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Water and Carbon Footprint of Wine: Methodology Review and Application to a Case Study

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Abstract: Life cycle assessments (LCAs) play a strategic role in improving the environmental performance of a company and in supporting a successful marketing communication. The high impact of the food industry on natural resources, in terms of water consumption and greenhouse gases emission, has been focusing the attention of consumers and producers towards environmentally sustainable products. This work presents a comprehensive approach for the joint evaluation of carbon (CF) and water (WF) footprint of the wine industry from a cradle to grave perspective. The LCA analysis is carried out following the requirements of international standards (ISO/TS 14067 and ISO 14046). A complete review of the water footprint methodology is presented and guidelines for all the phases of the evaluation procedure are provided, including acquisition and validation of input data, allocation, application of analytic models, and interpretation of the results. The strength of this approach is the implementation of a side-by-side CF vs. WF assessment, based on the same system boundaries, functional unit, and input data, that allows a reliable comparison between the two indicators. In particular, a revised methodology is presented for the evaluation of the grey water component. The methodology was applied to a white and a red wine produced in the same company. A comparison between the two products is presented for each LCA phase along with literature results for similar wines.

Keywords: Water Footprint (WF); Carbon Footprint (CF); Life Cycle Assessment (LCA); Wine Industry

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1. Introduction

The human influence on the climate system is evident, and present anthropogenic emissions of greenhouse gases are the highest in history [1].

Among all the production sectors, the food industry is one of those characterized by a significant impact in terms of greenhouse gas (GHG) emissions, which are estimated as 29% of all anthropogenic emissions [2]. Moreover, the food sector is also one of the major impacting sectors in terms of freshwater consumption, accounting for approximately 70% of all the human use [3,4].

Because of their success in reaching a large audience and their ease of understanding, Carbon Footprint (CF) and Water Footprint (WF) are two of the most widespread indicators for the evaluation of the total direct and indirect environmental impact related to food production and consumption.

CF and WF analyses of products are carried out with a Life Cycle Assessment (LCA) approach [5,6], which allows the evaluation of impacts from a cradle to grave perspective, following the requirements of their respective reference international standards, ISO/TS 14067 [7] and ISO 14046 [8].

Since wine is one of the most relevant products in the economic production and in the world distribution market, the wine industry emerges as one of the most analyzed sectors. Literature regarding CF [9–11] is quite extensive and encompasses studies that deal with a complete LCA of a wine bottle, studies concerning specific phases of the production process [12–21], supply chain analyses [22,23] and also comparative analyses between conventional and unconventional viticulture activities [24]. In addition, studies regarding conceptual and methodological aspects [25,26] and review studies regarding the use of CF as an environmental indicator in the wine industry [27] are available. Regarding WF, some case studies are available for agriculture and agri-food sector [28–33], and for wine in particular, with a focus both on grape-wine production [34] and wine bottle [35–37]. Some studies regarding the critical review of WF methodology, with a particular focus on grey WF in the winemaking industry, are also available in literature [38–40]. With respect to such works, improvements on the evaluation of indirect blue, and direct and indirect grey water volumes are presented.

This paper presents a complete review of the WF methodology and provides guidelines for all the stages of the evaluation procedure, including data acquisition and validation, allocation, application of analytic models, and interpretation of the results. A WF assessment is then carried out in parallel with a CF analysis for a white and a red wine produced by the same company in Umbria, Italy, and results are presented side-by-side for each lifecycle phase.

2. Methodology

2.1. Impact Assessment Methodology

The water footprint (WF) of a product is the sum of freshwater volumes consumed during the product life cycle [41], including real (green and blue) and virtual (grey) volumes:

$$WF = WF_{green} + WF_{blue} + WF_{grey} \tag{1}$$

Green (WF_{green}, Section 2.1.1) and blue (WF_{blue}, Section 2.1.2) components are the consumptive use of rain and freshwater, respectively. The grey component (WF_{grey}) is the amount of virtual water needed to dilute pollutants emitted to the natural water system during the process, quantified to guarantee that the quality of the ambient water remains beyond some reference water quality standards. Following the methodology presented in this paper for agriculture products, WF_{grey} is the sum of two components:

$$WF_{grey} = WF_{grey,direct} + WF_{grey,indirect} \tag{2}$$

where $WF_{grey,direct}$ (Section 2.1.3) is due to transport of pollutants applied to the crop (treatments and fertilizers), and $WF_{grey,indirect}$ (Section 2.1.4) takes into account all the emission of pollutants in water during other processes involved in the product life cycle.

The carbon footprint (CF) of a product is computed using a standardized procedure as defined in Section 2.1.5.

2.1.1. Green Water Footprint

The green water footprint is defined as the total volume of rainwater used by the crop for evapotranspiration, and it is directly connected to site meteorological data and soil properties of a specific vineyard (i.e., territorial unit). The calculation, performed on a daily basis, follows the FAO methodology [42], which is the standard procedure for calculating crop evapotranspiration. For rain-fed cropping systems, the green water footprint is equivalent to the sum of daily volume of water effectively consumed by evaporation and transpiration over an entire year

$$WF_{green} = \sum_i ET_{a,i} \tag{3}$$

The effective evapotranspiration of the crop for the *i*-th day ($ET_{a,i}$) is computed as a function of the water stress coefficient ($k_{s,i}$) and the single crop coefficient ($k_{c,i}$) according to

$$ET_{a,i} = k_{s,i} \cdot k_{c,i} \cdot ET_{0,i} \tag{4}$$

The daily reference evapotranspiration ($ET_{0,i}$) is the maximum amount of water (mm/day) that can be evapotranspirated considering meteorological conditions only. It is given by the FAO Penmant–Monteith equation

$$ET_0 = \frac{0.408 \cdot \Delta \cdot R_n + \gamma \cdot \frac{900}{t + 273.15} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot u_2)} \tag{5}$$

where Δ ($kPa \cdot {}^\circ C^{-1}$) is the slope of the vapor pressure curve, R_n ($MJ \cdot m^{-2} \cdot day^{-1}$) is the net radiation at the crop surface, γ ($kPa \cdot {}^\circ C^{-1}$) is the psychrometric constant, t (°C) is the mean temperature at 2 m height, u_2 ($m \cdot s^{-1}$) is the wind speed at 2 m height, and e_s and e_a (kPa) are the saturation and actual vapor pressures, respectively.

