Carbon Footprint: Concept, Methodology and Calculation

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Abstract Carbon footprint (CF) is nowadays one of the most widely used environmental indicators and calculations of CF have been recently in very high demand. Many approaches, methodologies and tools, from simplified online calculators to other more scientific and complex life-cycle based methods, have been developed and are available for estimations. CF evaluations are, in general, focused on products and organizations, but calculation approach have been developed also for specific themes/sectors, such as for instance cities, individuals, households, farms, etc. This chapter is aimed at giving an updated and comprehensive overview on the concept of CF, and also on methodologies, technical standards, protocols and tools for its calculation. Attention is focused on the two main and usual scopes of CF assessment, i.e. products and organizations, but also on other relevant specific study subjects, also discussing methodological differences and issues.

Keywords Carbon footprint · Methodology · Life cycle assessment · Product environmental footprint · Carbon footprint calculators · Environmental labelling · Greenhouse gas emissions · Global warming

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1 Introduction

It is nowadays recognized that greenhouse gas (GHG) emission represents a global environmental problem [19], and that the nonstop emission of GHG by human activities is responsible for an aggravation of the global warming trend, with consequent negative effects on natural systems and also on the economies [76, 32].

The aim to reduce GHG emissions has gained—and is increasingly gaining—worldwide consensus and the global climate policies and actions (such as, for instance, the Paris Agreement or, at the European level, the recent Green Deal and the other key legislation and policies) confirm the international community effort to deal with global warming in a systemic and trans-sectoral way. The perspective of carbon emission analysis has been gradually turned from the "macro" (global/national scale) to the "micro" level, i.e. to the accounting of GHG emissions related to individual, products or corporate activities, so to understand the problem in depth and to develop specific measures.

In such a context, the concept of Carbon Footprint (CF) has considerably evolved, becoming an important and widely used indicator of GHG emissions that has played—and is still playing—an important role in popularizing the issues of climate change and environmental impact of systems and products along the whole life cycle. Accordingly, the life cycle thinking approach, that allows relationships among industrial issues, sustainability, research and innovation, has become commonly accepted as strategic.

Several approaches, methodologies and tools—from simplified online calculators to other more scientific and complex life-cycle based methods—have been developed and are available for CF estimations, with a main focus on products and organizations, but also considering specific themes/sectors. CF research, therefore, actually covers a wide range of topics, such as countries, cities, organizations, enterprises, families, and individuals, but different methodological issues (e.g. critical issues in defining the CF model) still affect CF calculation. According to this, not surprisingly, the topic "CF calculation methods" is one of the currently popular topics in research [87].

Moreover, in parallel to the CF concept evolution, other footprint concepts have been developed, also as a consequence of "communication issues" related to CF. As a matter of fact, it emerged that to provide a complete information on the environmental performance of a system/product to the general public, not GHG emissions but other environmental impacts are the most significant. Consequently, the need for developing a harmonized environmental footprint methodology that can be unique, representative and that comprise a set of relevant environmental performance indicators has become more and more concrete in recent years.

This chapter is aimed at giving an updated and comprehensive overview on the concept of CF, methodologies, technical standards, protocols and tools for its calculation and also at providing an insight on CF-derived footprints, such as the Product Environmental Footprint proposed by the European Commission.

Section 2 provides general overview on the evolution and the conceptualization of CF, presenting the main differences between its calculation at the organization and product level and also the related reference documents. In Sect. 3 attention is focused on the methodologies developed to calculate CF of products, also presenting an overview of the Product Environmental Footprint methodology proposed by the European Commission. Section 4 discusses the main critical issues in defining the CF model, focusing on key aspect such as the functional unit and the temporal dimension of the assessment, and also on modeling approaches and relevant—and debated—GHG emission sources. Finally, in Sect. 5 an analysis of publicly available CF calculators focused on different themes, also through a review of relevant related literature, is presented, in order to provide an overall insight into the typology of the available tools and the characteristics of the currently used approaches.

2 A General Overview on Carbon Footprint

In the last years, the concept of carbon footprint (CF), has been used widely as an indicator of environmental sustainability. CF refers to the total amount of greenhouse gas (GHG) emissions directly or indirectly produced by an activity or accumulated during a product life cycle and can be used to evaluate the main environmental hotspots and the mitigation or improvement measures [55, 60].

The concept of CF originated as a subset of "ecological footprint", which refers to the amount of productive land and sea area, expressed in hectares, to sustain human population [60, 81]. In this context, CF can be expressed as the land area required to assimilate the CO_2 produced by humanity. However, due to the importance of the global warming problem in the world environmental policy and actions, the use of CF became independent from the ecological footprint [60, 17]. Carbon footprinting has been used in the last years but in a slightly different way, i.e. a life cycle impact category indicator, named global warming potential (GWP) [21]. The present form of CF is thus a hybrid concept, stemming from "ecological footprint" but representing an indicator for GWP [60].

In fact, while an ecological footprint represents a measure of the regenerative capacity of the environment (in terms of a corresponding area of productive land), the present concept of CF stands for a measure of a physical quantity of carbon (or equivalent gases) resulting from defined activities.

On the basis of this concept, CF can be defined as the CO_2 equivalent (CO_2eq) mass based on 100 years GWP [3, 8, 60, 85]. In other words, CF is quantified by indicators such as global GWP, which is the quantity of GHGs contributing to global warming and climate change, with a 100 years time horizon [56]. To obtain CF results expressed in kgCO_2eq, the actual mass of a gas has to be multiplied by its GWP factor, in order to be able to compare the GW effect of different GHGs [12, 22, 56].

CF allows companies to identify the most important GHG sources and to analyse reduction potential, thus increasing productive efficiency at the same time [60, 7, 41]. In this way, environmental improvements and costs reductions can be achieved. Due to the growing market interest for environmentally-friendly products, and the

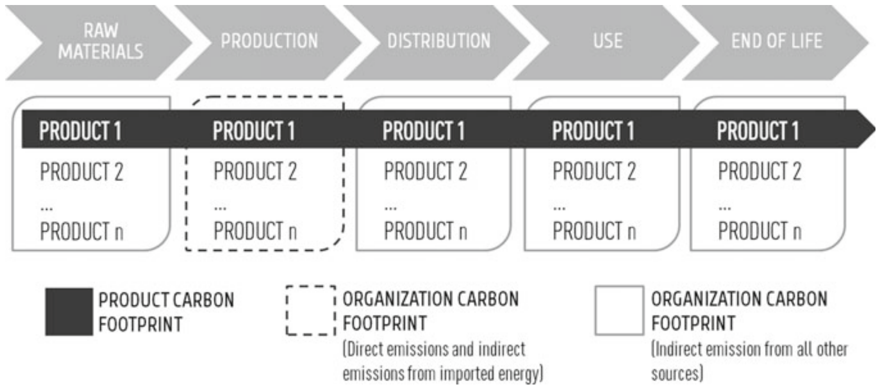

Fig. 1 Organization carbon footprint versus product carbon footprint

need of reporting CF to other business or to respond to consumers needs, different analytical methods for calculating product CF have been developed [56, 60].

The assessment of CF is therefore a strategic tool for companies and, more in detail, it may occur at the organization level (CFO) and also at the product level (CFP). The main difference between CFO and CFP clearly lays in the focus and the boundaries of the study, so that when a CFP is performed only a product is evaluated along its whole life cycle, while when performing a CFO all the products of the company are included in the assessment (Fig. 1). The reference documents for the assessment of CFOs are the GHG Protocol for Organizations [84, 85] and the ISO 14064 [29], that define what an Organization should do to identify, measure and communicate the GHG emissions produced, both directly and indirectly, from all its activities.

