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Product and corporate carbon footprint using the compound method based on financial accounts. The case of Osorio wind farms

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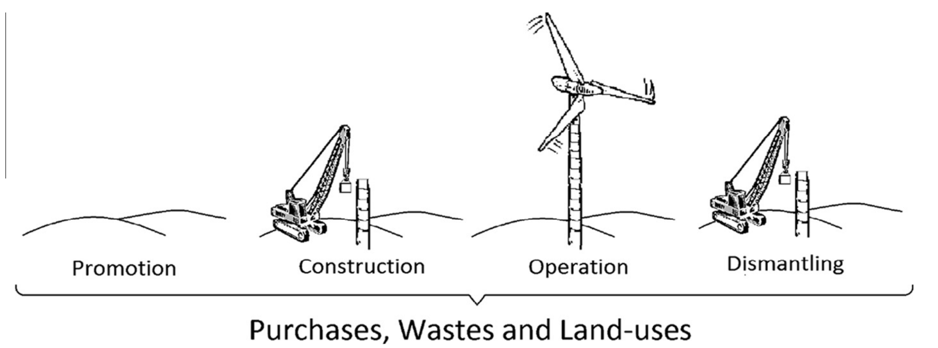
HIGHLIGHTS

- We applied novel organisation-product-based-life-cycle assessment to Osorio Wind Farms.
- This study includes sources, phases and areas previously unreported for the wind power sector.
- MC3 assess carbon footprint in a practical and comprehensive manner.
- MC3 is suitable for its application in major international projects.

GRAPHICAL ABSTRACT



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ABSTRACT

The challenge of developing clean and renewable energy sources is becoming ever more urgent. Over the last decade, the concept of carbon footprint has been used to report direct and indirect greenhouse gas emissions and as a support for sustainable consumption decisions. However, the discrepancies in the approaches based on either the product or corporate carbon footprint can seriously hinder its successful implementation. The so-called compound method based on financial accounts is a tiered hybrid method which enables the calculation of both the product and corporate carbon footprint. This work aims to assess this method as a tool for carbon footprint through its implementation in a comprehensive life-cycle assessment of the Osorio Wind Farms in Brazil. The total cumulative life-cycle emissions are 362.455 t CO_2eq, representing 18.33 gr CO_2eq per kW h delivered to the Brazilian national power grid. The difference with regard to previous works derives from its broader scope and different assumptions. In this study the comparable value from wind turbine manufacture, transport and construction is 8.42 gr CO_2eq per kW h, 56% lower than the mean figure reported by Arvesen and Hertwich (2012). This study includes sources, phases and areas previously unreported in the carbon footprint reviews for the wind power sector. We conclude that the compound method based on financial accounts is a practical method that allows the definition of a more comprehensive goal and scope. Its implementation at Osorio Wind Farms demonstrates the method's suitability for application in major international projects and institutions interested in closely monitoring their carbon footprint.

1. Introduction

Sustainable developmental science promotes management solutions and tools which integrate the fundamentals of sustainability (i.e. environmental quality, economic prosperity, and social

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Nomenclature

CF	carbon footprint
CO_2	carbon dioxide
CO_2eq	carbon dioxide equivalent
EEIO	environmentally extended input–output
GHG	greenhouse gases
ISO	international organization for standardization
MC3	compound method based on financial accounts
LCA	life-cycle assessment

justice) [1–3]. These initiatives include particularly the "footprint family" indicators, defined as a set of consumption-based indicators that measure the environmental burdens imposed by human society on the environment [4]. Among the footprint family indicators, the carbon footprint (CF) has been promoted over the last decade as a new easy-to-understand indicator [5–7]. The goal of reducing CF can serve as a key factor for stimulating innovation and increasing support for sustainable consumption decisions [8]. However, discrepancies between the product and corporate CF methods [9,10] are a serious obstacle to its successful implementation. A single approach to carbon footprinting is required in order to enable comparability and ensure consumer confidence. Nevertheless, the dichotomy between corporate and product CF remains unresolved, as demonstrated by the recent development of two ISO specifications for corporate and product carbon footprinting [11,12].

