the approximate distances of potential raw material and components suppliers of the main materials used in the manufacture of the photovoltaic power plant and wind power. The suppliers were selected for their possibilities of supplying material to Portugal and not for their

Table 7 Steel quantity present in the photovoltaic solar plant

	Steel profile (mm)	Mass/length (kg/m)	Length of the panels line (m)	Total length (m)	Total mass (kg)
Vertical structure	U (100 × 50 × 3.04)	4.48	27.0	135	604.8
Panels support	[] (50 × 30 × 4.75)	3.54	20.7	103	364.6
Total partial mass					969.4
Total mass (adding 5%)					1018

Table 8 Total photovoltaic panels mass of each main material

Component	Material	Panel area (m^2)	Linear length (m)	Thickness (mm)	Mass per panel (kg)	Total mass (kg)
Frame	Aluminum 6063 T5	–	5.264	–	5.648	33,550
EVA	EVA 9000	3.254	–	0.5	1.545	9177
Backsheet	Aluminum 5005	1.627	–	1.2	5.271	31,310
Glass	Anti-reflexive glass	1.627	–	3.2	13.02	77,340
Photovoltaic cell	Single crystalline silicon	1.460	–	0.3	0.964	5709

Table 9 Distances of potential raw material and components suppliers

Material	Origin	Approximate travel distance (km)	Transport mode
Steel	Duisburg, Germany	2200	Terrestrial
Cement	Loulê, Portugal	610	Terrestrial
Gravel and sand	Braga, Portugal	65	Terrestrial
Single crystalline silicon	Tianjin, China	14,000	Maritime
Aluminum	Marabá, Brazil	550 + 7800	Terrestrial + Maritime
Glass	Valença, Portugal	65	Terrestrial
EVA	Saint Paul, Franc	1700	Terrestrial
Glass fiber	UK	2000	Terrestrial
Resin/paint	Meneey, France	1600	Terrestrial
Copper	Aitik, Sweden	1400 + 1600	Maritime + Terrestrial

profiles, U and [], were hot-dip galvanized, and the amount of steel used in the photovoltaic power plant is defined in Table 7.

Photovoltaic panels are manufactured in a way that guarantees the protection of photovoltaic cells and the best use

current supply situation because buyers change suppliers frequently. The destination was considered the city of Viana do Castelo, a city with a tradition in renewable energy production systems and the development of efficient energy management devices.

Calculation of the embodied energy and carbon footprint using the EcoAudit

For the embodied energy and the carbon footprint determinations, the following items were considered:

- The reference location for all calculations for this study is the city of Viana do Castelo, north of Portugal (41º41′24″ N and 8º49′16″ W);
- The necessary electrical cabling transmission from the generation point to the connection point of the grid was not considered, being compliant with the same kind of simplifications that were considered for the wind power;
- The specific location of the photovoltaic solar plant was not defined, only the city, Viana do Castelo—Portugal;
- The transformation station location (substation) has not been defined;
- No electrical calculations were performed, such as short-circuit voltage, current, protection circuit, power loss, and other related calculations;
- Overhead and underground lines, foundations, supports, and other structural and complementary elements of the power transmission system were not designed.

As part of the conceptual and preliminary design of a product, the embodied energy and carbon footprint calculations have been made by knowing, at least, the mass of the main materials, the manufacturing process, the approximate travel distance from the origin country of the raw material, its use, and final destination. In particular, for this study, it was considered that the final destination of the energy produced would be the same as that given to the energy distributed by the national electricity grid.

Another important factor is the product's lifetime. For the wind generator, a 20-year lifetime was considered [40] and for the solar panel a lifetime of 25 years [41]. For the wind generator, 3000 h of power generation per year (34.25%) and for the solar panel 2500 h of power generation per year (28.54%) of a possible total of 8760 h per year were also considered.

Table 10 shows the values of embodied energy and carbon footprint for 1.5 MW, 2.5 MW, and 3.0 MW generators assembled over towers of 80, 100, 120, and 150 m built in steel sheet, concrete, and steel truss columns. It also shows the EE and CF values for the 1.5 MW photovoltaic power plant. In this calculation, the distances shown in Table 9 are included.