The main existing standards and guidelines for the calculation of product CF are, instead, the "GHG Protocol Product Life Cycle Accounting and Reporting Standard", developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), the United Kingdom's Publicly Available Specification (PAS) 2050 and the ISO 14067 [29].

The ISO 14064 explicitly refers to "GHG inventory" as the "list of GHG sources and GHG sinks, and their quantified GHG emissions and GHG removals" – that is to be considered the correspondent of CFO—while the ISO 14067 defines the CFP as the "sum of GHG emissions and GHG removals in a product system, expressed as CO_2equivalents and based on a life cycle assessment using the single impact category of climate change".

For any further information relating to the calculation of the CFO and to the abovementioned reference documents, refer to the Chapter by Scalbi et al. in this book, while an overview of the relevant documents for CFO calculation is given in the following Sect. 3.

All the CF methods and standards can be applied by companies to demonstrate their environmental responsibility, to improve their climate change performance and to differentiate from the competitors. Moreover, they can be used to respond to increasing consumers needs for more environmentally friendly products and for more climate related information along the production chain [20]. CF standards aim also to identify the most relevant life cycle phases, from a GHG emissions point of view, evaluate improvement potentials and increase the production efficiency.

Nevertheless, the solely use of CF as an environmental sustainability indicator, especially for the development of sustainability policies at both company and government level, can be misleading because environmental problems includes not only climate change but also other important issues, eg. eutrophication, toxicity impacts and resource use. Therefore, the use of only CF can lead to problem shifting, when GHG emissions are reduced but other environmental impacts increase. Policy-makers and companies which develop actions and policy on the basis of the results provided by the solely CF might thus ignore other environmental issues in their decisions, which could prevent the society to obtain a more environmentally sustainable and circular society [87].

3 Product Carbon (and Environmental) Footprint

In the previous Sect. 2, the origin and the general concept of CF has been explained. In this Section, instead, an overview of the methodologies developed to calculate CF of products will be given, without focusing on CF of organizations since, as already stated, this topic is treated in Chapter by Scalbi et al. in this book. Also, an overview of the Product Environmental Footprint methodology proposed by the European Commission is presented.

Several different schemes have been developed by national and international standard associations to calculate Carbon Footprint; while the name of the indicator is the same, the methodology can vary depending on the system adopted.

The PAS 20,250 was developed by the UK's Carbon Trust in 2008. The Carbon Trust is a publicly funded company, established by UK government in 2001, which aims to support companies and organisation transition towards a low-carbon economy. In those years, the Carbon Trust started an initiative to develop a robust and consistent standard for the assessment of GHG emissions throughout product life cycle, the Publicly Available Specification (PAS) 2050, in order to respond to market needs for more sustainable products and to inform all the stakeholders about product CF The PAS 2050 was published by the British Standards Institution (BSI) and co-sponsored by the Carbon Trust and the UK Department for Environment and is one of the first examples of the will to adopt the use of a single indicator to compare products for the assessment of the life-cycle GHG emissions of products. The standard has developed a framework to quantify GHG emissions of products life cycle and is based on ISO LCA method, focusing only on climate change impacts. More in detail, PAS 2050 can be applied to several products and it defines requirements for the development and application of "supplementary requirements" for specific product categories. A revised version of the standards was published in

2011, consistent with the GHG Protocol Product Standard about specific issues, such as the sector/product rules, biogenic carbon, recycling, land-use change, delayed emissions. PAS 2050 provides guidelines for the consideration of both common methodological topics (e.g. system boundary definition and allocation) and specific issues (e.g. carbon storage and delayed emissions). Anyway, PAS 2050 does not develop specific product or sector rules, but recommends the development and use of sector specific requirements, called "supplementary requirements" which are documents that provide directions, requirements, and guidelines to develop an equivalent assessment for single groups of products, [11, 23, 47, 56]. In 2011 the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) published the Greenhouse Gas (GHG) Protocol Product Life Cycle Accounting and Reporting Standard for the calculation and reporting of product CF. It is based on ISO 14040 series adopting a life cycle approach, and PAS 2050 (BSI) regarding key topics like the way to deal with biogenic carbon, land-use change and delayed emissions. The standard is addressed to companies and organisations in all economic sectors. This guideline allows companies to quantify six GHGs defined by the Kyoto protocol and provides general guidance and more specific guidelines for the quantification and reporting of product GHG emission inventories, called "product rules". In this way, companies can evaluate the product's GHG inventory and possible emission reductions in a certain time period. The GHG protocol can be used also for product comparison: in this case, additional requirements are provided for a certain product category, developed by a group of stakeholders interested in a specific product category [56]. The aim is to quantify and publicly report an inventory of GHG emissions and removals associated with a specific product also providing many practical examples. Product rules are promoted to allow a comparison between products [11, 23, 47].

In 2013 ISO published the ISO/TS 14067, revised in 2018, this Technical Specification provides requirements and guidelines for the quantification and communication of the CF of products, it is based on other ISO standards like Life Cycle Assessment (ISO 14040 series) and on environmental labels and declarations (ISO 14021, ISO 14024, ISO 14025) adopting also product category rules (PCR) developed in accordance with ISO 14025. ISO/TS 14067 also outlines specific requirements on specific issues relevant for carbon footprints like carbon uptake, land-use change, biogenic carbon emissions and soil carbon change. This Technical Specification aims at a quantification and communication clear and unique avoiding the so-called greenwashing and provides specific requirements for GHG emission removals.

Following this will to simplify the communication of the environmental performances, the environmental product declaration (EPD) system introduced the Climate Declaration. The procedure to obtain a Climate Declaration is the same of an EPD, ISO 14040 and 14044 standards for LCA methodology and ISO 14025 standards for environmental declarations, but the result is focused on greenhouse gas emissions. The strength of this methodology is the presence of product category rules and a well-known and internationally recognized EPD program [11, 23, 47].

In general, all the considered systems want to provide the practitioner with instruments functional to obtain a significative and comparable result. Methodologically the approaches described are all based on the ISO 14040 series, a common problem in the use of results to compare products is that the framework described in the standard leaves the individual practitioner with a wide range of choices that may affect the correctness of the results of the study. As we have seen, one of the solutions adopted to overcome the problem is the implementation of product category rules, with a more general approach, in 2010 the European Commission—Joint Research Centre—Institute for Environment and Sustainability published the International Reference Life Cycle Data System (ILCD) Handbook (Joint Reasearh Centre, 2010). The Handbook wants to provide technical guidance for detailed Life Cycle Assessment (LCA) studies and for all that methodologies based on the ISO 14040 and 14044 standards like Ecolabels or Carbon Footprint. It consists in a series of detailed technical documents, providing guidance for good practice in Life Cycle Assessment in business and government. In particular, the Recommendations for Life Cycle Impact Assessment in the European context handbook (Joint Reasearh Centre, 2010). reviews existing environmental impact assessment models and factors to define levels of maturity and define a set of indicators chosen for their strength and quality. In the guide the Carbon Footprint is indicated as Climate Change and the model suggested for the calculation is the Baseline model of 100 years of the IPCC for its wide consensus for characterization at midpoint level in LCA.

At a European level, the objective is to find a common voluntary methodology that can be representative for the categories of products, different Carbon Footprint systems have been tested and the result was that to provide a complete information for consumers on the environmental performance of some group of products not GHG emissions but other environmental impacts are the most significant. The consequence is the need of developing a harmonized environmental footprint methodology that can be unique, representative and that comprise a set of relevant environmental performance indicators. In the Communication to the European Parliament and the Council, Building the Single Market for Green Products, facilitating better information on the environmental performance of products and organizations, the Commission proposed the Product Environmental Footprint as a common method of measuring environmental performance. PEF requires a full life cycle assessment and define a set of relevant environmental performance indicators.