The single crop coefficient incorporates the characteristics of the crop to determine the crop evapotranspiration ($ET_{c,i}$) as a function of $ET_{0,i}$:

$$ET_{c,i} = k_{c,i} \cdot ET_{0,i} \tag{6}$$

It is given considering an interpolation of values for rest, initial, development, mid, and late stages of the crop cycle. Values for grapevines are reported in Table 1.

The water stress coefficient is a function of the water content in the root zone and it is used to compute the actual crop evapotranspiration:

$$ET_{a,i} = k_{s,i} \cdot ET_{c,i} \tag{7}$$

As a function of the soil properties, the totally available water content (mm) can be computed from

$$TAW = 1000 \cdot (\theta_{FC} - \theta_{WP}) \cdot z_r \tag{8}$$

where θ_{FC} and θ_{WP} ($m^3 \cdot m^{-3}$) are the water content at field capacity and at wilting point, respectively, and z_r (m) is the rooting depth. The water a crop can uptake is reduced before the wilting point is reached. The fraction of TAW that a crop can extract without suffering water stress (mm) is given by

$$RAW = p \cdot TAW \tag{9}$$

where p is the critical depletion factor and it is equal to 0.45 for grapevines. When the water content in the rooting zone is above RAW the crop is not water-stressed ($k_{s,i}$ = 1), otherwise

$$k_{s,i} = \frac{TAW - D_{r,i}}{(1 - p) \cdot TAW} \tag{10}$$

The water depletion in the rooting zone ($D_{r,i}$) can be obtained from a balance equation

$$D_{r,i} = D_{r,i\text{-}1} - P_{eff,i} - I_i + ET_{a,i} + DP_i \tag{11}$$

where $P_{eff,i}$, I_i, and DP_i (mm) are the effective precipitation, irrigation, and deep percolation, respectively. The initial depletion ($D_{r,0}$) is equal to the depletion at the end of the previous year, and it is 0 for the cases presented in this work. Deep percolation is zero if the water content in the rooting zone is below field capacity, otherwise it is given by

$$DP_i = P_{eff,i} + I_i - ET_{a,i} - D_{r,i\text{-}1} \tag{12}$$

The effective precipitation (mm) is the fraction of rainwater that reaches the rooting zone [43]

$$P_{eff,i} = P_i - \alpha \cdot LAI \cdot \left(1 - \frac{1}{1 + \frac{f_{sc} \cdot P_i}{\alpha \cdot LAI}}\right) \tag{13}$$

where LAI is the leaf area index (Table 1), P_i (mm) is the daily observed rain, and α is an empirical parameter (equal to 0.6 for grapevines). The soil cover fraction (f_{sc}) is given by [44]

$$f_{sc} = 1 - e^{-k_e \cdot LAI} \tag{14}$$

where the empirical value k_e = 0.385 was used for the extinction coefficient [45].

Results are in agreement with the output from the *CropWat* software [46].

Table 1. Values of single crop coefficients (k_c) and leaf area indices (LAI) for the red and white grapevines shown in this study (2012).

Stage		Rest	Initial	Develop.	Mid	Late	Rest
k_c		0.2	0.3	0.3 to 0.7	0.7	0.7 to 0.45	0.2
LAI		0.5	0.5	0.5 to 1.6	1.6	1.6 to 0.5	0.5
Duration (red)	(days)	91	30	60	40	80	65
Duration (white)	(days)	91	30	60	40	73	72

2.1.2. Blue Water Footprint

The blue water footprint is the consumption of freshwater (surface and groundwater) resources of a product during the entire life cycle. The WF_{blue} is evaluated as the sum of freshwater withdrawal using the EcoInvent database (ecoinvent, Zurich, Switzerland) [47]. All the freshwater volumes (lake, ground, river, and unspecified natural origin) classified as raw material in the LCI are considered. WF_{blue} includes both the direct contributions (i.e., tap/well water used in field and cellar activities) and the indirect contributions (e.g., leakage of the distribution grid, water for production of raw materials, transportations, etc.).

This methodology is applied to rain-fed cultures. In case of irrigation, blue water evapotranspirated by the crop ($WF_{blue,irrigation}$) must be included within WF_{blue}.

2.1.3. Direct Grey Water Footprint

The $WF_{grey,direct}$ is the virtual water volume needed to dilute the pollutant load applied in the vineyard, due to runoff, leaching and drift

$$WF_{grey,direct} = V_{runoff} + V_{drift} + V_{leaching} \tag{15}$$

Runoff is the transport of pollutants dissolved in the water that flows over the soil surface; the amount of pollutant that reaches the water body via runoff depends on slope, texture, amount and timing of rainfall and irrigation, if used, and the characteristic of active ingredient used [48]. The dilution volume for the pollutant load that reaches the surface water body via runoff (V_{runoff}) is the sum of the volumes to dilute each *i*-th pollutant load

$$V_{runoff} = \sum_{i} \left(V_{runoff,i} \right) \quad (16)$$

The virtual water volume $V_{runoff,i}$ ($m^3 \cdot ha^{-1}$) is estimated as follows

$$V_{runoff,i} = \frac{Runoff_i}{C_{NOEC,i}} \quad (17)$$

where $C_{NOEC,i}$ ($kg \cdot m^{-3}$) is the minimum value of No-Observed-Effect-Concentration (NOEC) limit among *Daphia*, *Algae* and *Fish* for the *i*-th pollutant [49]. $Runoff_i$ ($kg \cdot ha^{-1}$) is the predicted amount of active ingredient in surface water due to runoff and it is given by

$$Runoff_i = RATE_i \cdot (1 - f_{int}) \cdot f_{runoff} \cdot f_{slope} \cdot f_{buffer} \cdot f_{degradation,i} \quad (18)$$

where $RATE_i$ ($kg \cdot ha^{-1}$) is the application dose of the *i*-th active ingredient. The canopy intercepted fraction (f_{int}) depends on the phenological phase of the crop, as reported in Table 2.

