Preliminary Life Cycle Assessment of an innovative wave energy converter

Andrea Guercio
Department of Engineering
University of Palermo
Viale delle Scienze, Blg 9
Palermo, Italy
andrea.guercio@unipa.it

Domenico Cuto
Department of Engineering
University of Palermo
Viale delle Scienze, Blg 9
Palermo, Italy

Maria Anna Cusenza
Department of Engineering
University of Palermo
Viale delle Scienze, Blg 9
Palermo, Italy

Maurizio Cirrincione
School of Engineering & Physics
University of the South Pacific
Laucala Campus Suva, Fiji

Dhirendran Munith Kumar
Department of Engineering
University of Palermo
Viale delle Scienze, Blg 9
Palermo, Italy

Andrea Montalbano
Department of Engineering
University of Palermo
Viale delle Scienze, Blg 9
Palermo, Italy

***Abstract*—The University of Palermo is currently investigating the possibility of sea wave energy harvesting in the Mediterranean Sea, since this energy sources could have important applications, especially in small islands. With this purpose, the paper propones an innovative technology for the sea wave exploitation in onshore areas. A prototypical device is firstly described. Some improvements are introduced in comparison with a previous version of the device. In this manuscript the Life Cycle Assessment is performed to evaluate the environmental impacts of this technology.**

Keywords—Wave Energy Converter, Life Cycle Assessment, Power Take-Off, Sea Waves

I. Introduction

The achievement of the sustainable development goals 7 “Ensure affordable and clean energy” and 13 “Take urgent action to combat climate change”, set within the Agenda 2030 for sustainable development [1], requires the transition towards a worldwide energy sector where energy supply would largely be generated from renewable energy sources [2], [3].

Ocean energy is internationally recognised as one of the critical sources of green energy [4], [5]. In this context, great interest is concentrated on sea wave [6], [7]. It is believed that in near future sea wave might have a key role for the electrical energy production, thanks to its huge energy potential [8], [9].

Wave energy is a more concentrated and predictable than other aleatory renewable energy sources. It is estimated a total energy potential up to 80,000 TWh per year [10], [11], the same order of the worldwide electricity production 21653 TWh in the last year [12]. Thus, the sea wave harvesting may play a relevant role to the green target of sustainable development around the world [13], [14].

It is also evident how this source will be able to exploit areas which are not used nowadays, at the same time creating important supply chain and local job opportunities [15], [16].

However, although these technologies can be considered environmentally friendly during the operational phase (electricity generation) several environmental impacts can be generated during manufacturing, installation, maintenance, and disposal stages due to the consumption of materials and energy. Currently, most of the available ocean energy technologies are at the research and development stage [17].

The estimation of the potential life cycle environmental impacts of these emerging technologies is paramount to support the technology developers from the early design stage towards an environmentally sustainable scaling up at the industrial scale. Life cycle assessment (LCA) is an internationally standardized and scientific-based methodology for assessing potential environmental impacts associated to a product, a process or a system, along its life cycle [18]. It allows to identify hotspots of impacts and to compare several options. Currently few LCAs have been focused on wave energy converter [18]–[21].

In this framework, the authors apply the LCA methodology to assess the energy and environmental impacts associated to an innovative prototypical wave energy converter realized in the Department of Engineering of the University of Palermo [22], [23]. The device is based on a mechanical motion converter able to transform an oscillating rotation into a unidirectional rotary motion and run commercial generators [24]. In this study, the perspective is expanded in order to integrate the environmental protection criteria into design and innovation of the energy system examined following a life cycle approach. Then this research can provide an important contribution to technology developers looking to improve the environmental sustainability of ocean energy technologies.

II. Sea Wave Energy Harvesting

Around the world, there are many regions, called “hot spots”, where the sea wave energy potential achieves the highest values. As example, the Southern part of Australia, Africa and America are exposed to the highest values of wave energy

978-0-692-93559-0 ©2021 MTS

potential. Other more moderate areas can be found in the regions between USA, Canada and Japan in the Pacific Ocean and between European Union, Greenland, USA and Canada in the Atlantic Ocean. Unfortunately, all these areas are affected by extreme bad weather conditions, due to the high level of energy potential, complicating the utilization of this renewable energy source [8], [25], [26].

In this context, the device able to extract energy from sea wave and produce electrical energy or other useful energy output is commonly defined as Wave Energy Converters (WEC) [27], [28].