In 2010 JRC published the Analysis of Existing Environmental Footprint Methodologies for Products and Organizations: Recommendations, Rationale, and Alignment, a systematic comparison of main Footprint methodologies available; starting from that report, Manfredi et al. in 2015 made a review with the aim at spotting the differences between Environmental Footprint methodologies and the PEF, he indicated 10 core criterions: life cycle approach, applicability of results, boundary of the evaluation, multi-criteria evaluation, input data type and quality, solving multifunctionality problems, reporting elements, evaluation of uncertainty and review of the study. Results show differences and common points concerning methodological issues, starting from the more evident like the number of impact categories evaluated, stressing the importance of having a wide range of indicators to better understand the environmental burdens of a product and underling the importance of the Product Environmental Footprint Category Rules (PEFCR) to limit the costs and time necessary to complete the complex assessment required according to the PEF guide. Another important issue identified is the data quality, actually, in the PEF method minimum quality requirements that go beyond the requirement to simply report quality are required considering its use as a decision support especially in a policy context. The result of the review confirms the high consistency of PEF method, concerning the core criterion analyzed, guidelines and directions given, even reducing flexibility minimizing the number of choices and decisions that the user would have to make, allow a high level of reproducibility and comparability between studies [47].

What we are going to do here is to propose our point of view based on our experience and knowledge.

Comparing standardized Carbon Footprint and Product Environmental Footprint, the common points are plentiful, first of all both are based on ISO 14040 series, they consider the wall life cycle of the product. Also, the method to calculate impacts from GHG emissions in all the case is the IPCC.

The first and more important difference between Carbon Footprint and Product Environmental Footprint is the number of impact categories, while the CF is focused on the Climate Change and all the methodology is set to evaluate source and effects of greenhouse gas emissions, the PEF describes the environmental profile of the product using a set of indicators. The main objective to have a single indicator is to simplify the communication to the public, a single number that comprehend a lot of information would have been very useful, the problem is that Carbon Footprint is not always able to be the key indicator in many product categories, this is why PEF has a set of indicators that can be limited in the PEF category rules.

Considering product category rules, they are not mandatory for all the considered l methodologies, like for example in ISO14067, but they are very important to drive the practitioner during the analysis. PEF category rules (PEFCR) go further in this role and suggest also the correct dataset to use when primary data are not available.

A huge work has been made regarding database, the main objective is to furnish users with data with a high level of quality. These because an LCA database can be used in a vast number of evaluations, like in product assessments, development of standards, certification and product labelling, product, process, and system development [57].

In the PEF guide a series of instruction are set to define the dataset quality. It is based on four criteria: Technological representativeness (TeR), Geographical representativeness (GeR), Time representativeness (TiP) and Precision (P). The Data Quality Rating (DQR) result in the average of the categories and is used to identify the corresponding quality level. The overall data quality of the dataset requires the evaluation of each single quality indicator. (PEF Guide revised) The data quality requirements for primary and secondary data are set in PEFCR.

The problem concerning data quality is not new, database contain a vast number of datasets that allow practitioners to model products in software and their quality may vary even in the same database, in PEF method each data used must be evaluated using a data quality matrix while in Carbon Footprint methods, there are not minimum data quality requirements.

The work on data brought to the development of initiative like the Life Cycle Data Network and the European reference Life Cycle Database (ELCD) to make data available to the users. With the Life Cycle Data Network (LCDN), launched on February 2014, different data providers can share their data. This network, with its defined requirements, will ensure data availability and quality and assure interoperability and coherence as well as a convenient basis for comparison of available data [69]. Life cycle inventory datasets from different independently operated LCA databases (nodes) are provided thought an interface where the user can access and find them. Datasets are made available by the Global LCA Data Access (GLAD) network. To participate at GLAD, single nodes have to fulfill a set of requirements like for example a common format and a defined flows nomenclature [57].

The PEF method requires the modelling of product waste by the "Circular Footprint Formula" (CFF), which is a combination of "material + energy + disposal" and includes the production burdens, the burdens and benefits from secondary materials input and output, the energy recovery and disposal. The CF methods do not provide guidance on how to approach multi-functionality at End of Life, with the exception of the PAS 2050 which provide different formulas to be applied in specific contexts and does not consider energy recovery, thus do not account for potential energy credits [47].

PEFCR for a specific product category are developed by Technical Secretariats consisting of technical experts such as companies and industry association (representing over 51% of the total European market for each product category), non-governmental organizations, research centres and universities. The Technical Secretariats are supported by a Steering Committee with representatives from member countries and the European Commission as well as by a Technical Advisory Board for providing technical support to specific methodological issues. On the contrary, Product Rule of GHG protocol and Supplementary Requirements for PAS 2050 are developed similarly to PCR of ISO 14025 standard, i.e. they are based on an open and participatory process developed by companies and organizations in cooperation with other interested parties, institutions involving LCA experts in cooperation with companies or single companies and organizations.

The CF standards allows companies and organizations to obtain an environmental label for the certification of the GHG emissions of their products, but this possibility is currently not available for the PEF, which does not have a real environmental label recognized and certified by a third party.

A further difference is the characterization factors for Global Warming impact category, in particular the global warming potential of fossil methane: according to the PEFCR Guidance, its value is 36,75 CO_2 eq., adjusted from IPCC 2013 using the stochiometric balance. IPCC 2013 uses instead a characterization factor for methane equal to 34 CO_2 eq.

The application of the PEF method can be quite difficult and time-consuming, especially regarding the calculation of data quality requirements and data quality rating and the use of Circular Footprint Formula for the End-of-Life stage. Therefore, the application of this method seems not so quick and straightforward as it was expected to be, if the goal is to involve many companies in Europe, especially SMEs.

The application of CF standards could be more viable for companies, due to the lower specific methodological requirements.

4 The Influence of Methodological Choices on CF Results

Despite CF is a standardized methodology, different methodological choices can lead to a difficult comparison of the results. In this paragraph the main critical issues in defining the CF model are discussed. Harmonization initiatives should be evaluated to enhance the comparability of CF case studies through the use of consistent methodological choices.

4.1 Selection of Functional Unit

Definition of the functional unit is a key aspect in a CF study because it allows to compare the results of different but functionally equivalent systems.

The existing CF methodologies provide similar guidance for the selection of the functional unit, but none of them suggest functional units for specific products. For example, ISO/TS 14067 suggests "Where relevant PCR or CFP-PCR exist, they shall be adopted" and "If CFP-PCR are adopted for the CFP study, the quantification shall be conducted according to the requirements in these CFP-PCR".

The influence of the choice of functional unit on CF results has been highlighted in different sectors, such as food, biorefinery, and building materials.

In the food sector, Notarnicola et al. [55] point out that yield or area are the most used functional units, even if neither takes into account the true function of the products. At this regard, they highlight that more accurate choices could be based on the nutritional or the hedonistic value of the food. Saarinen et al. [71] suggested that, despite the nutrient content of food could reflect food function better, it is not possible to evaluate food CF based on individual nutrients (carbohydrate, protein, vitamins, and minerals) because CF/individual nutrient vary greatly and randomly. Therefore, recently different nutrient density models have been developed and applied to compare CFs of food products [48, 86]. In particular, Sonesson et al. [77] adopted a functional unit which reflected the nutrient content of each food in relation to the nutritional supply of the diet, in order to consider the nutrient quality in a given dietary context.

Another interesting option could be the one suggested by van der Werf and Salou [82] which is based on the economic value of the product,in this way the product quality is considered in the product price. They found that a mass-based functional unit favors systems that focus on quantity rather than quality while an economic-value based functional unit favors systems producing food products of greater quality.