Table 2. f_{int} values for the phenological stages [50].

BBCH	0–8	11–19	53–57	60–69	71–79	>80
$\mathbf{f_{int}}$	0.2	0.3	0.5	0.8	0.6	0.2

The fraction of active ingredient that participates to runoff (f_{runoff}) is a function of BBCH [51], perimeter P (m) and surface S (ha) of the vineyard, and it is calculated as follows [52]:

$$f_{runoff} = \begin{cases} 1 - \dfrac{0.758173 \cdot P}{2 \cdot 10^4 \cdot S}, 60 < BBCH < 79 \\ 1 - \dfrac{0.250698 \cdot P}{2 \cdot 10^4 \cdot S}, \text{elsewhere} \end{cases} \quad (19)$$

The slope factor (f_{slope}) is equal to 1 if the field slope (s) is higher than 20% [53]:

$$f_{slope} = \begin{cases} 0.02153 \cdot s + 0.001423 \cdot s^2, s < 20\% \\ 1, s \geqslant 20\% \end{cases} \quad (20)$$

The factor f_{buffer} depends on the distance between the vineyard and the nearest surface water body z (m) [53]:

$$f_{buffer} = 0.83^z \quad (21)$$

The fraction of the *i*-th active ingredient ($f_{degradation,i}$) that survives long enough to reach the surface water body is given by:

$$f_{degradation,i} = \frac{e^{-\Delta t \frac{\ln(2)}{t_{1/2,i}}}}{1 + K_{OC,i} \cdot OC} \quad (22)$$

where $t_{1/2,i}$ (days) is the half time of active ingredient in soil, K_{oc} is the sorption coefficient of active ingredient to organic carbon ($m^3 \cdot kg^{-1}$), OC is the organic carbon content in the soil ($kg \cdot m^{-3}$), and Δt (days) is the time between application and rain event. In this study an average value of three days is considered for Δt.

Drift is the airborne movement of droplet spray away from the field during application. The dilution volume for the pollutant load that reaches the surface water body via drift (V_{drift}) is the sum of the volumes to dilute each *i*-th pollutant:

$$V_{drift} = \sum_{i} (V_{drift,i}) \tag{23}$$

The virtual water volume $V_{drift,i}$ ($m^3 \cdot ha^{-1}$) is given by:

$$V_{drift,i} = \frac{Drift_i}{C_{NOEC,i}} \tag{24}$$

The predicted pollutant load ($Drift_i$) depends on the application dose $RATE_i$ ($kg \cdot ha^{-1}$) of the *i*-th active ingredient

$$Drift_i = RATE_i \cdot f_{drift} \tag{25}$$

where f_{drift} is a fraction representing the drift deposit at a certain distance from the field, and depends on crop type, stage and distance from water body (z). The drift curves [54] were used to predict drift at certain distance downwind the field, as a percentage of the applied dose [55]

$$f_{drift} = \begin{cases} 0.157926 \cdot z^{-1.608}, & BBCH < 60 \\ 0.44769 \cdot z^{-1.563}, & BBCH \geqslant 60 \end{cases} \tag{26}$$

where z (m) is the distance from the nearest water body.

Leaching is the movement of pollutants through the soil. The dilution volume for the pollutant load that reaches the groundwater via leaching ($V_{leaching}$) is the sum of the following two terms:

$$V_{leaching} = V_{leaching,N} + \max(V_{leaching,i}; V_{leaching,tot}) \tag{27}$$

The virtual water needed to dilute nitrates ($V_{leaching,N}$) is given by

$$V_{leaching,N} = \frac{Leaching_N}{C_{legal,N}} \tag{28}$$

where $C_{legal,N}$ ($kg \cdot m^{-3}$) is the maximum allowed concentration of nitrogen in groundwater [56]. $Leaching_N$ ($kg \cdot ha^{-1}$) is the amount of nitrogen that reaches the groundwater reservoir and it is computed according to

$$Leaching_N = Q_{fert} \cdot f_N \cdot f_{leaching,N} \tag{29}$$

where Q_{fert} ($kg \cdot ha^{-1}$) is the amount of nitrogen fertilizer used in the field, f_N is the fraction of nitrogen in the fertilizer, and $f_{leaching,N}$ is the fraction of nitrogen that reaches the groundwater reservoir. A constant value of 0.06 is used for $f_{leaching,N}$ [38].

$V_{leaching,i}$ and $V_{leaching,tot}$ are the volumes to dilute the *i*-th pollutant and the total of pollutants other than nitrates, respectively.

The virtual water volume $V_{leaching,i}$ ($m^3 \cdot ha^{-1}$) is estimated as follows

$$V_{leaching,i} = \frac{Leaching_i}{C_{legal,i}} \tag{30}$$

where $C_{legal,i}$ is the legal limit, which represents the maximum allowed concentration of the *i*-th pollutant in groundwater [56]. The pollutant load is given by

$$Leaching_i = RATE_i \cdot AF_i \cdot (1 - f_{int}) \cdot f_{runoff} \tag{31}$$

where $RATE_i$ is the active ingredient applied ($kg \cdot ha^{-1}$), and f_{int} and f_{runoff} are the fractions defined above.

The attenuation factor AF_i is a function of half-life of the pollutant considered, field capacity of the soil, depth of soil layer [57]

$$AF_i = e^{-t_{d,i} \cdot \frac{\ln(2)}{t_{1/2,i}}} \quad (32)$$

where $t_{1/2,i}$ is the pollutant half-life in the soil (day). The travel time $t_{d,i}$ (day) is defined as

$$t_{d,i} = \frac{L \cdot \theta_{FC} \cdot RF_i}{J_w} \quad (33)$$

where L (m) is the soil depth. The soil average daily water net recharge J_w ($m \cdot day^{-1}$) is given by

$$J_W = -0.2855 + 0.0008637 \cdot P_{year} \quad (34)$$

where P_{year} (mm) is the annual precipitation. The retardation factor (RF) represents the delay of the pesticides leaching with regard to the water flow in the soil and it is given by [58]

$$RF_i = 1 + \frac{\rho \cdot f_{OC} \cdot K_{OC,i}}{\theta_{FC}} + \frac{\delta \cdot H_i}{\theta_{FC}} \quad (35)$$

where ρ ($kg \cdot m^{-3}$) is the soil bulk density, θ_{FC} is the field capacity, H_i is the Henry's constant water-air pesticide partition coefficient, f_{OC} is the soil carbon volumetric fraction, $K_{OC,i}$ ($m^3 \cdot kg^{-1}$) is the soil-carbon pesticide partition coefficient. The soil air volumetric fraction (δ) is given by:

$$\delta = (\phi - \theta_{FC}) \quad (36)$$

where ϕ, the soil porosity.