Historically, the first patent was registered in France in 1799 by Monsieur Girard and his son [27]. After that, many types of WEC have been proposed over time.

These systems can be classified using different criteria like the position with respect to the coastline, the typical size, the orientation with respect to the direction of wave propagation or the working principle.

Considering the orientation of the device in comparison with wave propagation, the following terms are used:

- **Attenuators**, that are parallelly oriented to the wave direction. Since the device has a length of the same order of the wavelength, it adapts its shape to the wave profile, extracting energy from sea wave.
- **Point absorbers**, these systems work independently of wave direction due to their small sizes in comparison with the wavelength.
- **Terminators**, that are perpendicularly oriented to the wave direction. Sea wave ends on the device, transferring its energy.

About the working principle, the following groups are introduced:

- **Oscillating water column**, in this system sea wave enters inside a chamber open to the atmosphere. Inside the chamber, sea wave produces a vertical water oscillation. The air inside the chamber is pressurized and depressurized by the water oscillation, producing a bidirectional air flow usable to run special wind turbines. The system can be installed on the coastline or integrated in a floating device.
- **Wave-activated bodies**, in this case sea wave produces relative motions on the systems, running the energy converters. This kind of system can be assembled in several configurations in order to produce a rotation or a translation. About the installation, there are floating systems and submerged ones.
- **Overtopping devices**, in this case, sea water is conveyed in a reservoir, using a ramp to convert the kinetic energy of sea wave into potential energy. The water is consequently spilled from the reservoir and used to produce electricity, by using a low head hydro turbine.

III. CASE STUDY: THE MECHANICAL MOTION CONVERTER

As introduced above, the Engineering Department of Palermo University is currently designing an innovative device for the sea wave energy harvesting [24], [29].

The machine here reported is designed for the exploitation of sea wave close to the coastline. Indeed, a potential installation could be on the breakwaters of harbours [24]. Preliminary simulations were carried out at laboratory scale to evaluate the energy performance of the device [24].

The first prototype is shown in Figure 1. This is essentially a demonstrator of the working principle. In fact, the machine collects the alternating input motion applied to the bar, and produce a unidirectional rotary motion, that can be used to run a commercial alternator.

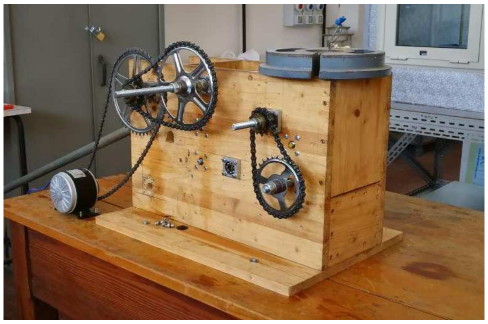

Fig. 1. Prototypical wave energy converter

The working principle is better explained by Figure 2. Assuming that the WEC is installed on the breakwaters, the motion of sea wave is used by a floater to produce an alternative rotation on the input bar.

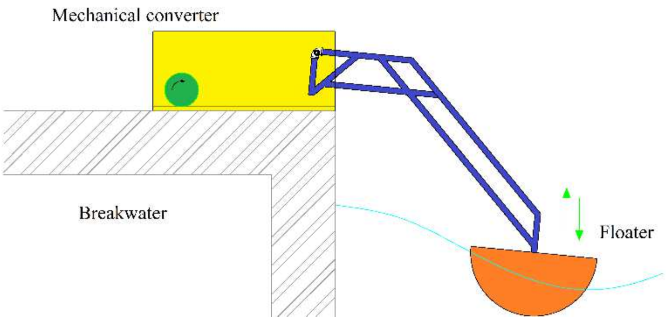

Fig. 2. Prototypical wave energy converter examined and working principle

The version depicted in Figure 1 has been recently upgraded by the replacement of the slider used to connect the input bar with two chains and consequently to flywheels.

This important upgrade is introduced in order to strengthen the machine and allow the production of an electrical power output up to 1 kW. Figure 3 shows the main changes: the old structure (a) was made of wood, while the new one is made of iron (b), as well as the new railways.