The difficulties in the selection of the appropriate functional unit in the CF studies of biorefineries are due to their multifunctional nature. Ahlgren et al. [1] identified four different categories of functional units: use of feedstock (e.g. 1 ha, 1 ton of biomass), single product (e.g. 1 kg of product, 1 MJ of product), function of single product (e.g. 1 MJ of electricity, 1 person*km), and multifunctional (e.g. 1 biorefinery). They suggested that 1 biorefinery could be the most suitable functional unit for LCA models of biorefineries with multiple functions. Sills et al. [75] analyzed the influence of three different functional units (1 MJ fuel, 1 kg animal feed, and 1 ha of production area) on the LCA results of an algal biorefinery. An area based functional unit was indicated as the best choice, even if it does not significantly influence the CF results.

In the building materials sector, the effect of functional unit on the LCA and CF results was evaluated for the concrete production. In particular, Panesar et al. [61] compared the LCA results obtained using six functional units with different complexity. They concluded that the global warming impact category is largely influenced by the functional unit and it should capture the concrete's functional performance metrics specific to its application.

4.2 Consequential Versus Attributional Approach

LCA and CF studies can be carried out following two different modelling approaches: consequential (CLCA) and attributional (ALCA). ALCA and CLCA approaches are defined in the UNEP/SETAC guidance on LCA (UNEP/SETAC, 2011) as "system modelling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule" and "system modelling approach in which activities in a product system, are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit", respectively. Thus, ALCA allows to calculate the CF of the processes used to produce, use and dispose of a given product while CLCA evaluates indirect effects arising from changes in the level of output of the product, defining a cause-effect relationship between a change in demand and the related changes in supply. However, CF standards, such as ISO 14067, do not define which approach is considered or if it is recommended to include the system-wide change in emissions due to a variation in demand for the product. In literature, several studies were carried out to evaluate how the different modelling approaches affect the GWP of a product.

Kua and Kamath [39] analyzed the GWP impact of replacing concrete with bricks in Singapore. They found that while, using ALCA approach, the GHG emissions increase due to the highly energy intensive process of brick manufacturing, with the CLCA such substitution might result in small reductions in GWP because the domestic changes in demands for concrete and bricks produce a change in the imports of these products.

Also in the building materials sector, Kua and Lu [40] evaluated the impact of the modelling approach on the CF results of replacing tempered glass with polycarbonate at different percentages in the Singapore building industry. This study determined how the changes in the import demand of raw materials for tempered glass and polycarbonate production, due to the increase in the market share of polycarbonate, affect the CF of both materials over long term. The results highlighted that replacing tempered glass with polycarbonate does not produce significant changes in terms of GHG emissions with ALCA approach, while under the long term consequential scenario, when the import of both materials respond consistently to the change in demand in Singapore, the replacement causes a substantial increase in GHG emissions.

In general, the influence of the selected approach on the CF results has been also demonstrated in other research fields, such as biofuels [67], electric versus internal combustion engines [10] and milk production [13], revealing that its choice should be carried out on the basis of the LCA aims and clearly stated.

4.3 Impact of Land Use Change Emissions

In the CF analysis of agricultural and forestry commodities, an important source of GHG emissions is related to the carbon stock changes due to land use change (LUC), that is the conversion of land from one use to another use. In particular, carbon emissions can be released directly (dLUC), accounting the conversion of the original land use, or indirectly (iLUC), when current agricultural or forest production is shifted to other areas which causes dLUC there. Since dLUC occurs within the system boundaries of a given product, it can be included into the ALCA system model while the inclusion of iLUC effects implies the shift towards the CLCA model. All the CF standards, ISO/TS 14067, PAS 2050, and the GHG Protocol, are in agreement that LUC emissions should be accounted for in a product's CF if they are due to a change in land management within a studied product system [51]. On the other hand, none of them provide the accounting of iLUC emissions because of the lack of a consensus methodology.

As regards the dLUC emissions, in the ISO/TS 14067 the calculation is based on the IPCC Guidelines [28] which consider the direct changes in four carbon pools (above ground biomass, below ground biomass, litter and deadwood, and soil carbon stock); however, estimates of the size of these pools and the related changes typically involve substantial uncertainty. Furthermore, another critical key hypothesis is the amortization period used for LUC emissions, that is the period over which the GHG emissions are linearly distributed for accounting [5]. IPCC Guidelines, as well as the European Renewable Energy Directive (RED) [18], recommend to assume a time horizon of 20 years, dividing LUC emissions equally across years. However, this assumption does not reflect the real dynamics because the LUC disturbance generate immediate GHG emissions, when associated to above and below ground biomass, and long term GHG emissions, when associated to the soil [66].

The inclusion of dLUC is essential when the CF analysis concerns food, feed and bioenergy products because it could deeply change final value of GHG emissions [65]. Moreover, this remark is more relevant for developing countries than developed countries due to the significant increase of land intended for agricultural use. Maciel et al. [45] highlighted the importance of dLUC inclusion in the CF analysis of soybean cultivation in Brazil, showing that the GHG emissions increases up to 205% when the contribution of carbon emissions from the transformation of 15.4% of land from grassland to farming is considered. Papong et al. [62] evaluated the GHG emissions of bioethanol production from cassava and molasses in Thailand, excluding or including dLUC effect according to two different scenarios (land transformation from perennial crop to annual crop and from rice field area to annual crop). Results showed that dLUC emissions can increase the CF of bioethanol from 10 to 73% depends on the considered scenario.

The assessment of iLUC emissions is an even more challenging mission due to the influence of the employed model, input data, spatial coverage and scenario assumptions. Among the different approaches, the one elaborated by Schmidt et al. [73] is one of the most interesting which is based on the assumption of perfect elasticity in the markets for products dependent on land use and it avoids the amortization of the GHG emissions by using discounted Global Warming Potentials (GWPs). The iLUC issue is mainly felt in the biofuels sector due to the expansion of energy crops in response to increased biofuel demand. At this regard, the European Commission has included the iLUC emissions in the RED [18], by defining a single factor by type of crop. However, this approach is too simplified as suggested by Garrain et al. [24] who proposed origin-dependent iLUC factors. In particular, they analysed the iLUC impacts caused by an additional demand of biofuel in Spain, showing different values of GHG emissions of biodiesel and bioethanol from iLUC depend on where the biofuel is produced.

4.4 Impact of Temporal Dimension

4.4.1 Time Horizon

It is well-known that the results of a CF study are significantly influenced by the choice of time horizon in the GWP. Typically, in literature the most used time horizon of the GWP is 100-year, maybe because it was the middle value of the three time horizons (20, 100, and 500 years) analyzed in the IPCC First Assessment Report [46]. Time horizon is the time over which the radiative forcing have to be integrated, therefore a 20-year and 500-year time frames are used to evaluate short and long term environmental effects, respectively. However there is no scientific reason to choose 100 year time scale than the other two. Lueddeckens et al. [44] reviewed that the definition of the time horizon is a subjective decision and it depends on the goal and scope of the analysis and the interests of stakeholders of the CF study. De Rosa et al. [70] analyzed the influence of time horizon on the GHG emissions from the production of sawn spruce timber in Sweden, demonstrating that 20-year time frame causes an increase in GHG emissions from 502 kg CO_2e/m^3 of structural spruce timber (100-year time frame) to 3220 kg CO_2e/m^3. For this reason, Ocko et al. [58] encourages to report both time horizons, mostly due to the much higher CO2e emissions of CH4 over 20 than 100 years.

4.4.2 Dynamic Carbon Footprint

The variable time in the CF or LCA analysis plays a fundamental role because it can be considered at different levels, leading to a wrong estimation of the impacts. In particular, two areas can be considered priority: the Life Cycle Inventory (LCI), by clearly assuming the temporal profile of emissions, and the Life Cycle Impact Assessment, by using time-dependent characterization factors for GHG emissions taking into account the exact instant when the emissions occur [9].