The corporate CF approach was established under the schemes proposed for inventorying greenhouse gas (GHG) emissions developed according to ISO 14064-1, the GHG Protocol and the Emissions Trading Directive, among the most relevant Refs. [13–15]. Recent advances in the corporate CF approach have led to the ISO/TR 14069, a guide for the application of ISO 14064-1 [11]. The product CF approach was developed under the guidelines for life-cycle assessment (LCA). LCA is a method that explores how the delivery of or demand for a specific product or service sets off processes that may cause environmental impacts (see, for example [16]). LCA seeks to give a complete picture of the environmental burdens caused by a single product through a systematic mapping of operations and associated environmental pressures throughout a product's life cycle [17]. The latest advances in product CF include the consideration of two general approaches for quantifying life-cycle emissions: (1) process-LCA and (2) environmentally extended input–output (EEIO). Process-LCA is the conventional LCA methodology, comprising a bottom-up method to define and describe specific operations under consideration, meaning that the results can potentially be generated at a high level of detail and accuracy (see, for example [18]). On the downside, there is a need to apply cut-off criteria to exclude operations that are not expected to make significant contributions. Some authors have found that process-LCA fails to account for 30% or more of the total CF value [19,20]. EEIO, on the other hand, is a top–down technique in which inventories are quantified using monetary data at a high aggregation level (see, for example [21]). As EEIO requires no cut-offs to be made, it does not pose the same problem with truncation as process-LCA. However, EEIO is not detailed enough to support comprehensive sustainable consumption decisions. A recent advance in the product CF approach is the ISO/TS 14067, containing requirements and guidelines for the quantification and reporting of product CF [11]. This development in corporate and product CF has led to new hybrid methods that exploit the advantages of both approaches. Despite their acknowledged developments [22], hybrid techniques have not yet become standard practice in LCA [19]. A recent review of the wind power sector demonstrates that hybrid LCA studies are still relatively scarce [23].

One of the latest advances in hybrid methods is the compound method based on financial accounts (MC3, from its Spanish acronym "*Método Compuesto de las Cuentas Contables*") [24]. This is an organisation-product-based-life-cycle assessment able to calculate both product CF and corporate CF in an updated and comprehensive assessment [25]. The method is one of the most widely accepted approaches in Spain [26,27]; MC3 is now supported by the Technical Committee of the Carbonfeel Initiative [28] and was approved as a valid approach for assessing corporate CF within the framework of the Spanish Voluntary Reduction Agreement [29]. A large number of pilot experiences have been developed under the MC3 approach. However, few are discussed in detail in the scientific literature, and none are applied to renewable energy production. Wind power is the fastest-growing energy technology of all the renewable sources. Despite the worldwide financial crisis, annual installed wind capacity has grown exponentially from 3760 MW in 2000 to 35,467 MW in 2013, and the world's installed wind capacity reached a total of 318,137 MW at the end of 2013 [30]. In the current world scenario, Brazil is considered to be one of the more promising markets for wind power in the long term [31]. The wind power capacity in this country has grown significantly in recent years. Annual installed wind capacity was 583 MW, 1077 MW and 948 MW in years 2011, 2012 and 2013, respectively. Moreover, this rapid growth is only the start; the 6.7 GW of new power already contracted ensures a potential market investment of around 15 billion US dollars in the coming years. Brazil has managed to attract several wind turbine manufacturers who have set up factories in the country, and 15,000 new jobs were created by the wind industry in 2012 [30,32].

Lenzen and Munksgaard [33] developed one of the first comprehensive reviews to assess the environmental impacts of wind turbines, highlighting the need to reduce uncertainties by using hybrid methods for CF. Kubiszewski et al. [34] further extended this wide-ranging study by reviewing 119 wind turbines from fifty different analyses published between 1977 and 2007. Their findings place wind power in a favourable position compared to fossil fuel, nuclear and solar power generation technologies. Subsequent reviews were conducted under the Intergovernmental Panel on Climate Change (IPCC) with a high level of consensus [35,36]. Finally, Arvesen and Hertwich [23] reviewed 44 selected studies and identified weaknesses and knowledge gaps to be addressed by future research. The results of the analyses of wind power CF reveal significant differences; their spread is due to discrepancies in the energy contents of materials and the methodology and scope of the analysis. Despite these advances there are still areas without environmental assessment. For example, environmental impacts from wastes and land use are not commonly assessed and environmental impacts from the promotion phase or processes related to office activity, access roads and drainage have not previously been assessed.

This work aims to assess MC3 as a tool for CF through its implementation in the comprehensive life-cycle assessment of a Brazilian wind farm. To our knowledge, this paper is the first CF analysis in a wind farm under this novel approach. MC3 was built under the