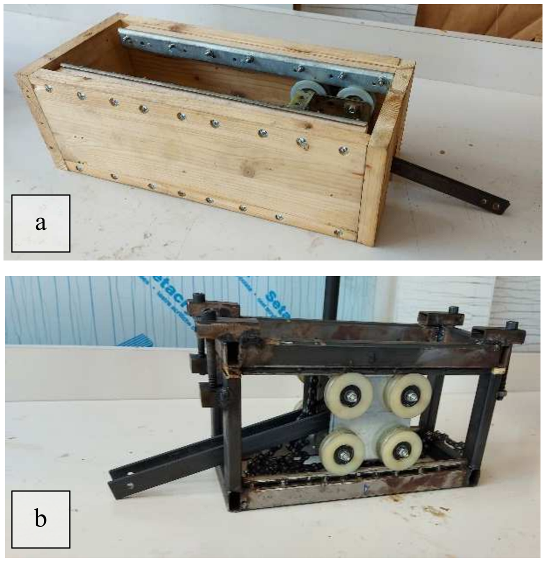

Fig. 3. Replacement of the slider: (A) old configuration, (B) new version

Another change is the position where the slider is installed. In the previous version, the slider was installed in the lower part of the machine, forcing the motion of chains as shown in Figure 4 (a), while the new configuration proposes the installation of the slider in a central position.

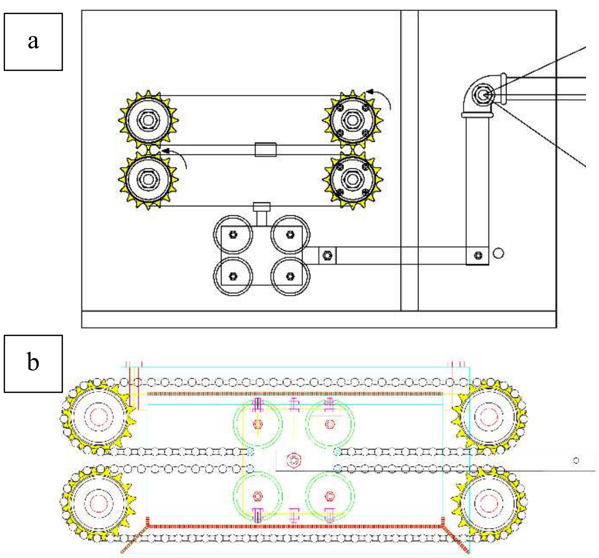

Fig. 4. Position of the slider: (A) old configuration, (B) new version

The study provides a wide set of life cycle energy and environmental indicators and identifies the "hot spots" of the examined energy system.

IV. Life Cycle assessment

The LCA is carried out in compliance with the international standards of series ISO 14040 and ISO 14044 [30], [31].

A. Goal and scope definition

The main goals of the LCA study are:

- to estimate the potential environmental impacts related to the production process of the examined energy system.
- to identify the hotspots of the production process examined.

The functional unit selected as the reference for the LCA is the prototypical wave energy converter described in Paragraph III. The system boundaries are defined according to a "from cradle to gate" approach and include the raw material supply, materials and components production and device assembly.

The impact assessment is based on the Environmental Footprint 3.0 method [32] developed in the framework of the European Union Recommendation on the Environmental Footprint methodology (2013/179/EU) [33]. In detail, the following environmental impact categories are considered:

- **Climate Change** (CC) indicating the potential global warming due to the emission of greenhouse gases. This is expressed as kg CO_{2eq}.
- **Ozone Depletion** (ODP) is used to evaluate the potential damaging of the stratospheric ozone layer. It is expressed in terms of kg $CFC11_{eq}$ (Trichlorofluoromethane).
- **Ionising Radiation** (IR) represents the potential damage to human health and ecosystems due to the emissions of radionuclides. It is measured in kBq $U^{235}{}_{eq}$.
- **Photochemical ozone formation** (POF) indicates the emissions of gases promoting the creation of photochemical ozone in lower atmosphere. It is indicated in terms of kg $NMVOC_{eq}$.
- **Particulate matter** (PM) measures the potential incidence of disease due to particulate matter emissions.
- **Human toxicity, non-cancer** (HT-nce) and **Human toxicity, cancer** (HT-ce) are used to indicate the impact on humans due to toxic substances emitted into the environment and producing an increase in non-cancer morbidity and cancer morbidity, respectively. The measuring unit is CTUh in both cases.
- **Acidification** (AP) expresses the potential acidification of soils and water due to the release of gases like nitrogen oxides and sulphur oxides. It is expressed in terms of mol $H^{+}{}_{eq}$.
- **Eutrophication, freshwater** (EP_{FW}) is used to indicate the potential enrichment of freshwater ecosystem due to the emission of nitrogen or phosphorous compounds. It is expressed as kg PO_{4eq}.
- **Eutrophication, marine** (EP_M) indicates the potential enrichment of marine ecosystem due to the emission of nitrogen compounds. It is measured in terms of kg N eq.
- **Eutrophication, terrestrial** (EP_T) indicates the potential enrichment of marine ecosystem due to the emission of nitrogen compounds. It is expressed by mol N_{eq}