In the conventional approach, steady-state (static) conditions are assumed and inventory data are aggregated directly without considering their temporal differences and disregarding their potential variation over time. The limits of this approach are amplified when biogenic carbon and long life cycles are analyzed [35]. Pignè et al. [64] identified two different approaches to include temporal aspects in the LCI. In the first one, the practitioner does not built any dynamic model but defines several scenarios with different LCIs, happening at different times of the life cycle. In this way, each scenario is built when substantial changes occur in the mass and energy flows and it is related to a given time period. This approach allows to take into account changes in foreground processes while it is much more difficult to consider modifications in background processes. The second approach aims to allocate the processes, flows, and LCI of a given system over time, on the basis of the evidence that the linked processes of the life cycle are time-deferred. In particular, Pignè et al. [64] developed a temporal database in order to include full temporalization of background system, highlighting that temporal differentiation of the LCI, and especially of the background processes, can significantly change the overall results.

This issue is particularly significant for the buildings which are characterized by long life cycles (usually 40–70 years) and are characterized by time-dependent parameters [54]. Negishi et al. [53] identified the main time-dependent characteristics of a building system related to the building technology level (performance degradation over time, replacement and use of new technologies, inclusion of biogenic carbon), end-user level (occupancy behaviour), and external system level (energy mix, regulations).

In a fully dynamic CF, it is necessary to consider also dynamic characterization factors of global warming. In a static analysis, a unit emission released today is assumed to have the same impact of a unit emission released decades later. However, the radiative forcing of a unit mass pulse emission differs considerably over time [43]. In the last years, different metrics have been proposed to take into account time effect of GHG emissions which also allow to count CO_2 uptake and biogenic emissions. Kendall [36] proposed a new metric, named Time-Adjusted Warming Potential (TAWP), which considers the difference in global warming effect over a specific time between an emission occurring in the future and an emission released today. Levasseur et al. [43] calculated dynamic characterization factors for 1-year time steps, using radiative forcing as a physical parameter without the definition of any fixed time horizon. Negishi et al. [53] adopted time-dependant climate change metrics, such as instantaneous radiative forcing, cumulative radiative forcing and global mean temperature change, which are based on the IPCC models [27]; in this way, the result of the CF study is not a single indicator, as in the static approach, but different values of indicators as a function of time.

Obviously, it is difficult to compare the CF results obtained with static approach with that calculated with dynamic models, first of all due to the major differences in the nature of the indicators. Negishi et al. [53] tried to compare conventional and dynamic LCA of several building components in terms of GHG emissions, revealing that the difference can be very considerable, especially when the biogenic carbon is included in the LCI.

5 Analysis of Available CF Calculation Tools

Carbon Footprint (CF) has become a mainstream environmental indicator in recent years, due to the growing and pressing issue of climate change, and interest in calculating carbon impacts of different subjects and activities has significantly grown. As a consequence, CF calculators have been developed with several different focuses (such as nations, organizations and individuals), being developed both for public and private use.

Available CF calculators differ from each other by a series of features, that are in general the intended users, the goals they intend to achieve, the reference geographical area, the input data required, the calculation methods, the databases used as data sources and the emission factors. Anyway, even if CF calculators can adopt a variety of outlines and approaches, all of them seek to measure the carbon emissions resulting from a given activity or set of activities [83]. Moreover, since they provide estimates of contributions to climate change, CF calculators can play an important role in educating and motivating lifestyle changes geared toward carbon emissions reduction [4].

The aim of this section is to analyze publicly available CF calculators focused on different themes, also through a review of relevant related literature, so to provide an overall insight into the typology of the available tools and the characteristics of the currently used approaches.

5.1 CFO and CFP Calculation Tools

Concerning CF calculators at the corporate level, attention was focused on freely available online calculators which, being in general simple and easy-to-use, can be beneficial for providing preliminary estimations and having a view on GHG emissions for all kind of enterprise (also for those that do not have adequate financial/human resources for detailed calculations or hiring external experts). A summary description of the identified calculators, together with details on the developer and the links to access them, are given in Table 1

All the reported calculators seem to have the ability to well cover the estimation of Category 1 and Category 2 emissions (according to ISO 14064 classification), even if in some cases they do not allow to separate these emissions in specific subcategories. On the other hand, the estimation of emissions falling in the ISO 14064 3 to 5 categories seem to be a little bit more problematic, since some of the calculators cover them only partly (both in terms of covered categories and emissions typologies) and the calculation approaches are quite different. Moreover, most of the calculators are focused only on the calculation of CO_2 emissions and disregard the ones related to other GHG (Fig. 2). For these reasons, most of these calculators can be considered inadequate for detailed assessments of complex production processes (that include GHG emissions other than CO_2) or companies with extended and diverse supply chains, but rather valid for a first insight in companies CFO and useful for temporal comparisons at the level of one company in order to monitor potential improvement.

Five of the abovementioned CFO calculators were compared by Harangozo and Szigeti [25] using a fictitious enterprise and analyzing three different scenarios in terms of its characteristics (different energy consumption and different suppliers activities) in order to have input data. Their findings in terms of results consistency—i.e. in terms of capability to deliver the same or similar result using the same input data—show a relatively low calculators reliability, with differences mainly related to the calculation approaches (consumption—estimated or calculated based on input data) and to different emission factors (based on differences in the country energy mix and because of methodological differences). Scientific literature also includes studies related to the comparison of CFO calculators focused on a specific industry or sector, such as for instance [78], that selected different farm-level carbon accounting tools and tested them using data from a variety of beef production enterprises, highlighting the differences between estimates produced and exploring the reasons behind them. They also underlined that, even where estimates from different tools appear consistent, the breakdown of an estimate may vary independently of variation in the overall results.

The situation of calculators regarding CFP is quite different. In fact, since the CFP quantifies and communicates the amount of GHG emissions across the whole life cycle of a product, it is closely related to the specific supply chain of the product itself and it is more difficult to set out a calculator generally applicable to different kind/categories of products.

Calculators available online mainly offer the opportunity of evaluating the CF related to different food products (see Table 2 for an indicative summary) and thus to dietary consumers' behaviors. All these calculators appears quite simple to use and allow estimations based on low-level data, such as food category, food commodity and quantity purchased. In a few cases it is possible to take into account the emissions related to the origin of the food product and the mode of transportation, but also in these cases the evaluation is based on simple input data (Fig. 3). Kim and Neff

Table 1 Summary of CFO calculators

Calculator	Calculation Features	Link (accessed on July 08, 2019)
Carbon Footprint Ltd	Category 1, Category 2 and Category 3 emissions with a simplified approach	https://www.carbonfootprint.com/businesscarboncalculator.html
Carbon Footprint Management	Category 1, Category 2 and Category 3 emissions with a simplified approach	https://carbonfootprintmanagement.com/free-co2-carbon-calculator/
Carbon Fund	Category 1, Category 2 and partly Category 3 emissions	https://carbonfund.org/take-action/businesses/business-calculators/
Carbon Neutral	Category 1 and Category 2 emissions, Category 3 and Category 4 emissions with a simplified approach	https://carbonneutral.com.au/carbon-calculator/
Carbon Trust	Category 1 and Category 2 emissions	https://www.carbontrust.com/resources/sme-carbon-footprint-calculator
Clear	Category 1 and Category 2 emissions, Category 3 and Category 4 emissions with a simplified approach	https://clear-offset.com/business-carbon-footprint-2019/
C-Level	Category 1, Category 2 and partially Category 3 emissions	https://www.clevel.co.uk/business-carbon-calculator/
Climate Neutral Group	Category 1 and Category 2 emissions, Category 3 and Category 4 emissions with a simplified approach	https://co2-compensatie.nl/en/
Cool Climate Network	Category 1 and Category 2 emissions, Category 3 and Category 4 emissions with a good detail	https://coolclimate.org/business-calculator
Green Key	Specific tool for hotel or other type of accommodation. Category 1 and Category 2 emissions, Category 3 and Category 4 emissions with a simplified approach	https://www.greenkey.global/online-hcmi
National Energy Foundation	Category 1 and Category 2 emissions	https://www.carbon-calculator.org.uk/
TerraPass	Category 1, Category 2 and partially Category 3 emissions	https://www.terrapass.com/carbon-footprint-calculator
SYKE (Finnish Environment Institute)	Quite detailed calculator (.xls file) for Category 1, Category 2, Category 3 and Category 4 emissions	https://www.syke.fi/en-US/Research__Development/Consumption_and_production/Calculators