2.1.4. Indirect Grey Water Footprint

This component is defined as the virtual water volume needed to dilute the pollutants emitted in water during all the processes involved in the product life cycle other than ones already taken into account in Section 2.1.3. $WF_{grey,indirect}$ is evaluated considering two pollution indicators that assess the water quality: Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD). The $WF_{grey,indirect}$ is the maximum value between the volumes (V_{COD} and V_{BOD}) needed to dilute COD and BOD. They are computed considering EU legal limits (C_{COD} and C_{BOD}) for pollutant concentration [56]

$$WF_{grey,indirect} = \max(V_{COD}; V_{BOD}) \quad (37)$$

$$V_{COD} = \frac{COD}{C_{COD}}; V_{BOD} = \frac{BOD}{C_{BOD}} \quad (38)$$

In this analysis, only dilution volumes for COD and BOD are considered, in the assumption that other pollutant emission in water requires lower dilution volumes.

Unlike different approaches (e.g., [38,41]), both direct and indirect grey volumes are computed every time a pollutant reaches a water body and not just when some limit value is exceeded. This choice was adopted in order to avoid underestimations in the case of multiple processes insisting on the same water body.

2.1.5. Carbon Footprint

CF is a single-issue indicator commonly used to express the pressure of human activities on the environment. CF quantifies the impact of a given activity/process/product in terms of equivalent carbon dioxide (CO_{2eq}) emissions, considering the total amount of direct and indirect GHG emissions related to activity/process/product itself. The carbon footprint of a product (CFP) is evaluated with a Life Cycle Assessment (LCA) approach [5,6], according to the ISO/TS 14067 standard [7], which details principles, requirements, and guidance for the quantification and communication of the CFP, including goods and services. Among the different quantification methodologies, an approach based on activity data multiplied by appropriate emission/removal factors has been adopted in this study. Therefore, the CF related to *i*-th process included in the lifecycle of the product (CF_i) is computed using the following equation:

$$CF_i = EF_i \cdot A_i \tag{39}$$

where A_i is the activity data and EF_i is the emission factor of the *i*-th process.

The emission factors used are in compliance with the IPCC methodology [59], computed considering each GHG emission generated by the process and characterizing them through their Global Warming Potential (GWP), which relates the impact generating by the emission of a generic gas to that of an equivalent mass of CO_2:

$$EF_i = \sum_j GWP_j \cdot e_{j,i} \tag{40}$$

where $e_{j,i}$ is the emission (in mass unit) of the *j*-th GHG associated to the *i*-th process per unitary amount. As an example, Table 3 shows the GWP of some relevant GHGs (considering the time horizon of 100 years recommended for CF assessments).

Table 3. Global Warming Potential of relevant GHGs [59].

Name	Formula	GWP	
Carbon dioxide	CO_2	1	$kgCO_{2eq}/kgCO_2$
Methane	CH_4	25	$kgCO_{2eq}/kgCH_4$
Nitrous oxide	N_2O	298	$kgCO_{2eq}/kgN_2O$

Site-specific activity data were as far as possible used to implement the calculation methodology for the studied product, using the PRé Consultants SimaPro 8.0 software [60] and the associated EcoInvent database [47].

2.2. Boundaries and Functional Unit

The system boundaries represent the interface between the product system and the environment and their definition determines which unit processes shall be included within the assessment. Consistently with the goal of the study, the system boundaries include grapes production, vinification, and marketing of the final product, while the final transportation of the product from the retailer to the end consumer is not included. According to point 6.2.1 of the ISO/TS 14067 that suggests adopting existing relevant Product Category Rules (PCR), the product lifecycle was modeled considering three main modules: upstream, core, and downstream [61]. Within the upstream module are included all the inflow of raw materials and energywares required for the wine production, the core module includes the production and the packaging of the final product (including internal transportation and external transportation of raw materials and energywares), while the downstream module comprises the transportation to a distribution platform and the handling (recycling or disposal) of packaging materials (Figure 1).

The functional unit (FU) is defined as a quantified performance of a product system for use as a reference unit in a LCA study and its primary purpose is to provide a reference to which the inputs and outputs are related. The FU used in this study is a 0.75 L wine bottle.

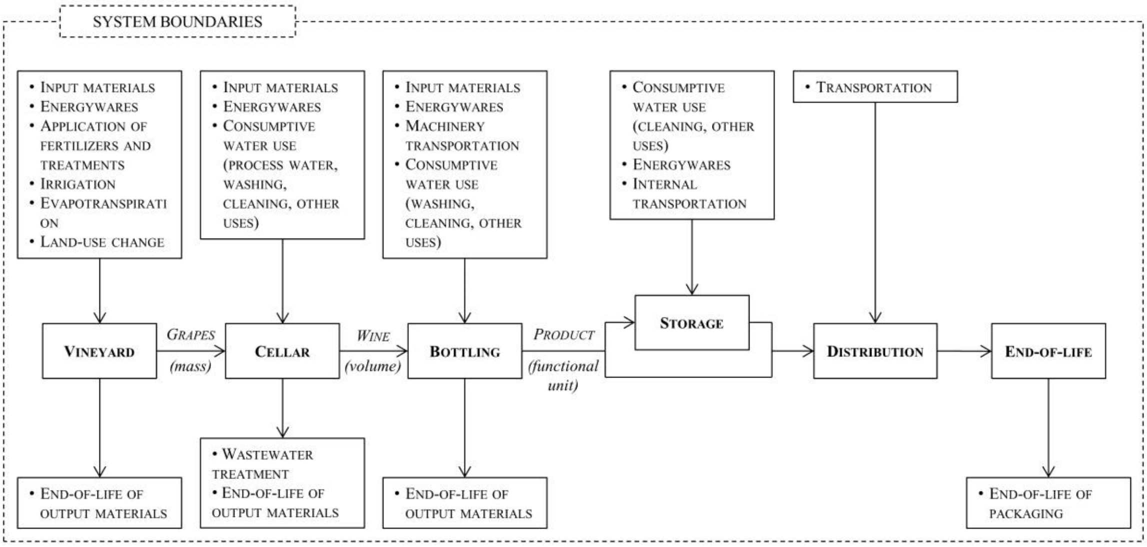

Figure 1. System boundaries and flow diagram.