- **Ecotoxicity, freshwater** (E_{FW}) is used to evaluate the impact on freshwater organisms of toxic substances emitted to the environment. The unit is CTUe.
- **Land Use** (LU) measures the changes in soils quality. This parameter is dimensionless.
- **Water Use** (WU) measures the water consumption, and it is expressed in terms of m^3_{depriv}.
- **Depletion of abiotic resources – fossil fuels** (R_f) indicates the consumption of natural fossil fuels. It is expressed in MJ.
- **Depletion of abiotic resources – minerals and metals** ($R_{m\&m}$) indicates the consumption of mineral and metals resources. It is expressed in term of Sb_{eq} (Sb: Antimony).

B. *Life cycle inventory (LCI)*

Primary data, collected at the laboratory, are used for modelling the foreground processes, while secondary data inferred from the Ecoinvent 3.6 Database [34] are used for modelling the life cycle inventory of materials and energy sources used to produce the energy system examined.

The prototypical converter production process includes the utilization of semi-finished materials, like bars, panels, and pipes. The main materials are steel, aluminium and wood. There are also commercial components, like screws, threated bars, bolts, bearings.

To assemble the device, some parts are produced in laboratory, by using circular saws for metal and wood, drill, lathe, arc welding. For each activity, the amount of required materials and energy were measured.

V. RESULTS: LIFE CYCLE IMPACT ASSESSMENT AND INTERPRETATION

The results of the LCA are reported in Table 1, while the contribution of each material and the energy used for components preparation and device assembly to the total impacts is detailed in Figure 5. The process contribution analysis shows that steel components contribute to the overall impacts with percentages ranging from a minimum value of about 1% for ODP to a maximum value of 85.7% for HT-ce. The contribution of the aluminium components is between 1% (for $R_{m\&m}$) and 21% (for WU). The impact of the brass component is significant on $R_{m\&m}$ (about 91%), E_{FW} (about 63%), HT-nce and AP (about 47%). The wood components cause 74% of the impact on LU due to the land occupation and transformation for tree growth. Finally, the impacts associated to energy uses are negligible (lower than 2%) in all the impact categories investigated.

TABLE I. LIFE CYCLE IMPACT ASSESSMENT RESULTS FOR THE REALIZATION OF THE PROTOTYPE

Impact category	***Units***	***Value***
CC	kg CO_{2eq}	8.08E+01
ODP	kg CFC-11_{eq}	6.23E-04
IR	kBq U^{235}_{eq}	7.48E+00
POF	kg $NMVOC_{eq}$	3.08E-01
PM	Disease incidence	5.56E-06
HT-nce	CTU_h	8.85E-06
HT-ce	CTU_h	3.86E-07
AP	mol H^+_{eq}	7.44E-01
EP_{FW}	kg PO_{4eq}	8.41E-02
EP_M	kg N_{eq}	8.12E-02
EP_T	mol N_{eq}	8.98E-01
E_{FW}	CTUe	6.16E+03
LU	Pt	1.63E+03
WU	$m^3_{deprived}$	1.77E+01
R_f	MJ	7.30E+02
$R_{m\&m}$	kg Sb_{eq}	2.87E-02

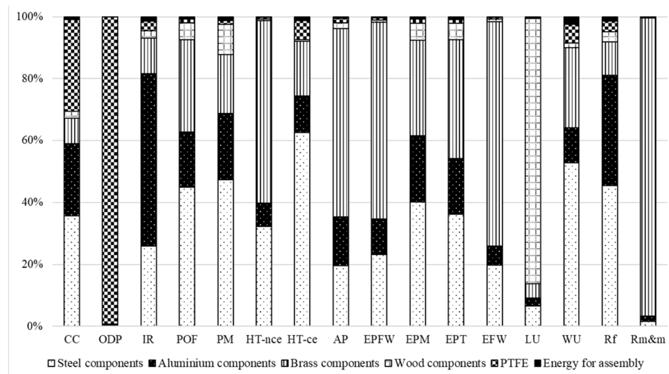

Fig. 5. Life cycle impact assessment results – contribution analysis

VI. CONCLUSION

The sea wave energy harvesting is currently receiving a considerable attention for the relevant implications, especially in small islands. Many technologies are under development, but a real application of them requires firstly a careful evaluation of the environmental impacts.