(continued)

Table 1 (continued)

Calculator	Calculation Features	Link (accessed on July 08, 2019)
US EPA Center for Corporate Climate Leadership	Quite detailed calculator (.xls file) for Category 1, Category 2 and Category 3 emissions	https://www.epa.gov/climateleadership/center-corporate-climate-leadership-simplified-ghg-emissions-calculator

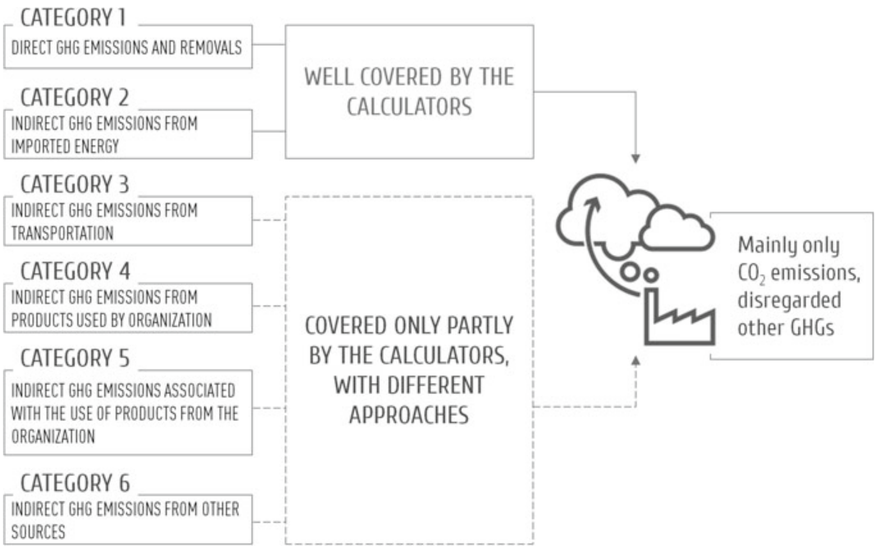

Fig. 2 Brief overview of CFO calculators features

Table 2 Some CF calculators for food products

Calculator	Calculation features	Link (accessed on July 08, 2019)
CelanMetrics	Choice of a food category and a food commodity (evaluated trough a cradle to farm gate approach), transportation by truck and waste production included	https://www.foodemissions.com/Calculator
Eat low carbon	Provision of CO_2 emission for familiar food items, without allowing personalized calculation	https://www.eatlowcarbon.org/
Meals for the Planet	Choice of a food category and a food typlogy	https://meals4planet.org/calculator/
The Vegan Society	Provision of the CF of different menu options, based on the choice of the ingredients and their Countri of origin	https://www.vegansociety.com/take-action/campaigns/plate-planet/carbon-calculator

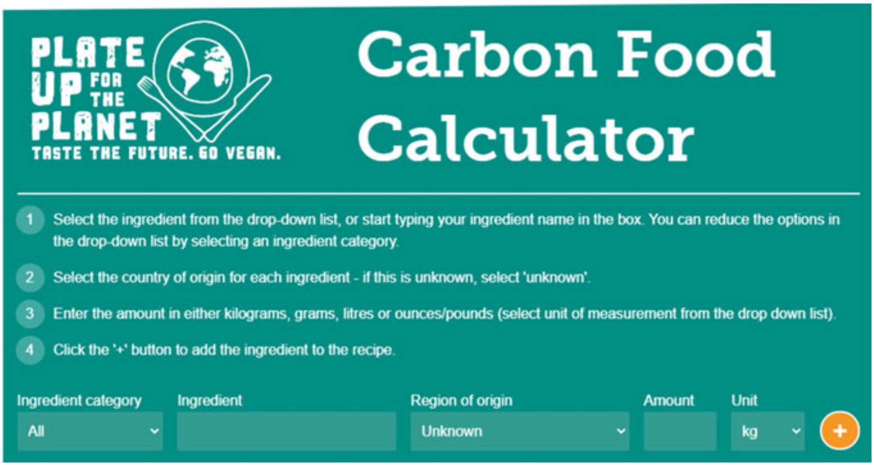

Fig. 3 Example of a CFP calculator data entry interface (https://www.vegansociety.com/take-action/campaigns/plate-planet/carbon-calculator)

[38] reviewed 8 carbon calculators for measuring and communicating indirect GHG emissions from food consumption and included U.S. users among the target audience. Their findings confirm a general lack of consideration of diet-related emissions among CF calculators, under-representing the significance of diet in contributing to indirect GHG emissions, thus highlighting that there is room for improvement and a need for more rigorous methodologies.

Another recent study by in the scientific literature [63], analyzed 18 available calculators (out of 44 environmental assessment calculators identified for agricultural products) conceived for assessing GHG emissions from energy crop cultivation based on CFP approaches. Results of the study show that 9 out of 18 CF calculators were developed for product assessment and that all of them allow an assessment with a "cradle to (farm) gate" approach, while only 8 calculators are able to extend the system boundary to the end of life of the assessed production chain. In conclusion, from the study emerged that calculators address different goals and user groups, with differences in the level of complexity (both in terms of use and data required) and also in the accuracy of results, confirming the abovementioned difficulty to have a calculator generally valid different kind/categories of products.

5.2 Other CF Calculation Tools

Between the available CF calculators regarding study subjects different from organizations and products, the majority is focused on individuals, according to the constantly increasing attention paid to individual behavior as a source of global CO_2 emissions.

These calculators usually divide the individual's profile into common activities and produce estimates on an annual basis through the use of different input data. The simplest calculators allow to obtain a CO_2 emissions value based only on energy-related activities, while more detailed calculators consider lifestyle and/or consumption attitudes (household, food and travel), with also some attempts to provide recommendations on reducing CO_2 emissions.

Scientific literature includes several studies that analyzed and compared individual CF calculators, highlighting the differences between them.

Padgett et al. [59] compared 10 calculators in the United States, founding significant differences in the individual CF estimates despite the use of the same input parameters and thus stressing the need for a higher degree of standardization. Similarly, Kenny and Gray [37] analyzed the inconsistencies and contradictions related to the differences in assumptions, input parameters and methodological aspects (e.g. emission factors used) between individual and household calculators in Ireland, underlining that the available models are able provide estimates rather than accurate measures of CO_2 emissions. Čuček et al. [12] explored different tools for footprints evaluation in their work, identifying CF calculators as the main tools and pointing out that these calculators lack consistency and calculate different results. Birnik [6], reviewing the existing literature, derived a set of 13 normative and evidence-based calculation principles concerning how personal and household carbon footprints have to be calculated, and then evaluated 15 commonly used online CF calculators in order to assess the extent to which they conform to these identified principles.

A summary list of online individual CF calculators, in part also critically examined in a recent study by Mulrow et al. [50], is reported in Table 3.