2.3. Data Collection

As mentioned above, the Life Cycle Inventory (LCI) was built up with activity data directly gathered from the winery (Tables 4 and 5), except for the end-of-life phase, which was modeled considering representative scenarios based on average national and international data (Table 6). Red and white wines have different end-of-life scenarios according to the different distribution of the two products. Recycling, landfill, and incineration rates were computed according to [62].

Table 4. Input data—1.

Product	Surface	Grapes Yield	Wine Yield	Soil Texture	Altitude a.s.l.
	Ha	10^2 kg· ha^{-1}	l· 10^{-2}· kg^{-1}		m
Company avg.	24.11	99.43	78.19	-	-
Red wine	0.67	100.00	60.00	loam	271
White wine	4.00	80.00	68.00	loam-clay	214

Table 5. Input data—2. All data are allocated to the functional unit.

Parameter	Unit	Red Wine	White Wine	Parameter	Unit	Red Wine	White Wine
N fertilizer	kg	2.80×10^{-3}	3.10×10^{-3}	Diesel consumption	l	3.00×10^{-2}	3.30×10^{-2}
P fertilizer	kg	1.20×10^{-3}	1.30×10^{-3}	Electricity	kWh	1.80×10^{-1}	1.80×10^{-1}
K fertilizer	kg	3.50×10^{-3}	3.90×10^{-3}	Water use grape production	m^3	5.50×10^{-4}	6.10×10^{-4}
Organic fertilizer	kg	2.30×10^{-3}	2.60×10^{-3}	Water use cellar activities	m^3	2.20×10^{-3}	2.20×10^{-3}
Generic pesticide	kg	4.00×10^{-4}	4.40×10^{-4}	Bottle (glass)	kg	4.50×10^{-1}	3.90×10^{-1}
Triazine compounds	kg	2.80×10^{-6}	3.10×10^{-6}	Cork	kg	4.00×10^{-3}	4.00×10^{-3}
Fosetyl Aluminium	kg	5.30×10^{-4}	5.90×10^{-4}	Capsule	kg	1.00×10^{-3}	1.00×10^{-3}
Sulphur	kg	6.70×10^{-3}	7.40×10^{-3}	Labels	kg	1.00×10^{-3}	1.00×10^{-3}
Acetamide compound	kg	5.50×10^{-5}	6.10×10^{-5}	Core board box distribution	kg	4.80×10^{-2}	4.80×10^{-2}
Copper	kg	5.10×10^{-4}	5.70×10^{-4}	Packaging PET	kg	8.80×10^{-3}	2.80×10^{-3}
Dichloro	kg	6.20×10^{-5}	6.90×10^{-5}	Packaging PET (Hazardous)	kg	1.10×10^{-4}	1.20×10^{-4}
Metalaxil m	kg	4.10×10^{-6}	4.60×10^{-6}	Packaging Paper (Hazardous)	kg	3.00×10^{-4}	3.30×10^{-4}
Lubricating oil	kg	2.20×10^{-4}	2.20×10^{-4}	Packaging Paper	kg	1.60×10^{-6}	1.60×10^{-6}
Propylene glycol	kg	3.00×10^{-6}	3.00×10^{-6}	Packaging film	kg	5.60×10^{-4}	5.20×10^{-4}
Potassium metabisulfite	kg	1.70×10^{-4}	2.30×10^{-4}	Packaging Coreboard box	kg	3.00×10^{-4}	4.70×10^{-4}
Enzyme	kg	1.60×10^{-6}	1.60×10^{-6}	Transport lorry < 3.5 t	tkm	4.60×10^{-3}	4.60×10^{-3}
Yeast	kg	4.00×10^{-5}	4.00×10^{-5}	Transport lorry 3.5–7.5 t	tkm	3.20×10^{-2}	2.90×10^{-2}
Carbon dioxide	kg	3.40×10^{-3}	3.40×10^{-3}	Transport lorry 16–32t	tkm	2.50×10^{-3}	2.50×10^{-3}
Acetic acid	kg	1.30×10^{-5}	1.30×10^{-5}	Transport car	tkm	3.40×10^{-2}	3.40×10^{-2}
Diammonium Phosphate	kg	4.00×10^{-4}	4.00×10^{-4}	Distribution Lorry < 3.5 t	tkm	1.50×10^{-1}	1.40×10^{-1}
Soap	kg	1.50×10^{-3}	1.50×10^{-3}	Distribution lorry 3.5–7.5 t	tkm	2.80×10^{-1}	2.60×10^{-1}
R404A leakage	kg	8.40×10^{-7}	8.40×10^{-7}	Distribution ship	tkm	0	4.20×10^{-1}

Table 6. End of life scenario.

Waste	Material	Red Wine			White Wine		
		Recycling	Landfill	Incineration	Recycling	Landfill	Incineration
		%	%	%	%	%	%
Box	Cardboard	77.50%	22.50%	-	77.05%	22.95%	-
Bottle	Glass	70.70%	29.30%	-	68.95%	31.05%	-
Cork	Cork	-	100%	-	-	100%	-
Label	Paper		29.30%	70.70%		31.05%	68.95%
Capsule	Plastic	34.72%	65.28%	-	35.65%	64.35%	-

3. Results and Discussion

Results of the carbon and water footprint analysis are shown for the red wine (Figure 2 and Table 7) and for the white wine (Figure 3 and Table 8).