With the simplified LCA it could be shown, how significant the choice of materials alone can affect the environmental performance of a product. A detailed LCA study may even become an efficient tool to design an eco-friendly wave energy device.

The case study here reported was limited to the device, currently at a prototypical step. It should be reminded that a future industrialization could significantly reduce some impacts, mainly the ones related to raw materials and energy consumptions.

Future works will consider LCA applied to the kWh of electrical energy, in order to make sea wave energy harvesting comparable with other energy sources.

ACKNOWLEDGMENT

This work is realized thanks to the support of Engosys Enterprise, by using informatic tools for the simulations.

The research on sea wave harvesting is promoted by the Italian project "Ondaflex" (PO FESR Sicilia 2014/2020), financed by Sicilian Region.

References

[1] United Nations, "Resolution adopted by the General Assembly on 25 September 2015. Transforming our world: the 2030 Agenda for Sustainable Development," vol. 16301, no. October, pp. 1–35, 2015.

[2] M. A. Cusenza, F. Guarino, S. Longo, M. Mistretta, and M. Cellura, "Environmental assessment of 2030 electricity generation scenarios in Sicily : An integrated approach," *Renew. Energy*, vol. 160, no. September 2015, pp. 1148–1159, 2020.

[3] D. Curto, V. Franzitta, A. Viola, M. Cirrincione, A. Mohammadi, and A. Kumar, "A renewable energy mix to supply small islands. A comparative study applied to Balearic Islands and Fiji," *J. Clean. Prod.*, p. 118356, Sep. 2019.

[4] J. Hodges *et al.*, "An International Evaluation and guidance framework for ocean energy Technology. IEA-OES.," 2021.

[5] European Union, "Transforming the European Energy System through Innovation. Integrated SET Plan Progress in 2016. Luxembourg: Publications Office of the European Union, 2016," 2016.

[6] D. Vicinanza, P. Contestabile, and V. Ferrante, "Wave energy potential in the north-west of Sardinia (Italy)," *Renew. Energy*, vol. 50, pp. 506–521, Feb. 2013.

[7] D. Curto, V. Franzitta, M. Trapanese, and M. Cirrincione, "A Preliminary Energy Assessment to Improve the Energy Sustainability in the Small Islands of the Mediterranean Sea," *J. Sustain. Dev. Energy, Water Environ. Syst.*, pp. 1–19, 2020.

[8] L. Liberti, A. Carillo, and G. Sannino, "Wave energy resource assessment in the Mediterranean, the Italian perspective," *Renew. Energy*, vol. 50, pp. 938–949, Feb. 2013.

[9] V. Boscaino *et al.*, "Experimental validation of a distribution theory based analysis of the effect of manufacturing tolerances on permanent magnet synchronous machines," *AIP Adv.*, vol. 7, no. 5, p. 056650, May 2017.

[10] World Energy Council, "World Energy Resources: Marine Energy 2016," p. 79, 2016.

[11] T. Aderinto and H. Li, "Ocean Wave energy converters: Status and challenges," *Energies*, vol. 11, no. 5, pp. 1–26, 2018.

[12] Enerdata, "EnerOutlook 2050," 2021.

[13] D. Curto, A. Viola, V. Franzitta, M. Trapanese, and F. Cardona, "A New Solution for Sea Wave Energy Harvesting, the Proposal of an Ironless Linear Generator," *J. Mar. Sci. Eng.*, vol. 8, no. 2, p. 93, Feb. 2020.

[14] D. Curto, S. Favuzza, V. Franzitta, R. Musca, M. A. Navarro Navia, and G. Zizzo, "Evaluation of the optimal renewable electricity mix for Lampedusa island: The adoption of a technical and economical methodology," *J. Clean. Prod.*, vol. 263, p. 121404, Aug. 2020.

[15] K. Gunn and C. Stock-Williams, "Quantifying the global wave power resource," *Renew. Energy*, vol. 44, pp. 296–304, 2012.