Analyzing the calculation features of these CF calculators it emerges that the emissions related to home energy and transportation are generally considered (all the calculators collect at least basic information on energy use, and all but one take into account transportation), with a commonly detailing also of air transportation and flight categories. Other emission categories, such as for instance food, water and wastewater are instead less common to the various calculators and, furthermore, additional specific categories (waste and recycling, purchases or consumption activities, etc.) are considered in each one of them. Other common features of the calculators are the advice for lowering emissions and the opportunity to have the breakdown of CO_2 emissions for the different considered categories (Fig. 4).

Salo et al. [72] examined 10 online calculators for non-professional users, focusing the attention on the ones available for Nordic citizens in their own languages and also including two calculators outside these focus regions. They also interviewed 6 calculator hosts to study their expectations and experiences on engaging people to use calculators and to guide consumption. The outcomes of their work show that knowledge intensive calculators are able to reflect lifestyle and activities from an environmental perspective, with tips and pledges are included in calculators to support taking action. However the possibility to engage people in using calculators, especially more than once, is often considered to be a challenge. Salo et al. [72] also point out how calculators' features hold potential for further improvement, as

Table 3 Other CF calculators

Calculator	Calculation features	Link (accessed on July 08, 2019)
Carbon Footprint Ltd	Home energy (by energy sources), transportation (by means of transport, including flights by type) and lifestyle (food, miscellaneous spending and waste)	https://www.carbonfootprint.com/calculator.aspx
Carbon Independent	Home energy (detailed by energy sources), transportation (by means of transport, including flights) and lifestyle (various goods and services based on spending amount)	https://www.carbonindependent.org/
Carbon Offsets to Alleviate Poverty (COTAP)	Home energy use (by US state and energy sources) and transportation (car travel and air travel)	https://cotap.org/carbon-footprint-calculator/
Carbon Solutions Group	Home energy (by US state and energy sources) and transportation (only by car)	https://www.carbonsolutionsgroup.com/carbonfootprintcalc.html
Carbonify	Home energy use (by energy sources), transportation (car, train, air travel) and food consumption	https://www.carbonify.com/carbon-calculator.htm
CarboTax	Home energy use, food, waste, water, transportation, holydays. Based on multiple choice questions	https://www.carbotax.org/
Chuck Wright	Home energy use (by energy sources) and transportation (car, air travel)	https://www.chuck-wright.com/calculators/carbon.html
Cleaner and Greener	Home energy use (electricity, natural gas) by US state	https://www.cleanerandgreener.org/resources/pollutioncalculator.html

(continued)

Table 3 (continued)

Calculator	Calculation features	Link (accessed on July 08, 2019)
Climate Care	Energy (by, energy sources and Country), transportation (car by fuel and flights by type), event (travel and accommodation) and business (energy, travel and freight transportation). Calculation aimed at emissions offseting	https://climatecare.org/calculator/
Conservation Fund	Home energy (by energy sources and Country), transportation (by means of transport, including air travel) and waste	gozero.conservationfund.org/calc/household
Conservation International	Individual and household, events and trips (based on guided choices from pull-down menus)	https://www.conservation.org/carbon-footprint-calculator#/
Empowerment Institute	Home energy use (by energy sources), transportation (car, air travel) and waste	https://www.empowermentinstitute.net/lcd/LCDcalcNet_2012.html
Green Progress	Home energy (by energy sources), transportation (car, air travel) and lifestyle (eating habits and waste)	https://www.greenprogress.com/carbon_footprint_calculator.php
Henkel	Housing (energy by sources and water consumption), nutrition (diet habits and eating out), mobility (by means of transport) and holiday and leisure (travel, accommodation and sports)	https://footprintcalculator.henkel.com/en
Lehigh University	Home energy (by type of home), transportation (by means of transport) and food (eating habits). Tool tailored for students	https://ei.lehigh.edu/learners/cc/carboncalc.html
Michael Bluejay	Home energy (by energy sources), transportation (car, air travel) and food	https://michaelbluejay.com/electricity/carboncalculator.html

(continued)

Table 3 (continued)

Calculator	Calculation features	Link (accessed on July 08, 2019)
My Climate	Home energy (by energy sources), transportation (by means of transport) and lifestyle (eating and shopping habits). Based on multiple choice questions, more detailed calculation provided for household, company, events, flight, car and cruise	https://www.myclimate.org/carbon-offset
Native Energy	Household (by energy sources and US subregions), travel (by means of transport) and events (based on US state, number of attendees and days)	https://native.eco/for-individuals/calculators/
Resurgence	Home energy (by energy sources), transportation (by means of transport, including private flights by type) and lifestyle (dietary choices and food sourcing, leisure activities)	https://www.resurgence.org/resources/carbon-calculator.html
Shrink Your Foot	Home energy (electricity and fuel use) and transportation (car and air travel)	https://store.shrinkyourfoot.org/carbon-footprint-calculator
TerraPass	Home energy (by energy sources) and transportation (car and air travel)	https://www.terrapass.com/carbon-footprint-calculator
The Nature Conservancy	Home energy (by energy sources and US state) and water usage, travel (by fuel typology, including air travel) and lifestyle (eating and shopping habits)	https://www.nature.org/en-us/get-involved/how-to-help/carbon-footprint-calculator/
UN CF calculator	Home energy (by type of housing, energy sources and Country), transportation (by means of transport, including private flights by type) and lifestyle (dietary choices and waste recycling)	https://offset.climateneutralnow.org/footprintcalc
US EPA CF calculator	Home energy (detailed by energy sources and Country), transportation and waste recycling	https://www3.epa.gov/carbon-footprint-calculator/

(continued)

Table 3 (continued)

Calculator	Calculation features	Link (accessed on July 08, 2019)
World Wide Fund for Nature (WWF)	Food (eating habits), travel (by means of transport, including flights), home (by type of housing and living habits) and stuff (home items, shopping habits and waste recycling). Based on multiple choice questions	https://footprint.wwf.org.uk/#/

well as have limitations, which should be taken seriously in considering the role of calculators in policy-mixes to steer household consumption.

Specific calculation methodologies/case studies were also investigated in the available scientific literature. For instance, Shirley et al. [74], presented a top-down accounting model for typical households within the US Virgin Islands, using an Economic Input Output calculation methodology based on spending and consumption patterns. The model allows to estimate GHG emissions during the different life cycle phases (extraction, processing, transport, use and disposal) of various commodities and map this to their respective consumption by households, showing electricity use and private road transportation to be major contributors to spending and energy use. Similarly, Isaksen and Narbel [32] calculated CF of Norwegian households, combining a consumer expenditure survey with emission coefficients from an environmental input–output model, that take into account embodied emissions in goods and services, also comparing direct and indirect emissions from consumption activities to the expenditure level of different households.

Regarding individual CF calculators, recent literature also focused on novel calculation approaches, following the idea that real-time evaluations through continuously updated data can be useful to see the effects of lifestyle changes, thus supporting individual action and choices oriented to counteract climate change. Results of previous studies (e.g. [7, 15, 21, 26, 49, 52, 14], in fact, allow to state that general information is ineffective to encourage pro-environmental lifestyles, while personalized information (i.e. information tailored to the receiver's situation, as for instance feedback on the personal energy use/carbon footprints, or specific energy saving tips) allows to obtain better results in encouraging behavioral change.

According to these evidences and ideas, Rahman et al. [68] developed a CF calculator application (named "Ubiquitous Carbon Footprint Calculator") based on an a specific platform (named "Open Carbon Footprint Framework"), that allows users to be aware of their personal CF on the base of their ubiquitous activity and act accordingly. More recently, Andersson [2] presented a mobile application, available for use in Sweden, that estimates users' GHG emissions by means of a hybrid approach based on pairing financial transaction data from the users' bank with environmentally extended input output analysis, claiming it as a new and interesting approach that merits further consideration.