Table 11 shows the values of embodied energy and carbon footprint considering the same configuration described in Table 10, but here only steel and concrete values were included. Table 11 does not show the values of embodied energy and carbon footprint of the concrete and steel used

Table 10 Embodied energy [EE—kWh/kWh] and carbon footprint [CF—gCO_2/kWh] of the materials used in the wind power and photovoltaic plants

Tower height (m)	Steel sheet column		Concrete column		Steel truss column		Photovoltaic plant		References
	EE	CF	EE	CF	EE	CF	EE	CF	
80	0.0208	5.84	0.0150	4.77	–	–	–	–	Oebels and Pacca [34] (1.5 MW)
80	0.0289	8.79	0.0152	5.05	–	–	–	–	Rocha [35] (3.0 MW)
100	0.0443	12.88	0.0221	7.29	–	–	–	–	
120	0.0761	21.78	0.0260	13.23	–	–	–	–	
150	0.0739	21.55	–	–	0.0415	11.44	–	–	Henriques [36] (2.5 MW)
–	–	–	–	–	–	–	0.0638	16.21	This work (1.5 MW)

Table 11 Embodied energy (EE—kWh/kWh) and carbon footprint (CF—gCO_2/kWh) of the steel and concrete used in the wind power plants

Tower height [m]	Steel sheet column		Concrete column		Steel truss column		Photovoltaic plant		Ref
	EE	CF	EE	CF	EE	CF	EE	CF	
80	0.0163	4.93	0.0106	3.85	–	–	–	–	Oebels [34] (1.5 MW)
80	0.0252	7.88	0.0111	4.14	–	–	–	–	Rocha [35] (3.0 MW)
100	0.0388	11.71	0.0146	5.78	–	–	–	–	
120	0.0695	20.67	0.0197	7.55	–	–	–	–	
150	0.0652	19.44	–	–	0.0338	8.68	–	–	Henriques [36] (2.5 MW)

in the photovoltaic plant due to the insignificant amount of these materials in this plant.

Comparing the values presented in Tables 10 and 11, it is possible to verify that there is a small increase in EE and CF generated by the towers of Table 10, roughly 10%, despite the addition of the complementary materials used for: manufacturing blades (glass, epoxy resin, and epoxy paint), transmission of energy (copper), and finishing of the towers (epoxy paint), showing that these materials have a small contribution in the total production of EE and CF from the wind power plants. The amount of the concrete and steel is irrelevant in the photovoltaic plant, as shown for the steel in Table 7.

In the 80-m tower designed for the 1.5 MW generator, the following changes occurred in the values of the embodied energy and carbon footprint, after the addition of the complementary materials:

- In the sheet steel tower, concrete and steel represent 78.4% (0.0163 to 0.0208 kWh/kWh) in the embodied energy and 84.4% (4.93 to 5.84 gCO_2/kWh) in the carbon footprint.
- In the concrete column tower, concrete and steel represent 70.7% (0.0106 to 0.0150 kWh/kWh) in the embodied energy and 80.7% (3.85 to 4.77 gCO_2/kWh) in the footprint of carbon.

Conclusions

When comparing wind against solar photovoltaic power plants to choose which energy generation system has the lowest embodied energy and carbon footprint, it was possible to conclude that the Rocha steel sheet column with a tower height of 120 m and a 3.0 MW generator has the highest value among the evaluated systems, with an EE of 0.0761 kWh/kWh and a CF of 21.78 gCO_2/kWh, as shown before. It was established that the determining factor for this result is the 3.0 MW generator combined with the 120 m tower height.

Taking into account that the towers of the wind power generator are built in steel or concrete, the result was favorable to the concrete column, which achieved the best result of EE and CF. The Oebels and Pacca 1.5 MW tower with an 80-m concrete column showed an EE of 0.0150 kWh/kWh (19.71% of the Rocha 3.0 MW 120-m concrete column) and a CF of 4.77 gCO_2/kWh (21.90% of the Rocha 3.0 MW 120-m concrete column). Comparing the 1.5 MW photovoltaic plant with the concrete column 1.5 MW wind power, the result is favorable to the concrete column. Considering that the values of the photovoltaic power plant are EE of 0.0638 kWh/kWh and a CF of 16.21 gCO_2/kWh, the concrete column 1.5 MW represents 23.51% of the EE and 29.43% of the CF. This advantage of the concrete towers repeats for the other columns,

This work shows that it is possible and practicable to use a simplified LCA software with only two parameters of evaluation, embodied energy and carbon footprint, to select the material of lower environmental impact still at the beginning of new product development, that is, in the project design stages and its early development. However, this work does not preclude or exclude a more detailed evaluation of the product life cycle, through a more complex and detailed LCA software.

Finally, the results show that the best configuration among those evaluated is the 1.5 MW wind tower plant with an 80-m concrete column. Nevertheless, for a more precise conclusion, it is necessary to make a comparison between the steel sheet and truss columns at the same working conditions, in different models.

Our work shows that it is possible and practicable to use a simplified LCA software with only two parameters of evaluation, embodied energy and carbon footprint, to select materials with lower environmental impact still at an early stage. However, there are obstacles and hindrances to be observed. Simplified impact factors may hide significant aspects to be considered in the delicate phase of material selection. In this regard, we feel that it is not advisable to assume a linearity when comparing wind and photovoltaic power plants: A case-by-case study must be carried out. For instance, in further studies, a comparison between concrete and truss tower at the same work conditions is suggested.

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