[16] V. Franzitta and G. Rizzo, "Renewable energy sources: A Mediterranean perspective," in *2010 2nd International Conference on Chemical, Biological and Environmental Engineering*, 2010, no. Icbee, pp. 48–51.

[17] A. Uihlein and D. Magagna, "Wave and tidal current energy - A review of the current state of research beyond technology," *Renew. Sustain. Energy Rev.*, vol. 58, pp. 1070–1081, 2016.

[18] M. G. Paredes, A. Padilla-Rivera, and L. P. Güereca, "Life cycle assessment of ocean energy technologies: A systematic review," *J. Mar. Sci. Eng.*, vol. 7, no. 9, 2019.

[19] Q. Zhai, L. Zhu, and S. Lu, "Life cycle assessment of a buoy-rope-drum wave energy converter," *Energies*, vol. 11, no. 9, 2018.

[20] N. Patrizi *et al.*, "Lifecycle environmental impact assessment of an overtopping wave energy converter embedded in breakwater systems," *Front. Energy Res.*, vol. 7, no. APR, pp. 1–10, 2019.

[21] X. Zhang, L. Zhang, Y. Yuan, and Q. Zhai, "Life cycle assessment on wave and tidal energy systems: A review of current methodological practice," *Int. J. Environ. Res. Public Health*, vol. 17, no. 5, 2020.

[22] D. Curto, S. Neugebauer, A. Viola, M. Traverso, V. Franzitta, and M. Trapanese, "First Life Cycle Impact Considerations of Two Wave Energy Converters," in *2018 OCEANS - MTS/IEEE Kobe Techno-Oceans (OTO)*, 2018, pp. 1–5.

[23] A. Viola, V. Franzitta, D. Curto, V. Di Dio, D. Milone, and G. Rodono, "Environmental Impact Assessment (EIA) of Wave Energy Converter (WEC)," in *OCEANS 2015 - Genova*, 2015, pp. 1–4.

[24] D. Curto, V. Franzitta, A. Guercio, and G. Napoli, "First analyses on a mechanical motion converter to produce electrical energy from sea wave," in *Global Oceans 2020: Singapore – U.S. Gulf Coast*, 2020, pp. 1–7.

[25] G. Mørk, S. Barstow, A. Kabuth, and M. T. Pontes, "Assessing the Global Wave Energy Potential," in *29th International Conference on Ocean, Offshore and Arctic Engineering: Volume 3*, 2010, no. 2008, pp. 447–454.

[26] V. Franzitta, A. Milone, D. Milone, S. Pitruzzella, M. Trapanese, and A. Viola, "Experimental Evidence on the Thermal Performance of Opaque Surfaces in Mediterranean Climate," *Adv. Mater. Res.*, vol. 860–863, no. February 2016, pp. 1227–1231, Dec. 2013.

[27] A. F. de O. Falcão, "Wave energy utilization: A review of the technologies," *Renew. Sustain. Energy Rev.*, vol. 14, no. 3, pp. 899–918, Apr. 2010.

[28] A. Bonanno, V. Franzitta, F. P. Muzio, and M. Trapanese, "A multiphysics approach to the design of a seawave energy conversion system," in *2008 IEEE International Conference on Sustainable Energy Technologies*, 2008, pp. 665–668.

[29] F. M. Raimondi, D. Milone, and D. Curto, "An innovative mechanical motion converter for sea wave applications," in *2018 Thirteenth International Conference on Ecological Vehicles and Renewable Energies (EVER)*, 2018, pp. 1–6.

[30] ISO (International Organization for Standardization), *UNI EN ISO 14040. Environmental management - Life cycle assessment - Principles and framework*. 2021.

[31] ISO (International Organization for Standardization), *UNI EN ISO 14044. Environmental management - Life cycle assessment - Requirements and guidelines*. 2021.

[32] S. Fazio, V. Castellani, S. Sala, E. Schau, M. Secchi, and L. Zampori, "Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods, EUR 28888 EN, European Commission, Ispra, 2018. ISBN 978-92-79-76742-5.," 2019.

[33] European Union, "Commission recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations. 2013/179/EU. Official Journal of the European Union." 2013.

[34] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, and B. Weidema, "The ecoinvent database version 3 (part I): overview and methodology," *Int. J. Life Cycle Assess.*, vol. 21, no. 9, pp. 1218–1230, 2016.