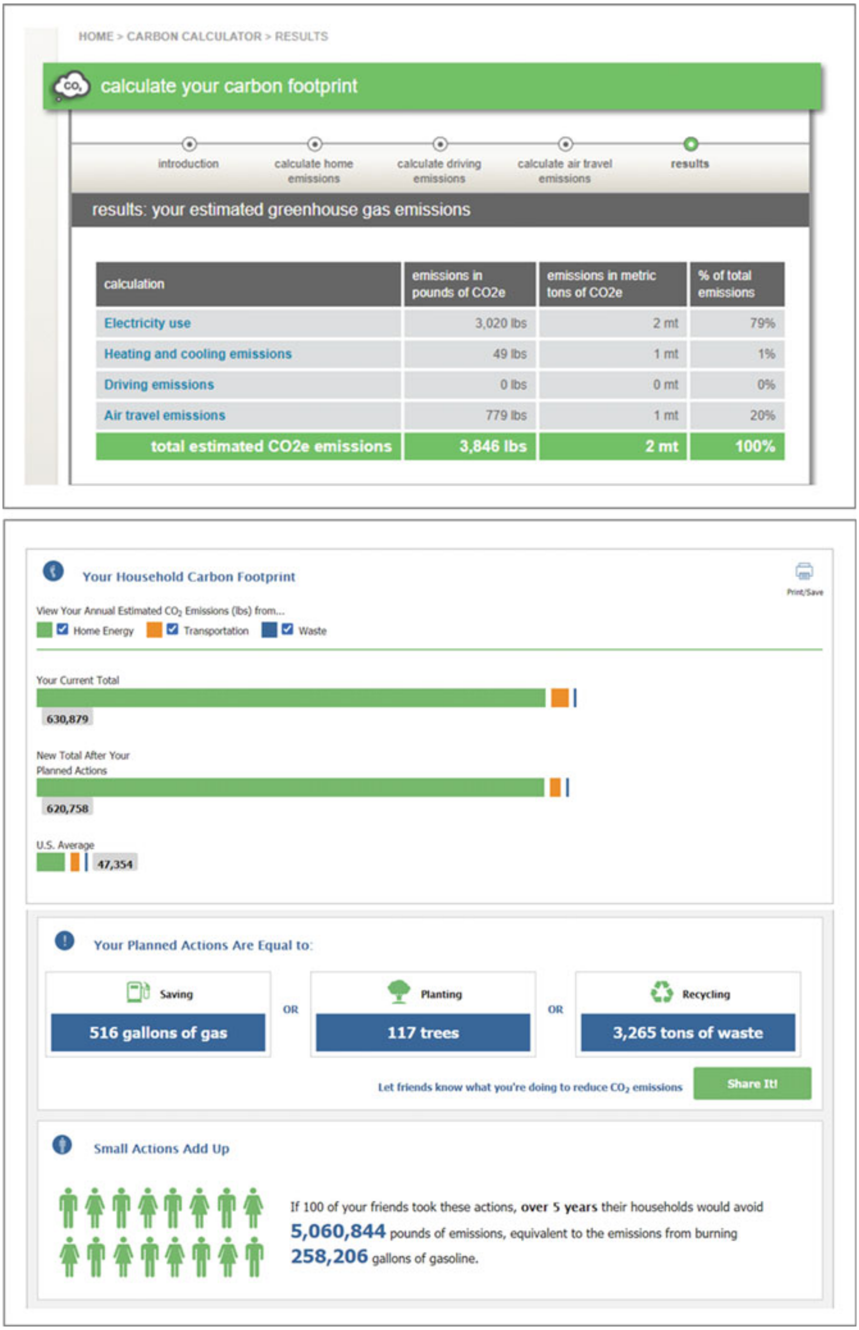

Fig. 4 Examples of CF calculators results presentation (https://store.shrinkyourfoot.org/carbon-footprint-calculator; https://www3.epa.gov/carbon-footprint-calculator)

6 Conclusion

One of the main global environmental problems is represented by GHG emission by human activities, that constitutes a significant contributor to the global warming issue and the related worldwide negative effects. Consequently, the reduction of GHG emissions has become in recent years one of the main efforts of the international community to cope with global warming thorough strategies towards a climate-neutral world based on initiatives of decarbonisations and resource efficiency policies.

The estimation of the GHG emissions has initially focused on the global and national scales, but it has been gradually turned from this levels to more detailed ones, such as cities, sectors, organizations, products and individuals. As a consequence, a lot of approaches, methodologies and tools, characterized by different levels of feature and complexity, have been developed for CF estimations.

Starting from a general overview on the concept of CF and the main differences between its calculation at the organization and product level, this Chapter focused its attention on the methodologies developed to calculate CF of products, also presenting an overview of other CF-derived footprints and, in particular, of the Product Environmental Footprint methodology proposed by the European Commission. Then, a discussion centered on key aspects such as functional unit, temporal dimension of CF assessment, modeling approaches and specific relevant GHG emission sources, highlighted that the LCA approach is the main used for CF estimation and that there are some critical issues that affect the CF calculation model. The subsequent analysis of publicly available CF calculators supported by a review of relevant related literature, provided an overall insight into the different typologies of tools and the characteristics of the currently used approaches, confirming the already cited change of focus of CF (calculators tailored for individuals activities and lifestyle resulted the most widespread).

Given the above, the following considerations can be made as a conclusion of this Chapter.

- LCA-based estimation represent the most used approach to calculate CF. However, some critical issues are intrinsic in the definition of CF calculation model and, despite CF well standardized as a methodology, different methodological choices can lead to a difficult comparison of the results. Therefore, critical issues have to be faced and harmonization initiatives should be evaluated to enhance the comparability of CF case studies through the use of consistent methodological choices.
- LCA-based estimation, as indicated by various research results (see Udara Willhelm [80]), neglect several uncertainties and this may result in a relevant variation of actual emissions and predicted emissions. Therefore, it is desirable that new calculation approaches aimed at facing this issue will be explored. In this regard, Udara Willhelm Abeydeera et al. [80] propose discrete event simulation and system dynamics as newer approaches and also suggest the integration of information technology related tools (such as Building Information Modelling

and machine learning) as a possible way to support global researchers in a more effectively estimation of emissions.

- There is a lack in the practical utilization of research outcomes on CF as a basis to understand the current situation of GHG emissions and consequently implement effective action plans. Thus, it is crucial to fill this gap between the research and practices, employing research to estimate CF, but also to identify and implement reduction/mitigation strategies.
- As observed, the perspective of CF analysis has been gradually turned from the "macro" to the "micro" level and, in this context, it is acknowledged the significant role that individuals are playing and will play. Moreover, citizen engagement in science and policy-making is becoming more and more central in policies and strategies. At the EU level, in particular, the importance of more citizen engagement has been recognized and strengthened in the Lisbon Treaty with the European citizens' initiative and in a number of documents and political declarations, such as the Commission contribution to the Sibiu Declaration for a "new strategic agenda for the EU 2019–2024". In such a context, therefore, the promotion of research regarding individuals CF represents a key aspect to provide a scientific basis for developing a low-carbon economy.
- Today's efforts to combat climate change have focused mainly on specific sectors/actions, such as for instance transportation or energy production and consumption (with the significant role of renewable energy and energy-efficiency measures). However, in order to meet emission reduction targets it is also necessary to tackle other emissions and, as already well stressed, products have consequently become one of the main focus of CF calculation. In this regard the Circular Economy represent a unique opportunity to help tackle the climate crisis by reducing GHG emissions along supply chains, preserving the embodied energy of products and materials and increasing carbon sequestration through the regeneration of natural systems [17]. It is therefore crucial to strengthen research on the nexus between CF and Circular Economy actions, also integrating CF with other tailored indicators in a specific circularity measurement scheme.

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