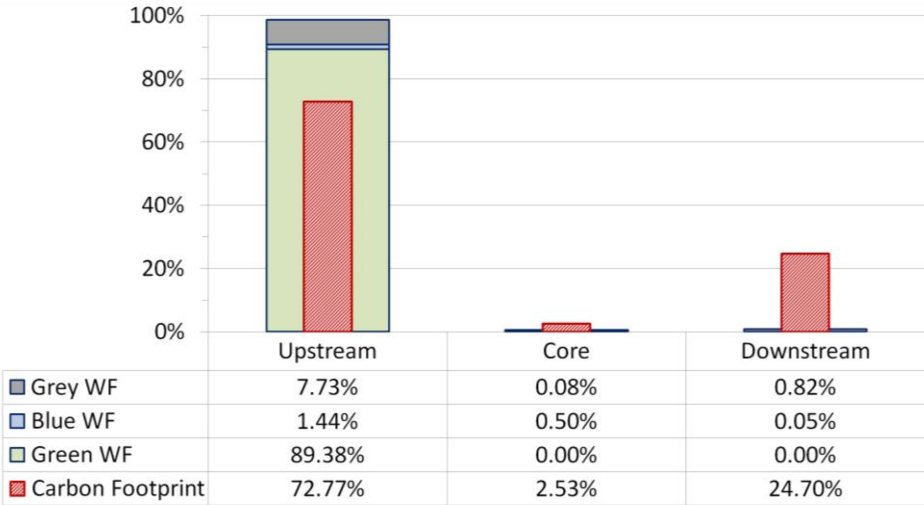

Figure 2. Carbon and water footprint results for the red wine.

Table 7. CF and WF results for the red wine.

Module	Phase	Carbon Footprint		Water Footprint		Green WF	Blue WF	Grey WF
		$kgCO_{2eq}$/Bottle	%	L/Bottle	%	%	%	%
Upstream	Energywares	0.1262	8.75%	1.823	0.36%	0.00%	0.12%	0.24%
	Field Water	0.0002	0.01%	0.6	0.12%	0.00%	0.12%	0.00%
	Grapes	0.2689	18.64%	458.43	90.95%	89.38%	0.22%	1.34%
	Other Materials	0.01491	1.03%	1.663	0.33%	0.00%	0.19%	0.14%
	Packaging	0.62660	43.43%	15.843	3.14%	0.00%	0.78%	2.37%
	Use of fertilizers	0.0131087	0.91%	18.3750	3.65%	0.00%	0.00%	3.65%
Core	Cellar Water	0.000767	0.05%	2.4535288	0.49%	0.00%	0.48%	0.00%
	Materials	0.00216	0.15%	0.0002	0.00%	0.00%	0.00%	0.00%
	Transportation	0.0336308	2.33%	0.470	0.09%	0.00%	0.02%	0.08%
Downstream	Distribution	0.4277	29.65%	5.0911	1.01%	0.00%	0.19%	0.82%
	End-of-life	−0.07136	−4.95%	−0.71	−0.14%	0.00%	−0.14%	0.00%
Upstream total		1.0499	72.77%	496.8	98.55%	89.38%	1.43%	7.74%
Core total		0.0366	2.53%	2.9238	0.58%	0.00%	0.50%	0.08%
Downstream total		0.3564	24.70%	4.38	0.87%	0.00%	0.05%	0.82%
Total		1.443	100%	504.1	100%	89.38%	1.98%	8.64%

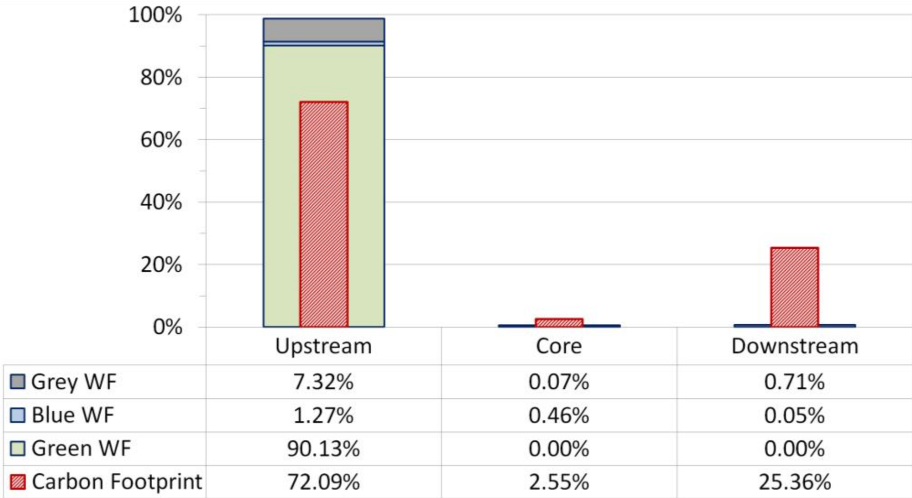

Figure 3. Carbon and water footprint results for the white wine.

Table 8. CF and WF results for the white wine.

Module	Phase	Carbon Footprint		Water Footprint		Green WF	Blue WF	Grey WF
		$kgCO_{2eq}$/Bottle	%	l/bottle	%	%	%	%
Upstream	Energywares	0.1277	9.28%	1.897	0.34%	0.00%	0.11%	0.23%
	Field Water	0.0002	0.02%	0.7	0.13%	0.00%	0.13%	0.00%
	Grapes	0.2965	21.53%	505.30	91.70%	90.13%	0.22%	1.35%
	Other Materials	0.01500	1.09%	1.665	0.30%	0.00%	0.18%	0.12%
	Packaging	0.53854	39.11%	14.155	2.57%	0.00%	0.63%	1.94%
	Use of fertilizers	0.0144583	1.05%	20.2665	3.68%	0.00%	0.00%	3.68%
Core	Cellar Water	0.000767	0.06%	2.4535288	0.45%	0.00%	0.44%	0.00%
	Materials	0.00216	0.16%	0.0002	0.00%	0.00%	0.00%	0.00%
	Transportation	0.0321622	2.34%	0.453	0.08%	0.00%	0.02%	0.07%
Downstream	Distribution	0.4040	29.34%	4.7998	0.87%	0.00%	0.16%	0.71%
	End-of-life	−0.05479	-3.98%	−0.64	−0.12%	0.00%	−0.12%	0.00%
Upstream total		0.9925	72.08%	544.0	98.72%	90.13%	1.27%	7.32%
Core total		0.0351	2.56%	2.9065	0.53%	0.00%	0.46%	0.07%
Downstream total		0.3492	25.36%	4.16	0.75%	0.00%	0.05%	0.71%
Total		1.377	100%	551.0	100%	90.13%	1.77%	8.10%

Total CF and WF of the red wine are 1.433 $kgCO_{2eq}$/bottle and 504.1 L/bottle, respectively. The major impact is due to the upstream phase, representing 72.77% and 98.55% of total CF and WF, respectively. Most impacting phases, in terms of CF, are packaging (43.43%), distribution (29.65%), and grapes production (18.64%). The WF is almost entirely associated to grapes production (90.95%), followed by use of fertilizers (3.65%) and packaging (3.14%).

Total CF and WF of the white wine are 1.377 $kgCO_{2eq}$/bottle and 551.0 L/bottle, respectively. As for the red wine, the major impact is due to the upstream phase, representing 72.09% and 98.72% of total CF and WF, respectively. Most impacting phases, in terms of CF, are packaging (39.12%), distribution (29.34%), and grapes production (21.54%). The WF is almost entirely due to grapes production (91.70%), followed by use of fertilizers (3.68%) and packaging (2.57%).

As a result of this study, it can be noted that some processes do not produce impacts on CF and all the WF components in a homogeneous way. For example, crop evapotranspiration is entirely responsible for the WF_{green}, but no CF is associated to the process. Similarly, no CF is associated to $WF_{grey,direct}$. Absolute values of CF and WF phases, not taking into account WF_{green}, are shown in Figure 4 (red wine) and Figure 5 (white wine).

A correlation analysis between CF and WF phases was performed testing CF vs. $WF_{grey,indirect}$ and CF vs. WF_{blue}+$WG_{grey,indirect}$ for red (Figure 6) and white (Figure 7) wine. Values were grouped considering a 0.1 $kgCO_{2eq}$ bin size and data were fitted using a linear regression. Fit results for CF vs. $WF_{grey,indirect}$ are 15.38 L/$kgCO_{2eq}$ (red wine) and 15.29 L/$kgCO_{2eq}$ (white wine), with a fit probability of 70% and 73%, respectively. Fit results for CF vs. $WF_{blue}+WG_{grey,indirect}$ are 20.32 L/kgCO_{2eq} (red wine) and 20.17 L/kgCO_{2eq} (white wine), with a fit probability of 42% in both cases. As a result, data show a reasonable correlation probability (above the 1-sigma threshold) for CF vs. $WF_{grey,indirect}$, while it is below the acceptance level when testing CF vs. $WF_{blue}+WG_{grey,indirect}$.

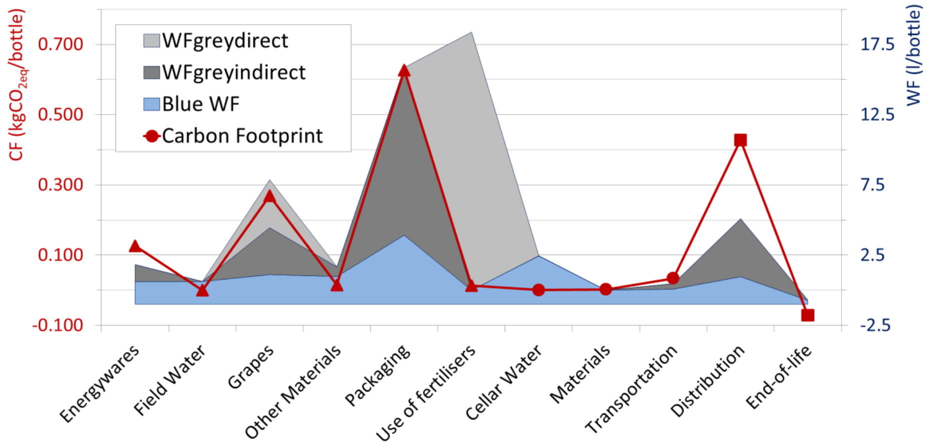

Figure 4. WF vs. CF for the red wine. WF_{green} is not shown.

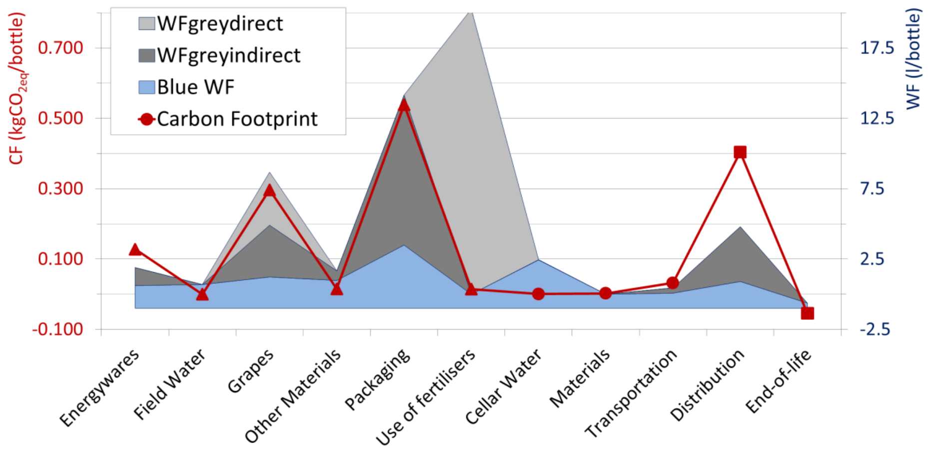

Figure 5. WF vs. CF for the white wine. WF_{green} is not shown.

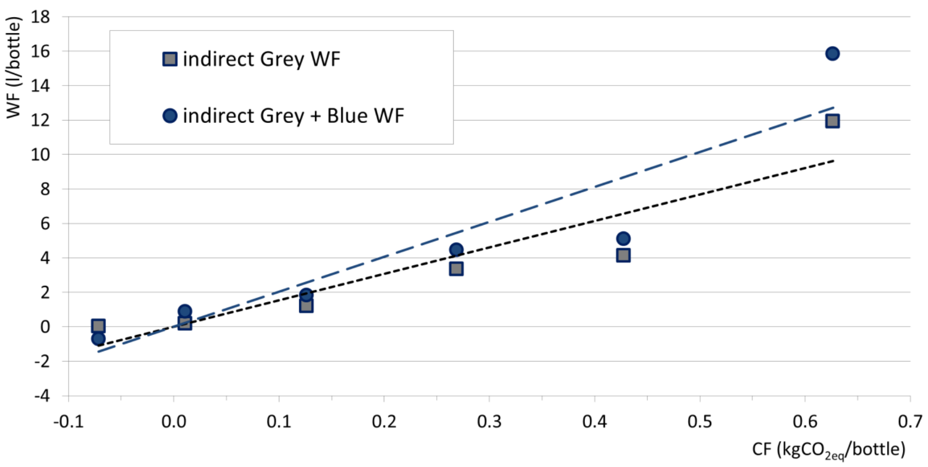

Figure 6. Correlation analysis for the red wine: CF vs. $WF_{grey,indirect}$ (grey) and CF vs. $WF_{blue}+WF_{grey,indirect}$ (blue).

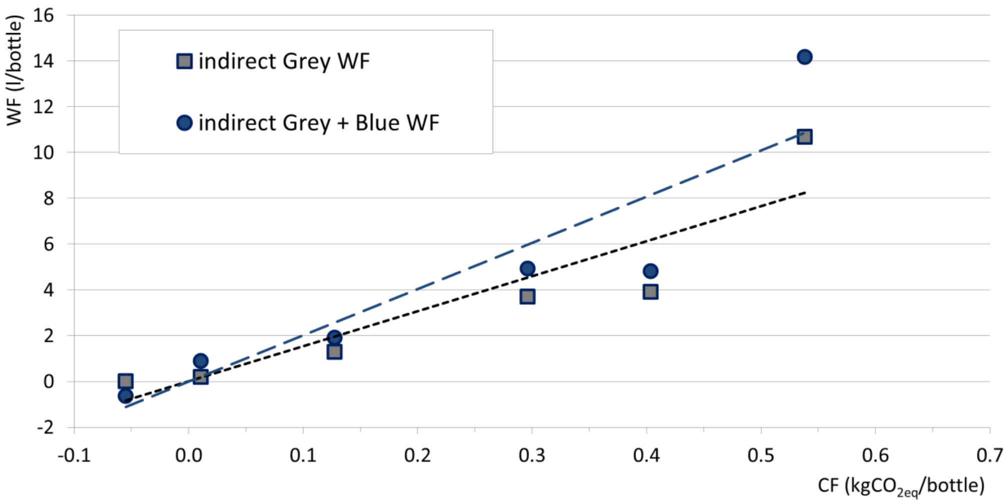

Figure 7. Correlation analysis for the white wine: CF vs. $WF_{grey,indirect}$ (grey) and CF vs. WF_{blue}+$WF_{grey,indirect}$ (blue).

Results were finally tested against different cut-off criteria applied at a phase level. If a 1% cut-off rule is applied, the resulting CF and WF of the red wine are 1.427 $kgCO_{2eq}$/bottle (−1.14%) and 497.7 L/bottle (−1.26%), respectively. CF and WF of the white wine are 1.374 $kgCO_{2eq}$/bottle (−0.25%) and 539.7 L/bottle (−2.05%), respectively. The variation of both CF and WF of the two products is consistent with the cut-off, with a maximum of approximately −2% with respect to the reference case. However, a general cut-off criterion for the proposed methodology and its effect on final results could only be established after more products are evaluated.

4. Conclusions

An original and comprehensive methodology for the joint assessment of carbon and water footprint is presented. The methodology was setup in order to include all the phases of the life cycle of a wine product in a cradle-to-grave approach and it could be easily adapted for application to other agricultural products. The main advantage of a comprehensive approach is the use of the same system boundaries, allocation procedure, and product modeling, guaranteeing the uniformity of final results between CF and WF and hence a reliable comparison. The functional unit is a 0.75 L wine bottle. Impacts are computed in terms of GHG emission (kg of equivalent CO_2) and water intensity (L of freshwater consumed). The product life cycle was divided in a total of 11 phases, grouped into three modules (upstream, core, and downstream).

The water footprint is defined as the sum of green, blue, and grey volumes of freshwater consumed during the product life cycle. A detailed review of the assessment methodology is presented for the evaluation of evapotranspirated water (WF_{green}), ground and surface freshwater withdrawal (WF_{blue}), water pollution generated by the use of treatments and fertilizers ($WF_{grey,direct}$), and water pollution generated by other processes ($WF_{grey,indirect}$).

The methodology was applied for the evaluation of CF and WF of two wines (red and white) produced by the same winery during vintage year 2012. CF and WF of the red wine are 1.433 $kgCO_{2eq}$/bottle and 504.1 L/bottle, respectively. CF and WF of the white are 1.377 $kgCO_{2eq}$/bottle and 551.0 L/bottle, respectively. The CF of the red wine is higher than the white wine because of the heavier bottle used (0.45 vs. 0.39 kg). The WF of the white wine is higher than the red wine because of the lower productivity of white grapes per unit surface (5440 vs. 6000 L/ha).

A correlation analysis was finally performed to test the proportionality between CF and WF results from the 11 phases. A good probability (>70%) is found when fitting $WF_{grey,indirect}$ vs. CF for both wines. The result is 15.38 L/kgCO_{2eq} (red wine) and 15.29 L/kgCO_{2eq} (white wine). A more robust estimate of correlation parameters will require the evaluation of larger number of products.

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Author Contributions: Sara Rinaldi and Emanuele Bonamente were responsible of the methodology revision, lifecycle modelling, results interpretation, and general coordination. Flavio Scrucca and Maria Cleofe Merico supported data acquisition and modelling activities. Francesco Asdrubali and Franco Cotana supervised the project.

Conflicts of Interest: The authors declare no conflict of interest.

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